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Microsystems technology: objectives

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Abstract

This contribution focuses on the objectives of microsystems technology (MST). The reason for this is two fold. First of all, it should explain what MST actually is. This question is often posed and a simple answer is lacking, as a consequence of the diversity of subjects that are perceived as MST. The second reason is that a map of the somewhat chaotic field of MST is needed to identify sub-territories, for which standardization in terms of system modules and interconnections is feasible. To define the objectives a pragmatic approach has been followed. From the literature a selection of topics has been chosen and collected that are perceived as belonging to the field of MST by a large community of workers in the field (more than 250 references). In this way an overview has been created with 'applications' and 'generic issues' as the main characteristics.

Keywords: Microsystems technology

1. Introduction

This contribution focuses on the objectives of microsystems technology (MST). The reason for this is two fold. First of all, it should explain what MST actually is. This question is often posed and a simple answer is lacking, as a consequence of the diversity of subjects that are perceived as MST. The second reason is that a map of the somewhat chaotic field of MST is needed to identify sub-territories, for which standardization in terms of system modules and interconnections is feasible.

2. A short history of microsystems technology (MST)

The roots of MST lie in the early 1980s when a number of activities gave birth to this working field explicitly. Of course 'roots' develop only in a fertile soil and we can go back to the times when the soil was fertilized by a number of ingredients: the microprocessor concept, solid-state sensors and actuators, optical waveguide technologies, bulk and surface micromachining, etc. A broad awareness of the promises of systems in microtechnology, however, had to wait for the early 1980s (although a real microsystem like the silicon micromachined gas chromatograph had already been developed in the 1970s).

This contribution is dedicated to Simon Middelhoek, one of the great pioneers cultivating the soil, particularly with silicon sensors [1], in which MST grows and shows her promise.

2.1. USA

Based on existing know-how concerning silicon micromachining and the prospects of the micro actuator, in the USA the IEEE Micro Robots and Teleoperators Workshop was held in 1987 and after that the landmarking report of the Workshop on Microelectromechanical Systems Research appeared under the title: 'Small machines, large opportunities: a report on the emerging field of microdynamics' [2]. Original copies of this report might become collector's items. These activities led to the regular MEMS Workshops and after that to the IEEE/ASME Journal of Micro Electro Mechanical Systems.

The symbols of MEMS-USA are the electrostatic linear and rotating micromotors (rotating around UC Berkeley), devices with free-running parts completely etched free from the substrate.

2.2. Europe

From Europe the invention of the scanning tunnelling and the atomic force microscope inspired many activities, as did the LIGA technology, a spin-off development from nuclear physics research. The first formal activity in MST was the start of the Micro Mechanics Europe Workshop in Twente in 1989, followed by the first MST Workshop in Berlin in 1990.

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After that, many workshops and meetings were held all over Europe, showing the need for 'The United States of Europe', although the foundation of the ESPRIT network NEXUS in 1992 has led to a converging trend in the European activities. In the 4th Framework Programme of the EC, MST has finally got its own chapter [3].

2.3. Japan

In Japan the global trends of the mainly silicon-based developments in the USA were followed at universities (Tokyo, Sendai) and easily integrated in the more liberal context of miniaturization and precision engineering. MST in Japan has a pronounced 'mechanical' background. More than in other countries, the Japanese activities were characterized by an open approach concerning materials, technologies, industrial cultures, etc. In 1988 the Micro Machine Research Society was founded and in 1991 the MITI-supported R&D project in MST started, with the Micromachine Centre as a supporting organization [4]. The word 'micromachine' (a miniaturized machine) seems characteristic of the Japanese perception.

Of course, this short history of MST is grossly incomplete. We shall not work out the details. We simply conclude that in a very fruitful environment, in some period in the early 1980s MST was born, and the world jumped onto it.

3. Perception of MST

MST stands for microsystems technology. The term 'micro' is used in its meaning 'opposite to macro' and does not refer to 'micron' or 'micrometre'.

'Micro' in 'microsystems technology' is used as in 'microscope', a device to look at small things. How small does not matter. A standard optical microscope goes down to the optical wavelength limit. But a scanning near-field optical microscope (SNOM) or an atomic force microscope (AFM) goes down to the nanometre range and beyond. Nevertheless, they are all called microscopes. So, in our approach we include issues related to nanotechnology, which is also a term used to specify a certain area of activities in the field of MST.

Historically 'micro' refers to 'hardly or not visible with the bare eye', i.e., all beyond, say, 0.1 mm or 100 μm. This is a good tongue in cheek definition, which should be used in a lenient way. In a recent report [5] a measure of 10 μm is suggested.

It is difficult to imagine practical questions in which such a measure will be really conclusive.

To define MST properly, and to omit issues of minor importance, our approach is: (a) to find out how MST is perceived up to now; (b) to find out for what purposes a definition is desired.

To start with the latter, a definition is desirable for proper communication. There are many terms that are used in the literature in a rather ambiguous way. Mostly these are terms that are used within the field of MST, such as bulk and surface micromachining, micromechanics, micromotors, microrobots, micromanipulation, etc.; and somewhat deeper, aspect ratio, sticking, closure of valves, etc. In fact a proper definition of such terms is more urgent than the proper definition of MST. A proposal for the standardization of terminology is being worked out at the Micromachine Centre in Japan, while first proposals concerning standardization have appeared at the moment of writing this text [5]. As we shall see, the maturing of certain areas in MST into industrial activities depends on the success of proper specification, normalization and metrology. So, in a sense the meaning of MST should be derived from definitions of these more specific terms. That is the way we go for the present: we shall dig into the more specific levels and return to the level of generalities afterwards.

Practical situations where a general definition is needed are non-technical in character, e.g., in the definition of programs to be subsidized, or in the selection of papers for, say, the MEMS Workshop or the MST Workshop. Occasionally the question arises: Is this really MEMS or MST? One might wonder if such practical situations are of enough importance to bother about the meaning of MEMS or MST? We think they are, as we shall explain at the end of this section.

Anyway, up to now common sense solved most problems of this kind, which means that some inherent perception of MST has grown in the minds of those participating in the discussion. Therefore it is interesting to analyse these perceptions. They strongly depend on the working fields, but what is shared is the fact that they all refer to the impression: This is a real new approach to miniaturization, or to increasing the functional density; a real new approach to solving problems in the micro field; a real new function that can be implemented thanks to micro technology. And so on.

Characteristic examples are given below (a mixture oriented towards applications, technologies, principles, etc.).

3.1. MEMS (microelectromechanical systems)

In MEMS, as suggested in the USA report mentioned in Section 2.1, (surface) micromachined accelerometers (like the one proposed by Analog Devices [6]), comb drive systems [7], gyroscopes, projection displays (like the one proposed by Texas Instruments [8]), micromotors, etc., are considered without hesitation as characteristic for MST. The technology and the typical dimensions are related to IC technology and there are free moving parts. That is the news (see Fig. 1).

3.2 Cell biology

From the point of view of the foregoing example (MEMS, with moving parts), one can wonder if there are any static devices perceived as MST devices. There are! For instance, microprobes to sense or stimulate nerves (Fig. 2) [9] are seen as objects of MST, as are micromachined filters to sep-

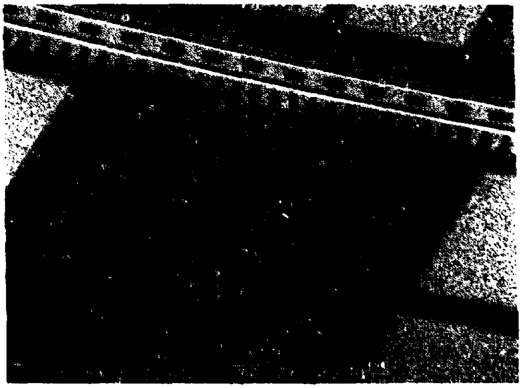

Fig. 1. Characteristic example of an original MEMS-type device. A polysilicon structure, in this case an electrostatic lower stator wobble motor, is etched free from the ground plane by removing a sacrificial layer. The axis of the motor is underneath and has the form of an upside down pin head kept in position by a matched cavity in the ground plane. This structure transforms a rotation into a linear movement (courtesy of Dr Rob Legtenberg, University of Twente).

arate cells [10] and micro punchers for DNA injection in cells [11]. In these cases the really new thing is that micro technology gives access to the micro world of biology. Here micro is perceived in connection with the typical dimensions of advanced bioresearch: the cell and its parts.

3.3. *Micro surgery*

In micro surgery things are different again. An example is minimum invasive surgery based on the expanding art of catheter-tip manipulation. A catheter tip and the means for catheter-tip manipulation are in the (sub)millimetre range. Reliability in aggressive environments, often with slurries, and the need for force or power in the case of micro surgery are important. The characteristic dimensions are those in the field of precision engineering on which current devices are based. Here MST comes in with everything that may give added value or new functionality to the existing products. Precision engineering meets MST in this field.

3.4. *Precision engineering*

By precision engineering we mean the classical field, developed as a part of mechanical engineering, and in existence for a long time. The field is evolving and leads to marvels, which are often unknown to MST engineers, with a background in electrical engineering and which are strongly biased by IC technology. Integration of MST and precision engineering is of great importance. Here we find a new characteristic: the meeting of disciplines. Or even: the meeting of cultures in technology (Fig. 3).

3.5. *Exploitation of effects of downscaling*

Downscaling of geometry may shift the relative usefulness of physical properties. On the level of phenomenological physics this has been emphasized by Trimmer [12], e.g., leading to the conclusion that for small micromotors electrostatic drive is favourable to magnetic drive. Another example is in chemical sensors/actuators with respect to diffusion effects and scale [13,14].

On a still smaller scale short-range binding forces become manifest and can play an important role.

3.6. *Nanoscale manipulation*

At the smallest end of the MST spectrum we find the world of DNA manipulation, molecular self assembly [15,16],

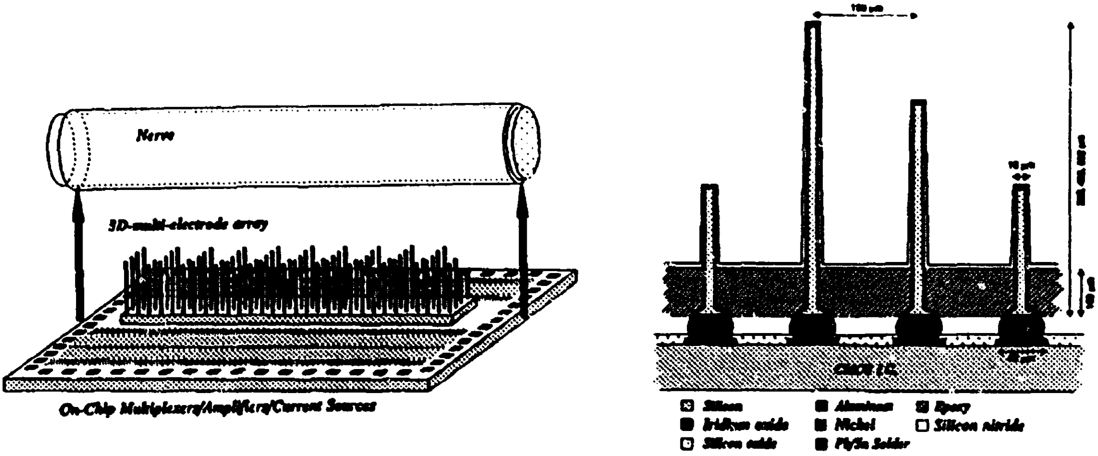

Fig. 2. Micromachined multi-electrode array for use in intrafascicular nerve stimulation. Left, the device as a whole; right, a close up showing the solder bump interface between the stimulator and a CMOS chip carrying multiplexers, current sources and buffer amplifiers. This hybrid approach (be it virtually monolithic) points to an important development in designing microsystems. Note that the multi-electrode is three dimensional (courtesy of Dr Wim Rutten, University of Twente).

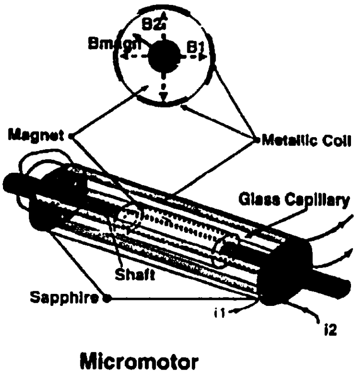

Fig. 3. Magnetic synchronous motor with a diameter of 1 mm. Use is made of conventional sapphire bearings and the device can be seen as the result of conventional precision engineering. Nevertheless, there is a notion of the meeting of disciplines as mentioned in the text. Best results are obtained by considering all options offered by modern technologies (courtesy of Philips Research Laboratories).

laser microchemistry [17], etc., a world in which by artificial means individual structures in the nanometre range are handled or where self-organizing properties of aggregates are exploited in a controlled way. Here the characteristic dimensions are derived from big molecules like DNA or even proteins. This world is perceived as belonging to MST because the chemicals are not treated in bulk reactions alone, but are manipulated almost individually or controlled in a determined way.

3.7. *Miniaturization*

To sweep back to the biggest end of the spectrum of MST, if one follows the development in, e.g., camcorder design, it can be seen that the art of hybridization is blooming. Here we live in the (sub)-millimetre range, with devices crammed on multilayer boards, exploiting sophisticated bonding and connection technologies and using advanced automatic production. Also this field is connected to MST by the experts who are working in it, and they are right because the spin-off of these technologies (interconnection, bonding, packaging, mounting, etc.) will go through the whole field of MST. Here miniaturization is the driver: a camcorder or a hard-disk drive in the palm of your hand (Fig. 4). Miniaturization of functions related to information technology is almost a law of nature [18].

3.8. *High-aspect-ratio technologies (HARTs)*

Almost right from the start the traditional LIGA technology [19] has been considered as a typical MST. Why?

IC technologists as well as precision engineers recognize the well-known art of lithography, with some exclusive features attractive for both parties. The first party appreciates the deep-etching possibility and the possible extension of their designs to three-dimensional structures. The precision engineers appreciate the high aspect ratio and the typical dimensions of LIGA: right in their own working field. Anyway, LIGA might have played a historical role in bringing these parties together. In the mean time, LIGA has provoked intensive research in alternative HARTs like reactive ion etching [20] (Fig. 5) and laser ablation.

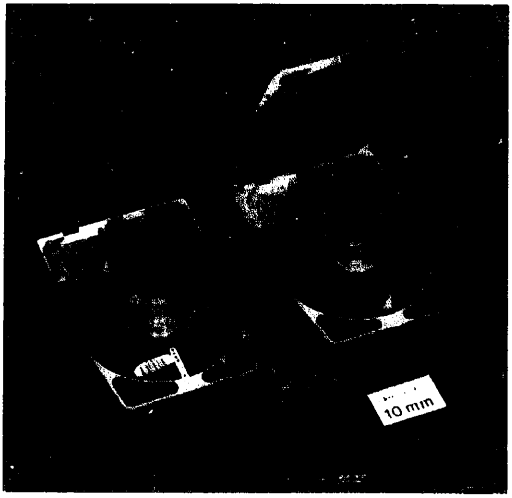

Fig. 4. Miniaturization in information technology is almost a law of nature. The increase of information density in space and time is an ongoing process in all aspects of information technology. The matchbox-sized hard-disk drive shown here has shrunk from its frigidaire-sized predecessor within a period of 25 years (courtesy of Mosaic of Philips Research).

We could continue with such examples and outsiders might get the idea that MST is just a basket full of new things that are glamorous because of their smallness and often inherent beauty. They may conclude that in the end it is better to keep things apart and give up the aspirations of an MST as a whole.

Such a conclusion would be disastrous, however. The value of MST is in the meeting of disciplines (which is not only valid for MST). Therefore it is urgent to define MST by means of a collection of characteristic examples, on the one hand, but on the other hand by an identification of the results of the multidisciplinary approach and the characteristics thereof.

A conclusion based on this is that there is a need for conferences, journals and other means of communication that keep these things together. That is why it is important to bother about the meaning of MST in selecting papers for an MST workshop.

On the other hand, the list above points to a clear problem. We can agree to keep things together for the benefit of the inventors. But inventions must lead to products and the producers want to know how to find the way in this impressive wood of possibilities, where the price of pathways to interesting trees is unknown and probably high as well. So from their point of view order is desired and we therefore have to develop such an order and see how we can define means for producers to arrive at the right actions.

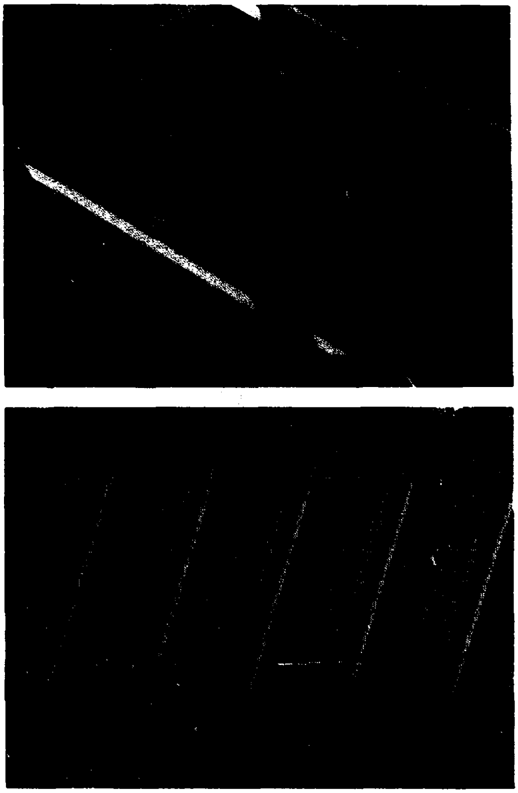

Fig. 5. Well-tuned reactive ion etching may lead to well-defined deep-etched structures with aspect ratios between 10 and 100 as is shown in the upper photograph. The long deep channel etched in silicon can be used in a micro chemical analysis systems. Very promising is the combination of reactive ion etching and techniques to release the structure from the ground plane, as is shown for the comb drive system in the lower photograph (courtesy of Dr Henry Jansen, University of Twente.)

4. The quest for standards

What defines MST is not so much determined by the characteristic feature sizes of less than 10 or 100 μm, but by the new production methods that bring such feature sizes, with all the promises of new functions and functional densities, within the range of possible and cost-effective production. These production methods have their roots in the lithographic techniques from precision engineering and above all, from IC technology. Mainly from the latter comes the possibility of integrated or batchwise production, leading to well-defined functions, processed in a parallel or wafer-scale mode. Wafer-scale production can be much cheaper than piecewise production, depending on the investments in technical facilities, development costs and the production volume.

Two important remarks must be made here:

(1) The proposition that chip-level manipulation cannot compete with wafer-scale manipulation is not true in general. It is only valid for complex structures and feature sizes in the (sub)micron region. This can simply be checked by inspection of an IC line. At the end of the line there are testers, scribers, bonders and pick and place machines to position and package the chips. These automates work on chip scale and not on wafer scale and they do not destroy the low process costs. Of course, the chip-manipulation machines have larger minimum feature sizes to handle than the wafer-scale machines. They start at the moment that the micro work is finished and the macro work starts. The feature size, which is characteristic for this turnover to individual manipulation, is roughly the size of the bond pad.

(2) Waferscale fabs in IC technology increase sharply in price as the feature sizes go down to the predicted 0.18 μm level. In fact, the costs become so large that only some tens of fabs can survive, producing volumes that cover a world-wide demand [21].

Micro systems differ considerably from sophisticated ICs. They are generally much less complex and have larger feature sizes. The often stipulated analogy between ICs and micro systems is artificial to a large extent. Of course in historical perspective, MST can be seen as a logical extension of IC technology, but the differences are still so large that it is easy to arrive at the wrong conclusions when this analogy is taken too far.

Another point is the diversity of micro systems, as we shall see in Section 5. The generic factor in IC technology is much larger than in MST. Therefore it is much easier for IC technology to achieve standards for large-volume activities than it is for MST. ICs are much more variations on a theme than MST products are.

For the evolution of MST this leads to two extremes:

(1) Either MST is forced to follow the trends of IC technology, which means that only those MST products survive that have the character of ICs as mentioned above. This will drastically reduce the promises of MST. (It is even difficult to buy commercial ICs in low-volume quantities from the big IC houses [22]).

(2) Or MST products are produced in a wide range, which means that the trend to follow the IC production technology must be left to a great extent and a lot of hybridization must be accepted. In fact hybrid technology can be seen as a part of MST itself (see Section 3.7). The development of IC technology to ever-larger wafers and ever-smaller feature sizes is not in the interest of MST at all. Small wafers, small machines and a modest IC facility are sufficient to produce MST novelties. Many people working in the field of MST are very unhappy with the thought that eventually they may be unable to buy small wafers.

The developments in bonding technology, e.g., solder bump technology, might be a stimulus to think in terms of hybrids. (As a matter of fact, with such technologies the difference between monolithic and hybrid becomes rather vague.) They might be of great help in the diversification of production technology, unless the degree of sophistication of these technologies, when oriented towards high-volume multichip module production, again lifts it outside the cost range of medium-scale production.

The conclusion is that the current technological context is not MST friendly at all. Despite all its promises it is difficult to plan for a production facility for medium-scale production. MST seems to be locked between the world of precision engineering that has reached its limits and the world of IC technology that is far too overdimensioned for MST.

A necessary condition to overcome this situation is to achieve standardization of MST products and MST production facilities. Of course standardization reduces the variety of possible products, but a compromise between variety and production volumes must be found and such a compromise must be different from that in the IC world. This conclusion is not new at all, but the difficulty is how to implement standardization in the chaotic world of MST. It is a topic that cannot be treated in general terms.

Therefore it is necessary to identify the most important sub-domains of MST and to identify communities of interested persons that are large enough to put some weight on the scale. Without that the quest for standardization is just a sigh without any effect.

So, we have to work out the topics that are perceived as belonging to MST topics and see how we can define the MST sub-domains and the standardization issues at stake. As an example of an outcome, we mention micro fluid-handling systems where first proposals have been made concerning standardization of modules [23].

5. Specific applications and generic functions

In order to get a clear overview of MST, we have to choose the main characteristics. After some efforts, we found that application and generic function are the best to work with.

The procedure is to start from an application and decompose the systems gradually into subsystems until we finally reach the basic micro parts. This gives rise to a tree-like structure. The finest branches are the basic micro parts.

After many trees, it can be seen that the finest branches may coincide. If this overlap is for a large number of applications, we can conclude that we have identified a generic function.

After finding the generic functions, we can turn around the procedure and start from the generic functions and look for applications. In a sense, trees are growing now from the other side. After some time the numbers of applications and generic functions saturate and the exercise is completed. A first result is presented below.

Of course a continuous effort will be needed to keep the data base up to date. The full picture of these trees is very complicated. Therefore we first present the lists of applications and generic functions we found by following this method. Next we present a more detailed scheme with many references. However, even this scheme is a reduced representation of all that exists.

5.1. Short list

Applications

A1. Portable workplace for information handling
A2. Portable workplace for materials handling
B. Personal tools, domotics and leisure
C. Portable or implantable diagnostic and therapeutic means
D. Hospital
E. Production
F. Transport
G. Safety, monitoring
H. Research
I. Characterization and analysis
J. Communication

Generic issues

A. Sensors
B. Actuators
C. Resonators
D. Switches
E. Valves
F. Filters
G. Array-type systems
H. MST production
I. Energy supply
J. Materials supply
K. Energy conversion
L. Microrobotics

Note: There is no correlation in the order of the columns.

5.2. Extended list

Reference is made to recent contributions in conference proceedings, journals, company brochures, etc. Yet, the list is incomplete (e.g., patent literature has not been covered) and must be updated every now and then. Since we have restricted ourselves to recent literature, many core papers are most probably not in the list, but may easily be found by tracing them from the reference lists in the papers.

Applications

A1. *Portable workplace for information handling (laptop, etc.)*

Data storage	(Dig.) Video recording [24,25]
	Magnetic disk
	Smart recording slider [26–29]
	Micromotor/disk [30,31]
	Optical recording [32,33]
	Magneto optical recording [34]
	Nanometre recording [35–37]
Displays	Review [38]
	Flat panel displays [39,40]
	Cathode ray tubes [41]

	Projection displays [41,42]
	Digital mirror device [8]
	Viscoelastic display [43]
	Vacuum field emitter [44–47]
Printers	Laser printers [32]
	Inkjet [48–50]
Scanners	Rotating micromotors
	Polygon scanner [51]
	Diffraction grating [52]
	Torsional motors [53]

Keyboards
Mouse (or other 'animal')
Microphones/loudspeakers
(see also hearing aids)

A2. *Portable workplace for materials handling*

Micro chemical analysis
Systems (see under I)

Microfluidic systems	Flow controller [54,55]
LIGA-based [56]	Fluid mixer [57,58]
Silicon based [59–63]	Pressure regulator [64]
Polymer based [65]	Amplifier [66]

Microoptical systems
  Devices and/in systems [66–69]
    Deformable lens [70,71]
    Integrated encoder [72–74]
    Scanning system [75]
    Modulator [76]
    Fibre alignment [77]
    Micro optical bench [68]
    Micro spectrometer [78]

B. *Personal tools, domotics and leisure*

Personal tools	Watch	Micromotor [79,80]
	Phone	
	Compass	
Domotics	House of the future	
Leisure	Multimedia [81]	Television [82]
		HDTV (*IEEE Spectrum*, April 1995)
	Communication [83,84]	
	Virtual reality	
	Cameras	
	Camcorders [85]	

C. *Portable or implantable diagnostic and therapeutic means*

Body function monitoring [86,87]	Microdialysis [88–90]
Drug delivery	Precision infusion [91]
Smart pills	
Artificial sense organs [92]	Cochlea implant [93,94]
	Middle ear implant [95]
	Hearing aids [96–98]
	Artificial eyes
Artificial body functions	Islets of Langerhans [99]
	Eye pressure controller [100]
	Tonometer + telemetry [101]
	Movement monitor [102]
	Pacemaker, defibrillator
	Neural interface
	Channels [103,104]
	Channels + telemetry [105]
	Prickers [106,9]
	Electrodes [107]
	Electrodes + telemetry [108]
	Mechanical stimulation [109]
	System connector [110]

D. *Hospital*

Tele-operation	Catheters
	Ultrasonic catheter [111]
	Active catheter [112]
	Tip assembly [113]
Minimal invasive surgery	Minimal invasive heart surgery [92]
	Minimal invasive eye surgery [114]
	Catheter tip surgery [115]
	Micromotors [116,117]
	Power ultrasonics [118]
	Tissue fastener [119]
Intensive care monitoring	Microdialysis (see C)
Imaging apparatuses	
Therapeutic means	Tonometer [120]
	Movement monitor [102]

E. *Production*

Process industry	Monitors moving with process
Product industry	Engine, plant inspection (see G)
	Pneumatic control (valves)
	Paintjet
	Micro stitching
Farming [121]	Cattle monitoring
Agriculture, horticulture [121]	Crop monitoring (see G)
MST production facilities	Position (and fix)
	(see also: arrays) [122]
	Comb drive [123]
	Vibromotor [124]
	Scratch drive [125,126]
	Nano lithography [127–129]
MST test facilities	IC probe tester [130–132]
Production equipment	Micro assembly [133–136]
	Micro manipulation [137–140]
	Teleoperation [141]
	HARTs
	LIGA [19,142]
	DEEMO [143]
	Stereo lithography [144–146]
	Surface finishing [147]
	Conductive adhesives [148]

	Micro connection	
		Flip chip [149–151]
		Multichip module [152]
Precision products	Micro optics (see **A**)	
	Micro fluidics (see **A**)	

F. *Transport*

Motorcars [153,154]	Airbag inflation system [155]
	Combustion control system [156]
	Antilock braking system
	Traction control system
	Tyre performance system
	Gyroscopes [157,158]
	Fuel atomizer [159]
	Driver monitoring [160]
Aeroplanes	Turbulence control [161,162]
Spacecraft [163]	Remote viewing [164]
	Fluidic system [165]

G. *Safety, monitoring*

Safety of buildings		
Burglary prevention	Infrared imaging tunable IR filter [166]	
	Acoustic intrusion alarm [167]	
Children, handicapped, elderly people	Movement monitoring [102]	
Engine, plant inspection	Mobile robots [168]	Cameras [38]
		OMRON Micro Photonic device [169,75]
		Crack detector [170,147]
Crop monitoring [121]		
Environment	Air	
	Surface water	Heavy metals detection [171]
	Ground water	

H. *Research*

Micro probe techniques [172]	
Cell manipulation [173]	Cell imaging [174]
	Grippers [175]
	Cell fusion [176]
	Cell separation [10,177]
	Cell cultivation [178]
	Cytometry [179]
Nano manipulation	DNA manipulation
	Microchemistry [17]
	Probe tip manipulation [172]
Nano synthesis [180]	

I. *Characterization and analysis*

Chemical analysis systems [181]	Chemical sensors [182,183]	
	Sensors in microchemical analysis systems [184,185]	
	Microfluidic systems (see **A**)	
	Microreactors [186]	
	Chromatograph [187–189]	
		Injector
		Thermal cond. device
	Micro electrophoresis [190,191]	
	Enzyme reactors [192]	
	DNA analysis system [193–195]	
	DNA diagnostic array dispenser [196]	
	Micro mass spectrometer	
	Spectrometer	
		Variable slit [197]
		LIGA [78]
Micro atomic clock [198]		
Micro probe microscopy	STM [199,129]	
	AFM [200,35,36]	
	MFM [201]	
	SNOM [202]	
	Multiprobe [203]	

J. *Communication*

Optical communication [204]	Switches [205]
	Sensors [206]
	Mechano-optical interface

Generic issues

A. *Sensors*

In situ calibration [207–209]

Chemical sensors
(see Chemical analysis systems, **Applications I**)

Proximity	Ultrasound [210]

Gyroscope [157,158,211]

Accelerometer [8] etc.

B. *Actuators*

Thermal

Electrostatic [212]

Electromagnetic

Electrochemical [213]

Pneumatic [60]

Thin-film SMA [214]

S-shape actuator [215,216,167]

C. *Resonators*

Resonator type sensors [217]

Fluid density sensor [218]

Optical scanner [75]

D. *Switches*

Relay [219–225]

Fluid flow switch [226]

Optical switch [205,227]

E. *Valves*

Fluids [228,55,64,229,230]
see also **B**: S-shape actuator)

F. *Filters*

Cells [177,10]
Light [76]

G. *Array-type systems*

Artificial muscles [231–234]	
[212,235,236]	
Odour sensors [237]	
Positioning array [238–242,139]	
Mirror arrays [8]	Viscoelastic [43]
Vacuum emitter arrays [44]	
Tactile sensors [137]	

H. *MST production*

Tele operation	Observation	
Micro manipulation	Observation	CCDs [138]
Particle handling [243]		
Monolithic/hybrid		

I. *Energy supply* [244]

Telemetry	Tonometer [245]
	Neural interface [105,108]
Optical	Fibre
	Air
	Photovoltaic [246,247]
Batteries	Micro batteries [248,249]

J. *Material supply*

Pumps [250–252,54]

K. *Energy conversion*

Micromotors	Rotational	Electric [254,255]
[253]		Magnetic [256,257]
		Electric vs. magnetic [258]
		Wobble motors [259–264]
		Motor + gear [265]
		Scanners [51,52]
	Linear	Vibromotor [124]
		Scratch drive [80,126]
		Comb drive [123]
Micro gear [265,266]		

L. *Microrobotics*

Mobile robots [267]	
Flying robots [268,269]	Wings [270]
Swimming [271]	

N. *Trends*

Microelectronics [272,274]	Yield [273]
Conducting polymers [275]	
Organic transistors [276]	
Thin-film transistors	

6. Conclusions

We have made an overview of what can be considered as elements of microsystems technology using the characteristics application and generic issues. There are others, e.g., technology, or discipline in physics and/or chemistry. During our work we found out that the latter are much harder to use as a guideline for an overview.

With this overview the diversity of MST, as well as a possible order, is shown. This might be of help in getting a grip on the issue of standardization and preparation of MST for production.

The developments in IC technology to ever-larger wafers and ever-smaller feature sizes are not in the interest of MST. An MST production environment will be supported by the development of down-scaled equipment, while the trend is in scaling them up. Here is a chicken and egg problem: MST products and MST production facilities. Maybe this is at the heart of the problem of getting MST off the ground.

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