STT Netherlands
Study Centre for
Technology Trends

Microsystem technology

exploring opportunities

edited by Gerben Klein Lebbink

Samsom

STT 56

MICROSYSTEM TECHNOLOGY: EXPLORING OPPORTUNITIES

**Stichting
Toekomstbeeld
der Techniek**

The Netherlands Study Centre for Technology Trends (STT), founded in 1968 by the Royal Institution of Engineers in the Netherlands, has the following aims:

- to evaluate technological trends from the viewpoint of the engineering sciences and to explore their interaction with other developments in society as a whole;
- to give wide publicity to its findings as a contribution to a more integrated picture of the future of society in the Netherlands and elsewhere.

The STT adresses itself to industry, government, science and, of course, the interested layman.

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MICROSYSTEM TECHNOLOGY: EXPLORING OPPORTUNITIES

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Preface

Every technology evolves. Every day, new elements or improvements are added to existing technologies. This is a gradual process to which companies respond by changing their products and processes.

Sometimes an industrial process makes a major step forwards. Microsystem technology is such an advance. Extreme miniaturization coupled with new ways of bringing together a number of conventional technologies have enabled us to develop components of considerably smaller dimensions than hitherto practicable. Great advances have also been made in the functionality of such components, as a result of which it is now possible to develop and market new products and processes.

Microsystem technology imposes different and more stringent demands on the organization of both products and production. New forms of collaboration are needed, both from the point of view of knowledge transfer and to ensure the economic viability of producing and using these systems. This book does not offer ready-made solutions for all these problems. It does, however, chart some important aspects of development and application. Naturally it looks at developments in the world market, and it also goes into some detail in making connections between those who may use microsystems in products, the producers of system components, the necessary research and the required training at research institutions.

Thanks to the enthusiasm of a large number of experts from industry and the world of research, both in the Netherlands and abroad, STT has succeeded in surveying a variety of market sectors and drawing a picture of what microsystem technology can offer us in the future and what still needs to be done. The book is thus a good starting-point for building an acquaintance with developments in the field of microsystem technology and gaining insight into the opportunities that it can offer. I hope it will give companies ideas which will ultimately lead to new products in the marketplace.

M.C. van der Harst
Director General, Industry & Services
Ministry of Economic Affairs
The Netherlands

Microsystem technology is more a new generic way of thinking about the miniaturization of systems rather than a novel technology. Indeed, existing state-of-the-art technologies in sensing and actuating principles, information processing, microelectronics fabrication and interconnection are combined in a new miniature system with increased performance and functionality by spatial integration.

A similar trend is also seen in other disciplines of science and technology. Whereas microsystem technology originates from research into microelectronics and precision engineering, material scientists nowadays study 'smart materials and structures' and biologists investigate the principles of 'biomimetic systems'. All these trends have in common that optimal spatial integration of different functionalities results in powerful systems. These systems have a natural interface with the outside world and are therefore well integrated into their environment.

An essential requirement for success in these trends is the degree of cross-functional and multidisciplinary integration we can achieve in our microsystem development programmes. Microsystem technology is not a new technology, but rather the fusion of different technologies.

A recent study of Flemish companies active in the field of information technology (IWT study *IT in Vlaanderen*, commissioned by the Minister-president L. Van den Brande), confirms that they are most of all system builders and integrators active in niche markets. This is exactly where microsystem technology can prove its worth. The study performed by STT, of which the results are summarized in this book, will therefore be of great significance to Flemish as well as Dutch industry, by providing a reference as to what microsystem technology means today, who is active in this field and what future possibilities may bring. This book is a good example of how technology diffusion in a new technically challenging area can be achieved.

One must be aware, however, that microsystem technology and miniaturization does not offer a solution to every problem. The tendency is usually to overestimate the possibilities of a new technological trend. A danger therefore exists that, after the initial enthusiasm, industry will become disappointed in the outcome and will refuse further investment in research and development in this new area. This danger also applies to microsystem technology.

One therefore has to address microsystem technology projects with commonsense and a good sense of reality. Added value, recognition of its own competence and an economically acceptable unit price remain key factors.

Christine Claus
Director General
Flemish Institute for the Promotion of
Scientific-Technological Research in Industry (IWT)
Belgium

Samenvatting

De publikatie *Microsystem technology: exploring opportunities* is het resultaat van een tweejarige verkenning van de microsysteemtechnologie (MST). Voor dit project, dat bij ons de naam *MUST* draagt, heeft STT gebruik kunnen maken van de kennis en ervaring van een groot aantal Nederlandse en Europese deskundigen. Omdat de industrie vaak kritiek heeft op het *technology push*-karakter van MST heeft STT gepoogd de behoefte centraal te stellen. De technische realisaties worden kort in de appendices behandeld.

Hoofdstuk 1

Hoofdstuk 1 geeft de achtergrond en de historische ontwikkeling van MST. Tevens worden de aanpak en de werkwijze van het project MUST toegelicht.

MST is gedefinieerd als de verzameling van alle technologieën die nodig zijn om produkten en componenten te maken die afmetingen hebben kleiner dan enige millimeters. Zodra er componenten met dergelijke afmetingen worden ingezet in half- of eindprodukten is er sprake van microsysteemtechnologie. De componenten waaraan gedacht kan worden, zijn microsensoren, micro-actuatoren en microsystemen. Deze laatste groep bestaat uit de combinatie en integratie van sensoren en actuatoren met intelligentie.

Hoofdstuk 2

Hoofdstuk 2 beschrijft de basis van de microsysteemtechnologie. Besproken worden de produktietechnologie, hybride en monolitische microsystemen en miniaturisatie van energiebronnen.

Silicon micromachining is een verzameling produktietechnologieën die gebaseerd is op etsen en depositie van silicium en siliciumverbindingen. Een tweede verzameling produktietechnologieën is de fijnmechanica, die bestaat uit klassieke technologieën zoals microfrezen maar ook uit moderne technieken zoals laserbewerkingen. Speciale aandacht wordt gegeven aan een veelbelovende techniek (*LIGA*) die een combinatie is van lithografie en galvanisatie.

De verwachting is dat al deze technieken zullen leiden tot hybride en monolitische componenten en systemen. Bij hybride systemen worden de afzonderlijke elementen geproduceerd met de meest geschikte technologie en vervolgens geassembleerd; bij monolitische systemen wordt het hele systeem geïntegreerd geproduceerd. De verwachting is dat hybride systemen in eerste instantie de belangrijkste rol zullen spelen en dat pas later monolitische systemen op de markt zullen komen.

Energie speelt in alle microsystemen een rol, en miniaturisatie van energiebronnen is daarom een essentiële factor. Uit het gepresenteerde overzicht van de ontwikkelingen van energiebronnen wordt geconcludeerd dat het ontbreken van geschikte batterijen en accumulatoren een beperking zal zijn bij de toepassing van MST.

Hoofdstuk 3

Hoofdstuk 3 beschrijft de behoefte aan MST in instrumentatie voor de industrie, het milieu en *high-end* toepassingen. Daarbij zijn de te vervullen functies het uitgangspunt. De functies die in verschillende toepassingen worden besproken, zijn meting, inspectie, automatisering, informatieverwerking en identificatie. In vier voorbeelden worden de kansen van MST nader uitgewerkt, waarbij de gebruikerseisen, de potentiële markt en de mogelijkheid voor produktie worden toegelicht.

Het blijkt dat de marktverwachting voor MST in instrumentatie groot is, maar dat het de grote vraag is wanneer succesvolle systemen op de markt komen. Op korte termijn worden sensoren en eenvoudige microstructuren op de markt voorzien. Het midden- en kleinbedrijf zal een belangrijke rol kunnen spelen bij de toepassing van MST in instrumentatie. Het perspectief voor de langere termijn is minder duidelijk en hangt af van de mate waarin een aantal drempels kan worden genomen.

Belangrijke drempels zijn de moeizame transfer van MST naar applicaties, het interesseren van eindgebruikers en het denken in systemen bij het ontwerpen van MST-produkten. De conclusie van het hoofdstuk is dat MST veelbelovend is, ondanks de drempels die moeten worden genomen.

Hoofdstuk 4

In hoofdstuk 4 worden toepassingen van MST in medische technologie beschreven. Voor acht medische disciplines wordt de relevantie van MST aan de hand van voorbeelden toegelicht. De voordelen van MST liggen bij de mogelijkheid tot een snelle en accurate diagnose, een gerichte en zeer lokale behandeling en de ondersteuning of vervanging van lichaamsfuncties. In één voorbeeld, een *closed-loop* bewakingsysteem, worden de gebruikerseisen en de produktie van het op MST gebaseerde systeem uitgewerkt.

De markt voor medische toepassingen van MST is complex door de hoge eisen die worden gesteld door medici en overheid, en door het relatief lage marktvolume. De verwachting is dat de medische markt een volger zal zijn op MST-gebied en dat voor succesvolle applicaties samenwerking van kleine en grote bedrijven noodzakelijk is. Met name voor kleine bedrijven lijkt er een groot aantal kansen te liggen voor relatief eenvoudige systemen, zoals bijvoorbeeld systemen voor naast het bed van de patiënt, en voor produkten voor thuiszorg.

Het potentieel van MST en de mogelijke voordelen zijn enorm, met name in het licht van de toenemende aandacht voor thuiszorg, non-invasieve technieken en revalidatie. Om echter te kunnen profiteren van deze kansen moet aan een aantal voorwaarden worden voldaan, zoals coördinatie van onderzoek en ontwikkeling, het betrekken van medici bij ontwikkelingen en eenduidige Europese regelgeving.

Daarnaast moet in het hoger en universitair onderwijs aandacht worden gegeven aan MST.

Hoofdstuk 5

Hoofdstuk 5 geeft een overzicht van mogelijke toepassingen van MST in consumentenprodukten. Succesvolle toepassingen zijn op het moment nog schaars. De nieuwste digitale opneem- en afspeelapparatuur maakt echter reeds gebruik van MST en de verwachting is dat MST een belangrijke bijdrage zal leveren aan verdere miniaturisatie van informatiedragers. In het hoofdstuk worden zes voorbeelden gegeven, waaronder ideeën voor automobieltechniek en telecommunicatie. Twee uitgewerkte *cases* worden besproken; beide betreffen produkten voor persoonlijk gebruik, namelijk een veiligheidsysteem en een systeem voor de analyse van de gezondheid.

Het marktmechanisme voor consumentenprodukten leidt ertoe dat MST alleen zal worden toegepast als daaraan een duidelijke behoefte is. Daarnaast zijn consumentenprodukten kostprijsgevoelig, en het idee is dat succesvolle toepassingen van MST eerst in professionele produkten zullen plaatsvinden. Zodra er echter een consumentenmarkt ontstaat zal de economische betekenis aanzienlijk zijn en zullen ook buitenlandse producenten op deze markt verschijnen. Ook de maatschappelijke invloed kan groot zijn, zoals bijvoorbeeld die van een draagbaar systeem dat de persoonlijke gezondheid analyseert.

De introductie van MST in consumentenprodukten kan worden versoepeld door de aanwezigheid van een algemene infrastructuur. Met name de mogelijkheid om haalbaarheidstudies te laten uitvoeren, kan ertoe bijdragen dat bedrijven MST gaan gebruiken in hun produkten. Verder is coördinatie van onderzoek en samenwerking in produktontwikkeling noodzakelijk. Promotie van de mogelijkheden van MST bij de eindgebruiker zal er tevens toe bijdragen dat deze technologie gemakkelijker wordt geaccepteerd.

Hoofdstuk 6

Hoofdstuk 6 geeft een overzicht van agrarische toepassingen van microsystemen. De nadruk ligt in het hoofdstuk op landbouw, veeteelt, tuinbouw en voedingsmiddelenindustrie. Voor ieder van deze sectoren wordt een voorbeeld gegeven en is een *case* uitgewerkt. Bij deze *cases* worden de technische vereisten beschreven en de economische randvoorwaarden aangestipt. De meeste toepassingen zullen naar verwachting dienen ter verhoging van de efficiency, verbetering van de kwaliteit en beheersing van ongewenste emissies.

In de agrarische sector zijn de aantallen groot en bestaat er een duidelijke behoefte aan gegevens voor beheer en controle. Tevens kan MST bijdragen aan duurzame en milieuvriendelijke landbouw en veeteelt door bijvoorbeeld gerichte dosering van meststoffen en bestrijdingsmiddelen. Op korte termijn worden toepassingen verwacht op het gebied van sensoren, op de lange termijn kan de toevoeging van intelligentie leiden tot complete microsystemen.

Vanwege het conservatieve karakter van deze sector en de lage marges zal MST alleen worden toegepast als daarvoor dwingende economische of maatschappelijke redenen zijn. Een belangrijke drempel is de diversiteit in de regelgeving. Uniforme (Europese) regels zijn daarom essentieel. Verder is het noodzakelijk om gebruikers, ontwikkelaars en universiteiten te betrekken bij de ontwikkeling van MST-produkten. De bewustwording van MST kan worden gestimuleerd door het onderwerp op de onderwijsagenda van de landbouwuniversiteit en de hogere agrarische scholen te plaatsen.

Hoofdstuk 7

In hoofdstuk 7 wordt behandeld wat er nodig is voor het ontwerpen en de produktie van microsystemen. Daarbij wordt speciale aandacht gegeven aan het midden- en kleinbedrijf (MKB), omdat er grote kansen liggen voor produkten in nichemarkten met een jaarlijkse omzet van 1.000 tot 100.000 stuks.

Testbaarheid en produceerbaarheid zijn items waaraan bij het ontwerp reeds aandacht moet worden gegeven. Dank zij de grote diversiteit in technologieën zijn er in het algemeen verschillende manieren om een produkt te realiseren. Dit wordt geïllustreerd met enkele voorbeelden van analysesystemen. Voor één van de componenten van deze systemen, namelijk een micropomp, wordt een systematisch methode gepresenteerd waarmee de benodigde produktiestappen in kaart kunnen worden gebracht.

Omdat het MKB onmogelijk alle benodigde technologieën in huis kan hebben, wordt voorgesteld een MST-centrum op te richten. Dit onafhankelijke centrum kan bedrijven assisteren bij het vinden van oplossingen en kan aangeven waar de benodigde technologieën beschikbaar zijn. Tevens kan het centrum de technologieën die op de markt ontbreken zelf aanbieden.

Hoofdstuk 8

Hoofdstuk 8 beschrijft de toekomstverwachtingen en de kansen van MST. Tevens wordt de visie van het Europese netwerk voor microsysteemtechnologie (NEXUS) kort toegelicht.

De verwachting is dat MST-produkten volgens twee routes op de markt zullen worden geïntroduceerd: produkten met een hoge omzet en lage kosten, en gespecialiseerde produkten voor nichemarkten. MST-produkten zullen bestaande functies verbeteren of functies toevoegen, maar er zullen ook geheel nieuwe produkten op beide markten verschijnen.

Bedrijven waarvoor MST kansen biedt zijn organisaties die componenten maken, zoals sensoren en actuatoren, assemblagebedrijven die een aantal componenten samenvoegen tot systeemmodulen en bedrijven die de componenten en modulen in hun eindprodukt toepassen. Daarnaast is er behoefte aan de omzetting van MST-onderzoek en -kennis in produkten. Dit vraagt bedrijven die actief potentiële gebruikers van MST benaderen voor deelname in de produktontwikkeling.

Bewustwording en onderwijs zijn van groot belang voor het succes van MST. In het onderwijs moet daarom speciale aandacht worden gegeven aan de systeembenadering die MST vraagt. Daarnaast moeten het ontwerp en de produktietechnologieën van MST worden onderwezen.

Omdat Nederland en België een goede kennisbasis hebben, zijn er voldoende kansen om een rol te spelen in MST. Op dit moment worden er op verschillende plaatsen in de wereld reeds voorbereidingen getroffen voor activiteiten in MST; het is van belang tijdig voor een MST-basis te zorgen. Innovatieve markten waarin MST kan worden toegepast, zijn consumentenelektronica, telecommunicatie en instrumentatie (bijv. medisch en ruimtevaart). Daarnaast zijn er kansen voor toeleverende bedrijven aan de automobielindustrie. De agrarische sector in Nederland loopt ten slotte in de wereld voorop wat betreft de toepassing van technologie, en heeft daarmee een goede uitgangspositie voor MST-toepassingen.

Hoofdstuk 9

Hoofdstuk 9 bevat de conclusies en aanbevelingen van het project. Uit de voorgaande hoofdstukken blijkt dat een aantal drempels moet worden overwonnen voordat MST grootschalig zal worden toegepast. De overheid kan een belangrijke rol spelen bij het nemen van deze drempels. Eventuele acties van de nationale overheid zouden de volgende componenten moeten bevatten:
- de initiatie van een aantal demonstratieprojecten, zo mogelijk via *public purchase*-contracten;
- een programma voor de stimulering van produktontwikkeling;
- de opzet van een onafhankelijk MST-centrum;
- een programma voor het op peil houden van de goede kennisbasis.

Bij dergelijke programma's is de betrokkenheid van de industrie essentieel; deze moet zelfs als voorwaarde worden gesteld.

Management summary

Microsystem technology: exploring opportunities is the result of a two-year exploration of microsystem technology (MST). For this project, which we have called *MUST*, STT has been able to draw on the knowledge and experience of a large number of Dutch, Flemish and other European experts. As there has been much criticism from industry of the technology-push nature of MST, we have done our best to focus principally on the need for microsystems. Engineering mock-ups of components are dealt with briefly in the appendices.

Chapter 1
Chapter 1 outlines the background and historical development of MST. It also sets out the approach and methodology of the MUST project.

MST is defined as the constellation of all the technologies required for the manufacture of products and components whose dimensions are less than a few millimetres. Microsystem technology is involved as soon as components of such small sizes are used in semimanufactures or final products. The components concerned are microsensors, micro-actuators and microsystems. Microsystems are the combination and integration of sensors and actuators with intelligence.

Chapter 2
Chapter 2 describes the basic features of microsystem technology, including production technology, hybrid and monolithic systems and the miniaturization of energy sources.

Silicon micromachining is a collection of production technologies based on the etching and deposition of silicon and silicon compounds. Another collection of production technologies is precision engineering, which consists of such classical technologies as micromachining alongside new techniques such as laser machining. Particular attention is paid to a promising technique (*LIGA*) which is a combination of lithography, galvanizing and moulding.

All these technologies are expected to lead to both hybrid and monolithic components and systems. In hybrid systems the individual components are produced with the most appropriate technology and then assembled; in monolithic systems the entire system is produced as an integrated whole. Hybrid systems are seen as likely to predominate initially, with monolithic systems coming onto the market at a later stage.

Energy plays a part in all microsystems, and the miniaturization of energy sources is thus an essential factor. The overview of energy source developments presented in the book leads to the conclusion that the lack of suitable batteries and accumulators will be a constraint on the application of MST.

Chapter 3

Chapter 3 describes the requirement for MST in instrumentation for industry, the environment and high-end applications. The point of departure here is the function required. The functions described in a variety of applications include measurement, inspection, automation, data processing and identification. In four examples the potential of MST is examined in detail, with particular attention to user requirements, possible markets and the feasibility of mass production.

What emerges is that market expectations for MST in instrumentation are large, but that the big question is when successful systems will reach the marketplace. Sensors and simple microstructures are expected to be available quite soon. Small and medium-sized businesses are expected to play an important role in the implementation of MST in instrumentation. Prospects for the longer term are less clear and depend on the degree to which a number of hurdles can be surmounted.

Important obstacles are the difficulty of transferring MST from the laboratory to applications, generating interest on the part of end users, and thinking in system terms when designing MST devices. The conclusion of this chapter is that MST is a promising technology despite the obstacles.

Chapter 4

Chapter 4 concentrates on applications in medical technology. The relevance of MST for eight medical disciplines is examined by reference to examples. The advantages of MST lie in its potential for rapid and accurate diagnoses, focused and highly localized therapeutic procedures, and support for or substitution of body functions. In one example, a closed-loop monitoring system, user requirements and the large-scale production of a system based on MST are elaborated in detail.

Due to the high standards demanded by both medical science and government, coupled with the comparatively low market volume, the market for medical applications of MST is a complex one. The expectation is that in the field of MST the medical market will be a follower rather than a leader, and that for successful applications the collaboration of companies both small and large will be essential. Small companies in particular are expected to find numerous opportunities in the area of relatively simple systems such as bedside monitoring systems and ambulatory care systems.

The potential of MST and its possible advantages are enormous, particularly in the light of growing interest in home care, non-invasive techniques and patient rehabilitation. However, to be able to benefit from these opportunities a number of conditions will have to be fulfilled, including the coordination of research and development, the involvement of medical scientists in system development, and unambiguous European guidelines. At the same time it is essential for more attention to be paid to MST in higher education.

Chapter 5

Chapter 5 is an overview of possible applications of MST in consumer products. At the time of writing such applications are still thin on the ground. However, MST can already be found in the latest digital recording and playback equipment and it is expected to make a major contribution to the continuing miniaturization of data carriers. The chapter includes six examples which include ideas for automobile technology and telecommunications. Two cases are discussed in detail, both of them products for personal use: a safety system and a health analysis system.

The market mechanism for consumer products means that MST will only be used if there is a clear demand for it. At the same time, consumer products are sensitive to cost price, and the feeling is that the first successful applications of MST will be in products for the professional market. However, as soon as a consumer market emerges the economic significance of MST will be considerable, and foreign manufacturers will appear in the market. The social implications will also be considerable, with such products as portable systems to analyse the state of health of the individual.

The introduction of MST in consumer products will be facilitated by the presence of a general infrastructure. In particular, the possibility of having feasibility studies carried out can help ensure that companies start using MST in their products. At the same time research will need to be coordinated and there will have to be collaboration in product development. Promotion of the possibilities offered by MST amongst end users will expedite the acceptance of the new technology.

Chapter 6

Chapter 6 is an overview of agricultural applications of microsystems. The chapter deals with arable farming, animal husbandry, horticulture and the food and drink industry. For each of these sectors an example is given and a case examined in detail. In these case studies the technical requirements are described and the economic constraints outlined. Most applications are expected to serve the goals of raising efficiency, improving quality and controlling undesirable emissions.

In the agricultural sector the potential number of systems is large, and there is a clear need for data for management and control. At the same time MST can make a contribution to sustainable and environmentally friendly agriculture by providing systems which, for example, can accurately deliver measured doses of fertilizers and pesticides. In the short term applications are expected in the field of sensors. Later the addition of intelligence may lead to complete microsystems.

Because of the conservative nature of the agricultural industry and its low margins MST will only find applications where there are compelling economic or social reasons for using it. One important obstacle is the large differences in regulations from country to country. Uniform regulations, particularly in the European context, are an essential prerequisite. It will also be necessary to involve users, developers and the universities in the development of MST products. Awareness of MST must be stimulated by placing the subject on the educational agenda at universities and colleges of agriculture.

Chapter 7

Chapter 7 discusses what is needed for the design and production of microsystems. Particular attention is paid to small and medium-sized businesses, since there are major opportunities for products in niche markets with annual sales of between 1,000 and 100,000 units.

Testability and the ease of mass production are two aspects which require attention at the design stage. Thanks to the great diversity in technologies there are generally several ways of achieving the goal of a particular product. This is illustrated by a number of examples of analysis systems. For one of the components of these systems, a micropump, a systematic method is presented by which the required production stages can be mapped out.

Since small and medium-sized businesses cannot possibly have all the technologies required in-house, the establishment of an MST centre is proposed. This would operate independently and would be able to assist companies in finding solutions and indicating where the appropriate technologies can be found. At the same time the centre would itself be able to offer those technologies that were not available in the marketplace.

Chapter 8

Chapter 8 describes the future prospects and chances of success for MST. There is also a brief exposition of the views of the European network for microsystem technology (NEXUS).

The expectation is that MST products will reach the market by two routes: products with high sales volumes and low costs, and specialized products for niche markets. MST products will improve on or add to existing functions, but the technology will also lead to completely new products in both markets.

The organizations most likely to benefit from MST are the manufacturers of components such as sensors and actuators, assembly houses which put numbers of components together to make system modules, and companies which use the components and modules in their own end products. There is also a need for MST research and knowledge to be translated into products. This calls for companies which will actively approach potential users of MST to solicit their participation in product development programmes.

Greater awareness and education are vital to the success of MST. It will therefore be necessary for education to pay specific attention to the system approach demanded by MST, while MST design and production methods must become part of the curriculum.

Since there is a good knowledge base, there are opportunities enough for the Netherlands and Belgium to play a role in the development of MST. At the time of writing, preparations are now in hand at various places in the world for activities in MST; it is important that an MST base be laid down in good time. Innovative markets in which MST may be used include consumer electronics, telecommunications and instrumentation (e.g. medical and aerospace applications). There are also opportunities for suppliers to the car industry. In the Netherlands, the agricultural industry is at the forefront of the application of technology and is thus in a good starting position for MST applications.

Chapter 9

Chapter 9 contains the conclusions and recommendations to have come out of the project. From the preceding chapters it is clear that there are a number of hurdles to be overcome before MST reaches application on a wide scale. Government can play an important part in overcoming these obstacles. Any future government action ought to include the following components:

- the initiation of a number of demonstration projects, where possible through public purchase contracts;
- a programme to stimulate product development;
- the establishment of an independent MST centre;
- a programme to maintain a strong national knowledge base.

In programmes like these the involvement of industry is essential; indeed, this must be regarded as a *sine qua non*.

1. General

1.1 INTRODUCTION

G.C. Klein Lebbink

Ever since his first origins man has been devising technological means to help him push back his limits. In the twentieth century mankind is experiencing a veritable technological revolution in all kinds of fields. Comparing the world of 1900 and now shows how rapidly and thoroughly technology has influenced our way of life. One recent example is microminiaturization – the shifting back of the dimensional limits of structures. Microelectronics, which is at the heart of everyday companions like the digital watch or the personal computer, is one of the offshoots of this development. But during the last decade large progress was also made in the field of mechanical structures with dimensions between a few millimetres and a nanometre. This progress resulted from the developments in mature technologies like precision engineering but also from the application of technologies derived from microelectronics. These technologies are commonly referred to collectively as MicroSystem Technology (MST). Examples are relatively new technologies such as micromachining and its combination with e.g. integrated optics, thin film technologies, electrochemistry and biochemistry. Even smaller structures are envisaged using molecular engineering, which uses individual atoms and molecules as building blocks.

Examples of the application of microsystems are dosage pumps for intravenous use in medical technology, pressure sensors for use in combustion engines, tiny accelerometers in airbags or in intelligent shock absorbers. Further examples of the products that have become possible with this new technology are given throughout this publication.

1.1.1 WHAT IS MICROSYSTEM TECHNOLOGY?

Although it is almost impossible to give a well-defined meaning to microsystem technology two aspects are evident. First of all, microsystem technology covers the domain of structures with characteristic feature sizes between a few millimetres and a nanometre. Figure 1.1 shows that the structures provided by nature in this extended range go from grains of sand over smoke particles to even the width of the DNA molecule.

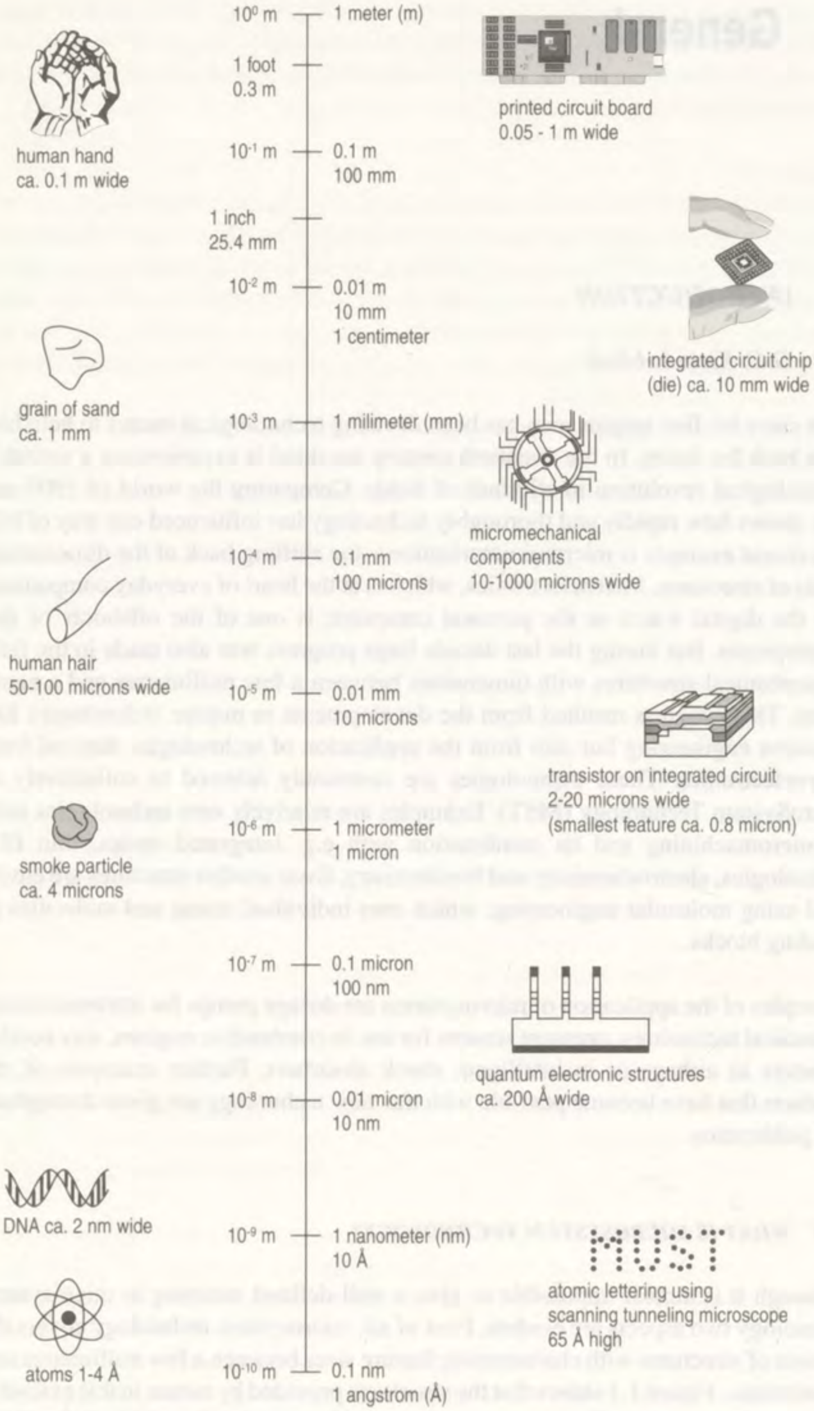


Figure 1.1 Dimensions of microsystem technology

Source: Office of Technology Assessment

Secondly, we speak of systems. In the case of microsystems we can identify parts that are designed as sensing elements, parts that process the information and decide on the actions to be performed, and actuators (figure 1.2). This last category covers micromotors and structures like filters and gears.

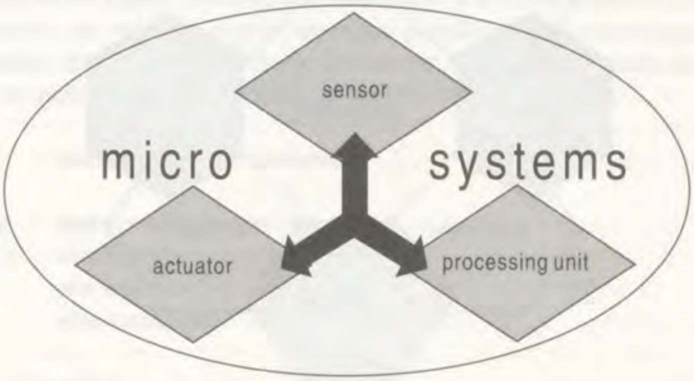


Figure 1.2 Scope of microsystems

A general aspect of these systems is that information is relayed and transformed. Whenever this transformation occurs in a system with feature sizes of less than a few millimetres we speak of microsystems. As a consequence an intelligent microsensor is a microsystem but an IC or Application Specific IC (ASIC) is not a microsystem because the information it handles remains in the electrical domain.

Finally, microsystem technology includes all technologies that are necessary to make microsystems. Both the challenge and the opportunities of MST lie in the combination and integration of the technologies involved. This requires an interdisciplinary approach towards the system as a whole. To illustrate the interdisciplinarity of MST figure 1.3 gives several disciplines involved.

Although MST is often compared with microelectronics it lacks the high degree of generality characteristic of microelectronics. ICs can be grouped in a limited number of classes, within which design and production follows well defined and common steps. As a consequence the price-performance ratio allows industry to make profits on complex ICs and it makes ICs suited for mass production. Sensors and actuators are on the contrary very specific. They have to be in contact with their surroundings, and each environment imposes its own constraints. As microsystems are the combination of sensors and actuators this non-generic character applies even more strongly to microsystems. However there are exceptions as described in section 1.2.

An inventory of all the research programmes and activities in microsystem technology [4-6], and especially the growth rate of the number of organizations and people involved can only lead to the conclusion that MST is a present-day reality and a fast growing area in which the possibilities are huge.

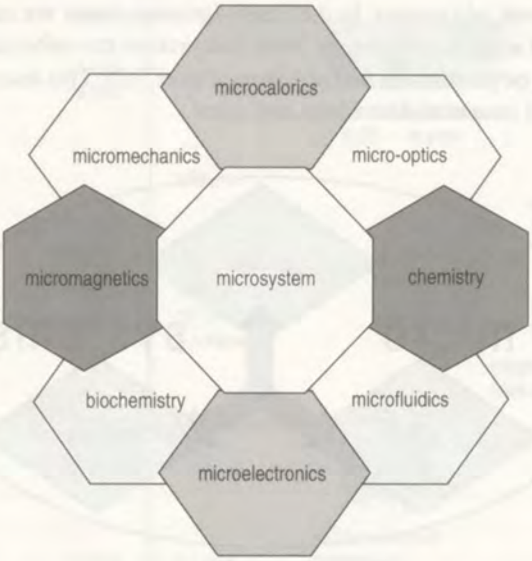


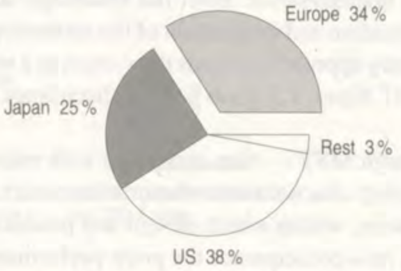
Figure 1.3 Disciplines involved in microsystem technology

1.1.2 PROJECT BACKGROUND

Several market oriented studies [1, 2] predict a rapid rise in the use of microsystem technology. Figure 1.4 gives an indication of the expected market volumes for microsystems [3].

year	worldmarket (million DM)
1990	12.2
1995	25.0
2000	65.1

market for microsystems
source: Helmut Kaiser (1991)



production (1990) of microsystems
source: Helmut Kaiser (1991)

Figure 1.4 Market volumes and production for microsystems
Source: IMEC

A growing number of persons involved in this technology foresee a sharp rise in applications. At the present time, however, the number of successful market applications is limited. Present commercial applications are mainly microsensors like pressure sensors and acceleration sensors. Actuators are under development for the positioning of optical fibres, and microstructures are used as filters. Other types of micromachined sensors and actuators are still in their infancy. Criticism of industry focuses on the lack of tangible applications and a general point of concern is the lack of a common policy for microsystem technology in Europe and the Netherlands. Table 1.1 shows the problem at a glance.

The technological limits have been pushed back; however, up to now the economic thresholds for most ideas have not been overcome. If we look at nature and natural microsystems we can only expect enormous possibilities for microsystems. For these reasons the Netherlands Study Centre for Technology Trends decided to perform an application-oriented study on microsystem technology.

limit	*concerned with*	*determined by*
fundamental	what is possible	laws of nature
technological	what is practical	man's ingenuity
economic	what is profitable	costs and markets
subjective	what is acceptable	personal preference

Table 1.1 Types of limits

1.1.3 APPROACH

The starting point of the assessment is existing demand in four main areas. These areas are:

- instrumentation (environment, industry and high end);
- medical technology;
- consumer products (including automotive applications);
- agricultural applications.

Because the publication focuses on microsystem technology, alternative solutions to existing problems are not considered.

For each of the application areas a task force was formed with representatives from industry, research institutes and universities. Table 1.2 presents an overview of the background and the number of people involved in the so-called MUST project. The names of all the people involved are listed at the end of this publication.

groups	*universities*	*institutes*	*industry*	*total*
Steering Committee	3	4	2	9
Instrumentation	2	3	4	9
Medical	3	2	2	7
Consumer products	2	3	2	7
Agriculture	2	4	2	8
Production	3	1	3	7
Total	15	17	15	47

Table 1.2 Participants in the MUST project

The first task of the task forces focused on the demand for microsystem technology in their area. They all had a parallel approach that consisted of the following steps:

1. Structuring the area they were looking into. All task forces split up their specific area in more addressable subareas. Most of the task forces subsequently set up a matrix with these subareas along one axis and motives or technologies on the other axis. In these matrices the growth areas for MST were identified.
2. For the most important growth areas the task forces made an inventory of the demands and possibilities of MST. Brainstorming gave rise to new ideas.
3. From the ideas that were brought up a number of cases were selected and are described in detail in the various chapters. Furthermore several promising possibilities of MST are briefly described.

A second task was the formulation of a common vision of MST and its impact on the areas of application. This vision covers aspects like:

- the context of MST in the area of application;
- the necessary infrastructure;
- the required education;
- the European perspective.

Besides these application-oriented task forces one additional task force focused on producibility and on the demands that microsystems impose on production. They came to the conclusion that such an analysis requires a complete design step and intense interaction with the demand side. Because of the scope of the project and the complexity of the analysis required to assess the producibility of the cases presented, the conclusions are of a general nature. However, to give the reader an idea of what the production of a microsystem entails, one example of such an analysis is included in Chapter 7.

1.2 THE TREND TOWARDS MINIATURIZATION

prof. J.H.J. Fluitman

1.2.1 INTRODUCTION

This section follows the developments of the past 25 years, and shows that the trend towards miniaturization is almost a law of nature. There are two ingredients, which are of great importance in this history. At first the natural drive to miniaturization was carried by the sophistication of precision engineering. IC technology later opened up a completely new area of technology. For example, the introduction of the microprocessor as a functional unit has formed a tremendous attractor to new intelligent miniaturized products.

1.2.2 COMPUTER PERIPHERALS

The number of transistors on a memory chip has grown faster then tenfold every five years. Computer peripherals follow this trend.

External memories
Hard disk drives have shrunk from the size of a refrigerator (1970) to the size of a matchbox (see for example HP's Kittyhawk described in section 5.1.5), with a much lower price-performance ratio. The area bit density of a recording disk has grown by 4 or 5 tens in the last 25 years. It is astonishing to see how magnetic recording breaks through barriers that were previously assumed impossible to break.

Displays
Today's workhorse, the Cathode Ray Tube (CRT), is perfect for use in a fixed place, but portable computers require a small and flat panel display. This has led to Plasma Discharge Displays and Liquid Crystal Displays (LCD). The pixels have to be controlled and the most efficient way to do this is to have an electronic function at every position. We cannot think of large sheets of silicon as the basic substrate in an LCD display. Therefore it is necessary to apply Silicon On Glass (SOG) technology. This means that silicon spots carrying the required electronics, e.g. a pair of diodes, are placed at any pixel position. For an overview of these techniques the reader is referred to Kuijk [7]. The interesting thing occurring here is that transducers (sensors and actuators) are not integrated on a silicon chip, but the reverse is true: electronics is integrated on a non-silicon substrate.

Projection displays
Texas Instrument's new mirror array [8] is a marvellous example of miniaturization. On a Random Access Memory (RAM) chip a mirror array is placed, using surface micromachining techniques after the RAM is produced. The mirrors (pixels) have a size of 16x16 microns and are fixed to torsional hinges in two opposite corners. The mirrors can be rotated over 10 degrees to both sides. The rotation is forced by electrostatic attraction of the aluminum mirror and a ground electrode (see also Appendix 1: mirror based laser beam deflectors).

Communication channels and devices
The basis of future communications hardware is the optical fibre with a core diameter of a few microns. Compared to classical communications lines the amount of transported information has made a quantum leap while the medium is much cheaper still. For fast communication fast switching functions are necessary and this means that the use of integrated optical devices is essential. The ideal is an opto-optic switch and research is being done to develop integrated devices exploiting Non Linear Optical (NLO) materials [9].

1.2.3 INTEGRATED SENSORS

A number of silicon based sensors were known to be feasible in the seventies, like the Hall sensor, the membrane piezo resistive pressure sensor and the Ion Sensitive

Field Effect Transistor (ISFET). After the breakthrough of the microprocessor two things became evident:

- First it was foreseen that the price-performance ratio of IC functions would decrease drastically, so that the existing peripherals were seen as constraints for a wide use of ICs.
- Second, with such a huge number of IC functions on a single chip there was room for one or more sensors on the chip. Or the converse, which is more realistic: if one or more sensor functions could be realized on the basis of silicon properties, then the non-optimal performance of silicon as a transducer material could easily be compensated for with some electronics right on the spot. Almost all transducer mechanisms (except piezo-electricity) are present in silicon to some extent.

How far is this 'smart' sensor concept at this moment? To answer this question it is important to realize that any sensor must look out on the world. A sensor cannot be housed safely like an IC because it must be able to see through the window. Some windows are relatively safe and others are not. To give an idea: if you want to measure a magnetic field you can shield the sensor completely. The only constraint is that you use no magnetic material in the housing. On the other hand a sensor for measuring heavy metals in ground water must be exposed to a dirty substance and is nevertheless expected to send reliable information to the controls for a reasonable period of time. And if we concentrate on a single parameter: pressure, say, we need separate sensors to measure blood pressure, the pressure of a gas at 1000 °C, or the pressure in a highly corrosive environment. This means that sensors are in general not generic structures like ICs. There are 50,000 different sensor products for about 100 parameters for sale in Europe at the moment [2].

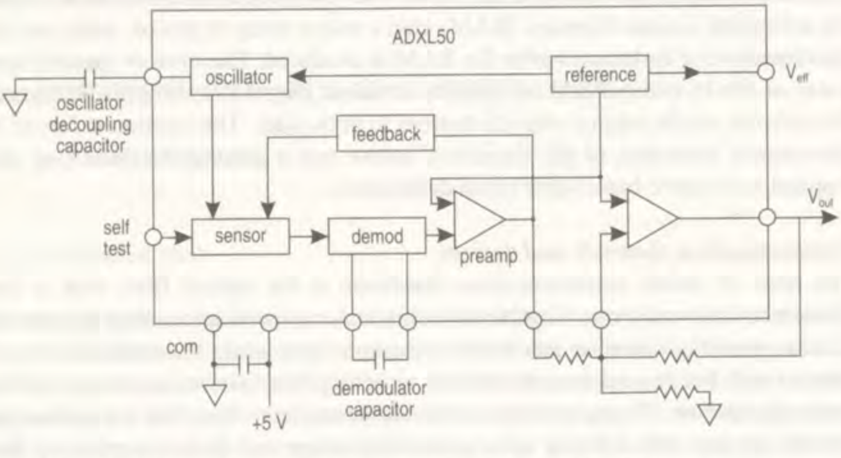


Figure 1.5a Block diagram of sensor and electronics integrated on a single chip
Source: Analog Devices [10]

So it is good to take an example from these applications, say, the acceleration sensor (or deceleration sensor, if you think of triggering the inflation of the airbag, one of today's Holy Grails). Analog Devices [10] offers a very elegant design (figure 1.5). These 'state of the art' products are on the market now.

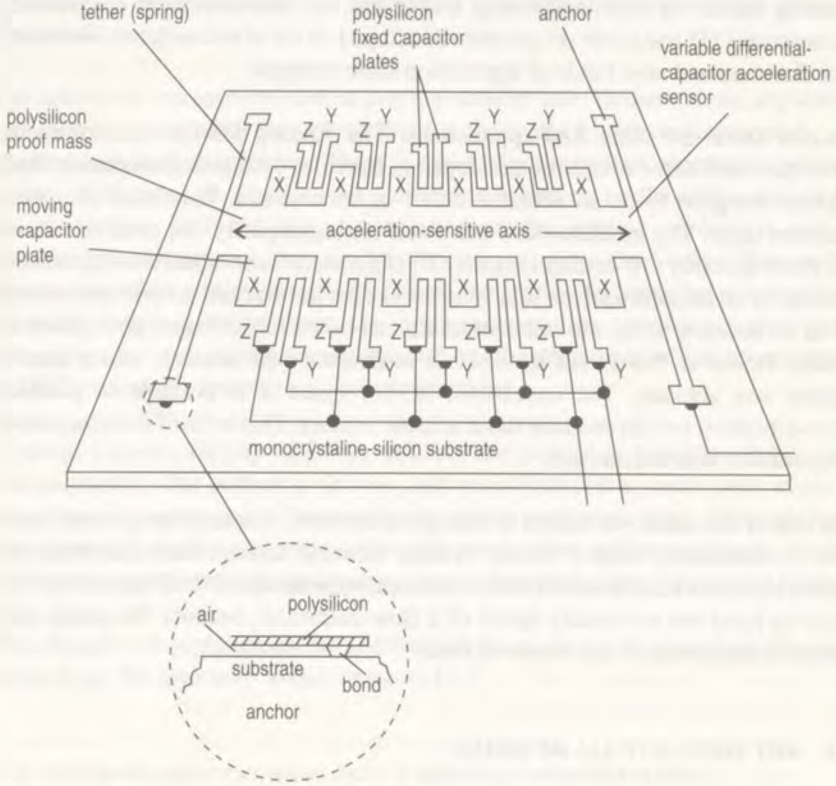


Figure 1.5b The sensor part of AD's accelerometer. The proof mass is attached to the 'electronic' plane by four small anchors
Source: Analog Devices [10]

Smart sensors, in the original meaning, must operate in the temperature range of well-functioning microelectronics and must be reasonably protectable, which places a constraint on the encapsulation technology. Nevertheless there is a large market for sensors in this area. Examples are the pressure, flow and acceleration sensors used in the automotive world. And many of the high volume domotic and medical applications are working around room temperature.

The large expectations of sensors in the automotive sector are also illustrated by the number of companies involved in micromachining in this field, examples are Lucas Automotive, Bosch, Toyota, Daimler Benz, Philips, Texas Instruments and the Ford Motor Company.

1.2.4 ACTUATORS

An actuator acts and needs some power to do so. This distinguishes the actuator from the sensor. Although in principle sensing too has to do with power in one way or another, the possibility of miniaturizing sensors is more obvious than that of miniaturizing actuators. Nevertheless the eighties showed a breakthrough of micro-actuators, based on micromachining techniques. As demonstrators electrostatic micromotors [11] and comb drives were developed. A lot of research has been done since that time and new fields of application have emerged.

However there are some first applications. The Analog Devices accelerometer shows the comb drive structures developed in Berkeley [12] and other places. Here a device designed to be an actuator shows up in a sensor. This leads to a very important issue. The accelerometer has a self-testing capacity. (In itself this is not new, there are other self-testing sensors.) The important issue of selftest requires the presence of an actuator and the best solution is a device that can act both as a sensor and as an actuator. If so, the same structure can be switched from one function to another. However this is not possible in modulator type sensors, which need a separate test actuator. The conclusion is that, since it is possible to produce micro-actuators, we can produce more reliable sensors. This in itself is an important application of micro-actuators.

Note that at the outset we started to talk about systems. A sensor, an actuator and a piece of electronics build a 'smart' system. Reliable sensors need actuators and reliable actuators need sensors like the micropump in section 2.1. If there is no flow sensor to hand we can hardly speak of a flow controller, because the pump may change its properties in the course of time.

1.2.5 WHY SHOULD IT ALL BE SMALL?

Why should it all be small? The answer is hidden in the foregoing but there are also a number of additional reasons.

Small things are portable. The more features you can carry the happier you are. It means that in doing your work, you are not pinned to a certain place. Work and workplace are uncoupled, because you carry your workplace with you. As portability is directly associated with individuals this motive is especially valid for consumer products, and Chapter 5 on MST and consumer products lists several applications for which the drive for microsystems is found in portability. Portability is also important in medical care. In that case the patient can carry the diagnostic means and possibly the therapeutic means too. If the latter is not possible the device can communicate with a physician or a hospital, which helps to make medical care cheaper. Diagnostic means coupled to therapeutic means may lead to artificial organs (e.g. an artificial pancreas) or to so-called 'smart pills'. Again the answer to the question: 'Why small?' is rather trivial. The medical needs and the possible solutions offered by MST are discussed in detail in Chapter 4.

In transport the number of microsystems must increase for better control of fuel costs and environmental impact. Systems must be small to leave room for the payload. This is important in the automotive world, but even more so in aerospace applications. The same urge for control and measurement exists in agriculture. Modern animal husbandry relies on in-animal systems and the need for reliable local measurements in farming and horticulture will clearly benefit from micro-analysis systems. An outline of what we can expect from MST in agriculture is given in Chapter 6.

The control of our environment is priority number one. In due course, legislation and controls concerning the task of keeping the world livable will impose the use of chemical analysis systems. There is need of an immense number of sensors, mostly (bio)chemical. On-the-spot calibration seems to be the only solution for reliable sensing. Drift and degradation, which are the greatest problems in making reliable sensors, can never be solved by 'smartness' of the electronics. You need an actuator and thus a microsystem. But apart from this, the quest for microsystems doing the sampling, the transport, the mixing and reacting, the sensing, an so on, is necessary if we are to replace bench equipment. Chapter 3 deals with the possibilities of MST in analysis systems and instrumentation.

Minimal invasive surgery and drug delivery are two other functions that require miniaturization. For both drug delivery and microchemical analysis there might be a need for disposable parts. Disposables should be small and cheap. Although batch manufacture is not the only way to produce microsystems it allows cheap production and is a strong argument for designing systems that can be manufactured in batches.

The chapters on applications list additional arguments for the use of microsystem technology. We also refer to the literature [11].

1.2.6 MICROSYSTEM TECHNOLOGY: A MEETING OF DISCIPLINES

Microsystem technology is a working field to which all the new miniaturizing technologies are oriented. Here all disciplines meet; it requires a new management of disciplines to uncover the treasures which are hidden in the MST field.

This management is required not only for successful designs, but also for defining the infrastructure needed for industrial production. Production and producibility go hand in hand. Right at the start of a new design the disciplines, including the fabrication technologies, should come together and cooperate. Generally the production facilities for MST products are very expensive; often they are dedicated. Time-sharing of facilities, especially for deposition of thin layers of different materials, will be highly problematic, at least in terms of the facilities as they exist now.

Of great importance is the development of new production facilities which can do more, are more flexible, have a smaller volume and lower price. So it is not only the products that miniaturize, production facilities will go the same way, including clean rooms as a fabrication unit. If we calculate the ratio of the volume of the silicon present in an IC line to the volume of the complete IC line, including all the air handling, etc., we arrive at crazy numbers. It is a great challenge to bring these numbers into a reasonable balance and to arrive at an acceptable ratio.

Up to now only so-called 'sculpturing' technologies, in the line of the IC technology, are treated. A 'sculpturing' technology starts with raw material, in MST mostly a silicon wafer, which is treated and formed into its final form. However, there is an approach from the other side. Instead of shaping raw material, one can take the smallest building blocks available, molecules, and build structures out of them. Chemistry is a form of shaping matter, but our perception of chemistry is somewhat different. Supra Molecular Chemistry [13] has shown the possibility of creating structures that are closer to our perception of functional units than just as chemicals.

Self-assembly of Supra Molecular Structures can be exploited as a method to create molecular thin films. There is a whole world waiting to be discovered by the microsystems engineer with no education in chemistry, but it is impossible to compress all this knowledge from different disciplines into a single person's head. Nevertheless, it is predictable that the sculpturing type of technology will increasingly meet Supra Molecular Chemistry, and again the necessity of managing the disciplines and keeping control over the wealth of possibilities is clear.

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2. Basic technologies and functions

2.1 MICROSYSTEM TECHNOLOGY AND SILICON MICROMACHINING

Prof. J.H.J. Fluitman

2.1.. INTRODUCTION

This section discusses the history of microsystem technologies as they have emerged from IC technology. As we are dealing with the structuring of devices at close to submicron accuracy the processes involved are referred to as micromachining. There are two kinds of micromachining:

- bulk micromachining: whereas some parts of the silicon are unaffected, others are almost completely removed leaving a thin membrane or small bridge;
- surface micromachining, meaning the formation of structures at the surface of the silicon.

During the development of these technologies others have emerged. Perhaps the most important new technology is one which is known by its German name *Lithographie Galvanoformung und Abformung (LIGA)*, which is discussed in section 2.2.

2.1.2 SILICON MICROMACHINING

Silicon micromachining is a well-established process. It is based on local etching, either wet or dry, of the silicon wafer through a suitable mask. Making V-grooves is one of the first applications and the production of thin membranes for membrane pressure sensors dates from around 1970 [1]. A landmark in bulk micromachining is Petersen's review paper of 1982 [2]. This paper and the rise of the microprocessor have given considerable added impetus to work on silicon-oriented sensors.

Silicon wafers used for IC production are brittle. If they fall on a hard floor they break into sharp pieces revealing their crystalline structure. Nevertheless the elastic properties of silicon are impressive. Its yield strength is comparable to stainless steel and there is no region of ductility. The brittleness suggests that a silicon beam cannot bend without breaking. This is not true. A silicon beam a few microns in thickness and a few hundred microns in length can be bent over 90 degrees without breaking and afterwards return to its original position.

It is important to remember, however, that the third dimension created by micromachining is more a thickness control system rather than true three-dimensional structuring as is commonly known in mechanical engineering. This is due to the planar nature of the technologies involved.

There are two kinds of wet micromachining, bulk and surface micromachining. Moreover wet bulk micromachining can be isotropic or anisotropic depending on the etchant. Characteristic examples of devices made by either method are given. Moreover the so-called dry etching methods are treated.

Anisotropic bulk wet etching

Anisotropic etching in mono crystalline silicon is caused by the different etch velocities in different crystalline directions of a number of etchants. Ethylene Diamine, Pyrocatechol and water (EDP) was one of the first etchants used, but its toxicity has led it to be replaced in most cases by potassium hydroxide (KOH), which is the most popular etchant today although its selectivity for silicon oxide is less than EDP. Potassium however is not IC-compatible (poisoning of the IC process) and even after thorough cleaning KOH-etched samples will not be accepted in a standard IC production line. This means that the etch must take place after the IC process in an 'integrated' device (post processing). TetraMethyl Ammonium Hydroxide (TMAH) is an emerging etchant that is IC-compatible.

The etchants have a different etch rate with respect to the crystal orientations. In mono crystalline silicon the main orientations are (100), (110), and (111). The (111) plane etches the slowest by far. Using silicon wafers with a (100) or (110) top surface and the right selection of masks it is possible to produce a variety of structures.

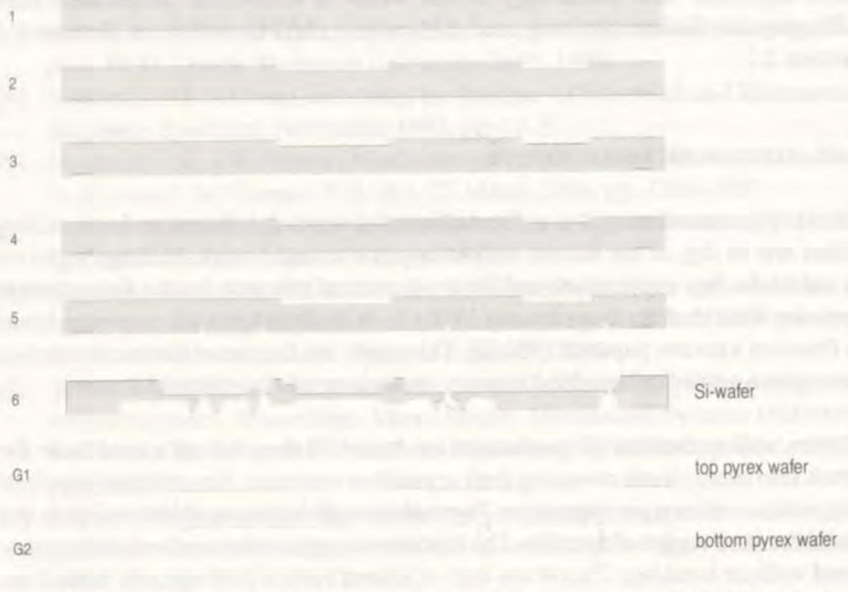


Figure 2.1a Processing sequence for the Si-wafer and two glass wafers for an integrated flow controller
Source: [3]

Figure 2.1a shows the steps that are used to shape a wafer. It can be seen that the principle of the method is to create windows to give access to the etchant. In this case an anisotropic etch is used in order to prevent underetching at the window edges. The micromachined wafer is sandwiched between two pyrex wafers, which are anodically bonded to the silicon afterwards. Figure 2.1b shows four pumps side by side on a three-inch wafer. Appendix 1 describes the working principle of the micropump. Bonding techniques, whether silicon to silicon or other (possibly intermediate) materials, are described in [4, 5] and the following sections.

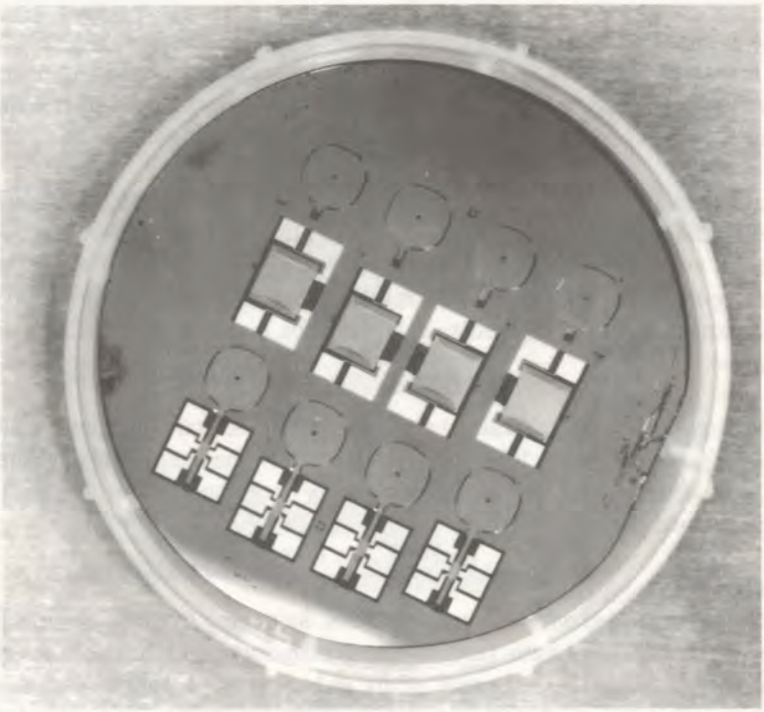


Figure 2.1b Four micropumps with micro flow sensors side by side on a three-inch wafer
Source: [3]

One important aspect of bulk micromachining is the etch-stop mechanism. To make well-defined membranes we must be able to stop the etching at the required time. There are several methods to do so [6].

Isotropic bulk etching
Some etchants do not 'see' the crystal planes and display an isotropic etch velocity. Most commonly used for this purpose is a mixture of HNO_3 and HF. Anodic etching, using an aqueous HF solution, is also used for thinning and polishing wafers and to produce porous silicon layers. Compared to anisotropic etching, the possibilities of bulk etching for structuring purposes are far less. It may be useful to round off sharp concave or convex corners produced by anisotropic etching (important for e.g. microfluidics). It may be wondered why some etchants etch isotropically and others

anisotropically, and why different etchants act differently. This is not a trivial question and is still under debate [7].

Surface micromachining
Surface micromachining received a boost from the breakthrough of surface micromachined actuator parts [8]. The idea is that a free standing structure can be made by deposition on a sacrificial layer. The latter is subsequently removed by selective etching. An example of a surface micromachined product is the best explanation of the process.

Figure 2.2a gives the procedure for producing a surface micromachined encapsulated resonator. Such a resonator has a resonance frequency depending on a force applied in the longitudinal direction. This force can be introduced by bending the surface the resonator is built into. It then acts as a strain gauge.

A prerequisite for a structure like this is the residual stress in the free-etched layer. Therefore the mechanical properties of the layers used must be well-known in order to prevent buckling of the free-etched layer. Figure 2.2b gives a Scanning Electron Microscope (SEM) photograph of the resulting sensor (with the top removed). The second structure is a non-resonating dummy for the compensation of parasitic influences.

There are quite a number of material combinations and selective etchants for surface micromachining which are IC-compatible. Up to now the integration of electronics with surface micromachined parts seems to be more successful than with bulk micromachined parts.

Dry etching
Dry etching is applied with increasing success. Stemming from the manufacturing process of dynamic and static random-access memory chips it has been developed for micromachining. The advantage of dry etching is its capacity to etch trenches anisotropically without affecting the crystal structure and with good control of size and etch profile. It is mainly a physical impact process, often supported by chemistry. The mask determines the pattern to be etched. Dry etching uses a plasma, made and applied in different ways and the etching method in fact forms quite a varied family of plasma etching: reactive ion/sputter etching, sputter etching, ion milling, ion beam assisted chemical etching and reactive ion beam etching. Too much to be treated in detail here, a good review is given in [10].

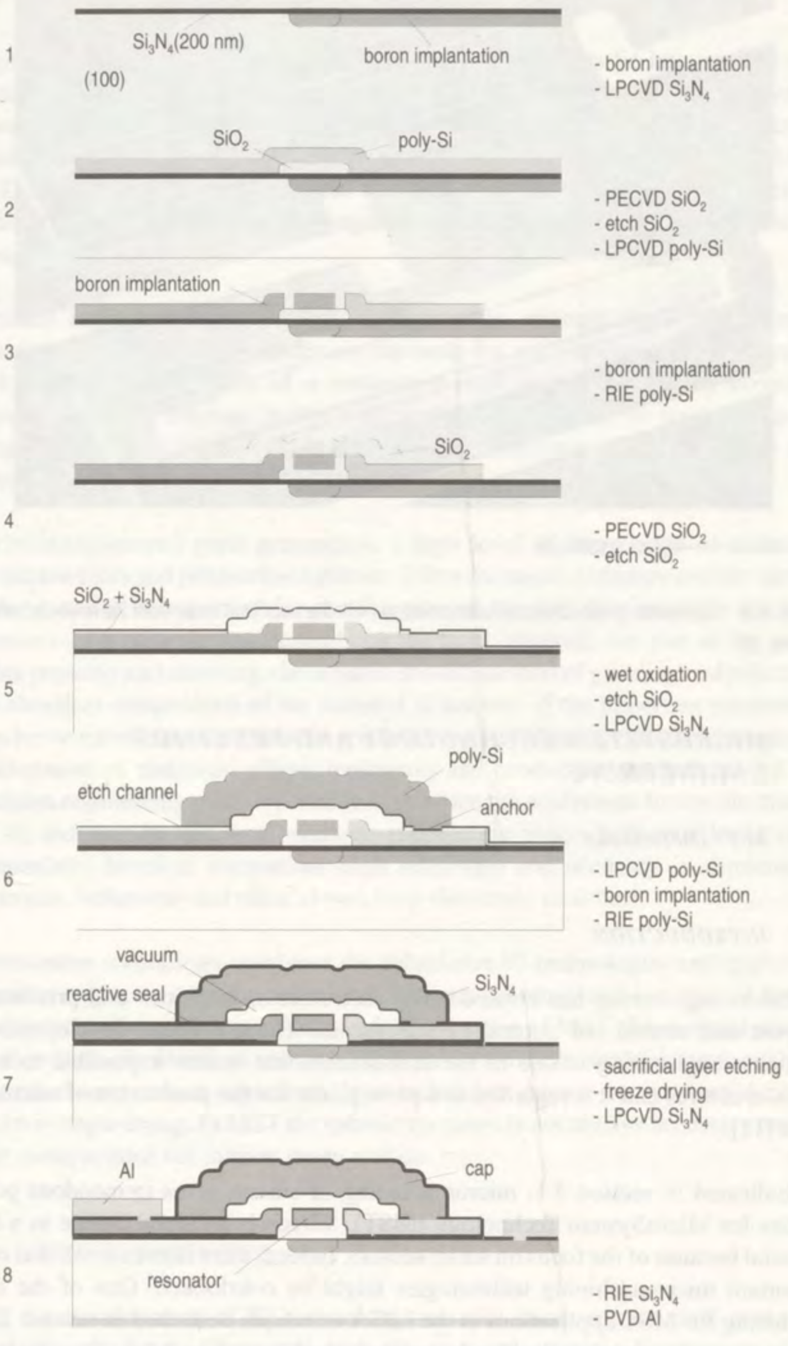


Figure 2.2a Processing sequence for sealed resonators

Source: [9]

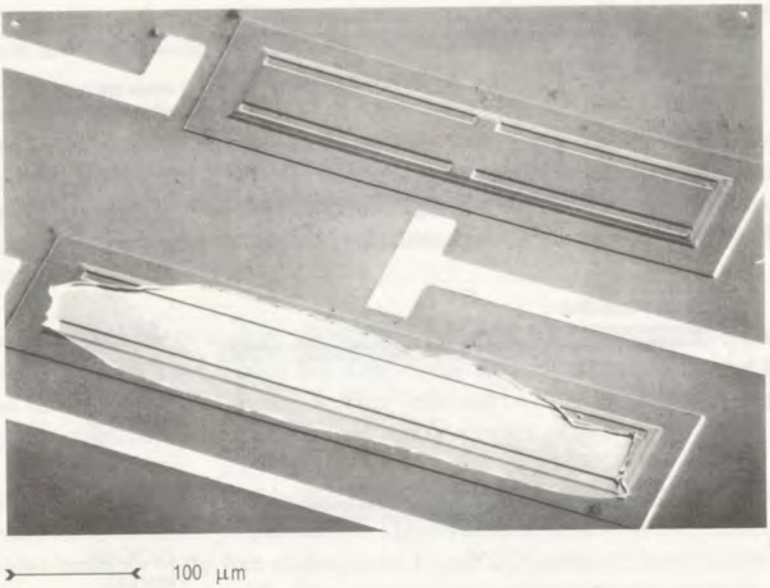


Figure 2.2b SEM-photograph of encapsulated beams (with the 'roof' torn away from the lower left one)
Source: [9]

2.2 *MICROSYSTEM TECHNOLOGY AND PRECISION ENGINEERING*

M.F. Dierselhuis

2.2.1 INTRODUCTION

Precision engineering has created many instruments, machines and products to support and extend our natural human senses. The continued development of precision engineering is one of the constituents that makes it possible to build microstructures and it is regarded as a prerequisite for the production of microsystems [11].

As indicated in section 2.1, micromachining of silicon gives tremendous possibilities for MicroSystem Technology (MST). Silicon is a natural choice as a base material because of the focus on smart sensors. Indeed, there is even a risk that other important micromachining technologies might be overlooked. One of the most promising for MST applications is the LIGA technique described in section 2.2.3. Other micromachining technologies are described in section 2.2.4. That list is not meant to be complete but will show the broad range of production methods that will reach accuracies within the micron range.

2.2.2 PRECISION ENGINEERING

In general the dimensions of precision engineered products lie between 0.1 millimetre and 10 metres and tolerances are in the range of 0.5-100 microns. However, dimensions and tolerances are not the basic characteristic of precision engineering. Most important are the approach and procedure which are related to those used with MST. In fact, MST can be seen as a logical further development of precision engineering combined with a new organization of production and new production techniques [12].

Precision engineering concentrates on dimensions, strength, static and dynamic behaviour, etc. Material properties are the basis for calculations and the technique used for creating the parts of a component will be selected taking economic considerations into account. In this way every item, including the connections of a design or structure, can be calculated; it thus becomes possible to define the total product.

Precision-engineered parts presuppose a high level of knowledge of materials, production tools and production methods. Often the matrix structure and the surface of the material is important for the function of the part. For example the wear resistance of a ceramic part depends on the basic material, the size of the grains before pressing and sintering, the dopants and the method of grinding and polishing. The chemical composition of the material is just one of the important parameters. To achieve more accurate results in precision engineering there has been a constant development of materials, alloys, treatments and production methods and in fact precision engineering made it possible to produce the equipment for the electronics and IC industry. In that way precision engineering makes high-tech low-cost. It encapsulates function integration, high reliability and accuracy in dimensions, tolerances, behaviour and often closed-loop electronic feed-back.

Microsystem technology combines the submicron IC technologies and traditional precision engineering in the submicron and micron range and is a logical further development of precision engineering. In the domain of MST, the material properties of crystals, the chemical and physical behaviour of bulk material, stress analysis, wear resistance, surface treatments, layer techniques etc. are more essential than in precision engineering. In MST the submicron range is not always necessary and for most constructions the micron range will do.

2.2.3 THE LIGA TECHNIQUE

With the development of IC technology we now know a great deal about the behaviour of silicon. Compared with the size and strategic importance of the production of electronics there is no other industry that explores one specific material in such a way. Even so, MST will enlarge our knowledge and use of silicon by bulk and surface micromachining, the use of porous silicon and silicon as a mandrel for transfer replication.

Nevertheless there are other technologies and other materials that can be micromachined. One of the most promising for MST applications is the LIGA technique, invented in Germany over ten years ago [13].

LIGA is a combination of lithographic and moulding techniques. A huge layer of photoresist (50-1,000 micron thick) is deposited on a substrate. With this thickness of the resist, normal photolithography results in a high level of dispersion and very inaccurate parts. High-energy X-ray radiation does not have these disadvantages and its use results in extremely accurate structures. After developing, the resist structure has the function of a mould. By galvanizing techniques the mould is filled with a conductive material such as gold, nickel or cobalt-nickel. Afterwards the resist structure is removed and a metal product results. The metal product can serve as a mould by itself and in this way can be used for precision plastic injection moulding. This plastic part again can be a mould, just like the original resist structure, but produced fast and cheaply. Figure 2.3 shows the production steps of the LIGA process.

With X-ray lithography the roughness of the product walls varies from 20 to 50 nm and the lateral dimensions are very stable. To unmould a material, angles are therefore not needed. The great advantage of LIGA besides this accuracy is the free choice of materials. Instead of filling the mould with metal or plastic it can be filled with ceramic slurry which can then be sintered. Another advantage is the freedom in patterns, enabling the use of forms which would be impossible to produce by cutting or stamping operations [14, 15].

Like IC technology, LIGA is a batch process on a wafer and the smaller the product the higher the number of products from one wafer. Typical dimensions start at 2 microns, with heights of 200-1,000 microns and tolerances in the range of 0.2-0.5 microns.

Although the number of materials used in LIGA at the moment is limited, it is rising steadily and the range of potential applications is enormous. Using the technique of sacrificial layers, free moving parts like bar springs can be produced. Or even a whole metal gearbox with axles etc. can be realized in a single production cycle.

Using a wafer it is possible to assemble other components simultaneously or to bond protective shields or planar actuators, such as piezo substrates. Furthermore, accurate positioning on the wafer scale is simple and cheap. LIGA is a mass production technique that enriches the field of microsystem technology drastically. When an electronic circuit is used as the substrate LIGA offers the possibility of electronic, mechanical and optical integration [16].

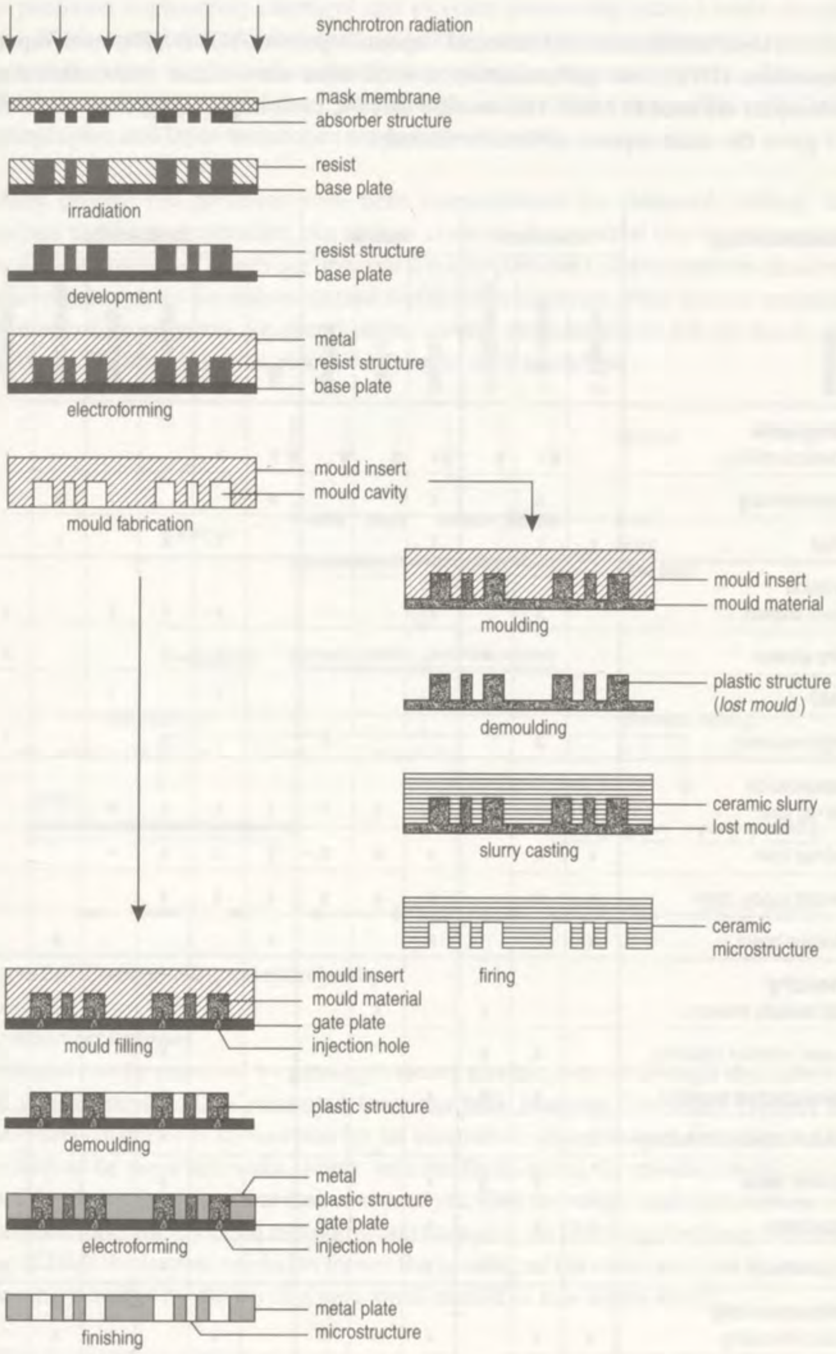


Figure 2.3 The LIGA process

2.2.4 OTHER NON-SILICON MICROMACHINING TECHNIQUES

Besides layer techniques like Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD) and galvanization several other non-silicon micromachining techniques are used in MST. This section lists the most important groups and table 2.1 gives the main aspects of these techniques.

microtechnology	*tolerances*			*material*			*characteristics*					
aspects	0-1 micron	1-10 micron	10-100 micron	metals	plastics	ceramics	foils	bulk	near shape	structuring	low roughness	high roughness
lithographic												
chemical milling		x		x			x	x				x
electroforming		x		x			x				x	
LIGA	x	x		x				x	x		x	
erosion												
spark erosion		x		x				x	x	x		x
wire erosion			x	x				x	x			x
EMD	x			x				x		x		
high frequency		x				x		x	x			x
vaporization												
NdYag laser		x	x	x	x	x	x	x	x	x		x
eximer laser	x	x		x	x	x	x	x	x	x		
copper vapour laser	x	x		x	x	x	x	x	x			x
electron beam	x			x			x				x	
moulding												
hot isostatic pressing			x		x				x			x
plastic injection moulding		x	x						x			x
metal injection moulding		x	x	x					x			x
ceramic injection moulding		x	x			x			x			x
powder metal		x	x	x					x			
replication	x	x		x	x					x	x	
cold forming		x	x	x					x			x
micromachining												
diamond cutting	x	x		x	x	x		x		x	x	
grinding, lapping, polishing	x	x		x		x		x			x	

Table 2.1 Characteristics of non-silicon micromachining techniques

Lithographic techniques

In precision engineering chemical and physical processing started some decades ago. Basic materials and substrates can be covered with layers of specific materials and, in the same way as a silicon wafer is prepared, a photoresist can be added onto metals and materials like kapton, polymers etc. and etched with specific acids. Most lithographic and layer techniques are batch processes.

Many precise foil products have been manufactured by chemical milling, like springs and heating elements. An etchant removes the material that is not protected by a resist. Instead of removing material it is also possible to add a material dissolved in an electrolyte to the non-protected surface of a substrate. Well-known examples of electroformed parts are razorblades, sieves, encoder discs, ink-jet heads and flexfoils. Figure 2.4 shows electroforming as well as etching.

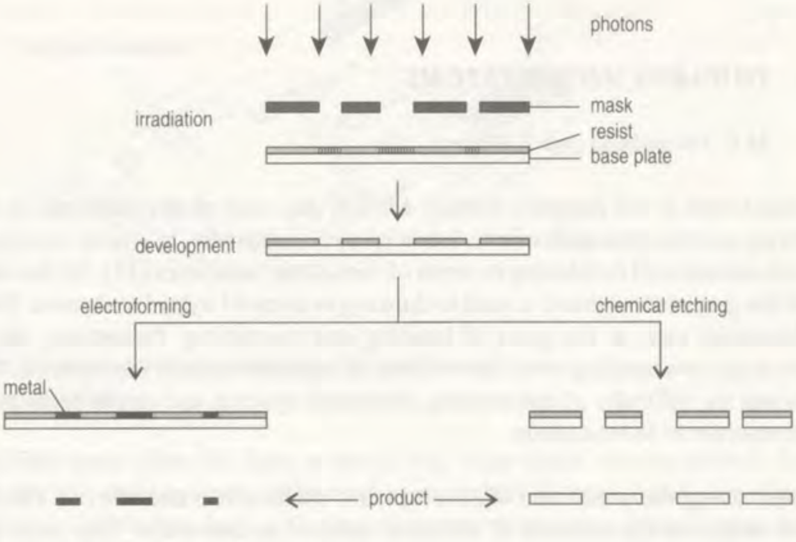


Figure 2.4 Chemical milling and electroforming

Erosion techniques

Material can be removed by passing a strong electric current through the material, by which chips will be separated from the bulk material. For spark erosion the processed material is surrounded by an electrolyte. A cathode in the shape of the section to be removed sinks slowly into the fluid, using the product as the anode and the electrolyte as a heat sink and catalyst. This technique and wire erosion are standard tools for injection moulding and stamping. In Electron Discharge Machining (EDM) the current needed to loosen the bonding of the molecules can be brought into the material by the tip of a very small needle (a few atoms thick).

Vaporization techniques

Transforming the material from the solid state directly into the gas state by vaporization is another technique. This requires heat in very small spots at the right place, making laser techniques an obvious candidate. Besides photons, however, electrons may be used to convey the energy needed for vaporization. Most masks are produced with the aid of this technique (electron beam vaporization).

Moulding techniques
The last few decades have seen rapid development in moulding techniques such as injection moulding, pressing and sintering techniques and mandrel transfer replication. In the last of these, the mould is produced by a shaped carbon or silicon part and coated (usually by a CVD process) with relatively thick metal layers.

Abrasive techniques
Developments in earlier techniques such as cutting, grinding, milling and polishing enhance the tolerances that can be achieved. This development is assisted by better machines, tools, cooling systems and understanding of material and process parameters.

2.3 TOWARDS MICROSYSTEMS

M.F. Dierselhuis and J. Roggen

As mentioned in the previous sections MST is the result of developments in two different technologies each of which has its own philosophy. In silicon machining we are accustomed to thinking in terms of monolithic structures [17]. On the other hand the precision engineer is used to thinking in terms of hybrid structures. These philosophies meet at the point of bonding and assembling. Present-day silicon technology uses bonding techniques to join the separate modules into systems. This indicates the difficulty of constructing monolithic systems and can be regarded as a prerequisite of hybridization.

In considering the production of microsystems we have two alternatives. The first is the design and production of complete systems on one wafer. This leads to a production cycle with many steps resulting in a batch of final products. The other is to build system modules with specific functions and combine these modules afterwards. This means that relatively simple production steps can be used to manufacture basic modules, but it also means that we have to have several assembly stages.

As long as integration can be achieved within one or just a few compatible production stages, it will be worth while. As soon as integration needs costly special processing, hybridization is a better alternative.

In electronics hybrid integration means classical multilayer, thick- and thin-film and interconnection technology [18]. In this book hybridization is seen in a broader way and on different levels.

2.3.1 THE HYBRID APPROACH

Coming from the silicon angle the hybrid approach to microsystems means that sensor, actuator elements, flow channels, signal processing and control electronics are combined into one final product. Coming from the precision engineering angle, hybridization means joining and assembling parts produced by different technologies such as the technologies mentioned in section 2.2. Both kinds of approach are considered to be examples of the hybrid approach to microsystems (figure 2.5).

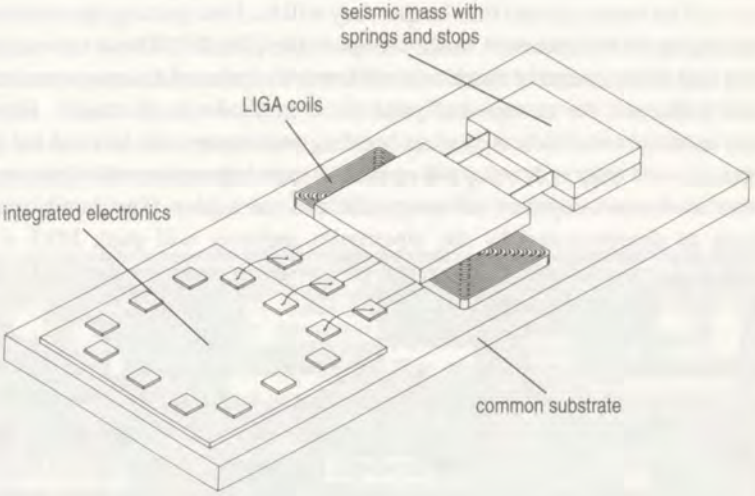


Figure 2.5 Accelerometer in hybrid version. Total size 2 x 5 mm²
Source: MicroParts

In recent years there has been a strong shift from smart sensors towards smart systems and these systems often need more functions than silicon can offer. In particular LIGA technology, which has now come to maturity, opens the possibility of new functions. It would not be surprising if precision engineering became an essential addition to silicon micromachining enabling the creation of a large number of new products.

In all probability, MST will be propelled towards the market by hybridization, and it will therefore be wise to pay appropriate attention to this approach and to take hybridization into account in the concept and design of products from the very beginning.

The strength of MST will come from the precision engineering approach applied on an even larger scale and with more disciplines involved.

2.3.2 INTERCONNECTION AND PACKAGING

Imagine a planar gearbox with an outer diameter of 50 microns. It could be built into a human hair. There is no problem in producing it. However, the availability of such a product will be irrelevant as long as we cannot drive the central gear from outside, have the gears in the box, are able to hold the box and pick up the movement of the inner gear system. In other words, MST products have to communicate with the outer world.

In order to lower the barrier of costly precision joining and assembly techniques it may be possible to use self-positioning actuators using magnetism, capacity, forms, coils, springs etc. These actuators are only needed to assemble the product and are useless afterwards. The smaller and more accurate the final system, the more these add-ons will be necessary and the cheaper they will be. New joining, interconnection and packaging techniques will make this possible [19, 20]. These new assembly methods and clean assembly machines will lower the price of microsystem technology and influence the design and production methods at all stages. However, ordinary assembly methods, including bonding techniques, can be used for hybrid concepts and will help to develop the market. A growing market will allow industry to invest in the development of more efficient machinery. The same industrial evolution as demonstrated by the electronics industry will push MST to new frontiers and will probably lead to new production techniques that make higher degrees of integration possible [21].

Because many of these methods will be new, the associated complexity and multidisciplinarity will also appear to be new, but in fact it will be a matter of 'more of the same'. Basically the required interconnection technology is an adapted Multi-Chip Module (MCM) approach which has proved successful as a high-density, high-speed interconnection technology. Whereas the concept of the multilayer interconnection is maintained, the electronic constraints are relaxed towards lower integration density and moderate speed, while the resistance of the sensing and actuating elements to the environment (liquids and gases) becomes a prime requirement.

In many MST products connections are not just mechanical, but also electrical and optical. This calls for clean rooms, clean benches or clean machines and knowledge of micro-joining techniques. Furthermore it needs people with a broad knowledge of the technologies involved [22].

2.3.3 MONOLITHIC INTEGRATED MICROSYSTEMS

In the US, at the Micro-Electronics Center, North Carolina (MCNC), multi-user projects in which surface micromachining is applied to standard CMOS wafer lots are currently proving successful at manufacturing hitherto rather simple silicon integrated micromachined devices [23, 24]. This approach produces benefits which include low cost, high yield and ease of integration of digital and analogue electronics, with the reliability of a standard process automatically built into the circuit. If such a service were available in Europe, integrated silicon micromachining would be accessible for universities, research laboratories and Small and Medium-sized Enterprises (SMEs) lacking their own in-house custom integrated circuit fabrication facility.

Most of the smart micro-electronic sensors and actuators reported to date consist of substrate electronics with one or more additional specialized layers of polysilicon, nitrides, piezoelectric or pyroelectric material. The substrate electronics contain the drive and control functions, while the additional layers carry the sensing and actuating functions. These functions are based on the material properties of the additional layers. When such systems are produced in large numbers, the concept is generally referred to as integration. Sensors or actuators that are integrated with substrate electronics are considered to be smart transducers. Figure 2.6 gives an example of an integrated acceleration sensor.

The circuitry of smart transducers is usually first manufactured in a standard IC fabrication process. Afterwards, the sensors and actuators are added in post processing steps. These steps include not only the deposition or etching of specialized layers, but also the micromachining of silicon (see section 2.1). Such post processing steps usually create suspended structures (e.g. diaphragms or cantilevers) by removing a sacrificial layer or by micromachining a portion of the silicon substrate.

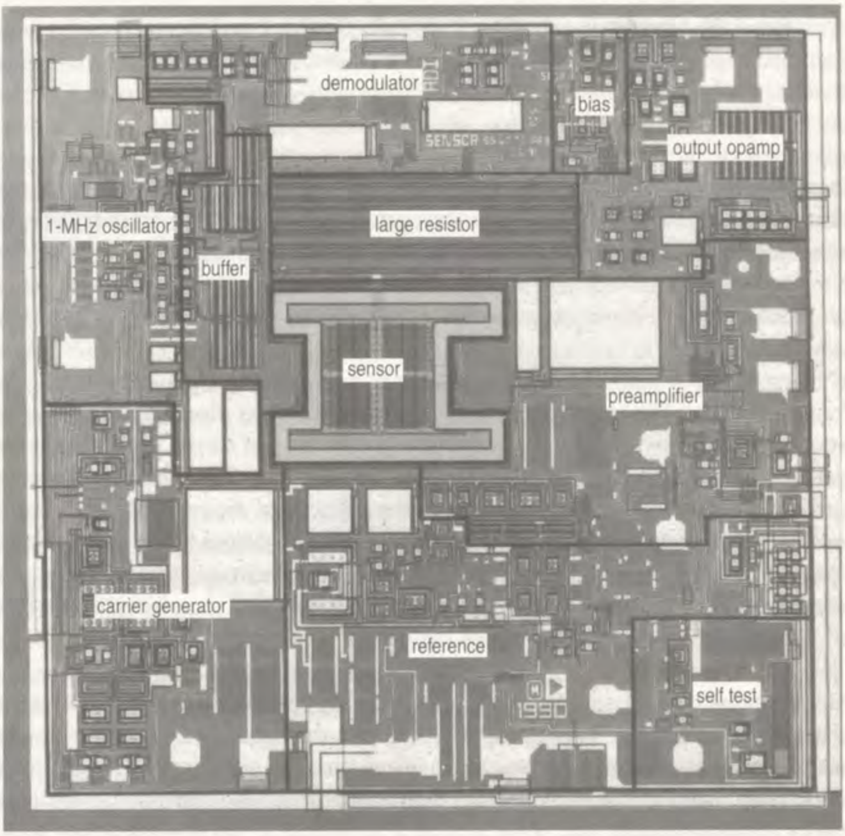


Figure 2.6 Monolithic acceleration sensor AD. The chip size is less than 10 mm^2
Source: Analog Devices

In general, microsystem technology introduces a new way of system integration including micro-electronics, sensors and actuators. The basis is provided by the integrated circuit fabrication methods and especially by using silicon as an integration substrate. However, several supplementary techniques such as three-dimensional pattern generation, deposition and etching of new materials, passivation and packaging have to be developed. A high priority should be given to the development of Computer Assisted Design (CAD) and simulation tools.

Where a variety of sensors or actuators have to be integrated into one system, monolithic integration can give rise to a variety of problems as it relies heavily on the compatibility of the fabrication processes used for each sensor or actuator. Such heterogeneous integration greatly increases the number of process steps and extends the overall fabrication process. Single-chip integration is also hindered in cases in which the application is not well-defined. A hybrid approach to microsystems is then preferable.

2.4 MICROSYSTEMS AND ENERGY

P.A.F.M. Goemans

2.4.1 THE ROLE OF ENERGY

Energy is an elusive abstraction – we mistakenly assume that we know quite well what energy is. In daily life we are confronted with it, either as an indispensable commodity for which we have to pay, or as a hot political item. An important law of nature is the conservation of energy, which means in effect that energy is suitable for 'bookkeeping'. In whatever guise energy shows up, the books will always balance.

Transformation of energy from one form to another takes place in every physical process in any micro- or macrosystem. Due to the laws of nature such transformations are inevitably accompanied by the generation of heat or the production of other kinds of chaos. Unless heat production is the purpose of the process itself, heat is considered as loss or waste. In any event, the energy lost from the system has to be replaced in order to keep the process going. Replacement must be done from an external or internal energy source; i.e. new energy has to be transferred either from an on-board storage reservoir or from the outside.

Microsystems differ from macrosystems in having higher natural frequencies and smaller time constants. These parameters reflect the behaviour of energy storage and energy dissipation in a system. Mechanical, thermal, electromagnetic and many other time constants shrink with advanced miniaturization, generally resulting in shorter response times.

With few exceptions, at the scale of microsystems material properties are still macroscopic. Where the cause of faster system response is not to be found in the material itself, the conclusion must be that this distinguishing feature is a consequence of scaling laws [25-27]. One important exception of a material property that benefits from small size is the electric breakdown field strength. It is not at all surprising, therefore, that chemical reactions and processes in living cells should be controlled almost exclusively by electrical forces.

Faster systems lead to higher speed or frequency to increase performance. In some cases higher speed or frequency is a deliberate choice; higher resonance frequency is the consequence of smaller size. Higher frequency of a cyclic process generally leads to larger losses and consequently to lower efficiency. This should serve as a warning or even a prohibition against transposition of macrosystems to the microworld by application of a geometrical reduction factor. The roles of energy storage and energy dissipation in microsystems differ considerably from the world of practical daily experience. Designing microsystems requires close consideration of energy budgets, for taking advantage of the merits of smallness as well as minimising its adverse effects. The following properties are typical of the energy balance of microsystems: mass inertia is small, thermal isolation is difficult and cooling is excellent.

Some microsystems are specifically designed to transform energy; for example to perform the conversion from chemical energy to mechanical work or to electromagnetic radiation. For enhancing the energy handling capability of a microsystem of a given size (in other words, to increase the specific power, i.e. the power per volume), we could increase the speed of the process, or if it is cyclic, its frequency. This may result in a configuration producing a large specific energy output over a considerable length of time, while the system itself still has a comparatively small energy content. If that type of system has an energy output which needs to be replenished from a built-in storage, the dimensions of the storage reservoir will certainly dominate the size and weight of the microsystem, which resembles an electric Formula One racing car with a storage battery instead of a fuel tank. In such microsystems one should think of the energy being supplied – in electrical or electromagnetic form – from an external source.

The most rational choice is on-board energy storage, rendering vulnerable connections to the microsystem unnecessary. This argument is invalid when data-communication should be done by wire anyhow. The alternative solution is obtaining energy from an external source. The energy supplied is usually electric or electromagnetic. The connection between source and microsystem can be by conducting wire or optic fibre, although a wire- and fibreless energy supply may not be excluded. For on-board energy storage there are various methods of 'refuelling'. Drained batteries can be replaced or recharged. Recharging may be accomplished by drawing energy from an external source (by wire, by fibre or wireless) or by taking renewable energy from the environment (light, heat, movement). In the latter case, special miniaturized on-board energy converters are indispensable. Fortunately, the watchmaking industry has achieved many useful developments in that area.

Finally, the more microsystem technology is implemented the more nanotechnology will evolve. Systems in the nanometre range offer serious possibilities for the exploitation of intermolecular and interatomic energy. The methods to be used will probably be more or less modelled on natural processes in living cells. An example could be controllable catalyzed chemical reactions which function as miniature fuel cells. For the time being this remains a futuristic dream.

Here follows a survey of various possibilities for miniaturized energy sources. Existing solutions are mainly derived from the medical world (pacemakers and other implants) and watchmaking technology.

2.4.2 PRIMARY AND SECONDARY CELLS, SUPERCAPACITORS

During the past 25 years, industry has given much attention to developing miniature batteries (primary cells), accumulators (rechargeable, secondary cells) and supercapacitors, for application in quartz watches, hearing aids, photographic cameras, calculators, and other electronic consumer articles [28, 32]. What was irritatingly lacking in 1970 is now available in several different technologies, voltages and sizes: namely, leakproof 'button cells' (figure 2.7) with a high storage capacity, low self-discharge, suitable voltage-discharge characteristics, ability to withstand a reasonable amount of electrical, mechanical and thermal maltreatment and finally, containing no harmful materials like cadmium and mercury or, if at all, only in minimal quantities.

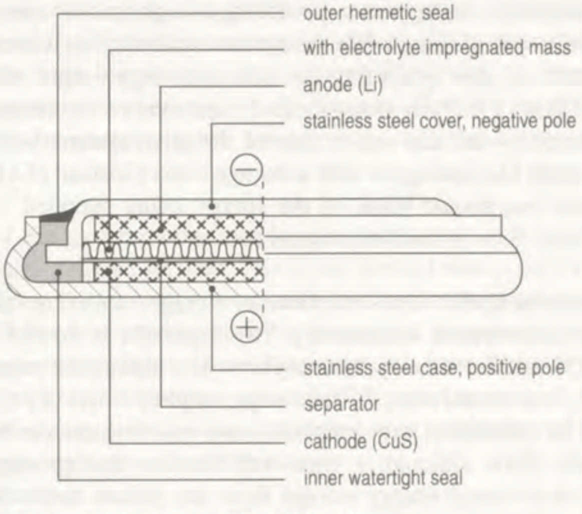


Figure 2.7 Button cell, primary Li-CuS system (RENATA No 44)

Common to all button cells is the disproportionate contribution of the strong stainless steel case to the volume and weight of the storage element. Industry has learned this from bitter experience, as in the past much irreparable damage was caused by leaking, burning or even exploding button cells. It is moreover a consequence of the large surface-to-volume ratio of any miniature device that its packaging seems at first sight to be out of proportion.

The development of watch batteries has been a successful combination of market pull and technological push. Yet history warns against overoptimism on the near availability of special batteries for microsystems. The introduction of the quartz watch in 1970 was considerably hampered by the disappointing quality of miniature batteries then available: a short life caused by low capacity, high self-discharge and (in the worst case) leakage. Moreover, the height of the batteries precluded (the design of) elegant wafer-thin quartz watches.

One requirement for a watch battery was at that time quite new and is even now still exceptional: if a watch is to be watertight, refitting new batteries is somewhat problematic. This means the battery can only be fitted by the manufacturer, although it is not known how many years later the watch will eventually be used. Energy consumption during the watch's 'shelf-life' is stopped by a switch, but the battery's self-discharge and corrosion cannot be eliminated. When the watch is in use its battery has to function perfectly for one year at the very least.

The economics of watch production (now some 800 million items per year) has generated incentives to develop 'ideal' miniature batteries. This has been a process of trial and error, which is still going on. 'Final solutions' have consistently been announced which in practice have proved to be failures. The most interesting example is the earliest version of the miniature lithium cell, originating from military and medical applications. This was expected to last as long as the watch itself – i.e. eight years or so – with its excellent energy density and extremely low self-discharge. In actual fact, too many analog quartz watches equipped with this so-called ideal battery stopped within the first year. This phenomenon was due to an unforeseen increase in the cell's internal resistance, resulting in its inability to supply the current pulses for the watch motor. In some watches the lithium actually exploded or caught fire.

It seems amazing that the simple scaling down of a thoroughly researched device has been so unsuccessful. The electrochemical cell in general is a treacherous element which, contrary to the optimistic results of meticulous laboratory experiments, repeatedly deceived the expectations of technical designers. It should therefore be obvious that the smallest button cells for watches are now the best available energy sources for microsystems, and will probably remain so for some time. Some of the smallest standard sizes are 4.8 mm (dia) x 1.4 mm (high) and 6.8 mm x 0.96 mm. Progressive miniaturization, to attain reliable cells with submillimetre size, will probably only progress slowly. A smaller risk factor, among other things, in respect of ageing, is possessed by supercapacitors, as they work based on reversible physical processes rather than chemical reactions.

Primary and secondary cells

Several electrochemical systems have been used for button cells, some exclusively for primary (disposable) cells, others for secondary i.e. rechargeable cells [28, 29]. Some of the best chemical combinations appeared to be suitable for both primary and secondary cells, the secondary version however gives a lower energy density. Systems based on the suspect metals cadmium and mercury have passed into disuse, mainly because of lack of quality. Most button cells for watches are still of the silveroxide-zinc type; in the future these will give way to batteries and accumulators based on lithium. After many years of disappointment, manufacturers have succeeded in producing reliable packaging systems for Li-cells, and in limiting the gradual increase of its internal resistance. The next best system for normal size cells is the nickel-hydrogen system: a reversible hydrolysis effected by an anode consisting of NiO-OH, and a cathode which strongly absorbs hydrogen. Ni-H will possibly give outstanding results with miniaturized cells.

Energy density determines the proper active volume of a cell for a given application. The consumption profile of the load (constant low drain versus pulses) fixes its maximum internal resistance, and thus its minimum diametre. The mixed profiles of analog quartz watches (constant low drain for the IC: e.g. 0.2 µA, pulsewise high drain for the actuator: e.g. 200 µA) require active diameters which for lithium cells are considerably larger than for equivalent Ag_2O-Zn cells. In this way, large thin 'coin-type' Li-batteries have come into use; typical diameters are between 12 and 23 mm. It will be clear that for such thin cells the relative volume of the packaging is larger.

Lithium systems have the highest intrinsic energy densities. If the volume of the packaging is taken into account, the energy densities of miniature primary Ag_2O- and Li-cells (200 to 500 mm^3) are more or less comparable; that is, between 1 and 2 Ws/mm^3. Extremely low self-discharge is the major property of Li-cells; a life of 10-20 years is claimed for some types.

In miniature Li-cells the anode, consisting of high-purity lithium, can be combined with many different cathode materials, resulting in different voltages ranging from 1.5 V to 3.9 V. For the electrolyte, which assures the transport of specific ions between anode and cathode, there are three different classes:

- non-aqueous solutions of inorganic salts, which moreover function like cathode;
- organic solvents in which lithium salts are dissolved to enhance conductivity;
- conducting solid polymers.

The reactivity of lithium with water and water vapour is extremely high. A special seal between anode and cathode (figure 2.7) needs to prevent the ingress of water to ensure a low self-discharge as well as safety. With the highly reactive anorganic electrolytes this seal can lead to problems. Due to the total absence of water, Li-cells can function between -50 °C and +70 °C; some types, with a special construction, function even up to +175 °C. Following the 'inorganic – organic – solid' sequence there is a decrease of the electrolyte's chemical aggressiveness, the sealing problem's seriousness, self-discharge and the maximum current drain that can be sustained per unit electrode area (the rate capability).

Since 1983 there have on several occasions been announcements of ultrathin solid state Li-cells, occasionally called 'energy paper'. The given specifications are: high energy density, reasonable rate capability, absence of sealing problems and adaptation to any size merely by cutting. It would apparently be the ideal basic material for electrochemical cells to be combined with microsystems, but it did not advance beyond the stage of experimental results [29-31]. In 1993 the Japanese firm KANEBO introduced its 'PAS accumulator', a product which resembles energy paper in many ways. A 200 µm polymer film (PAS = Poly-Acenic Semiconductor) is heat-treated in a nitrogen atmosphere in order to make it porous. In this way its active surface becomes some 2200 m^2/g, with 10 µm pore diameter. The porous film can be n- or p-doped, i.e. the pores can be permeated with donor and acceptor material. Doping means charging the cell; de-doping the film (by drawing the dopant back into an organic electrolytic solvent) means decharging.

The accumulators consist of a PAS anode and a cathode doped with lithium ions, which are placed in standard-size button-cell cases. The voltage is 3.3 V, corresponding to 3 Ni-Cd elements in series. As opposed to many other cell types, PAS accumulators tolerate electrical maltreatment such as overcharge and deep-discharge. Although an energy density of 0.6 Ws/mm^3 is claimed for the PAS material, complete PAS accumulators have only 0.02 Ws/mm^3.

It is by now probably obvious that developing suitable batteries and accumulators will become a major hindrance to the advancement of MST.

Supercapacitors

In 1978 Matsushita and NEC introduced the supercapacitor as a new element for energy back-up of electronic memories [32]. Its advantages are a seemingly endless life, electrical robustness and an absence of polarity. Supercapacitors were needed to replace accumulators, which all cease working sooner or later. The working principle of the original supercapacitors is the formation of an electrical double layer on the surface of activated carbon. This type of supercapacitor has been very successfully used in watches for about eight years now.

The element (0.33 F, 2.4 V), placed in a standard 9.5 mm x 2.0 mm button-cell case, has an energy density of 7 mWs/mm^3. For PAS supercapacitors made by KANEBO, on the market since 1993, better properties still are claimed [29]. The same 9.5 mm x 2.0 mm encapsulation holds a 0.6 F PAS capacitor.

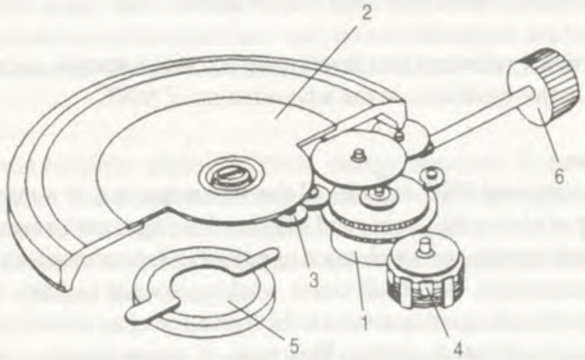
2.4.3 MICROGENERATORS

From 1950 to 1975 the automatic wristwatch came to be used more and more as an everyday timekeeper. An eccentrically rotating mass driven by wrist movements supplies energy to the main spring of the automatic watch. After half an hour or several days – depending on the activity of the wearer – the spring will be fully charged. The potential energy in the spring may then keep the watch working for about 48 hours after it has been removed from the wrist. As the mechanical watch requires 1 to 2 µW, its spring must contain on average some 0.25 Ws.

A typical small automatic watch mechanism (Calibre 04 from Büren Watch, 1967) has a volume of 0.9 cm^3, of which at most 25% is taken up by the energy system. Consequently, the system stores only about 1 mWs/mm^3, which is two orders of magnitude smaller than the specific storage capacity of a button cell for quartz watches.

The automatic quartz watch, on the market since 1988, uses the eccentrically rotating mass to drive an electric generator [32]. The electrical energy thus generated is stored in a supercapacitor, from which it is supplied to the quartz oscillator, the IC and the stepping motor of the timekeeper. The Japanese firm Seiko uses a multiple gear transmission between rotating mass and generator, plus a complicated electronic up-converter, for increasing the level of the voltage generated.

The Dutch firm Kinetron developed a system for the Swiss watch industry with much simpler electronics. Here a sufficient voltage level is easily obtained by the use of a multipole generator, in combination with a small version of the above-mentioned spring (figure 2.8).



A coiled spring in a barrel (1) is tensed by an eccentrically rotating mass (2) via a mechanical rectifier (3). As soon as the spring torque surmounts the magnetical pull in the microgenerator (4), the generator starts to rotate and supply electrical energy to a supercapacitor (5). A freewheel prevents tension of the spring in the reverse direction after unwinding. The spring can also be wound by hand with a winding-button (6).

Figure 2.8 Microgenerator system for quartz watches
Source: Kinetron

The average power consumption of a high-quality analog quartz watch can be as low as 0.5 µW. A fully charged capacitor keeps the automatic quartz watch functioning for 10 days. In this case the system's storage capacity must be 0.45 Ws. The volume of the mechanical-to-electrical conversion system (rotating mass, gears, generator, spring, electronics, supercapacitor) is comparable to the volume of the mechanical-to-mechanical energy system.

Again 2 mWs/mm^3 is a low score in comparison with the specific capacity of batteries and accumulators for watches. Yet the microgenerator's power generating capacity – to be discerned from energy storage capacity – is not restricted to the relatively low figure for watches. Supposing the electrical power generated to be 20 µW – i.e. 40 times the quartz watch's average power consumption – and the total volume of the microgenerator system to be 0.25 cm^3, then the specific power is 80 nW/mm^3. That 20 µW is the result of a 'cyclotest', the classic method for the accelerated testing of automatic watches.

It has been mentioned above that, at least for the time being, weight and volume of an on-board energy supply for a microsystem are disproportionate to the microsystem itself. The possibility of converting motion into electrical energy can be extremely attractive for applications where battery replacement is unacceptable, kinetic energy is abundantly available and space is not too severely restricted. A few examples are: implants for animals and humans, electronic locks, and automatic pressure control system in car tyres. All of these applications become increasingly more attractive with the decreasing size and weight of the total system.

2.4.4 MINIATURE STIRLING ENGINE

If a microsystem requires mechanical action, either to communicate continuous motion to part of the system or to cause operation of a device by applying stationary force or torque, the necessary effect can be delivered by an electromechanical actuator. That actuator needs a supply of electrical power, to be taken from a local storage battery or from an external source. A possible alternative is to supply power in the form of heat, for driving a miniature heat engine. Particulary in the case of combined data and energy transport by fibre, it seems obvious to use infrared light to drive a miniature Stirling machine for actuation, rather than by transforming light to mechanical energy via the intermediate of electrical energy.

A Stirling engine contains a pressurized 'working-gas' in its hermetically sealed system of two interconnected cylinders. A diagram of this is given in figure 2.9.

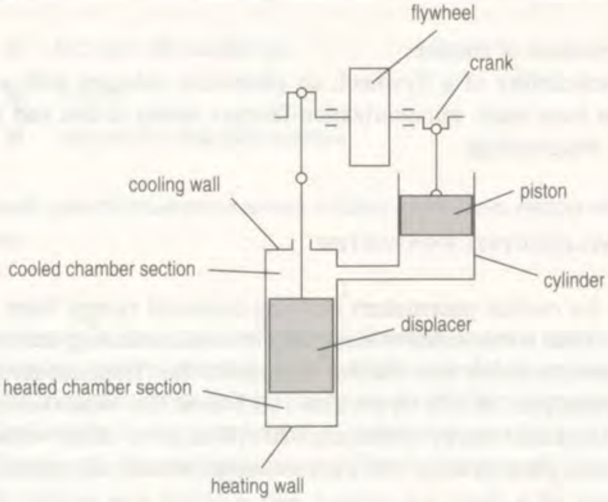


Figure 2.9 Diagram of a Stirling engine

Power is generated by the alternate heating and cooling of the working gas. From an external heat source, heat is taken up by the gas on one side of the first cylinder, and partially converted to mechanical action by expansion of the gas in the second cylinder containing the piston. The gas is then isolated from the heat source and brought into contact with the cooling side of the first cylinder by the movement of a porous 'displacer'. While the gas expels its 'waste heat' into the cooler the piston is moved back to its original position. The next cycle starts when the gas is again transported to the heated section of the first chamber by the return of the displacer. The out-of-phase movements of displacer and piston are governed by a crankshaft and flywheel and power is extracted from the crankshaft.

In theory the efficiency of the Stirling engine is equal to the efficiency of the Carnot cycle. The power output is approximately proportional to the 'swept volume' (i.e. the variation of the working gas volume) and the pressure of the hot working gas. Output and efficiency are strongly influenced by increasing the pressure difference of the hot and cold working gas; in other words, by increasing the difference between high and low temperatures. If mechanical power is supplied to the Stirling engine it can function as either a refrigerator or a heat pump.

A Japanese group has developed a miniature Stirling engine with a swept volume of 110 mm^3, working at 10 Hz frequency between 373 and 273 K, with an output of approximately 20 mW [33]. It is expected that the actual power-to-weight ratio of 1 μW/mg can be raised between 10 and 100 times for a 100 mg micro Stirling engine measuring 5 x 5 x 5 mm^3. With actuators using Shape Memory Alloys (SMAs) ratios up to 1 mW/mg would be obtainable, but with an efficiency ten times lower (figure 2.10).

The main problems encountered in designing the micro Stirling engine appear to be typical of microsystems. These are related to:

- the thermal isolation between the heating and cooling sections of the displacer chamber;
- the minimization of friction;
- the impracticability of a flywheel; an alternative solution with a snap-action spring has been used; miniaturization favours spring action and puts rotating mass at a disadvantage.

2.4.5 THERMO-ELECTRIC CONVERTER

Patents exist for cardiac pacemakers deriving electrical energy from a thermonuclear process. Heat is converted to electricity in semiconducting thermocouples. In 1980 the American-Swiss firm Bulova introduced the 'Thermatron' watch, based on the same principle [28, 32]. Of the total 100 W heat flux which leaves the human body, the miniaturized energy system uses 50 mW at 9 cm^2 of the wrist. The energy conversion takes place in some 350 thermocouples, electrically put in series. Each couple consists of a (hot) n-p contact and a (cold) p-n contact between two semiconducting elements, manufactured in bulk technology from a Bi-Te compound. The 700 elements are (mechanically parallel) clamped between the cool face and the warm back of the watch case. With a temperature difference of 1.5 K the no-load voltage generated is 200 mV. The output of the thermo-electric converter is only 10 μW, resulting in an efficiency of 0.02%. This figure is low even in comparison with the Carnot efficiency (0.5%).

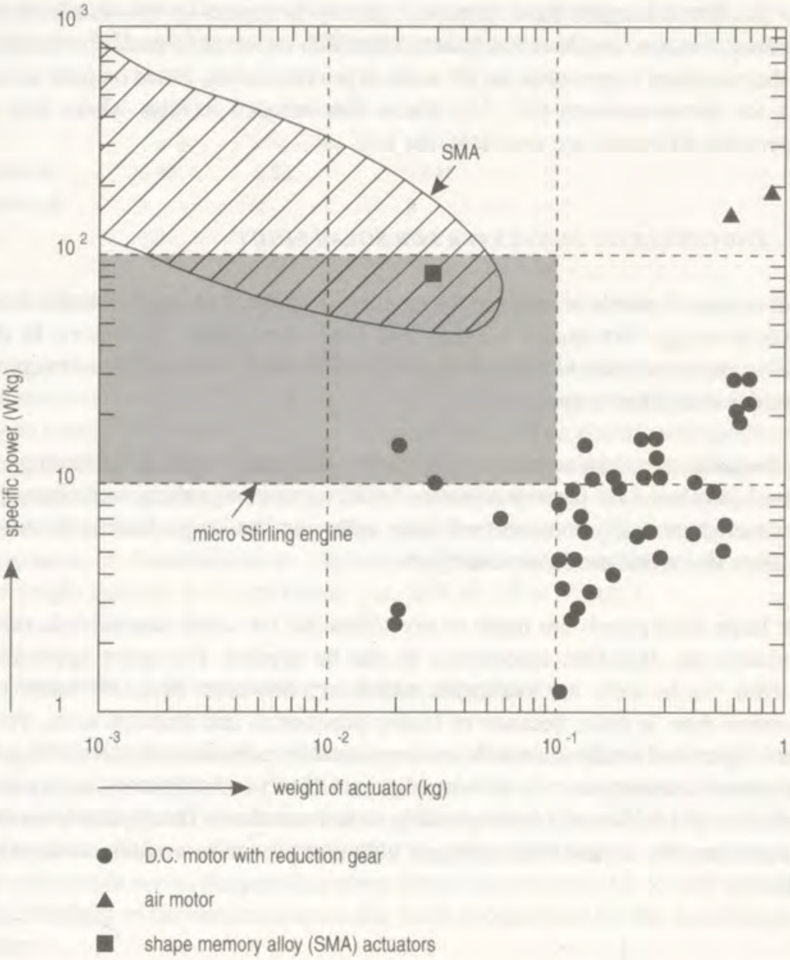


Figure 2.10 Specific power of miniaturized actuators. A Stirling engine, shape memory alloy actuators and other actuators
Source: [33]

This is not surprising, as the generated current, through its Joule heating and Peltier cooling and heating, reduces the temperature difference of the contacts. The generated current thus counteracts its origin, the Seebeck voltage. A major restriction in this special application is the poor thermal isolation between the two halves of the watch case. Small scale thermal isolation is difficult in any event [25, 33].

The electrical energy generated has to be stored in an accumulator or supercapacitor. Supposing the volume of converter plus storage element to be 0.25 cm^3, the system's specific power would be as low as 40 nW/mm^3; a comparable figure has been found with an optimistic calculation for microgenerators.

Since 1980 a lot of work has been done on the development of thermo-sensors based on the thermo-electric effects (Thomson, Seebeck, Peltier). The manufactured thin-film thermocouples have improved greatly in regard to volumetric density, efficiency remains very low. It seems worthwhile, however to study the feasibility of a thermo-electric generator on the scale of microsystems, based on new technologies for thermo-sensors [30, 31]. These can be used in sites where heat and temperature difference are available 'for free'.

2.4.6 PHOTOVOLTAIC CONVERTER FOR SOLAR LIGHT

Small solar-cell panels are used in the smallest portable appliances which consume electrical-energy, like quartz watches and credit-card sized calculators. In these applications the surface of a panel is several cm^2, which is two orders of magnitude above the size of microsystems.

The manufacture of solar panels, originally comparable with IC technology, has evolved into low-cost mass production based on screen-printing techniques [34]. To manufacture really miniaturized solar cells one should go back to basics and reactivate discarded production methods.

Most large solar panels are made of crystalline Si; for small photovoltaic cells in calculators etc. thin-film amorphous Si can be applied. For space applications, thin-film Ga-As cells are preferred, which are however 10 to 50 times more expensive than Si cells, because of higher production and material costs. Performance figures of small solar cells are expressed by open-circuit voltage V_{OC} (V), short-circuit current per mm^2 cell-area I_{SC} (mA/mm^2) and efficiency η (%), for an irradiation of 1 mW/mm^2 (corresponding to fine weather). The typical form of the I-V curve, and the almost linear effect of light intensity on it, are illustrated in figure 2.11.

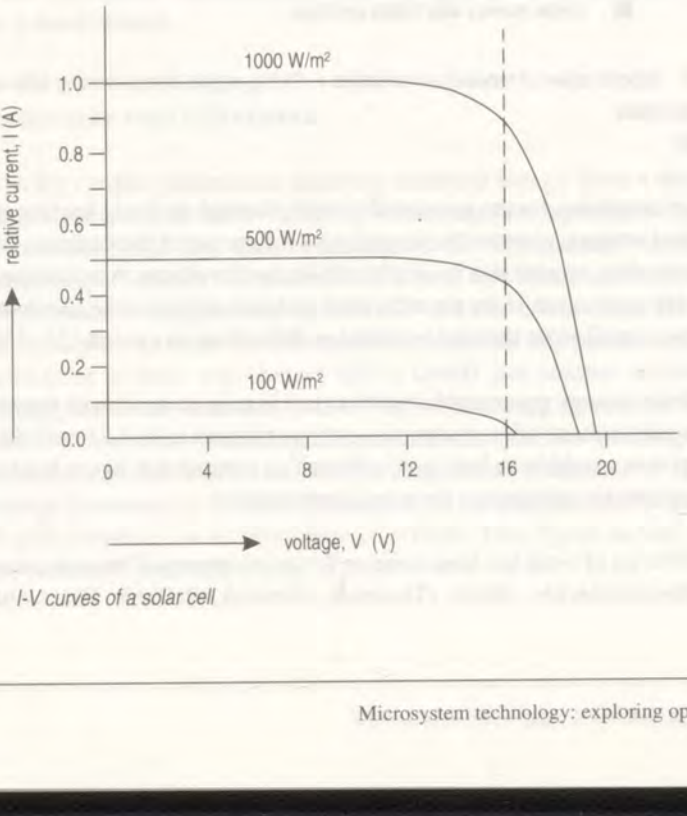


Figure 2.11 I-V curves of a solar cell

Most solar cells have been optimized for a standard spectrum of terrestrial solar light. State-of-the-art figures for different types of solar cell are given in table 2.2.

	V_{OC} (V)	I_{SC} (mA/mm^2)	η (%)
crystalline Si	0.60	0.33	13-16
amorphous Si	>	<	5
Ga-As	1.0	0.25-0.30	20

Table 2.2 Characteristic values of solar cells

For future thin-film photovoltaic cells, efficiencies of over 30% are expected [30, 31]. It should be realized that solar light is only intermittently available, and usually not at its maximum intensity. This necessitates the use of an electric storage element (supercapacitor or accumulator). Bright sunlight may be concentrated and irradiated at perpendicular incidence with movable mirrors or lenses; such auxiliary means are however useless in cloudy weather, and moreover, do not comply with the requirements of miniaturization. Consequently, the maximum output of a Ga-As cell in bright sunlight is 0.2 mW/mm^2 (i.e. 20% of 1.0 mW/mm^2).

2.4.7 PHOTOVOLTAIC CONVERTER FOR LASER LIGHT

A solar cell is a large-area photovoltaic-conversion device, optimized for the broad frequency spectrum of solar light. With a narrow beam of monochromatic laser light it is more profitable to use a small-area photodiode. A photodiode has the same working principle as a solar cell; basically it is a p-n junction, which generates an electrical current across the junction when absorbing photons [34, 35]. By influencing the bandgap of the semiconductor, the diode is optimized for the wavelength of the laser.

The photodiode is normally used as a sensor or signal detector, but may also be applied as an energy converter. Because of the better adaptation of the semiconductor bandgap to the laser wavelength, energy conversion is effected with a higher efficiency than in solar cells: about 50% for λ = 650 nm (red) or λ = 780 nm (infrared) and even 90% for λ = 1310 nm (far infrared). The commercially available semiconductor-diode lasers are used for optical communication (telephone via glass fibre) and optical recording (compact disc). Lasers with λ = 650 and 1310 nm are not very interesting for energy conversion as their output is only 3 mW. An appropriate choice for the photovoltaic converter is a 30 mW diode laser with λ = 780 nm. The conversion efficiency of this diode is 50%. With 15% further losses due to the propagation channel (fibre and couplers), a total efficiency of 35% would be feasible. Within the last few years laser power has been increased through the use of multi-emitter laser arrays. With a monolithic array of 100 emitters, output in excess of 5 W has been shown.

The main problem is apparently not how much energy can be pumped into a microsystem, but how much heat can be removed from it. Let us therefore take the example of a cube-shaped microsystem, measuring 2 x 2 x 2 mm^3. One side of the cube is covered with photodiodes and fitted to a fibre bundle; at room temperature the other five sides are cooled by the surrounding still air. Uniform temperature rise of the microsystem is supposed to be 60 K. Heat transfer by radiation and natural convection is calculated to be at least 1.2 mW/mm^2 in this case [36]. With a cooling surface of 20 mm^2, the maximum allowable dissipation is 24 mW. If the photodiodes are the only heat sources in the microsystem, the maximum output of a converter with 50% conversion efficiency equals the maximum cooling. Within the specified conditions the maximum specific output of the 4 mm^2 cell is 6 mW/mm^2, which is 30 times the maximum specific output of the solar cell. In fact this figure does not change if another size, e.g. 1 x 1 x 1 mm^3, is taken. When the microsystem is provided with cooling fins, immersed in a liquid (water, blood), in contact with animal or vegetable tissue or moving in any medium, heat transfer is much more effective than in still air. The cooling of microsystems is apparently not the biggest problem.

It can be concluded from the above that the photovoltaic converter for laser light is an extremely attractive option for microsystems.

The transmission channel between laser and photodiode, i.e. between energy source and microsystem, can in principle be the atmosphere or some other gas or liquid. In the R&D program for MST in Japan, photo-electric conversion is considered as an important option for wireless energy supply [37]. Yet, thinking of all possible complications caused by beam alignment, beam obstruction and damping, one may conclude that connection by fibre is preferable. For distances up to a few metres the standard 0.25 mm-diametre polymer fibre seems to be the proper choice; if required, those fibres can be bundled to increase capacity. Photodiodes may be either in series or parallel to form two-dimensional configurations adjusted to the size of the microsystem; the packing should be adjusted. Electrical energy generated by photodiodes in the microsystem can be stored in a supercapacitor or accumulator.

Laser light can be used for energy and data transport. Yet it seems unwise to transmit both simultaneously in a single channel. A better solution would be alternating transmission of data and energy, as desired, with one single or two separate lasers. The simplest option is probably to use separate fibres for energy and data; it is possible to combine them in the same bundle without risk of interference.

Until now it has been supposed that the data stream is directed to the microsystem. An attractive energy-saving option for data transmission from the microsystem is to use the laser at the other end. For this the microsystem (with no laser on board) should have some liquid-crystal device or tilting mirror to modulate the reflected laser beam. It has been mentioned above that a laser beam can also be used to produce heat in the microsystem module, e.g. to operate a miniature Stirling engine.

After all, one could ask if fibres are more suitable than copper wire. In the first place, fibres are safer: there is no risk of electric short-circuiting in the case of rupture or damage. Another reason for using fibres is the absence of interference with other (micro)systems, while the electromagnetic field of current-carrying copper wires may give rise to serious problems of electromagnetic compatibility. Microwaves are even less attractive for data communication for the same reason. Microwaves would certainly be an attractive option for wireless energy transport to the microsystem if extremely small receivers and converters were available.

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3. Microsystems and instrumentation

3.1 APPROACH AND FOCUS

3.1.1 INTRODUCTION

G.C. Klein Lebbink

This chapter deals with possible applications of MicroSystem Technology (MST) in instrumentation. By its very nature, instrumentation is a pervasive technology which finds application in a wide variety of areas. This chapter concentrates on environmental, industrial and high-end (space, military and R&D equipment) applications. Applications in medical technology, consumer products and agriculture are discussed elsewhere in this report.

In industry there is an ongoing need for more and more accurate measurements of processes in manufacturing installations and other plants to provide actual performance insight to the operators. Safety, environmental performance, quality assurance or improvement and operational effectiveness are the main thrusts for applying advanced measurement and control equipment in industrial plants. Distributed intelligence and the further exploitation of microsystem technology certainly enables the development of cost effective solutions to be pursued.

The need for instruments for environmental monitoring is strongly influenced by regulations. As these regulations are becoming more and more stringent this area might very well become a growing market for instrumentation. The need to transport the instruments will certainly lead to a reduction in weight. An environmental network with intelligent sampling systems could reliably monitor, for example, the quality of Rhine water and transmit warnings when hazardous elements exceed preset levels.

Designers and manufacturers of high-end technology, like the aeronautics industry, naturally demand the utmost reduction in the weight of their equipment. Several successful applications of microsystems can already be found in this area and the ongoing trend towards function integration and lightweight instruments will undoubtedly lead to more challenging examples.

Section 3.2 describes examples of possible applications for each of the areas mentioned above. Section 3.3 portrays four cases of instrumentation in detail and analyzes the role of MST in these applications.

3.1.2 WHAT IS INSTRUMENTATION?

E.C.C. van Woerkens and J. Snoeks

In the widest sense instrumentation consist of a wide range of hardware, for the most part electronic, used for data capture and data processing. Much instrumentation consists of measuring instruments, but the term also covers instruments used for the control of industrial and other processes, in power generation, for communication, and so on. Instrumentation is also found in other sectors, such as agriculture and medicine. It is not always easy to make a definite distinction between industry and other sectors. For example, instrumentation can be used in meteorology for the benefit of agriculture, but data from the same instrumentation might also be used by the transport industry or in environmental monitoring.

It is a characteristic of instrumentation that it is often developed and installed for a particular application, frequently on an on-off basis or in comparatively small production runs. A complete instrument or system is seldom a mass produced item. However, system parts such as sensors may be manufactured in relatively large numbers.

3.1.3 IDENTIFIED FUNCTIONS

L. Hermans

Instruments can perform many different functions. Although in most cases instruments perform more than only one function, it is possible to characterize the complete instrument by a specific function. In order to define the field of instrumentation and to generate ideas for possible applications of MST in this field, the following five basic functions of an instrument have been identified.

Measurement

The purpose of a basic measurement system is to present an observer with a numerical value corresponding to the variable being measured. In other words, the measurement system transforms a certain quantity into a number. The important element here is the sensor. The quantities to be transformed can be of a physical, chemical or biological nature. Although, from the definition point of view, there is no fundamental difference between a physical, chemical or biological measurement system, from the practical viewpoint it makes sense to discriminate between on the one hand physical and on the other hand chemical and biological measurement systems. For the latter, the instrument, or at least the sensor, has to be in direct contact with the measurement sample.

Inspection

In order to create the inspection function a decision making step has to be added to the pure measurement. This implies that the instrument, based on the result of the measurement and using a knowledge database, takes a decision locally which is afterwards transferred to a processing unit for further action. The inspection system itself does not interfere with the process. For example, a system measures the length of an object and transfers the information to the processing unit that the object is too short or too long.

Automation, robotics and control

Automation, robotics and control supply the inspection function with the active intervention of the system or instrument in the process. To illustrate this we take the example of a microrobot performing maintenance. This robot measures certain parameters, interprets them and takes action where necessary, to repair the observed defect. The maintenance, robotics and control function are characterized by the direct influence of the system in the process.

Information handling

Information handling covers the transfer, storage and display of information. Whereas information processing is now executed at the micron or even submicron level, microsystem technology is also becoming more important for the storage, transfer and display of that information. Storage, transfer and display of data are essential functions of measurement systems. Thus the impact of MST on these functions should also be considered.

Identification with monitoring

A miniaturized instrument can, in addition to the above mentioned functions, also perform an identification function. This means that the instrument contains a unique code which identifies the instrument and, as a consequence, also identifies the object carrying that instrument. The instrument can be tracked continuously to indicate the actual position of the instrument. In many cases the instrument is continuously monitoring a certain variable. An example of such a system could be a microsystem attached to packaged goods for monitoring the environmental conditions to which these goods are exposed. This information could be used should there be discussion concerning responsibility in the case of damage to the goods. Historical information on time and location of goods can also be used to maximize production planning and logistics.

3.1.4 MOTIVES FOR USING MICROSYSTEM TECHNOLOGY

L. Hermans

The motives for using microsystem technologies for the development of new types of instruments are grouped into five categories.

Portability

A lot of existing instrumentation is heavy, large scale and power-hungry, causing its use to be limited to a restricted number of environments. In order to use such instruments in other more difficult, or at present, inaccessible environments, its weight, size and power consumption has to be reduced considerably.

In-situ operations

In-situ operations are important in industrial environments for monitoring equipment during processing, for maintenance, planning and possible repair. In-situ operations require the combination of local intelligence, reliability, limited power consumption and relatively small size.

Function integration

Miniaturization allows the use of a larger number of sensing or actuating elements within the same financial, geometric, weight and power constraints. An increase in the number of different sensors within the same instrument leads to higher sensitivity and selectivity. Comparison of data obtained from different sensors will help to eliminate cross sensitivities. The electronics needed for this first data processing step can be integrated into the microsystem. In order to increase reliability, several sensors of the same type can be integrated into the system to allow switching from one sensor to another in the case of malfunction.

Distributed systems

In many applications it may be necessary to measure one or more variables in several different places. In order to achieve this, systems must be low cost and easy to interface with central or distributed control units. Local intelligence will help to reduce the amount of data to be processed by the control units. Auto-calibration and self-test are important as a lot of these systems will be installed in places which may not be easily accessible. To promote the widespread use of these distributed systems, standardization of interfaces between the instrument and the data network is an important requirement. Such systems can be installed alongside pipes in civil engineering constructions for monitoring the internal state, in the chemical processing industry, in buildings to control the internal climate and inside cars.

Reduction of total costs

The total costs not only include the cost of producing and operating the instrument but also include environmental, social and safety aspects. The reduction in the use of raw materials and energy, the use of smaller amounts of chemicals and higher recyclability are all characteristics of microsystems. The relatively low cost of microsystems will generate their increasing use as systems which contribute to high levels of safety and environmental protection, not only by protecting the individual but also by decreasing the social burden resulting from possible accidents.

3.1.5 APPLICATION AREAS FOR INSTRUMENTATION

H. Leeuwis, O. Ongkiehong and L. Hermans

Environmental applications

One of the areas where MST when applied can have a great impact, is tracing, monitoring and prevention of environmental pollution, as existing technology is not sufficient to fulfil such requirements as continuous measurement, small size and low cost. MST can be applied for developing new kinds of sensing instruments (sensors or micro-analysis systems) with such features as (semi-)continuous, in-situ and on-line measurement of pollutive substances. These sensing instruments could be used to trace pollution in surface or ground water, soil or air (immission) or to measure emission from such sources as homes, factories and energy plants, either to prevent pollution or for safety reasons (e.g. for the detection of CO or explosives). In the future, sensing instruments could be used more and more in production processes, not only to enhance the quality of production through better control, but especially in preventing emission of pollutive substances.

One of the main problems of the market in environmental products in general, and certainly that for sensing instruments, is that it does not conform to normal market economics: there is as yet no commercial drive for the application of environmental technology. On the one hand, more legislation is necessary to prescribe the use of such pollution sensing instruments or to create artificially economic benefits for when these instruments are used to prevent pollution ('the polluter pays'). On the other hand, a lot of costly product development needs to be done before technology is advanced enough to be used for continuous emission measurement. However, with a 'sharper' environmental policy, as already exists in California, the vicious circle of lack of development and the lack of application of MST-based sensing instruments will be broken.

Because of the leading position the Netherlands (together with Germany) has in Europe on environmental legislation and the availability of a great deal of expertise in the area of MST there are ample opportunities for economic benefits. A rise in Dutch environmental investment was recently estimated to be from DM 103 million in 1987 to DM 302 million in the year 2000 [1]. For Europe these figures are DM 2.6 billion and DM 8 billion.

Industrial applications

Instrumentation forms an indispensable part of industrial production plants. Furthermore, the awareness of industries that their performance is now also measured in terms of operational safety, product quality, environmental impact and cost effectiveness is increasing. In addition, a prerequisite for managing factors of performance effectively is that production processes are under control under all circumstances. All this leads to an increased demand for instrumentation in industry.

The prime purpose of process control is to keep all process variables as near as possible to required values, even under the influence of disturbances. Process control systems maintain the processes within predefined operational windows safely on stream and support safe start up and shut down operations.

The discussion has so far concentrated on basic control requirements. However, strong competition in virtually every company puts increasing pressure on management to exploit their plant to the full, which exceeds basic control. Modern instrumentation, supervisory control and data acquisition offer advanced control, as well as Statistical Process Control (SPC), unit optimization and higher level optimization.

All control techniques are as good as the information they work with, so there is an increasing interest in better and more accurate instrumentation. The developments of today veer towards the direction of distributed intelligence (smart transmitters), on-line quality measurements, use of modern digital communication links (field buses), an increasing number of quantities that can be measured, and better man-machine interfaces. Instrumentation in industry has to meet stringent requirements. This applies especially to sensors. The surroundings of many sensors are 'hostile'. Important items of these hostile environments are electromagnetic interference, explosive gases, high temperatures, high pressures and aggressive substances. A contribution from MST is expected to support these developments and to meet these severe requirements.

The economic impact of instrumentation can be estimated from the following considerations. Fifteen years ago up to 15% of the total investment of chemical plants was dedicated to instrumentation. Today this percentage has risen to 20%. The worldwide turnover of instrumentation in industrial applications in 1995 is estimated at NLG 33 billion (33×10^9), divided equally over Europe, USA and East Asia. This includes the use of instrumentation in (petro)chemical plants, power plants, oil and gas production, refineries, water treatment, metal, food, beverage and paper production.

High-end applications

High-end applications cover very specific areas imposing requirements usually not met in 'normal' applications. Two high-end application areas for microsystems are considered in more detail: space technology and the military. Many high-end applications are also found in advanced scientific research such as high energy physics, biotechnology, chemistry, astronomy and medicine.

Although space and military technology have some common characteristics and are often discussed together, there are fundamental differences. The most important difference is related to the number of systems required. Whereas in space applications the number of systems rarely exceeds a few, the volumes required for military applications can be much larger and in some cases several thousands, or even more, may be required. This implies that cost reduction of the system as such may be an argument for the military but will never be a motive for the use of microsystems in space.

Reduction in volume, weight and power consumption will always be one of the most important reasons for using microsystem technology in space. For the military, the requirements will have to be studied on a case by case basis. This can be very important as far as the equipment of the individual soldier is concerned, but irrelevant for systems for armoured vehicles. The requirements concerning reliability and traceability are very similar for both application areas.

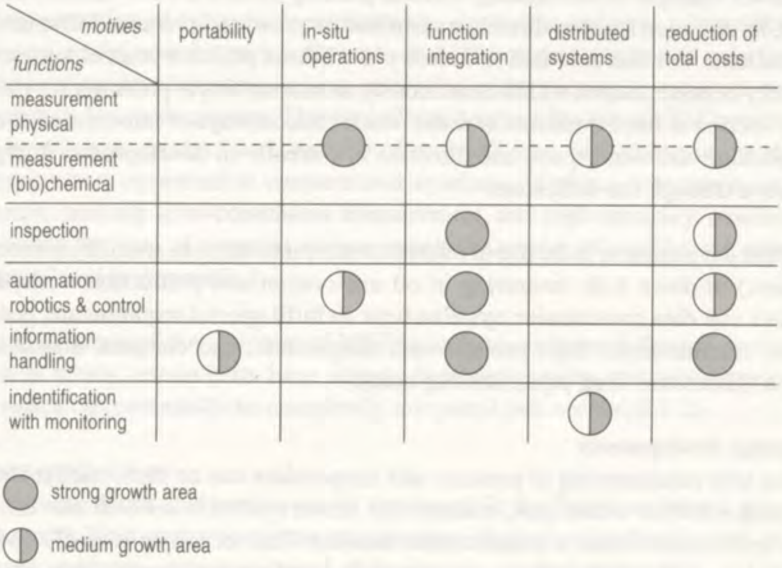
Microsystems could play an important role in the military in guidance systems for smart weapons and in systems for the protection of individual soldiers against chemical or biological warfare.

3.2 OVERVIEW OF IDEAS

3.2.1 INTRODUCTION

G.C. Klein Lebbink

In order to access the total area of instrumentation a matrix is set up with functions and motives to use MST along the axes. The items along the axes are discussed in sections 3.1.3 and 3.1.4. In the matrix each cross point is given a rating indicating the expected growth potential for applications of MST. The resulting ratings are indicated in figure 3.1.



motives / functions	portability	in-situ operations	function integration	distributed systems	reduction of total costs
measurement physical measurement (bio)chemical		●	◑	◑	◑
inspection			●		◑
automation robotics & control		◑	●		◑
information handling	◑		●		●
indentification with monitoring				◑	

● strong growth area

◑ medium growth area

Figure 3.1 Expected growth potentials for MST in instrumentation

Usually more than one motive applies to a function and it therefore proves very difficult to come to ideas specific for one cross point. This section presents an overview of the ideas and includes the motives for using MST in the applications described. The functions listed in figure 3.1 are subsequently discussed in this section for a number of applications. The four most tantalising ideas are worked out in section 3.3 as separate cases. The level of detail of the cases depends on the present state of the art. User specifications are discussed and, where possible, technological demands and deficits, and economic boundaries.

3.2.2 MEASUREMENT

3.2.2.1 WIRELESS PROBING

M.J. Vellekoop and J. Snoeks

Introduction

Wireless probing systems collect data at a certain distance from the location where the data is received and processed. Microsystems are attractive, and for some applications inevitable.

A known example of an existing wireless probing system is the weather balloon. Here, information is either directly transmitted or stored and processed after landing the balloon. For the automotive industry a wireless pressure control system has recently been developed which continuously monitors the tyre pressure. An electric buoy located at fixed positions in water which collects ways of information such as temperature and wind speed and direction is currently in development. Energy is obtained through sun-collectors.

Another development is the use of microsystems (or to be more specific, microcomponents) in down hole measuring in oil exploration and production wells. Both sensors and data transmission systems have to fulfil special requirements because of the circumstances: high pressure and temperature, and complex transmission media (kilometres-long pipes, drilling mud).

Ongoing developments

Down hole measurement of pressure and temperature can be performed manually by using wire line techniques, whereby the sensor system is lowered into the bore hole and retracted after a measurement mission. This technique is costly and can only be carried out while the production hole is off stream. Permanently installed down hole monitoring systems as available today rely on data transmission links via electrical wires or optical fibres. Wireless probing is considered an attractive option and developments are ongoing in which the data link is achieved via the tubing and casing which form a coaxial cable.

Measurement-while-drilling systems are also under development. The measurement system is integrated into the drilling head, while data transmission takes place via pressure pulses through the drilling mud column. A wide variety of measurements are carried out this way like the actual position, inclination, friction, speed and temperature.

The demand for microsensors in the bore hole is growing, for such obvious reasons as their small size and weight, but also for other reasons. In deep holes standard electronic circuitry cannot be used because temperatures reach over 150 °C. For the measurement of pressure in these deep holes a silicon micromachined pressure sensor, provided with an optical activation and read-out system by fibre, is employed. The electronics are located above ground. Other microsensors which might prove useful in the bore hole are flow sensors, viscosity sensors and density sensors.

3.2.2.2 ENVIRONMENTAL APPLICATIONS

H. Leeuwis and J. van Veen

Introduction

Measurement of a variety of substances concerning environmental pollution is expected to be an attractive market for MST. It is thought that one of the potential market pull areas (possibly the automotive market) can enhance the application of MST. The motives important in this category are small size (portable field instruments), function integration (a complete small size system) and cost reduction.

The ultimate goal is to have a chemical sensor as a small component that measures the concentration of substances continuously, accurately and over a long lifetime. However, in the near future it is foreseen that these requirements can only be met by the application of existing sensing principles into a microsystem that resembles conventional analysis systems. The micro Total Analysis Systems (µTAS) envisaged will be cheap to produce and, because of its small size, also cheap in the use of analytes when compared to conventional systems. Another advantage is its fast response, making semi-continuous measurement and high accuracy possible by processing the data of repeated measurements. Examples of a µTAS are given in Chapter 7 and in Appendix 1.

A good example of the adoption of MST in analysis systems is the gas chromatograph in which certain parts have already been replaced by micromachined ones and which can potentially be completely integrated (see section 3.3.2).

Future applications

Various other kinds applications can be envisaged. In the first place there is a market for portable field instruments that can measure immissions and emissions of, for instance nutrients, chlorinated and other organic microcontaminants, and heavy metals in water. Depending on the kind of application, even an indicative measurement may be sufficient. With the help of these instruments it is possible to trace pollution and, as a consequence, to reduce the number of costly laboratory analyses. In the case of soil clearance, special probes are used to trace pollution and to take samples for laboratory analysis. These probes are already equipped with sensors for conductivity, but more selective indicative sensing instruments, for example, heavy metals, organic substances (oil, solvents) and cyanide, will improve the efficiency of the clearance operation enormously.

In the second place, (semi-)continuous sensing instruments will be interesting for emission measurement at pollution sources like factories and homes, on condition that is required by legislation ('the polluter pays'). The market volume of such systems would be high because of the generic character of a great deal of pollution. The integrated gas chromatograph could be used to measure so-called stack emissions of combustion gases as CO, CO_2, NO_x and SO_x (in electricity plants and the chemical industry), as well as for motor engines and, in a more sophisticated form, also for Volatile Hydro Carbons (VHC).

And last but not least, MST-based sensing instruments will be applied to control processes in order to reduce or even avoid emission; examples are galvanic processes in which strong acids play an important role and are seldom controlled, as well as a lot of cleaning processes based on acids in food production. In such systems analyzing instruments based on Ion Sensitive Field Effect Transistors (ISFETs) could be applied. However, because of the necessary adaptation of the process application to a larger scale, it is generally envisaged to be in the longer term [2-9].

3.2.2.3 PRODUCT QUALITY CONTROL

J. van Veen

Introduction

Besides a growing need for information systems to control or maximize processes, there is also a need for monitoring equipment for the quality control of end products and, in some cases, for quality control of semi-finished products or raw materials. As a result, monitoring equipment forms an attractive market, especially for high volume applications. Quality measuring instruments focus on the measuring and monitoring of chemical or physical parameters in industrial process streams as well as in end products. There are wide variety of parameters to be monitored, like chemical ingredients, melange or odour, colour, turbidity, viscosity or dimensions (volume, height, flatness etc.). All these parameters reflect certain quality aspects of the end product. In addition, the overall specifications of certain products (e.g. a car or a watch) need to be guaranteed; for instance, for accuracy, speed and other features concerning its performance. In general it can be stated that in most cases the monitoring equipment needs to be robust (as it may need to operate in a harsh environment) and as well as fairly accurate (filling volume of beverages, bacterial contamination of food or the colour of paint etc.). In order to meet these demands special precautions have to be taken, like the integration of malfunctioning units or redundancy of sensitive parts to increase the reliability of the monitoring system.

Future opportunities

Opportunities for on-line or in-line monitoring equipment are expected in the chemical and food industries for measuring chemical constituents, contamination etc. Current fields of interest in the food industry are: the determination of water, fat and protein content [10], flavours, off-flavours, and bacteriological contamination in end products. A lot of research is being carried out to develop new chemical sensors for these kinds of applications. Most of the commercially available chemical sensors, however, are limited to the detection of gases.

In many cases the selectivity of existing sensors is not enough. A possible solution for solving this problem is to apply sensor arrays, in which a number of sensors with different responses are confronted with the same mixture. In this way, by using pattern recognition techniques, complex gas mixtures can be analyzed and the composition calculated. Appendix 1 further discusses the concept of sensor arrays. Another application of sensor arrays is the quantification of complex flavours or off-flavours, using advanced cluster analysis and artificial neural network techniques. This is known as the so-called 'electronic nose' [11] or 'artificial nose'.

Examples of successful applications include the characterization of different brands of whiskey, tobacco and coffee, as well as determining the freshness of fish.

Another field where various statistical techniques are used for multicomponent analysis, is Near-InfraRed (NIR) spectroscopy [12]. Near-infrared reflection measurements are attractive particulary in the food industry, as this is a non-invasive technique. Due to the recent availability of faster improved instrumentation and software, NIR spectroscopy is expected to become successful in many industrial branches in the coming years. This will include quality control for the specific determination of a wide range of organic compounds in liquids and gases.

The conclusion is that the use of sensor arrays for complex detection problems, as envisaged in the quality control of end products, is very promising. The same applies to spectroscopical techniques in combination with pattern recognition techniques. The advantage of MST in this field is the possibility of function integration, the use of microsensor arrays and low cost.

3.2.2.4 DISTRIBUTED SYSTEMS

E.C.C. van Woerkens

During a production process it can be helpful to monitor ambient factors affecting the process, such as temperature, pressure and humidity. Many properties of the process itself may also be crucial to the quality of the final product. These may be properties of bulk goods, such as temperature, pressure, viscosity or colour. Monitoring is particularly important in situations in which properties of this kind can vary under the influence of all sorts of factors thus causing deviations from the optimum production process. Other crucial factors include properties of production machinery; e.g. the speed of rotation of a shaft, the closing of a valve, or the number of hours spent on preventive maintenance.

A distinction can be made between monitoring applications for many different variables, which may or may not be distributed in place and time, and applications in which the same variable has to be measured at a great number of different points. An example of the first instance is a building management system, where many sorts of variable such as temperature, lighting, heating and access control need to be monitored at various locations in the building. In this example the measurements are not merely monitored but also directly employed to control the internal climate. Another example is the monitoring of pollution of a river where several different variables are measured in many places.

An example of a system in which the same variable is measured at a large number of points is a geophysical measurement system used for exploring the earth's crust (section 3.3.3). Here it may be useful to use a large number of sensors (geophones) over a large area in order to obtain an overall picture; in this case, the structure of the geological strata.

Another valid reason for distributed measuring is the desire to increase accuracy and reduce sensitivity to interference or to increase the directionality of a measurement. The physical spread need not necessarily be large: there may be many sensors close to each other in one- or two-dimensional arrays.

In all these applications it is essential for the sensors to be capable of being connected to a communication channel linking them to a central processing unit, particularly where the distance between sensors is large. In principle there is no limit to the distance between measurement points. Meteorologists for example, use data collected from all over the world.

One current trend is to give sensors built-in intelligence, e.g. for auto-calibration and self-testing. Other properties, such as interoperability and interchangeability are important aspects for distributed systems.

3.2.3 INSPECTION

J. Snoeks and M.J. Vellekoop

In the industrial environment the main justification for using microsystem components for measurement and control comes down to cost effectiveness, the reasons being:

- they are flexible;
- complex functions can be achieved (distributed intelligence and function integration);
- high reliability can be achieved;
- high robustness can be achieved;
- if manufactured in large numbers, the cost is low.

Intelligent field transmitters for measurement of plant performance parameters (pressure, flow, temperature etc.) and quality parameters (viscosity, chemical compositions) which can be connected to intelligent Integrated Control Systems (ICS), are emerging onto the market. An integration of field transmitters and ICS enlarges the possibilities that distributed intelligence can offer. Many of the involved applications can be categorized as permanently installed microsystems.

The application potential of mobile microsystems (mobile robots) is more specialized and the following areas can be identified:

- Process and chemical industry
  - tele-operated actuator systems;
  - miniature inspection robots.
- Nuclear plants and environments
  - Tele-robotics for performing human-supervised operations in hazardous environments (e.g. areas affected by radiation or chemically toxic atmospheres) including the inspection and dismantling of components.
  - Autonomous robotics to carry out missions independently without continuous control from a higher level system.

Today the processing and chemical industries invest significantly in development budgets with the objective of exploiting existing assets as much as possible. The consequence of this trend is that inspection of the physical condition of industrial installations becomes a significant operational factor. There is certainly a quest for smaller inspection tools which can carry out inspection missions in smaller parts of an installation as such parts cannot be accessed with traditional tools because of dimensional constraints. It is anticipated that the application of microsystems should facilitate on-line inspection for preventing shutdown of the installation for inspection. Keeping the plants longer on stream is an accepted cost-saving factor.

For installations which cannot be accessed during their operational lifetime, subsystems based on MST can be developed which are designed to be implanted inside the installation during the construction phase and will remain dormant in their docking position until they are activated. On activation they can carry out their preprogrammed mission (e.g. inspection or some other control action). Activation, energy supply and data exchange can be performed from external sources.

Apart from operational lifetime extension, another thrust for more enhanced inspection systems is recognized to be the environmental performance of the industry. On-line leakage detection and monitoring systems should benefit from new developments in microsystem technology.

3.2.4 AUTOMATION, ROBOTICS AND CONTROL

3.2.4.1 HIGH-END APPLICATIONS

L. Hermans

In the area of space exploration possible applications have already been identified (section 3.1.5). The most elaborate example is a miniaturized multisensor system for space life science experiments. At present, space life science research is limited by the availability of in-flight research facilities, physical space, crew time available, power requirements, safety aspects and altered physical properties (fluid dynamics in microgravity conditions) [13]. These constraints have a direct influence on the design, scope and implementation of experiments.

A microsystem implementation of space life science experiments, or some of its essential parts, is believed to significantly increase the possibilities of such experiments. An essential part of such a system is a miniaturized multisensor system. Such a microsystem should meet the following characteristics: stability up to 6 months, in-situ calibration and low power consumption. Basic analytes to be measured are partial pressures like p_{O2} and p_{CO2}, and pH, pressure, temperature, glucose, lactate, urea, creatinine, calcium, maltose and sucrose. In order to meet these requirements different types of sensor will have to be used, depending on the analyte. For a lot of analytes the sensors needed are already commercially available or have been realized in a research and development environment. The great challenge will come from the incorporation of these sensors into an integrated multisensor module. This module should include auto-calibration and self-test facilities. In addition, some pre-processing of the data collected should be included in order to allow for temperature correction or the transfer of data via a standard network. Such a system could also include some microfluidic devices for the handling of samples, calibration fluids and possibly also cleaning.

3.2.4.2 INTELLIGENT HANDLING SYSTEMS

H. Leeuwis

Instruments for the positioning, assembling and transporting of very small parts already exist and 'simple' forms of MST have been applied [14]. A good example is the equipment used in the production of integrated circuits, in which the tiny silicon chips have to be assembled in packages with a large number of electrical leads. In order to make these systems faster and more accurate, aspects such as moving mass, function integration, distributed systems and intelligence are becoming more and more important in subsystems for vision, probing, touching, gripping and actuation. An example is a miniature vision system located in a gripper with integrated data processing. As a consequence, the master processor of the system is not burdened and the total response time is decreased.

The potentially smaller size of handling systems is also attractive for IC production because a smaller clean room lowers the running costs drastically. A completely new opportunity is an IC test instrument with repair capabilities. The production yield of a complex IC can be so low that repair is an attractive option. The detection of short circuits by an intelligent vision system or by active probe micro-arrays could be followed by repair by a micromanipulated laser ray.

Micromanipulators to be used for the sorting of cells for diagnostic tests or counting of the number of (e.g. white blood cells) are already being researched (figure 3.2).

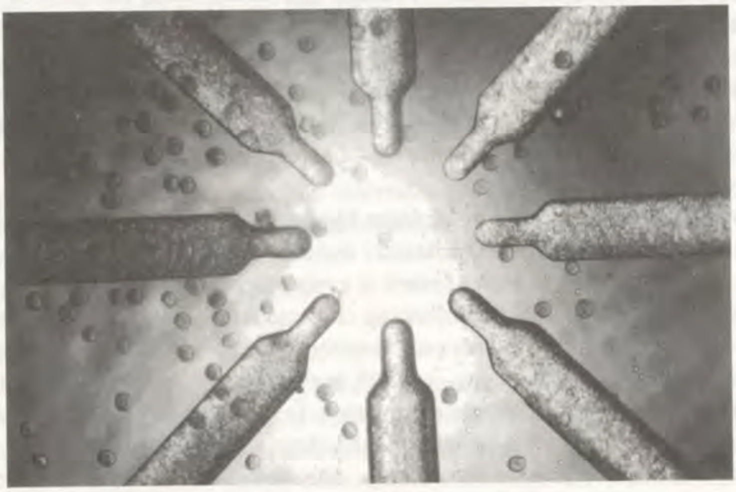


Figure 3.2 Micromanipulators for living cells
Source: [16]

One can imagine that the assembly of microsystems needs MST-based instruments, especially when the application of LIGA-manufactured plastic parts comes to mind. The LIGA technique opposes the silicon batch manufacturing technology in such a way that one-by-one assembly of a lot of parts is necessary [15]. Cost effective assembly will be a prerequisite for a successful generic adoption of LIGA-based products on the market.

New horizons for intelligent handling systems are offered by the processing of chemicals at the atomic or molecular level. Complete 'microreactors' for (bio)chemical processes for R&D as well as production of biological and pharmaceutic products could be built. The advantages of microreactors in the R&D environment are the low costs and fast feedback of results compared to R&D in bulk processing. The advantages in production can be found in better control of processes (easier temperature control in highly exothermal processes, higher yield, better quality) and, last but not least, faster upscaling by using parallel microreactors.

3.2.4.3 FLUID CONTROL AND DISPENSING TECHNIQUES

M.D. Dierselhuis

Dispensing is essential in various industrial applications. Fluid control and dispensing techniques are used in adhesives and ink-jet technologies, fuel (additives), atomizers and personal medical products like inhalers. As the dimensions of droplets are in the micron range, one can expect benefits from microsystems to influence or measure droplet parameters.

Scope of microsystems in dispensing

Nozzles with small tolerances and extreme shape conformity are essential for well-defined droplets. Therefore a microsystem by which parameters are measurable and adjustable allows very small quantities to be dispensed with high repeatability.

Examples of physical parameters of adhesives and ink are viscosity (dependent on temperature, pressure, alteration etc.), wetting characteristics of the surface and polymerisation or hardening of the glue. It should be possible to integrate the sensing elements concerned within one microsystem.

For microdispensing, precise, cheap nozzles are essential. Current forms of nozzle are:

- pyramid-shaped Si-nozzles used in ink-jet systems;
- straight long holes and channels (a few microns over a length of several hundreds of microns) produced with the LIGA technique and used in ink-jet systems, aerosol pumps and capillaries;
- glass/silicon capillaries with piezo actuators used in adhesive dispensing systems;
- capillaries used in pharmaceutical and chemical analysing systems.

Typical diameters are in the range of under 2 microns, 10-15 microns and over 30 microns (by conventional precision machining). In the range under 2 microns the pump function has sometimes been attained by the capillarity of longer nozzle holes.

Future development

An integrated microdispense system becomes feasible using the following system modules:

- a micropump (membrane, piston, gear, etc.);
- a microvalve (membrane, piston, ball, etc.);
- a flow sensor (heating, vibration, etc.);
- a viscosity sensor;
- a mixing room (in the case of mixed fluids);
- a nozzle or nozzle array.

All these elements can be effected by micromachining, mainly by silicon etching and the use of the LIGA technique. Most of these system modules have already been introduced. A monolithic solution is not yet under development but can be expected in the mid-term.

3.2.5 INFORMATION HANDLING: OPTICAL INFORMATION SYSTEMS

P.V. Lambeck

Introduction

In integrated optics a number of basic optical functions are integrated onto a single optical chip by applying MST methods similar to those known from microelectronics. These optical chips can be used for routing optical signals offered from fibre networks. Their specific power however originates from application or incorporation of appropriate active materials, affording their application as sensors (e.g. chemical ones) or actuators (e.g. an 8 x 8 switching matrix for optical signals).

The main fields of application are optical telecommunications and optical sensing, and may in future include optical computing [17-19]. An illustration of this is the transformation of the classical optical Mach Zehnder circuit into the integrated optical design. Figure 3.3 shows the classic solution, consisting of macroscopic optical function such as beam splitters and mirrors, which need careful mutual alignment.

The integrated design is shown in figure 3.4 and is a rigid configuration, where the optical waveguide channels define the lightpath, and the Y-junctions take over the light splitting and combining functions of the beam splitters.

It should also be mentioned that there is no standardization in MST. It has to be noted that both the fundamental research and development of integrated optics is strongly supported by the telecommunications field, leaving to sensor companies not only the task of slightly adjusting the principles, design and sometimes even technology to their needs, but also the task of developing the transduction elements, e.g. the chemo-optical interfaces themselves [20].

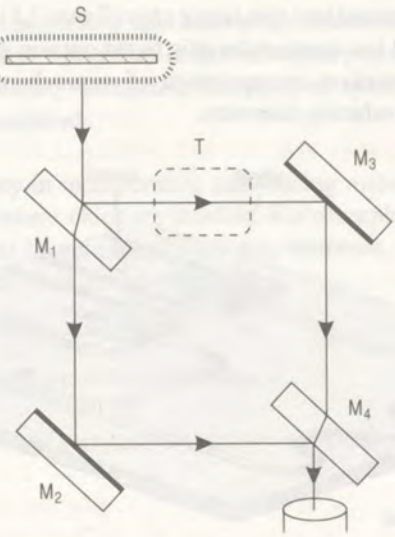


Figure 3.3 Classical optical Mach-Zehnder circuit

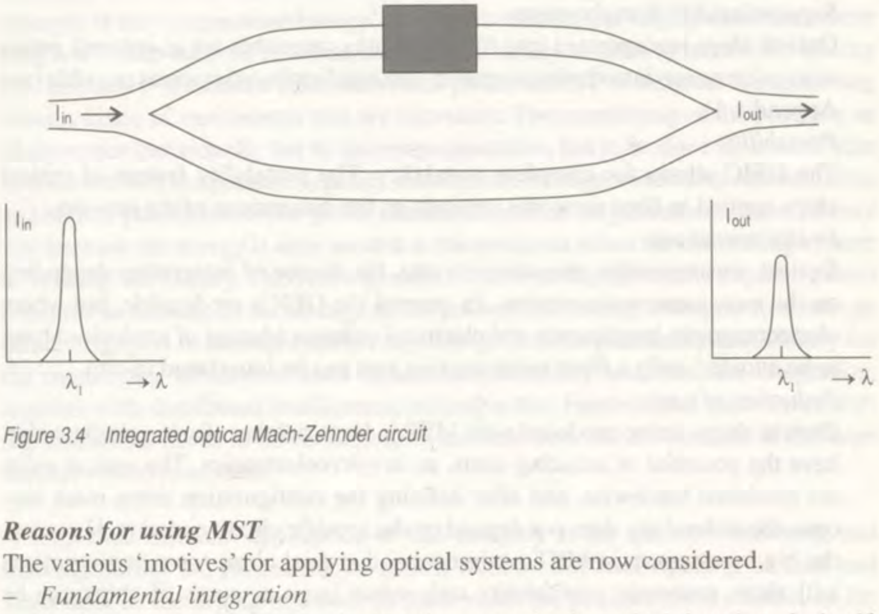


Figure 3.4 Integrated optical Mach-Zehnder circuit

Reasons for using MST

The various 'motives' for applying optical systems are now considered.

– *Fundamental integration*

A single optical chip already contains many basic optical functions in itself, affording definition of higher order functions. In fibre optic information networks these small optical functions have to be connected to optical fibres, the chips functioning as nodes or achieving routing and switching as parts of the source or receiver units. In applications like sensors the degree of integration can be tailored to the needs of the specific application. Extremes are an optical chip, containing only the active transduction element and the optical read-out circuit, the chip being connected to input and output fibres. The other extreme is an Opto-Electronic Integrated Chip (OEIC), where all optical and electronic functions are integrated into one single chip (figure 3.5). Here a power cord and an electrical signal bus connect the chip to the outside world. Chemical sensing integration also involves incorporation of microchemical systems acting as chemo-optical transducing elements.

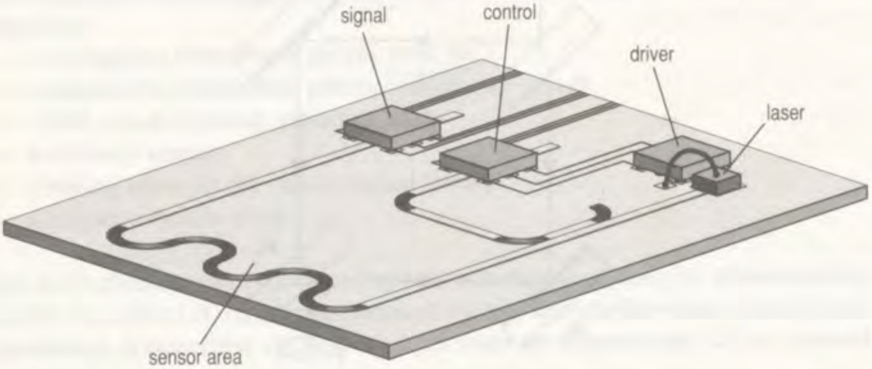


Figure 3.5 Hybrid opto-electronic integrated sensor circuit
Source: TNO

- *Supporting distributed systems*
  Optical chips incorporated into fibre networks can either act as network nodes or as information introducing elements making distributed systems possible (see Appendix 1).
- *Portability*
  The OEIC allows for complete portability. The portability feature of optical chips applied in fibre networks depends on the dimensions of the network.
- *In-situ operations*
  Optical sensors enable operations in-situ, the degree of integration depending on the measurement constraints. In general the OEICs are feasible, but where electromagnetic interference and electrical voltages (danger of explosion) have to be avoided, only a fibre-tailed sensing part can be introduced in-situ.
- *Reduction of costs*
  Optical chips, being produced with MST in large numbers from a single wafer, have the potential of reducing costs, as in microelectronics. The optical chips are produced batchwise, and after defining the configuration using mask layouts, the technology does not depend on the specific circuit aimed at. However, the big investments in MST equipment and special clean room environments will show economic profitability only when large amounts of chips can be produced (a condition that can be reached by an MST manufacturing facility, shared by various companies, for instance).

New horizons
Function integration of integrated optics and microelectronics has already begun. Integration can be extended to micromechanics, the opto-mechanical interaction allowing on the one hand optical read-out of micromechanical actions, and on the other hand micromechanical control for optical functions. Integration of chemical microsensors, like the integrated optical ones, with micromechanical liquid hand-

ling systems, is also just beginning. Just as in every function integration, complete integration is only justified if the yields of the individual process steps are sufficient for assuring an economically acceptable net yield of systems, otherwise hybrid solutions have to be considered.

Because of the flexibility in incorporating transducing materials into optical systems, multi-functional sensor chips are feasible. For example, by applying several reversible chemo-optical layers onto the sensing elements, a system sensitive to various types of chemical becomes possible.

3.2.6 *IDENTIFICATION WITH MONITORING*

3.2.6.1 *QUALITY MONITORING AND TRACKING OF GOODS*

H. Leeuwis

Transport and storage of perishable goods is a huge activity area in which a lot of expense could be saved if more was known about the quality status of individual products. Nowadays a substantial part of perishable goods is thrown away. An example is the 'temperature history' of a packet of milk that largely determines how long it will take until the milk has turned sour. Ideally in order to record this history it is necessary to monitor each individual product. MST is essential for achieving various kinds of instruments that are necessary. The monitoring of the products as likely as not individually but in moderate quantities, has to be done by a small-size instrument with temperature sensing, intelligence, storage, wireless communication and battery possibilities. The power needed to operate the instrument has to be very low because the energy is only needed at the moments when the controlling system is 'reading' the history. This reading could be done during the whole trajectory from producer to consumer, i.e. storage at the production facility, transport to a storage centre, transport to the supermarket and storage at the supermarket. Particularly for the monitoring instrument such aspects as portability and function integration, together with distributed intelligence, are important. Furthermore, such a monitoring instrument needs to be very cheap, which can be achieved because of the large numbers to be produced.

A somewhat different application in this category is the quality monitoring and tracking during the processing of goods, like the artificial ripening of fruit and vegetables or the drying of wood. In these cases the product is not mobile, so the whole system is less complex in relation to the communication and logistic aspects. However, other aspects such as defining and sensing the quality may be more difficult.

3.2.6.2 *CONDITION MONITORING*

H. Leeuwis and J. Snoeks

Condition monitoring of equipment and other functional systems is a well-estab-

lished concept which up to now has been based on the use of traditional measurement techniques and sensor systems. However, the features and functionality of these systems are not yet fully matured. Condition monitoring is a category of applications in which MST motives such as function integration, distributed intelligence, distributed systems and costs could play an important role. It has been observed that the possibilities of MST in these application fields have not yet been fully exploited. The impact of MST is high in those applications where traditional components cannot be used because of dimensional or energy constraints or extreme environmental conditions.
Examples are:

- on-line measurement at spots inside machinery which cannot be otherwise accessed;
- distributed sensor systems with limited energy availability locally;
- remote sensors.

In general, the main purpose of condition monitoring systems is to predict and plan maintenance and to detect the need of service. With up-to-date information on the physical condition of a structure or machinery life cycle costs will be kept to a minimum and performance to a maximum. It is important to provide the maintenance planners with information which can be used to prioritise the work to the extent that unnecessary maintenance actions are postponed in favour of higher priority needs.

Condition monitoring systems could be applied in unlimited numbers. Whether it is for a turbine, a pump, a Computer Numerical Control (CNC)-machine or even for livestock (section 6.2.1), the main purpose is monitoring the condition of the object in order to prevent malfunctioning. In many turbo machines, vibration data, temperature and pressure data is already being collected. The circumstances under which these installations are operating demands a high degree of reliability and availability, thus it is important to monitor the condition of the installation. For monitoring extra parameters and combining the various data, more sophisticated condition monitoring systems will be required. The huge amount of data collected by the sensors should be pre-processed (distributed intelligence).

This also applies to monitoring precision tools in CNC-machines. At the moment the tools are only identified by a small subsystem, the transponder. This transponder is equipped with identification and communication capabilities. Used time is recorded wirelessly. If the signals of other parameters like temperature, experienced forces and even fatigue (cracks) could be collected by the transponder (function integration) the performance would improve considerably.

Another field for applications of condition monitoring systems is the monitoring of the physical condition of civil and industrial structures such as bridges, buildings, railways, oil rigs, platforms and other large constructions. Distributed systems based on the fibre optics seem to be very appropriate for monitoring the condition of the concrete or steel in this sort of construction because of the long distances to be bridged and the integrated sensing capabilities.

3.2.6.3 INTELLIGENT BUILDINGS

L. Hermans

During the last ten years, intelligent buildings have received a lot of a attention and publicity [21]. The intelligent building offers a more agreeable working or living space for its human occupants through access to powerful, sophisticated computer and telecommunication services, micro-climate control, lighting control, and increased security and protection. The intelligent building is the result of the integration of a wide range of services and systems. These are characterized by a high degree of flexibility and modularity. The most promising areas for the application of microsystems in intelligent buildings and homes seem to be systems for:

- energy management
- air conditioning
- safety
- lighting
- maintenance.

Essential parts of the components required can be achieved with microsystem technology, which offers its typical advantages. A possible breakthrough for microsystems in this field is the standardization of the interfaces. It is clear that a building will have a central automation system that enables the grouping of all interactive smart products, including microsystems, into an integrated network. These interactive smart products can gain widespread acceptance only when a choice is given of purchasing these devices from different manufacturers and still being able to interface them together easily. International efforts have been underway to develop standards covering the communication between building automation system modules.

The main function of microsystems for intelligent buildings will be a measurement and inspection function. Such a microsystem will be part of a larger distributed system. It should include a self-test and auto-calibration function. A limited amount of data processing should be included to format data according to network requirements. In some cases local data processing will allow the microsystem to make local decisions which do not tax the central data processing unit. The microsystems could be stand-alone units or part of a larger module.

In conclusion, an indication is given in figure 3.6 of what microsystem technology could do in an intelligent building.

First of all, the system could be an essential part of a local climatic control system. The MST components include several sensors for the determination of the room climate: temperature, relative humidity, CO_2 concentration, noise level and typical room smells (e.g. cigarette smoke). In addition the system monitors the activity in the room: how many people are present, what are they doing etc.? The latter information can be obtained by a camera with local image processing and interpretation.

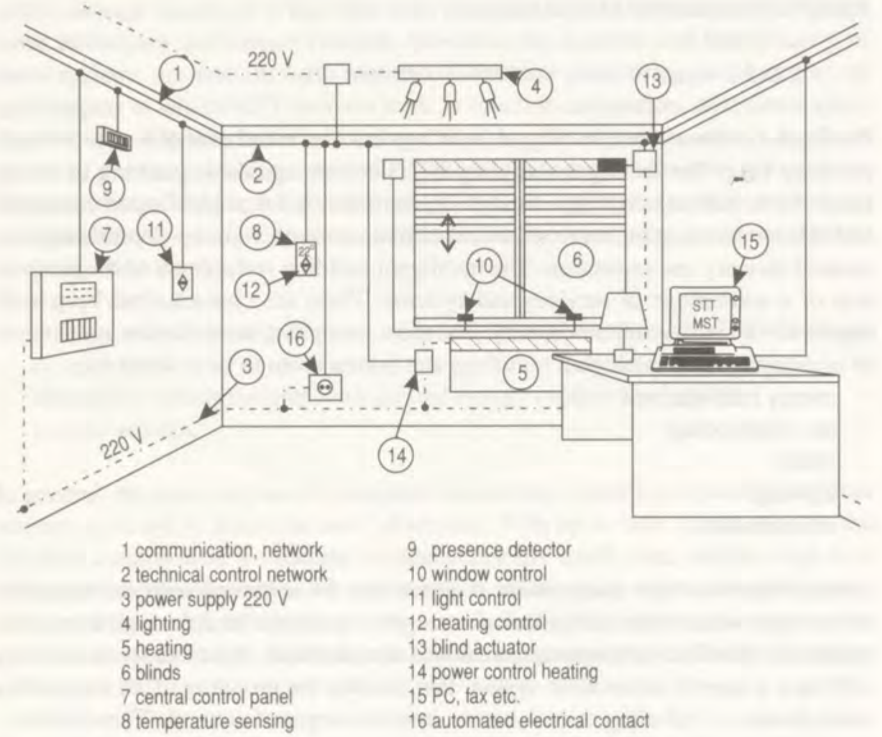


Figure 3.6 Fictional example of a room in an intelligent building

Additional safety aspects such as smoke or fire warnings can be included, and such functions as the detection and signalling of inflammable and toxic gases could be performed. These functions can be combined with control functions. The system can undertake localized safety measures like closing the windows, closing gas taps or turning off the water supply. If the light intensity exceeds preset levels, the blinds can close or the artificial lighting can be activated. The systems can also perform administrative functions like water, electricity and gas consumption metering or monitoring the status of sanitary installations and pipes. The systems communicates with the central management information system over a standard interface. If required, a local processor can be added to make local decisions about actions to take: activate ventilation, reduce heating power, activate air-conditioning etc. In order to be acceptable to the market, such a module should cost no more than a small TV set.

3.3 ELABORATED CASES OF THE USE OF MST IN INSTRUMENTS

The following four cases where MST could successfully be applied will be dealt with in somewhat more detail. The first case concerns quality measuring instruments in general, with smoke-stack gas monitoring taken as an example. The second case is an integrated miniaturized gas chromatograph, and the third case is a distributed system of geophones for oil exploration by seismic methods. Finally the fourth case is a microrobot for inspecting industrial installations not accessible to other means.

The introduction of these four examples does not mean that the relevant technology is readily available or that prototypes exist. Rather, requirements are defined and the need for MST to achieve such systems is indicated.

3.3.1 QUALITY MEASURING INSTRUMENTS

O. Ongkiehong

Introduction

Quality Measuring Instruments (QMI) are instruments used to measure qualities of gases, liquids or solids. Examples are:

- the composition and concentration of gases and liquids;
- density;
- viscosity and acidity (pH) of liquids;
- moisture in gases;
- dust particles in gases;
- the ion concentration in gases and liquids.

QMIs are also referred to as 'process analyzers'.

Application areas of QMIs are (petro)chemical plants, refineries, water treatment plants, and in metal, food, beverage and paper production. In these areas the instruments are usually used for measuring qualities of gas and liquid flows. Another field of application of QMIs is environmental care. In chemical plants about 1% of the total investment in the plant is used for QMIs. It is estimated that the annual investment for QMIs in Europe is $ 300 million.

General requirements

Investment and maintenance costs are important items when buying or developing a QMI. The annual costs for maintenance are high, today 10 to 20% of the investment. Other important requirements for these instruments are reliability and reproducibility of measurements, insensibility to disturbing influences, and information processing. Several of the instruments must be suitable for use in areas with explosive gases. It must be frequently taken into consideration that the gases or liquids whose qualities are being measured are sometimes not pure (polluted with dust, mixed with moisture) or that they are aggressive or have changing temperatures and pressures.

Description of QMIs

A QMI often consists of several functional parts, such as

1. sampling of the medium;
2. sample transport;
3. preparation of the sample for measurement;
4. measurement;
5. information processing and communication.

There is a large gap between the clean world of sensor technology and the rough world of (industrial) processes. Semiconductor sensors create an opportunity to integrate the functional parts for 4 and 5. Without much additional effort these are useful for monitoring the quality of air in garages, steel works, foundries or underground car parks etc. When used for monitoring the quality of process gases a great deal of additional effort is necessary and the functional parts 1, 2 and 3 become necessary. Preparation of the sample can include filtering, moisture control, flow control, pressure control, temperature control, auxiliary reactions and other adaptations to meet the requirements of the sensor [22].

Figure 3.7 Example of current quality measuring instruments

QMIs can often take up a lot of space and separate panels in cabinets are often necessary to accommodate them. A small building is frequently used for these cabinets. A separate air supply performs an overpressure to meet requirements concerning explosion risks supplying continuously fresh air for maintenance personnel and to protect the instrument against dust and moisture from the outside. Figure 3.7 gives an impression of sizes. The QMI shown measures CO, CO_2 and O_2 concentrations in four different gas streams in a production plant. Space is needed for sample transport and sample preparation.

Important motives for using MST could be a reduction in investment and maintenance costs or improvement of existing QMI technology. Furthermore, MST will allow in-situ operations and can greatly contribute to a reduction in size of the equipment. When most functional parts of a QMI are integrated on one unit, the QMI can be mounted closely to the point where the medium is sampled, leading to a reduction in time for sample transport. Response times as a result of sampling over long distances, when all QMIs of a plant must be placed in a small central building, can then be reduced.

A case for the measurement of smoke-stack gases
One example where QMIs are applied is in the measurement of process gases taking place through a stack. The case described here focuses on the measurement of CO concentrations. To meet the requirements of environmental care these measurements have to be performed continuously. The gases contain dust particles and a high percentage of moisture (raindrops frequently fall into the stack), and the temperature of the gas is high. In this case MST can be used for sample transport and sample preparation (functional parts 2 and 3). Sample transport and sample preparation in this case include: cooling, drainage of condensation, filtering of dust particles, flow and temperature control and transport to the sensor.

For the sensor, existing technology for CO measurement can be used. Information on the operation of the QMI available in digital form for the Distributed Control System (DCS) of the plant. This information includes:
- measured CO concentration;
- flow and temperature;
- status of the QMI ('I'm OK', 'lack of flow').

The QMI has to meet the general requirements for use in areas where there may be explosive substances. For the introduction of MST components the annual maintenance costs need to be substantially lower than the annual maintenance costs for a similar QMI without MST components. An instrument equipped with MST is able to perform auto-calibration and self-test.

Market
It is generally estimated that the annual growth of QMI market volumes will be 6-8% over the coming years. The case described will not introduce new functions but will contribute to an existing process of improvements in QMI technology. There will be no user scepticism because of new functions. Standardization of MST components, particularly concerning interfaces with non-MST components (sampling system and DCS), is essential and will contribute to user acceptance.

Producers
There is a wide range of specialized producers offering QMIs (Europe, USA and Japan) and products are continuously being developed and improved. Some typical results include reduction in size, increase of information processing capability, new principles of measuring and, in general, higher performance. Involvement of these QMI producers in the development of MST components and standards is necessary for wide acceptance. Manufacturing difficulties can only be solved when close interdisciplinary cooperation between QMI and MST producers has been established.

Conclusion
There are opportunities for the use of MST in several QMI functional modules. Conditions for success are the involvement of QMI users and producers at an early stage and close interdisciplinary cooperation between QMI and MST producers.

3.3.2 INTEGRATED MICRO GAS CHROMATOGRAPH

H. Leeuwis and J. van Veen

In 1941 the principle of gas chromatographic separation and detection was suggested. The theory was verified and the first commercial gas chromatographs became available around 1955. Since then gas chromatography has become an accepted detection technology for gases or volatile compounds. The basic lay out of a gas chromatograph is given in figure 3.8.

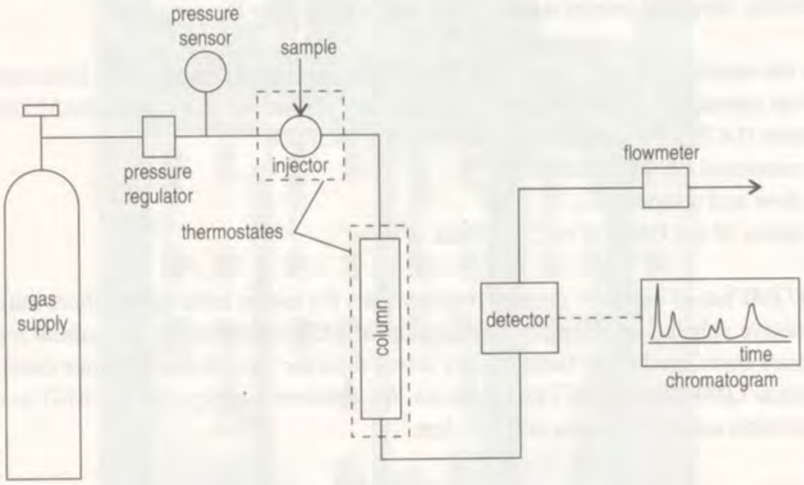


Figure 3.8 Schematic set up of a gas chromatograph

Relatively successful attempts have recently been made to miniaturize capillary gas chromatographs (and also liquid chromatographs) using separate components produced with silicon technology [23].

Applications
There is a need in environmental monitoring for a micro gas chromatograph for various applications. If the cost price is sufficiently low a micro gas chromatograph can be the heart of many sensing instruments.

- The main application is expected to be for emissions from smokestacks in electricity plants and for combustion processes in the chemical industry. Because of the small dimensions of the total system a number of measurements could be made across the diameter of the stack to provide a reliable value of the emission. For monitoring stack emissions the quantification of relatively simple inorganic gases like CO, CO_2, NO_x, NH_3 and SO_x is of particular importance. But emissions

of Volatile HydroCarbons (VHC) are also relevant in many industrial applications.
- Other applications refer to control measurements using hand-held instruments. For instance, the detection of organic microcontaminants in soil, like chlorinated benzenes, trichloro-ethylene or Poly Aromatic Hydrocarbons (PAH), or for determining the emission of CO, NO_x and SO_x in the exhaust of combustion engines (cars and trucks).
- Still other applications refer to the inspection of air quality monitoring systems or to very small personal safety detectors (both potentially high-volume markets).

Advantages and user requirements

The main advantages of a micro gas chromatograph are:
- small size, providing the means to integrate the instrument into a process or stack;
- portability, providing the means for a hand-held instrument;
- high selectivity in comparison to conventional sensors;
- broad application fields (high volumes);
- fast responses (order of 1 minute or less) in comparison with a conventional gas chromatograph with comparable plate numbers (the plate number is a characteristic figure for the separation capability of the column).

A low cost price may also be obtained for a system in which all parts, apart from the gas supply, are integrated. The usage of calibration and carrier gases is also reduced, as is maintenance. As a consequence, running costs will also be reduced. Higher accuracy is expected if repeated measurements are performed, which is possible because of the fast response times. A low dead volume is expected if a detector is integrated along the gas channel, leading to less sample dilution. Using a Thermal Conductivity Detector (TCD) a low time constant is expected for the small quantities of the sample passing by.

The system should be resistant to high temperatures (up to a few hundred degrees), particularly for stack monitoring. The possibility of coated walls (figure 3.10) as well as auto-calibration, self-testing and display of malfunctioning should be present.

Optional features are:
- more than one column, selected by a switch;
- integration of other detectors;
- preconcentration in a coated sample loop of a valve injector.

Implementation of other, more sensitive or more specific detectors might be needed, in particular for the detection of organic compounds with low concentrations. Several optical detectors are applicable, like planar waveguide and optical sensors with micromachined optical paths monitoring absorbency or fluorescence properties. Some specific electrochemical sensors might also be applicable.

The option of an integrated column and detector or of an integrated column and injector is attractive for many applications. It should be realized that the column has to be replaced on a regular basis due to ageing and fouling and for that reason the price of a total integrated system should be low.

Specifications and construction technology

High selectivity (a high plate number) is required, which can be obtained by proper choice of the dimensions of the column and the appropriate coating. The exact dimensions need to be calculated first.

For the application for stack emissions an integrated micro-katharometer (TCD) seems to be the most appropriate choice. For the other applications mentioned above more sensitive, or sometimes more specific, detectors are required. The feasibility of these detectors has to be investigated first.

The integration of a nanoliter injection port on the same chip is desirable. The reproducibility of such an injector is crucial to the operation of the gas chromatograph. For proper operation pressure, flow and temperature sensors also have to be integrated, as well as a heater, as indicated in figure 3.9.

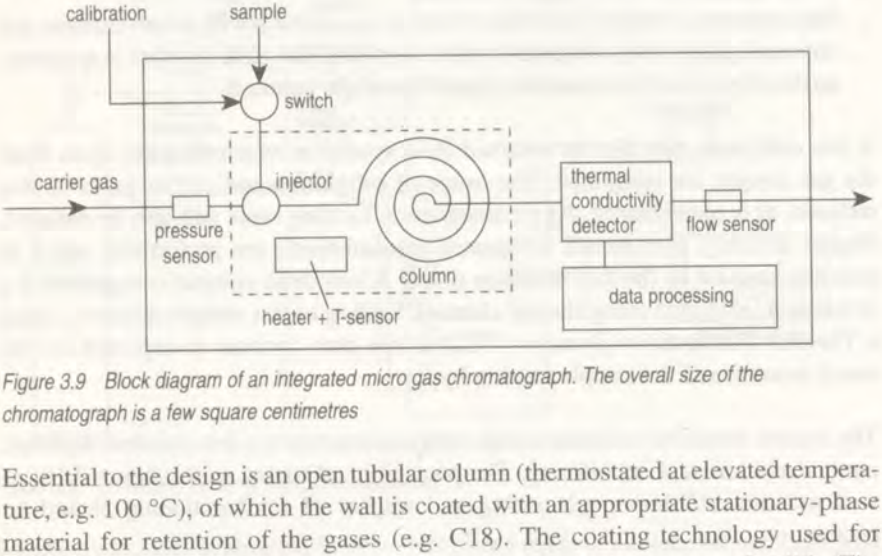


Figure 3.9 Block diagram of an integrated micro gas chromatograph. The overall size of the chromatograph is a few square centimetres

Essential to the design is an open tubular column (thermostated at elevated temperature, e.g. 100 °C), of which the wall is coated with an appropriate stationary-phase material for retention of the gases (e.g. C18). The coating technology used for conventional fused silica columns to the open tubular column seems feasible. The column itself will be even more accessible to modification. The desired plate number is at least 10,000. This figure depends on the dimensions and on the coating material of the column. A first estimate tells us that the length is at least 1 metre and the diameter is at most 20 µm. Preference is given to a design which is as far as possible tubular (see figure 3.10), and not with a V-groove [24]. The designs described in the literature usually consist of a cover sheet of Pyrex glass which is anodically bonded to the etched silicon wafer.

A low so-called dead volume is expected for the whole system, but attention should be paid to low dead volume particularly for the connections between components and for the injector and detector. In any case, a connection has to be made to a gas bottle filled with nitrogen, helium or argon. The integration of electronics, including a signal processing unit, is desirable. Diagnostics have to be implemented for malfunctioning by a pressure and a flow sensor. For stack monitoring, the whole system should be resistant to temperatures of a few hundred degrees and to high relative humidity. High temperatures could be a problem for the electronics. A micro Joule-Thomson cooler for local cooling might be an option for solving this problem [25].

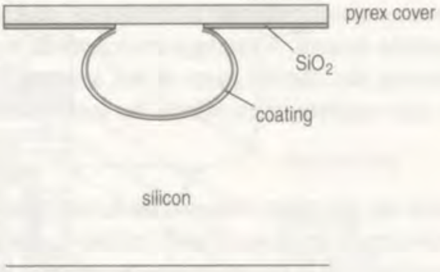


Figure 3.10 Cross section of the column

Market
The world market for gas chromatographs, used in laboratories as well as in process control, is very large. To a lesser extent this is true for environmental applications. The possibility of a micro gas chromatograph for continuous indoor air-quality monitoring and even more so for personal safety purposes, will open new markets thanks to its small size, low weight and portability.

As conventional technology also progresses we have to keep in mind that the primary goal is better performance and new features rather than low cost. Conventionally manufactured columns are cheaper in production than silicon columns, where the sales price is high because of the necessary expertise and technology which has to be built up. Thus MST can only be fully exploited when the greater part of the system is based on MST or extra features are possible through the use of MST (e.g. display of malfunctioning, higher precision, lower dead volumes and auto-calibration).

The environmental market is potentially very important but it is not typical a normal economic market as mentioned in section 3.1.5 and it can also impose barriers to the development of MST systems.

Producers
A company in the Netherlands, with its core business in gas chromatography, already has a strong international market position and is using MST parts in its most advanced instruments. Besides, the Netherlands and Germany are at this moment leaders in exploiting the market for environmental applications. In the long term the rest of Europe (including Eastern Europe) is a potentially large market. The company mentioned above could support new developments in this field, although it is not large enough to bear all the investments itself. This means that generic as well as basic technology development has to be performed in universities and supported both by governmental funding and special development programmes.

Technology

Although a micro gas chromatograph would be a real innovation, no fundamental breakthroughs are needed. The feasibility of producing the different components in the system has already been shown or has been in development for some time [26]. Very essential to the development is a sophisticated choice in the system set-up as to the degree of monolithic versus hybrid integration and which functions are to be incorporated and which not. In the Netherlands several small and medium-sized manufacturing companies cover different technologies necessary to the development of special parts of the system. A strategic choice could be to set up a dedicated facility for manufacturing the special parts of the system. Within the European framework there are also opportunities offered by larger manufacturing facilities (sensor foundries).

In conclusion one could say that there seems to be a good chance for the realization of a micro gas chromatograph, even as a Dutch initiative, but:

- a potentially big market such as the environmental market needs to be artificially opened (e.g. through legislation);
- the necessary technology seems feasible, but is not straightforward;
- cooperation between universities, research institutes and companies within the framework of Dutch or European Union programmes with financial government support is a prerequisite.

3.3.3 DISTRIBUTED SYSTEMS: GEOPHONES

E.C.C. van Woerkens

Background of the application

When prospecting for oil and gas reserves, acoustic techniques are employed to gain an insight into the structure of geological strata. An explosive charge is used to generate a Dirac impulse, the response to which is measured by geophones located at various sites over the area being surveyed. Measurements are sometimes made in the frequency domain using truck-mounted vibrators. This section describes a case for intelligent geophones as an example of distributed systems offering an opportunity for the application of MST.

The recording devices, the geophones, are essentially sprung mass systems, e.g. a moving coil in a magnetic field as shown in figure 3.11. Often a large number (up to several thousand) are set out over a large area (many hundreds of square metres). It is important that the geophone can be simply connected to a cheap 2-core link which in the case of an active geophone will provide power as well as signal transmission. Because long cables and large numbers of geophones are used, low energy consumption is important. It is also important to know that the geophone is working properly (this includes monitoring its orientation, its coupling to the ground and the communications link), and its precise location. Geophones are highly sensitive instruments which nevertheless for use under field conditions have to be rugged, with good resistance to dirt, moisture, shock and sharp temperature fluctuations. At the same time they must be designed to ensure the best possible coupling to the ground and the least possible sensitivity to wind.

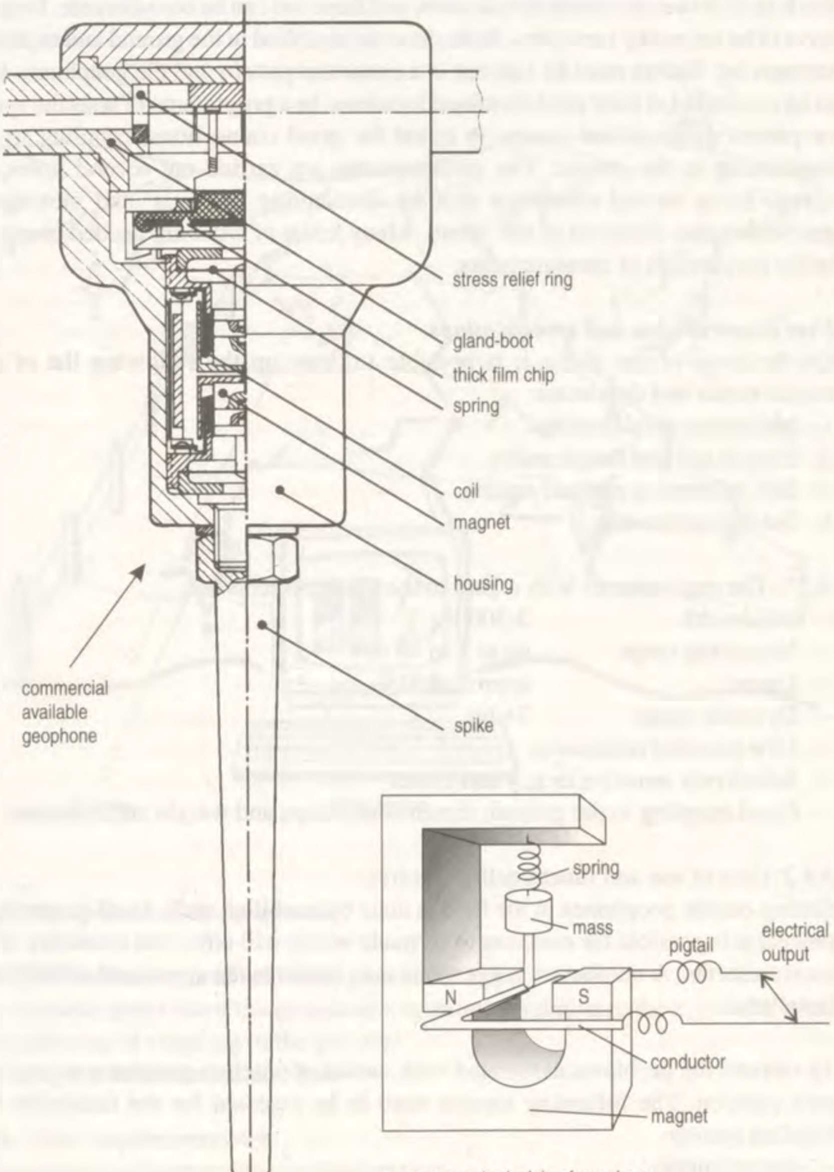


Figure 3.11 Cross section of a classical geophone, type ADR711
Source: De Regt Special Cable B.V.

A complete measuring system does not consist merely of a large number of geophones and a single central data acquisition unit: there are also distribution stations, repeaters etc. arranged in, for example, a tree configuration. Due to the

large number of geophones in such a system the cost price of a geophone is important. Geophones range in price from several tens of guilders for cheap passive units to several hundred guilders for high performance geophones.
Each shot, however, entails labour costs and these too can be considerable. Beacons have to be set out by surveyors. Holes have to be drilled in the ground and explosive charges set. Cables must be laid out in a particular pattern and the geophones have to be connected at their predetermined locations. In a programme of tests the spread or pattern of geophone groups is tested for good connections, coupling to and positioning in the ground. The measurements are carried out several times, the spread being moved after each shot by dismantling the 'rear' and moving the geophones thus removed to the 'front'. Many hours of work are needed every day in the preparation of measurements.

User requirements and specifications

On the basis of the above it is possible to draw up the following list of user requirements and desiderata:

1. Measuring specifications.
2. Ease of use and functionality.
3. Self-calibrating and self-testing.
4. Other requirements.

Ad 1: The requirements with regard to the measurements are:

– Bandwidth	2-500 Hz
– Measuring range	up to 1 to 10 m/s^2
– Linear	approx. 0.01%
– Dynamic range	24-bit
– Low parasitic resonances	
– Selectively sensitive in x, y and z axes	
– Good coupling to the ground: dimensions, shape and weight are important.	

Ad 2: Ease of use and functionality requires
Setting out the geophones in the field is done by unskilled staff. At all stages of the process it is possible for mistakes to be made which will affect the reliability of the measurements. A number of suggestions may improve the speed and reliability of installation.

To obviate the problems associated with cables, a wireless geophone would be a neat solution. The following aspects need to be assessed for the feasibility of a wireless system:

- energy supply;
- communication with base station;
- memory and data processing functions;
- position finding and locatability.

As an intermediate step towards a fully wireless, fully featured geophone, it might be possible to find a compromise by linking groups (strings) over relatively short distances by a 2-core cable connected to a secondary unit, incorporating a number of functions such as communication (probably by radio) with the base station, data storage, preprocessing and energy supply. Geophones embodying some of these features are already available for use in difficult terrain, such as swamps. Figure 3.12 shows a typical layout of a wireless system.

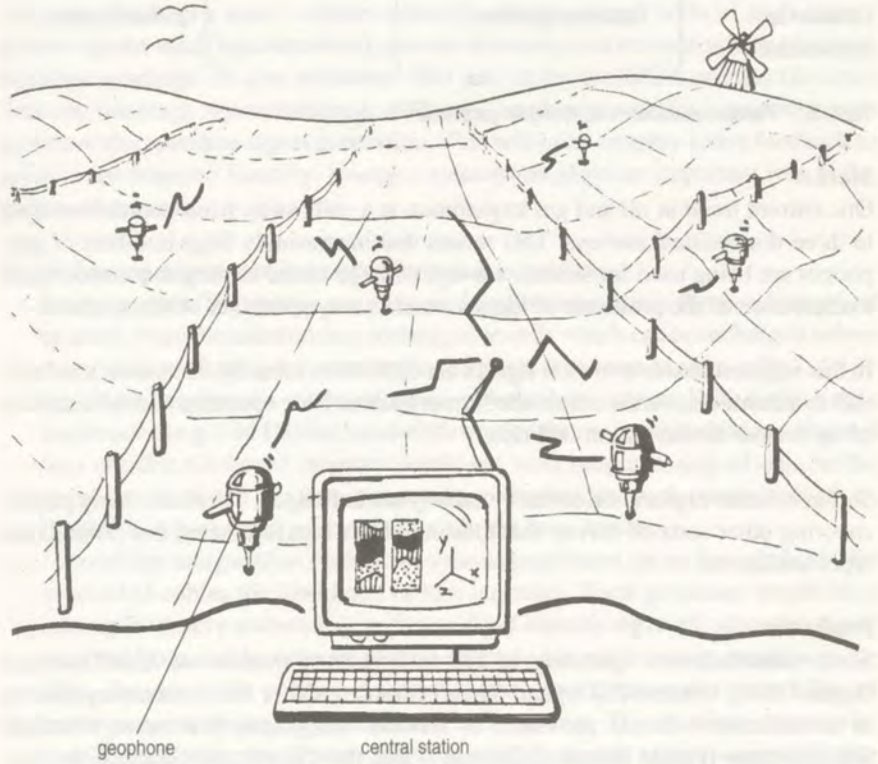


Figure 3.12 A wireless set up of geophones

Ad 3: Self-calibrating and self-testing include:

- automatic detection of the geophone's orientation relative to the x, y and z axes;
- monitoring of coupling to the ground;
- testing the communications link.

Ad 4: Other requirements are:

- resistance to electromagnetic interference;
- suitability for field use:
    - small dimensions, low weight;
    - it needs to be rugged, i.e. resistant to dirt, moisture, shock and temperature fluctuations.

The functional blocks required in an intelligent geophone are shown in table 3.1.

primary sensor	identification	diagnosis	power supply
signal processing	down- and uploading predefined functions	autocalibration	inclinometer
correction and compensation	data communication		position detector

Table 3.1 Functional blocks in an intelligent geophone

Market
One current trend in oil and gas exploration is a shift away from two-dimensional to three-dimensional surveys. This means that increasingly large numbers of geophones are being used for seismic surveys of large areas, leading to a concomitant exacerbation of the problems of logistics and survey reliability outlined above.

In this segment absolute market figures are difficult to come by. However, it is fairly safe to assume that demand from the former Eastern Bloc countries and the countries of the former Soviet Union will rise.

So far, seismic exploration seems relatively unchallenged. There are many patents covering other sorts of survey methods, e.g. laser interferometry, but no practical types are known.

Producers
Some manufacturers operating in the international market are Oyo/Geospace (Japan/USA), Western (USA) and Sercell (France). Other firms not acting directly as manufacturers but as providers of services for geophysical surveys include Schlumberger (Prakla Seismos, Germany) and the Compagnie Générale de Géophysique (France). One well-known Dutch-based geophone manufacturer is Sensor Nederland B.V. (a subsidiary of the American firm Western). The role of the large oil companies is that of end user. They hold numerous patents but as far as is known do not themselves manufacture the instrumentation.

Innovations seem possible making use of technologies already developed for other market sectors like accelerometers, digital signal processing and wireless communication. Knowledge of and production facilities for the basic microsystem technologies are available in Europe (Netherlands, Germany, Switzerland and France). The application of geophysical surveying techniques and technologies is a field in which the Netherlands plays an important role both at home and in the international field.

Technology
The case described here lends itself well to the use of MST:
- requirements include miniaturization and low energy consumption;
- it is necessary to integrate a large number of functions in a single product in order to improve ease of handling and reliability;
- the numbers involved appear to be large enough to warrant the concomitant production and assembly techniques.

Primary sensors can draw on the many developments already available in the field of micromechanical accelerometers. There are some particular problems in the miniaturization of such sensors, in view of the high sensitivity and large signal-to-noise ratio required. The current basic principle of a coil suspended in a magnetic field is suited for miniaturization. It is now technically possible to produce strong magnetic fields in a small volume relatively cheaply. Small coils of high copper density can be made by a combined process of etching and electroforming (distance between windings 20 µm, thickness 200 µm) or by the LIGA process (distance between windings 4 µm, thickness 600 µm). Another possibility is a sprung mass system with capacitive signal generation. This will often employ active feedback to achieve the required linearity. Energy consumption plays an important role in the choice of concept.

The following aspects are important for wireless systems:

- *Energy supply.* The energy requirement for all subsystems in the geophone must be small. Possible solutions are rechargeable cells which can be recharged before every shot, preferably by a contactless system, or the use of solar cells.
- *Signal processing and communication with the base station.* With high sample frequencies (e.g. 500 Hz) the bandwidth needed for the communications channel rises rapidly. On-board memory combined with preprocessing of data in the geophone itself can to some extent relieve the burden on the communications channel and the central processing unit in the base station.
- *Locatability and position finding.* As soon as geophones are no longer physically attached to cables the likelihood of loss increases. Each geophone would have to be individually addressable and capable of identifying itself, since the signal received from each geophone must be processed in relation to its position in the field. An automatic position finding system would reduce the probability of errors in correctly locating geophones before a shot. This need not necessarily be a Global Positioning System (GPS), but might also be a local position finding system based on beacons set out in the field. The required position-finding accuracy in the horizontal plane (x, y) is approx. 0.1 m.
- *Auto-calibration and self-test.* Auto-calibration and testing of coupling to the ground might be achieved by the use of a built-in actuator capable of causing a well-defined acceleration of the seismic mass. The accuracies required for a geophone are exceptionally high. If the three-dimensional accelerometer can also be used with DC it will also be possible to determine the angle relative to the z axis by means of gravitational measurements. In determining orientation on the x and y axes the system used for position finding in the field could be used.

Conclusions

There are still plenty of challenges to be met, but the elaboration of this case would appear to be realistic in the mid term (5 years).

3.3.4 MICROROBOTS FOR INSPECTION PURPOSES

J. Snoeks and M.J. Vellekoop

Internal inspection of industrial equipment and installations under running conditions is often impossible because of the inaccessibility of parts and the physical size of the standard measuring instrument used for inspection. In that case the equipment has to be taken apart for inspection. Great profit could be gained from the availability of miniaturized mobile platforms moving through the internals of installations and carrying sensors for monitoring physical quantities such as temperature and pressure and possibly actuators to perform required actions. Such mobile platforms, which also could be active in aggressive environments not accessible to humans, are called microrobots. The development of these inspection systems could be taken care of in two parallel activities, the mobile platform and the measurement and actuator subsystems.

Definitions

- *Stationary robots* are permanently installed robots that have movable parts which can be equipped with sensor and actuator subsystems.
- *Mobile robots* are robots that can move within a defined space and medium and which can perform missions either stationary or while moving and using sensor and actuator subsystems.
- *Tele-operated mobile robots* are robot systems that are remotely controlled by humans or other systems. Wireless tele-operation is distinguished from tethered systems. The tether could be umbilical, an electrical cable or optical link with fibres. Note that tele-operated mobile robots are also indicated as Remotely Operated Vehicles (ROVs).
- *Autonomous robots* are robots that can perform an autonomous mission. This includes capabilities to react to unforeseen circumstances.

Considering today's available techniques for inspection, application areas can be identified in which – for the purpose of internal inspection – no other alternatives are available than dismantling the installation. In such areas the necessity of dismantling could be removed by the availability of miniaturized inspection tools. Examples are:

- Internal inspection of pipeline systems with small diameters of typically less than 2 inches.
- Internal inspection of vessels or machinery spaces with small access openings.
- Internal inspection of vessels which are difficult to reach e.g. underground storage tanks used at retail stations for automotive fuels or storage.
- Tanks for domestic fuel in private homes etc.
- In-situ inspection tools where weight and dimensional constraints apply (e.g. space travel systems, portable inspection tools).

User requirements are very much dictated by the specific applications.

It is recommended to concentrate first on the development of a generally applicable miniaturized mobile platform for inspection purposes. Such development should result in a conceptual design and ultimately in the availability of a prototype system.

To demonstrate its application potential it is proposed to equip the mobile platform initially with a well established inspection technique. A visual inspection tool, e.g. miniature Charged Coupled Devices (CCD) camera, or an eddy current sensor subsystem for detection of cracks and other imperfections in steel surfaces, are considered useful demonstrator modules.

Miniature mobile platform

In developing a miniature mobile platform, the main challenges are:

1. Energy management.
2. Navigation (positioning).
3. Mission time.
4. Intrinsic safety (optional).
5. Fail-to-safe conditions i.e. fail safe by design.

Ad 1. Particularly for the wireless and autonomous options the problem of energy management, generation and storage on the vehicle is important. The main power consumption requirement comes from the propulsion system in combination with the mission profile, and to a lesser extent, from the measurement and communication system and other operational requirements. The solutions can be diverse, ranging from local energy storage (e.g. batteries), local conversion (generators) to energy transport techniques (wireless).

Ad 2. The actual position of the inspection platform is an important parameter for inspection measurements. The trajectory to be followed by the moving platform also has to be recorded or externally controlled. The propulsion system depends on the application, examples are:

- floating (on surface) or moving through fluids (sub surface) i.e. by propellers, paddles, jet streams, swimming etc.;
- being pushed by flow e.g. in pipelines;
- riding on wheels;
- walking.

Today significant research efforts are put into navigation techniques for robot systems where the problems of mapping the environment, trajectory planning and collision avoidance are addressed. The challenge here is to pick up those developments and transpose them to the miniaturized application domain.

Ad 3. Mission time varies per application. The range could be wide but it is felt that for remotely controlled systems that require human supervision the mission time will be in the range of several hours, while for autonomous systems this could be in the order of days or weeks. Applications are possible whereby the robot remains dormant for a long time and is activated either by events or by the calendar (clock) to carry out one mission and fall back into the dormant mode again after completion of this mission.

Ad 4. It is envisaged that miniature inspection tools should be applicable during normal operation of the installation to be inspected. If the device may have contact with potentially explosive mixtures (Zone 0 or 1), it is necessary that it cannot ignite the mixtures. For such applications the system has to be intrinsically safe by design.

Ad 5. Particularly autonomous and wireless systems must be fail safe. This includes the failure modes being predefined and acceptable. In general it must be guaranteed that a system cannot 'get lost' during its missions. For tele-operated systems this problem seems easier to overcome as such systems can always be retracted to the base position.

Assuming that mobile platforms as described above can be realized, it is envisaged that subsequent measurement system and sensor system developments will emerge aimed at the effective use of these platforms.

Measurement and actuator subsystems

The anticipated availability of a miniature mobile platform will stimulate development of microscale sensor systems and actuator systems to be integrated into the mobile vehicle. The challenges are:

- dimensional constraints;
- power and energy constraints;
- communication and control;
- performance and integrity.

It very much depends on actual applications which specific measurements or control actions are required. Microsystem technology can be applied in the following areas:

- chemical measurements (in line, fast response);
- microdosage systems;
- sample-taking systems;
- flow, temperature and pressure measurements;
- inspection sensors (ultrasonic, eddy current etc.) for measurement of blockages, deposits, leakages, cracks, corrosion and eventual coating condition;
- image acquisition and processing systems (e.g. visual inspection).

The market and related research projects

Microrobots are appropriate for inspection of equipment and structures in the following areas:

- The interior of process equipment such as pipes, heat exchangers, condensers, small vessels.
- Above-ground Storage Tanks (AST) and Underground Storage Tanks (UST).
- Difficult to access parts of structures, e.g. in oil rigs and production platforms.
- Nuclear plants.

The number of possible applications in these areas is huge. There is no doubt of the applicability of microrobots should they be available. The main problem is that it is questionable whether such systems can be developed and realized within a period of, say, 3-5 years. Appended to this section are some abstracts from literature which indicate that outside Japan there has been no sign of actual developments on microrobotics. Most recent publications on this subject originate from Japan. (Specific medical applications have been excluded from the search as that application field is covered in the next chapter).

Conclusions

The development of a miniature mobile inspection platform, as described in this section, is thought to be a challenging project. This is futuristic and would require a multi-functional and multi-disciplinary approach. A somewhat comparable development was considered in 1991 in Japan by the Japanese Agency of Industrial Science and Technology (Appendix 2). That project proposal concentrated on development of intelligent 'pigs' for inspection and repair, intended to move in small pipelines. It is concluded that new developments in the field of microrobotics might emerge from research programmes in Japan. It is recognized that the main barriers to be overcome will be technological difficulties.

Probable concentration will initially be on definition of modules and modest developments in order to build confidence and gain support. A fairly recent publication from Tokyo University [27] indicates a rationale for a more global cooperation in this field of technology.

ABSTRACTS

Design and fabrication of a piezo-magnetic mini-walker [26]

This paper (in Japanese) describes design, fabrication and performance of a miniature walker developed for a new precision production system. This machine consists of piezo-actuators and electromagnetic legs which are synchronized so as to move like an inchworm. These elements are jointed mechanically enabling the machine to walk on any curved surface including a wall or a ceiling. The magnetic forces of this small machine can be remote controlled to prevent it from slipping and falling down, although conventional inchworm mechanisms need some guide rails or are restricted to a horizontal plane. This arrangement also allows for the absence of mechanical elements which could provide a very high positioning resolution with a wider working area. The miniature machines, which are the size of a golf ball, can move on any inclined surface with continuous sub-micron steps. This means that the mini-walkers can be applied to a new precision production system where they can cooperate with conventional machines.

Summary report on microrobot research and development investigation [27]

(Department of Mechanical Engineering, Tokyo University, Japan)

This paper (in Japanese) gives an overview of microrobot research in Japan. The silicon micromachining process has resulted in research into the microrobot which is composed of surprisingly microscopic integrated mechanisms. The microrobot realizes minute operations in an extremely limited space, and in the near future hordes of microrobots will be able to work together like swarms of bees. These microrobot functions, as yet not experienced, are expected to find widespread use in medical and biological treatments, industry, basic science and daily life. Research and development of microrobots requires integration of various technologies from a wide range of specified fields, the results of which will influence the nation's technological and economic status. The author argues for the promotion of R&D projects by the Japanese government with the coordination of companies, national laboratories and universities. Because the development of this technology is universally beneficial, international cooperation is recommended.

Optimal position for elastic fins of a miniature mobile robot in a thin tube [28]
(NTT Transmission Systems Laboratories, Ibaraki, Japan)
This paper (in Japanese) describes a method for the design for a miniature mobile robot in a thin tube. The optimal position for the robot's elastic fins is investigated. The paper is written in Japanese and further details are not yet known.

Research & Development problems in nuclear telerobotics [29]
(Reactor Control Laboratory, JAERI, Ibaraki, Japan)
Nuclear telerobots, which perform in environments affected by radiation, such jobs as inspection, repair and dismantlement of components, must have radiation resistance, high reliability, ease of maintenance, mobility, accessibility, dexterity, and so on. The requirement of radiation resistance is a source of particularly difficult problems in the technological development. To improve the state-of-the art, the R&D concerns should include development of high-performance manipulators, powerful transporters, high-performance control systems, user-friendly man-machine interfaces, miniaturized sensors and signal transmitters, powerful compact actuators, high-capacity compact power sources, etc. The paper describing this project is in Japanese.

Intelligence for miniature robots [30]
(MIT Artificial Intelligence Laboratory, Cambridge, MA, USA)
The authors describe an exercise of building a complete system, aimed at being as small as possible, but using exclusively off-the-shelf components. The result is an autonomous mobile robot slightly larger than one cubic inch, which incorporates sensing, actuation, onboard computation and onboard power supplies. Nicknamed 'Squirt', this robot acts as a 'bug', hiding in dark corners and venturing out in the direction of last heard noises and only moving after the noises are long gone.

A miniature robotic boundary layer data acquisition system [31]
(Department of Mechanical Engineering, South Florida University, Tampa, Florida, USA)
A sophisticated, highly miniaturized, mobile robot has been developed to collect boundary layer velocity profile data over the surfaces of wind tunnel models. To reduce aerodynamic interference effects the robot was built with dimensions of only 150 mm tall, 70 mm long and 35 mm wide, yet it contains a substantial number of electromechanical and electronic systems for accurately positioning small pressure probes, and for transducing their pressure data. The robot system, which can be controlled in a tele-operator mode from outside the wind tunnel, is capable of traversing a pressure probe normal to the model surface at two speeds, and can position the probe at any desired location with a positional accuracy of 0.022 mm. The robot also includes systems that enable it to move over the model surfaces in a chordwise sense, and to rotate the probe through 180 degrees for use in reversed flow regions. When used operationally during actual wind tunnel testing, the robot functioned flawlessly, and returned high quality boundary layer data.

Gnat robot (and how they will change robotics) [32]
(MIT Artificial Intelligence Lab., Cambridge, MA, USA)
The use of micromechanical motors to achieve miniature (gnat-sized) mobile robots

is considered. The potential applications of such robots are discussed, and the necessary technology which already exists is identified. Design strategies and details of a proposed implementation are given. Problems in the micromachining area are briefly examined.

3.4 PERSPECTIVE OF MST IN INSTRUMENTATION

Task Force Instrumentation

The subjects of this section are the economical impact and the social benefits of MST in instrumentation. The required infrastructure to produce MST-based instruments and the education are not specific to instrumentation and these subjects are discussed in Chapter 8.

Several market reports exist on the business potential of microsystem technologies, microsensors or silicon sensors published by organizations such as Frost & Sullivan, MIRC, SRI, Battelle and many other market research companies. The numbers cited by these sources deviate considerably. The main reason for this situation is the novelty of the field. It is not yet clearly defined what a microsystem is nor is it always clear what is meant by instrumentation. An additional complication is the fact that for most MST applications in instrumentation the microsystem is indeed essential, but only one of the many components of the complete instrument and it is difficult to extract the exact contribution of the MST part to the numbers mentioned.

To our knowledge no specific numbers on the business potential of MST for the instrumentation field are given by these type of reports. None of these studies use instrumentation to indicate a certain market niche. The categories likely to be the closest to instrumentation and those being used fairly frequently are process control and analyzers.

A selection of relevant numbers given in those market research reports illustrates the enormous economic potential of silicon sensors and instrumentation. If hybrid components are included these figures can be expected to be even larger.

The numbers given in table 3.2 leave no doubt that microsensors, and in particular their application for process control, analytical instruments and environmental measurements, are very interesting potential markets. There is no doubt that MST will become the main technology in instrumentation. The important question that remains is: when, exactly?

It is expected that in the short term the more or less pure sensor applications and some relatively simple passive structures will represent the bulk of the market for MST applications. For success in the medium and long term, the involvement of the end users and as a consequence a system approach, will be of crucial importance for the further growth of MST applications in the instrumentation field. In the development of these applications Small and Medium-sized Enterprises (SMEs) can play an important role, if they have access to the required infrastructure for the design and manufacture of complete microsystems or miniaturized components. In many countries, including the Netherlands and Belgium, this infrastructure does exist for a large part. The important action to take is to lower the barriers which still make it difficult for a large number of companies, especially SMEs, to get access to this infrastructure. Therefore the main issue is the improvement of the logistic support for interested companies in using the existing infrastructure, to build new infrastructure if required, and to take actions to lower the financial risks for making use of that infrastructure.

		1985	1990	1992	1995	1997	1999	2000
European market for silicon sensors (1993)	Frost & Sullivan			$ 318		$ 673		
US air emission monitor and analyzer markets (1994)	Frost & Sullivan			$ 546.7		$ 1150		
European process analytical instrument markets (1993)	Frost & Sullivan			$ 650		$ 900		
world condition monitoring equipment markets (1993)	Frost & Sullivan						$ 711	
air emission monitor and analyzer markets (1992)	MIRC		$ 308			$ 900		
intelligent sensors (1988)	MIRC	$ 436			$ 1142			
microsensors applications and markets (1993)	Innovation 128			$ 300[1]				
sensors and instrumentation for advanced materials and metals (1992)	Innovation 128			$ 450[2]				
world sensor market	Intechno Consulting AG		$ 20,500[3]					$ 48,000
sensortechnik 2000[4]	Prognos							
sensors for gases					DM 320			DM 550
sensors for waste water					DM 450			DM 840

[1] Europe only, 25% process control applications

[2] worldwide, 35% Western Europe, 15% USA and Canada, 50% ROW

[3] $ 5.8 billion process engineering includes $ 3.1 billion for Western Europe

[4] worldwide environmental protection sensors

Table 3.2 Market expectations of MST and instrumentation in millions

It is believed that in the mid term (at least for the next 10 years) most microsystems will be hybrids. Only in the very long term will fully integrated systems appear on the market for very high-volume applications. In order to speed up the development of hybrid systems, standardization will be needed in order to be able to use already existing components in new developments. This will imply standard interfaces to be able to use a common bus.

To make MST successful in the instrumentation field, applications have to be identified with specifications which cannot be met by the classical approaches and which justify the high costs encountered during the development phase of these systems. Such applications can be found in space instrumentation, medical instrumentation, safety applications and specific instruments for scientific research (elementary particle physics, human genome project etc.). MST will also be successful if totally new functions can be realized by microsystem technologies only. The best example of such a totally new function is that all the different types of scanning microscopes (tunnelling, force, optical, thermal and magnetic) are based on the accurate position control of a miniaturized sensor tip. A reduction in the total life cycle costs will be needed for further expansion in the instrument market. These costs include maintenance, calibration, consumables and waste product disposal costs.

3.5 CONCLUSIONS AND RECOMMENDATIONS

Task Force Instrumentation

A number of recommendations are given, based on the aspects discussed in the previous sections.

A national stimulation programme is required
A national stimulation programme on MST should be set up. This stimulation programme should focus on the implementation of MST in commercial products and therefore stress the importance of the cooperation of parties with a different role, such as universities, institutes, technology transfer companies, foundries, MST-suppliers, system suppliers and end-users. Such a programme would strengthen the national position in Europe and assure successful participation in future European projects.

Facilitate technology transfer
In addition, R&D at universities and institutes should be stimulated in the direction of practical applications to maintain the technological base and facilitate technology transfer. The R&D programme should be tailored to the specific needs of SMEs. However, the participation of larger companies (end-users, system suppliers, MST-suppliers, R&D) is a prerequisite for a successful programme.

Set-up of a national network
A national NEXUS-like network on MST is considered essential. This network should play an active role in a stimulation programme through bringing together relevant parties, consultancy work, organizing workshops and increasing the awareness of MST potentials and the opportunities existing in the Netherlands and

Belgium. Such a network should furthermore enhance the accessibility of the existing infrastructure for potential users.

Stimulate public purchase contracts

Public purchase contracts should be part of a stimulation programme. These contracts could concern development of instruments with a high social benefit, such as can readily be found in the area of public health and environmental protection, both also being technologically interesting areas for MST. These developments would also act as demonstrators of MST potentials.

Educate the systems approach

The 'system approach' should be intensively dealt with on all courses of the different faculties in higher education related to MST, such as electrical, mechanical and chemical engineering and applied physics. There is no need to have dedicated courses on instrumentation in regular higher education.

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4. Microsystems and medical technology

4.1 APPROACH AND FOCUS

G.C. Klein Lebbink and J. Voûte

4.1.1 INTRODUCTION

Over the centuries medicine and its related technologies have developed from simple and often barbaric removal of tissues creating the 'problem' to early diagnosis and replacement of functions in the human body. With this development it has also become apparent that the traumatic side-effects of these medical procedures have often created similar risks to the patient as the primary cause or affliction, these effects impairing the quality of life after treatment.

Consequently three main trends have emerged.

- As the diagnosis has become increasingly sophisticated, it is now possible to treat an affliction at an earlier stage, thereby reducing the primary effect and the need for rigorous therapy. The need for early warning has called for ever more specific diagnostic procedures. Present technology has progressed to a level where non-invasive diagnosis through Nuclear Magnetic Resonance (NMR), ultrasound, X-ray and nuclear medicine makes it possible to identify parameters at cell-cluster level.
- With the identification of morphological and functional aberrations inside the body, the need for treatment without trauma to surrounding healthy tissue has increased. This has led to therapeutic procedures which are becoming more and more specific, both in treatment and in the space and time domain. In general, the precise delivery of very specific drugs in small volumes would fulfil this requirement.
- Quality of life would be dramatically improved if the body functions affected by the treatment or disease could be replaced. Rehabilitation has improved quality of life and dehospitalized many patients in recent years. From such simple devices as hearing aids to sophisticated pacemakers and insulin pumps, from artificial limbs to portable oxygenation and ventilation systems, patients experience tremendous relief and regain independence.

4.1.2 WHY MST IN MEDICAL TECHNOLOGY?

The trends introduced in the previous section have directed the development of medical needs. MicroSystem Technology (MST) has a number of advantages to offer:

In-situ operations
All three trends identified in section 4.1.1 call for specificity in measurement, be it a parameter or location, coupled with or followed by minimal traumatic therapy. The latter broadly covers minimal invasive procedures and highly specific treatment such as highly specific drugs and minimal invasive surgery.

Function integration
Not only can microsystem technology package functions in an extremely small volume, but it can also integrate sensors and actuators to a level only matched by nature itself. Furthermore, integration with a transponder reduces the need for active cabling and powering of the application. The need for improved reliability and immunity to external disturbances also calls for integration.

Reduction of costs
Production technology and ease of reproduction promise cost-effective production of MST devices in the long run. Presently, medical applications are divided into two types:

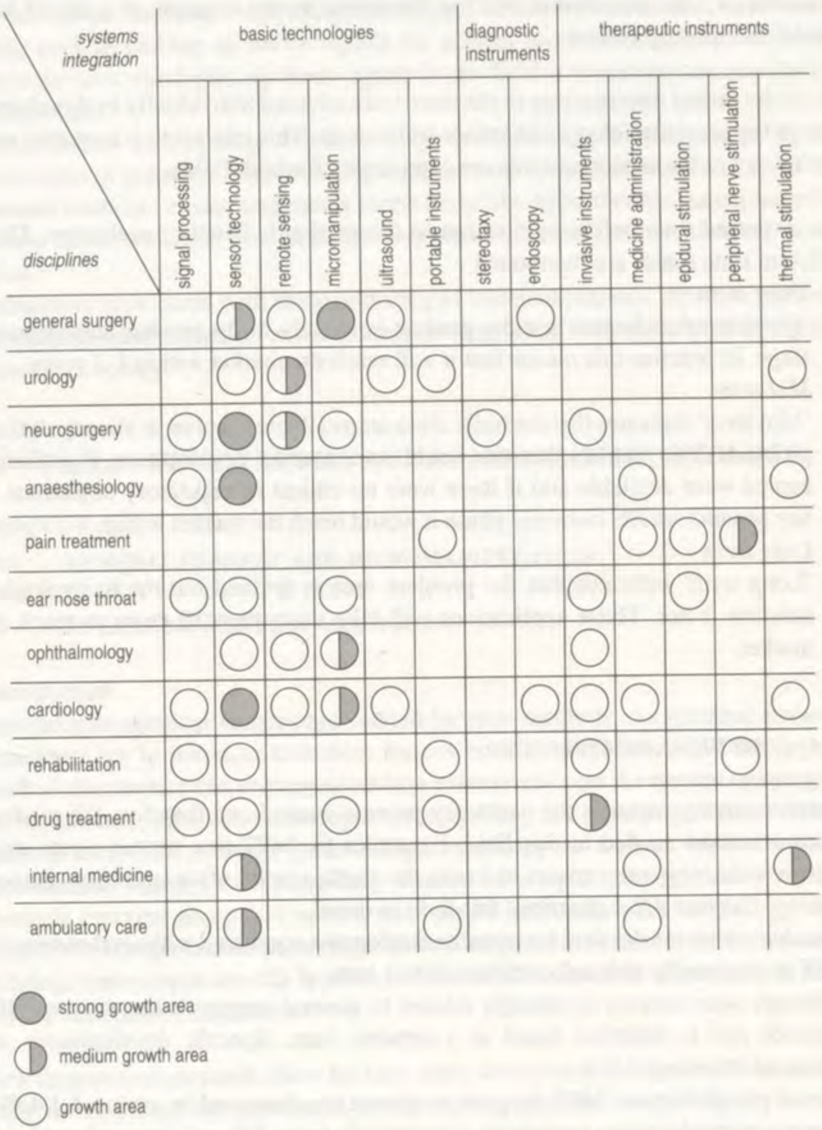
- High value-added, low-volume applications, where the specific advantages of microsystem technology provides solutions to a selected number of patients, at a relative high cost. For example implantable devices, where the cost of implantation is often much higher than the device cost itself, or highly sophisticated diagnostic procedures.
- Low-cost, high-volume applications, which replace other more traditional solutions. Here the production advantages are of prime importance. High volumes are generated by using subsystems or modules in different applications.

Reduction of size and power consumption
One common characteristic of medical applications is the need to relieve the user or patient of the constraints of present technology, and to improve the dwelling time inside the body or to reduce traumas in use. Precise placement improves specificity of use. A reduced power consumption is required to improve heat generation, and thereby to lengthen dwelling or usage times.

4.1.3 MEDICAL NEEDS AND TECHNICAL POSSIBILITIES

The most spectacular examples are to be found in low-volume applications, although the medical and economic impact of microsystem technology would be much higher for high-volume systems. Historically many new applications in medical technology have begun in the first category and gradually transformed into the second. A good example is the currently as ‘standard’ implanted pacemaker (VVI-pacemaker).

To classify the areas where the applications of microsystem technology will have the most impact, these areas are catalogued in a matrix (figure 4.1) listing medical disciplines on one axis and systems integration and specialization on the other. The headings in the systems-integration axis are classified in order of increasing complexity and nearness to the patient.



systems integration / disciplines	basic technologies						diagnostic instruments		therapeutic instruments				
	signal processing	sensor technology	remote sensing	micromanipulation	ultrasound	portable instruments	stereotaxy	endoscopy	invasive instruments	medicine administration	epidural stimulation	peripheral nerve stimulation	thermal stimulation
general surgery		◐	○	●	○			○					
urology		○	◐		○	○							○
neurosurgery	○	●	◐	○			○		○				
anaesthesiology	○	●								○			○
pain treatment						○				○	○	◐	
ear nose throat	○	○		○					○		○		
ophthalmology		○	○	◐					○				
cardiology	○	●	○	◐	○			○	○	○			○
rehabilitation	○	○				○			○			○	
drug treatment	○	○		○		○			◐				
internal medicine		◐								○			◐
ambulatory care	○	◐				○				○			

● strong growth area
◐ medium growth area
○ growth area

Figure 4.1 Growth areas for microsystems in medical technology

The important growth areas for MST are identified in the matrix and ranked in order of priority. This ranking is a subjective one based on the expertise of the participants in the task force underlying this chapter. For a brief description of the medical disciplines see section 4.1.4.

Section 4.2 describes the intersections indicated in the matrix with a filled dot dealing with

- the medical demands;
- the equipment that should be built or that has to be improved;
- the capabilities of MST.

In section 4.3 the potential of MST is illustrated by the example of a closed-loop patient monitoring system.

All of the dotted intersections in the matrix are covered individually in this chapter except for anaesthesiology and sensor technology. This intersection is treated with cardiology as the sensor systems are comparable for both fields.

The expected time before application in the market is listed in each case. Three different time scales are mentioned:

- *Short term*

  'Short term' indicates that the product is already in the product development stage. In practice this means that it will reach the market within 1-3 years.
- *Mid term*

  'Mid term' indicates that the basic ideas are available to solve an already defined problem. This implies that one could start product development if sufficient capital were available and if there were no ethical or regulatory objections. If any product results from this phase it would reach the market within 4-10 years.
- *Long term*

  'Long term' indicates that the problem area is defined but the technological solution is not. These applications will take more than 10 years to reach the market.

4.1.4 MEDICAL DISCIPLINES

General surgery includes the necessary process control and therefore the medical instrumentation needed in this field. Examples for MST are intensive-care units (sensor technology) or sensors to locate the starting point of an operation (remote sensing). Section 4.2.1 describes this field in detail.

In *urology* there is a demand for portable dataloggers combined with urethra sensors. MST is supposedly able to contribute in this area.

Although *neurosurgery* is strongly related to general surgery it has very specific demands and is therefore listed as a separate item. Specific developments are discussed in section 4.2.2.

Several possibilities of MST for *pain treatment* are discussed in section 4.2.4. For example portable pulse generators, implantable drug delivery, internal medicine monitoring and peripheral nerve stimulation.

For applications of MST in the *ear, nose and throat discipline*, one could consider programmable hearing aids (signal processing) or cochlea implants in the inner ear (epidural stimulation).

Ophthalmology could benefit from devices like eyeball pressure sensors, implantable eye pressure systems (invasive instruments) and micromotors to make incisions in the eye for cataract operation (micromanipulation). Section 4.2.5 gives examples in this field.

Section 4.2.6 describes the demands for and possibilities of MST in *cardiology*. Some additional examples are micro-electrodes on the body (remote sensing), colour sensing of the blood to detect oxygen content (remote sensing) and replacement of conventional balloon-techniques with ultrasound or endoscopic systems.

Rehabilitation includes everything that is used to control movement in a human being such as picking up nerve signals for driving protheses (signal processing). These devices which pick up these signals in the field of neurology are sketched in section 4.2.2.

Microsystems used in *drug treatment* might be for example micropumps for the medication of pancreas disease or implantable drug delivery systems.

Internal medicine covers treatments in the body like hyperthermia, as explained in section 4.2.8. We could also envisage very small heat radiators for thermal stimulation.

Ambulatory care deals with the monitoring of terminal patients, medical administration, and expert systems for use in the home including both signal processing and sensor technology.

4.2 GROWTH AREAS FOR MST IN MEDICAL TECHNOLOGY

4.2.1 GENERAL SURGERY AND MICROMANIPULATION

H. Lehr and R.M.E.M. van Heijster

Introduction

Advances in classical surgery are fuelled by new methods. As minimal invasive techniques try to avoid or minimize lesions both in diagnostics and therapy: so medical diagnostics and therapy nowadays extensively uses the natural openings of the human body to insert endoscopic systems. They are widely applied in various medical areas like urology, gynaecology, neurology as well as various internal applications. These systems typically consist of a rigid metallic tube with thin channels carrying an optical system and minute instruments for surgical applications. Even though certain parts of the human body are difficult to reach via normal openings endoscopes are still applied, with as small a diameter as possible in order to keep lesions to a minimum.

New diagnostical methods allow for very early detection of malignant tissue, so that local therapy may be performed at the earliest possible stage, e.g. by use of endoscopic systems and surgical instruments which have to be moved through the channels of the endoscope. Changes in parts of the instruments and the way they are applied will shortly call for dimensions in the micron range.

Present developments in endoscopy

The rod lens system, developed in 1960 by H.H. Hopkins, considerably improved the performance of endoscopes due to a wider viewing angle and higher light transmission. This allowed the construction of very thin optical systems with a minimum diameter of at present 0.3 mm, and the use of fibre optics. The whole instrument has become increasingly thin and the instrumentation minute.

Urologists were the first surgeons to make extensive use of the new endoscopes, followed by laparoscopy and paediatric gynaecology. Nowadays a variety of endoscopic systems are available, which are specialized for the application which they are needed. These are all developments of the last decade. Another explosion of endoscopic techniques is to be expected in applications which up to now were in the domain of classical surgery [1].

Although most medical disciplines make extensive use of endoscopic systems, a number of disciplines require an improved performance from such instruments. Namely, neurosurgery, a certain domain of laparoscopy and special applications in urology, to mention only a few. All these disciplines are in need of a navigation capability, by use of a movable tip, and in some cases like neurosurgery, complete control of the shape is mandatory. This is particularly true in endocranial diagnostical and therapeutical applications where lesions must be carefully avoided by following the narrow gaps between the convolutions of the brain. But the aim of neurosurgeons is even more ambitious: they require persistent curvatures of the endoscope during the movement in longitudinal directions.

Movable tips are well in the range of microsystem technology by applying for example shape memory alloys as actuators or pneumatic and hydraulic systems and are expected to be available in the short term. But to maintain a constant curvature in three dimensions with a high degree of freedom, for navigating a tube with a diameter of less than one millimetre is certainly a challenge for both microsystem technology and computerized control systems.

An endoscope of this sort may in principle consist of a number of segments (figure 4.2). Each of these segments would be subdivided into a part to perform small inclinations and a control unit for steering the direction and the degree of bending. A coded signal from the central control station would initiate the inclination of one actuator segment in the desired direction.

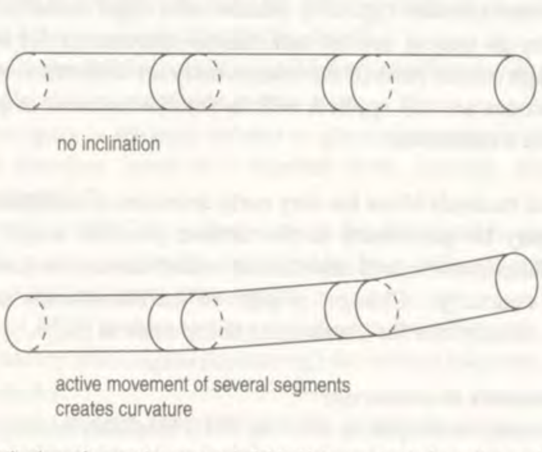


Figure 4.2 Schematic view of an endoscope subdivided into segments for action and control

Transducer systems are needed to convert external energy into force. This could be achieved by placing four stripes of shape memory alloy at the periphery of the tube (figure 4.3 left). An electric current will heat up one of the stripes to shorten or lengthen it, which leads to a bending of the segment. Another alternative is a hydraulic system making use of miniaturized valves situated in the control section of the endoscopic segment.

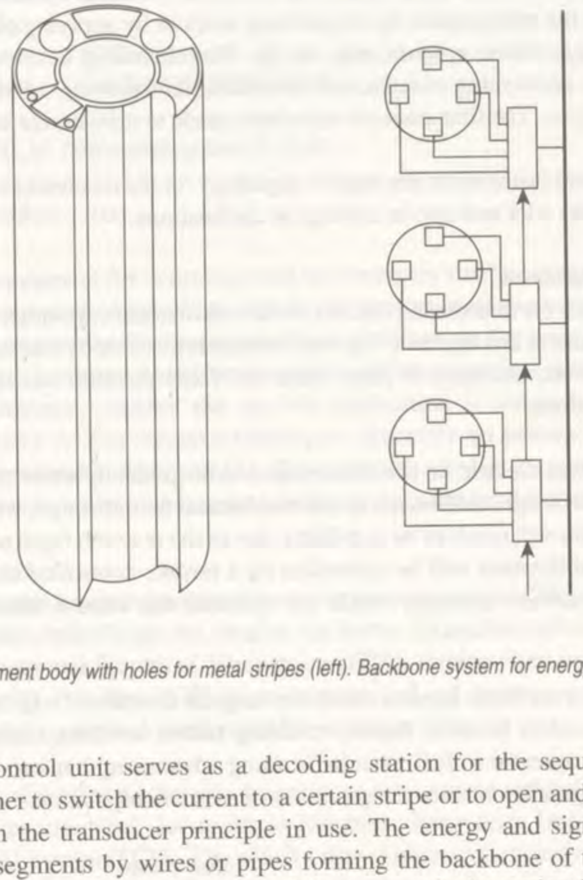


Figure 4.3 Segment body with holes for metal stripes (left). Backbone system for energy transfer and control (right)

The small control unit serves as a decoding station for the sequences from a computer either to switch the current to a certain stripe or to open and close a valve, depending on the transducer principle in use. The energy and signal line is fed through the segments by wires or pipes forming the backbone of the endoscope (figure 4.3, right). A hole in the centre of the segment body carries the instruments and fibres for visualization. If necessary a further subdivision into channels is possible. The bodies with the appropriate holes which could be made from a polymer material may simply be obtained by extruding the polymer through a spinneret plate with high precision holes. These could be produced by using the LIGA technique. The central channel is kept free for the feedthrough of a number of mechanical instruments which are actuated from outside, for example grippers to remove tissue or a stone, scissors, knives or pincers for cutting, loops to catch stones and electrodes for coagulating tissue. Optical fibres play an important role in guiding the intensive light of a laser being applied in surgery, mainly for cutting but also for local disintegration of stones in urological applications. In order to produce such an instrument, a number of problems have to be solved, in particular for diameters of less than 2 mm. For this reason a long-term development is expected.

Modern laparoscopy uses at least two endoscopes at the same time for observation and handling. It is obvious that position control and stabilization of the endoscope tips play a dominant role in the combined action of several endoscopes which are focused at a small area. Mechanical handling of the surgical instruments is, however, still achieved by pulling wires, which is uncomfortable and shakes the endoscope, making micromanipulation impossible. A foot switch similar to those in laser applications or for coagulation is certainly more appropriate. The force for movement of a gripper or closure of scissors to cut tissue, could in these cases, either be transferred to the endoscope's tip via moving wires or by applying electromagnets, hydraulic or pneumatic systems near the tip. Microhandling devices are required, in addition to performing complicated activities, like stitching up arteries, vessels and small lesions. The first attempts have been made to miniaturize such machines.

Extremely small instruments are used in angiology for the reconstruction of arteries, vessels, the bile duct and also in urological applications.

Future developments

Current systems for micromanipulation work with mechanical connections between surgical instrument and operator. Tip stabilization is possible by a remote-controlled balloon, however, accuracy is poor while the fixed position has relatively little degree of freedom.

In the short term electric or fluidic actuators will gradually enter the scene. The endoscope is no longer influenced by the mechanical feed-through, which enhances stability. The tip still needs to be stabilized, due to the reaction force of the actuator. Passive tip stabilization will be controlled by a remote-controlled clamp. A set of clamps will increase accuracy while the operator can choose almost any fixed position.

In the mid term the force used to move the surgical instrument will be fed back to the operator control handles, thereby enabling tactile feedback (figure 4.4). This will allow the operator to feel what he is doing when using a micro-knife. Tactile feedback will greatly enhance the precision of micromanipulation.

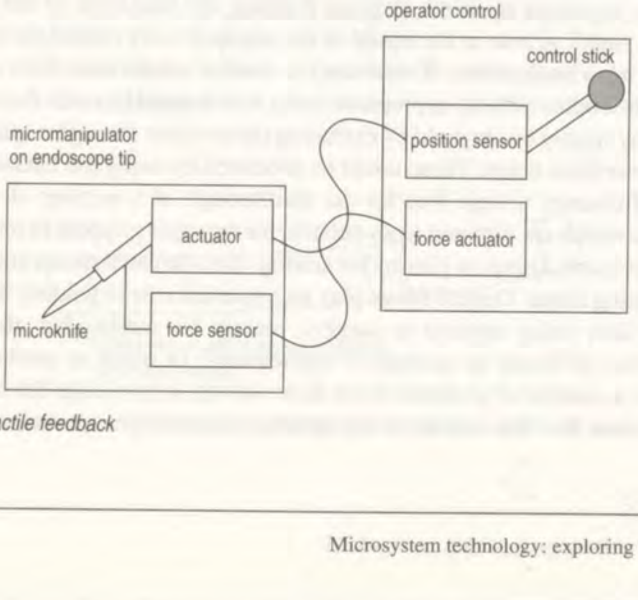


Figure 4.4 Tactile feedback

In the long term we will see active tip stabilization. The reaction forces can be guided to a given distance from the tip through the endoscope structure. The actual tip position is maintained by active steering of the endoscope; corrections for tip movement can be made by inverse steering of the micromanipulator. A tip-position measurement system is essential, which is not available at this moment, not even in a conceptual form. Active tip stabilization can be compared with the precision movements humans can perform with their hands without their arms being in a perfectly fixed position, using optical feedback for active hand stabilization.

4.2.2 NEUROLOGY AND NEUROSURGERY

M.W.C.M. Nieuwesteeg and H. Lehr

4.2.2.1 INTRODUCTION

Sensors and equipment for neurology and neurosurgery can be classified in several ways, depending on the item of interest. In the context of microsystem technology it is logical to emphasize the dimensional aspects. However, for several reasons that will be outlined in the process of evaluating the different systems available, one has to take into account whether the specific application is obtained by invasive, minimal-invasive or non-invasive techniques. Recently an attempt was made to formulate a systematic approach [2]. Basically, the clinical requirements of the neurosurgeon or neurologist come first. Subsequently, the product definition can be made.

In some cases this leads to 'minimal' invasive instrumentation. This creates a need for microsystem technology, the smaller the better. Examples include micro-electrodes for Functional Electrical Stimulation (FES), miniaturized pressure sensors for Intra-Cranial Pressure (ICP) measurement and, of course, microsurgery or micromanipulation devices as described in section 4.2.1.

However, it is also possible that non-invasive, or even remote technologies can fulfil the original requirements, for example Magnetic Resonance Imaging (MRI) or Trans-Cranial Doppler (TCD). The added value of microsystem technology in these fields stems not from the small geometries that have to be explored but from the improved performance of the complete machinery, like the handling of probes.

In the following, three categories are discussed:
- non-invasive and remote devices or applications;
- minimal invasive devices or applications;
- new devices and applications.

The potential for microsystem technology is outlined qualitatively for each category. It should be noted, as mentioned in the general introduction of this chapter, that this overview cannot constitute more than a rough indication of the possibilities for microsystem technology in the fields addressed.

4.2.2.2 NON-INVASIVE AND REMOTE DEVICES OR APPLICATIONS

In principal, non-invasive devices are considered to be ideal. Unfortunately, in many cases no non-invasive solution is available. Even techniques that are in principle non-invasive, may require invasive actions for example injection of a contrast agent during X-ray examination. Finally any non-invasive or remote technique depends by definition on an interaction with the patient. So in the ultimate extrapolation of non-invasive measurement technology, the definition loses its relevance.

X-ray, with or without computed tomography, and MRI are widely used in neurology and neurosurgery to obtain information on brain perfusion and in the localization of aneurysms, haemorrhages, damage or tumours. Subsequently, laser-assisted stereotaxy is used to determine the method of operation. A well-known and fiercely discussed non-invasive surgery technique is based on the use of gamma-radiation (the so-called gamma-knife). In addition Positron Emission Tomography (PET) is used for the localization of specific tumours. Brain perfusion is also probed with TCD equipment. Microsystem technology may be useful here to enable better handling, perhaps more reliability and possibly lower cost.

A specific example is constituted of Electro-EncephaloGram (EEG) electrodes. These are used to determine brain activity in general and more specifically to probe 'anaesthesia depth' based on adapted EEG measurements. These are treated extensively in the next section, according to their exact application as non-invasive or invasive devices.

An interesting trend in non-invasive (imaging) techniques is the possibility combining imaging with intervention. This trend is most clearly illustrated by the X-ray assisted Percutaneous Transluminal Coronary Angioplasty (PTCA) procedure (section 4.2.6.2), but might also expand into neurosurgery and neurology.

Spectroscopy is another interesting option for MRI in particular. This is also related to the options mentioned in the minimal invasive sensors for chemical parameters.

4.2.2.3 MINIMAL INVASIVE DEVICES AND APPLICATIONS

Electrodes

Applications for sensor systems in neurosurgery include sophisticated recording and stimulation electrodes, as for example used for the regeneration of peripheral nerves and for the monitoring of nerve functions during an operation. Increasing demands for long-term implantable devices and minimal invasive surgery require these electrodes to be miniaturized further, thereby improving their biocompatibility and maintaining their electrical functionality. From the solutions introduced so far, planar micro-electrode arrays manufactured by silicon micromachining techniques present a great number of electrodes (between 10 and 100) on a truly miniaturized device (typically 50 x 250 x 2000 μm^3). In addition they possess integrated electronics for the processing of data and have a high degree of reproducibility during the manufacturing process. Prototypes of 'semi-three-dimensional' micro-electrode arrays have been produced for recording experiments but they require high forces to be inserted into the neural tissue.

There are, however, some major disadvantages to silicon micro-electrode arrays: the biocompatibility of silicon and coated silicon is relatively low, such that long-term implants of planar silicon micro-electrode arrays have not been implemented to date other than in animal experiments for a couple of weeks. Furthermore, the tissue damage due to the insertion of these electrode arrays is rather high and single electrodes can not be moved. The development of versatile, long-term implantable micro-electrode arrays, therefore, requires new solutions for the manufacture of recording and stimulation devices.

A couple of novel micro-electrode arrays, either avoiding any direct contact with the surrounding tissue, by exploiting other stimulating or recording techniques, or minimizing the area of direct contact between the stimulating or recording metal and the surrounding tissue are described below.

Micro-electrode arrays using electrolytes

Recording and stimulation of peripheral nerves can in principle be carried out in an almost biocompatible way by use of salt bridges, which connect the extracellular potential to a metal electrode. The basic principle is that of the glass electrode, which is one of the oldest devices used for recording intra- and extracellular action potentials. Thin glass electrodes have, however, resistances exceeding 5 MΩ due to their long narrow tips (typical diameter: 1-5 µm at a length of 200 µm). Therefore they cannot be used for stimulation applications or manufacturing arrays with 100 or more micro-electrodes.

Microfabrication techniques on the other hand allow for the production of hollow chamber electrodes (figure 4.5). The system basically consists of three parts:

- a cover plate containing the electrodes and integrated electronics for data acquisition (stimulation);
- a hollow chamber plate (chamber diameter: 50 µm) containing the electrolyte for the salt bridge;
- a thin ground plate (typical thickness 10 µm) with narrow apertures (diameter: 1-5 µm), interfacing the neural tissue and the electrolyte.

All three parts can be manufactured by injection moulding using a LIGA mould form [3]. Thus any biocompatible polymer can be used for the replication of the hollow chamber array.

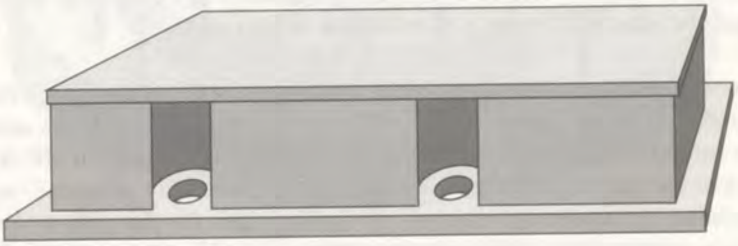


Figure 4.5 Hollow chamber micro-electrode array

This array has several advantages as compared to conventional multi-electrode arrays:

- high biocompatibility due to the separation of metal and tissue;
- high flexibility (as compared to conventional arrays of glass pipettes);
- relatively low resistances (as compared to conventional arrays of glass pipettes) in the range of 100 kΩ to 1 MΩ.

Typical overall heights of the hollow chamber plate range from 150 μm to 200 μm; Width and length of the array are determined by the number of chambers. The first prototype of the array will consist of 5 x 10 hollow chambers with a diameter of 50 μm and a distance of 100 μm between the electrodes. The total area of the array will be approximately 0.5 x 1 mm^2, which would easily allow for an implantation in peripheral nerves.

Carbon fibres with small diameters could be an interesting alternative to packing tubes with electrolyte. The biocompatibility of carbon is comparable to that of physiologic NaCl solution, but the long-term stability of this electrode material can be expected to be an improvement on that of electrolyte, where concentration changes over a long period can change the electrical characteristics of the microelectrode array. Manufacturing processes such as Laser Chemical Vapour Deposition (LCVD) for the production of long carbon fibres with diameters down to 20 μm have been systematically tested in recent years.

Prototypes of hollow chamber electrode arrays are in construction at the moment. The integration of the electronics used for the on-chip amplification and multiplexing of the signals and the optimum diameter of the hole in the base plate are still open questions. Firstly, *in vitro* tests will yield the electrical characteristics of these electrode arrays which will then allow for a basic optimization of the three parts. *In vivo* tests of the hollow chamber electrode array will then give systematic results for the functionality and long-term stability of these multi-electrode arrays.

Microcoil arrays for Functional Electrical Stimulation (FES)

Another attempt at the stimulation of nerves without direct contact between electrodes and neural tissue is stimulation with rapidly varying magnetic fields which then induce an electric field high enough for the depolarization of the membrane. Implantable arrays with coils making use of magnetic fields have not been produced to date, due to the lack of truly miniaturized coils. However, extracorporeal experiments with magnetic fields show that magnetic stimulation offers major advantages in clinical practice. Disadvantages due to a lack of specific stimulation can again be overcome by the miniaturization of the coils.

Macroscopic coils have been used for the extracorporeal stimulation of for example the phrenic nerve [4]. However, we now know that the current changes necessary for the stimulation of the nerve have to be very high, in the range of 100 A/μs. In the extracorporeal experiments these currents can be easily sustained, whereas implantation of the devices requires low inductivities for the coils to keep the necessary voltages low. Such coils have been made for the production of high precision distance sensors and for the production of micromotors [5]. A typical array of microcoils is given in figure 4.6. In the case of the hollow chamber multi-electrode array, the coils will be totally covered by a biocompatible polymer. Overall length, width and height of the array is again determined by the distance between the coils and can be fixed at 1 x 0.5 x 0.3 mm^3 for an array of 5 x 10 coils.

Figure 4.6 Array of micro-electrodes for the stimulation of peripheral nerves

Micro-electrode arrays for the stimulation of the retina

The devices described above are planar electrode arrays; the use for stimulation is limited to the exact locality of the nerve(s). Certain applications, as for example retina implants or cortical stimulation (or recording) require the electrodes to be non-planar, at typical heights of between 300 µm and 10 mm. For these purposes, arrays of thin Pt-Ir (or pure Ir) wire electrodes with diameters of 50 µm and below are convenient, due to their good electrical properties and their relatively high biocompatibility. Microfabrication techniques can be used for the production of guiding structures that fix the distance between the electrodes and possibly allow for independent movement of separate electrode groups. This last point is essential for the implantation procedure, where the force required for the insertion of the array has to be minimized.

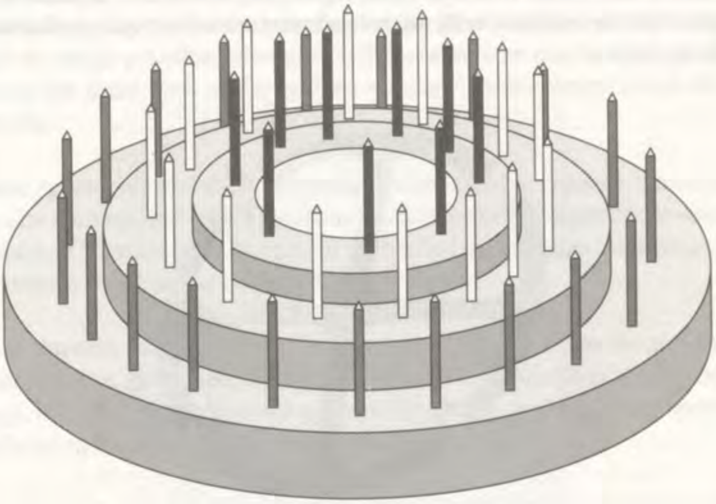


Figure 4.7 Proposed structure of movable concentric electrode arrays for a retina implant

One of the concepts for the implementation of a 2½-dimensional micro-electrode array for the retina is given in figure 4.7. Groups of electrodes are mounted on concentric, movable rings and can therefore be inserted with a relatively low force. The distances between the electrodes increase from the inside to the outside so that the largest stimulation density is at the centre of the array, where the sensitivity of the fovea centralis is highest. For a prototype of this array, electrodes with a thickness of 20 µm and a length of 300 µm at distances of between 50 µm and 100 µm are planned. As for all metallic stimulation electrodes, the wires have to be entirely insulated apart from the 10 µm long, rounded tip.

Electrode arrays using flexible hollow fibres and electrolytes

Multi-electrode arrays using hollow fibres and electrolytes can be used as an alternative to metallic electrodes. The functional principle is like that of glass pipettes, substituting the rigid glass wall for a flexible polymer material. Compared to metallic electrodes hollow fibre electrodes offer the advantages of a high biocompatibility, due to the lack of a direct interface between metal and neural tissue.

For medical applications, such as the removal of toxic substances from blood in an artificial kidney, hollow fibres are produced in a spinning process followed by a coagulation bath. The fibres have a typical diameter of between 50 µm and 200 µm, which is too large for recording electrodes and stimulation applications. Furthermore, the walls of these fibres have pore sizes in the submicron range, which is useful for the exchange of toxic substances. These pores lead to a reduced selectivity of the electrodes in multiple contacts between the electrolyte and the neural tissue, and to an increased concentration exchange in the electrolyte, if the non-physiological electrolytes are used for the transmission of the action potential.

Hollow fibre electrodes therefore require a modification of the production process used for the manufacture of hollow fibre separation membranes. Smaller diameters can in principle be produced with microfabricated extrusion tools similar to the one given in figure 4.8.

Figure 4.8 Spinneret plate for the production of hollow fibres. LIGA technique, Ni, diameter of 20µm

Producing hollow fibres with these extrusion tools will require parameters of the process such as the type of polymer and the coagulation bath to be optimized for the direct production of these microfibres.

Future developments of micro-electrodes

In the short term micro-electrode arrays will gradually appear on the scene. There is still however, a trade-off between biocompatibility, resistance and tip size. It will be impossible to have high biocompatibility, low resistance and small tip size in one array.

In the mid term tip sizes will gradually reduce. Promising concepts for high-density, small tip-size arrays however still lack biocompatibility. This is extremely important for large arrays since their primary use will be the substitution of human organs (retina stimulation) and lifelong implants.

In the long term we will solve the biocompatibility of high-density small tip-size electrode arrays. Means will be provided to transport the extremely high number of sensor signals. The microcoil array will enter the field; the energy conversion (electric to magnetic energy) problems of the coils will be solved by the availability of adequate micropower electronics. Focusing of the magnetic energy will also have to be achieved. As a result of the intrinsicly high biocompatibility of the microcoil array it can outrange the micro-electrode array in the very long term.

Sensors

Other applications of sensor systems are minimal invasive sensors for the determination of Intra-Cranial Pressure (ICP) which have been used for about a decade. Basically, ICP measurement is a tool to determine the extent of brain perfusion; a higher pressure may result in a lower perfusion. The pressure measurement can be taken with the combination of an extracorporeal pressure transducer and a fluid-filled catheter, or more recently with integrated pressure transducer systems. The latter could be based on the transduction of the physiological pressure signal by fibre-optic or piezo-resistive principles. ICP measurement can be taken at different locations in the brain such as the 'golden standard' measurement inside the brain ventricle [6].

One recent development is the combination of an invasive pressure transducer and a ventricular drainage catheter. This allows simultaneous drainage of the ventricular fluid and also ICP pressure measurement even when the drainage catheter is clogged [7], dimensions being in the 1-2 mm diameter range.

Perhaps in the near future, chemical parameters will be added to the physiological parameter pressure. For example, partial oxygen and carbon dioxide concentrations (p_{O2}, p_{CO2}). Minimal invasive sensor systems for pH, p_{O2} and p_{CO2} have been or will be introduced to the market soon, initially in cardiology.

In all cases, microsystem technology provides possibilities to improve the user friendliness (dimensions) of the systems, and may also create future opportunities to move towards integration of multiple functions on the devices.

4.2.3 ANAESTHESIOLOGY AND MICROSYSTEMS

Prof. R.M. Heethaar and M.W.C.M. Nieuwesteeg

The main purposes of anaesthesiology are to produce unconsciousness, analgesia, muscle paralysis, and autonomic depression to enable other medical, mainly surgical interventions. The drugs used to reach these primary effects however cause side effects, such as depression of functions in a majority of the organs of the body. The surgical procedure, although of ultimate benefit for the patient, may entail blood loss, interruption of normal physiological processes and stimulation of detrimental reflexes. All of these factors may occur when the patient's normal compensatory mechanisms are impaired. Furthermore, his ability to withstand stress may be limited by his age and general health, as well as by the particular circumstance of the surgical procedure that has been carried out. The anaesthetist should continually be aware of the effects of his actions on the physiological condition of the patient. Therefore careful monitoring of physiological parameters is crucial. If subtle physiological aberrations can be detected at an early stage, timely corrections can be made before there is any progression to obvious difficulties requiring heroic measures.

Anaesthesiology can benefit greatly from microsystem technology especially during the monitoring process. Heart rate and blood pressure were traditionally the two parameters monitored routinely by most anaesthetists. Currently many more parameters are accessible for monitoring the patient's condition.

ECG monitoring
The electrocardiogram (ECG) provides the anaesthetist with continuous information regarding heart rate and rhythm and myocardial oxygenation. It is sensitive to the effects of drugs like digitalis, presents clearly the difference between a systole and ventricular fibrillation and shows the presence of cardiac arrhythmias. For ECG recordings sufficient external electrode systems are available. However for intravascular or intracardiac recording of ECGs, improvements can be made in the catheters, especially if the electrodes are combined with other sensors, for pressure and chemical analysis of the blood. With the current status of technology new products in this area could be on the market within the next 2-5 years.

Pressure monitoring
Traditionally blood pressure referred to arterial pressure. However, there is an increasing interest in measuring the pressure in venous circulation which contains about 75% of the total amount of blood in the body and improvements in blood pressure monitoring can still be made. Possible applications are for intra-arterial, intravenous and non-invasive measurements. Ultra-thin sensors mounted on a catheter, or in a small needle will allow continuous, reliable and accurate measurements of intra-arterial or intravenous blood pressure. Although the sensors can already be produced sufficiently small, the integration into a catheter or small needle for long-term measurements still needs improvement. Special attention should be paid to the calibration of such devices. New products are expected to reach the market within 2-5 years.

Non-invasive continuous pressure measuring systems are increasingly used due to their simplicity and safety. These methods are mostly based on occluding (total or partial) a peripheral artery in an arm, a leg or a finger. This is achieved by an inflatable cuff and the detection of the responses of the cardiac contraction by recording pulsations using several physical methods, like optical, pressure and ultrasonic. Although some of these have already been on the market for many years, improvements are still to be expected in integrated data analysis modules with wireless transmission of the data to a further processing station. In this field of medical technology we expect that a continuous flow of new products will reach the market.

Ventilation monitoring

Most anaesthetic agents reduce the ventilatory effort of the patient and usually necessitate respiratory assistance. A reduction in minute volume occurs partially because of cerebral depression and partially because of muscle relaxants, which not only reduce the reaction of the skeletal muscles but also the respiratory muscles. To monitor ventilation separate pneumotachographic transducers are used, mostly based on the principle that gas flow is computed from pressure measured over a small but known resistance in the gas flow.

If no intrathoracic interventions are carried out impedance techniques may be explored. The electrical impedance of the thorax, which varies with the thoracic volume is an indirect method for assessing pulmonary ventilation. Bio-electric tomographic techniques [8] need further investigation with respect to their use in this area (see also section 4.2.6). As on-line continuous information is crucial fast solid-state processors need to be developed to achieve the extensive calculations required for the tomographic reconstructions. As many fundamental problems need to be solved first, easy-to-handle equipment will not be available within the next 5 years.

Flow monitoring

Although pressure is an essential parameter to monitor, acceptable perfusion of organs is not guaranteed by acceptable pressures. To be informed about perfusion of tissues, we must measure flow, especially cerebral blood flow as the brain is the key organ to protect against oxygen shortage. However electromagnetic flow probes can only be used if vessels can be reached by operation and their use is limited to vessels with cross sections above 0.5 mm. For smaller vessels ultrasonic devices may be applicable. Therefore new sensors for quick and easy quantitative blood flow measurements need to be developed. The use of ultrasonic devices, like Doppler catheter systems or transit time systems, is an expected area of growth in the near future [9]. Catheters with diameters of less than 1 mm may give vital information about the flow to the different organs. For obvious reasons non-invasive techniques are preferred. Laser Doppler devices may be of special interest for superficial flow monitoring processes if no direct contact with the patient is possible, for example in severe burns. Calibration devices for this technique still need to be developed and may reach its full clinical potential in the next 2-5 years.

On a long-term basis it is expected that MRI with surface coils will be developed

[10] and miniaturized so that routine flow measurements will become possible in the operating theatre.

Metabolism monitoring

Monitoring the metabolism of the different organs is possible by measuring the pressure of blood gases like p_{O2} and p_{CO2}, and assessing pH values of arterial and venous blood [11]. Sensors using other principles e.g. chemical or optical will be developed in the near future.

NMR spectroscopy [10] is expected to reach the stage that on-line applications in the operating theatre or intensive care units will become possible without using bulky and extensive equipment. A particular point of interest is the field of continuous blood analysis directly in or on the patient. Devices with which it becomes possible to temporarily extract minute amounts of blood from the circulation for direct analysis which is then released back into the patient, need further development.

Chronical pain treatment

In situations were patients have serious chronic pains, blocking of the impulse transmission along nerve fibres may well be the therapeutic intervention to choose. This can be by local treatment with drugs, heat or current. In a number of cases the nerve must be carefully located with a thin needle under continuous radioscopic control. Recording of nerve potentials may be a final indication of the right position. At this point the local treatment must take place by a small transducer that is located on the tip of the needle or by infusion of drugs (figure 4.9).

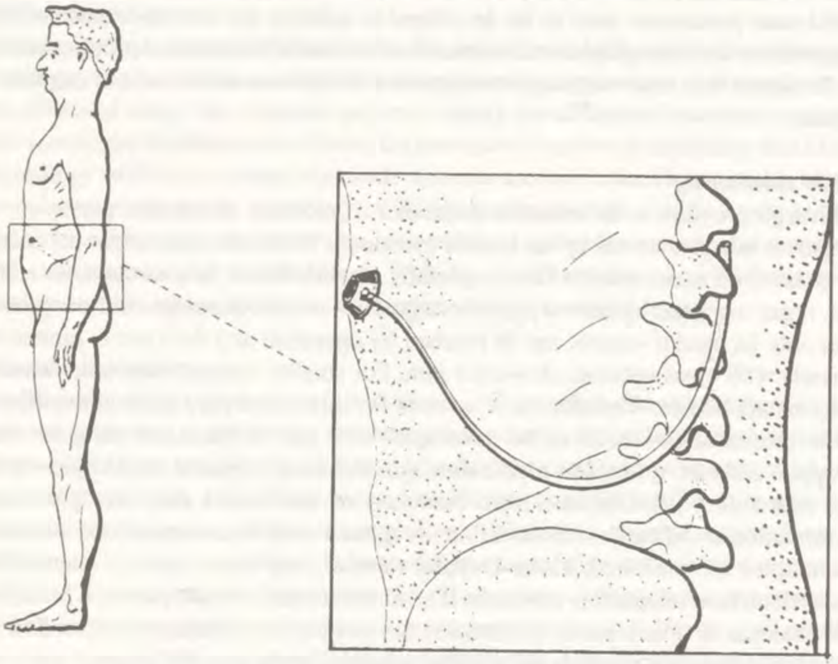


Figure 4.9 Artist's impression of a programmable, implanted drug delivery system with a catheter at lumbar level

The construction of such devices with sensing electrodes and therapeutic elements is expected to be an area of growth over the next 5 years.

It is obvious from the above that sensor technology in anaesthesiology is a crucial area of research with many interesting products still to be developed.

4.2.4 PAIN TREATMENT

W.A. van Duyl

Nonpsychiatric pain is a symptom of tissue damage which stimulates pain receptors passing activity to the central nervous system. This type of pain can be treated by drugs or by interruption of appropriate pathways. A small number of patients have neuropathic pain caused by neurological damage and are not susceptible to relief by narcotics or the interruption of pain pathways.

Continuous electrical stimulation over the hard membrane (dura) of the nervous bundle in the vertebral column in other words, epidural stimulation of the spinal cord, has proved an effective treatment for pain [12]. It is assumed that the success of this spinal cord stimulation is due to stimulation of the afferent thick A-nerve fibres which cause repression of the function of T-cells so that they no longer react to pain pulses arriving via the smaller fibres this is the so-called gate control theory of pain [13].

Constriction of blood vessels is known to occur in response to pain and may cause a localized lack of blood (ischaemia). It is thought that pain relief may release the constriction of the vessels and consequently improve local microcirculation. For this reason spinal cord stimulation is also applied as a therapy for ischaemia. So spinal cord stimulation is an alternative to a continuous infusion of drugs into the channel of the backbone (intradural).

Tremendous advances have been made in chronic intractable pain therapy in the last thirty years since the success of implantable heart pacemakers [14]. Implantable systems for spinal cord stimulation are widely available and deep brain stimulation offers a promising perspective. These techniques should be used only after conventional therapies have failed and patients have been psychologically screened for interventional pain management. However, financial constraints limit the application of these techniques, particularly for terminal patients who could be relieved of severe pain. Production of implantable integrated stimulators in larger series may reduce the price and lower the threshold for this application.

Possibilities for MST use in pain treatment by spinal cord stimulation and by continuous infusion of drugs into the vertebral column is related to the improvement in reliability, efficiency of stimuli, reduction of risks and inconvenience for patients and increase of capacity of batteries.

EPIDURAL STIMULATION

For treatment of the lower limbs under local anaesthesia a lead is introduced via a needle into the epidural space at the level of the vertebrae L 3-L 4 and is shifted upwards, guided by fluoroscopy, in the midline approximately at the level of the vertebra T 10 (figure 4.10).

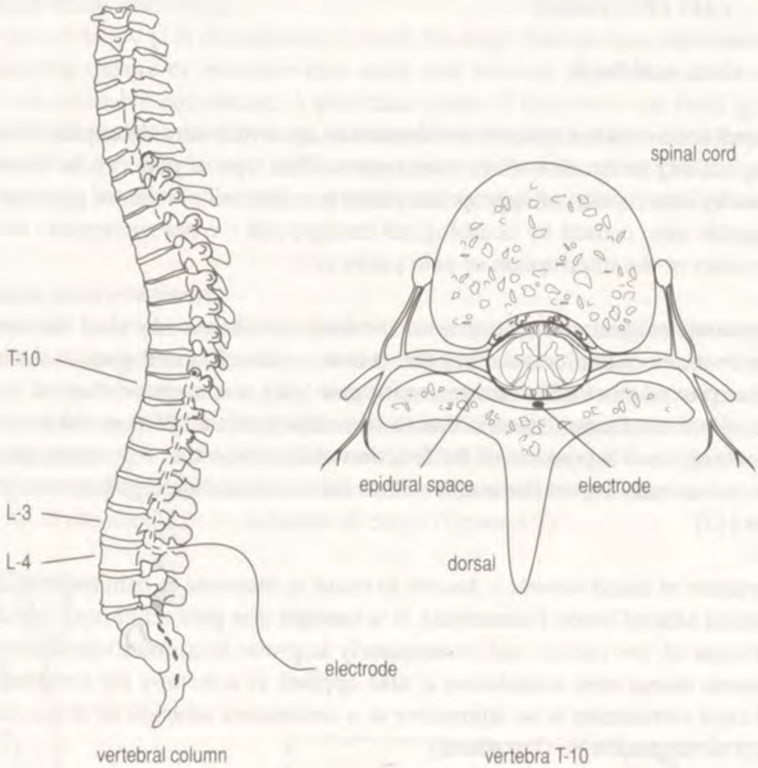


Figure 4.10 Epidural stimulation

For treatment of chronic pain in the thorax region and the upper limbs the same technique is used at thoracic or low cervical level. The higher the level the smaller the epidural space and the higher the risk of penetration of the dura. At one end the lead has one or more platinum iridium electrodes spaced to cover one or more vertebral segments. A displacement of the electrodes within 1 cm is tolerated. To test the effectiveness of stimulation the electrode is first connected to an external stimulator. Then the lead is fixed to prevent migration. An internal stimulator may be implanted in a pouch under the skin and under the ribs and connected to the epidural electrode via an extension lead under the skin. The pulse generator has a wide range of non-invasively programmable parameters and stimulation modes as well as a telemetric capability (pulse width 60-450 microsec), polarity (positive, negative or open), frequency (2-130 Hz) and amplitude (0-10 V), to be chosen by the patient on the base of subjective feelings of relief of pain. The system needs to be programmable to continuous or cyclic stimulation. In addition, the patient must be able to switch the stimulator on or off and switch to different modes (day-night). The system must be insensitive to the electromagnetic environment of a normal everyday life; for example, microwaves, household appliances and security systems.

Future developments

Placing of the electrodes by means of a long lead that is introduced at the level of the column where risk of damage to the dural sac is low, is clinically very attractive. A drawback of this technique is, however, that the position of the electrodes varies with the movements of the patient. This variation leads to a subsequent variation of the efficiency of the applied stimuli. However the patient can compensate for this effect by changing the amplitude. Some devices have a magnetically controllable switch to allow for the difference in stimulation needed by the patient in the standing, sitting or lying position.

In modern clinical practice risk of tissue damage is reduced so that the use of radiofrequency stimulators can be considered. These stimulators are locally implanted so that the lead can be avoided. With MST it is a challenge to make an integrated receiver and stimulator that can be placed in the epidural space. Because such a stimulator can be fixed closer to the nerve fibres than the electrodes, at the end of a lead, the efficiency of the applied stimulation energy is higher and no longer dependent on movements of the patient. Naturally the increase in efficiency of stimulation energy is relevant to the dimensions of the receiver. Increased efficiency of stimulation power also means an extension of the capacity of the batteries of an implanted transmitter.

INTRASPINAL INFUSION

The infusion catheter is placed in the epidural space in the same way the lead is placed in the technique for epidural stimulation. The catheter is connected to a programmable implanted infusion pump. This pump must be reliably programmable in order to feed a drug both continuously and intermittently from a reservoir to the catheter with a very small flow. Related problems concern the lifetime of the energy source and the size of the drug reservoir. Therefore simple facilities to recharge the battery and to refill the reservoir are important.

Future developments

As with the lead in the epidural stimulation it is better to avoid the long catheter in the intraspinal space. Ideally we would have a miniature pump that can be implanted at the location of drug application, combined with a receiver for control codes and energy and connected to a reservoir easy to refill located somewhere in the extraspinal space.

4.2.5 *OPHTHALMOLOGY*

H. Lehr

Introduction

Eyesight and the ability to recognize objects is one of the most important senses for human beings. Restoration of this sense either by an operation or by use of additional instruments such as spectacles has led to extensive development as well as intensive research. Consequently modern technologies have been introduced in eye surgery since the early Sixties by applying for example lasers for the coagulation of the retina. Other laser applications deal with cornea surgery utilizing an excimer laser. Sophisticated microscopes, specially developed for eye surgery are used, as well as minute instruments for performing for instance cataract surgery. But it should be emphasized that techniques or products based on microsystem technologies have been rather scarce in ophthalmology to date, although a number of treatments seem to be tailored for the application of microtechnical methods or the application of microproducts such as sensors, actuators and microsurgery instruments.

Sensor applications

A typical microproduct, a pressure sensor, may be used for the measurement of the intra-ocular pressure which up to now has been determined with applanation or impression methods. These methods unfortunately require the support from the patients which makes the measurement difficult to perform or even results in incorrect data. It is therefore an objective to develop a microsensor which could be implanted in the anterior chamber (figure 4.11) of the eye to measure the intra-ocular pressure without any contact. This could simply be done by making a microstructure which can sensitively change its shape in volume and length. The difference in shape might be observed either by the patient using a mirror, the relatives of the patient or an ophthalmologist via an optical instrument. Application of such sensors should be possible in the mid term.

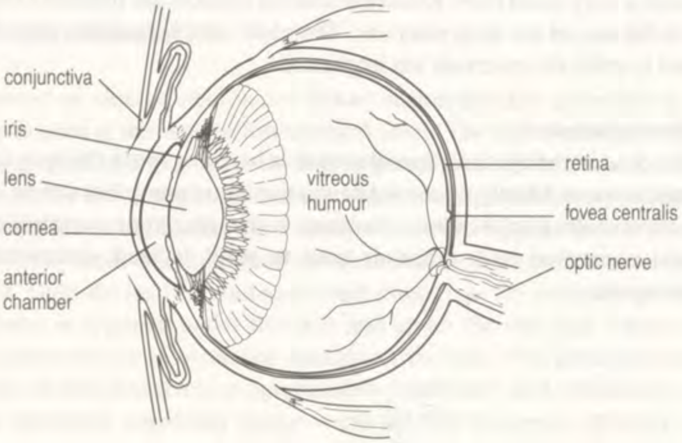


Figure 4.11 Eye cross-section

Actuator applications

The regulation and control of the intra-ocular pressure for instance after glaucoma procedures is another problem which could be solved with microtechnical methods. This could be achieved by a microvalve in a feedback loop similar to the systems which have been developed as part of micropumps. Such a valve could be implanted in the anterior chamber. Another simple method is the insertion of a flexible tube of less than 1 mm in diameter into the region of interest which makes it possible to control the pressure from outside the eye, again by utilizing a microvalve.

There is a number of cases where an active regulation and control of the intra-ocular pressure is needed rather than using a passive valve system. Possible applications are the infusion of drugs or the pumping of a liquid either to reduce the pressure in the eye or to suck a liquid from below the retina. In the majority of the cases the pump is not needed permanently.

In the case of permanent applications it would be desirable to localize the pump below the conjunctiva (figure 4.11) which requires a miniature system. Closing of such small pumps due to cells and proliferations will certainly be a problem in actual applications. Active systems are expected to be applicable on a long-term time scale.

Surgery

Cataract operations account for more than half of all eye operations in western countries. The surgical removal of the lens and its substitution with an artificial lens is the only effective treatment in these cases. The operation consists of removing a circular portion of the anterior capsule (only a few millimetre in diameter) by a multiple puncture and tearing technique. Part of the capsule is maintained and used for the fixation of the implanted lens. Due to this cutting technique the remaining capsule is ragged at the edges. A stretching of the remaining capsule necessary for the substitution of the lens, inevitably leads to tears when dealing with a ragged edge. As a consequence, a good fixation of the artificial lens is rather difficult. This may be avoided by removing the circular part of the capsule in such a way that a smooth edge to the hole results. Unfortunately it is obvious that this is almost impossible to achieve by hand.

An improvement of this operation technique will be obtained by using a proper tool for microsurgery. This could be for example a very flat electromagnetic micromotor with a small rotating knife fixed directly to the rotor. The motor should be very thin for pushing below the cornea into the anterior chamber just in front of the capsule. Once in its proper position an actuation or rotation of the knife cuts a smooth hole into the capsule, an important prerequisite for the success of this operation [15].

It is obvious that such an application requires torques which are rather unusual for true micromotors (typically 10^{-10}-10^{-12} Nm). There are now electromagnetic motors in development which are extremely flat, typically less than 1 mm, and which have diameters of several millimetres. Therefore a knife which is directly applied to the rotor could be used [5]. The torque of such a micromotor depends sensitively on its diameter and could result in 10^{-5}-10^{-6} Nm at diameters of 4-5 mm. Although the total size of the motor is far from having micrometre dimensions, parts of it like the stator or rotor require a very high precision of manufacture which might only be possible by applying MST. An instrument of this type should be available on a mid-term time scale.

4.2.6 CARDIOLOGY

4.2.6.1 HEART AND CIRCULATION AND MICROSYSTEMS

Prof. R.M. Heethaar and M.W.C.M. Nieuwesteeg

In the western world diseases of the heart and blood vessels, especially atherosclerosis, claim the largest number of lives of all diseases. Atherosclerosis points to processes which lead to reduction of elasticity and thickening of the vessel walls. This leads to the reduction of perfusion of the tissues distal to the affected sites or eventually even to total occlusion of vessels with disastrous effects to the tissues originally perfused. In the field of heart and circulation microsystems play an important role and individual areas of application can be clearly distinguished. The most important are:

- estimation of cardiac mechanics and pump function of the heart;
- determination of the electrical properties of the specialized conduction system and impulse propagation over the heart;
- temporary cardiac assist devices;
- artificial heart stimulation, defibrillation and anti-tachycardia pacing;
- imaging techniques of heart and vessels;
- measuring techniques for blood flow and tissue perfusion;
- chemical analysis of blood e.g. metabolites to monitor infarct development;
- *in vivo* metabolic analysis;
- *in vivo* tissue characterization;
- revascularization techniques.

Cardiac mechanics and pump function of the heart

To validate the contraction and pump function of the heart, cardiac output, left ventricular and aortic pressures are global parameters providing useful information. Regional information, especially important in areas affected by myocardial infarction or ischaemia, is obtained by analysis of regional contraction patterns of the heart [16, 17]. Solid-state miniature transducers have improved intracardiac and intraventricular pressure measurement recordings above the standard catheter manometer systems with their disturbing resonance characteristics.

Regional contraction analysis can be achieved by bio-electric impedance measurements via catheters inserted into the ventricular cavity (figure 4.12). The accuracy of this method is still under debate as the current injected into the ventricle does not only pass through the blood but also through parallel resistances like the ventricular myocardium and surrounding thoracic tissues. Further improvement of this technique is required which is feasible within several years.

With MRI tagging techniques, tags can be placed non-invasively into the ventricular muscle wall and followed through one cardiac cycle. From the displacements of the tags during the cardiac cycle a reconstruction can be made of the three-dimensional shape changes of the heart. Combined with pressure measurements and finite element techniques estimations about regional cardiac performance can be obtained. It is to be expected that these MRI tagging techniques will be improved tremendously and finally may reach the stage where through miniaturizing of the equipment measurements can be made during catheterization or in the intensive care unit.

Electrical processes in the heart

An ingenious network of excitable nerve fibres conducts the electrical excitation waves over the heart and causes the four chambers to contract synchronously [16]. Normally the impulse originates in the SA node. The AV node and bundle of His are essential components in this network as they are normally the only electrical conducting fibres between atria and ventricles. If the AV nodal transmission is impaired or blocked due to disfunctioning of cells, the atrial and ventricular contractions are no longer synchronized and ventricular rate becomes too slow to maintain acceptable life. Also if the sinus node does not continue to generate electrical impulses any more, usually another centre starts the impulse formation but with an overly low frequency. In this case implantation of a pacemaker is the therapy to choose. It is expected that microsystem technology will reach the stage where the pacemaker can be constructed so minutely that it can be inserted or screwed into the ventricular myocardium by catheter techniques. No pacemaker leads are needed as the unit is mounted directly into the ventricular wall (figure 4.12).

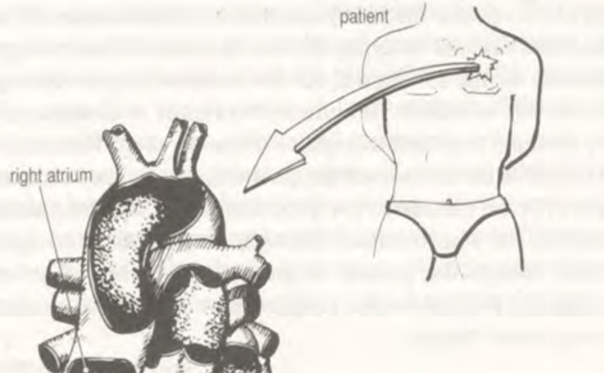


Figure 4.12 Frontal view of the heart. An impedance catheter is inserted into the right ventricle to measure chamber volume. Pressure sensors simultaneously measure right atrial and right ventricular pressure. In the inset an artist's impression of an implantable plug-in pacemaker is shown

A plug-in unit is advantageous because in the case of failure the electric circuitry can be removed. The great advantage of such a device is its lack of a pacing catheter. External programming to block the response in case of malfunctioning may be an essential feature. The pacing device should also be equipped with some features which allow storage of patient data such as heart rate or other information for a period of, for example, 24 hours with the possibility of retrieving this data via remote sensing and control devices. Solid state technology needs to be expanded in order to develop small components with large internal memories for these purposes. With the current state of technology such devices can be developed within 2-5 years.

Ectopic electrical foci in the heart may be the cause of atrial or ventricular rhythm disturbances or arrhythmias. To localize these foci catheterization is used. If the heart is under control of such a focus the site of the earliest response is the site of the ectopic focus. To localize and remove such a focus ECG recording catheters are required which can be positioned against the atrial or ventricular endocardium at any desired position. At the site of the ectopic focus ablation of the focus restores the electrical stability of the heart. The construction of such catheters is still an area of ongoing research. Within five years new devices may reach the clinical theatre.

Implantable devices to terminate life-threatening tachycardias or ventricular fibrillation by delivering well-timed electrical shocks to the heart are already on the market, but many improvements are to be expected in the coming five years.

Cardiovascular imaging

Imaging techniques play an important role to assess the function of the heart and the condition of the vessels. MRI [10] and ultrasound techniques [9] are under strong development. Intravascular imaging devices, based on echo or Doppler techniques are also currently being developed. At the moment single rotating crystals on a catheter are already available. Within 5-10 years it is anticipated that complete phased-array systems may find their place in the tip of a 3 French (1 mm diameter) catheter. To facilitate the analysis of the enormous amount of data and to reduce the number of wires in the catheter, a pre-processor in the tip of the catheter may make the data suitable for transmission, through a small flexible optical fibre to a processing unit outside the patient. If knowledge of the reflective properties of affected tissues and atherosclerotic plagues increases, tissue characterization may take place to optimize therapy.

Bio-electrical impedance tomography [8] is another field of increasing interest. Currently most techniques apply electrodes at the thorax of the patient to induce and record the currents through the body. This method is however also perfectly suited for application on catheters so that imaging of ventricular cavities and arterial or venous lumina becomes possible. As the different tissues of the body have different (frequency dependent) impedances for electrical current a multiple-frequency device may allow tissue characterization. Optimal therapy in the case of vascular stenosis may be chosen within 5-10 years on the basis of the tomographic results obtained.

Transoesophical imaging may also be an area of growing interest. With the usual sector-scanning devices, cross-sectional images of the heart can be obtained only if a sufficiently large window for transmission of ultrasound waves is present. Often the lungs form a barrier to complete three dimensional imaging of the heart. In contrast, transoesophical imaging does not encounter these problems. If suitable transducers become available complete three-dimensional reconstruction of the beating heart will come within reach. In addition valve functioning can be analyzed more thoroughly with this imaging technique. Transducers are already on the market to record one single cross section of the heart. Complete three-dimensional imaging of the heart is expected to be on the market within 5-10 years.

Blood flow and tissue perfusion

To sustain life, sufficient nutrients must be transported by the blood to the organs. To measure the blood flow quantitatively various systems are available based on a variety of physical principles. Invasive measurements include electromagnetic, thermodilution, ultrasonic Doppler, hot-wire anemometric and transit-time ultrasound systems. These devices are usually intended to be used mostly instantaneously in the operation theatre or intensive care unit. Implantation for chronic (animal) studies is also possible. Miniaturization of the probes and signal processing units is still a field of ongoing research and new systems are to be anticipated on the market in the next 5-10 years.

Of the non-invasive techniques of measuring blood flow ultrasound Doppler is the most widely used technique [11]. To reach the deeper vessels in the body focusing of the ultrasonic beam is essential which requires special transducers with focusing elements. As in principle only frequency shifts are measured, one needs information with respect to the vessel diameter to calculate volume flow. This cross sectional information can also be obtained with ultrasound imaging techniques. If multigated techniques are applied information about the blood flow profile and more accurate calculations of volume flow can be obtained. Improvement of the transducers over the years to come will make this ultrasound technique even more widely used. Another non-invasive technique which is gaining increasing interest, is blood flow and tissue perfusion measurement with NMR techniques [10]. New excitation pulse sequences and detection techniques make this technology one of the most promising for the near future. We can foresee in the next decade the equipment becoming much smaller and surface coils being used to retrieve the data from the patient.

Chemical analysis of the blood

Also in the field of cardiovascular diseases monitoring of blood gases, pH and chemical substances is of importance especially during cardiac surgery and in the intensive care unit [11, 18]. Progression of an infarcted area can be monitored by the release of enzymes in the blood. Taking blood samples and analyzing them in a specialized laboratory is a time-consuming process which only gives information at the time of the samples taken. Consequently a method which would provide data continuously and would use only very small amounts of blood is to be preferred. Therefore new devices should be developed which can be placed in or on the patient and which contain all the sensors needed for any chemical analysis required and with which the samples can be released into the patient after analysis. By a remote-sensing control unit the data can then be accessed by the clinician. Although many sensor techniques have just arrived on the market, much improvement is needed to construct such an *in vivo* 'laboratory' with telemetric data transmission. We can anticipate a long-term research and manufacturing endeavour.

Monitoring metabolic processes

Study of metabolic processes gives vital information about the condition of the organs under study. With respect to the heart, information about phosphate metabolism reveals much about the metabolism in infarcted areas. The technique which looks most promising in this field is NMR spectroscopy [10]. Currently NMR studies require a special facility with extensive and expensive equipment. Within 5-10 years miniaturization may well lead to applications in the operation theatre or catheterization laboratory.

Revascularization techniques

As previously mentioned one of the biggest problems in the cardiovascular field is atherosclerosis of the vessel wall of the great arteries. A reduced cross section of such an artery may lead to a reduced blood flow to the tissues supplied. Sustained insufficient blood flow may lead to irreversible damage to the tissues such as infarcted areas. To eliminate obstructions in the vascular lumen small devices on catheters or miniature 'submarine-like devices' released into the circulation and externally guided by strong magnetic fields may be the solution. For catheter techniques diverse solutions can be considered (figure 4.13) for example:

- an expanding device at the tip of a transducer like a balloon (already in wide-spread clinical use), that compresses the obstruction into the vessel wall;
- a surgical device at the tip that removes the material, like small rotating and cutting devices;
- devices that use the interaction of radiation and tissue like spark erosion or laser evaporation of tissue. If knowledge of radiation interaction with tissue increases this field is expected to grow fast.

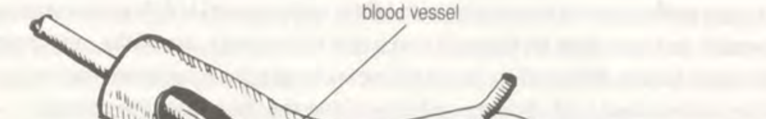


Figure 4.13 Tissue characterization and lumen measurement combined with a lumen restoration device on a catheter

Ambulatory monitoring

Monitoring the patient during his daily activities instead of during hospitalization found its origin in the activities of Holter (USA), who was one of the pioneers in recording ambulatory ECG tracings. Nowadays many more parameters can be monitored. This area of research is expected to expand in the near future. Currently the data is stored on magnetic tape. It is extremely likely that the storage capacity of solid-state components will increase so that the monitored and digitized data can be stored directly (or compressed) into solid-state memory. Then the monitoring device should include a 1-4 channel AD conversion unit, a signal analysis and datacompression unit, a solid-state memory and an internal timing device which is set by the currently transmitted time codes. With remote programming units the information can be retrieved and sent by modem to specialist laboratories for analysis. We can even envisage on-line automatic analysis which sets off an alarm if the monitored parameter exceeds the selected safety margins or when for instance extra-systoles or a tachycardia starts so that fast therapeutic action can be undertaken.

Vascular compliance

Vascular compliance is another important parameter which may inform us about the condition of the arteries or veins [19]. Presently, there are no direct systems available to measure vascular compliance. A catheter with pressure sensors and with for instance a piezo-electric element which can control the volume by electrical sinusoidal currents would make these measurements possible and open complete new areas of research. Such a catheter inserted into the left or right ventricular cavity of the heart, would give vital information about the stiffness of the ventricular myocardium during the complete cardiac cycle. This may possibly lead to a better understanding of cardiac mechanics. Such a project could be underway within 2-5 years.

Artificial valves

Checking the functioning of artificial valves in the patient may be of importance in predicting malfunctions due to tissue overgrowth or mechanical problems with the device. When the valve opens and closes sound waves are generated and propagated through the thorax. It is possible that characteristics of these sound waves, like the frequency spectrum could be analyzed immediately after implantation and stored in the memory of a sensor which could be placed on the thorax any time after implantation. If this device senses abnormalities it would warn the patient, who should then have the implanted device checked more thoroughly at the hospital. Such a project will be feasible within 2-5 years.

As discussed, many studies in the field of cardiovascular diseases need sensors to retrieve essential information from the patient. Microsystem technology is an interesting field of research that may lead finally to numerous new devices.

4.2.6.2 CATHETER SYSTEMS AND CARDIOLOGY

H. Lehr and Prof. R.M. Heethaar

Introduction

In order to avoid the high risk and acute complications occurring in heart surgery a fair number of minimal invasive techniques for both diagnostics and therapy have been developed over the last two decades. These methods rely heavily on the use of appropriate catheter systems which are small enough in diameter to be inserted into coronary arteries, that is, smaller than 2 mm. Due to the ongoing demand for imaging and interventional methods for utilization in vessels with even smaller cross sections it has become obvious that miniaturization and functional improvement of such catheter systems can only be obtained by the application of MST.

Catheter systems for diagnostics

Intravascular ultrasound is one of the prerequisites for the differentiation of coronary syndromes. It is superior to angiography for evaluating morphology and function of coronary arteries. This has been illustrated in a comparison of several post mortem studies with results obtained beforehand by angiography, where significant discrepancies appeared. The insufficient result of this study may be understood as a result of the reduced information given by angiography, presenting only a contour of the coronary vessels. Applying intravascular ultrasound, a cross-section of the vessel and its walls may be obtained, allowing for very early diagnostics of coronary diseases, which cannot otherwise be achieved by X-ray methods [20].

The current diameter of catheter systems is in the range of 1.1-1.5 mm with the aim of further miniaturization. Its main elements are concentrated in the catheter tip, which typically consists of a rotating mirror to deflect the ultrasound from a transducer, for example PZT ceramics, by 45 degrees (figure 4.14). Typical ultrasound frequencies range from 20-40 Mhz, depending on the resolution and depth of imaging required. The transducer is used as a signal transmitter and receiver to form two-dimensional images of the vessel's volume and walls. Thus we can determine the location and the geometry of an obstruction.

One of the main drawbacks of current systems is the use of a shaft which runs through the long catheter tube to drive the mirror, from outside the human body. Directional changes of the tube, which are necessary to steer the catheter to the desired position, lead to friction of the turning shaft with the guiding tube. This inevitably influences the angular velocity, in such a way that phase lags appear between the tip angle and the driving generator angle at certain angular positions. Real time scanning is therefore difficult to achieve in some cases.

Microfabrication techniques could be used to drive the mirror locally by for instance a high-pressure gas driven microturbine in order to obtain real time imaging (figure 4.14, top) or an electromagnetically driven micromotor (figure 4.14, middle). A refinement of such a system is the application of a mirror with a concave shape, thereby giving a higher resolution in the focal plane in depth of the wall tissue. Moving of the focal plane may possibly be obtained by driving the mirror back and forth so that a three-dimensional image could be registered (figure 4.14, bottom). It is expected that such systems could become available in the mid term.

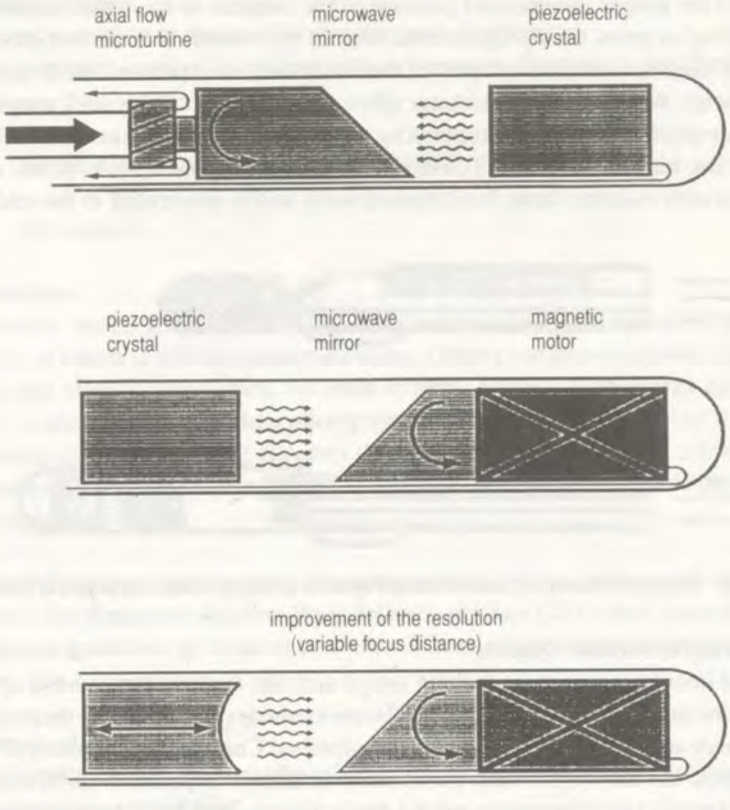


Figure 4.14 Schematic drawing of catheter tips with internal mirror drive (micromotor, microturbine, top and centre). The focus depth could be changed by moving the transducer with a concave surface back and forth (bottom)

Another difficulty found in current catheter systems is the relatively stiff tip which prevents effective steering when pushing the catheter to the desired position in the human body. Present actuator techniques allow for the construction of movable tips which could be used to steer the system by bending a small part in the head of the catheter. Mechanisms to be applied are for example shape memory alloys, whereas other developments aim for the use of hydraulic or pneumatic systems. Position control of catheter systems, presently carried out by X-ray imaging techniques, could be avoided a great deal by using steerable catheters, thereby reducing possible radiation effects to the patient. The implementation of such a system will be obtained in the short term.

To determine the nature of local lesions or obstructions appearing in coronary arteries, clinically we require the analysis of the material forming the plaque or narrow part in the vessel. A safe extraction of tissue from the required position will only be possible by close observation of the location and taking the necessary action.

This may be achieved with systems which are schematically shown in figure 4.15. The upper illustration shows a catheter tip which may be pushed to the required longitudinal position, controlled by use of signals given by a fixed transducer at the front. At the proper longitudinal position of the catheter in the vessel, a balloon is pumped up to press the tip against the wall of the vessel. A knife is then closed, possibly pneumatically, to cut part of the tissue, which is pressed inside a hole of the catheter. Removal of the catheter allows the analysis of this wall material. A more complicated system incorporating a micromotor M presents a two-dimensional view for position control of the cutting device (figure 4.15, bottom). Again, such a system requires some development work and is anticipated in the mid term.

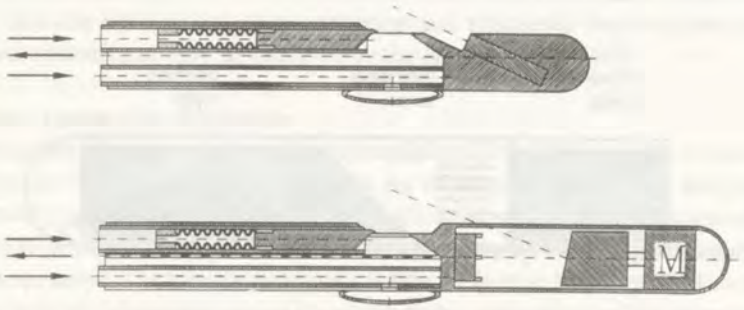


Figure 4.15 Schematic drawing of possible catheter systems for taking intraluminal probes of tissue

Therapeutical catheter systems

Minimal invasive techniques making use of catheter systems have useful applications in coronary therapy. Among the different methods of overcoming the occlusion of coronary arteries, the Percutaneous Transluminal Coronary Angioplasty (PTCA) has become the most renowned. However, a fundamental problem of PTCA is the high restenosis rate (depending on the basic disease 20-50 %) due to artery wall disruptions following stenosis dilatation by use of a balloon [20]. Therefore, new techniques have been developed which aim for a mechanical recanalization of coronary lesions. The success of these methods depends on the availability of:

- a local drive system to rotate balls, burrs or cutting devices, instead of using a rotating shaft from the outside;
- a flexible steering system for the catheter tip;
- imaging techniques to visualize the ablation process and its localization.

Currently, another application to avoid restenosis is the implantation of coronary stents. But here too, intravascular ultrasound is needed for the control of the appropriate position of the stents.

Conclusion

It is obvious that movement towards smaller systems, as well as a combination of diagnostic and therapeutical techniques for applying several therapeutical methods with the insertion of, for example an individual catheter system, depend heavily on the development of appropriate microsystems. Typical dimensions of these systems, for instance an electromagnetic motor, are in the millimetre range. The manufacture of the main components will only be possible through the utilization of MST.

An analysis of coronary artery diagnostics and therapy as presently applied indicates the need for intensified activities in the following areas:

- rotating actuators with high torque and small diameter;
- cutting devices;
- 'smart' materials or systems for the steering of catheters;
- imaging techniques to be applied both in coronary diagnostics and therapy.

4.2.7 *DRUG TREATMENT AND IMPLANTABLE INSTRUMENTS*

W. Sansen

Introduction

Implantable instruments have mainly been realized for vital functions, the best example of which is still the heart pacemaker. Other examples are insulin injection pumps and bladder stimulators. All such systems consist of an energy source by battery or transcutaneous link, a microprocessor for system control, input sensors and actuators to carry out the required therapy. Usually, telemetry is utilized both for monitoring purposes and in order to be able to modify the therapeutic parameters after implantation.

Implantable instruments for drug treatment consist of the same system modules. However, the actuators are now drug-delivery devices [21] which have to inject appropriate quantities of drugs at predefined times and provide calibration for the sensors.

Future developments

If implantable instruments could perform both the injection and the calibration we could envisage systems for:

- injection of drugs to regulate the heart functions;
- injection of insulin on the basis of data obtained from a glucose sensor;
- an artificial pancreas;
- delivery of heparin to prevent clotting during haemodialysis;
- control of depth of anaesthesia.

However, there are major technical difficulties to be overcome before these systems can be put into practice. The existing technical thresholds are as follows:

- Lack of a model of the physiological feedback system. It is very difficult to identify the parameters of a model if the feedback loop is closed, as is the case in our human physiological system. Model development is therefore an important task in every system in which the reaction of the system is predicted by the injection of an external disturbing quantity of drugs [21].
- Lack of knowledge on how to close the loop with an adaptive, and possibly fuzzy, control system. Once the model of the system is known, the parameters of the drug injection (stimulation) can be predicted and continuously adjusted.
- Availability of micropumps to dose the quantities of drugs accurately. The injection of minute quantities of drugs can be carried out by means of syringe pumps, micropumps, etc. [22]. Their main characteristics are their size and the

accuracy of the quantities delivered. Recent technologies such as micromachining and silicon wafer bonding allow the production of such micropumps including flow measurement and electronic control (figure 4.16). A specific problem is the method of introduction of fluid into an implantable micropump; percutaneous injection is only one possibility.

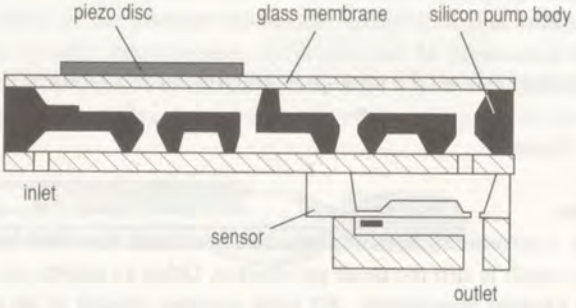


Figure 4.16 Schematic representation of encapsulated flow sensor and pump [22]

- Implementation of biosensors. The most important sensors are those for measurement of glucose, ureum, oxygen, pH, potassium and calcium. Although the ISFETs were the first with this capability, more voltametric and conductometric sensors are used nowadays [22]. These can be attained by means of IC technologies to reduce size and cost. In addition interface circuitry can be included yielding smart sensors. An example of a glucose sensor of this sort is shown in figure 4.17. It includes temperature compensation and can fit into a F6 catheter (diameter of 2 mm).

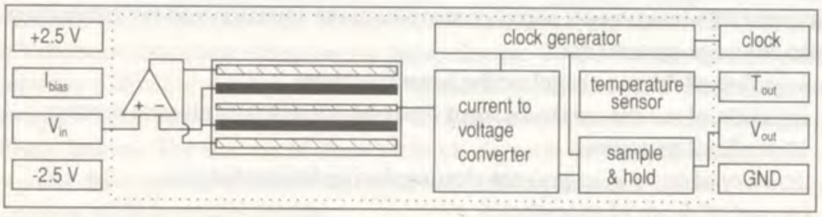


Figure 4.17 Block diagram of a smart voltametric sensor for glucose and oxygen sensing [23]

- Drift and calibration data of the physical sensors and biosensors used; sensors have shown very slow improvement over the last decade. Calibration is still necessary in addition to temperature compensation, etc. Micropumps also allow for inclusion of calibration steps before the actual measurement cycles.
- Signal processing of the input sensor data; sensors are never sufficiently accurate and selective to base drug delivery on. All available sensor data must be used in order to extract the relevant information.
- Reliability of signal processing software; because of the vital character of drug injections, the signal processing software must comply with software reliability standards.
- Shortage of battery power; the choice between batteries or transcutaneous links determines several technical parameters as well as social acceptance.

- Biocompatibility of sensors, micropump and packaging. All materials which are in contact with human tissue must not interact with it. This is especially true for sensors and the micropump. Therefore coatings have to be used which guarantee biocompatibility for at least limited periods of time.

In conclusion, it can be stated that drug-delivery systems are making strong demands on new technologies. On the other hand their use is imminent; they are essential for preserving important aspects of our quality of life.

4.2.8 INTERNAL MEDICINE

R.M.E.M. van Heijster

In the case of internal medicine, the focus is on applications of microsystem technology in hyperthermia. There is currently a huge interest in hyperthermia. In the Netherlands three university hospitals are involved in researching this area (Amsterdam AMC, AZ Utrecht and AZ Rotterdam).

One of the applications for hyperthermia is in cancer treatment. This application is still in an experimental stage, however first results look promising. Hyperthermia is the technique of heating certain parts of the body by RF energy; the frequency used is 70 Mhz. These body parts (the hot spot) will rise in temperature to 42 °C or above which causes the tissue to die. The great advantages of this technique are the absence of side effects and the low cost, both compared to such conventional techniques as chemotherapy and radiation.

The energy is supplied by a number of antennas, a so-called phased array. By the mechanism of constructive and destructive addition the majority of the RF energy is released at the hot spot. The hot spot can be moved by phase and amplitude control of the antennas in the array. Sensors are used to measure the RF field energy, which is proportional to the dissipated heat [24]. The resulting temperature is also measured by microthermo-couples. The antenna arrangement of the phased array, as used by the Academic Medical Centre of the University of Amsterdam, is given in figure 4.18.

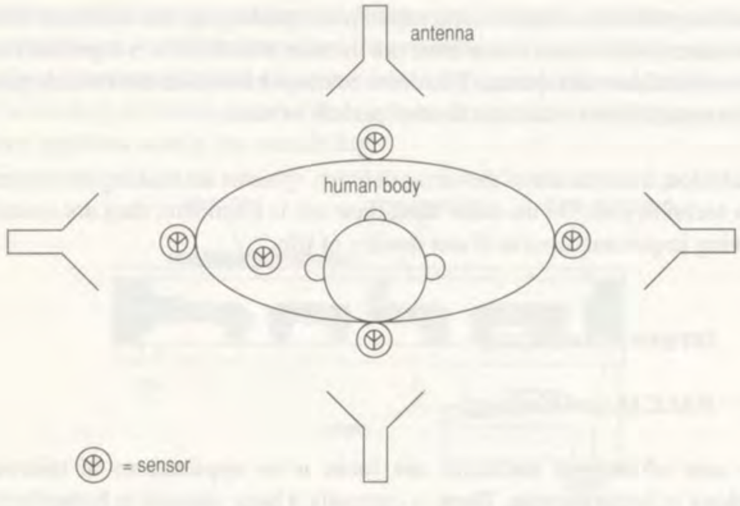


Figure 4.18 Antenna arrangement. The patient is lying with the antennas arranged around the lower part of his body

Sensor technology

The sensor is an extremely complicated piece of equipment which has a diameter of 2 mm to facilitate the use of all of the body's natural openings. Ideally the sensor has to be able to measure the RF field in amplitude, phase and direction. For defining the position, the distance to a given reference point is required, as well as the direction with respect to a given reference. Some sensors are placed on the outside of the body to measure the transmitted input power, others are placed inside the body, preferably in natural openings.

The sensor has to function with the following stringent requirements:
- the field strength is extremely high;
- the measurement takes place in optically dense materials;
- it must be able to withstand aggressive liquids;
- it should not contain metallic conductors, as these disturb the RF field distribution and heat will be dissipated internally.

The sensor microsystem will consist of the following subsystems:
- A sensor antenna structure.
- Sensor and position electronics.
- An umbilical cord that can serve as a guide to energy and communication which can be omitted when wireless communication and an internal energy supply are used. The umbilical cord however does not contain metallic wires.
- Communication electronics. Measurement data must be sent to the outside world either by wireless communication or by the umbilical cord. Reference data must be sent to the sensor system the same way.
- Power supply, for example internal supply such as a battery or external energy like a light source.
- Housing. The housing of the sensor has to protect against the high RF field

strength and the aggressive environment. It also has to support the antenna and accommodate the umbilical cord.

At the moment sensors are available that vary in diameter from 2 to 5 mm. Natural openings can be entered by sensors that have diameters of 2 mm and sensors of up to 5 mm can be used on a limited number of them. A diameter of 2 mm is also a practical upper limit for common artificial openings.

Presently, most sensors can only measure the amplitude of the RF field in one direction [25]. Developments have led to prototypes that measure amplitude and phase of the electric field, like the one shown in figure 4.19, which consists of a small dipole antenna that picks up the electric field component. The antenna voltage is combined with a reference signal of almost identical frequency, yielding a low frequency product. In order not to disturb the field the reference signal is sent towards the sensor by means of an optical fibre. The transport of the output signal is performed by a pair of high-impedance carbon fibres. This device does not require any additional electrical power. Application of the sensor in the context of Electro-Magnetic Compatibility (EMC) is a possible spin-off.

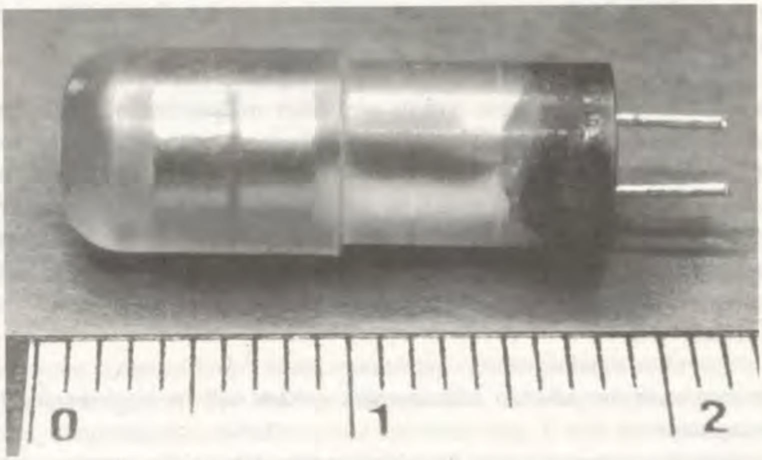


Figure 4.19 A sensor, capable of measuring both amplitude and phase of a RF field. The sensor is 5 mm in diameter and 18 mm long

Present sensors lack position measuring capabilities, and consequently X-ray and other techniques are used to obtain position information.

Thermal stimulation

Thermal stimulation requires the application of sufficient RF energy to an afflicted part of the human body to obtain a temperature of 42 °C or above. However, the surrounding healthy tissue should receive as little energy as possible.

Focusing or guiding the RF energy may meet these requirements. In the first case, the phased array requires relatively large and clumsy antenna systems in conjunction with huge support structures [26]. Future developments will definitely lead towards smaller antenna structures. In the second case, the RF energy is guided into the cancer tissue by waveguide or coaxed and released by a small antenna. Small antennas are required that can preferably gain access to the body via natural openings. To locate the antenna, it can be connected to micromanipulation equipment. But a major drawback of this method is the fact that its application is limited to an area within the same size as the antenna itself.

The success of hyperthermia depends entirely on the accuracy of positioning the hot spot. Computer models are available that can predict the hot spot inside the human body which are based on the information (amplitude, phase and bearing) of a limited number of sensors [27]. It is possible to use a computer program to adjust the amplitude and phase of the various antenna elements in the array to position the hot spot.

Future developments

In the short term, sensors will be available that measure amplitude, phase and direction. The antennas for thermal stimulation will be equipped with a field sensor indicating the RF field strength immediately in front of the antenna. This allows for adequate feedback, and hence a better definition of the hot spot. Programs to compute the RF field distribution based on the information of a limited number of sensors will become available.

In the mid term the main focus will be on further miniaturization of the present sensor and the umbilical cord. This will not only increase the applicability of the sensor, it will also create room for the position measurement system. The definition of the hot spot can be increased greatly by the application of more antenna elements [28]. The antenna and RF power generator can be combined to achieve a unit that is relatively small and that can operate independently. In the mid term computer programs will be developed that use the measured field distribution to control the beam focus.

In the long term the position measurement system will be implemented in the following steps.

- Additional antennas have to be added to the system; the antennas for field strength measurement and for position measurement must not influence each other.
- The energy supply has to be increased; for external supply via optical fibres in the umbilical cord high-efficiency solar cells are necessary.
- Communication bit rates must be increased to allow for the position data to be transmitted.
- A miniaturized positioning system must be developed.

A sensor that meets all the prerequisites for measurement of both RF field strength and position will need to use electro-optic integrated circuits. These circuits are presently under development. Prototype ICs that have lasers, photodetectors and solar cells integrated on the silicon chip will soon be available.

The use of a sensor able to measure amplitude, phase and direction is not yet in common practice; up till now only prototypes have been available. Although computer programs are in existence to evaluate data acquired with these sensors, it is not yet possible to state the real value of the data acquired.

Conclusions

The success of hyperthermia is largely dependent on the accuracy of the hot spot and therefore on:

- the accuracy of the sensors;
- the accuracy of the computer program that calculates the RF field;
- the number of antenna elements.

Future sensor developments largely determine the number of natural body openings that can be equipped with sensors. Furthermore, the number of sensors will greatly influence the accuracy of the computer program to calculate the RF field. Therefore, this will make the sensor the key item in future hyperthermia systems. Future developments in microsystem technology will be an important factor in the success of hyperthermia.

4.3 A CLOSED-LOOP PATIENT MONITORING SYSTEM

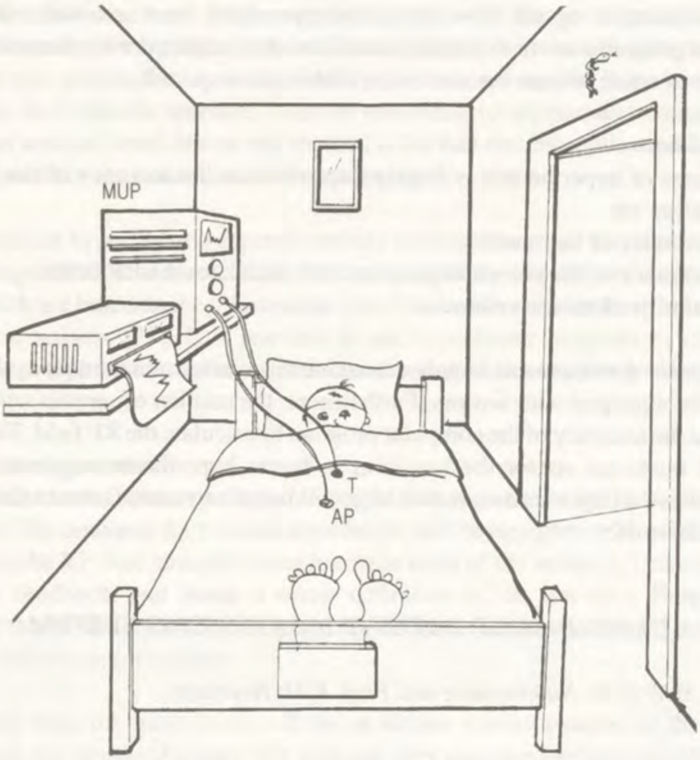
M.W.C.M. Nieuwesteeg and Prof. R.M. Heethaar

4.3.1 INTRODUCTION

To assess the feasibility of MST-based systems for medical use a closed-loop patient monitoring system has been selected and will be analyzed in some detail, particular attention being given to the manufacturability of its constituent parts.

The example, a closed-loop patient monitoring system includes an invasive transducer to be introduced into the bloodstream. The transducer will measure blood pressure, temperature, conductance and chemical data. It will work in association with an actuator – a micropump for accurate delivery of minute quantities of drugs into the bloodstream. Sensors and actuator are connected to an exterior datalogger and microprocessor which receives the sensed data and governs drug delivery by the micropump (figure 4.20).

The invasive transducer will be a future development of the tool presently used for invasive pressure measurement. This tool, which looks similar to the catheters used routinely, is called a microtransducer catheter.



T = invasive transducer
MUP = portable datalogger/microprocessor
AP = invasive actuator pump

Figure 4.20 Schematic outline of the closed-loop patient monitoring system

4.3.2 DESCRIPTION OF THE SYSTEM

The basic points to be considered in determining manufacturability are:

- costs, in relation to the number of systems to be produced;
- reliability;
- process control – will statistical process control be sufficient?
- logistics and traceability of the individual components.

The invasive transducer can measure temperature, pressure, conductance, pH, p_{O2}, p_{CO2}, lactate, NO, glucose, flow or any other interesting physiological parameter. The outer dimensions are limited to 1 mm, and are preferably less than 0.5 mm. The principle applied is based on microsystem technology in the form of an analogue transducer cell possibly combined with an AD converter. To illustrate the potential even further, three existing examples can be considered:

1. a miniaturized invasive pressure transducer used in 1 mm diameter Micro-Transducer Catheter (MTC®)[1], as introduced onto the market recently;

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[1] MTC is a registered trademark of Dräger Medical Electronics.

2. a miniaturized semi-invasive Laser Doppler Interferometry-based blood velocity transducer (prototype developed recently at Twente University);
3. a miniaturized pH, p_{O2} and p_{CO2} invasive blood gas transducer recently introduced by Pfizer Biosystems.

The electronic support system (MUP) includes a portable data logger and microprocessor. In addition, it contains a memory cell and a current source to drive the actuator pump. The MUP can regulate the pump speed and thereby the injection rate of a pharmaceutical agent. In the more immediate future the MUP will be a unit situated outside the body (figure 4.20). In the long run it might become a microsystem to be implanted for a longer period perhaps more than one month, into the human body, for example underneath the skin. This set-up would require batteries with a high specific energy content, a processor, a pump and a transducer with low power consumption. Application examples of the MUP are as follows:
- haemodynamic pressure regulating agents in anaesthesiology (see transducer example 1);
- antithrombogenic agents in cardiology (see transducer example 2);
- heart-lung equipment control via continuous bloodgas analysis (see transducer example 3);
- 'painkilling' agents (manually operated) in oncology;
- insulin for diabetics.

The invasive actuator pump can introduce microvolumes of pharmaceutical agents into the bloodstream. An example of this is the MST-based silicon micropump as introduced recently by MIT. The micropump performance is governed by the MUP but can be controlled partially by programs than are self-adaptive or that can be 'downloaded' from a central monitoring system. The position of the micropump is flexible and is determined by the specific application like that of the microtransducer.

Connections between the system components are made with medical tubing, for instance application-specific catheter-like materials, which are biocompatible, flexible, insertable, visible in X-ray or Magnetic Resonance Imaging techniques, etc. The catheter-like tubing, including the wiring needed for the signal transmission has recently become available under the name of 'signal transmission catheters'.

4.3.3 QUANTITATIVE ASPECTS

In table 4.1 relative values of the manufacturing related parameters are given. For the MUP, a price and production numbers are also mentioned. Obviously this is only an approximation.

	initial costs (IC)	*production costs per piece (PC)*	*production series in pieces/year (PS)*
T	10	0.01	100
Ctmup	0.5	0.05	10
MUP	1	1	1
Cmupap	0.5	0.05	10
AP	10	0.01	100
MUP absolute	ECU 100.000	ECU 100	1000

T	invasive transducer
Ctmup	catheter-like tubing and wiring of transducer
MUP	portable datalogger and microprocessor
Cmupap	catheter-like tubing and wiring of pump
AP	invasive actuator pump

Table 4.1 Costs of the closed-loop patient monitoring system

4.4 SIGNIFICANCE OF MST FOR MEDICAL TECHNOLOGY

Task Force Medical Technology

The subject of this section is the perspective of MST in medical technology. The discussion is limited to the economic and social benefits of MST. The required infrastructure and education are discussed in Chapter 8.

Economic aspects

Microsystem technologies draw their strength from the application of present-day technology to systems with limited complexity, in combination with very specialized new etching and deposition techniques for the creation of microstructures. Two kinds of companies are, therefore, active in MST development. Firstly, large corporations with extensive know-how in silicon technology development and large-scale micro-electronics manufacturers. However, they are hesitant to enter the medical market because of its relatively low volume and complex market structure. Secondly, SMEs are interested, especially in exploiting the medical potential of usually one specific technology. Many SMEs do not have the complementary technologies or market positions to build and market complete systems. Therefore, the advent of relatively simple self-control, home-care or bedside equipment is creating a wealth of opportunities.

The economic expectations for MST have been listed in a recent publication [29]. This report anticipates a central role for (micro)electronics in future products of telecommunication, computers, consumer electronics, multimedia and industrial electronics. Medical instrumentation is expected to provide a considerable market, however, this trend is comparable to those areas previously mentioned. Biocompatibility and legislative aspects also have to be added. Examples of medical microsystem technology include (miniaturized) transducers for pressure, temperature, pH, p_{O2}, p_{CO2}, other chemical substances and the devices for (invasive) ultrasound or micromanipulation.

For basic breakthroughs the medical applications depend in most cases on the research executed in the context of other industrial areas. Subsequently, considerable value can be added in the process of making these basic findings to fulfil medical needs. The requirements to do so are outlined below.

In order to create considerable economic activity, both kinds of companies have to see ways of profitable cooperation. In many other cases, small start-up companies are 'swallowed' by large corporations after reaching their first success. In this respect, medical microsystem technology is no different from DNA-recombinant or computer software technology. In other cases, universities or research institutes can play an important role. These institutes are big enough to cope with a large amount of technologies and have a sufficient time horizon to bring basic technologies to a point where an SME can start product development. It is interesting to note that the cutbacks, particularly in the US defence industry may lead to an innovative wave in medical technology as the researchers there are fiercely looking for other applications for their military technological know-how. Cooperation between SMEs, large corporations and research institutes must therefore be more heavily promoted. It is also important to continue market evaluation to detect needs at an early stage.

Social benefits of MST for health care

Social benefits of MST in the context of medical technology can be identified by using the definition of 'health' as a starting point. The Dutch Commission *Keuzen in de Zorg* defines health in relation to the normal functioning of a person in society [30]. The World Health Organization (WHO) makes use of another definition, which however also clearly addresses not only 'technological', but also psychological and social aspects. The WHO states that health is a state of physical, social and mental well-being, in other words, not only the absence of illness.

In the Netherlands, the government is obliged to ensure access to and quality of health care (article 22 of the Constitution). Microsystem technology in general and medical technology in particular can only provide social benefits if they enable better health care in the above-mentioned situation. This implies that both citizens and patients have to perceive the fruits of the technology as an improvement and are willing to pay for it via their insurance companies. In the Netherlands, where privatization is not so far developed as for example in Germany or the USA, the government also plays an important role, because access to all has to be guaranteed to a reasonable extent.

A rough indication of the trends in society is given by the following statements

- 'Health is increasingly observed as a right that can be secured.'
- 'Technology is increasingly seen as an important factor in preserving or regaining health.'
- 'Society is increasingly individualised.'

- 'Life expectancy is increasing thus the percentage of elderly people in society is increasing.'

The medical significance of MST can only be outlined by carefully defining scenarios based on medical and technological developments. At this moment the medical significance of pressure transducers, endoscopes, intravascular ultrasound etc. is already considerable. The impact of MST is difficult to predict exactly. However, one can expect the main impact in medical care to follow current trends:

- For diagnostic purposes in neurology and neurosurgery, the trend is towards non-invasive, fast methods, possibly with multiple purposes to prevent a flood of investigations of the patient.
- For treatment the trend is towards effectiveness and elimination of risks, in combination with a sort of 'quality assessment and assurance' system.
- For monitoring, the trend is towards cost-effectiveness and accuracy. In addition, the amount of (new) parameters used to monitor a patient will become subject to discussion. The monitoring of even the standard physiological pressure can still be improved drastically by means of microsystem technology, and new parameters like lactate or nitrogen-oxide level also show great potential.
- For rehabilitation the trend is towards the development of technologies that may assist individuals to improve their level of functioning. In particular this creates a demand for flexible and reliable human-machine interfaces. Microsystem technology can play an important role in miniaturization and flexibility.

It is up to the policy makers, the health care 'consumers' and their insurance companies to determine the fate of the many options that will be created in the coming years by means of MST. With respect to this, it is worthwhile noticing, that 'technology assessment' might play an interesting role here. A short survey of these activities, however, has shown us that emphasis to date has been placed on the assessment of 'mature' technologies, preferably by comparison with two well-defined alternatives (for example the comparison PTA versus stents or X-ray versus Magnetic Resonance Imaging [31]). Obviously, it is difficult to study a technology in its earlier stages, because we do not know beforehand, whether the technology chosen will later be used at all. Predicting the future is not an easy job. Nevertheless, by picking a broadly defined technology, like microsystem technology, we can be more certain that a future medical application will originate. In fact, the MUST project is a pioneer in this field. A follow-up of this work by professional technology assessment groups might be worth considering however.

4.5 RECOMMENDATIONS

Task Force Medical Technology

Need for coordination centres

To stimulate MST, coordination centres should be established to identify niche markets and form industrial groups around them. These centres cannot have a manufacturing role themselves, in order not to distort the coordination.

The Dutch and Belgian governments could stimulate the use of MST by directed market stimulation and by taking the initiative for a coordination centre, for example through the dedicated ministries. This would involve imposing requirements on new purchases in terms of size, power consumption and reliability, etc. supported by MST. Not only would the quality of health care be improved, but MST-based innovations stimulated.

Clear definitions should be used by all parties

For development of a microsystem, the following requirements should be fulfilled:

- there should be a need for the microsystem;
- the microsystem must be feasible;
- the microsystem has to be produced at reasonable affordable costs;
- the profit produced by the use of the microsystem has to outweigh production and development costs;
- clear definitions should be used by all parties involved, for:
  - clinical research;
  - feasibility study;
  - product development.

To fulfil these requirements, all four parties should be involved:

- *Hospital*. Doctors should formulate the need for treatment systems focusing on the medical benefits and the social relevance of the system. The hospital should also perform the clinical evaluation.
- *Development institute*. Development engineers should focus on technical feasibility and cost effectiveness.
- *Industry*. Industry should focus on the production aspects of the system, providing information on production costs in relation to production quantity.
- *Financing institute*. The financing institute is preferably the institute that profits from the reduced health care costs by the use of the microsystem introduced. This institute should focus on return of investment, the financial plan and the market plan.

Health care must be involved at an early stage

For a successful follow-up of MST in health care it is necessary to involve the 'Medical Technology Assessment' discipline to take into account the specific (both stimulating and inhibiting) conditions of health care at an early stage of technological development.

Required support

Support is needed for specific technologies in industries in cooperation with universities considered to be of strategic importance.

These strategic microsystem technologies should be identified and the developments supported by subsidies aimed at lowering the barriers to MST use. This can be attained by programmes similar to 'Mitoe' for microelectronics (by subsidising the first MST application in any company). This subsidy would allow industry to involve institutes of knowledge and suitable suppliers more easily. The result would be that the markets created could be harvested by industry on the basis of presently available know-how.

As the present-day economy needs swift return on investment, developments should focus on:

- near and mid-term development;
- the use of micro-components that are available from other developments (military, consumer, communication) and avoid the use and development of expensive micro-components;
- systems that significantly decrease the costs of national health care. Ideally a plan should include a financial paragraph on this subject. The possibility of involving health care insurance companies in development, in return for lower costs of health care, should also be investigated.

Education is necessary

MST concerns a high-tech aspect of medical technology; clinicians are not trained to consider the possibilities of MST. On the other hand, engineers are not trained to consider clinical needs. Therefore, it is recommended that we organize a specialized course to bridge this gap.

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5. Microsystems and consumer products

5.1 APPROACH AND FOCUS

5.1.1 INTRODUCTION

G.C. Klein Lebbink

Consumer products offer many opportunities for the application of MicroSystem Technology (MST). Whereas in past decades high technology would be developed for professional fields, either aerospace or the military, there would be a gradual spin off to the consumer level, but nowadays it is often the consumer market that takes the lead and, by virtue of its large production runs, is an attractive place to develop new technologies. High-definition television is a case in point; digital recording of sound and pictures is another. But also microsystems may find the consumer world a favourable place for developments. Many interesting applications can be envisaged, and large-scale production is the answer to high initial costs. Microsystems, measuring a few hundred microns, will not be stand-alone items, but part of end-user products.

The definition used in this chapter for a consumer product is comprehensive and includes all applications that finally end up in consumer products. This means that parts or subsystems for which MST is essential are all covered in this chapter.

It is anticipated that microsystems will become modules or essential parts of consumer articles because of the ongoing trend for increasingly small-scale products. This trend is caused by user demand for portable systems (entertainment, communications, assistance etc.) with low energy consumption, and for systems that incorporate several functions within the same volume (watches, electronic diaries, etc.). The micro-electronics race with all its associated products is a good example. Huge amounts of money are spent to keep up with competing industries in the race for submicron circuitry. Section 5.1.5 describes the trends in data storage devices. As these elements are essential for many consumer products, miniaturization of these elements is both a condition and an example of the tendency to reduce dimensions.

Environmental considerations open up a new market. Producers are urged to miniaturize their products in order to use less material and reduce power consumption. People might wish to carry small portable monitors that give warnings against air and water pollution. In an ageing society, personal health monitors might also find widespread use.

Sections 5.2 and 5.3 give examples of MST applications in consumer products. Section 5.2 is limited to a general description of ideas, while section 5.3 treats two cases of MST in consumer products in more detail. The first is a personal safety monitoring system, the second a personal health monitoring system. Both are meant to be carried permanently by the user. Common to both cases is that one can think of several generations of products. A simple not fully developed product could evolve into a whole series of products. The examples mentioned should be considered as ideas typical for a technology and for a field of application. By no means all the proposals mentioned should be taken as directly applicable to a new product in the short term. The ideas presented serve as a trigger for other, possibly more practical, ideas. Particularly in the field of consumer products new applications of a long-known technology may suddenly come to life. The recent enormous growth of stand alone games equipment and software is a typical example of this characteristic of the consumer market. Other areas of the market behave in a more predictable way, such as the data storage functions mentioned in section 5.1.5 or products that are dependent on major standardization either nationally or internationally, e.g. for communications. The conclusion is that the success of consumer applications of a technology depend more on good marketing than applications in professional markets like medical technology and industry.

5.1.2 MOTIVES FOR MICROSYSTEM TECHNOLOGY

G.C. Klein Lebbink

The motives for using microsystem technology in consumer products are clustered into five main groups. The motives are roughly similar to those for instrumentation: portability, in-situ operations and function integration. Two additional groups are identified for consumer products.

Constraints

This motive concerns such aspects as dimensions, comfort, weight and 'invisibility' of a device. Although there is some overlap in portability and function integration, this motive is specific to consumer products. For security applications it is often essential that they go un-noticed, which may also be an advantage in personal care applications. Consider, for example, a hearing-aid, where 'invisibility' is certainly appreciated by the wearer.

Competition

As previously stated, competition in itself may be a motive for reducing the size of products. For example, competition, not dimensional or weight constraints, is the main reason for smaller systems in security applications such as smoke detectors. Furthermore, the reduction of direct costs is the main reason to anticipate applications of MST in the automotive field.

5.1.3 APPROACH

G.C. Klein Lebbink

To date, there have only been a few commercial applications of MST in consumer products. Particularly looking at the applications where sensors, actuators and intelligence are integrated in (sub)systems there are hardly any successful examples of such applications. If we look into new possibilities we have to keep in mind the characteristics specific to MST. In the ideas listed in sections 5.2 and 5.3 the criteria taken into account are:

- Necessity of micromechanics. It is considered essential that applications of MST should be at least for some element dependent on the micromachining technologies listed in Chapter 2.
- Incorporation of sensors and actuators. The use of sensors and actuators for a wide range of parameters is a typical characteristic of MST.
- Incorporation of intelligence. It is fairly likely that any complete application will need intelligence for control and interfacing.
- Integration in (sub)systems. This criterion expresses to what extent a proposed application is completely stand alone or part of a system or infrastructure.
- Economic feasibility. It is essential that an opinion is available on the probability of economic success.
- Urgency or need of application. This is actually a measure of market opportunities.
- Expected spin-off. A possible application becomes more valuable if it yields other products, services etc.
- Suitability for mass production. This is essential for consumer applications where a product has to be made at a low cost.

In order to demonstrate the possibilities of MST in consumer products a few characteristic applications are mentioned. Two categories have been identified. Firstly, section 5.2 briefly lists ideas that have a relatively low score from the above criteria. The ideas described are:

- automotive applications;
- very small camcorder;
- maintenance and repair;
- autofocus eye glasses or contact lenses;
- microrobot household cleaner;
- personal communicator.

Secondly, products which have a rather high score for the above mentioned criteria are included in section 5.3. Described are:

- a personal safety device;
- a personal health analyzer.

5.1.4 *CONSUMER MARKETS*

G.C. Klein Lebbink

Applications of MST in consumer products are considered possible in the six areas. indicated in figure 5.1.

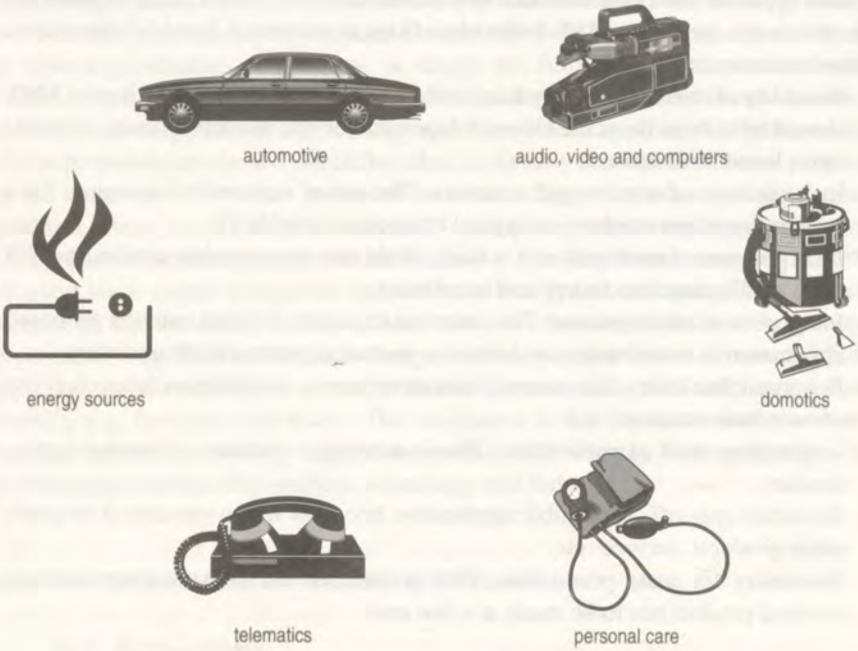


Figure 5.1 Expected consumer markets

Automotive

This area covers applications in cars and by suppliers of subsystems to the automotive industry. For example, suspension in cars (smart shock absorbers), sophisticated car guidance systems, crash sensors and Anti Blocking Systems (ABS). This area is subdivided into:

- navigation and guidance;
- motor management;
- safety and maintenance;
- comfort and entertainment.

Navigation and anti-collision systems are expected to see only a few applications of MST, because the dimensions are not very critical in cars. Nevertheless, as previously mentioned an additional motive for small dimensions may well be competition and the associated reduced costs of smaller systems.

For combustion, the amount of fuel in one stroke of the piston is very small and the dosage of additives in the fuel requires very accurate microdosage systems. This could lead to cleaner exhaust gases and optimized combustion.

Audio, video and computers

In the area of sound, visual display and computers, microelectronics plays an important role. As there are moving parts in all three groups (CD players, cassettes, disks) this area seems a promising field for applications of MST. A possible development is expected for micromechanical screens. The idea being that micromechanical mirrors in such screens function as pixels. The advantage is that such systems are influenced less by low temperatures (in contrast to LCD screens in cars). Other possibilities are repair or controlling functions.

Household applications (domotics)

This area covers all applications in the home but also applications like intelligent buildings or even intelligent districts. (Demands for the professional market like climate control in offices or schools are not covered here. They are described in section 3.2.6.3). Applications for domotics are grouped as follows:

- safety;
- maintenance;
- food and kitchen;
- climate and environment;
- entertainment and leisure.

Personal care

Personal care covers an area closely related to safety and medical applications. The boundary between the medical field and the consumer market is indistinct for such applications, but if these systems can be bought without a medical prescription and used without the help of a doctor they are considered to be consumer products. Safety applications are limited to applications directly associated with the human body.

Telematics

Telematics consists of the integration of informatics and telecommunication. A good example of telematics is a digital telephone board which can relay conversations, but can also process information. Optical sensors and optical switches are important micro-elements in this area. Switches could be incorporated in telephones, faxes, computers, etc. The connection between microelectronics and optical fibres is another related topic (Chapter 3).

Most of the ideas for telematics in consumer products, such as wristwatch applications or calculator-size devices can be divided into banking, faxing, computing etc.

Energy sources

Energy sources with dimensions of less than a millimetre will not be introduced to the market for direct use by consumers. However, energy is a vital element for microsystems as they can only function with a sufficient supply of energy. A detailed discussion of small energy sources and their developments to date can be found in Chapter 2.

5.1.5 AN EXAMPLE OF MINIATURIZATION IN CONSUMER PRODUCTS: HIGH DENSITY MAGNETIC RECORDING

J.C. Lodder

This section was added for a special reason: although high density magnetic recording originated in the professional sector, it is now essential for many of the newer consumer applications such as digital sound recording, camcorders etc. This example is also illustrative of a group of products relatively predictable in their development. The trends in density combined with reduction in size and cost has followed a distinct pattern [1-10]. Further development will certainly be a growth area for the application of MST.

Although only a small fraction of all available information is stored on magnetic and optical storage media, the information storage industry is presently a $ 50 billion industry in the USA (1993). Magnetic recording technology is continuing to evolve at a rapid pace resulting in longer playing times and more data being stored in ever decreasing volumes. It spans: audio, video and data storage applications in the form of tapes, floppy and harddisks in products such as digital video recorders, digital camera-recorders, audio equipment, electronic games, video telephones, fax machines and personal organizers. Magnetic recording technology has an excellent future growth potential. Market requirements include continued reduction in peripheral device size and power consumption while maintaining an exponential increase in capacity with time. In this section only a very few types of magnetic recording are briefly discussed as an example of the trend toward miniaturization.

DENSITY VERSUS TIME

In figure 5.2 the areal density (linear density multiplied by track density) in bits/mm^2 is shown as a function of time for commercial products. The trends are given for magnetic tape (audio as well as video) and magnetic harddisk (computer and pc). Two results of laboratory demo's are also presented.

In the future, a further increase of density can be expected by the continued development of the magneto-resistance head and perpendicular magnetic contact recording. Further development of the magneto-optic recording technology will also give higher densities. In figure 5.3 the most important technological factors responsible for the development of higher areal densities are given.

Here influences of the various dimensions for track pitch, bit-cell length, head gap, medium thickness and head-disk spacing are given. It is clear that all aspects are moving into the area of (sub)micron technology.

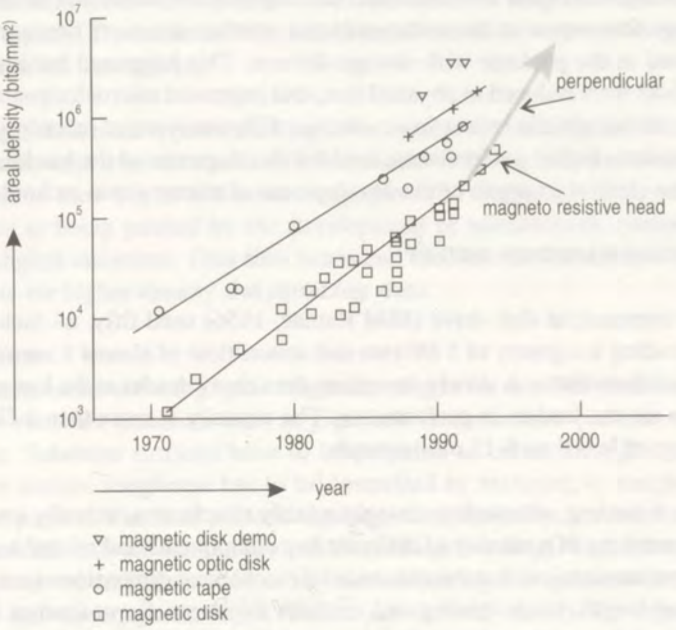


Figure 5.2 Areal recording densities

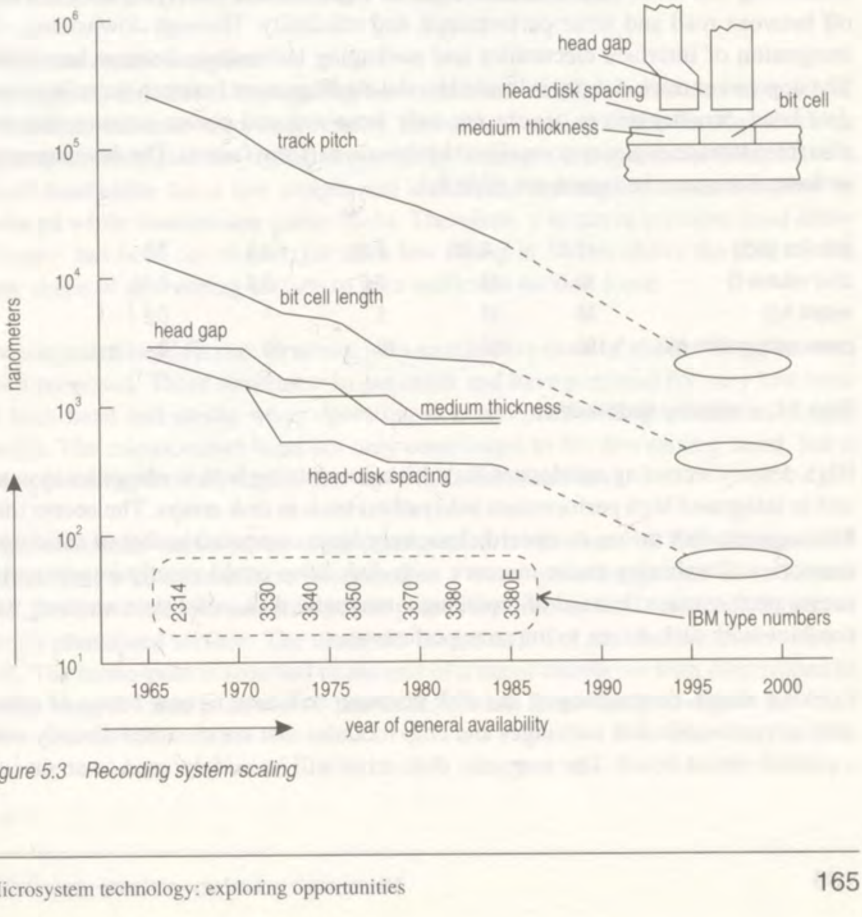


Figure 5.3 Recording system scaling

The past forty years have seen the birth, development and evolution of data storage technology. One aspect of these changes is the number of control functions that can be included in the package with storage devices. This happened because devices such as disks were reduced in physical size, and improved microelectronics became available. Although it is interesting to discuss different types of recording and their development to higher performance, here the development of the harddisk drive is used as the clearest example of the development of microsystem technology.

DOWNSIZING HARDDISK DRIVES

The first commercial disk drive (IBM Ramac, 1956) used fifty, 24 inch diameter disks providing a capacity of 5 Mbytes and access time of almost 1 second. Today, the 2.5 inch form factor is slowly becoming the volume leader at the low end, while 3.5 drives are the leaders in performance. The capacity is more than 1 Gbyte with access time of less than 6-11 milliseconds.

Magnetic recording, although seemingly a fairly simple area, actually involves the complex meshing of a number of different key components and related techniques. Most improvements involve the reduction of mechanical dimensions such as flying height, gap length, track spacing and medium thickness. Several other important technological innovations have also been made in the history of magnetic disk drives. Head and medium technology, signal processing and precision mechatronics such as spindle motor and head positioner have been improved. Head to medium interfacing has always been hard to control. Reduction of the flying height trades off between read and write performance and reliability. Through downsizing, the integration of interface electronics and packaging technology became inevitable. The uppermost track density is limited by the misalignment between servo head and data head. Smaller drives benefit not only from reduced power consumption but also from storage capacity normalized by drive size (form factor). The developments in downsizing can be seen from table 5.1.

disk size (inch)	10.5	8.25	5.25	3.5	2.5
drive volume (l)	30	12	2.5	0.6	0.12
weight (kg)	36	17	5	1	0.2
power consumption (W)	180	100	40	10	2

Table 5.1 Downsizing harddisk drives

High density recording accelerates disk drive downsizing both in computer systems and in integrated high performance subsystems such as disk arrays. The access time for magnetic disk drives is, nevertheless, very large compared to that of solid state memories. Combining cache memory with disk drive could greatly improve disk access performance. Instead of replacing a magnetic disk, solid state memory will combine with disk drives to improve performance.

Looking ahead, downsizing of the disk diameter will lead to new forms of drive, such as removable disk cartridges and chip modules that are mounted directly onto a printed circuit board. The magnetic disk drive will be widely used as an on line file in information network systems. The dimensions of magnetic disk drives are shrinking rapidly. The common 5.25 inch disk drive is being superseded by 3.5, 2.5, 1.8 and even 1.3 inch drives.

According to disk trend reports, the long-term trend is towards smaller drives which will gradually take over the market [6]. Shipments of 2.5 inch drives are increasing rapidly due to their use in notebook computers. The technology for even smaller disk drives is being pushed by the development of subnotebook computers and personal digital assistants. Thin film heads and medium are the components most responsible for higher density and shrinking sizes.

Disk medium

Disk manufacturers are using sputtering technologies for thin film medium production. New substrate materials such as glass and ceramics now promise to replace aluminum. Substrate surfaces have to be prepared to create the right properties. Firstly the surface roughness has to be controlled by texturing to roughen it in a controlled pattern. The final surface topology should then be smooth but not too smooth in order to avoid stiction (a kind of molecular bonding). To develop the right microstructure of the magnetic layer an intermediate layer is sputtered between the substrate and the magnetic layer. This layer is used mainly for adjusting the coercivity. The magnetic layer consists of Co-Cr-X (where X stands for Pt, Ni, Ta etc). Finally, an overcoat layer has to be deposited, consisting of mostly carbon. This layer has to be thin, hard, dense and as diamond-like as possible. Additionally, a thin fluorocarbon lubricant is applied to reduce disk friction.

Head and media interface

In magnetic disk drives the spacing between head and disk is reduced as much as possible to increase recording density. Contact recording is the final goal which various technologies are trying to reach. For example using a microslider head: a small head slider has a low weight and inertia; the loading force can therefore be reduced while maintaining stable flight. Therefore, a negative pressure head slider 'Guppy' has been developed, for ultra low flying at 50 nm above the disk with a new shape of air-bearing surface to give sufficient suction force.

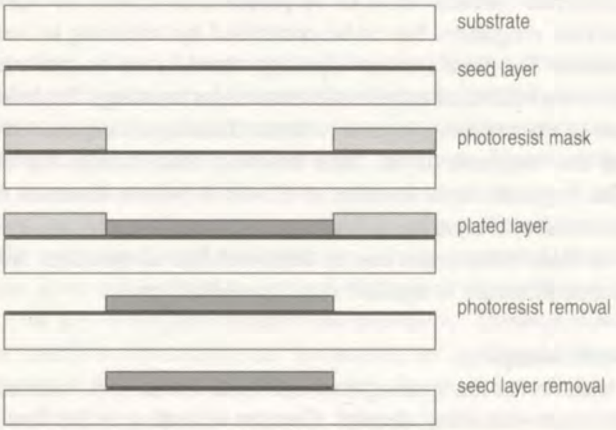
An integrated head flexure structure with an effective mass of about 300 μg has also been proposed. These structures do not crash and have potential for very low wear of both head and media when operating in continuous sliding contact with rigid media. The microcontact head not only contributes to the downsizing trend, but is also promising for very high linear and high track densities.

Fujitsu recently achieved an areal density of 3.1 Mbit/mm^2 (4700 bits/mm, 670 tracks/mm) with an inductive head used as a mono-pole design that has a 33 turn coil, ferrite return yoke and a magnetic pole of amorphous CoZr which is deposited over a planarized surface. The headpole thickness is 0.4 μm and the track width 1 μm. The mono-pole is attached to the end of a metal cantilever with dimensions of 8 mm long, 0.4 mm wide and 40 μm thick, contact force being 50 mg.

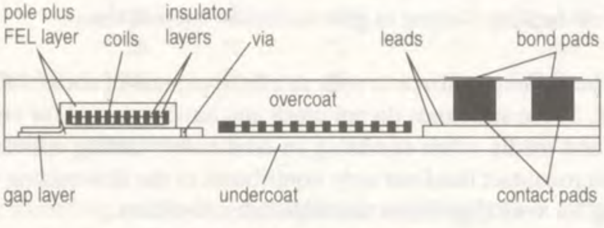
THIN FILM HEADS

Thin film heads hold the future for many reasons. For instance, the ferrite head technology supposedly reached its limits with respect to machining processes and high frequency magnetic characteristics: although the newer developed metal-iron-garnet head offers performances similar to thin film heads.

Smaller disk diameters give lower linear velocities and as a result a weaker signal for the inductive heads (sensing the change of magnetic field with respect to time). Also, at a smaller track size the signal will be weaker. Consequently, the signal level decreases as density increases. The magneto-resistive head offers a way around both problems since they are not velocity dependent and in any case, provide larger signals.



photolithography and plating process



manufactured wafer cross-section

Figure 5.4 Thin film head wafer process

Producing an inductive thin film head is a complex process since masking techniques (photolithography), selective etching processes (ion milling) and deposition techniques (electrodeposition, sputtering) are needed to make a wafer consisting of hundreds of such elements. Figure 5.4 shows the basic steps of the production process. The head consists of various different layers (roughly 10-20) prepared on a ceramic substrate. After slicing the wafers the heads are mounted on aerodynamic sliders and subsequently finished to fly over the surface of a rotating disk. Then a precision polishing step is performed to realize the correct air bearing surfaces and the desired electromagnetic characteristics. After assembly of the finished slider suspensions and wires the complete heads are tested for their writing and reading functions.

Because of the vertical head dimension limiting the number of platters that can be added to a disk drive, the size of heads has also been decreasing. Here, the throat height is the distance from the head tip to the coil region (figure 5.5). This has to be as short as possible because it is an area of constant reluctance. This can be achieved by very accurate polishing.

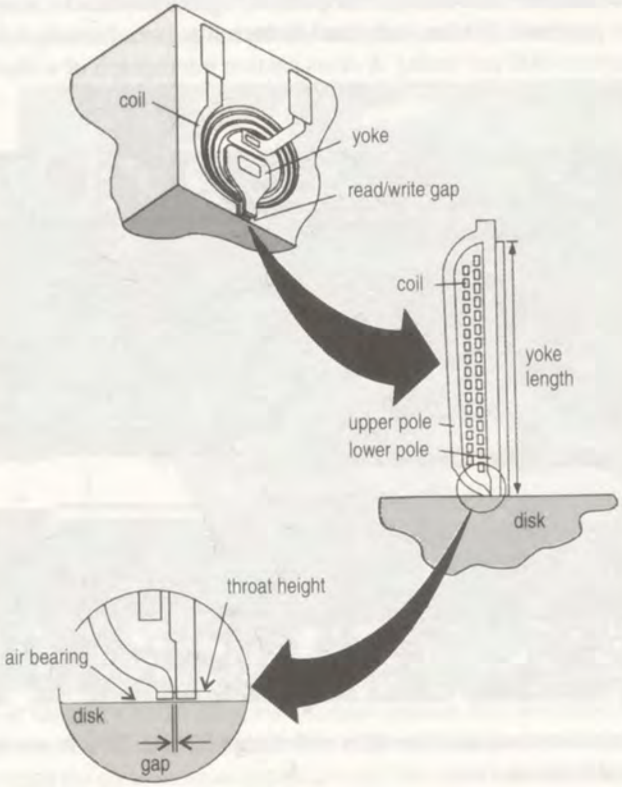


Figure 5.5 Read and write thin film head

Magneto-resistive (MR) head

The MR head is based on the principle that the electric resistivity of a magnetic material changes slightly when it is placed in a magnetic field. At a steady current through the MR strip the change in resistance produces a change of voltage. For reading increased densities, the MR element can be used as an integrated element in the inductive write head. The inductive head part writes a wide track and the MR head reads only in the middle of the track. Consequently, the head will not jump to or pick up information from another track. The sensitivity of the MR head is multiplied about four times which is an advantage when reading the inner tracks of the smaller disks (lower velocity). Not all problems around the MR head have been solved. Beside magnetic and material problems careful design also has to be completed.

An important new application for MR heads is the introduction of Philips Digital Compact Cassette (DCC), which suggests multitrack MR heads. The DCC audio system was launched in 1992 by Philips and Matshushita. The DCC head is the first consumer multitrack thin film tape head. It can handle the digital multitrack format as well as play back standard analog compact cassettes. On the digital side there are eight parallel audio tracks with a total bit rate of 768 kbit/s, including bits for error correction. The entire head contains nine parallel digital channels for recording (185 μm wide) and playback (70 μm wide) and furthermore two channels for the analog playback function (600 μm wide). A cross section micrograph of a digital channel is shown in figure 5.6.

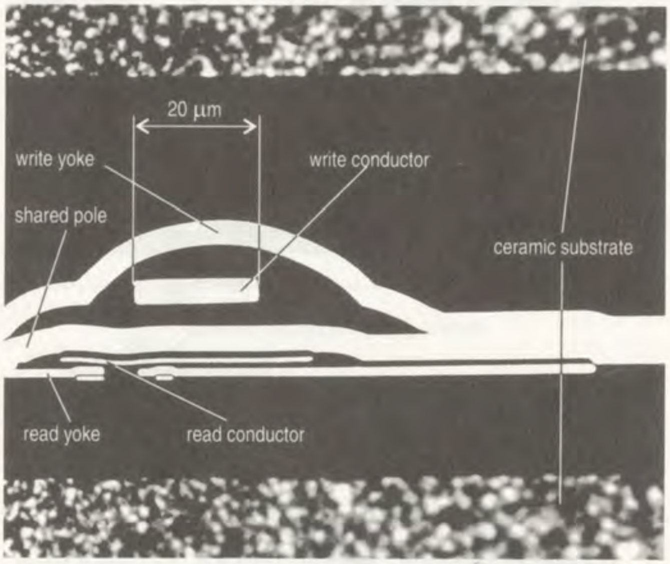


Figure 5.6 Cross section micrograph of one digital channel of a DCC head. The write yoke has been processed on top of the playback yoke

As higher recording densities lead automatically to a weaker magnetic flux above the medium, more sensitive head materials are required. A new issue at present is the study of the so-called Giant Magneto-Resistive effect (GMR). GMR materials are metallic multilayers prepared by deposition techniques consisting of alternating ferromagnetic and non-ferromagnetic layers e.g. Co-Cu. It is expected that GMR based heads can increase the recording density in harddisks by a factor of 4 to 6 in the next five years.

AN EXAMPLE OF DOWNSIZING: HP KITTYHAWK

The HP Kittyhawk Personal Storage Module (PSM) is a new 1.3 inch disk drive (figure 5.7). HP began development of the Kittyhawk in 1991. The great advantage of this system is its compact size which enables its use in a range of new applications. It can be used as a modular, removable data storage system in portable products such as subnotebooks and palmtop computers, patient monitoring systems, scientific instruments and cellular telephones. Other applications such as cars and navigation systems will surface, establishing the HP Kittyhawk as core storage technology. Although the HP Kittyhawk PSM resembles a disk drive, its size, ruggedness, package design, removability and lower power requirement open the door to a wide range of new applications previously not associated with this technology. In order to achieve the required performance it has been essential to develop the main components especially for this purpose: integrated circuitry, integrated power circuit (average power consumption while reading and writing of only 1.6 W), spindle motor, glass media and read and write heads.

Figure 5.7 The HP Kittyhawk PSM 1.3 inch disk drive module has 21.4 Mbytes of storage space
Source: Hewlett Packard

Performances

The HP Kittyhawk can perform 100,000 starts and stops without failure. To lower the height of the drive to 0.4 inch, the shortest spindle ever developed for a rotating medium device has been engineered. The medium substrate is made of glass. This is stronger than the conventional substrates and has an inherently smoother surface. The latter is critical to achieve the lower flying heights necessary to enable higher areal densities. The bit density achieved is 2 kbit/mm and track density is 94 tracks/mm. For a conventional 1.8 inch drive these figures are 1.9 kbit/mm and 79 tracks/mm.

Nanoslider

The slider head technology allows the required disk-to-disk spacing to fit within the 10 mm height ceiling and provides an exceptional reliability of head and disk. HP has developed a proprietary technology that acts much like an airbag sensor of an automobile. It detects impending impact and causes the drive to revert to a protective mode instantly to ensure no loss of data. This technology increases the impact force the HP Kittyhawk can take while in operations to a 3-millisecond shock of 100 g. A force large enough to break a liquid crystal display screen.

CONCLUSIONS AND TRENDS

Magnetic and magneto-optic recording technologies are good examples of microsystem technologies, the dimensions of the various essential parts being within the definition. There is a complete integration of technologies based on electrical and electronic engineering, mechanical engineering, physics, thin film technologies and microsystem technologies such as etching and masking and magnetism. There is an evolution to higher densities not only in harddisk applications but also in other consumer applications such as HDTV recorders.

The minimum tape volume needed for 1 bit has decreased drastically in the last twenty years. In 1975, a conventional VHS-system needed 500 μm^3/bit. Ten years later in 1985 the 8 mm system needed 34-130 μm^3/bit and it is expected that in 1995 digital HDTV will only need 7 μm^3/bit.

Continuous improvements in head design, airbearing design and disk surfaces have narrowed head-to-disk spacing from over 10 μm thirty years ago to less than 100 nm today (in an IBM harddisk application for 1.5 Mbit/mm^2 it is 50 nm).

For very high densities new medium materials (like multilayers) can give another factor of 3 so that in the coming twenty to thirty years 100 Mbit/mm^2 can be obtained. However, this will require technological breakthroughs in the fields of micromechanics, micromotors and micro-actuators. Furthermore, from other recording modes such as perpendicular recording and (magneto-)optic recording we can expect an increase in density. Laboratory demonstrations have already shown 7.8 Mbits/mm^2 in the case of submicron trackwidth perpendicular recording.

Head design presently concentrates on constant flying height and the reduction of flight height aiming at a result in contact recording. This requires more development in the areas of microtribology and hard coatings.

In the case of microsystems, many changes are needed concerning the construction and manufacture of the slider. Firstly, the size of the slider (1 x 1 mm^2) has to be reduced. Furthermore, a reduction of the flexure and automatic bonding is needed. Finally, for faster positioning a lower mass is essential. The future probe head will have a needle shape.

To increase the density in magneto-optical recording a smaller spot size is needed which can be obtained by smaller wavelengths (blue laser technology). In addition, integrated optics combined with magneto-optic detection can lead to a more compact, lower mass head (faster access time). With integrated optics and microsystem technologies, laser arrays for multitrack recording can be implemented. To show the potential for a further increase of density, the key aspects of recording are given in table 5.2 with possible improvement factors.

parameter	*from*	*to*	*improvement factor*
head to disk spacing	0.15 μm	0.05 μm	2
medium coercivity	112 kA/m	224 kA/m	2.5
mode of recording	longitudinal	perpendicular	4
signal processing	peak detection	MLSD[1]	2.5
head materials	NiFe	multilayers	5
head principle	inductive	magneto resistance	4
total improvement			1000

[1] MLSD, Maximum Likehood Sequential Detection is a signal processing method

Table 5.2 Key aspects of recording

5.2 AN OVERVIEW OF MST IN CONSUMER PRODUCTS

This section lists suggestions for applications of MST in consumer products. The discussion of ideas is limited to a general overview.

5.2.1 AUTOMOTIVE

G.J. Ketelaars

INTRODUCTION

The most important function of the automobile will always be to transport people and goods. At this moment reliability of all systems is high and needs little development. However, *how* to carry people and goods is gaining importance. Besides, the automobile is a status symbol. This means that exterior as well as interior design of a passenger car plays an important role.

Because of the increasing number of cars in the industrialized part of the world, safety is becoming ever more important. In addition, new methods of communication tend to transform a passenger car into an office: telephone, telefax, modems, television and other communication options, as well as temperature control are required. In view of environmental pressures, low fuel consumption and exhaust emissions are required.

All of these goals above can be reached by using electronic control systems in combination with sensing and actuating elements. At this moment these control systems already play an important role in automobiles.

RECENT APPLICATIONS

Figure 5.8 and table 5.3 show recent applications of control and measurement functions.

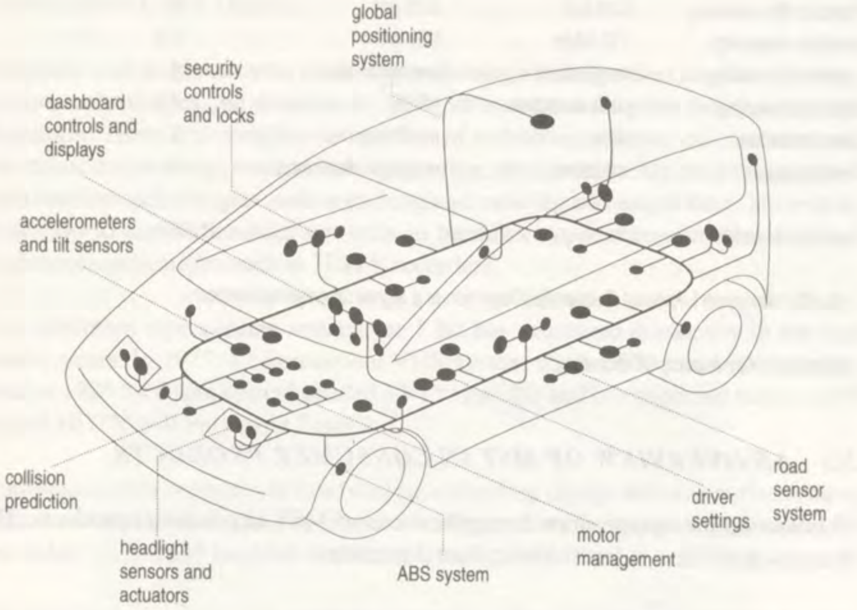


Figure 5.8 Recent applications of control and measurement functions in cars

engine and drive line	*navigation and guidance*	*safety and maintenance*	*comfort and entertainment*
electronic diesel injection	speech synthesis	distance control	cruise control
idle speed control	trip computer	headlight cleaners	door-lock system
lambda control (dosage)	traffic flow harmonization	diagnosis	heating control
start-stop system	travel and transport management	tyre pressure	chair displacement and height control
electric transmission control	multiplex cable	cleaning system	radio
digital engine electronics – injection, ignition – knock rating		anti skid control service-interval indication liquid and wear control	auto telephone
electronic throttle		airbag anti theft system	

Table 5.3 Recent applications of control and measurement functions in cars

Developments will be concentrated on four areas: engine management, safety, comfort and navigation. Considering the drive line; control and measurement systems are used for gasoil injection, idling speed, start-stop systems, transmission control and engine electronics.

With legislation on the emission of noise and exhaust gases ever tightening, the onus is on powertrain engineers to come up with new and innovative solutions. Developments in safety concentrate on headlight cleaner diagnostics, tyre tension and anti-skid control. To increase comfort, the main factors are cruise-speed control by lock systems, heating systems, suspension control and seat adjustment developments. Many developments have taken place in the navigational area. Future applications are considered in the following section.

FUTURE APPLICATIONS

In the future miniaturized control systems will gain importance in the automobile and the infrastructure. Some examples are considered below.

Combustion

Combustion is considered in relation to microdosage. It is assumed that fuel liquids or gases in an automobile will have to be distributed with increasing accuracy and flexibility. It may even be that additives in very small amounts will have to be metered out accurately and at high speed. Microsystem-based components and systems could play a role here; not because of their size and weight but because of small dosage and high resolution and accuracy. If such parts are incorporated inside engines or other vital parts of the car, their small size may well become important.

To give an idea of fuel dosage we can easily calculate that a conventional Otto or Diesel engine uses about 0.02 cm^3 of fuel per stroke (based on a four cylinder engine using 1 litre every 10 km, a 4000 rpm engine and a speed of 100 km/hr). Imagine an additive with separate control requirements and with 1:1000 consumption.

The microdosage application in general requires chemical inertness of the system material in relation to the chemicals dispensed. This is more likely to be brought about by developments in the field of ceramics than in the presently more common silicon and electroformed nickel.

Fuzzy logic

BMW has evolved a 'learning capability' in which the driving style of the individual motorist is observed by electronics, recorded, analyzed and allowed to modify the previously set control programme. Since the driver's mood and general driving style can and does change as he perceives the situation, there is a need to constantly update the memory; this occurs at about 20 second intervals and is preferable to the cheaper alternative of utilizing three different selectable 'driving styles'.

Radar mirror

Mirror blind spots can be avoided by a miniaturized radar built into the driver's door mirror. It covers the rear-view area usually obscured by body metal, and warns you to remain on the same course when you are about to be passed. Any approaching vehicle that intercepts and reflects the beam will trigger an audible warning bleep or flashing light, depending on a driver control option. Traffic in the opposite direction is ignored, since this radar uses the Doppler effect to discriminate between objects which are coming and going.

Accelerometers

Accelerometers consist of a spring-mass system which moves in response to acceleration and are a means of detecting that movement. The basic system is a cantilever beam with a mass located at the unsupported end. As acceleration is applied the beam is deflected. Add a means of detecting the deflection, and a simple open-loop accelerometer results.

If a means of applying a restoring force to the beam is added, a closed-loop force rebalance accelerometer results. Closed-loop accelerometers generally have higher accuracy due to the fact that movement of the beam can be minimized, eliminating nonlinearity, hysteresis and non-repeatability. This improved accuracy comes at the expense of increased mechanical and electronic complexity.

The accelerometer is a key component in the area of ride control; fixed damping is being replaced by damping which is programmed based on vehicle parameters such as speed and load. Self-contained sensing by the shock absorbers will be replaced by electronic sensing to improve performance. In anti-skid braking systems, sensing of wheel speed is being augmented by sensing deceleration to improve performance. In passive-restraint deployment systems, electromechanical g switches can be replaced by accelerometers for ease of system calibration and to obtain a wider range of actuation conditions.

Prometheus

Prometheus is a European cooperation of all major automobile manufacturers, electronics and supply companies, as well as leading research institutes. Its task is to enhance the utilisation of advanced information and communication technologies to address the complexity of today's traffic problems. It was launched in 1986 as a pre-competitive research programme at the initiative of Daimler-Benz. The project concentrates on the following items:

- *Safe driving*. Vision enhancement aims at the reduction of accidents in low visibility with, for example, video cameras, infrared cameras and UV headlights. Proper vehicle operation, and improved driver actions and vehicle reactions, will be supported by on-board information and warning systems, advanced vehicle control systems and support functions. A collision avoidance system investigates driving strategies for avoiding collision by identifying critical situations.
- *Traffic flow harmonization*. 'Copdrive' is a general approach for cooperative driving using information from the infrastructure, or other vehicles, which may inform, warn or interact. Autonomous Intelligent Cruise Control (AICC) is a first step towards cooperative driving; it is an assisting system for control of the relative speed and distance between vehicles in the same lane. Emergency systems support vehicle and traffic control by emergency warning, call and rescue services.
- *Travel and transport management*. Commercial fleet management is a specialization of the Prometheus approach for the transportation of goods. A dual mode

route guidance system combines on-board systems and infrastructure support for optimized performance. Travel information services inform the user of the ability of the whole transport system (including various kinds of transportation modes) to meet his needs. In the short term, warning and some support systems will be implemented in passenger cars. In the mid term, control and support systems will be integrated in on-board systems. In the long term, full integration of on-board systems with infrastructure systems will be available.
- *Braking system*. Brakes and braking systems have to cope with ever increasing energy dissipation; they have to match other vehicle developments as the demands of comfort, safety, cost and durability are of prime importance. Lucas Chassis Systems is designing a technique for comfortable automatic braking in vehicles fitted with intelligent cruise control for maintaining a fixed distance from a leading vehicle in motorway cruising. If a solenoid is used to connect the outlet part of the hydraulic booster to the pressure accumulator, control of the solenoids enables the braking pressure to be modulated independently of ABS.

CONCLUSIONS

To fulfil the driver's obligations and to fulfil the prescribed requirements, the use of measurement and control systems is essential. Developments concentrate on the drive line, safety, comfort and navigation. Sensors, actuators and electronics can be used in all four areas either as a control system or as support to new systems.

5.2.2 AUDIO, VIDEO AND COMPUTERS

F. Pool and W. Prinsen

Microrobots in disk drive slots for maintenance and repair

The idea has been launched to allow super-small robots enter disk drives through the entry slots to perform maintenance and repair. These beetle-like free moving helpful mechanical pets are an extension of the MITI proposals for small submarine robots for inspection and repair in tubing (Appendix 2). What is suggested is a small 'clean and repair' robot that is pushed into a disk drive slot which goes further inside and does clean and repair jobs on its own.

Alas, it must be assumed that the economic feasibility for this is rather low. Even if disk drives are not replaced by completely different data storage media, their design will become maintenance free and very reliable, without the need for repair robots. The idea however, of the little bug that can be sent out to do some useful job unattended may find application elsewhere, for example in the home (section 5.2.3), in much the same way as a snail in an aquarium cleans the glass on the inside.

Super-small camcorder

A super-small camcorder can be seen as a straight extrapolation of the tendency to shrink the camcorder as seen in recent years. These products are an extension of the movie camera which ended its economic life at the Super 8 mm colour and sound stage about 10 years ago. Camcorders for consumer use started as bulky systems weighing several kilos, sometimes in two packages. Today, the 8 mm camcorder weighs far less than one kilo, fits in one hand and contains many more features (figure 5.9).

Figure 5.9 Present-day camcorders (1993/1994)
Source: Sony Nederland

Assuming a storage medium continues to need moving parts like tape or disk, a super-small camcorder of cigarette packet size would require small mechanical and perhaps optical components. Some of these parts may need microsystem technologies to be manufactured. Of course, the shrinkage of electronic circuits, including the image sensor will be a major part of the effort. The storage of video data should be in digital form which would make direct computer enhanced editing possible.

The requirements to be fulfilled are not simple because next to the obvious ones such as playing time and ease of use we have to assume that demands for picture and sound quality will continually increase in the coming years. Substantially reduced picture quality will not be accepted just because the equipment is small. In the meantime, the public will have got used to better quality transmitted and stored video pictures and sound. The ultimate design could be so compact as to fit into a pair of spectacles, which can be directly controlled by the eyes. Voice control could also make operation extremely simple.

5.2.3 HOUSEHOLD APPLICATIONS

F. Pool and W. Prinsen

Autofocus eye glasses or contact lenses
An extremely futuristic idea is that of eye glasses or contact lenses that focus themselves. Such a system or device should be able to detect the distance a person wants to see and automatically adjust its focus. As it is not clear how this could be accomplished with the technologies presently available, this idea has to be a long-term application. Nevertheless, it could be a useful product with many potential customers in an ageing society. Also it should be looked at in the more general sense

if there are opportunities in the field of personal help for people with common deficiencies.

Essentially, the equivalent of autofocus glasses exists in the audio field. Hearing instruments exist that fit completely inside the outer-ear and still automatically adjust to changing conditions. For people with reduced vision, like a reduced range of focus, near- or long sightedness, fixed focus glasses pose a solution, but also a problem. Of course, double focus and multifocus lenses already exist, but they are far from ideal. The additional requirements for small dimensions and lightweight glasses are obvious. The real challenge for microsystem technology is to develop a lens with suitable optical properties that can be focused by micromechanical actuators which would probably be made of a non-transparent material.

Microrobot household cleaner

A microrobot for household cleaning is the domestic version of the more specialized disk drive cleaner. The idea of more or less specialized small bugs that do useful household cleaning jobs entirely on their own is very attractive. Imagine the window cleaner 'snail' which relentlessly cleans the inside or outside of the aquarium glass; slow perhaps but unceasing. Because it is powered by light or by material found along the way, it would be possible to leave it alone and never concern ourselves about dirty windows again. Figure 5.10 gives an artist's impression of these domestic microrobots.

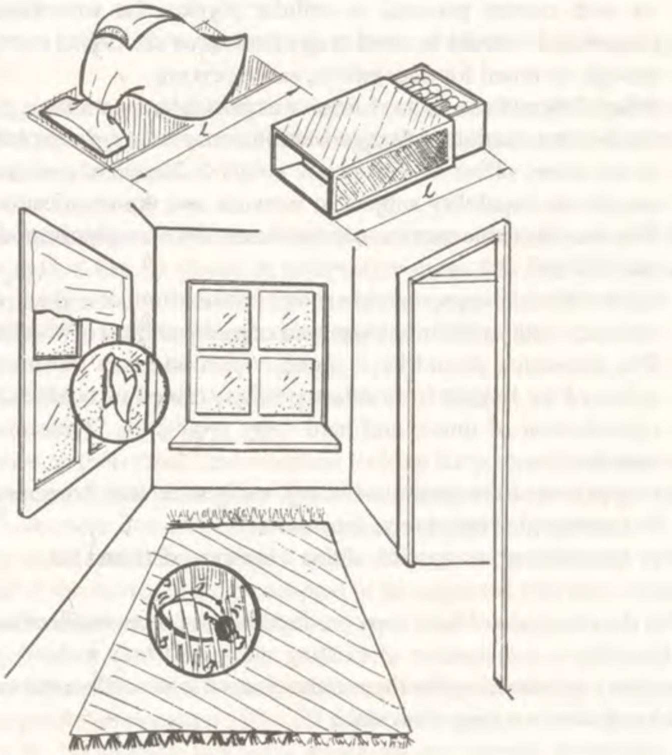


Figure 5.10 Microrobots for domestic purposes

Let us consider a 'beetle' that crawls along the carpeted floor and 'eats' dust, mites and anything else we want to remove. They would work during the night or whenever there is nobody present so that they are not crushed underfoot. Again, its feeding on refuse would be very helpful in solving the power supply problem.

5.2.4 TELEMATICS

H.J. Bosch

Personal communicator and personal digital assistant

A system that functions both as a communication device and as a digital assistant might be a useful application of microsystems. Starting points and basic specifications are:

- Being cordless, that is to say, carrying a device on the body like the James Bond wristwatch in the 1960s film 'Goldfinger'.
- Who? Would the application be for consumers or professionals?
  Wristwatch communicators could be targeted at both consumers and professionals. The constraint in this case is targeted at the consumer himself. The device could be suitable for the consumers in their private and business environment, and in principle for all ages and economic classes; the market mechanism in the same vein as Ikea and McDonalds.
- Would use be occasional or continuous?
  As with current personal or cellular phones, the wristwatch communicator ('comwatch') could be used at any time, provided it had energy capacity large enough on board for transmitting and receiving.
- Where? Would use be anywhere or at particular locations, e.g. phonepoints?
  On the introduction of first generation comwatches, the probable use would be in the home, office or with phone points. Subsequent generations would have worldwide capability subject to network and communications infrastructure. This would enable users to communicate, for example, from the desert, using a satellite link.
- What? Would use incorporate sound (voice or music), vision (colour or monochrome), data (with or without hard copy capability) or combinations of these?
  The comwatch should have sound, vision and data transmission capabilities achieved by linking in to other systems, cabled or cordless, for high quality reproduction of music and hard copy production. Transmission capabilities include:
  - *receiving*: time, position-finding, navigation, telephony, radio, teletext, television, video telephony, data and fax.
  - *transmitting*: navigation, video telephony, data and fax.

With the exception of hard copy production and power requirements, such a device is basically a combination of existing microelectronic technology. However, the necessary infrastructure for the communication features does not exist, and therefore such a system is a long-term ideal.

5.3 ELABORATED CASES

This section describes two examples of consumer products in which MST could find application, namely personal safety devices and personal health analyzers. For each group several examples are worked out and the opportunities for MST are indicated.

5.3.1 PERSONAL SAFETY SYSTEMS

E. Mos and P.V. Pistecky

INTRODUCTION

Introducing microsystem technology in consumer safety products means small dimensions (portability, unrestricted use), low power needs and the opportunity for cheap mass manufacture.

New products for personal safety can be circumscribed by answering a few classifying questions:

- Who should be protected (e.g. men or women, elderly people or children, housewives or policemen)?
- When should the protection work (e.g. in the daytime or at night, daily or at weekends only)?
- Where should the protection be active (e.g. at home or on the road, in smog or on the water)?
- What will they protect against (e.g. fire or noise, burglary, robbery or disasters)?
- How should the protection be accomplished (e.g. alarm or prevention information, cordless or on the body)?

The following two examples of a personal detector of environment quality and a burglar detection system can be placed in perspective using this list. The list can also be used as a trigger to define other, personal safety products not as yet in existence, regardless of what promising technology could be used.

PERSONAL DETECTOR OF ENVIRONMENT QUALITY (PEDEQ)

This device analyzes an individual's environment looking for potentially dangerous conditions. It measures a limited number of parameters representative of civilian situations. The instrument consists of two parts: a very small detector with an integrated display and a small 'home based' cradle. During the introduction to the market, the layout of the device could be adapted to the expected first user. Figure 5.11 gives examples of detector and cradle.

The detector (dimensions 30 x 30 x 5 mm^3) can be carried by the user as a badge or a wristwatch. The cradle (dimensions 100 x 50 x 10 mm^3) supports the tasks of the portable detector by performing functions which do not require portability or continuous access to the environment.

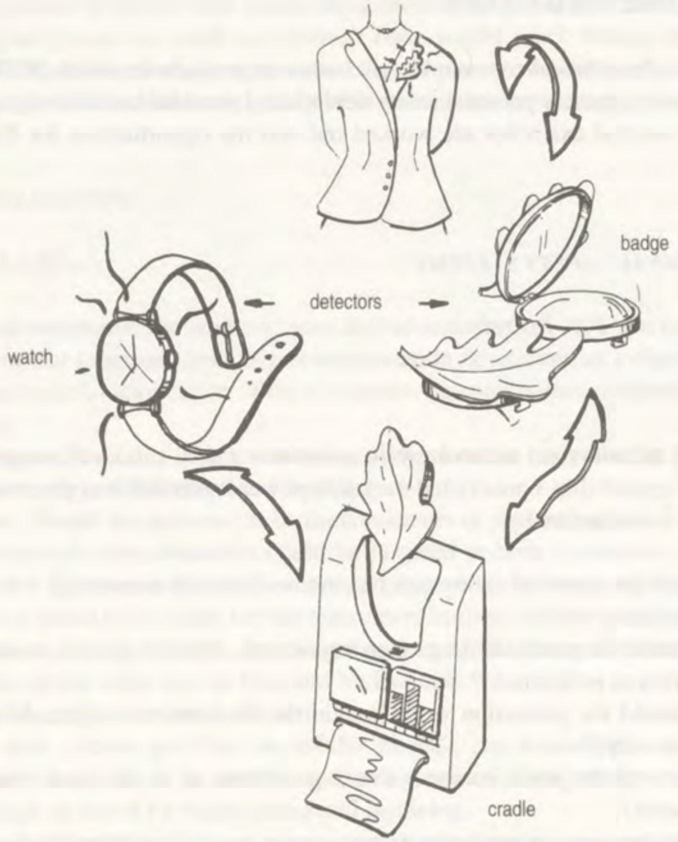


Figure 5.11 Impression of the layout of the PEDEQ

The small portable detector takes quantitative measurements, collects data during a limited timespan (a day) and gives warnings when preset limits are exceeded. The tasks of the home based cradle can be:

- setting of warning limits of the detector device;
- calibration of the sensors;
- refreshment of sensor surfaces;
- rinsing of filters;
- resetting of the microcontroller;
- energy recharge;
- long term data storage;
- interface to computer systems.

Basically, the following parameters can be measured by the PEDEQ:

- air quality e.g. smoke, dust particles, pollen, limited number of organic and inorganic gases (N_XO_X, CO, SO_2, halogenated compounds and hydrocarbons;
- radiation e.g. UV-radiation, ionizing radiation from natural sources;
- water quality e.g. for purpose of consumption: measurement of chloride, nitride, sulphide, micro-organism detection.

Physical and chemical sensors must be available to perform these tasks. However, the complete detector system contains a large number of additional components. Figure 5.12 gives a block diagram of all expected components and their mutual connections.

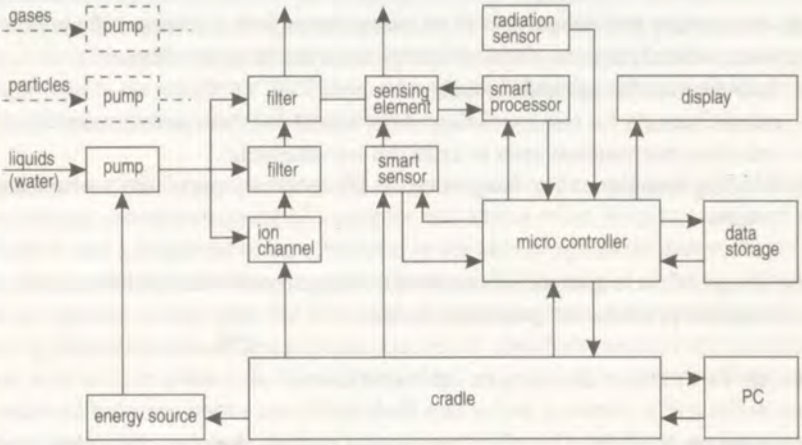


Figure 5.12 Block diagram of a possible PEDEQ layout. All blocks except for the cradle and PC are part of the portable detector

Physical sensors for radiation measurement are already available due to extensive research in this field. However, miniature physical sensors for detection of dust particles and pollen are not yet available.

Although there are a number of electronic chemical sensors on the market, the performance of solid state chemical sensors is sadly lacking when compared to physical sensors. Chemical sensors tend to suffer from poor stability, interference from non-target gases and poisoning effects. Therefore, a good deal more effort is needed to develop appropriate chemical sensors.

Recent research and development into chemical sensors aims at three different basic applications:
- quantitative and selective determination of individual components (concentration of particular gases);
- determination of 'gross parameters' (toxicity, combustible and organic molecules);
- quantitative characterization of complex odours.

The complete chemical sensor system will generally consist of: components for gas or liquid handling (pumps), filters or membranes for sample preselection, catalysts or enzymes for sample preconditioning, individual sensor elements, electronics for data preconditioning, reference components for calibration and last but not least intelligent circuits for pattern recognition. Just as the weakest link in a chain, the component with the weakest performance determines the overall performance of the system. The most critical parts of the sensors are usually the materials of the individual sensors and transducers. Therefore, there is a need to optimize the sensor materials toward high selectivity, sensitivity and stability.

Besides the necessary development of improved sensing materials, the main task for microsystem technology, in developing the proposed PEDEQ, will be a further miniaturization and integration of all components into a compact device. For this purpose, several micromechanical components are to be developed:

- micropumps for gas and liquids;
- microchannels for transportation of the media to filters and sensors;
- selective micromembranes or artificial ion channels;
- bonding techniques for integration of all necessary parts into a small detector volume.

The design of these components must allow large batch-wise manufacture to assure a reasonable price for the proposed device.

SECURITY SYSTEMS BURGLARY PREVENTION

Envisage an 'invisible' burglary prevention system. A system like this would be useful in both private and business applications.

As may be clear, even to the inexperienced customer, existing systems have some major drawbacks:

- The system components are rather bulky. Consider for instance the infrared sensors that can be bought readily in various shapes. Although the detecting element is itself small, some cm^2, the complete housing amounts to some 150 cm^3.
- The components are connected to a central alarm unit primarily by means of copper wires. This is not attractive: it is offensive and expensive on account of the indoor installation wiring. However, the possibility to extend or reconfigure the system is limited. One is not invited to install many detectors.
- The detection components need energy, derived either from the central alarm unit or from local batteries. Both of these methods have their drawbacks.
- The system is prone to failures such as false alarms, but a high 'positive true' detection reliability is required. Existing systems often lack the intelligence needed to realize such a high performance.

With microsystem technology one can think of different detection components and therefore of other systems.

New detector principles

A glass-crack detector could take the form of a piece of adhesive tape stuck onto a window. Such a component would have the following features:

- The energy is supplied by a solar cell which is part of the tape itself.
- The tape emits a 'detect'-signal (1 bit) to the central alarm unit via a low power spread spectrum transmitter.
- Detection principle is noticed by a change in impedance of the glass itself. No other tapes or foils should be applied. Such an impedance could be optical,

electrical, mechanical etc. An example is a miniature ultrasonic vibrator, which vibrates the window at certain times and reacts to changes in vibration behaviour of a broken window.

Another possible microsystem detector is an IR detector with the shape of a flexible strip, or even adhesive tape as mentioned above. Replacing the bulky conventional IR detectors, this ultra-thin component could be positioned almost anywhere in the house, almost invisible or even as an ornament. It could be mounted without screws, having virtually no weight or thickness. Already in the early nineties, all kinds of microsystem technologies could be applicable.

When a window is left open accidentally an open-window detector could be of help. Many existing detectors consist of a magnet and a reed relay. Why not use a small Hall-sensor and a magnetic strip, connected to the spread spectrum transmitter? Of course, the same detector also notices the unauthorized opening of a closed window. When an intruder comes into the house an ultra-miniature camera makes a video recording. Specifications of this minicamera are: its ultra light-sensitivity, its ability to cope with over-exposure, its lack of accuracy in optical terms, its small enough to be stacked between books on a bookshelf and is low powered when not in use. Such an ultra small-camera with data recording will have many more applications, many outside the security field. Think of for example a personal camera for use in a library, making copies of important documents for later study at home.

As a last tantalizing, tempting example, one could define a body odour detector! Such a detector discriminates between individuals' or dogs familiar odours belonging to a household, and the unfamiliar smell of a burglar entering at night. But what would the response of this detector be to a new perfume of the lady of the house or a new pungent aftershave emanating from her lover?

Intelligence

Once small, and preferably cheap detector elements are available, it is possible to apply a reasonable detector 'overkill'. The antiburglar system will then possess redundant information (and artificial noise). By intelligent postprocessing and application of adapting algorithms in the central alarm unit, new functionality can be developed, such as: self-deciding, self-starting security systems, integrating fire and smoke alarm, extensive status display per room, available in the parents' bedroom or the porter's lodge. Next to sensors, actuators could be introduced such as automatic lock-in of a thief, in an empty room of the house, on the basis of the reliable information from the microsystem security system.

5.3.2 PERSONAL HEALTH SYSTEMS

Chr. Titulaer

Microsystem technology may find useful applications in the field of personal health. Although examples would border on medical technology they are supposed to be available without the consent of a doctor or medical expert and are therefore products for the consumer market. Furthermore, they are considered consumer products because of the number of devices one can expect to sell.

Blood analysis system

One useful product that might be developed in the near future is a micropump. This could be inserted and fixed in place inside a blood vessel, but would also be linked to the outside world to provide a drop of blood on demand for analysis. To ensure the wearer of such a pump was not inconvenienced in any way, it would have to be extremely small; perhaps 1 mm^3 including control electronics and motor. The whole apparatus might be implanted in, say, a fingertip. On account of its small dimensions the wearer would not be aware of its presence.

The fingertip position is required because most measurements, like that of glucose, need capillary blood. A blood analysis system could find use in large numbers. In the Netherlands alone there are 100,000 – 300,000 people who need monitoring of their glucose levels. This number depends on the groups we consider: is this group limited to insulin-dependent diabetics, or do we also take the non-insulin dependent diabetics into account? Apart from this group there are 100,000 people in the Netherlands who have to monitor their cholesterol levels and a similar number has to perform related measurements. The conclusion is clear: such a device is an interesting consumer product.

A product of this kind would call for:

- a micropump;
- a motor;
- control electronics;
- an energy supply.

The pump would have to be capable of supplying a drop of blood at a moment's notice. This could then be analyzed by using either existing or yet to be developed biochemical methods. A product which goes some way to meeting these specifications is the pen manufactured by the Medisense company, which uses biosensors to measure glucose levels (figure 5.13). This company also makes devices for measuring parameters such as cholesterol levels.

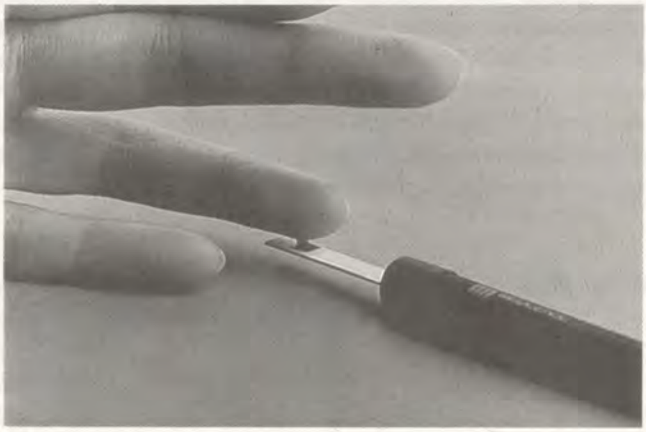


Figure 5.13 Glucose pen for measurement of glucose levels
Source: Medisense

The great advantage of a stepwise development of this sort is that it looks first at where the problem lies: in providing a drop of blood. This is solved by using micromechanical systems in such a way that the user is unaware of them. A system like this could be used by anyone needing to measure elements in his blood from time to time, e.g. glucose, cholesterol or fatty acids leading to a product that could ultimately be sold over the counter at chemist shops in the High Street: the micromechanical system would then have become a consumer product.

The drop of blood thus obtained could then be analyzed by existing sensors, but a second phase might involve building sensors into the microsystem itself though it might be wise, in view of the exposed position of a fingertip, to choose another location. This would also make the whole system a great deal larger, since there would have to be some kind of display for reading out the result of the analysis. The natural solution at this stage would probably be to replace all biochemical sensors with silicon sensors (perhaps but not necessarily in the form of biosensors). Figure 5.14 gives an artists impression of the system.

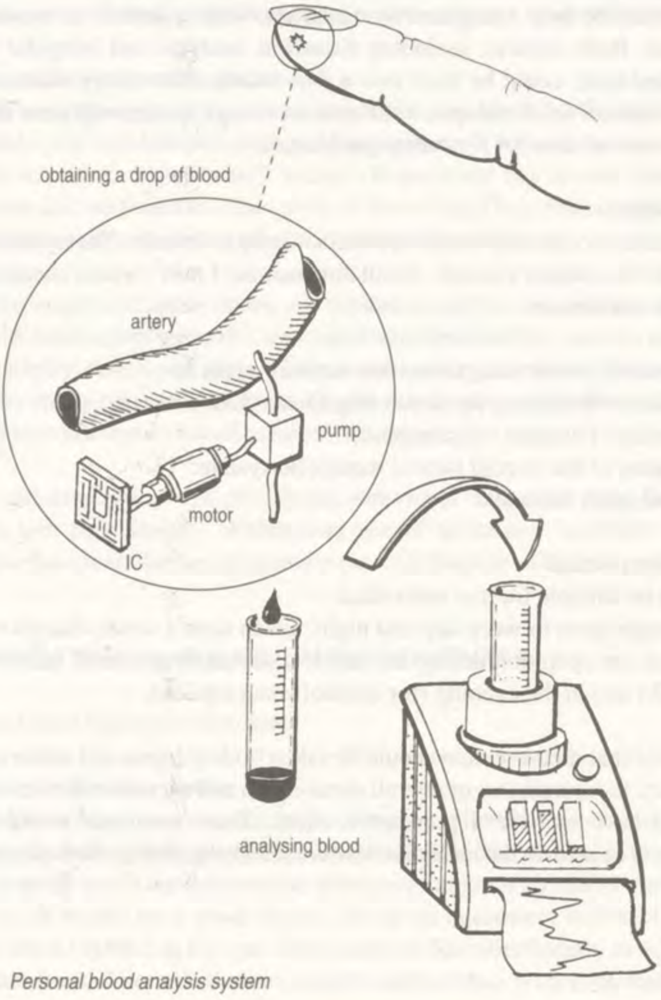


Figure 5.14 Personal blood analysis system

The functional requirements of the entire system would be:

- imperceptible micropump implantation;
- small set of measuring equipment that would be easy to carry (as in the Medisense pen);
- highly reliable measurements;
- high reproducibility of measurements;
- the question is, of course, for which users such a system would be useful. In general it would be suitable for those who need to have blood analyzed occasionally in a clinic or laboratory, for example, or diabetics or those with high cholesterol levels;
- measurements must be capable of being carried out at any hour of the day or night, seven days a week, at home, on the road, at sea or in an aircraft;
- measurements would have to have a preventive effect, for example signalling excessively high or low blood sugar or excessive cholesterol levels.

Heartbeat analysis

A second example is heartbeat analysis and warning of irregular heartbeat. Such a system would be best integrated immediately with a device to measure body temperature. Both sensors, including heartbeat analysis and irregular heartbeat warning hardware, could be built into a wristwatch. The energy source could be body heat, though the development of such an energy system will pose difficulties of its own (see section 2.4 for energy problems).

Breath analysis

This is a microscopically small system to analyze breath. The system may be implanted in the subject's mouth. Small dimensions (1 mm^3) would ensure complete comfort for the wearer.

The purposes of breath analysis by this method might be:

- regulation of breathing by monitoring O_2 and CO_2 levels;
- monitoring of alcohol consumption;
- monitoring of the overall human metabolic system;
- monitoring for halitosis.

Such a system would:

- need to be suitable for any individual;
- in principle have to work day and night, seven days a week, though with some emphasis on operation during the day (for monitoring overall metabolism, O_2 and CO_2) and in the evening (for alcohol consumption).

It is essential that measurements could be taken both at home and while travelling. Furthermore, measurements of overall metabolism and excessive alcohol consumption would have to have a preventive effect. Thus, warnings would be given automatically as soon as the measured levels exceeded (or fell) below predetermined limits.

5.4 RELEVANCE OF MST IN CONSUMER PRODUCTS

Task Force Consumer Products

As can be seen in the previous sections, there are certainly potentially attractive applications. It is also clear, however, that there is uncertainty about what type of product will become successful in the consumer market and so have an economic potential. It is quite reasonable to assume that more professional applications such as medical, industrial or agricultural applications may have an earlier impact because they are less cost sensitive. Once the real low-cost manufacturing promises come true, consumer applications can be expected to surface. Examples of applications where MST is already successfully applied are CD players and the DCC head in figure 5.6. However, MST is not actually in widespread use as yet and it might be concluded that general applications in consumer goods are still some years off.

Obviously, this does not mean that such applications should not be anticipated and unexpected ‘hits’ could well show up. Certainly these products will not be technology pushed, but will most probably appeal to yet unknown market needs.

Economic and social consequences
MST-based consumer products, when introduced onto the West European market, may certainly gain considerable economic importance. It remains to be seen to what extent the economic benefits will accrue. Experience has shown that suitable suppliers can also be found in other parts of the world. They will certainly become interested should a mass market of new consumers materialize.

Many of the suggested applications are dependent on the assumption that a communications mechanism will exist, and a general infrastructure, such as can only be found in a highly-developed and well-structured society. Personal health monitors, if carried by many people, would change the relationship with the medical world and would also affect the cost of medical insurance.

On-going miniaturization will provide the individual with even more functions to carry with him permanently. Widespread use of these new facilities should be expected as mass manufacturing promises to offer them at affordable prices.

5.5 CONCLUSIONS AND RECOMMENDATIONS

Task Force Consumer Products

Set up of a coordination centre
To make MST a European venture, inter-company relations and cooperation with institutes, universities and governments is essential. The chances of one single company making major inroads into the consumer market with MST-based products is quite low. It would be a good idea to set up an equivalent to the MITI Micro Machine Centre (MMC) in Europe. This centre is described briefly in Appendix 2. For a certain limited period of time a centre such as this, with contributions from

several companies and other participants, would form a good breeding ground for MST. MESA in Enschede and IMEC in Leuven could be among the participants.

Encourage European cooperation

The MMC in Japan is a challenging example of how such highly innovative technologies could be initiated in cooperation with independent companies under the guidance of a government institution. STT's Task Force Consumer Products is of the opinion that an approach of this sort should be applied on a European level for MST initiatives. A first step is the European Union's NEXUS network. Moreover, it is recommended that a European MMC should not work by itself but should seek close cooperative relations with the MMC in Japan. This advice is not directly related to MST in consumer applications but to MST in general. The Netherlands could take the initiative for such a centre.

Enhance user awareness

We can expect in the case of real consumer products, the user taking no initiative until these products come onto the market. Then, independently of origin and guided by little market research, the individual consumer and user will decide to make a purchase. To prevent the consumer remaining completely unaware of what the future could bring, information about new products should be widely published. It is well-known, however, that consumers quite readily accept new technologies once they are aware of the useful or entertaining functions that are offered.

Stimulate feasibility studies

On the level of SMEs, we should primarily think of set makers and trading companies. For these companies it is very helpful if the right type of information is provided, including training and possibly some help in setting up a new business, which might be risky. Subsidizing feasibility studies by request of and defined by private companies is an effective way of governmental support. To be pre-competitive the feasibility studies could be carried out by the above-mentioned European Micromachining Centre, which would then be financed in accordance with industry-driven projects.

Identify priorities

Universities and institutes should realize that they have to direct their efforts towards the highest chance of success, not only technologically but also in business terms. They will need to look for a favourable position in relation to other institutes and universities, either by trying to be a winner in a field where many others are active or by exploring a particular niche.

Governments and the European Union, should make up their mind about the importance of this technology. No highly industrialised country should ignore or neglect MST. A combination of the MITI approach and supportive action for smaller groups of companies and institutes should be started. This effort should be directed towards carrier-based projects around consumer products.

Consider the economy of scale

The consumer market requires specific knowledge of the typical marketing aspects of consumer products. In the opinion of the Task Force Consumer Products, designers of these products should learn to consider manufacturability on a sufficiently large scale and at low cost.

Conclusion

MST in consumer products is not a phantom. It is a logical consequence and a progression of existing technologies, meeting the need for miniature, complex and cheap mass-produced products. The next millennium will see MST come into its own.

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6. Microsystems and agriculture

6.1 *APPROACH AND FOCUS*

G.C. Klein Lebbink

6.1.1 INTRODUCTION

The agricultural sector is a significant sector of the economy where several trends can be identified which could lead to opportunities for MicroSystem Technology (MST).

In the first place there is the constant striving to attain more efficient production. Production also has to be controlled and monitored in detail. This applies to inputs (such as sunlight, nutrition etc.), production units and end products. In order to make representative measurements of living systems the sensors should not be allowed to influence the system. Sensors and actuators therefore must be extremely small and in most cases biocompatible. Microsystems can fulfil these requirements.

Secondly, society exerts increasing pressure for realizing sustainable agricultural production which translates into directives for fertilizer use, emission of gases (NH_3, NO_x, etc.), waste handling, herbicides, pesticides etc. A reduction in pesticide dosages as well as emission control would clearly benefit from small dosage systems and sensors.

Thirdly, demands for higher quality products is rising and the necessity of determining the condition or freshness of products is growing. One could envisage systems for monitoring the condition of stored or transported goods (jolts, temperature, handling, humidity etc.) or indicating the quality of such perishable goods as milk and meat.

An additional reason to consider MST in agriculture is that vast numbers need to be dealt with. The Netherlands currently has 2 million head of cattle and annually raises 22 million pigs.

Nature has supplied us with a lot of bio microsystems (e.g. insects) which perform both desirable and undesirable functions. With a little imagination one could imagine artificial microsystems performing similar tasks. Although this is not in itself an argument for using artificial microsystems it may suggest entirely new devices.

This chapter gives a summary of possible applications of microsystem technology in agriculture. Sections 6.2 and 6.3 describe where MST might help to satisfy existing needs and may have a certain added value. Section 6.4 addresses such general questions as the relevance of microsystem technology in agriculture. Finally, conclusions and recommendations for the agricultural sector complete the chapter.

6.1.2 MOTIVES FOR USING MST

The reasons for considering microsystem technology in agricultural applications have been mentioned in the previous section. When these motives are grouped together the following categories emerge:

In situ operations

In situ operations include measurements in plant saps (section 6.3.2), operations in food production processes (section 6.3.3), and the hormone level detector described in section 6.3.1. The agricultural processes to be analyzed are on a microscale; namely, in cells. Optimization thus requires monitoring on a microlevel.

Reduction of costs

Reduction of costs covers not only direct costs but also environmental costs (see pesticide control, section 6.2.4).

Portability

The ability to transport or move systems is important when monitoring storage or transport conditions (see section 6.2.3). This also applies if one wants to perform measurements on an individual animal (see section 6.2.1).

Distributed systems

As mentioned in Chapter 3, distributed systems are identical systems performing the same tasks at different locations. This is particulary applicable to agriculture where, for example, the same information is needed about many individual animals in a herd or flock (see sections 6.2.1 and 6.3.1), or if one wants to monitor the processes taking place in plants in a greenhouse (see sections 6.2.4 and 6.3.2), or especially if actions have to be taken for many individual items (see section 6.3.4).

Function integration

Integration of various different functions becomes essential wherever several functions need to be realized in a reduced volume (see sections 6.2.2 and 6.3.4).

6.1.3 APPROACH

A matrix diagram, represented in figure 6.1, allows a quick survey of possible MST applications in agriculture. Along the vertical axis the application areas are listed. The horizontal axis presents different aspects under which the areas are viewed. The discussion in this chapter is based on the crossover points in this matrix.

pull / area	efficiency	sustainability	safety	ethics	regulations	quality monitoring	R&D
animal husbandry	●	◑		◑	○	◑	○
arable farming	●	○				○	○
horticulture	◑	○				○	
food processing	●	○	○		○	◑	○
agrification							
logistics	◑					○	
valorisation	◑	◑				○	
forestry	○						
fishery	○					○	

● strong growth area

◑ important growth area

○ growth area

Figure 6.1 MST matrix for agriculture

6.1.4 APPLICATION AREAS

This section defines the application areas shown in figure 6.1 and a further subdivision is given in order to narrow down the field when searching for possible MST applications. A subdivision is only given for the four areas expected to benefit most from microsystem technology. This covers:

- applications linked to the input: nutrition, absorption or conversion of nutrients;
- applications related to the production units, e.g. the health of plants or animals;
- the end product: harvesting, packaging or storage.

Animal husbandry involves all agricultural production processes in which animals are used as the productive elements. Examples of the products of animal husbandry are meat, dairy products and eggs. Animal husbandry is limited to livestock and does not cover other domestic animals. There are applications for MST:

- outside the animal, for example during milking;
- on the animal, like (non-implantable) identification;
- in the animal, such as implantable devices.

Arable farming focuses on the growing of plants for food and non-food products. Vegetables and plants grown under glass are covered in a separate application area, under horticulture. In farming we can distinguish:

- the microsurroundings of plants: soil monitoring, nutrition, radiation, position, etc.;
- health (plagues, growth and development) and harvest (cob weight, ripeness, date of blossom);
- the plant itself: photosynthesis and sap flow.

Food processing is an extremely broad area. Examples are dairy processes, flour milling, cheese production and meat processing. Application areas are:

- the production process itself;
- areas surrounding the product (transport or storage);
- locating of items (quality measurement).

Horticulture covers the production of fruit, flowers, pot plants and vegetables. Horticulture allows for special applications because of the available infrastructure in greenhouses (nutrient and waste systems, climatic control, electricity, tracking systems, etc.). An aspect worth looking into is decorative cultivation, like spots on flowers and the shape of plants.

Agrification is the use of agricultural products as raw materials. Examples are elephant grass and flax.

Logistics focuses on storage, transport, packaging, identification and automation.

Valorization involves extracting vestiges of valuable material from waste products (e.g. the production of cardboard). Possible MST applications could be the detection of this material.

Forestry may find such applications as mineral detection, infrared sensing, quality control, plague control and ground water level monitoring.

Fishery offers applications in detecting fish or monitoring the quality of sea water.

6.1.5 MOST PROMISING AREAS

In a Delphi method survey growth areas were designated as listed in figure 6.1. In these areas there is a need for microsystem technology or, at least, technical opportunities exist. The four most promising crossover points are:

- animal husbandry and monitoring (efficiency);
- arable farming and monitoring (efficiency);
- food processing and efficiency;
- horticulture and efficiency.

Figure 6.2 presents a few ideas for each of these areas.

6.2 SURVEY OF SUGGESTED MST APPLICATIONS

To identify the most interesting and most challenging ideas, those listed in figure 6.2 are evaluated according to a number of specific criteria. The criteria are derived from the characteristics for MST as mentioned in the previous chapter (section 5.1.3). An additional aspect that has been taken into account are the expected spin-offs and the encouragement derived from a successful application. This means that ideas expected to demonstrate MST's potential are included.

Animal husbandry and monitoring	*Farming and monitoring*	*Food processing and efficiency*	*Horticulture and efficiency*
Outside the animal [1] Measurement of milk during milking: composition, temperature, protein fat, cell number Food conversion	**Micro surrounding** Dispersion processes Monitoring of humidity Nutrition in the soil (H_2O, ions, etc.)	**In process** Origins and control of decay: cleanliness, humidity Prevention of contamination Food handling [1] Moving sensors in a process [3] Detection of pollution, allergenes or pathogens	**Groups of plants** Monitoring of the surroundings (temperature, atmosphere, humidity and light, nutrients) [1] Monitoring of pesticides Detection of hazardous organisms Early plague detection [1,2]
On the animal Resistance vagina mucous membrane Lean-meat ratio	**Entire field** Humidity on leaves Early plague detection (fungus, insects) [1] Decontamination of the soil (e.g. microwaves) Image analysis	**Surrounding** Scent analysis [2] (baking of bread) Storage conditions like shocks, humidity or temperature [2]	**Surrounding** Nutrition detection in substrate e.g. humidity, pathogenes Process control
In the animal [1] Identification (implantable, up to slaughter) Measurement (implantable) of temperature, [2] activity or heartbeat Hormone levels (specific hormones) [3] Internal pressure in birth passage One per group applications [1] – detection of food pathogens – infectious disease detection	**On/in plant** [1] Detection of leaf defects Fungus detection during growth, harvest or storage Measurement of plant saps [3] Fluorescence (chlorophyl) Ripeness detection (fruit)	**Tracing of individual items** Monitoring of origin Quality measurements [1] Safety of food: detection of pollution, detection of allergenes Monitoring of conservation Microsensors in critical points (HACCP) [1] Monitoring/fermentation control	**In plant/on plant** In plant processes (fluids, temperature, activity) Product handling Measurement of speed of growth Pollination mechanisms [3] Refinement (R&D)

Figure 6.2 Ideas for agricultural applications of MST. Ideas marked [1] are discussed in section 6.2, for [2] see sections 6.2.1 to 6.2.4 and for [3] see sections 6.3.1 to 6.3.4.

The evaluation led to four ideas which are briefly discussed in the following sections, and four cases discussed and worked out in section 6.3. For these four cases the technical feasibility has been evaluated and, where possible, the economic conditions are described. The remaining ideas referred to in figure 6.2 are briefly discussed in the following.

A problem common to all the ideas is the power supply to the miniaturized devices. This means that miniaturized energy sources will become an important feature of agricultural applications (and all other applications) in the near future.

Animal husbandry [1, 2]

In milkstream sensors it has been observed that it is possible to detect the contamination of milk caused by a sick cow (cell number); thus it should be possible to transmit the occurrence of the contamination to a central unit which could directly notify the vet.

'In animal ideas' could be combined to an *in vivo* analysis laboratory. Generally speaking, implanted systems should use as little energy as possible; a collar could transmit data at desired moments. The requirements for those 'in animal ideas' naturally resemble the medical demands in Chapter 4.

Taking information on each individual cow seems economically feasible; for other animals, however, such as pigs or chickens, individual systems do not seem feasible in the short term. One option is to select a few animals from a flock or herd and use their output to give a general indication.

Arable farming

Arable farming is expected to benefit from MST if the condition of plants or the soil could be measured at several locations. This would give an insight into the performance of different regions and could lead to local or regional action.

Priority is given to applications that will help to identify causes at an early stage, e.g. early warning systems for pests during storage (insects, fungus). Combating pests by the usual methods should if possible be avoided, as this cures the symptoms rather than the causes.

Food processing

A possible field of application for MST is the handling of food (e.g. sensors in grippers). An artificial hand for sorting tomatoes should do so naturally with the least possible force.

Hazard Analysis Critical Control Points (HACCP) is a philosophy for identifying several critical points for measurements in a process eliminating the necessity for end-control and saving storage time. MST could help to realize this kind of strategy.

One other possible MST application is the quality control of meat. Determining the freshness of meat is still a difficult problem, but quality demands for meat clearly exist and thus lead to a need for quality control systems. A challenging parameter to measure is the hardness or the elasticity of the meat.

Horticulture

The ideas mentioned under farming also apply to horticulture. Other ideas however seem more feasible in horticulture, e.g. image analysis or (almost) individual nutrition and monitoring.

6.2.1 PHYSICAL MEASUREMENTS IN THE ANIMAL

H.J. de Jong

Introduction

In farm management animals can be recognized automatically and individually by providing them with a Radio Frequency IDentification (RFID) tag with nearby an RF interrogation antenna. The tag will pick up RF energy via a built-in antenna coil and start to transmit its unique identification code. These RFID tags, normally fastened to the outside of the animal (on the collar or ear), can now be made so small that combined with a sensor it is possible to inject them with a special type of syringe.

Aim

Once inside the animal such an RFID device is in the ideal place for performing important physical and even chemical measurements, making use of the same radio link to transmit the encoded measured data together with the ID code. The link also includes a microprocessor to provide intelligence, i.e. interpretation of the data received.

This section considers only physical measurements; section 6.3.1 provides an example of chemical measurements. This combination, although interesting, is very complicated but may be possible in the distant future, followed by the addition of intelligence for making diagnostic decisions. Physical parameters which can be monitored by an injectable RFID device are [3]:

- temperature: for health monitoring and heat detection;
- pressure: for health monitoring (heartbeat) and detection of the time of birth by sensing the tissue pressure near the birth canal [4];
- movement: heat detection by monitoring the intensity of physical activity of the animal;
- inclination: detection of the onset of labour; e.g. horses will lie down while giving birth.

Technical realization

Microsystem technologies can be used to produce the built-in sensors, for example:

- temperature measurement can be realized with resistance thermal sensors;
- an integrated pressure sensor on a chip (membrane with strain gauges or capacitive detector) can monitor pressure;
- movement can be detected by an integrated acceleration sensor on a chip,

perhaps combined with a pressure sensor by adding mass to the sensor membrane;
- inclination can be measured by sensing the position of a mass on a bending beam with strain gauges.

The form of the RFID and sensor insert should be cylindrical and is illustrated in figure 6.3. The surface of the insert must be biocompatible to prevent migration through, or even repulsion by, the body of the animal.

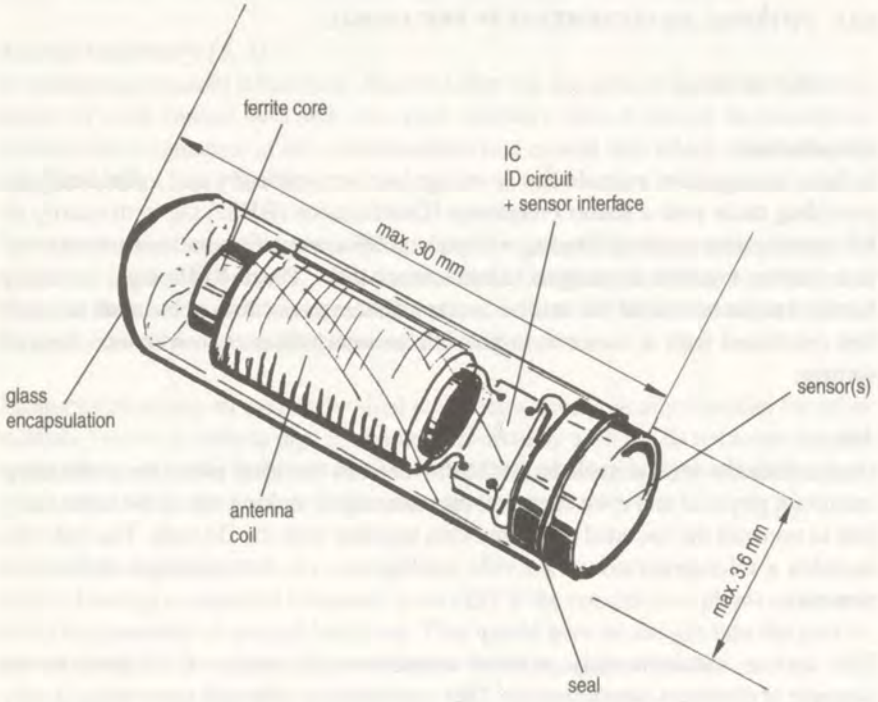

Figure 6.3 Layout of cylindrical RFID and sensor

Energy for operating the electronics of the RFID and sensor device can be derived in several ways:

- A built-in battery. This is not recommended for the life of the battery is limited (at least 4 years are required for applications *in vivo*) and pollution reasons. However, a battery may be the only solution when continuous monitoring is necessary.
- Generation of energy in the movement sensor during physical activity of the animal; possibly not sufficient due to the small dimensions of the insert.
- A turbine generator picking up energy from the flow of body fluids (blood, lymph); precipitation of parts of these liquids may give problems.
- From the RF energy, picked up from the RF interrogation field, which is an approved method with RFID. In this case, the insert works only when the animal is within reach of the interrogation antenna (e.g. in the feed box); this may be sufficient in practice.

6.2.2 ODOUR SENSING

G. Huyberechts

Introduction

Upon investigation, the dictionary offers a great variety of nouns to describe smells of different quality: scent, perfume, fragrance, aroma, stink, etc. In daily life the sensory stimulus called odour does much to complete the observation of our surroundings; its subtle variety, although carrying essential information, is hard to express in words or to quantify.

The quality of various end products from industrial and agro-industrial processes is determined, at least in part, by the presence (or absence) of specific odorous compounds. Examples can be given in obvious domains such as beverages (wine, beer, fruit juices, coffee and tea) and foodstuffs (cheese, fish and grapefruit). However, one can imagine not only the use of odour or aroma-sensing for end products, but also as a valuable tool during food processing (the aroma development during the roasting of coffee or baking of bread), quality control (freshness of fish) and efficiency of storage (loss of aroma during storage of truffles) and transport (scent monitoring of shipped flowers), animal health monitoring and environmental impact control (odour emission and emission reduction control).

Aim

In most of these applications either complex analytical instrumentation or olfactory panels are currently used. It is clear that in a variety of applications this approach is quite expensive and limited in both space and time. One can imagine that in a number of applications the continuous monitoring of volatile organic compounds, or other substances contributing to the odour impression of a sample, would be advantageous. Even measurements which are not possible to perform with olfactory panels or separation based analytical techniques become feasible [5]. Microsystem technology can aid in the realization of small, low cost and reliable sensor arrays with appropriate signal processing (see Appendix 1). The 'electronic noses' thus formed can either be used for continuous monitoring of odour impressions in the domains mentioned above or, with the use of artificial neural networks, can even be taught to combine the signals of several sensors and report the resulting information in a way which comes close to subjective human response.

Microsystem aspects

Due to inherent advantages of microsystems, such as miniaturization and incorporation of intelligent signal processing electronics, it becomes possible to create relatively small 'electronic noses'. These consist of a number of miniature gas and vapour sensitive devices and the resulting array is combined with, for example, an artificial neural network or a fuzzy logic based signal processor. A variety of sensors based on different working principles is reported in literature and is even commercially available. Whereas the 'classical' Taguchi gas sensors are based on resistance changes in semiconducting metal oxides, other designs, materials and measuring techniques offer specific advantages. Sensor materials based on electronic conducting polymers, semiconducting organic macromolecules, etc. can be used and combined into an array of sensors giving a typical fingerprint of the measured substances. Once these microsystems have 'learned' to recognize and discriminate the odours by the patterns generated by the sensor array, they can be used in several of the above-mentioned applications, not as a substitute for the complex analytical off-line instrumentation or the human expert, but as a dedicated and reliable process monitoring and control element.

6.2.3 MONITORING GROWTH AND STORAGE CONDITIONS OF AGRICULTURAL PRODUCTS

L.G. van Willigenburg

Introduction

Most agricultural products are developed and stored under conditions that can be influenced. Improvement of product quality demands accurate and distributed monitoring of growth and storage conditions. Off-line study of the data allows for the development of mathematical models describing the influence on product quality of surrounding conditions during growth and storage. On the basis of actual data and these mathematical models, information about product quality becomes available that is important for customers. Furthermore these mathematical models allow for the design of automatic control systems to optimize both growth and storage conditions. Until now a major drawback in the development of mathematical models and automatic control systems is the high price, poor handling capability and limited accuracy of sensors to monitor growth and storage conditions. The main types of sensors required are those that measure humidity, gas concentrations (often CO_2), illumination spectra, temperature, pressure and concentrations of several liquids.

Compared to laboratory situations agricultural products are developed and stored in hostile environments. This puts severe demands on the robustness of sensors. In conventional situations sensors are connected to a central data collecting device through wires. The wiring is expensive, inconvenient, vulnerable and may introduce inaccuracies in the data (e.g. due to grounding problems). The recording of data is performed by the central device and therefore the data is not portable.

Implanted electronic measuring device

In medical and agricultural research (and in some applications) a recent technique consists of implanting small electronic devices (often single-chip) to perform measurements. The electronic devices usually consist of a single chip connected to sensors that may be part of the chip itself, signal processing circuitry, memory and a radio link. The radio link is used to send data to a wireless receiver. The radio link also creates the possibility of sending commands to the implanted device. Figure 6.4 shows a block diagram of the devices for climate control and for quality detection.

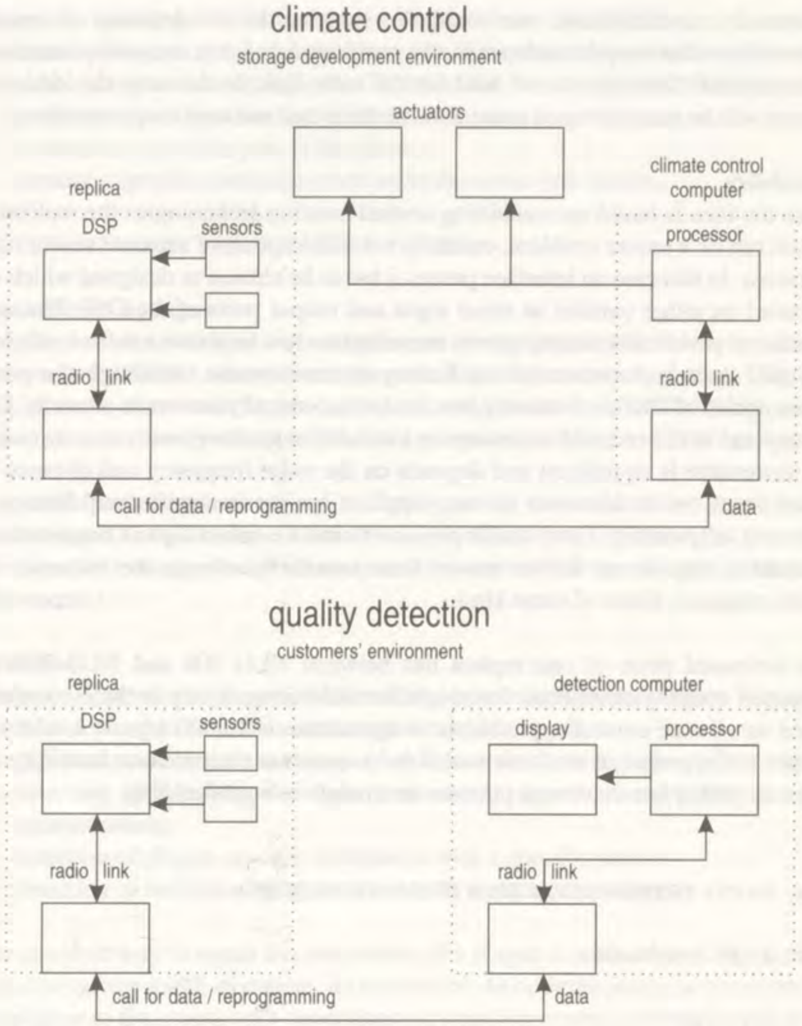

Figure 6.4 Block diagram of implantable electronic measuring device

Recently a special type of single-chip computer, called Digital Signal Processor (DSP), has become available commercially against very low prices. These computers are characterized by a very sophisticated architecture based on parallelism which results in a very high speed performance. Therefore DSPs are extremely suitable for sophisticated on- line digital signal processing.

The main idea is to develop DSPs that contain a radio link and 'on chip' sensors suitable for monitoring and analyzing data in agricultural products, or their replicas, after implantation. Obviously this development has also many other areas of application. This development would circumvent all of the problems mentioned above. Furthermore the implanted system with the computer and the radio link permits complete reprogramming. Obviously the number of different sensors that can be integrated 'on chip' strongly influences the range of application of such a device. Since the positioning of several sensors, such as radiation and pressure sensors, is a crucial factor, one could also imagine the development of separate sensor chips that may be independently positioned and that are easily interfaced with the DSP. The same could hold for the radio link. In this way the implanted system will be manufactured using several chips that are very easily interfaced.

Feasibility

Since the idea is based on combining several existing technologies the realization should not be a severe problem, certainly not if the option of separate sensor chips is chosen. In this case an interface protocol has to be chosen or designed which can be based on either parallel or serial input and output ports of the DSP. The most significant problem is to keep power consumption low to obtain a sufficiently long lifetime, since replacement of the battery is cumbersome. Although the power consumption of DSPs is relatively low, i.e. in the order of microwatts when the DSP is busy and in the order of nanowatts in a standby state, the power consumption of the transmitter is significant and depends on the radio frequency and distance the signal has to travel. However in many applications the transmitter will have to be activated only during a very small period of time i.e. when data is requested. An alternative may be to deliver power from outside to charge the battery using electromagnetic fields of some kind.

The estimated price of one replica lies between NLG 100 and NLG 200. An estimated quantity of replicas that might be sold commercially in the Netherlands based on climate control applications in agriculture is 10,000 a year. A relatively simple but appropriate test case would be to measure temperature, humidity and pressure within one or several potatoes in a potato storage building.

6.2.4 EARLY PLAGUE DETECTION IN HORTICULTURE

J.J.H. van Nunen

INTRODUCTION

In horticulture, especially in greenhouses, plague detection is most important. Plagues can be disastrous due to the monoculture and the total absence of natural enemies in a greenhouse setting. If a plague is detected at an early stage control can be more effective and the use of pesticides and the related economic and environmental costs can be diminished drastically.

Plagues are generally caused by bacteria, viruses, fungi or small insects. They all are minuscule and hardly visible to the naked eye, so the detection of plagues before significant harm is done is extremely difficult. MST devices can deal with the causes of the plague on their own scale. To detect the plagues at an early stage, the plague detector should either detect the damage to the crop immediately or detect the first intruders. This type of detection is more readily feasible, and is an easier option than detecting damage to the crop. Furthermore, the initial intruders can be detected in specific places.

Generally speaking it will be almost impossible to monitor every plant in the greenhouse. To get a good global impression of the situation, a number of detectors should be placed in strategic places. To attract the insects the detector system can:

- generate a specific attractive microclimate;
- emulate an attractive part of the plants;
- possess a specific (sexual) attraction to the unwanted insects.

SPECIFICATION OF THE DETECTOR SYSTEM

Attraction of a plague

In order to maintain a specific microclimate the system should be able to measure and control different climatic components, like temperature, moisture, CO_2 level and, perhaps, also some plague-dependent components. It should therefore contain different sensors and actuators, like small pumps and cooling and heating elements.

A specific part of a plant can be imitated by giving the detector the corresponding colour(s), texture and shape. Moreover, a special (flower) scent can be generated. The detector system can also attract insects by emission of specific sexual attractors (feromones).

Detection

The occurrence of the plague and should be detected and depending on its nature a number of possible detection mechanisms could be used:

- registration of the colour change of an infected substrate with a colour sensor;
- detection of the change in light transmission or reflection by light intensity measurements;
- detection of plague-specific substances with a specific sensor;
- detection of individual plague causes with imaging techniques.

The simplest way to signal the occurrence of a plague is with a visual signal on the detector system itself; of course, it is preferable to communicate the occurrence of the plague to the greenhouse supervisory system, for example by radio.

Energy supply

The energy to operate the detector system can be delivered in several ways:

- by built-in battery; the detector is used for only one growth season, so this is a real option if the maintenance of a microclimate is not needed or does not need much energy;
- by photovoltaic cells with a short-term buffer; a disadvantage is the size of the photovoltaic elements;
- through energy supply by wire; a disadvantage here is the more complex installation but on the other hand it simplifies communication with the greenhouse supervisory system.

6.3 CASES OF APPLICATION OF MST IN AGRICULTURE

This section describes four cases where MST can be applied in agriculture. Whenever possible the technical feasibility and the economic conditions are discussed. The first case concerns a detector for hormone levels in living animals. The second case introduces a device for the monitoring of plant saps. The system extracts an amount of plant sap and analyses its composition in a microlaboratory. A further case is a microsystem that 'swims' in a production process and travels with the product while performing all kinds of measurements. Finally an artificial bumblebee is described as a challenging and imaginative example of what could be achieved with microsystem technology.

6.3.1 IN VIVO MONITORING OF HORMONE LEVELS IN FARM ANIMALS

H. Hofstra, H.J. de Jong and G.A. Schwippert

Aim

A detector unit is envisaged for *in vivo* monitoring of a number of hormone levels, both of natural and of artificial (growth stimulating) hormones in farm animals, predominantly pigs and cattle. Conditions relevant to farm management in general, like heat, pregnancy and stress will be monitored using a more direct method. For cows the aim is a reduction of the number of days between two calves. Moreover, the system described here will allow an effective check on the use of prohibited additional hormones. The case seems suitable for development by industry (in cooperation with universities), which makes this a short-term application.

Specification of the detector unit

The sensor to be implanted in the animal should preferably be suited for the *in vivo* monitoring of several hormones at the same time. Hormone levels should be transferred to the farm management computer several times a day; for example, during the animals' visit to a feeding station. Hormone levels of progesterone, oestrogen, prostaglandins and adrenalin should certainly be monitored and, in addition, a number of such growth stimulating hormones or β-agonists, as for example, clenbuterol.

Apart from sensors for hormone levels, the detector unit will contain a thermosensor to monitor the animal's internal body temperature (disease conditions, heat) and should contain an identification system for coupling the data transferred to the animal's individual ID code.

In addition to the specifications given so far, the device should also meet high standards concerning longevity and reliability. The sensor should show a constant sensitivity combined with a service life of at least 4 years *in vivo*. The effectiveness of the device should not be influenced by encapsulation or fouling. The sensor should be easily implantable, preferably by the farmer. It should not migrate inside the host animal or rotate more than 30°. It should be easily removable from the live animal or during slaughter. Afterwards it should be reprogrammable and thus reusable.

The sensor will not have its own energy source (battery). It will preferably be fed by an external Radio Frequent (RF) energy source, operating with a frequency between 100-135 kHz and with a field strength in accordance with national regulations. The receiver of the sensor unit will make use of a tuned coil on a ferrite-bar. It will also function as a transmitter to transmit the coded signal from the sensors and the identification (ID) code to the receiving unit in the feeding station. The ID code will be 64 bits according to an ISO proposal [6]. Transmission and reception can be based on existing technology, e.g. by short-circuiting the coil of the sensor in the rhythm of the operating frequency. The external receiving unit has one or more antennas which receive the code as a modulation of the signal from which the code can be derived.

Location, size and shape of the hormone sensor

There are only a few locations inside the animal suitable for accommodating the detector unit, if the above requirements concerning encapsulation and fouling are taken into account. Attachment to the peritoneum and detection in the intraperitoneal liquid could allow for a long service life. However, the implantation in this site is difficult and probably requires the skills of a vet.

Another location could be the bladder. Insertion into the bladder and attachment near the front end of the urethra could probably be performed by the farmer with the help of a catheter. A second important advantage of this location is that no tissues have to be passed. Positioning the sensor in or around the frontal end of the urethra would allow an optimal reception of RF energy and interaction with the external receiver unit. A prerequisite for the use of this location is that the sensor is neither obstructing the urine flow nor is driven out by its force. These requirements can probably be met by providing the sensor with an 'umbrella-like' structure to immobilize it and keep it in the right position (figure 6.5). Measures should be taken to protect the device against corrosion by salts and urea in the bladder environment.

Technical possibilities for the sensors

The development of the sensor for *in vivo* hormone detection can, in principle, be based on a combination of several existing techniques:

- Hormone recognition by specific antibodies or preferably by the natural receptor proteins of the hormones concerned.
- The use of antibody or receptor molecules, immobilized on a semiconductor substrate that is accessible to the analyte which also serves as an interface for the generation of a physically detectable signal. The availability of the hormone-recognizing molecules on a solid phase allows the development of a continuous sensing device for *in vivo* detection.
- The application of physical techniques to read out the interface. The following techniques could be applied:
  - Piezo-electrochemistry, Surface Acoustic Waves (SAW) or Bulk Acoustic Waves (BAW) which are all based on mass changes on the surface of the receptor.
  - Conductometry depending on a change in impedance of the receptor surface.
  - Magneto-induction; an alternative for conductometry based on a change in damping, probably with a higher selectivity for the surface of the receptor.
  - Chrono-amperometry, which is based on a change in the redox condition.

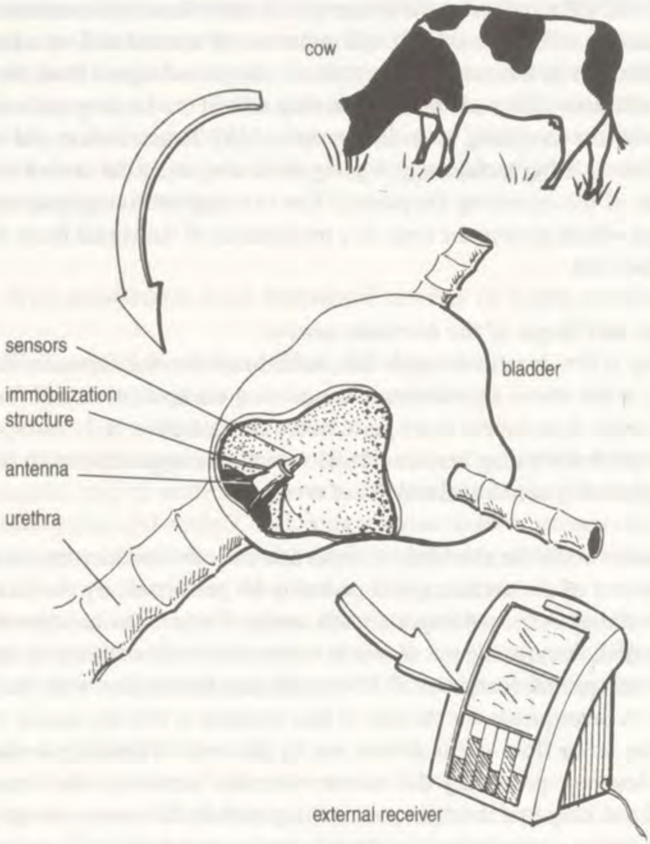

Figure 6.5 Hormone level monitor

A simple model based on one hormone can serve as a pilot system to evaluate the application of the above principles. Other hormones, relevant to the purpose described in this section, will then be introduced into the system one by one, re-tuning the system after each introduction.

Economic feasibility

The economic feasibility of the hormone detector has been calculated for cattle and for pigs. One arrives at the following statistics:

- *Cattle*. In the Netherlands there are 2 million cows of which 25% are exchanged each year. If about half of the animals would be equipped with a hormone level detector this would lead to a turnover of 200,000 sensor systems a year. Worldwide one can expect 10 times as much. If the number of days between calves could be reduced from 385 days at present to 365 days, this would earn the farmer an extra NLG 60 per cow each year. In four years this would be NLG 240 per cow. Monitoring pregnancy saves another NLG 40 per cow, totalling NLG 280. The price per complete sensor system should not exceed NLG 150. For calves for slaughter, the sensing system should only be used to monitor illegal growth hormones. The system should contain a thermosensor to detect disease, an adrenalin sensor to detect stress and an ID code. However, this market is too small to be profitable unless the use of the device were legally prescribed.

- *Pigs*. In the Netherlands 1-2.10^5 detectors per year could be sold. Ten times this number could be expected worldwide. The total financial benefit from a higher number of births per sow is estimated at NLG 50 maximum, which means that the system should not cost more than NLG 25 per animal.

6.3.2 PLANT SAP MONITOR

F.W.H. Kampers, G. Huyberechts and H.J. de Jong

Introduction

There are two types of sap flow in a normal plant: water and dissolved nutrients are transported from the roots to the plant parts above the earth through the xylem vessels, and water and dissolved sugars flow from the leaves to fruits, roots and other non-photoactive parts through the phloem vessels. Both types of flow contain important information on the condition of the plant, particularly the fruits. By monitoring specific parameters of these flows the plant can be kept in optimum condition to perform its productive tasks. It is possibly sufficient to monitor only a few typical plants in a bed to optimize the conditions for them all.

Scope

A plant sap monitor should be able to measure the flow speed of liquids in both the xylem and phloem vessels. Leaf evaporation can be derived from the xylem flow which gives an indication of the overall condition of the plant. From the flow in the phloem vessels the demand of the consuming organs can be derived.

Apart from the flow the concentration of certain ionic and organic components is of interest. The concentration of nitrogen-containing ions largely determines the growth rate of a plant – as one of the main building blocks of proteins they have to be transported from the roots to the growth areas. The concentrations of calcium and potassium ions also influence the condition of the plant. A low concentration of these ions (and probably others) gives rise to certain specific depletion sicknesses. The concentration of glucose and fructose in the phloem flow is indicative of the supply from the leaves and the demand from the fruits and other non-photoactive parts. A plant sap monitor should be able to measure all these concentrations.

The development of a plant and the specialization of certain plant tissue is governed by plant hormones. Examples are abscisic acid (ageing), several giberilines (stretching of stems, ripening of fruits, etc.), auxins (sprouting and root development) and cytokinines. Apart from these internal hormones, plants also make use of external hormones. One known external plant hormone is ethylene. By monitoring the concentration of these hormones in the plant saps or in the atmosphere in the vicinity of the plant, the development of the plant, the ripening of fruits and the development of flowers can be determined and possibly changed to fit specific needs (e.g. ripeness of fruits at a convenient moment or availability of flowers on ‘Mother’s Day’).

The temperature of the plant saps also contains information on the health of the plant. In this case an absolute measurement is not necessary as the information is contained in the temperature difference between the saps and the surroundings of the plant.

The technology developed for a plant sap monitor might also be used to measure the acidity in the meristem and the vacuoles of leaves, and the concentration of nitrate in the vacuoles of, for instance, lettuce.

Description and technical feasibility

The plant sap monitor can take two forms: it can be a device (semi-)permanently attached to a plant for monitoring that individual plant, or it can be a device with which plants can be monitored periodically. In the first case it is assumed that the measurement data obtained from a limited number of individual plants is representative for the entire population; in the latter case a person can temporarily connect the device to individual plants as a diagnostic tool for the health of that plant (figure 6.6). Although these two separate applications of a plant sap monitor on a larger scale will result in different devices, the modules on a microsystem scale will be very similar: both will have to make contact with the two types of vessel, both must be able to extract fluids from these vessels, both must be able to analyze the fluids, and both must be able to measure temperatures in the vessels and in the micro-atmosphere around the plant. Since the focus is on the microsystems involved in this application the distinction between a monitoring and a diagnostic tool will not be made.

The development of sensors for the detection of various hormones can be based on the same techniques as described in section 6.3.1. Again, a simple model based on one hormone can serve as a pilot system to evaluate the applicability of the principles.

In order to make a chemical analysis of the different plant saps it is first necessary to extract a small amount of these saps from the plant. This means inserting a syringe-like structure. The plant should naturally suffer as little damage as possible, so the structure must be very small. Although by carefully changing the depth of insertion it should be possible to enter both the xylem and phloem vessels, it may be simpler to insert two syringes of different lengths, especially since the microlaboratories equipped to analyze the two fluid types will be different.

The pressure inside a plant is not sufficient to transport the saps through the syringe, and pumping elements are necessary to lower the pressure on the laboratory side. A microsystem must be constructed which can build up a sufficient difference in pressure. Although pumping microsystems have been presented in the literature, further study will probably be necessary to obtain a pressure difference which is high enough to extract enough of the liquids in a limited period of time.

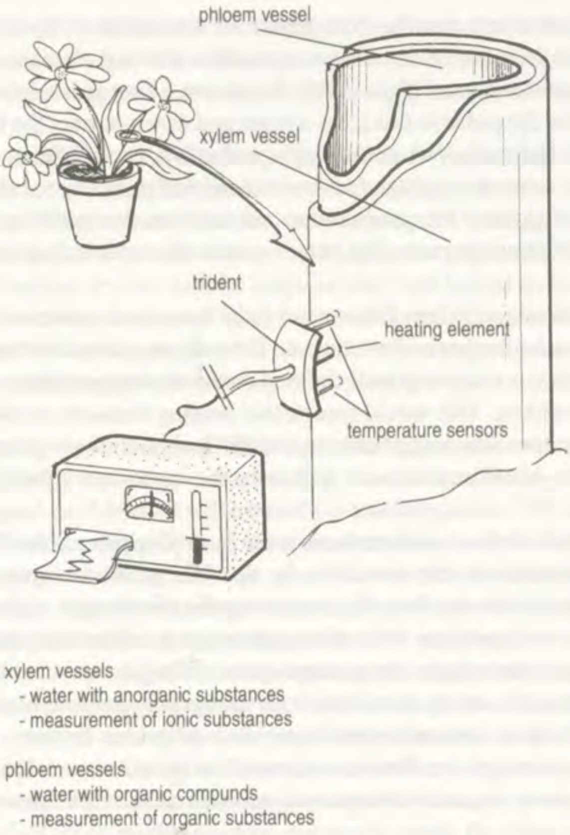

Figure 6.6 Plant sap monitor

The microlaboratories needed to analyze the two types of liquid will have different capabilities. The xylem vessels carry water with dissolved inorganic substances; the phloem vessels carry water with organic compounds. Both flows contain specific hormones. The xylem laboratory should therefore focus on the measurement of ionic substances, whereas the phloem laboratory must be able to measure organic substances.

The temperature difference between the liquids and the surroundings of the plant can be measured with various techniques. Most of these techniques will require a heat contact between the sensor and the liquid. Contactless measurement of temperature is also possible but requires an optical link between the sensor and the liquid.

The measurement of flow speed in the outer vessels of the plant can be taken from outside the plant. This has already been reported in literature and does not require a microsystem. However, if the flow speed in the inner vessels has to be measured, invasive techniques are required. Since the extraction of plant saps also requires penetration into the plant it is obvious that the two measurements are combined. Internal flow measurement can be done in two ways: by using heat pulses or with laser-Doppler methods. In the first case a microtrident can be inserted into the stem of a plant in such a way that the flow passes all three teeth of the trident consecutively. The middle tooth of the trident contains a heating element, the outer two contain temperature sensors (figure 6.6). By giving a heat pulse and measuring the time required for the pulse to travel up-stream and down-stream the flow speed can be determined. Naturally, one of the teeth, preferably the middle one, can be made hollow and can serve as a syringe for the extraction of plant sap for analysis. Before giving the heat pulses, the temperature sensors can be used to determine the temperature difference between the plant sap and the surrounding atmosphere.

If both the phloem and xylem flows need to be measured, a second trident can be used with somewhat longer or shorter teeth. If the distance from both types of vessels to the stem surface is relatively well-defined it may also be possible to measure both flows with one trident. This would require two heating elements on the middle tooth and two temperature sensors on both outer teeth. It would also require that two teeth are built as syringes. For reasons of symmetry the outer ones would be preferred.

A second method of flow measurement is the laser-Doppler method. In this case a light guide is entered into the vessel. At the tip of the guide a micromirror redirects the beam 90° parallel to the flow. By comparing the wavelength of the light – which is scattered by small particles in the flow and which is collected by the same mirror – with the original laser light, the average speed of the particles can be determined. Again the light guide can be combined with the syringe and can also incorporate a temperature sensor to determine the temperature difference between the liquid and the surrounding atmosphere. First measurement of the outer vessels would be done, then the syringe can be pushed deeper and measurement of the inner vessels can be performed.

The signals coming from the different sensors will be conditioned for transport as close to the sensor as possible to limit the influence of distortion. If necessary signal processing and data storage can also be done close to the sensor. Depending on the application, the plant sap monitor can be connected to a data bus or can make use of a radio link. The radio link can be a telemetry link between the (active) plant sap monitor, which is powered by an internal power source, and a receiver. It may also be possible to design a passive plant sap monitor powered from an RF field of a nearby interrogator.

The data is made available to a central computer system either via the bus or by reading out the interrogator. This system will combine the data with measurements of other parameters (temperature, humidity, radiation intensity, soil moisture, concentration of certain elements in the soil, wind speed and direction, rainfall, etc.) and will feed the information into models to estimate the production. Perturbation analysis can be used to determine the influence of parameters that can be changed (e.g. soil moisture, temperature and humidity in greenhouses), enabling optimized production.

Economic aspects

The plant sap monitor's use will be predominantly in greenhouses. Moreover, its use principally focuses on plants grown for their fruits. To estimate the potential market within the Netherlands for such a device this field of application in particular should be investigated. Because of the invasive nature of the device described above, application for plants grown for aesthetic purposes is less interesting.

It is expected that the hand-held measuring device will be developed first. Those in the greenhouse sector must first familiarize themselves with the technology before they invest in it. With the hand-held device they can get a feeling of the information that can be obtained and how it can be used to optimize production. At a later stage the fixed monitoring devices will be implemented and linked to computers which control both the environment and growing conditions of the plants. However, the number of hand-held units per greenhouse will be limited, whereas the number of monitoring devices per greenhouse may be extensive.

In the Netherlands there are about 4000 crop-growing greenhouse market gardeners. Suppose that – after a start-up period – 50% use the hand-held units and that on average five hand-held devices will be used per market garden. The potential market in the Netherlands for the hand-held units can then be estimated to be 10,000. After positive evaluation of the information obtained with the 'hand-held units, 50% of the users may then decide to implement monitoring devices. Depending on the type of plant, the type of crop and the growing method, the number of monitoring devices may vary greatly. To obtain an estimate tomato growers are considered. On average the number of devices may be two per row of tomato plants. There are on average 80 plants per row and an average of four plants per square metre. The number of monitoring devices can therefore be estimated to be 0.1 per square metre. The Netherlands contains about 60 million square meters of tomato-growing greenhouse area. If 25% of all these market gardens eventually apply the plant sap monitor, the number of monitors would amount to 1,500,000. One can assume that the successful application of the monitor to tomatoes will result in application of this technology to other crops as well, which will increase the number of units substantially.

Remarks

Apart from the application of the plant sap monitor to agriculture and horticulture, such a monitor would open new possibilities for plant physiologists. It would give agricultural researchers tools currently unimaginable for studying specific processes in plants. As a result these processes will be better understood and methods to further improve production can be developed with the resulting knowledge.

The plant sap monitor described uses invasive techniques to determine specific parameters of plant saps. Unfortunately these techniques by their nature also give rise to stress in the plant. This may cause a distortion of the measurements resulting in erroneous predictions for the other plants in the bed that have not been monitored. Non-invasive techniques which can measure specific parameters would overcome this problem (e.g. reflection by carotenoids in citrus fruits, impedance or inductance tomography, near-infrared measurements or magnetic imaging techniques).

As the feasibility of the plant sap monitor is not yet clear its time scale can be reckoned to be in the mid or long term. The plant sap monitor focuses on the plant. New sensor systems are presently in development for the post-harvest evaluation of fruits such as apples and tomatoes, mainly based on conductometry and acoustic impedance measurements, and can be expected to appear on the market within 2-5 years.

6.3.3 AN IN-FLOW MOVING MICROSYSTEM FOR MONITORING BREWING PROCESSES

G. Huyberechts, J.J.H. van Nunen, W. Olthuis and G.A. Schwippert

Introduction

Beer is an alcoholic drink obtained by the fermentation of barley malt aromatized by hop. Beer, and other similar beverages obtained by fermentation of other grains, are among the oldest and most widespread alcoholic drinks. The case described in this section consists of a freely moving microsystem which is able to monitor the processes taking place during the transformation of the basic materials into the end product.

Different techniques exist in the brewery, but in general the following sequence of processes is observed. The first treatment is the drying of the malt, at around 70 °C for light and around 110 °C for dark beer, followed by a milling process. The preparation of the malt extract occurs at 70 to 75 °C and the extract is separated from the pulp by decantation or filtration. The extract thus obtained is heated with the appropriate amount of hop, which results in the aromatizing of the extract (and the separation through coagulation of some of the proteins present). After cooling to around 5 °C the aromatized extract is transferred to fermentation barrels. In general there are two main production processes distinguished by the temperature at which the fermentation process occurs (between 15 and 25 °C or between 5 and 10 °C). On completion of the main fermentation process the beer is allowed to ripen in a cool environment. Other fermentation processes for completing the organoleptic characteristics of the beer occur during this stage of the production process.

Aim

The aim in this case is the continuous monitoring of the brewing processes (or fermentation processes in general). This demands the development of a microsystem unit that represents the current and past history of an on-going process – which may be continuous – a batch process or a combination of both.

The functions of an in-flow moving microsystem require the integration of a variety of operational units into the microsystem:

- *Autonomous measurement at different locations in the process stream.* This requires either passive or active movement of the microsystem through the fluid. Passive movement implies a microsystem drifting with the process flow. On the other hand, active microsystem transport opens perspectives to the autonomous movement of the microsystem in order to obtain information of the occurrence of inhomogeneous processes. In either case the determination of the actual position of the microsystem is required. In the case of active movement, silicon based micromotors, propellers or liquid propulsion systems can be integrated but require an energy source.

- *Measurement of physical parameters.* Several relevant physical quantities, such as temperature, pressure and turbidity can be measured without too many problems concerning sensor-liquid interfaces. Appropriate sensor types for temperature (semiconductor band gap sensor, thermopiles, etc.), pressure (membrane type silicon sensors with integrated pressure reference, etc.) and turbidity can be integrated along with, for instance, Lamb wave sensors for density measurements [7].
- *Measurement of chemical parameters.* A variety of chemical parameters could be measured in a complex environment of fermenting material. However, the current state-of-the-art teaches us that the realization of reliable chemical sensors is far more complicated than the realization of physical sensors. Inherently the selector material comes in contact with the surrounding environment which results in an encapsulation problem. Furthermore absolute selectivity is very seldom observed. The improvements resulting from a well developed selector chemistry (enzymes, synthetic macromolecules, etc.) and dynamical measuring techniques will continuously extend the possibilities in this field.
- *Signal processing and data storage.* A control unit is an indispensable part of the moving microsystem, performing tasks such as signal processing, impedance matching and ranging, sensor selection, multiplexing, data fusion, sensor conditioning and sensor failure detection. Data storage on the system is considered only necessary in order to allow the moving sensor to gather data in between two relay stations. The microsystem is to be considered as a smart self-controlling data generation system. Smart signal processing, i.e. the generation of information from the raw data using for instance artificial neural networks or fuzzy logic, is not necessarily to be included in the microsystem itself, but can be part of an overall control system.
- *Taking action, the actuator unit of the microsystem.* The actions undertaken by the microsystem are implicitly covered in the above discussion. These include movement in the case of active transport, conditioning of the sensors including eventually a reagent delivery system, and transmission of the data obtained by the various sensors including an identification code (batch identification and localization of the microsystem).

It should be noted that a similar approach can be used in a variety of processing environments, based on fermentation and other processes. The gathering of physical parameters in particular is believed to be fairly universal, while the development of the chemical analysis part of the microsystem will require a more application-oriented approach.

As indicated in the introduction, the brewing of beer, as an example of fermentation processes, is a sequence of processing steps in a variety of conditions. It is obvious that some of these conditions can easily destroy chemical selector materials. On the other hand it is also obvious that not all chemical parameters are relevant throughout the whole process. As a consequence, the point of introduction of the microsystem(s) is of importance and either different microsystems for monitoring consecutive sub-processes are to be developed (with communication capability) or techniques to protect the sensitive layers from destruction are to be investigated.

In-flow moving microsystems for monitoring physical and chemical quantities are somewhat similar to a Hazard Analysis Critical Control Points methodology (HACCP). Indeed, the in-flow moving microsystems offer some advantages and their use is complementary to the application of the HACCP methodology. In principle one can follow a batch from the beginning to the final product (and even consumption of this product). At a Critical Control Point the information gathered and stored by the microsystem is passed to a receiver. At this point the current status of the process is obtained as well as the relevant history since the previous Critical Control Point (i.e. location of possible problems).

MST aspects

As mentioned above, an in-flow moving microsystem for monitoring brewing processes should fulfil a variety of functional demands. It is clear that a variety of functionalities is to be included into a single device. The examples described further can be seen as a non-limiting list of parameters to be measured and functions to be performed. It will be clear from this enumeration that a variety of sensors and processing units using different (often non-compatible) technologies have to be combined. This also results in the need for a microsystem assembly and interconnection technology combining compounds and devices into a single operational device.

Again the advantages of an MST approach are found in the possibility of miniaturization, mass production and integration of the constituting elements. A multi-chip module-like approach for the interconnection of the different sensors, signal processing and data transfer units is used, combined with packaging techniques allowing selective encapsulation. Figure 6.7 shows a possible realization of an in-flow moving microsystem.

The following functions are included in the system:

- Autonomous movement, obtained by a liquid propulsion system based on small piezo-electric driven 'ink jet' nozzles in well-defined channels in the encapsulant. Alternative approaches based on micropropellers might also be considered. In either case the nature of the liquid to be displaced should be taken into account and energy sources should be included.
- Measurement of physical parameters can in some cases be realized without direct contact with the liquid environment.
- Measurement of chemical parameters, as well as density and turbidity, for instance with Lamb wave devices or integrated optics, require a direct interface with the surrounding fluid. Parameters that can be expected to be of relevance to the brewing process are sugar content, alcohol content, gas development, proteins and specific compounds (alkaloids, humulone, isohumulone). In contrast to the physical parameters, which are almost universal, the chemical parameters to be measured will be strongly dependent on the application. Possible sensor principles are ISFETs and potentiometric devices, amperometric sensors, enzyme electrodes (or even micromachined enzyme reactors) and biomaterial based sensors, all of which can be realized in a miniaturized approach of analytical instrumentation and combined towards an Application Specific Sensor Array (ASSA).

- Signal processing, data storage and transmission asks for electronic circuitry which is interlinked as well as linked to the sensors but covered from the influences of the surrounding environment in order to guarantee proper functioning. Again there is an obvious need for an appropriate interconnection and encapsulating technology, allowing wireless communication through and protection against electrolytes.

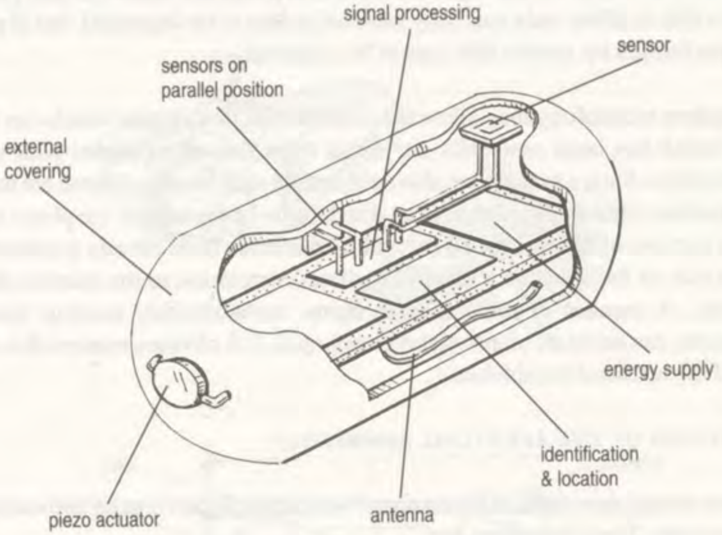

Figure 6.7 An in-flow moving microsystem

Remarks

As the feasibility of an in-flow moving microsystem has not yet been assessed, such a system is a mid to long term development. As a consequence the economic conditions are hard to predict and are not addressed here.

6.3.4 ARTIFICIAL POLLINATION MICROSYSTEM, THE ARTIFICIAL BUMBLEBEE

W. Olthuis, F.W.H. Kampers and J.J.H. van Nunen

INTRODUCTION

Of the several cases described in this chapter, the one proposed in this section is the most advanced. The functions included in this application each require a mid to long-term development. There is a 'however' to this application: this is the only example that not only tries to eliminate influences that negatively affect both the quality and quantity of products, but also proposes to take over a part of what nature is at present doing more or less successfully. Because there are so many challenging aspects to this application, especially with respect to microsystem elements, this remarkable proposal has been fully elaborated here.

AIM

Pollination in nature is in many cases performed by insects. In horticulture these insects are largely absent or not as abundant as in the open field. Lately, insects (bumblebees) have been specially raised and released in the greenhouse to overcome this problem. Moreover, pollination by insects is not selective. Pollen of neighbouring plants is deposited on the stigma of the bloom the insect currently visits. It would be preferable to allow only specially selected pollen to be deposited, but if pollination is performed by insects this cannot be achieved.

Microsystem technology may allow the construction of a system which can deposit pollen which has been especially harvested from flowers of plants with specific characteristics. Such a system can also deliberately skip blooms if these are too close to one another (this would improve the distribution of fruits over the plant) or if the optimal number of blooms for an individual plant has been already pollinated (the average size of the fruits of a plant is in direct correlation to the number of fruits per plant). A number of these microsystems, autonomously moving through a greenhouse, can serve all plants in the greenhouse. For obvious reasons this system is called the artificial bumblebee.

SUB-SYSTEMS OF THE ARTIFICIAL BUMBLEBEE

There are several functions of the artificial bumblebee to perform its pollination task autonomously. These functions are:
- locomotion;
- position determination;
- bloom detection;
- pollen extraction and deposition;
- communication;
- energy supply.

In the following subsections each of these functions will be separately discussed. Figure 6.8 gives an artist's impression of the artificial bumblebee.

Locomotion

If one aims at a faithful copy of an actual bumblebee with its freedom of movement, then the artificial bumblebee should also be able to move autonomously. This, of course, implies flight. For this reason all possible principles known to maintain the artificial bumblebee airborne have to be considered. These are:
- use of hot air or gas with a low specific mass;
- use of thermals (by convective air currents);
- flapping wings;
- propellers;
- rotors;
- jet propulsion.

The availability of very small conventional electromagnetic motors and, moreover, the successful emergence of ultra-small electrodynamical motors manufactured from silicon by three dimensional micromachining, enables the choice of a combination of rotors for the vertical lift and propellers for the subsequent lateral movements.

A combination of rotors and jet propulsion, however, should not be ruled out. Jet propulsion might be achieved by mechanical compression and subsequent expansion or by sudden thermal expansion.

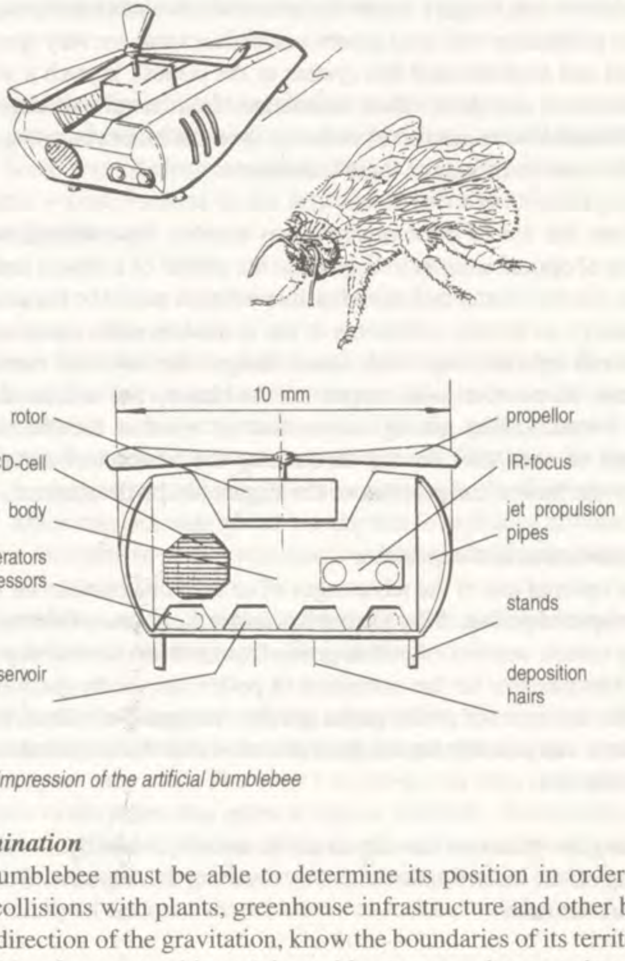

Figure 6.8 Artist's impression of the artificial bumblebee

Position determination

The artificial bumblebee must be able to determine its position in order to find blooms, avoid collisions with plants, greenhouse infrastructure and other bumblebees, know the direction of the gravitation, know the boundaries of its territory, etc. It can do this with reference to objects (plants, blooms, greenhouse or beacons) or in an absolute manner. To determine its rotary position it can make use of inclination sensors in three directions.

Although in theory it is possible to determine the position relative to the starting point by measuring three independent linear and three independent angular accelerations, and by integrating these twice, the measuring accuracy must be extremely high to allow a sufficiently accurate position determination after an extended period of more or less random movements.

A more reliable method for determining its position might be the use of infra-red distance sensors, as currently widely used in auto-focus cameras. Three of these sensors in x, y and z direction enable a fairly accurate determination by the artificial bumblebee of the boundaries of the greenhouse.

Bloom detection

From its three dimensional position, in combination with the knowledge of the position of the plants and the fact that some plants may bloom at a certain height, the bumblebee can roughly locate the area where blooms can be expected. A bloom ready for pollination will emit gaseous substances that are very specific. Nature has improved and sophisticated this system to the utmost, in such a way that the type of target insect can detect these substances from relatively large distances. The artificial bumblebee must therefore home in on the bloom by using sensors that can detect low concentrations of these substances.

Apart from the use of these sensitive gas sensors, the artificial bumblebee could make use of optical sensors to determine the colour of a bloom and to fine-tune its position. An even better and more feasible solution would be the use of optical CCD sensor arrays, as already commonly in use in modern video cameras. By comparing the received optical image with stored images, the artificial bumblebee not only determines its position with respect to the bloom, but is also able to recognize specific characteristics giving information on whether the bloom is ready to be pollinated or not. After having determined the location of certain characteristic points of the flower, the position of the stigma can be determined.

Pollen extraction and deposition

To make optimal use of the advantages of an artificial bumblebee the system must carry the special pollen. After the bee has found the stigma of the bloom it must then extract a certain number of pollen grains from a reservoir and deposit them on the stigma. Mechanisms for the extraction of pollen may be by suction or electrostatic forces. Certain types of pollen grains are also ‘designed’ to adhere to insects bodies. An actuator can possibly be designed in such a way that a limited number of pollen grains stick to it.

Depositing the grains on the stigma can be accomplished by reversing the suction, switching off the electrostatic field or by touching the stigma with the pollen-loaded part of the actuator.

Communication

Although a fully autonomous bumblebee would be able to perform these the tasks alone, some basic means of communication should be available. This communication would primarily serve to send instructions to the bumblebee (‘there are no blooms at the moment because the plants are being changed’). Secondly, it could be used to receive information on the progress of the bumblebee’s tasks (the number of flowers visited, the amount of pollen deposited etc.). Thirdly, the communication link (by radio-frequency waves or by optical means) could be used to track the progress of the artificial bumblebee.

Communication with a local computer system might be necessary to process the large amount of sensor data adequately. Artificial neural networks or fuzzy logic techniques might be necessary to enhance the specificity or to enable accurate recognition of some gaseous components from the data of the gas sensors. In addition, the comparison of data from the image sensors with images of flowers previously stored in the computer requires considerable data processing capacities. If these functions can no longer be performed by the local computer capacity of the artificial bumblebee itself, then communication must help to send this data to and from the larger computer system in the greenhouse.

Energy source

It is questionable whether the artificial bumblebee is able to supply its own energy, the more so because it should also carry this energy source, which requires extra energy in itself. Some way of electromagnetic field coupling by using coils or by RF electromagnetic waves, focused on the artificial bumblebee, should guarantee the supply of energy necessary.

REMARKS

Although until now the description of the artificial bumblebee has focused on pollination, it is clear that the system can also be used to perform other tasks. For instance, if pollination is to be performed only with the pollen carried by the bumblebee, the anthers of the blooms must be removed. This must be done just before the bloom is ready to be pollinated, because otherwise the flower would not reach that phase. Since this is a task which is comparable to that of pollination the bumblebee may be designed in such a way that it can also sterilise the blooms.

If the artificial bumblebee can be designed to detect certain harmful insects it may also be able to remove them (or their eggs, for instance).

The term artificial bumblebee suggests a flying microsystem. However, a microsystem at the end of a robot arm which moves through the greenhouse on a small lorry would serve the purpose very well. The lorry can move over rails and make rough movements relative to the plants that grow at regular intervals. An industrial robot arm moves the 'bumblebee end-effector' towards the area where blooms are to be expected. Then a fine movement mechanism comes into effect to bring the 'bumblebee' into the vicinity of a chosen bloom, where an actuator can deposit the pollen onto the stigma.

COSTS

Of the three cases presented this one can only be realized on a long-term basis. Who would have thought that the computing power of a $ 1,000,000 mainframe system of 15 years ago can nowadays sit on your desk, and for approximately one-thousandth of the price? For this reason, the eventual costs have not been estimated and a profit analysis has not been made.

CONCLUDING REMARKS

Due to the absence of large numbers of insects in greenhouses, there is a need for systems capable of taking over the function of pollination: that is, artificial bumblebees. Almost all subsystems of an artificial bumblebee are already available separately on other systems or are being developed in research institutes [7-10]. The main challenge now is to make a unique combination of the separately described subsystems into one complete microsystem: the unique integration of a number of sensors from several domains (chemical, mechanical and optical) with an intelligent processing unit and a number of mechanical actuators.

6.4 PERSPECTIVE OF MST IN AGRICULTURE

Task Force Agriculture

The subject of this section is the perspective of MST in agriculture. The discussion is limited to the economic and social benefits of MST. The required infrastructure and education are not considered to be specific to agriculture and the reader is referred to Chapter 8 for these subjects.

Economic expectations for MST

MST, and IC-like bulk production techniques in particular, promise very low prices when produced in large numbers. These large numbers are potentially present in the agricultural sector, where a distinct need exists for extra data obtainable with MST devices for farm management, diagnosis, logistics, etc. However, these large numbers will only become reality when the price is low enough for use in this sector, where profit margins are notoriously low.

Agricultural production units (farms) are relatively small-scale operations that do not have much capital for investing in risk-prone technology. These investments must be made by larger organizations. However, these organizations seldom produce agricultural equipment. Moreover, agricultural entrepreneurs and companies may tend to be conservative and seldom innovative when it comes to applying new technology. This makes the market for microsystem devices very uncertain, especially in the beginning. The average time for a return on investment will therefore be large, which makes this field of application unattractive to large companies. The national government and the European Union may overcome these problems by financing pathfinder projects. If the risks of agricultural MST projects can be shared with the government, agricultural companies will be more willing to engage in innovative projects. Positive results of these projects will result in other agricultural applications of MST. Moreover, the spin-off will be that new technology becomes available for medium-scale applications.

Short, mid and long-term developments of MST

It is expected that physical MST sensors (temperature, pressure, acceleration etc.) will be available in the short term because of their relative simplicity, their expected long life *in vivo* and their current state of development.

Biochemical sensors (blood composition, hormones in animals, chemicals in plant saps etc.) will require much more time for development, because of their far more complicated nature. The lifetime *in vivo* is still a particular subject of intensive research: many of these sensors are attacked by biofluids or loose their activity due to deposits on or poisoning of active layers on the sensor surfaces during application.

In the long term it seems feasible that computer intelligence will be added to MST devices. The amount of power required for on-chip computers is diminishing rapidly, but is nowadays still far too much for passive implantable MST devices. Built-in intelligence, however, is a challenge for autonomous internal diagnosis in animals and plants.

Expected social benefits of MST

New products will not only become a success because of their efficiency, but they also need to be accepted by society. People are becoming increasingly aware of the effects of technical achievements on welfare, ethics and the environment. And on these points especially MST may score well in agriculture, as demonstrated in the previous sections.

Simple automatic RFID of each individual animal is already possible. Now animals no longer have to be tied into their stalls, but can move around freely and eat whenever they wish from automatic feed boxes. With MST sensors mounted within implantable RFID devices, the health and behaviour of each animal can be monitored better than before, resulting in less suffering of animals *and* better productivity.

And last but not least, the environment will benefit from the application of MST devices. In agriculture, pollution of the ground and water are well-known threats: far too many insecticides, pesticides, herbicides, fertilizers and additives to nutrients are used for protection and growth of crops and cattle. In the intensive livestock industry the large concentration of manure produced causes high levels of phosphates and heavy metals in the ground and the water supply. MST devices offers a new method for monitoring the amounts of pollutant.

The devices will contain tiny physical and biochemical sensors that can be inserted into the animal and into plants. With the aid of these devices continuous monitoring of the effect of pesticides, as well as fertilizers, nutrients and additives, becomes possible in a very individual and precise manner, leading to better knowledge of the metabolism in crops and animals and thereby to a precise calculation of the necessary amounts of the above-mentioned substances. Together with automatic dosing systems, the use of MST devices will thus enable us to prevent overdosage, which will result in less wastage and pollutants in the environment, and at the same time leading to more efficient production.

6.5 CONCLUSIONS AND RECOMMENDATIONS

Task Force Agriculture

Involvement of all parties

The development and initial implementation of MST in agriculture requires the active involvement and financial participation of potential users, developers, universities and research institutes, national governments and the European Union. Specialists from universities and research institutes will have to convince potential users of the benefits of MST. In addition, they will have to convince governments and the European Union that the development and implementation of MST can only be successfully achieved if the R&D is supported by substantial funding. As the first microsystems will consist of several system modules, standardization should be taken into account, which will stimulate the use of MST and lead to larger numbers being produced. However, standardization is only worthwhile when the technological possibilities are sufficiently clear.

Universities should transfer knowledge

Universities will be involved in the first steps along the road that leads from a 'brilliant idea' to a cheap, mass-produced but reliable application of MST in agriculture. This means that universities will be responsible for the first step: from idea to the first prototype. Universities should therefore not be afraid to descend from their ivory towers and recognize the opportunities present in agricultural applications. They should transfer and further develop their knowledge and expertise, for instance through Ph.D. studies carried out in close cooperation with research institutes or companies.

Education should stimulate technology

In the opinion of STT's Task Force Agriculture, the Agricultural University of Wageningen and the many *Hogere Agrarische Scholen (HAS)* in the Netherlands should focus more on the opportunities offered to agriculture by technology. Courses on computer architecture and its applications, and on sensing in combination with signal and system analysis, modelling and control, are all of vital importance. These courses would improve scientific knowledge and would stimulate the use and development of sophisticated production systems in which microsystems can play a key role. This in turn will result in cheaper and more sophisticated production methods with less environmental impact.

Research institutes have to demonstrate feasibility of applications

Research institutes can bridge the gap between prototypes and initial application. In other words, they will have to show that prototypes will function in the given situation and in the environments they were designed for. This is probably the most expensive of the steps towards routine and mass application. Research institutes should also use their relations with small, medium sized or large companies to involve them in this development and to interest them in small-scale pilot production of MST applications. Small and medium size enterprises are needed to close the gap that exists between the 'inventors' of MST in research laboratories and the potential users. Their role will be to take the important step from pilot project to mass production.

Necessity of consortia

When the expected market volume is compared with the market volume for integrated circuits, and the small number of European IC producers is taken into account, it is obvious that a European market for MST producers will only support a limited number of successful producers. Given the diversity of applications and technologies, an MST consortium with a common strategic goal might prove to be advantageous.

Government support is required

The government has a number of instruments for supporting and influencing the R&D route leading to MST applications in agriculture. Research projects can be supported by the ministry of Economic Affairs through the stimulation of technology and development funding (*Programmatische Bedrijfsgerichte Technologie Stimulering (PBTS)* and *Technisch Ontwikkelings Krediet (TOK)*). The ministry of Agriculture can support R&D in MST through project-targeted grants and through agricultural research institutes.

Uniform regulations are essential

Uniform regulations concerning the production, specifications and application areas of MST in agriculture are of the utmost importance. Without uniform regulations the effect of quality control and guarantee – so important for the export of Dutch and European agricultural products – cannot be achieved. The design and confirmation of uniform regulations is the most important task of the European Union in this field. The importance of uniformity should be stressed as this will be a prerequisite for entering non-European markets and for competing successfully with the USA and Japan.

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7. Production of microsystems

In this chapter we concentrate on microsystem production, design and opportunities, focusing on Small and Medium-Sized Enterprises (SMEs). There are of course opportunities and obstacles for large enterprises as well, but SMEs can play an important role in furthering microsystem technology for two reasons:

- after the rapid progress of technology over the last few years it is now the market's turn to make the next move. Niche markets especially hold opportunities for microsystems, and niche markets are the typical domain of SMEs.
- SMEs may soon have to face the threat of foreign competitors driving their present products out with MST-based products.

This chapter shows the difficulties in taking up MST technology and presents an approach for supporting SMEs. Subsequently reviewed are:

- the characteristics of MST;
- production costs;
- the underlying technologies;
- the manufacturing of microsystems;
- how SMEs could be assisted with their implementation of MST.

7.1 DESIGN AND PRODUCTION

7.1.1 CHARACTERISTICS OF MICROSYSTEM TECHNOLOGY

Prof. C.I.M. Beenakker and Prof. J.H.J. Fluitman

Important characteristics of microsystems for design and production are:

- the application of microsystems demands a systems approach and requires knowledge of all the disciplines involved (see figure 1.3).
- MST differs considerably from IC technology: where IC technology is generic and consists of a wide array of standard processes, MST is application specific and extremely diverse.
- MST is a combination of many different technologies coming from widely differing origins such as precision engineering and LIGA. The materials used include silicon, ceramics, metals and plastics.

A concept for a product idea may consequently lead to different solutions. As example four alternatives of a microfluid total analysis system (μTAS) and two different solutions of a crash sensor are discussed.

There is hardly any doubt about the desirability of microfluid total analysis systems, but there are quite different concepts, which is shown by the different schemes possible:

- Planar systems based mainly on silicon or related technologies (figure 7.1).

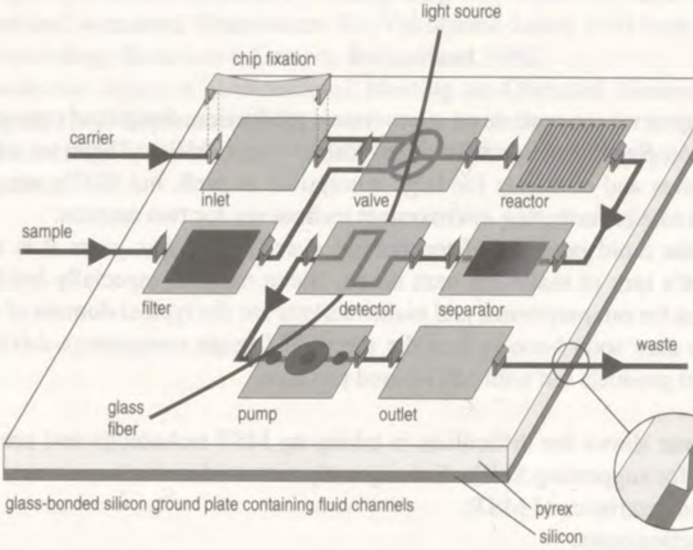


Figure 7.1 MESAs set up of a μTAS
Source: [1]

- A system based on thermoplastic moulding (figure 7.2).

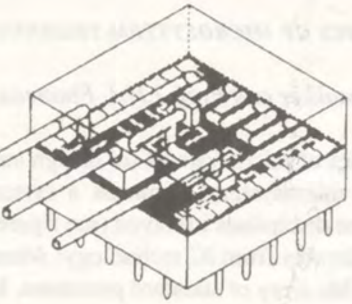
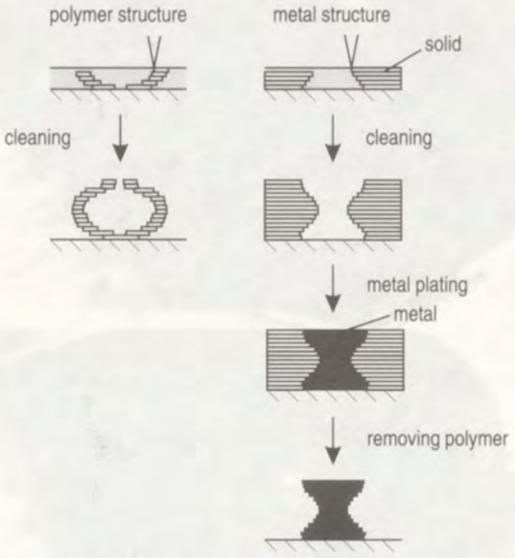
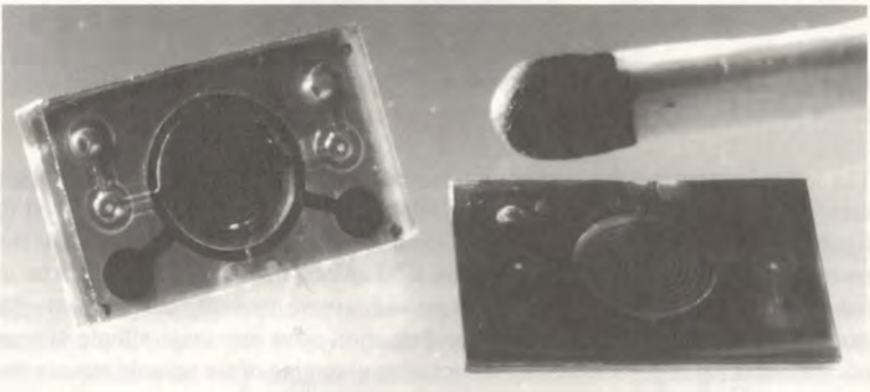


Figure 7.2 μTAS based on thermoplastic moulding
Source: [2]

- A system built using an 'Integrated Hardened Polymer Process' (figure 7.3).



integrated hardened polymer process



integrated fluid system

Figure 7.3 A three dimensional micro-integrated fluid system
Source: [3]

- Stacked systems based on tsilicon or related technologies with different functions in different layers (figure 7.4).

It may be clear that a choice for one of the concepts depends on the application (think of biocompatibility, use of erosive fluids, shock resistance, necessity of disposable parts and self diagnosis).

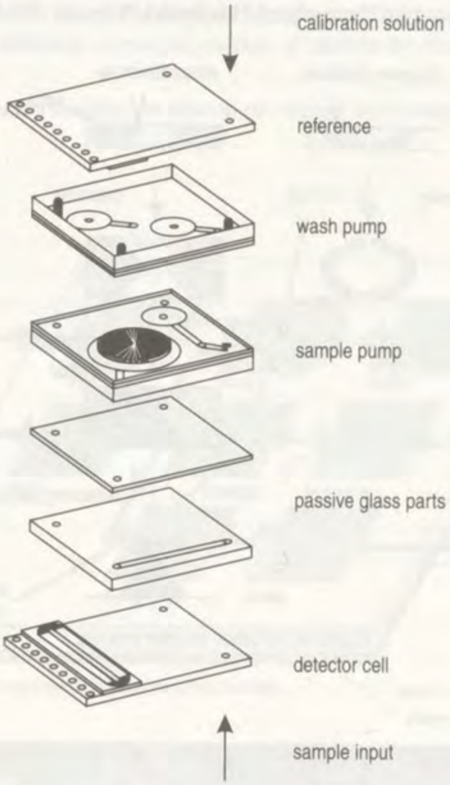


Figure 7.4 A stacked microfluid analysis system
Source: [4]

The second example is the acceleration sensor applied for airbag inflation in motor cars, the so-called crash sensor. The solution from Analog Devices, described in figure 2.6, is a highly integrated silicon system: an almost smart sensor [5]. At the moment of writing they sell for less than $ 50 apiece, but the price needs to be in the order of a few dollars to be competitive with a more conventional approach. An example of the latter is the design by Sensonor, who use some simple silicon micromachining steps followed by the accurate mounting of the seismic mass to the silicon cantilever (figure 7.5). This is done by a precision assembly machine (Automelec [6]), which sells for $ 300,000. The machine has a throughput of more than 500 sensors per hour, which amounts to 3 million sensors a year. Of course quite a number of other steps are needed, and we have to take labour, material and overhead costs into account. However the price-performance ratio of the rather simple approach is presently still competitive with the fully integrated solution from Analog Devices.

Because of this diversity there is only a limited pre-competitive body of technology; almost all developments of MST applications are specific and therefore of a proprietary nature.

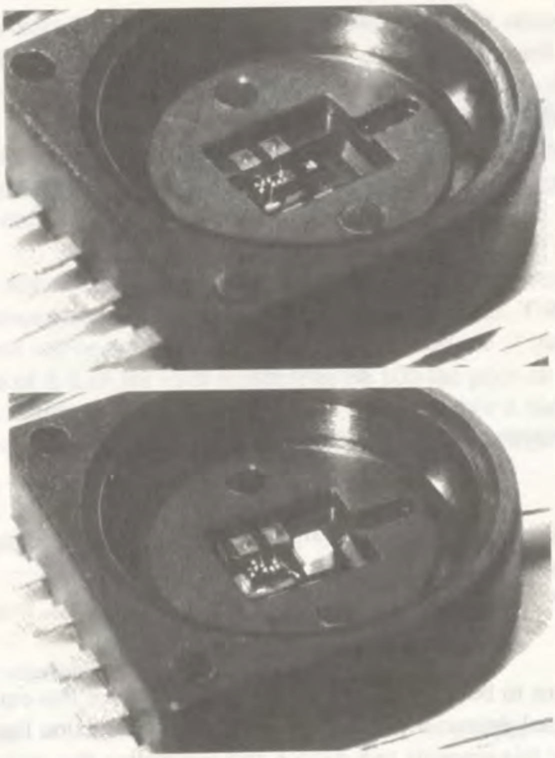


Figure 7.5 Crash sensor layout Sensonor. The outer dimension is about 2 cm.
Source: Sensonor

7.1.2 COST STRUCTURE FOR THE PRODUCTION OF MICROSYSTEMS

G.C. Klein Lebbink

Exploiting a production line for microstructures demands high investments. Unfortunately, it is impossible to have these investments step by step. All investments have to made at the very same time as it is then that all the equipment is needed. As an example of the costs associated with the production of MST devices, the manufacturing process of a temperature sensor is described.

Such a sensor measures the temperature by means of a thin-film Ni resistive structure. Basically the microsensor is a two-dimensional structure consisting of a:
- silicon or ceramic substrate;
- meander structure (Ni);
- contact system;
- protective layer.

The equipment for producing these sensors demands a total investment of $ 4.3 million, as shown in table 7.1.

equipment	*costs*
cleanroom	$ 625,000
equipment for cleaning the substrate	$ 125,000
sputtering	$ 750,000
depositing	$ 500,000
CVD equipment	$ 310,000
coating	$ 250,000
exposure	$ 280,000
development station	$ 65,000
etching equipment	$ 125,000
dry etcher	$ 310,000
tester	$ 100,000
measurement tools (microscope)	$ 250,000
trim laser	$ 625,000
total	*$ 4,315,000*

Table 7.1 Equipment needed to produce a Ni-temperature sensor
Source: [7]

Five years seems to be a reasonable economic lifetime for this equipment, which leads to an annual depreciation of $ 863,000. If the production line is operational 200 days a year this amounts to $ 4315 a day. Estimating that such a line requires ten operators ($ 500,000) and that the material costs are $ 300,000 a year, one day of operation costs $ 8315.

step	*batch* (# wafers)	*process time batch* (min)	*process time one wafer* (min)
cleaning of substrate	25	10	0.4
depositing Ni	60	120	2.0
lithography	1	3	3.0
etching	25	20	0.8
lithography	1	3	3.0
deposition of contact system	60	120	2.0
lift off	25	60	2.4
annealing	25	480	19.2
trimming	1	30	30.0
protective layer	1	5	5.0
lithography	1	3	3.0
development	1	5	5.0
total			75.8

Table 7.2 Process steps for the manufacturing of Ni temperature sensors
Source: [7]

To calculate the costs for one sensor we have to know the time needed to manufacture one element. Table 7.2 shows the processing times and batch sizes for each production step. The lowest costs per wafer are realized when each machine is used to full capacity. This means that the optimum batch size is 60 as this is the number of wafers that can be processed simultaneously (Ni depositing). This means that the total processing time for one wafer is 75.8 minutes. If the line is operated in three shifts the daily costs of $ 8315 result in $ 438 for each wafer.

The size of one sensor chip depends on the width of the Ni structure used. Table 7.3 shows three sensor types for two different substrate materials. The number of Ni 1000 sensors that can be manufactured on a ceramic substrate (2 inch) is 194. This leads to a price of $ 2.26 for each sensor. For Ni 100 the price is 26 dollar cents apiece. Silicon allows even smaller structures and therefore a higher number of elements are feasible. The optimum is 7068 sensors leading to a price of 6.2 dollar cents.

	structure width [µm]	*sensor area* [mm^2]	*sensors on 1 substrate* [#]	*occupation of surface* [%]
nickel on ceramic substrate				
Ni 1000	35	34.29	194	84.7
Ni 500	30	19.05	353	85.6
Ni 100	20	4.18	1676	89.2
nickel on silicon substrate				
Ni 1000	12	2.21	3198	90.0
Ni 500	10	1.50	4712	90.0
Ni 100	8	1.00	7068	90.0

Table 7.3 Different sensor layouts
Source: [7]

The calculation method used here is very basic. Yield, overhead, interest, maintenance etc. are not included, but the approach indicates the costs of producing a simple microstructure. We have to realize that a batch of 60 wafers, as suggested, leads to 11,500 to 420,000 sensors. This latter number is roughly equal to five times the number of houses built in the Netherlands each year and about equal to the number of new cars sold here annually. Thus it becomes clear that MST is enormously productive and that large numbers apply to microsystems. The conclusion we arrive at is that MST production lines should be flexible and ideally suitable for production of different components.

7.1.3 DESIGN FOR PRODUCIBILITY AND TESTABILITY

Prof. C.I.M. Beenakker and Prof. J.H.J. Fluitman

It is important to design for a minimum of production restrictions and to compare production steps with alternatives which may require more but less-vulnerable steps. Furthermore it is important to design for testability, even if this increases complexity. It is a common experience that design efforts to include testability will pay off and finally, good design leaves an opportunity for defining modules and interconnections at a later stage.

There are no overall procedures available for design; one can only exploit Computer Aided Design (CAD) for sub-systems or production steps. Examples are:
- programs to design masks for silicon bulk micromachining;
- Finite Element Method (FEM) packages to design mechanical structures (e.g. to get an idea of the mechanical stresses in the device);
- bond graph oriented programs to design devices like microfluidic systems;
- programs to simulate diffusion profiles resulting from annealing.

A few efforts are made to develop master programs linking the sub-programs mentioned above with huge databases. For sub-programs one must rely on existing workstations, numbercrunchers and the skill of the user and the quest for better, faster and more user-friendly hard- and software will remain.

7.1.4 UNDERLYING TECHNOLOGIES

P. van Pelt

Microsystem technology is based on a large number of technologies [7]. We distinguish core, key and basic technologies. A *core technology* is one that has no real substitute, is applicable to a wide range of products and is essential for a company in order to gain and keep a competitive edge. Core technologies for the manufacturing of microsystems are:
- deposition and patterning of thin layers like CVD, PVD, lithography and etching;
- economical accuracy in assembly;
- simulation and modelling of processes (chemical and physical);
- making connections between metallic and non-metallic materials;
- parts manufacturing in metal, plastic, glass, silicon and ceramics;
- electronic interconnects, carriers, assembly and microelectronics;
- measuring, testing, inspection of processes and products;
- mechatronics, meaning the combination of (micro)mechanics, servo-technology, sensors and actuators;
- optics and optical measurement methods;
- design of production systems including architecture, flow, flexibility, process control, data management and human interfaces.

area	(sub-)technologies important for MST				
know-how and know-why	CAD/CAM, CAE	mechatronics	heat and flow	(low) power ICs	DfP, DfA, DfR
assembly	3D vision, 3D measurement	active assembly, micro-adjusting	stressfree packaging	precision engineering	automation logistics
machining	micromachining	LIGA, microgalvany	precision moulding	chemical milling	precision forming
thin layers	lithography, etching	CVD, PVD, MBE	surface modifications	optical layers	laser ablation
measuring and inspection	microscopy, vision, image manipulation	measuring on nm-scale (AFM, STM)	testing, testsystems	software, control procedures	optics (X-ray, light, IR)
environment (chemical/physical)	clean machine technology	particle control	polishing, cleaning	surface preparation	chemical/physical analysis
connecting (mechanical)	glueing	welding	positioning	laser technology	direct bonding
connecting (electrical)	bump and TAB technology	soldering	Z-glues, zebras	wire-bonding	MCM and multilayers
circuit technology	mini PCB	microelectronics	small pitch ICs	miniature SMDs	design rules

Table 7.4 Important key technologies for microsystems

A *key technology* is important for realizing products in a limited range; there are other technologies that can produce (nearly) the same results, but a key technology must be completely mastered to be competitive. Table 7.4 lists more than 40 key technologies for microsystems.

A *basic technology* is useful but not essential for a company (it can be farmed out to specialized companies).

The distinction between core, key and basic technology depends on the goals and markets of a company and what is core technology for one company can be basic or even unimportant for another company. It is however beyond the scope of this book to describe all the technologies in detail. The reader is referred to Chapter 2 for silicon micromachining, LIGA and precision engineering. With the exception of wafer bonding and wafer scale assembly, described below, reference should be made to the literature [7-13].

Wafer bonding or direct bonding is the joining or fusing of smooth surfaces of the same or different materials in such a way that vacuum-tight, jointless and glueless bonds are formed at the interfaces. Surfaces to be bonded must be very flat and smooth (surface roughness less than 2 nm), free from defects and contamination and able to form strong chemical bonds. Many materials are able to bond directly, either spontaneously or under slight pressure; for instance silicon, fused silica, diamond, pure metals (Cu, Bi, Ge, Ti, Ta) and many metal oxides ($SrTiO_3$, $BaTiO_3$, $LiNbO_3$). The right polishing technique to obtain a smooth, defect-free surface is essential. Besides direct bonding, anodic bonding is suitable to connect hybrid materials (e.g. pyrex to silicon) at fairly low temperatures.

Wafer scale assembling offers an option for manufacturing electronic or optical components (ICs, laser diodes, waveguides etc) on the same substrate as mechanical components (transducers, gears, connectors etc.). In this way batchwise production can take place of many miniature components and sub-assemblies and the parts can be separated later with laser-scribing or other techniques.

That great efforts and perseverance are required to master such technologies is demonstrated by Surface Mount Technology (SMT); 15 years elapsed between its conception and general application.

7.1.5 MANUFACTURING OF MICROSYSTEMS

P. van Pelt

Because of their multi-disciplinarity and the many technologies involved, manufacturing microsystems is a complex undertaking. The more so because of the diversity of applications. There are no standard components or modules, nor standard procedures. The design of microsystems largely depends on producibility and testability; as a matter of fact, technology has more impact than the market on design. To quote Dr Kroy of DASA (during MEMS '94): 'It is easier for a technologist to do the marketing of his product than it is for a market specialist to understand what technological product he is trying to sell.' More than with any other category, product design should cover the entire creation process from research through to the market and vice versa. A systematic approach is essential for mastering the complexity involved. Procedures like Quality Function Deployment (QFD) may contribute to visualizing the manufacturing process and for facilitating communication between the many participating parties.

QFD can help in finding the quickest and most reliable route to manufacturing [8]. Since microsystems are typically products with a high level of sophisticated technologies, many disciplines are involved in determining this route to manufacturing. QFD brings these many different disciplines together in an organic process of 'making the manufacturing plan'. The discussion often starts with a Quality Map (QMAP), an outline describing the flow of raw materials or primary components through the manufacturing process to the finished product. The whole manufacturing process can be broken up into sub-processes, where semi-finished products or sub-assemblies are manufactured. Depending on the complexity of the end product, the sub-processes are broken up into smaller process steps, until unit operations are encountered. The QMAP is in fact a visualization of the manufacturing plan. A QMAP of a microdosage system is given as a schematic illustration (figure 7.6).

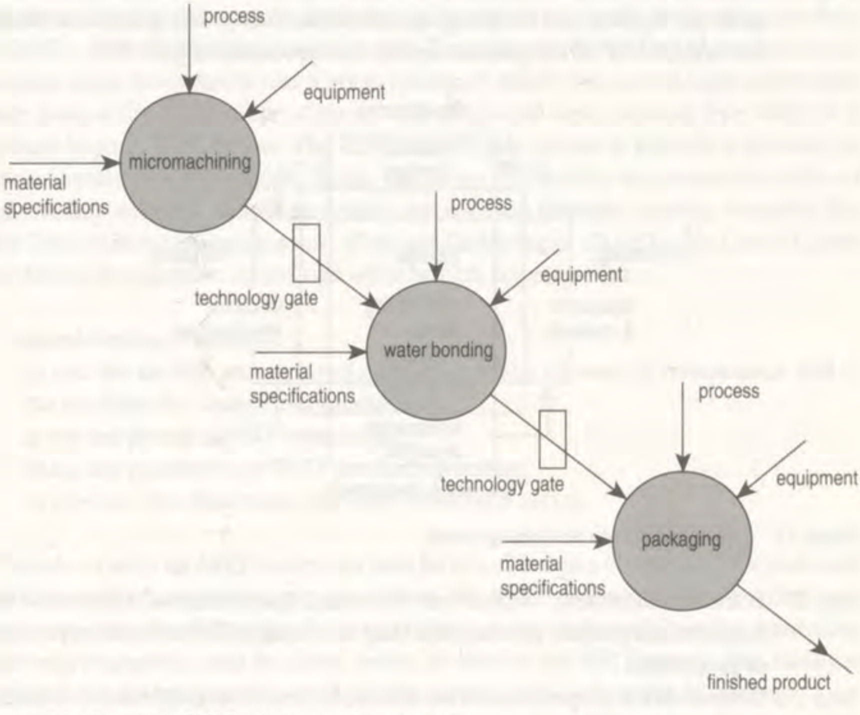


Figure 7.6 Schematic QMAP of integrated flow controller

The manufacturing for this product uses three different technologies: micromachining the pump, the valves and the sensors out of silicon, as well as drilling and shaping the glass parts, assembling them to the silicon micromachined parts by anodic wafer bonding, connecting the device electrically and to tubes and, finally, testing and packaging the device to seal it from the hostile environment in which it must operate. Most microsystem devices will go through these three phases of manufacturing. Between these phases technology gates can be defined; decision points where the output of the previous phase can be specified and tested before the next step is begun. In most cases the financial risks of losing the product increase as one goes further down the manufacturing chain.

Whereas the QMAP illustrates the (manufacturing) process, QFD links the four important forces in the design process:

- marketing and product development;
- process development;
- engineering;
- (pilot) production.

The customer's wishes are translated first into functional properties. Product development translates these functional properties into fundamental product parameters. These intended product parameters are realized in a set of process conditions which – in turn – require a set of manufacturing tools and tool-settings (the area of engineering and production). The following steps are often intuitively carried out to progress from research conditions to full scale manufacturing conditions:

Step 1: Divide the whole process into relevant sub-processes. Through QFD determine the ingoing and outgoing specifications for the sub-processes. Make the first QMAP of the process and its sub-processes (figure 7.7).

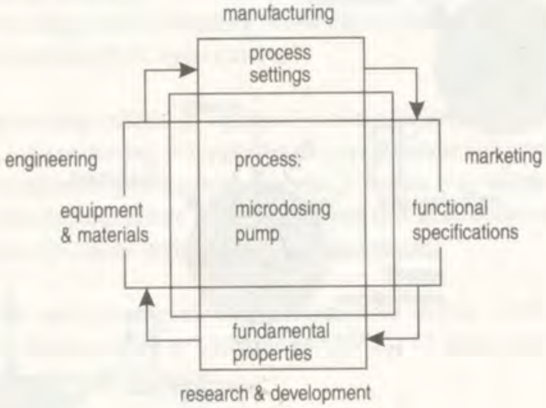


Figure 7.7 Schematic QFD of a microdosage pump

Step 2: Translate customers' wishes into functional specifications. Determine the fundamental product parameters. Map the relations between these two sets of properties.

Step 3: Determine the proper process conditions for the (material) transformations. Apply the economic boundary conditions here and determine the suitable production tools to bring about the desired transformations. Determine the settings and tolerances for the process conditions.

Step 4: Determine the relations between functional and fundamental properties, and between fundamental product parameters and the process conditions.

Finally, determine the relations between the necessary process conditions and the production tool settings.

Step 5: Go back to step 1 and correct QFD and QMAP (fine-tuning). Repeat as often as necessary to converge to the optimal production process.

The most important function of QFD is the structured visualization of a very complicated process, i.e. the concerted effort of many people from various specialist backgrounds, often with conflicting views and goals, to arrive at a consistent and optimal way of manufacturing a given product design. The use of QFD forces people to make the correlation between different activities in the product creation process explicit and quantitative. It enables management to follow this process clearly and gives early warnings for potential difficulties or problems along this road to manufacturing.

7.2 ENABLING SMEs TO BECOME INVOLVED IN MICROSYSTEM TECHNOLOGY

Prof. C.I.M. Beenakker and Prof. J.H.J. Fluitman

SMEs are in a unique position for generating new ideas and developing niche markets. Most of these niche markets require relatively small production numbers (10,000 – 100,000), perhaps even smaller. Concurrently the underlying technologies require large investments and a great variety of skills. Even some large enterprises only have a limited number of these technologies at their disposal. For SMEs it is simply beyond their means. The only conceivable inroad is through a network of shared resources (knowledge, skills, facilities). Promotion and communication of this facility network should preferably be realized through existing channels like the '*Nederlandse Vereniging voor Precisie Technologie*' (NVFT), the Dutch Centre for Micro-Electronics, or through other branch organizations.

A central facility is needed:

- to run the facility network and connect it to the sources of competence and to the facilities for design and production;
- to try out possible MST inventions;
- to try out possible new MST production routes;
- to produce demonstrators and small prototype series.

The role of such an MST centre can best be described as a Centre of Expertise with facilities which are necessary to almost all MST products (e.g. the first two mentioned in the following list) and with advanced knowledge for mediating between companies and facilities inside or outside the MST centre. The facilities which it would bring within reach of the users would include the following:

1. Facilities for mask pattern generation, photo lithography, mask alignment, etc.
2. Deposition and etching facilities.
3. Packaging and interconnection.
4. For standard mounting and packaging there are existing facilities that should be mapped by the centre.

5. LIGA. Production facilities are identified.
6. Dedicated assembly machines. Design and production facilities are identified.
7. Precision engineering. Workshops are identified.
8. ASIC-foundries, facilities are identified.
9. Multi Chip Module (MCM) technology.
10. Moulded Interconnection Devices (MID) technology.
11. MST production equipment.

Ad 1. Modest minimum feature sizes are acceptable. For sub-micron specialities there is access to external facilities.

Ad 2. Feasibility studies should be done under contract with universities and institutes and not within the MST centre. A critical point in development is the first prototyping and the production of a small test series of plain parts. In so far as deposition or etching facilities are really needed, purchase of facilities should be carefully considered. Again a close relationship with a university or institute is highly advisable (compare the University of Neuchâtel and CSEM), as the option of a cheaper start-up on a university machine is possible if such a machine is not being fully used by university researchers. Equipment for production must be purchased by the user. Placing the machine in the MST centre is in the interest of the user because of the possibility of time sharing. Again, concentration on SMEs and an annual production of lots between 10,000 and 100,000 must be emphasized. For MST parts like the ones described in section 7, this may mean use of the equipment for only a few days or weeks. If time sharing is possible, cleaning and tuning of the equipment will also take time.

Ad 3. Should the packaging and interconnection procedures be non standard, it is generally not the fine tuning or time sharing of equipment that is required but 'problem solving' and the design of special machinery. Here the sharing of know-how is important. Considering that packaging is an art, skilled personnel are needed, who are free to exchange experiences. Specific inventions of course should be treated as confidential in order to give the client the opportunity to patent the invention. Rules concerning these issues are well-known and in use in contract research with universities, for example.

Ad 9. This is an emerging technology. Facilities are available in the Netherlands.

Ad 10. With MID it is possible to mould 3-dimensional circuit boards. Facilities are identified.

Ad 11. Up to now (see ad 2) the starting point has been the use of large expensive production machines. It can be expected, however, that the current facilities and their environment (clean rooms) will be scaled down. It is reasonable to think of small and relatively cheap production machines for smaller lots as soon as the market for such facilities develops. It can be concluded that much cheaper production lines may be designed for small- or medium-scale production. This might become an attractive market in itself.

Setbacks in development and production could occur with items 2 and 3 and this should be circumvented as much as possible by making use of well-proven existing technology steps. Nevertheless they cannot be omitted in certain new products.

7.3 CONCLUSIONS AND RECOMMENDATIONS

Task Force Production

Take the diversity of MST into account

MST is not comparable with IC technology. The diversity in microsystem technology is much larger than that in IC. Because of the diversity in MST the volume of pre-competitive research is small. This might be a problem for starting up activities.

MST should always be considered together with precision engineering, LIGA, etc. A fusion of points of view on technology and on user groups can be reached most effectively by taking existing infrastructures as a starting point.

Use shared resources

There is a large niche market in the annual production range of 1000-100,000 items. A production infrastructure is required for SMEs on the basis of shared activities. In the future low throughput cheap production lines may become available. MST offers chances for builders of new equipment adapted to production rates of 10,000 to 100,000 annually. Only large enterprises can create dedicated production lines for MST products using equipment currently available.

Set up an independent MST centre

The required knowledge for MST is available at present in the Netherlands and it is ready to be exploited on the basis of mutual interest and esteem. The Netherlands has a high rating for MST activities on a global scale. An MST centre should be established to coordinate the information transfer along existing communication lines. This centre should be outside the interests of any company or organization entering into MST activities. It should therefore not compete with its ‘clients’. The centre should be part of an existing network of facilities and, if possible, use these facilities in the design of a production process. It should have close connections with a university. In this way advantage can be taken of university equipment when not being utilized, as well as the reservoir of available knowledge.

The centre should contain a minimum configuration of facilities which cannot feasibly be made use of elsewhere. Financial support is naturally essential although this should be synchronized with the centre’s needs.

Establish a European centre

A similar centre should be formed on a European level. Such a centre should also act as a Centre of Expertise and establish contacts between different parties that have working knowledge on specific technologies. The centre would act as the ‘lubricant’ between parties with dissimilar or even conflicting interests, much in the same way as brokers operate in the stockmarket or in the housing market. There should naturally be an intensive contact between the national centre(s) and the European organization.

Support research

While application of MST is being promoted research should continue for maintaining our relatively strong base. Top priorities are:

- standardization;
- integration of the different domains of MST: IC technology, precision engineering, LIGA (for example compatibility);
- high priority subjects, to be determined for each application area treated in this report.

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8. Perspectives and opportunities

This chapter is based on discussions in the task forces of the MUST project and on the opinion of the European Network of Excellence in Multifunctional Microsystems [1].

8.1 MARKETS AND INDUSTRY

The introduction of MST onto the market

MST will reach the market through two different routes. The first route will be for MST to expand in high volume agricultural applications such as animal husbandry, in consumer-oriented markets like consumer electronics, or in personal communication devices. These high-volume low-cost markets require MST to be taken up by large companies that operate on an international or even global scale. Once successful components and modules become available smaller companies have a chance to find consumer markets for their finished products or system parts. The second route towards microsystem applications is to reach niche markets and highly specialized applications. SMEs are expected to come up with MST products for these markets. As the new products are realized using a combination of different technologies – such as sensors, electronics, microcontrollers, software and precision engineering – cooperation or clustering of companies is necessary. In both markets the greatest challenge comes from totally new products or functions. A good example of such a product is the Atomic Force Microscope (AFM), which can only be realized with MST.

Production facilities are essentially the same whether MST devices are considered for consumer products, medical applications, agriculture or instrumentation. Chapter 7 describes the facilities, the need to stimulate awareness of their existence and the way to address them. MST's success in high-volume markets will stimulate the set up of new facilities and the maturing of existing facilities. Technical requirements will differ considerably for each application (for example biocompatibility and packaging) and the translation of an existing demand into a product will be specific. The design and engineering of an MST device thus requires close cooperation between experts in the different disciplines involved.

Future industrial landscape for MST

Profiles of enterprises supplying MST may be quite diverse and cover the range from MST component manufacturers through MST assembly houses to MST system builders. Because many silicon IC foundries are large, one tends to conclude that microsystem producers should also be large. However, the microsystem market is very diverse and extremely fragmented. For instance, in industrial and medical applications batches are often limited to several thousands, a volume of little interest to the large foundries who think only in terms of millions. Expanding and changing running processes is not attractive to them. On the other hand, high-volume applications need foundries with sufficient capacity. MST component manufacturers can be either divisions of large silicon foundries or SMEs dedicated to the development and realization of specific MST components. Assembly houses might combine these components (if not monolithically integrated) to interconnected and working systems using a variety of different technologies. MST system builders arrange and combine the MST sub-systems into ready-to-use systems, which may include control functions and data transformation for interfacing to the macroscopic world. It should be noted that the various production steps can eventually be realized within one single company.

Next to the suppliers of MST, companies are needed who can translate industrial needs into product concepts and transfer research into products. These transfer organizations can play an active role by uniting companies behind a product idea. The diversity of the technologies required might well result in a co-makership or even a consortium of SMEs with specialized and closely interrelated tasks.

8.2 AWARENESS AND EDUCATION

It is clear that to be able to produce and sell an MST-based product we need know-how, and education plays a decisive role in acquiring this. There are two fundamental approaches to education: the subjects to be covered and those to be educated. The latter are the people involved in technology and who have a basic knowledge of a specific field like agriculture or transport technology. Then there are the 'users' of MST, a group ranging from surgeons, farmers and marketeers to policymakers, who should all be aware of the possibilities of MST. Only when people operating in the various application areas are enlightened as to the major possibilities of MST will improvements eventually be realized.

8.2.1 SYLLABUS

System thinking

As the design of an MST product strongly influences the required technologies, and vice versa, it is essential to assess the entire system and to bring together all available disciplines. This requires a filter-down approach from the people involved in MST, enhanced by teaching a system approach at tertiary education (universities and higher vocational education). The formation of interfaculty institutes at universities, such as MESA, will facilitate the awareness of the importance of such a system approach.

Technologies and manufacturing

Microsystems are interdisciplinary from the technical point of view. Their development requires knowledge of mechanics, electronics, packaging and chemistry, etc. The individual engineer should to some extent be knowledgeable in all disciplines. Section 7.1.4 lists the technologies that are available for the production of microsystems and those involved in production should have good knowledge of these technologies, be expert in one group of technologies and also be aware of the available alternatives.

Apart from these specialists, operators have to be trained to master specific equipment and know 'which buttons to press'. For low number series even skilled manual workers could operate the equipment, as is presently the case with certain products achieved with conventional precision technology.

Design and testing

Besides training in design tools and formal methodologies, designers need to have a good knowledge of the state of the art of production technology. Furthermore the designer should keep testability and recyclability in mind. He or she should have a 'catalogue' of existing modules and standardization requirements in mind. And because the design is strongly related to the production steps, the designer should be aware of process compatibility etc.

Permanent education

As MST is a rapidly developing field those involved should ideally update their knowledge on a regular basis. This implies the need for postgraduate courses and a vivid exchange of newly acquired knowledge.

8.2.2 EDUCATION: THE EXAMPLE OF MEDICAL TECHNOLOGY AND MST

To demonstrate the type of education needed for MST, a possible approach is suggested for MST and medical technology.

Medical microsystems involve many disciplines. Microsystems themselves are, however, already interdisciplinary from the technical point of view. Indeed, their development requires a knowledge of mechanics, electronics, packaging and often chemistry, etc. Medical microsystems are also interdisciplinary from the medical point of view and are linked to the medical discipline involved; for example, programmable insulin injection systems require expertise in diabetic care. In addition they usually involve some biochemistry; for instance where biocompatibility is considered. As a consequence, engineers in MST development must to some extent be knowledgeable in at least one medical discipline as well as in several – or preferably all – engineering disciplines.

The technical education of medical MST engineers must therefore be very broad. Here there are two possibilities. They can be educated in depth in a specific discipline – for example electronics – and acquire the other disciplines such as chemistry, as research and development proceeds. As an alternative they can receive a broad education to begin with and specialize later. STT's Medical Technology task force believes the second situation is preferable.

The 'broad education to begin with' for medical MST engineers fits in perfectly with modern ideas on the transfer of knowledge [2]. The engineer performs as actuator in the technology transfer from a technology generator at a university or research institute to a technology user in industry. This means that the ability to absorb complex technologies, on the one hand, and to communicate with technology generators, on the other hand, are among the prime skills of an engineer. Education adapted to technology transfer will facilitate later specialization.

In-depth education in a specific discipline does not however facilitate technology transfer. This not only leaves the engineer with the problem of absorbing other technologies later on, but also impairs technology development in general.

Moreover, the technical difficulties of medical microsystems should not be underestimated. The electronics required is of a high level as are the biotechnical aspects. It is therefore preferable to add biomedical specialization after technical specialization. It is suggested that the biomedical engineering education is at graduate rather than at undergraduate level. Courses are currently available on subjects such as biomechanics, medical instrumentation, including imaging equipment and sensors, biochemistry and fluid mechanics. Parallel to this some medical courses should also be included, such as anatomy, physiology and cell biology. Undergraduate teaching is then reserved for technical education.

In conclusion, medical MST engineering education demands a very broad base, supplemented by elementary medical courses, preferably at graduate level, in order not to compromise the technical education aspect.

8.3 EUROPEAN PERSPECTIVE AND THE ROLE OF THE NETHERLANDS AND BELGIUM

To avoid complete dependency on resources outside the Netherlands and Belgium (or outside Europe) a certain competence in at least some areas will be crucial. It is not sufficient to do MST at research level only, although it might help to have a bargaining position based on patents. A much better position would be one that is based on product development and manufacturing of at least a selection of essential components and end products.

Looking at the whole of Europe one might say that the large industrial companies are certainly capable of developing microsystem technology. There is a reasonable starting position based on existing research and there is an industrial infrastructure such as is needed for the mass-production of sophisticated products. Furthermore, in the Benelux region there are several SMEs already working in the field of microsystem technologies, such as silicon micromachining, integrated optics, LIGA, assembling and interconnection, and packaging [3]. Besides the volume markets to be addressed by large companies there are also niche markets, of special interest to SMEs. From a technology point of view there is hardly a difference, therefore co-operation between bigger companies and SMEs could be fruitful. Some successful high volume product developments would contribute to accelerating the implementation of a strong infrastructure.

Knowledge of almost all the key technologies is present in our universities and institutes. In fact, the Netherlands and Belgium are both strong in MST know-how at university level. Facilities are present as well, be it that they are often not open for manufacture or even for pilot production. In both countries as well as in Europe as a whole it proves to be very difficult to transform this know-how into commercial products. The best transfer is obtained in Switzerland and Germany, thanks to their better industrial climate and, not least, to the considerable financial support of the German government in particular. In Japan and, to a somewhat lesser extent, the USA the application of new technology in commercial products is achieved more easily. For this reason, technology transfer as a professional activity is likely to be necessary. This could be carried out by institutes such as TNO in the Netherlands and by companies specialized in the development of new products based on the results of scientific research. In the future, university institutes could also play a role by forming special technology transfer units, like the MST centre discussed in Chapter 7. These units will not only be necessary for generating direct funding for university research but also indirectly, as universities need their scientific results transferred into economic activities to be certain of support for their future research.

As regards process instrumentation equipment, it is worthwhile mentioning that there are no large Dutch or Belgian producers. Moreover, it is clear that the industrial climate here is not ideal and the willingness to take investment risks is low, as can be seen in the ASIC area, for instance. However, there are several subsidiaries of foreign producers with R&D departments which, together with a reasonable number of SME-type and niche-oriented Dutch and Belgian companies, could play a future role in the commercialization of MST. Besides instrumentation manufacturers, there are also suppliers of precision machined instrument parts, which have a natural affinity with micromechanics. These companies could become interested in MST developments if financial risks were lowered by government regulations.

When one considers medical instrumentation Europe has a long tradition, but the most important markets (pacemakers, kidney dialysis equipment, diabetes diagnostics equipment) are dominated by the USA and Japan. Europe has also a tradition in a limited number of specialized areas such as biosensors. However production capabilities are largely lacking. Telecommunications is generally accepted to be highly innovative and a growth market. In Belgium telecommunications is an important drive for new developments and it can be expected that the telecom industry will become one of the biggest users of MST.

Because of the large investments necessary to develop microsystems in general, the European Union will have a decisive role in funding ambitious projects to develop microsystems. Within these projects the technology has to be developed that in the intermediate future will bring microsystem technology within reach of applications on a smaller scale. With microsystem technology it may very well be possible to measure parameters, important for environmental measures etc. Since directives are drawn up by national governments as well as the European government, new possibilities created by MST can be made use of. Examples are agricultural policy and environmental regulations where the EU can stimulate the development of MST devices and their application. In this way farmers are required to use the results of these developments and a lucrative market, and consequently, an attractive time to return on investment will be created.

8.4 EUROPEAN PERSPECTIVE: VIEW FROM NEXUS

NEXUS is a joint European effort sponsored by the European Union (ESPRIT) and stands for Network of Excellence in Multifunctional Microsystems. It was initiated with the aim to prepare European industry for the microsystems market by coordinating European R&D in microsystem technology. Presently over 100 organizations are represented in NEXUS. One of the actions taken by NEXUS is the establishment of an Industrial Working Group (IWG) to define industrial needs and strategies and to ensure that the actions taken by the network are application and production oriented. In 1992 the IWG prepared a strategy paper on MST [1]. The document describes the situation in Europe concerning MST and includes a proposal on how to develop this new technology in Europe. The document is summarized in this section.

The IWG has identified ten areas for MST based products. These areas are:
- consumer electronics and mobile telecommunication;
- automotive engineering;
- medical engineering;
- environmental control;
- domotics, household;
- automation, manufacturing, process and plant technology;
- aerospace technology;
- traffic control and communication networks;
- safety and security systems;
- vision systems for the future.

The main strength of European industry presently lies in manufacturing products in the first four areas. This strength is endangered by the increasing dependence of European industries on imported technologies and components. Examples are memory chips, mass storage devices and flat panel displays. Components will be integrated in miniaturized products and become the key modules in higher systems. As a consequence more and more product know-how will migrate into the components and the producers of the components will gain increased influence on the product architecture. As a consequence industry will have to disclose its system know-how. It is therefore considered essential that European industry be involved in manufacturing miniaturized components and systems.

The IWG foresees two ways in which new products will penetrate the market. In the short term conventional solutions will be replaced by MST solutions and in the long term entirely new products will be developed that rely on microsystems as key components. The markets will be in both cheap mass products in standard applications and specialized systems that require the specific advantages of microsystems. The market estimates for the substitution of conventional solutions by MST alternatives for the three areas with the highest relevance for European industry are, with annual growth rates, in the year 2000:

- mobile telecommunications: 3600 MECU with a 50% growth rate;
- automotive electronics: 280 MECU with a 15% growth rate;
- environmental control: 160 MECU with a 20% growth rate.

It is expected that MST will trigger a new cycle of innovations and that this will hold the key to technological progress during the next two decades. These figures apply to components only and new products have been excluded. These key components will have a leverage that is estimated to lead to a 10 times higher turnover of more than 40.000 MECU.

Companies in Japan and the USA have already recognized the opportunities for MST. In Japan all the major industries in the automotive and electronics fields are engaged in MST research and in 1991 the MITI initiated a 10 year program on micromachining (see Appendix 2). In the United States various major companies are involved in MST. Some of them produce large volumes of sensors and actuators (for example Delco Industries produces about 6 million silicon pressure sensors a year). However, Europe has a lead in basic research and has the chance of major breakthroughs in MST. One disadvantage is the problem of insular activities and the lack of cooperation and coordination between the players. Furthermore many of the activities are neither product nor production oriented.

Because of the high investments needed for MST, cooperation is necessary and consortia should be set up and research cooperation could be coordinated by the European Commission. Before setting up a broad technology programme it is recommended to start with a definition phase for formulating objectives, the required R&D and analyzing application areas and markets.

The IWG has identified four basic technological fields for R&D:

- Manufacturing technologies, being the required processing technologies described in Chapter 2 of this publication. The critical deficits are supposed to be in the integration of conventional IC processes and silicon with microstructuring techniques and different materials, and bonding and encapsulation technologies.
- Design and simulation techniques. Here the crucial activity is supposed to be the expansion, modification and combination of existing methods to an MST development environment. The resulting methodology should be suited for designers who are not experts in the various process technologies.
- System technologies, which are necessary for the planning and realization of complex microsystems and the integration into macrosystems. These technologies are lacking for industrial production of microsystems.
- New materials and structures will be combined with information processing functions in MST based products. Examples are biocompatible materials, ceramics and functional materials and structures such as chemical devices or integrated power devices for actuation.

The IWG has formulated the following conclusions:

- MST is viewed as an indispensable new technology essential for Europe to secure its industrial independence and competitive edge.
- MST is a complex technology requiring high investments and as a result demanding European efforts and European – or even global – markets.
- MST requires a production infrastructure with a close relationship between foundries and users. Furthermore an education and training infrastructure is necessary. The first step is the coordination of research and development and cooperation between European companies. Then a network of a limited number of foundries must be established.
- Consortia combining system vendors, foundries, research institutes and users should be set-up that translate R&D results into products.
- The European Union should initiate and sponsor an MST programme focusing on application-oriented projects, standardization and training activities. Furthermore the EU should coordinate R&D and stimulate the set-up of consortia.

Finally the IWG concludes that a broad technology programme has to be defined within a period of 1-1½ years. To support the definition of such a European programme the IWG defined four pilot projects in the most important application areas. The priorities resulted in estimating the market relevance for European companies of the previously mentioned areas. For each area one pilot project was defined with a time frame of 3 years and a budget of about 15-20 MECU:

- in consumer electronics and mobile telecommunications – a personal portable communicator;
- for automotive engineering – a sensor system with integrated electronics;
- in medical engineering – an implantable health supporting system;
- in environmental control – an environmental monitoring system.

On the basis of the experiences to be gained from these projects an MST programme can be formulated.

Recently NEXUS decided to set up a limited number of MST service centres. The first concept of these centres is for services like assistance and guidance of potential appliers of MST. The idea resembles the MST centre described in Chapter 7, but the NEXUS centres may not have their own facilities and activities are therefore limited to technology mediating.

References

[1] *Strategy paper on microsystems technology*, NEXUS Industrial Working Group on Microsystems, Berlin, 1992

[2] PRAKKE, F., E. VAN DER SCHAFT, W.C.L. ZEGVELD, *Het draagvlak voor technologie in de Nederlandse samenleving*, TNO, 1992

[3] NEXUS, *Who is who in NEXUS?*, Preliminary version of Almanac, NEXUS office, Berlin, 1993

9. Conclusions and recommendations

The conclusions and recommendations included in this chapter represent the common opinion of all those involved in the MUST project.

9.1 CONCLUSIONS

Microsystem technology is a present day reality. Successful applications exist and several companies are already working in this field. However, MST is not yet fully mature and offers many opportunities for industrial development by both large and small companies. These activities will cover the application of MST components in existing or new products, but also the production facilities for these components. It is expected that MST will form the basis of a new cycle of technological innovations for the coming decades.

Europe is strong in basic research, and the technical know-how required for MST is available in the Netherlands and Belgium. However, the translation of this knowledge into manufactured products is poor. This is caused by the limited awareness of potential users of MST and by the existing gap between universities and industry.

Restrictions for MST development are the specificity of the components, the complexity of integrated systems and miniaturization of energy sources. It is therefore expected that hybrid systems will emerge as the first successful applications.

From the technology viewpoint MST is a follow-up of IC technology. MST is, however, far more diversified. The requisite investments are high, and when the limited number of European IC manufacturers is taken into account, it can be expected that the number of MST foundries will be small. It is recommended that SMEs working in niche markets use existing facilities when available and thereby reduce the level of necessary investments.

Microsystem technologies derived from IC technologies, classical precision engineering and other microtechnologies like LIGA, can be integrated into a single but extended field of available technology. If this is fully recognized and proper use is made of it, the speed of product development will be enhanced.

9.2 RECOMMENDATIONS

Identify priorities

National governments and the European Commission should come to a decision on MST. They should also identify the application areas with the highest national and European priority.

Involvement of all parties

For the success of MST it is essential that all parties be involved. This means that the users should become aware of the capabilities of MST, that the universities should readily transfer their knowledge and that institutes should demonstrate the feasibility of MST. Furthermore, each party should underline its commitment by funding the required financial, material and personnel resources.

Consortia and cooperation

Companies wishing to become involved in MST should have an open mind towards cooperation and be willing to form consortia with a common strategic goal. Such consortia should cover all parties involved, i.e. MST foundries, universities, institutes and the appliers of MST.

The systems approach

Because of the complexity of MST and the disciplines involved it is necessary to teach a systems approach to those who want to become involved in MST. Such a systems approach is essential for the designers of microsystems and the successful translation of R&D to applications.

Demonstrate the potential of MST

In order to demonstrate MST and its superiority to conventional solutions it is advised to define pilot projects based on an actual 'need' in industry. The ideas discussed in the application oriented chapters could form a primary basis. In order to select these demonstrators the application areas should be weighed as to their economical and social relevance and the ideas should be evaluated as to their time scope and feasibility. To allow comparison with present-day solutions these projects should lead to modules or sub-systems that can be used in existing products. The joining of European pilot projects (such as defined by NEXUS) should be considered. However, national projects should also be initiated which focus on applications with high national priority.

Furthermore it is advised to define and assess the feasibility of long-term projects and to map the existing deficits that thwart the realization of such projects. This will urge the coordination of research and stimulate participation in European projects.

Governmental support of MST

Governments should take measures to stimulate MST. National support should ideally have four components:

- A number of demonstrator projects to be initiated, possibly by means of public purchase contracts.

- A programme for stimulation of product development. A first emphasis could be the stimulation of feasibility studies.
- An independent MST centre to be set-up with easy access for all interested parties. This centre should be able to show the way and coordinate MST projects and bring interested parties together.
- The relatively strong position in basic research should be maintained. The Dutch government might think of an 'Innovative Research Programme' ('*Innovatief Onderzoek Programma, IOP*') to support this goal.

Focus on applications

In all cases the focus should be on applications. The amount of knowledge already available is enormous and it is time to translate the results of MST research into products. As a consequence companies should be involved in the pilot projects and give financial support (possibly related to the amount of success).

10. Keywords and abbreviations

ABS	Anti Blocking System
Abscisic acid	Plant hormone responsible for ageing of plant tissue
Access time	The time a system takes to find (or store) a given data item
Actuator	Component that causes a change in condition
AFM	Atomic Force Microscope: microscope enabling to 'view' separate molecules
AICC	Autonomous Intelligent Cruise Control
Alkaloids	Any of a group of nitrogenous basic compounds found in plants, typically insoluble in water and physiologically active
Anaesthesia	Loss of bodily sensation with or without loss of consciousness
Analgesia	Loss of the ability to feel pain while awake
Aneurysm	Bulging and thinning of some point in the wall of a blood vessel
Angiography	The making of X rays photo's of blood vessel using contrast liquids
Anisotropy	Condition where properties change with direction
Arteriosclerosis	Hardening of the arteries
ASIC	Application Specific Integrated Circuit
ASSA	Application Specific Sensor Array
AST	Above-ground Storage Tank
Atrium	Chamber of the heart that receives blood from the veins
Auxin	Plant hormone that promotes growth and controls fruit and flower development
AV node	Atrioventricular node controlling the contraction of the ventricles
Basic technology	Technology useful for a company but not essential
BAW	Bulk Acoustic Wave
Bile duct	Channel transporting liquid (bile) formed in the liver to the bowels
Button cell	Battery with the shape and size of a small button
Cache memory	A solid state memory used as a fast buffer memory between a processor and its main store
CAD	Computer Aided Design

CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
Cardiac	Relating to, situated near, or acting on the heart
Carotenoids	Any of a group of red or yellow pigments found in plants and certain animal tissues
Cataract	Clouding of the lens of the eye or the transparent cover around it, blocking the passage of light
CCD	Charged Coupled Device
Cerebral	Relating to the brain
Cervical	Relating to the neck or cervix
Chemometrics	Statistic method used to calculate chemical composition of complex mixtures
Clenbuterol	Medicine against respiratory diseases (low dosage), sometimes illegally used as growth stimulating hormone (high dosage)
CMOS	Complementary Metal Oxide Semiconductor
CNC	Computer Numerical Control
Co-makership	Combination of a number of organizations for the joined development of a product
Coagulation	Changing from liquid to solid by chemical action
Coercivity	Resistance to demagnetising
Conjunctiva	Mucous membrane that lines the inner surface of the eyelids and is continued over the front part of the eyeball
Consortium	Combination of a number of companies, industries, universities etc. for a common purpose, like the production of an MST product
Core technology	Technology essential for a company to gain or keep a competitive edge and without a real substitute
Coronary stent	Frame used in the vessels that supply blood to the heart
Coupler	A device that connects three or more fibre ends, dividing one input between two or more outputs or combining two or more inputs into one output
Coupling	Transfer of light into or out of an optical fibre
Cranial	Relating to, or directed toward the skull
Creatinine	Nitrogen containing waste product of proteins
CRT	Cathode Ray Tube
Cutaneous	Relating to or affecting the skin
CVD	Chemical Vapour Deposition
Cytokinesis	Division of the cytoplasm of a cell occurring at the end of mitosis or meiosis
DCC	Digital Compact Cassette
DCS	Distributed Control System
Demultiplexer	A device that separates a multiplexed signal into its original components; the inverse of a multiplexer
Detrimental reflexes	Harmful reflexes

DfA	Design for Assembly
DfP	Design for Producibility
DfR	Design for Recyclability
Digitalis	Powerful drug used to stimulate the heart (prepared from the foxglove)
Domotics	Application area of electronics and microsystems in buildings and households
Doping	Process of adding small amounts of impurities to intrinsic semiconductors, to improve the conductivity
DSP	Digital Signal Processor
ECG	Electro CardioGram
EDM	Electron Discharge Machining
EDP	EthylenDiamine Pyrocatechol (etchant)
EEG	Electro EncephaloGram
EMI	Electromagnetic Interference: noise generated when stray electromagnetic fields induce currents in electrical conductors
Emission	Emitting of fluids or gases to the environment
Endocardium	Inner muscular layer of the heart
Endocranial	Relating to or concerning the inner side of the skull
Endocrine gland	Gland producing hormones that are distributed in the body directly by way of the bloodstream
Endoscope	A fibre-optic bundle used for imaging and viewing inside the human body
Ethylene	$H_2C=CH_2$ Colourless flammable gaseous alkene with a sweet odour. External plant hormone which stimulates ripening of fruits and flowers
EU	European Union
FEM	Finite Element Method
FES	Functional Electrical Stimulation
Fibrillation	Rapid, uncoordinated contractions of the heart
Fovea	Area in the middle of the retina that gives the sharpest vision
Fructose	Simple monosaccharide sugar ($C_6H_{12}O_6$) also called fruit sugar
Giberiline	Plant hormone responsible for stretching of stems and riping of fruits
Glaucoma	Pressure increase within the eyeball
Glucose	Simple monosaccharide sugar ($C_6H_{12}O_6$) also called dextrose
GMR	Giant Magneto-Resistive
GPS	Global Position System
Gynaecology	Branch of medicine that is concerned with women and their diseases

HACCP	Hazard Analysis Critical Control Points: hazard analysis system to control critical points regarding safety and quality in a (food)production line
Haemorrhages	Great loss of blood from the blood vessel especially when caused by injury
Halitosis	A condition of having offensively smelling breath
HAS	*Hogere Agrarische School*
HDTV	High Density TeleVision
Head flexure structure	Very small flexible head assembly for high density contact recording
High-end applications	Applications in space, military and R&D equipment
His-bundle	Fibre between AV node and left and right bundle branches
Humulone	Chemical substance causing beer to go stale under the influence of light
Hybridization	Product concept in which the parts of a system are produced with different technologies
IC	Integrated Circuit
IC-foundry	Place where silicon is shaped into parts or systems
ICP	IntraCranial Pressure
ICS	Integrated Control System
Identification	Identifying the state of a device or the identity of a living thing
Immission	Pollutive substances immersed in the soil, water or air
In vitro	(Biological) processes that take place outside the living body
In vivo	(Biological) processes that take place inside a living organism
In-situ operations	Actions performed within a living being or inside a machine
Infrared	Wavelengths longer than 700 nm and shorter than about 1 mm
Infrastructure	A network of companies, institutes and universities needed to develop, design and produce microsystems
Inspection	Measurement of a quality and the interpretation of the resulting signal
Integrated Optics	Optical devices that perform two or more functions and are integrated on a single substrate; analogous to integrated electronic circuits
Interchangeability	The ability to substitute a field device for another device without loss of functionality and without sacrificing the degree of integration with the control system or host

Interoperability	The ability to let operate a field device with another device in a system without loss of device functionality and without sacrificing the degree of integration with the control system or host
Intraperitoneal fluid	Fluid inside the peritoneum
IOP	*Innovatief Onderzoek Programma*
IR	InfraRed
Ischium	One of three bones making up each side of the pelvis that is uppermost and in back
ISFET	Ion Sensitive Field Effect Transistor
Isohumulone	Chemical substance causing beer to go stale under the influence of light
Isotropy	Condition where properties do not change with direction
IWG	Industrial Working Group
Key technology	A technology important to realize products in a limited range. To be mastered completely to be competitive
KOH	Potassium hydroxide
Lactate	Salts and esters of lactic acid (milk)
Lamb wave sensor	Sensor consisting of thin plate supported by silicon die. Measurement principle based on changes in oscillator frequency of the thin plate
Laparoscopy	Endoscopy of the abdominal cavity
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
LIGA	LIthographie, Galvanoformung und Abformung
Light-Emitting Diode	A semiconductor diode that emits incoherent light at the junction between p- and n-doped materials
Lithography	The method of achieving a two-dimensional pattern on a suitable surface by using either a mask or directly copying from a two-dimensional pattern
Livestock	Cattle, horses, ponetry, and similar animals kept for domestic use but not as pets, especially on a farm
Lumen	The cavity in tubes (arteries, vessels)
Maltose	Disaccharide ($C_{12}H_{22}O_{11}$) also called malt sugar
MBE	Molecular Beam Epitaxy: growth of layers of pure atoms or molecules on a crystal, in such a way these layers adopt the crystal structure of the substrate
MCM	Multi Chip Module
MCNC	Micro-Electronic Center of North Carolina
MEMS	Micro Electro Mechanical Systems
Meristem	Plant tissue responsible for growth, whose cells divide and differentiate to form tissues and organs of the plant

Microstructure	Structure with dimensions of less than 1 cm
Microsystem	A system with feature sizes less than 1 cm
MID	Moulded Interconnection Devices
MITI	Ministry of International Trade and Industry (Japan)
MMC	Micro Machine Centre (Tokyo)
Molecular engineering	The making and planning of structures, devices etc., using molecules as building blocks
Monolithic system	System formed from or produced in or on a single crystal
MR	Magneto Resistive
MRI	Magnetic Resonance Imaging
MST	MicroSystem Technology
MST-foundry	Place where microcomponents or microsystems are produced
MTC	MicroTransducer Catheter
Myocardium	Muscular wall of the heart
n-type semiconductor	Semiconductor doped to have an excess of electrons
Nanotechnology	Technology concerning the design, production and application of structures with dimension of a few nanometres
Near Infrared	The part of the infrared near the visible spectrum, typically 700 to 1500 or 2000 nm; it is not rigidly defined
NEXUS	Network of Excellence in Multifunctional Microsystems
NIR	Near InfraRed
NLO	Non Linear Optics
NMR	Nuclear Magnetic Resonance
Nociceptor	Sensory structure in organism responding to painful stimuli
NVFT	*Nederlandse Vereniging voor Precisie Technologie*
OEIC	Opto-Electronic Integrated Chip
Oesophical	Concerning or relating to the muscular tube that leads from the cavity behind the mouth to the stomach
Oestrogen	Hormone group that induces oestrus and controls development of secondary female characteristics
Olfactory	Relating to, or concerned with the sense of smell
Oncology	Study of tumours and their causes, treatment etc
p-type semiconductor	Semiconductor doped to have a deficiency of electrons
Packaging	Provision of a device with a protective layer
Paediatrics	Care for the health of children and treatment of childhood diseases
PAH	Poly Aromatic Hydrocarbons

PAS	Poly-Acenic Semiconductor
PBTS	*Programmatische Bedrijfsgerichte Technologie Stimulering*
PCB	Printed Circuit Board
p_{CO_2}	Partial pressure CO_2
PEDEQ	Personal Detector of Environment Quality
Percutaneous	Through the skin
Peritoneum	Thin translucent serous sac that lines the walls of the abdominal cavity and covers most of the viscera
PET	Positron Emission Tomography
pH	Acidity
Phloem	Tissue in higher plants that conducts synthesized food substances to all parts of the plant
Photodiode	A diode that can produce an electrical signal proportional to light falling upon it
Photovoltaic cell	Element generating a voltage when light strikes the junction between a metal and a semiconductor or a junction between two semiconductors
Phrenic nerves	The nerves which control the movement of the diaphragm
Piezoelectric effect	The interaction of mechanical and electrical stress-strain variables in a material
Plate number	Characteristic figure to identify the separation capability of the column of a chromatograph
Pneumotachography	Method to determine the speed of in- and out flow in the lungs
p_{O_2}	Partial pressure O_2
Precision engineering	The making and planning of structures, devices etc with conventional technologies like milling, turning etc
Probing	Measuring where accessibility is a problem
Progesterone	Steroid hormone that prepares and maintains the uterus for pregnancy
Prostaglandins	Any of a group of potent hormone-like compounds composed of essential fatty acids and found in all mammalian tissues. It stimulates the muscles of the uterus and affects the nervous system, blood vessels and metabolism
PSM	Personal Storage Module
PTCA	Percutaneous Transluminal Coronary Angioplasty
Purchase contract	Contract where the client has the obligation to buy the results of the agreed development or research
PVD	Physical Vapour Deposition
Pyroelectric effect	Effect in which the heating of a material results in electricity
PZT	Lead Zirconate Titanate (Piezoelectric material)
QFD	Quality Function Deployment

QMAP	Quality MAP describing the flow of raw materials or primary components through a manufacturing process
QMI	Quality Monitoring Instrument
RAM	Random Access Memory
Remote sensing	Perception of status without direct contact
Retina	Light sensitive nerve membrane lining the back of the eye
RF	Radio Frequent
RFID	Radio Frequency Identification
ROV	Remotely Operated Vehicle
SA node	Sinoatrial node: the natural regulator of the heartbeat
SAW	Surface Acoustic Wave
SEM	Scanning Electron Microscope
Sensor	Component or device which discovers an effect or quality
Signal processing	Transformation and processing of signals, e.g. imaging
SMA	Shape Memory Alloys
Smart sensor	Sensor with integrated signal processing
SMD	Surface Mounted Devices: electronic parts directly connected to a circuit board
SME	Small and Medium-sized Enterprise
SMT	Surface Mount Technology
SOG	Silicon On Glass
SPC	Statistical Process Control
Spinal	Relating to or located near the backbone
Stenosis	Constriction of vessels of channels
Stereotaxy	Localisation of a certain area in the body (especially in the skull) with the aid of a device functioning on coordinates
STM	Scanning Tunnelling Microscope
Substrate	Thin wafer used as basis to generate micro-elements
Sucrose	Disaccharide ($C_{12}H_{22}O_{11}$) also called cane sugar or beet sugar
Supra molecular chemistry	See: molecular engineering
Systems approach	Looking to and designing an entire system in a filter-down way
Systole	Period of contraction of the ventricles
TAB	Tape Automated Bonding: connection of electronic parts to a printed circuit board by means of a flexible foil with electrical tracks
Tachycardia	Abnormal extra heart beats

Taguchi sensor	Semiconductor gas sensor. The principle is based on changes in electrical conductivity of the surface due to chemical reactions
TCD	Trans-Cranial Doppler (medical)
TCD	Thermal Conductivity Detector (instrumentation)
Telematics	Combination of informatics and telecommunication
Thoracic	Relating to the thorax (chest)
TMAH	TetraMethyl Ammonium Hydroxide (etchant)
TOK	*Technisch Ontwikkelings Krediet*
Transducer	Element transforming energy from one form to another
Umbilical cord	Cord connecting the fetus with the placenta
Under etching	Etching, usually unwanted, below the surface of a wafer
Urea	Colourless crystallize compound produced chiefly by oxidation of proteins
Urethra	The canal that conveys urine from the bladder out of the body
Urology	Study and knowledge of the kidneys and urinary tracts
UST	Under-ground Storage Tank
Vacuole	A fluid-filled cavity in the cytoplasm of a cell
Vascular	Relating to a tube or channel for carrying a body fluid (blood or plant fluids) or relating to a system of such channels or tubes
Venous stenosis	Slow-up of blood flow in the veins
Ventricle	Chamber of the heart receiving blood from the atrium and from which blood is forced into the arteries
VHC	Volatile Hydro Carbons
Wafer	Slice out of which a batch of microdevices is manufactured
Waveguide	A structure that guides electromagnetic waves along its length. An optical fibre is an optical waveguide
WHO	World Health Organization
Xylem	Plant tissue that conducts water and mineral salts from the roots to all other parts
Z glues	Anisotropically conductive glues
β-agonist	Any of a class of drugs that inhibit the activity of the nerves that stimulate secretions of adrenaline and that therefore decrease the activity of the heart
µTAS	Micro Total Analysis System

III-V semiconductor	A semiconductor compound made of one or more elements from the III A column of the periodic table (Al, Ga and In) and one or more elements from the V A column (N, P, As or Sb). Used in LEDs, diode lasers and detectors

Appendix 1

System modules for MST-based products

In this appendix a number of modules are described which have been produced using the microsystem technologies outlined in chapters 2 and 7. These modules are expected to function as essential building blocks in the applications indicated in chapters 3 to 6 and, doubtlessly, elsewhere.

A.1.1 MICRO-ACTUATORS

G.C. Klein Lebbink

Micro-actuators are a basic group of microsystem components, the main types of which are [1]:

- valves
- pumps
- manipulators
- motors
- switches
- optical elements, like shutters, mirrors and LEDs.

Most actuation mechanisms used in the microdomain are known from the macroworld, but some of these concepts gain more significance when miniaturized. Movement and actuation can be realized when the following effects are used [2]:

- electrostatic
- piezoelectric
- electromagnetic
- thermal
- photothermal
- pneumatic
- biological.

A thermo-mechanical micro-actuator is shown in figure A.1 as an example of a basic actuation function.

These actuators are based on thermal effects and have been realized in various configurations using the difference in thermal expansion for separate materials. One of the basic structures is a bimetal-type element with two materials of different thermal expansions combined in a sandwich structure. Cantilever-type thermo-mechanical actuators have been studied extensively using silicon-gold as a sandwich, heated by an integrated poly-silicon resistor as a driving element [3].

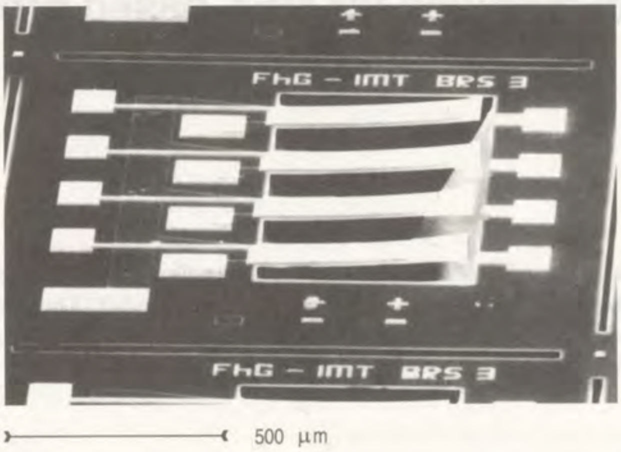

Figure A.1 A SEM micrograph of a thermo-mechanical micro-actuator. The overall chip size is 1.5 x 1.25 mm^2

Source: Fraunhofer-Institut für Mikrostrukturtechnik [1]

Analysis of these structures shows that the bending radius of the beams is proportional to their thickness. Scaling down or miniaturization is therefore attractive if high deformations or deflections are required. Response times and power consumption decrease for small-scale devices. On the other hand, the conversion effect is a volume effect and small-size devices have a limited range of force available for actuation. Generally speaking thermo-mechanical actuators can be operated with standard microelectronic voltage levels, which is advantageous from the system point of view. The bimetal type of micro-actuators have been used for the realization of microswitches and microvalves.

A.1.2 MICROMOTORS

G.C. Klein Lebbink

Many new product concepts for a variety of applications require miniaturized rotational motors. Examples are minimal invasive surgery and diagnosis techniques in medical technology, as well as miniaturized harddisk assemblies or drive systems for portable electronic components. Three kinds of micromotors have recently been developed:

- electrostatic rotational or linear motors [4-6];
- piezoelectric micromotors [2];
- electromagnetic micromotors.

Electromagnetic micromotor

Most of the applications do not need a micromotor with a diameter of 100 µm or less, but require a miniaturized drive with outer dimensions in the range of several mm delivering torques of typically 10^{-6}-10^{-7} Nm. Micromotors need to be operated at high speeds (up to 10^{6} rpm) to achieve useful amounts of power. Professional applications necessarily require extremely high reliability and a long working life of the motor.

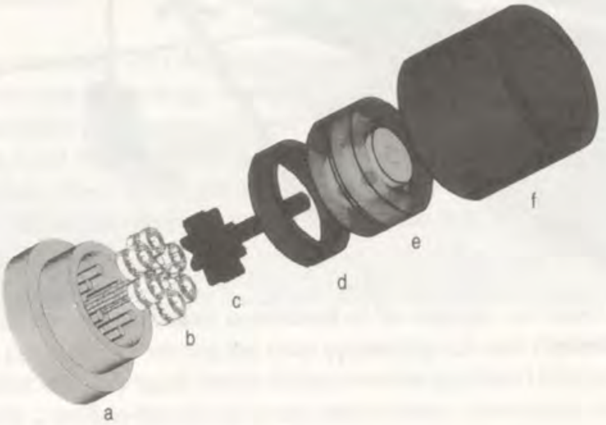

Figure A.2 Exploded view of a micromotor
Source: IMM

The micromotor shown in figure A.2 uses a drive system based on the magnetic reluctance principle. Essentially, a soft magnetic rotor follows a rotating magnetic field produced by the currents in the stator coils in order to minimize the magnetic reluctance. The motor is a good example of the application of a variety of techniques for producing the individual parts, which have to be assembled afterwards. Only the components with high precision requirements are produced by means of microfabrication techniques, whereas the other parts are produced by precision mechanical methods.

The exploded view shows the soft magnetic stator (a) produced by the LIGA technique. Double-sided coils (b) (LIGA technique) are inserted in the stator. The soft magnetic rotor (c) (LIGA technique) is pressed on a shaft (diameter 0.24 mm) made by conventional methods. The distance of 20 µm between rotor and stator poles is fixed by a LIGA-produced distance ring (d) between the stator and the two conventionally produced micro ball-bearings (e) (1.6 mm outer diameter). Figure A.3 shows the size of the complete motor. The outer housing of the motor (f) is realized by a conventionally produced small tube with an outer diameter of 2 mm to be pressed on the stator. All assembly processes involve axial movements only and require specific assembly tools.

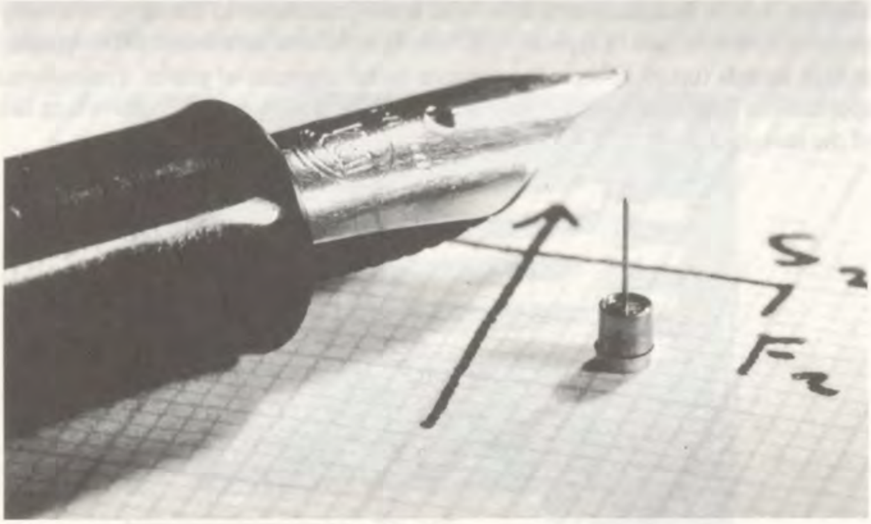

Figure A.3 Micromotor
Source: IMM

A.1.3 MICROPUMPS

G.C. Klein Lebbink

A flow controller is a system that controls small amounts of liquids or gases. It can be seen as part of a larger system, such as a micro Total Analysis System (µTAS) or ink-jet system. Figure A.4 depicts a prototype system based on bulk micromachining techniques. The realization of this pump is shown in figure 2.1b in Chapter 2.

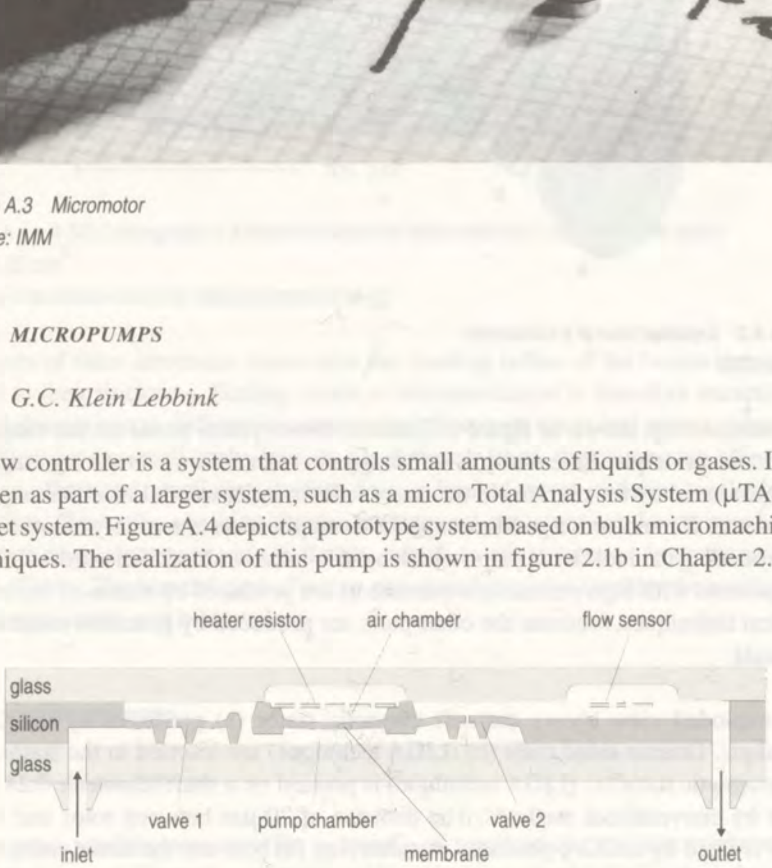

Figure A.4 Cross-section of a micropump
Source: MESA [7]

The driving membrane is controlled by a heater in an expansion room. As a result of the driver membrane's periodical movement, the two valves are opened and closed in opposite phase, which results in a net flow. In order to measure and control the amount of fluid pumped, an integrated flow sensor is used which works by heating an electrode and comparing the temperature of the up and down flow at equal distances. It is clear that the sensor plays an essential role. Without the sensor the flow cannot be guaranteed (actuator drift) and will show cross sensitivity; for example, for counter pressure and temperature.

A.1.4 MIRROR-BASED LASER BEAM DEFLECTORS

P.V. Pistecky

In the future miniature laser beam reflectors will be used for many applications. Using microsystem technology makes it possible to reduce weight, volume and power consumption and improve dynamic properties. The combination and integration of mechanical and electronic systems will also improve the cost-benefit ratio of these devices. There are several research groups throughout the world reporting on such micromirror devices and it is expected these will be produced using mass production techniques.

To achieve the desired rotational movement of the mirrors, actuators based on the electrostatic principle are among the most promising actuator types. The deflector usually consists of a very small mirror (reflective area less than 1000 μm^2) connected to the base by 2 torsion beams for a one-dimensional movement, or by 4 torsion beams for two-dimensional operation (figure A.5 and A.6).

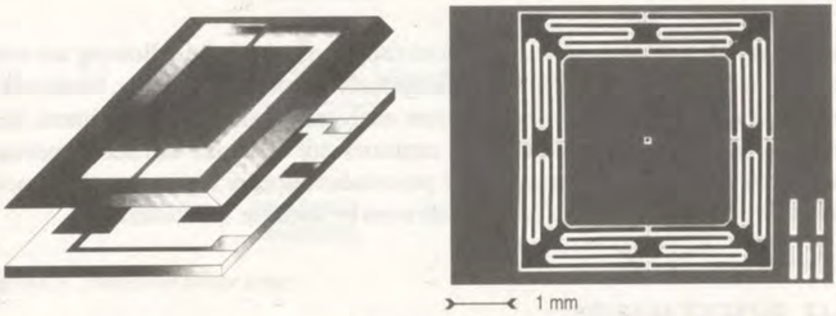

Figure A.5 Basic shapes of a one-dimensional (left) and two-dimensional mirror suspension (right)
Source: [8]

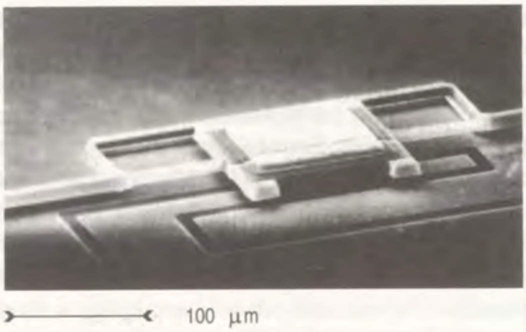

Figure A.6 SEM picture of 30 µm by 30 µm torsional micromirror
Source: [9]

A set of activation electrodes placed under the mirror causes the mirror to rotate by several degrees (up to 30°; figure A.7). The mirrors work in a static or dynamic mode. In static mode it is necessary to obtain large torsional angles with high accuracy and repeatability. In dynamic mode the deflection amplitude at the natural frequency characterizes the properties of the mirror.

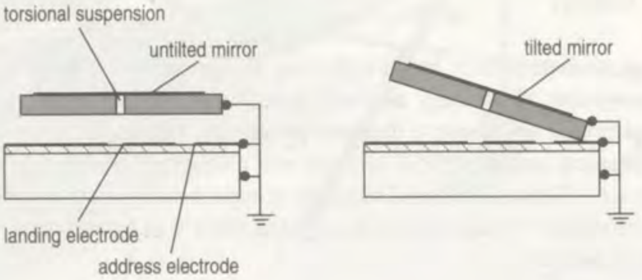

Figure A.7 Cross-sections of rest and tilted mirror positions
Source: [9]

In a two-dimensional array of mirrors each mirror may be addressed individually. In some applications the mirrors can be driven in a resonance frequency range of 200 Hz to 10 KHz.

A large number of applications can be envisaged of which the following are some examples: image processing, three-dimensional measurement devices, Moiré-effect techniques, tunnel microscopes, spectrum analyzers, scanners, laser printers, laser processing equipment, environmental measurement of smoke and dust concentrations, position indicators in assembly processes, displays and screens. In microchemistry and biology these devices can even be used for microstirring.

A.1.5 DIPSTICK SENSORS

H. Leeuwis

A dipstick sensor is usually a chemical sensor in the form of a pen-like stick with electrical connections at one end and a sensing element at the other. For measuring a concentration it is simply dipped into the fluid. The idea behind the dipstick sensor is to have a simple measurement set up similar to that used for measuring physical parameters. The measurement of chemical quantities is much more complex because of the need for frequent calibration and the danger of fouling effects. The trend initiated by microfluid systems is to integrate sensors into micro Total Analysis Systems (μTAS), which leads to improved performance and reliability. The drawback of a μTAS is that it is a more complicated device and one which is far from standard.

A.1.6 SENSOR ARRAYS

J. van Veen

It is possible to arrange a number of sensors in such a way that they are optimized for certain variables like temperature or chemical components. The idea of a sensor array is to loosen the requirements connected with optimization and to let electronics compensate for cross sensitivities. With an array it becomes possible to compensate for the lack of selectivity of many existing chemical sensors and to recognize complex flavours and off-flavours (electronic or artificial nose). Usually both reasons apply when gas sensors are used in combination with pattern recognition techniques (figure A.8). In some cases one can also use sensor arrays in liquids; for detection of metal ions in surface waters, for instance.

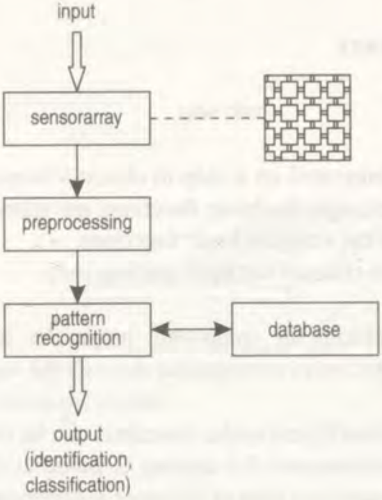

Figure A.8 Principle of sensor arrays

The optimum number of sensor elements is determined by both performance (prediction error) and cost considerations. If the cost-performance ratio is displayed as a function of the number of sensor elements the graph shows a minimum [10]. For most applications in which a complex odour is to be identified 8 to 12 sensor elements are likely to be sufficient.

A major challenge in this field is to mimic the human nose with a sensor array in combination with chemometrical analysis or neural classifiers. This is referred to as an electronic nose. After the first article on this subject in 1982 many research groups have developed this kind of system.

At this moment the majority of sensor elements used in sensor arrays are semiconductor sensors (both n- and p-type) for the detection of oxidizable gases (H_2, H_2S, CO, alcohols etc.) or reducible gases (NO_2, halogenated compounds etc.). Piezoelectric and surface acoustic wave (SAW) sensors are also frequently applied in sensor arrays [11]. The use of conducting polymers as a selective layer in semiconductor sensors is relatively new. In contrast to semiconductor devices, conducting polymer devices do not require heating of the sensor element and are therefore better suited for mimicing the human nose.

Successful performance of sensor arrays has been demonstrated by the identification of five alcohols in a gas mixture using Principal Component Analysis (PCA), the classification of different roasts and blends of coffee with Discriminant Function Analysis (DFA) and the analysis of various beers with Artificial Neural Networks (ANN) [10]. ANNs are particularly useful for recognizing complex odours. After a learning period, in which the error of prediction is minimized, these systems are trained to classify vapours unsupervised. These systems have the potential to replace sensory panels of expert human noses to obtain or maintain odour quality (see also section 6.2.2).

A.1.7 OPTICAL ELEMENTS

P.V. Lambeck

Optical functions are integrated on a chip to obtain a monolithic system of higher order. As in microelectronics the basic functions are relevant in the design stage only. Figure A.9 shows the simplest basic functions:

- a straight waveguide channel for light guiding only;
- a bend;
- a Y-junction for splitting or combining intensities or different modes (i.e. different ways of light wave propagation through the waveguide).

From these basic functions higher-order functions can be built, for example:

- Mach-Zehnder interferometers for sensing or modulation;
- multiplexers which combine light of different wavelengths or mode patterns into one channel;
- couplers which act as wavelength or mode filters.

In addition to passive functions dynamic functions can also be realized by introducing 'active' elements, like electro-optic materials. In that case the optical functions can be controlled by electrical signals and an optical switch can be realized. When measurement signals influence optical performance sensing circuits are created. Using III-V compounds (like GaAs, InP and AlGaAs) light sources and optical detectors and amplifiers can be implemented. If other waveguide materials are used these active functions have to be inserted by hybrid integration, i.e. either by use of fibres or by attaching them directly to the integrated optical circuit. Research is in progress for the development of light sources and amplifiers for non-III-V compound circuits.

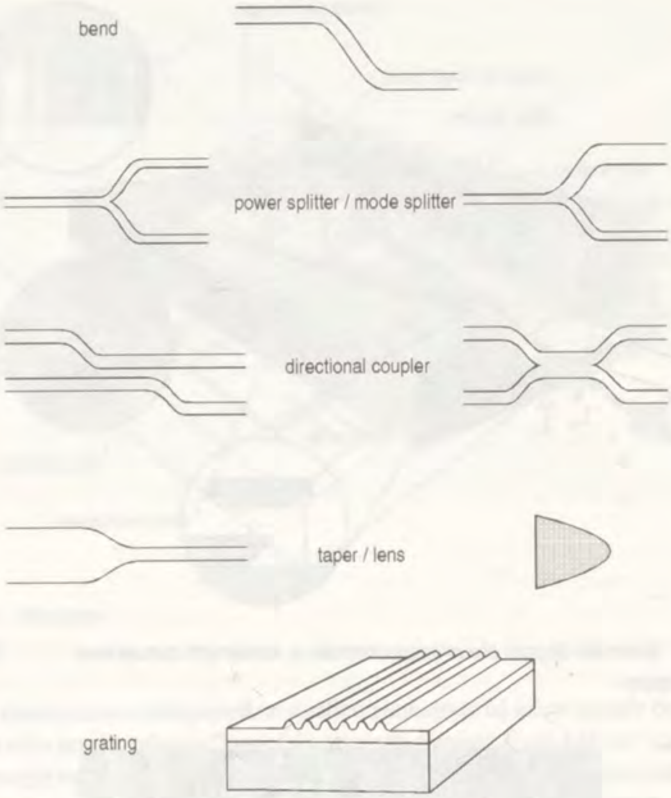

Figure A.9 Basic optical functions and modules

A.1.8 MICROSPECTROMETER

G.C. Klein Lebbink

Figure A.10 shows a miniaturized spectrometer made from a three-layer polymer resist [12, 13]. Light enters the resist through a multimode fibre. The polychromatic light is transmitted by the three-layer resist to a self-focusing grid coated with gold or silver (figure A.11). The spectrometer is suited for wavelengths of 500-1100 nm.

The monochromatic light can either be reflected to a photodiode or led to multimode fibres and used for external analysis and further processing. The device shown in figure A.10 can be produced with the LIGA technique. Fibre shafts, a three-layer wave guide and a grid can be produced in one process. This eliminates the necessity for careful positioning. The option for coupling this microspectrometer with a diode array makes compact spectrographs for visible and near infrared range possible.

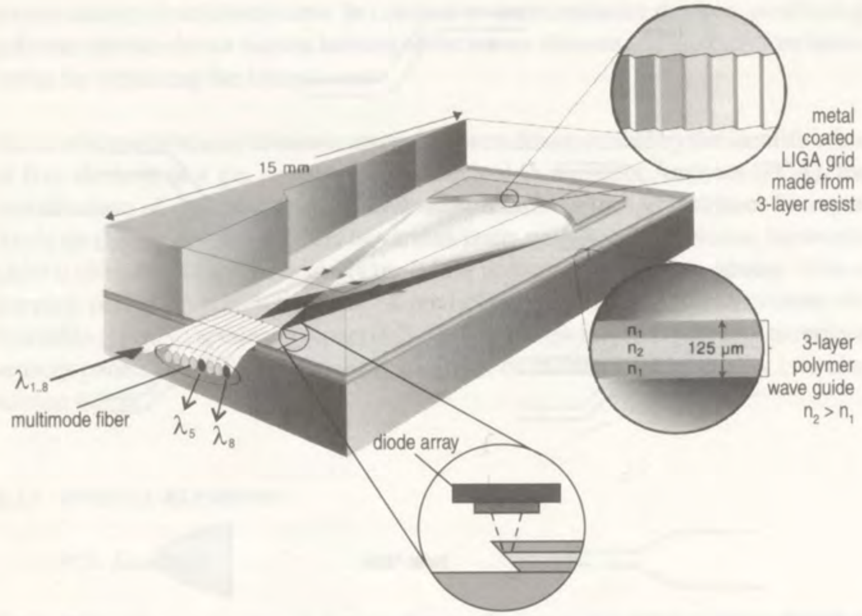

Figure A.10 Schematic diagram of a microspectrometer or wavelength demultiplexer
Source: Microparts

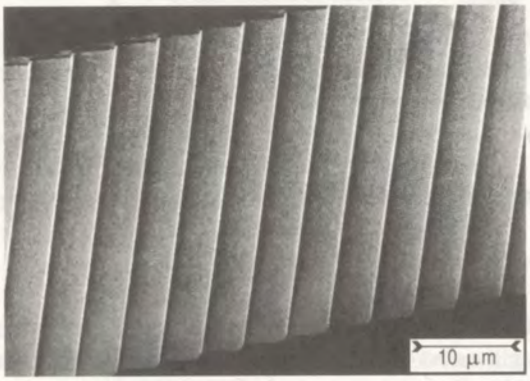

Figure A.11 Self-focusing reflection grid
Source: Microparts

A.1.9 MICROLASER

G.C. Klein Lebbink

Figure A.12 shows a microlaser presently under development in Germany [14].

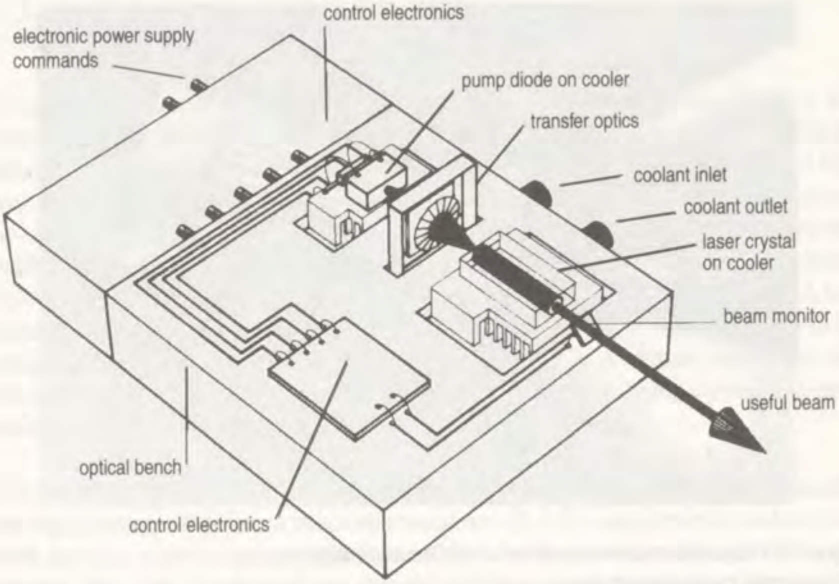

Figure A.12 Microlaser
Source: [15]

All laser functions are integrated on a silicon substrate of a few square centimetres. The light of a semiconductor laser (wavelength ranging from 650 nm to 1500 nm) is led through microlenses and excites a laser crystal. In this way acceptable power ratings can be produced. The integrated electronics, temperature sensor and photodiode monitor control the beam and temperature of the microlaser. The thermal control of the device is effected by means of liquid cooling channels etched into the silicon substrate.

A.1.10 MICROCOOLERS

L. Hermans

Microcoolers are defined as cooling systems where one or more essential parts are produced using micromachining techniques. Cooling techniques using micromechanical technologies are still in their infancy. Micromechanics has primarily been used to produce miniaturized heat exchangers [16]. The required structure of the heat exchanger can be realized not only by using anisotropic etching but also isotropic techniques. Wafer bonding also plays an important role in the realization of miniaturized heat exchangers. Different structural designs have been produced which depend on the particular type of application and cooling principle used, including natural convection, forced convection and Joule-Thomson cryogenic refrigerators. The micromachined Joule-Thomson refrigerator consists of a heat exchanger, an expansion capillary and a reservoir. These microminiature Joule-Thomson refrigerators are already commercially available (figure A.13).

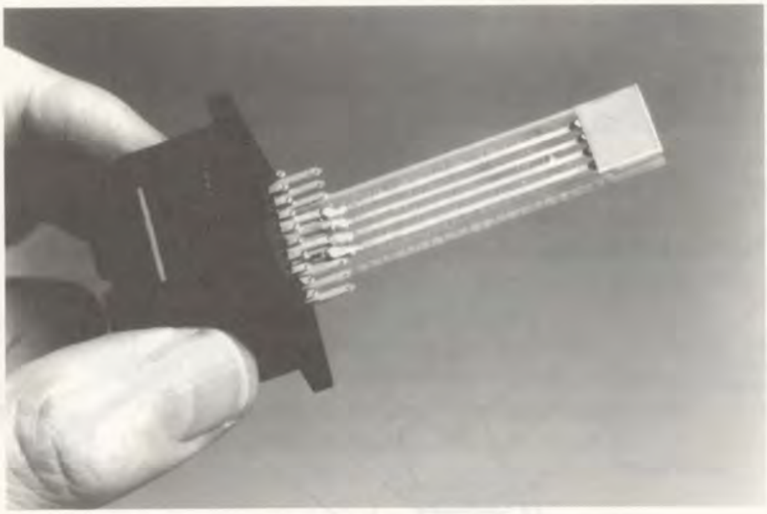

Figure A.13 Example of a micromachined Joule-Thomson refrigerator
Source: MMR Technologies California

Microcooler applications include the cooling of electronic systems and radiation detectors and laser diodes, control of a microcalorimeter, and cooling in SEM and X-ray diffractometers. The principal advantages of the refrigerators in many applications have been their small size, low gas consumption and fast cool down, which allows rapid turnaround time for a large number of experiments.

A.1.11 MODULES FOR IN-SITU MEASUREMENTS

J. Snoeks

To improve the overall effectiveness of industry, advanced quality control of manufacturing processes is an absolute requirement. Next to on-line monitoring of traditional physical parameters there is an industrial need for in-situ determination of quality indicators, chemical composition and quantities. Non-invasive techniques providing measurements of chemical composition on a real time basis are preferred.

One of the techniques which seems fairly easily transferable from the analytical laboratory environment to field instrumentation is optical spectroscopy. The absorption of light in the Near InfraRed (NIR) waveband in particular provides much information about the sample, and the signals are relatively easy to handle in rough industrial environments. For this application new components and modules are emerging onto the market such as:

- Solid-state detector arrays
  - Silicon diodes: 300-1100 nm
  - Indium Gallium Arsenide detectors: 900-3200 nm
- Tunable lasers
- Solid-state lasers and LEDs

- Laser diode arrays
- Gratings and optical filters (e.g. Acousto-Optical Tunable Filters)

It is recognized that the Mid-InfraRed (Mid-IR) region is most attractive for spectroscopy as the fundamental vibration modes of molecules are in the Mid-IR rather than Near InfraRed (NIR) in which the overtones are to be observed. Until now existing components were special and intended only for use in delicate laboratory-type spectrometers, but new demands from industry are leading to the availability of more robust modules, fit for use in field and plant instrumentation. Now emerging on the market are robust analyzers limited to the NIR region. A key factor for the realization of such field-mountable and robust systems appears to be miniaturization. Figure A.14 shows the development of a system module by the '*Kernforschungszentrum Karlsruhe KfK*' where research is being carried out on a microsystem capable of spectral analysis of fluids.

The external dimensions of the system measure no more than a few millimetres and the main components are a microspectrometer (A.1.7), micropumps and valves. With the help of these components the sample is led to a cuvette with opto-chemical sensors. The light led through the sample to the spectrometer projects the spectre on a diode array. This integrated diode array transforms the spectrogram into electrical signals and the components present in the sample are revealed by data processing. The KfK expects that such a system will cost a few thousand DM.

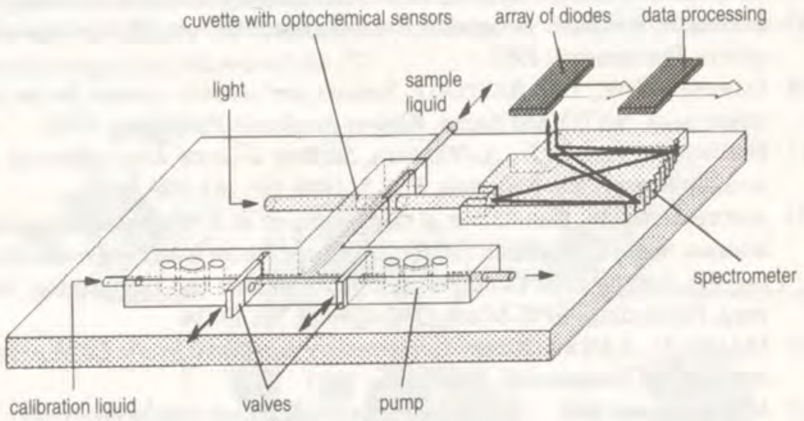

Figure A.14 Opto-chemical analysis system
Source: Kernforschungszentrum Karlsruhe

Application of these modules is enabled by the general availability of processing power – i.e. microcomputers – which can be employed in dedicated field-mounted measurement systems. Optical spectroscopy (especially NIR) is computer intensive because of the need to apply multivariate statistical techniques (chemometrics) to correlate the spectral absorption curves to chemical quantities (or properties).

Other technologies are under development. Attractive examples are component selective Field Effect Transistors (ChemFETs) and component selective optical fibres. Practical use of these modules in the applications as described above will take much longer than the optical spectroscopy approach.

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Appendix 2
The Micro Machine Centre

To give an illustration of the Japanese contribution to MST we will here describe the Micro Machine Centre (MMC). The MMC was founded in January 1992 and is supported by the Japanese Ministry of International Trade and Industry (MITI). The institute started with 23 directors, representing 28 companies and five organizations. The targets of the MMC are:
- investigation and research into micromachines;
- collecting and providing information on micromachines;
- exchange and cooperation relating to micromachines with organizations in Japan and in other countries;
- promoting micromachine standardization;
- providing and disseminating education on micromachines.

In addition to the above-mentioned activities the centre actively strives to attain its goals, and to enhance the international exchange of information publishes the quarterly magazine, Micromachine [1].

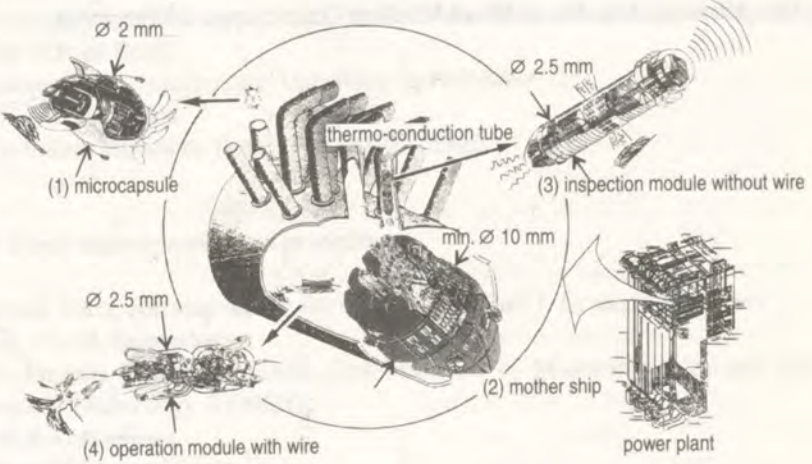

Figure A.15 MMC vision of micromachines for industrial purposes

The MMC is also conducting the research and development operations of a 10 year large-scale project called 'micromachining technology', which was started in 1991 by MITI's Agency of Industrial Science and Technology. MITI expects a growing need for micromachines for performing tasks in highly sophisticated industrial systems or for medical applications. Some MMC concepts are shown in figure A.15.

The large-scale 'micromachining technology' programme aims at the development of minute machines which are capable of moving in very fine tubing or for operating inside the human body for the purposes of examination. For the first five year period the total funding is 10 billion yen. The overall ten year project is estimated to cost 25 billion yen. The MMC's long-term plans are illustrated in figure A.16.

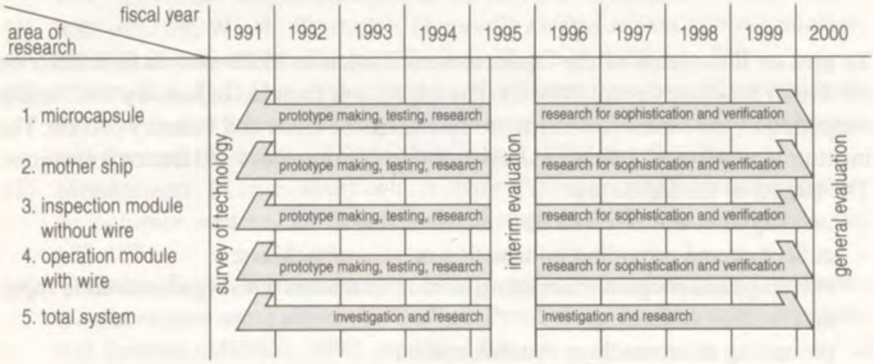

Figure A.16 MMC's long-term research and development plan
Source: MMC

Reference

[1] *Micromachine No. 1*, Micro Machine Centre Japan, Tokyo, 1993

Survey Organization

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To determine the precise questions to be answered, establish the framework for the survey and oversee the running of the project, a steering committee was set up consisting of:

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From time immemorial man has constantly devised technological devices to help him push back his limits. And now, at the end of the twentieth century, a veritable technological revolution is being experienced in almost every field of enterprise. By comparison with only 50 years ago we can't help noticing how technology now influences every aspect of our daily lives.

A recent example of this influence stems from developments in precision engineering and techniques derived from microelectronics: microsystem technology, or MST. Here the dimensional limits of structures are shifted back to be measured in microns (1 micron = one millionth of a metre). This is the technology of the very, very small. And we only have to look at microsystems operating in the natural world to envisage the enormous possibilities awaiting us if only we could harness these systems for our own technology.

And, as has been seen in recent years in consumer electronics, this is where the future lies. But until now the economic hurdles for most new ideas have not yet been overcome. For this reason the Netherlands Study Centre for Technology Trends recently decided to explore the almost boundless opportunities microsystem technology has to offer. This book shows the results of that exploration.

Microsystem technology: exploring opportunities focuses not only on the demand for microsystem technology but also on its impact in the areas of instrumentation, medical technology, consumer products and agriculture. For each given area examples demonstrate microsystem technology's myriad opportunities and several technologies for manufacturing are also described.

This book is a must for those interested in current technological trends and how they can (and will) alter our lives.

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