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| VDI/VDE/IT | VDI/VDE-Innovation und Technik |
| | Network of Excellence in Multifunctional Microsystems |
| EUROPRACTICE | Microsystems Service for Europe |
| mst germany | German Microsystems Technology Programme |
| | Eureka Industrial Initiative for Microsystems Uses |
| Patent-DfMM | Design for Micro & Nano Manufacture |


# mst news

international newsletter on micro - nano integration


No. 3/04
June 2004




www.mstnews.de

# Contents

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## Look ahead to the next issues:

- **mstnews 4/04 on "Micro- and Nano Materials" in August:**

  Overview about new developments in the fields of new and promising materials for Micro- and Nano components and systems

  Deadline for press releases, short news, event announcements and advertisement orders: July 12th, 2004

  Date of distribution: Aug. 3rd, 2004

- **mstnews 5/04 on "Applications in Logistics" in October:**

  Applications of MST/MEMS Solutions, such as RFID, Smart Labels, distributed data acquisition systems and other, in the field of Logistics

  Deadline for abstracts: June 15th, 2004

  Deadline for press releases, short news, event announcements and advertisement orders: Sep 13th, 2004

  Date of distribution: Oct 7th, 2004

*Dear Readers,*

*If you were in Germany in April, didn't you find the week from April 19th as straining as I did? I didn't know where to go first: Semicon Europe 2004 in Munich or MicroTechnology at the 2004 Hanover Fair. How to manage participation in all the MST/MEMS related events? Flying from Munich to Hanover and back again, or rather use a car? I really have no idea why it is so difficult for the two fair organisers to come to a more visitor-friendly spacing of the two important annual events... In June two other relevant events will be held at nearly the same time: the SMD/Hybrid/Packaging 2004 in Nuremberg and the Actuator 2004 in Bremen. But in this case both events are much more specific and therefore the overlap may be negligible.*

*And this brings me to the special topic of our new issue: Micro actuators and micro drives. Surely it is not necessary to explain to you why micro actuators are an integral part of microsystems and play a similarly important role as micro sensors. That's why it is high time to deal with them in mstnews too. The attentive reader may have noticed that we have tacitly expanded the title to "Micro Actuators and Drives Applications". When the authors of the leading article had agreed on a clear (and surely acceptable) definition of "micro drives" we found this definition too narrow for our mstnews issue. We had obtained for you also some contributions on interesting micro actuators that fulfil a certain function (here an optical function) by themselves. I hope the broadness of the examples shown will give you an idea of the great application potential of micro actuators! Please enjoy our new issue!*

*Bernhard Wybranski*


**Mini-gearbox as the central part of an upper limb prothetic device. Source: Instituto de Automática Industrial (CSIC), Spain; see contribution on page 38 in this mstnews issue**

**Main Topics of mstnews until 2/05**

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| Aug. 04 | Micro- and Nano-Materials | passed |
| Oct. 04 | Applications in Logistics | Jun. 15, 2004 |
| Dec. 04 | MST/MEMS for Safety and Security | Aug. 15, 2004 |
| Feb. 05 | Assembly and Packaging | Oct. 15, 2004 |
| Apr. 05 | Smart Textiles | Dec. 15, 2004 |
| Jun. 05 | Design for Manufacturing | Feb. 15, 2005 |

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# Microdrives - Bringing Actuators into Application

***Hubert Borgmann, Eberhard Kallenbach and Helmut Kergel***

*Microdrives are typical micro-mechatronic systems that can generate motion. They consist of elements capable of processing information and energy. The main element of any microdrive is the energy converter (microactuator), which converts arbitrary energy into mechanical motion energy. Today the field of microsensors is better developed than the field of microactuators because the miniaturisation of energy conversion elements is not as simple as the miniaturisation of data-processing devices.*

The volume of the microactuator is mostly determined by the active volume in which the energy conversion is taking place. Therefore, the miniaturisation is limited. During the design process, the microdrive must be optimised as a whole system through a mechatronic approach (VDI 2206, a new directive of the German Association of Engineers VDI on the methodology of the development of mechatronic systems). Microdrives are often realised in the form of a hybrid construction. The general structure of a microdrive is shown in figure 1.

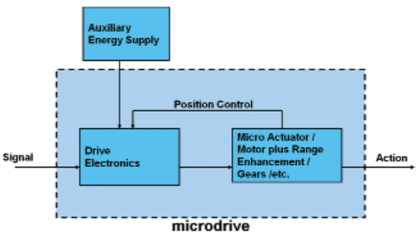


**Figure 1: Principle set-up of a microactuator / microdrive (source: Messe Bremen, VDI/VDE-IT)**

Microdrives may be more advanced than miniaturised actuators. The key issue is to improve the initial movement of the actuator to achieve an operation that can be practically used. Furthermore, microdrives may also include the driving electronics and some control mechanisms. In general, a microdrive should be seen as a (complex) system rather than a (less complex) actuator component.

It is possible to distinguish between rotary and linear microdrives and apply several different actuator principles (electromagnetic, piezo, electrostatic, ...). The device improving the actuator movement to obtain something that can be practically used may take advantage of mechanic, pneumatic or hydraulic mechanisms and auxiliary energy supplies.

The application fields for microdrives are broad. Microdrives can be found nearly everywhere, sometimes operating even in a hidden environment, but carrying out absolutely indispensable functions. No computer would work without hard disk drives, incorporating at least two microdrives for driving the disks and positioning the read/write heads. Industrial automation technology, as a second example, would not exist without pneumatics, driving valves, linear stages, etc. Innumerable more examples could be listed.

According to a market survey conducted by WTC Wicht Technologie Consulting (www.wtc-consult.de), the world market for micromotors and microactuators in 2003 added up to 65 MEUR. It is problematic, however, to work with such numbers, as a clear borderline between "micro" and "macro" has not been defined yet. Unfortunately, there is no common understanding of this issue. Therefore, a look at other surveys may result in totally different figures.

## Rotary microdrives (micromotors)

At least three physical principles are used for realising rotary micromotors: electromagnetism, inverse piezo effect and electrostatics. In terms of practical usage, only electromagnetic micromotors and piezomotors have achieved broad industrial application.

Electrostatic micromotors are often more of an experimental approach, applying semiconductor micromechanics for designing such device. During the TRANSDUCERS 2003 and the MEMS 2004 conferences for instance, a large number of papers and posters from research institutes covered issues of micromotors based on silicon or other planar technology mainly using electrostatic principles. During other events in the past, similar observations were made as well. Broad industrial applications of such motors are only possible if small forces and momentums are needed (yaw sensors with integrated electrostatic oscillating actuators, digital micromirror device, etc). One reason is probably the lack of momentum that can be achieved with such motors and the stability and reliability of the necessary bearing between the actuator and the stator of such motors.

Electromagnetic microdrives, on the other hand, are well applied within industry. Several sources for highly miniaturised electromotors and dedicated gearboxes are known. At least within Europe, the Faulhaber group (www.faulhaber.de and www.penny-motor.de) and the Maxon motor AG (www.maxon.ch) can be seen as market leaders. The Faulhaber group has been manufacturing high-performance micro actuator systems for a wide variety of applications for more than 50 years, being famous for the development and production of the world's smallest motor-gear unit with a diameter of only 1.9 mm.


**Figure 2: Brushless micromotors in a range down to 1.9 mm in diameter (source: Faulhaber group)**

A very interesting approach for gearbox system achieving reduction ratios of up to 1000:1 in combination with highly miniaturised motors was introduced by Micromotion GmbH (www.mikrogetriebe.de). Most details you will find in a further article in this issue.

**Linear microdrives**

Linear microdrives can be designed by using initial linear motors or by transforming a rotary movement into a linear movement by dedicated gearbox systems. Fluidic linear units, driven by compressed air controlled by valves, are known as well. Concentrating only on linear drives without using initial rotary motors, different physical actuating principles are again applied.

The basic element of linear microdrives are magnetic microactuators which directly generate linear continuous or oscillating motions. Linear magnetic microactuators can be divided on the basis of the operating principles into the following groups:

- Reluctance microactuators: forces are generated in the interfaces between the poles (electromagnets for microrelays and microvalves, stepping motors),
- Electrodynamic microactuators: forces are generated on the current flow wires in the magnetic field (permanent DC motor),
- Magnetostrictive microactuators: magnetic field generates shape change of ferri- and ferromagnetic materials (magnetostrictive bimorphous elements for valves and optical scanners),
- Magnetic shape memory actuators (twin boundary motion),
- Magnetorheological fluid actuators (valves and clutches).

Piezo actuators are the most developed actuator technology based on smart materials. The precise field-induced strain (inverse piezo effect) is the key effect for a large area of products in all fields of applications, including nanopositioning and active vibration control. The main advantages of piezo stacks are: ultrahigh precision, very high dynamics, and position blocking without applied field. For a number of applications, the available stroke may be enlarged by carefully designed cantilever constructions to achieve required values. Furthermore, piezoelectric multilayer actuators may help to keep the driving voltage in a moderate range.

A great variety of commercial piezo stacks are available from Physik Instrumente (PI) GmbH & Co. KG, Germany (www.pi.ws), Noliac A/S, Denmark (www.noliac.com), Piezomechanik GmbH, Germany (www.piezomechanik.com); special adaptations for the textile industry are available from Argillon GmbH, Germany (www.argillon.com).

A very successful example of serial introduction of piezo actuator technology is the piezo common rail technology for fuel injection. Its greatest advantage is again its speed compared to solenoid valves. This opens the chance to have multiple injections designed to produce clean and efficient combustion without a steep pressure rise, which results in quieter operation. In Europe about one million passenger cars have already been supplied with such injection systems and their number will rapidly grow within the next few years (www.siemens-automotive.com).

Linear piezo drives with positioning ranges in the centimetre range may be obtained by making use of the inchworm principle or of stick-slip motors. Even loads up to 200 N may be successfully controlled. This is achieved by micro-ridges in hardened steel enabling the motor to carry large forces over a 30 cm range.

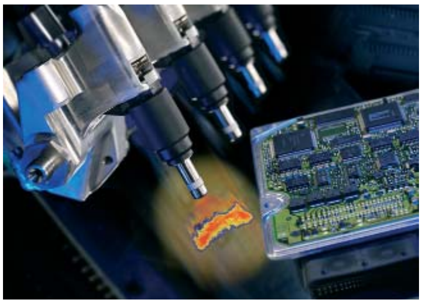

**Figure 3: High-pressure direct injection system for a charged SI engine based on piezo actuators (source: www.siemensvdo.com)**

Pneumatic or hydraulic linear drives represent cascading actuator systems: The fluid actuator may be driven by an electromagnetic or a piezo actuator. Market leaders in the area of highly miniaturised pneumatic components are SMC Corporation in Japan (www.smcworld.com) and FESTO AG & Co. (www.festo.com) in Germany, which both account for a market share of approximately 22% of the West European market of 340 million EUR for miniaturised pneumatic components according to a recent market study by Frost&Sullivan (www.frost.com). Pneumatic systems offer advantages because of their simplicity and their low costs compared to electric systems. Applications in various areas are increasing, resulting in a constant market growth (in terms of units and value).

Looking at a pneumatic driven linear unit, further R&D is necessary to optimise speed, volume and thermal behaviour. A general, still unsolved problem, for example is the direct absolute measurement of the stroke of such a drive, especially when device sizes shrink further.

**Micropumps**

Micropumps can be seen as microdrives dedicated to the specific function of liquid (or gas) transport. Various principles for such pumps are known, driven by rotary motors as well as working with other principles, such as the use of membranes, pneumatics, piezos, etc.

The full technology range for the construction of pumps is applied, From precision mechanics (example: micropumps by HNP Mikrosysteme GmbH, www.hnp-mikrosysteme.de, micro annular gear pumps for various applications) to monolithic integrated silicon micropumps (example: Tricumed Medizintechnik GmbH, www.tricumed.de, implantable drug delivery pump).

Only recently a very detailed review of micropumps was published in the "Journal of Micromechanics and Microengineering" (www.iop.org/EJ/journal/JMM) Vol. 14, pages R35-R64, surveying the last 25 years of development and pointing out in summary, that micropumps suitable to be applied in various applications still remain a fertile area for future research.

**Micro-mechanic switches**

Relays can be seen as typical representatives of drives with specific end stop positions, an application field in the area of electro-mechanics that is still increasing, even though solutions using MEMS or fully electronic switching are more and more being implemented. Even though relays can be seen as "old technology", the market volume still remains at least constant on a high level.

MOEMS and RF-MEMS have been the main drivers of microsystems technology innovation for the telecommunication markets. It is, however, questionable if we should speak of microdrives when referring to such devices. Several issues of mstnews covered the areas RF-MEMS and telecommunication in the past. Therefore these topics should not be discussed further here.

**Conclusions**

Microdrives are characterised as a highly miniaturised complex system. There is no clear borderline to distinguish microdrives from "macrodrives". In order to perform actions (forces, momentums, displacements) that can be practically used, a certain minimum geometry is necessary that limits geometries on the lower side.

Therefore, when characterising microdrives, we often come upon a hybrid construction incorporating precision engineering technology and micro technologies. The price of such systems depends very much on the automation degree of the production technology applied for such systems. On the other hand, system costs greatly limit the spread of the systems to (new) application sectors.

While the automated production of microdrives in huge volumes is not seen as a general technical problem, the lack of production technologies capable of covering small lot sizes, a volume ramp-up phase, and flexible small volume production can be seen as a major drawback for doing business in the area of microdrives. Wafer-level packaging concepts comparable to the sensor technology cannot be applied because of the hybrid construction. The hybrid construction again is due to expected outputs of such actuator systems.

Nevertheless, the role of actuators and corresponding microdrives in the area of microsystems technology applications will increase and will become a key factor.

This issue is well addressed by the ACTUATOR 2004, the 9th International Conference on New Actuators in conjunction with the 3rd International Exhibition on Smart Actuators and Drive Systems, which will be held in Bremen, Germany, on June 14-16, 2004.

The implementation of actuators into systems requires intelligent solutions in the areas of packaging and (automated) production technologies. The integration of "micro" into "macro" is still an industrial challenge worldwide, especially for specific, rather specialised, lower volume solutions. Production and assembly issues need to be investigated further in order to develop more options for production-oriented solutions. The availability of suited micro-mechatronic production technology will poster the further devolopementand diffusion of micro drivers technology into industrial applications.

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# Hollow-shaft Micro Servo Actuators for Semiconductor Applications

*Dr. Reinhard Degen and Dr. Rolf Slatter*

*The trend to miniaturization cannot be overlooked. The use of very small electronic components in a variety of consumer goods makes necessary the use of small-scaled servo actuators for positioning applications in production equipment. The previous generation of micro gears and micro actuators was not suited to this type of application because of an unacceptably low positioning accuracy. The Micro Harmonic Drive® (Fig. 1) gear was introduced into the market in 2001 as the world's smallest backlash-free micro gear. In the meantime this gear has been implemented in a new range of miniaturized servo actuators, which provide zero backlash, excellent repeatability and long operating life.*

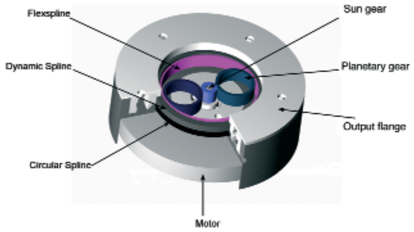


**Figure 2: Components of the Micro Harmonic Drive®**

Micro gear systems represent a key element in micro drive systems. Only by using suitable micro gear systems is it possible to apply existing micro motors operating with speeds of up to 100,000 rpm at output torques in the range of some μNm in a wide field of different applications.

## The Micro Harmonic Drive®

To access new innovative fields of application in the range of micro drive

**Figure: 1: Size of a Micro Harmonic Drive® gearbox (right) and servo actuator (left) compared to a jelly baby**

systems Micromotion GmbH has developed a new generation of high precision and zero backlash micro gear systems: the Micro Harmonic Drive®. The world's smallest backlash-free precision gear was developed as a result of cooperation between the Institute for Microtechnology Mainz (IMM) and Harmonic Drive AG in Limburg.

**Principle of Operation**

The basic elements of the Micro Harmonic Drive® gear system are the Wave Generator (WG), consisting of two planetary wheels and a sun gear wheel and the three gear wheels Flexspline (FS), Circular Spline (CS) and Dynamic Spline (DS) (Fig.2 and 3). The Wave Generator deflects the elastically deformable Flexspline elliptically across the major axis. Due to that the teeth of the Flexspline engage simultaneously with the two ring gears - Circular Spline and Dynamic Spline - in two zones at either end of the major elliptical axis. Across the minor axis of the ellip-tically deflected Flexspline there is no tooth engagement. When the sun wheel of the WG rotates, the zones of tooth engagement of the FS travel with the angular position of the planet wheels

**Figure 3: Principle of operation**

of the WG. A small difference in the number of teeth between the FS and the CS (the latter has two teeth more) results in a relative movement between these gear wheels. After a complete rotation of the planet wheels of the WG the FS moves relative to the CS by an angle equivalent to two teeth. The DS is used in the flat type gear system as the output element and has the same number of teeth as the FS and therefore the same rotational speed and direction of rotation.

**Method of Production**

Conventional methods of gear production can be used down to a module of ca. 60 µm, depending on the tooth geometry. To manufacture a gear with a module in the range of the described micro gear, micro-technological methods, such as the LIGA-process (Fig. 4) have been successfully applied. These methods are derived from processes for the production of semiconductor components and utilize lithographic techniques. Horizontal dimensions are represented in a blocking absorber coating on a mask and are projected precisely into a photo-resistant material during exposure. In order to achieve structures with heights up to several millimeters yet with tolerances better than 1 µm

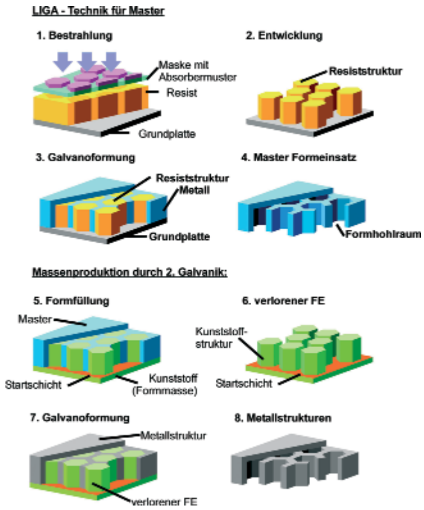


**Figure 4: The LIGA process**

on horizontal dimensions it is necessary to use a Synchrotron X-ray source. This provides high energy, short wavelength, highly parallel X-rays that minimize reflection scattering in the photoresist and so make high aspect ratio, highly accurate structures possible.

The production process for the micro gear is based on a modified LIGA process, called Direct-LIG. The synchrotron radiation is used to create a 2.5-dimensional mould in the photoresist. An electroplating process is then applied, in order to "grow" the individual gear components on this mould. These are then separated from the mould and assembled to produce the complete gear set. For very high production volumes the complete LIGA process can still be applied, as shown in Figure 4.
A gear module of 34 µm must be used to realize the necessary high reduction ratio and the small dimensions. The single gear wheels of the Micro Harmonic Drive® are manufactured in a nickel-iron-alloy. Due to the high yield point of 1800 N/mm², low elastic modulus of 135,000 N/mm², high hardness of 55 HRC and its good fatigue endurance this alloy possesses the necessary properties for perfect functioning of the flexible gear wheels of this micro gear system.

**Micro positioning in high vacuum**

An increasing number of processes within the semiconductor industry or in research are performed under vacuum conditions to provide an extremely pure environment. For the applied drive technology this is a special challenge because the use under vacuum conditions can cause special problems, e.g. conventional lubricants or conventional gear materials cannot be used any more.

The Micro Harmonic Drive® gear now has proven its vacuum compatibility since it provides highest precision and positioning accuracy even under these conditions. For the output bearing dry lubrication is applied. The pure-metal components make it resistant to corrosion and wear and tear.

**Application example: Semiconductor manufacturing**

The semiconductor manufacturing process can be divided into a front-end process, consisting of the photolithographic processing of the silicon wafer, and a back-end process, which starts with cutting the wafer into individual chips and ends with final electronic components that are packed and ready to be assembled. So-called Die Attach machines are used during the assembly phase within a back-end process. Alphasem AG is one of the leading manufacturers of Die Attach machines. These machines are used for the assembly and connection of semiconductor chips while they are in their protective packaging.

The tiny chips - often not bigger than 0.25 x 0.25 mm - must be aligned and positioned with high precision. A new machine type called Easyline 8032 (Fig. 5) from Alphasem is equipped with a new type of rotary bond tool (Fig. 6) which ensures that the chips are positioned in any required angular position with extremely high accuracy. Key element of this assembly is a Micro Harmonic Drive® gearbox in a customized design. The gear is driven by a micro stepping motor, which is connected to the Micro Harmonic® Drive by means of a spur gear stage. The gearbox features a central hollow-shaft that allows vacuum to be provided through the gear. This is necessary in order to grip the semiconductor chips for the next positioning process. The hollow-shaft enables the use of an optical sensor to ensure that the chip has been gripped successfully. The output shaft is supported by means of a pre-tensioned ball bearing to achieve the required guide accuracy. With this assembly the chips

**Figure 5: Die Attach Machine (source: Alphasem AG**

can be positioned with sub- µ accuracy and high speed. During the development of the rotary bond tool comprehensive endurance tests were performed; more than 30 million cycles were run without a noticeable difference regarding the positioning accuracy.

Other applications for the micro gear are in the field of optics, e.g. to adjust lenses and mirrors, in medical equipment, e.g. to dose drugs or to drive surgical instruments, in optical communication, e.g. to switch or adjust fibers, in robotics, e.g. to drive axes for micro robots with high accuracy, in laser technology, e.g. to adjust the beam by means of mirrors and lenses, in measuring machines, e.g. to adjust non-contacting sensors or in aircraft and spacecraft, e.g. to control nozzles or valves in nanosatellites.

**Technical Data:**

| | |
|---|---|
| Transmission ratio: | 160, 500, 1000 |
| Dimensions: | |
| Diameter: | 6 and 8 mm |
| Axial length: | 1 mm |
| Gear module: | 34 µm |
| Material: | Nickel-iron |
| Efficiency: | up to 82 % |
| *(at rated operating conditions)* | |
| Max. output torque: | 50 mNm |
| Torque loss: | 16 µNm |
| Repeatability: | +/- 10" |
| Lost motion: | 10 " |
| Torsional stiffness: | 2.6 Nm/rad |

## Conclusion

The Micro Harmonic Drive® sets new standards. This gear systems combines the advantages of a compact design, high power density and excellent positioning capabilities. This all is realized using only six components. The consequences are that the Micro Harmonic Drive® is more pre-cise, smaller, simpler and therefore more reliable than existing solutions.

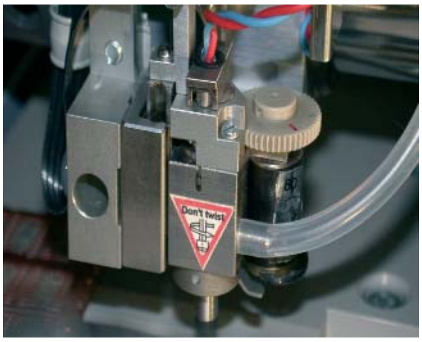

**Figure 6: Rotary Bond Tool (source: Alphasem AG)**

Micromotion GmbH, located in Mainz, develops and manufactures the Micro Harmonic Drive®.

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# A Full-Time Accelerated Vertical Comb-Driven Micromirror for High Speed 45-Degree Scanning

***O. Tsuboi, X. Mi, N. Kouma, H. Okuda, H. Soneda, S. Ueda and Y. Ikai***

*This paper presents a new structure and driving method for a vertical comb-driven micromirror which enables full-time acceleration and optically 45-degree scanning with a 4-mm long mirror. Its optimal application is as a scanning mirror for laser beam printers, replacing polygon mirrors which have technical limits in relation to scanning speed.*

## Introduction

Rotating polygon mirrors are widely used in laser-scanning applications including laser-beam printers, 3D profilers, and laser-scanning microscopes. However, polygon mirrors face technical difficulties in relation to scanning speeds, which can reach tens of thousands rotations per minute.
MEMS-based scanning mirrors can be used to replace polygon mirrors for high-speed scanning because of their small moment of inertia and non-requirement for a ball bearing [1]. Since a millimeter-sized mirror with a surface flatness of hundredths of a nanometer is required for such applications, bulk-micro-machined, electromagnetically driven mirrors have been developed [2]. Electrostatically driven mirrors are especially suited to LBPs because the electrostatic actuator has negligible Joule's heating loss and good controllability because it is voltage driven. In comparison, an electromagnetic actuator is current driven and has Joule's heating loss.
Table 1 shows the characteristics required for LBP application. The 3-kHz-frequency corresponds to hexagonal polygon-mirrors with a speed of 60 000 rpm.

| | |
|---|---|
| Mirror length [mm] | 4.0 |
| Mirror width [mm] | 1.0 |
| Resonance frequency [Hz] | > 3,000 |
| Scanning angle [deg.] | 45-60 (optical) |
| Surface flatness | [nm] < 159 (=lambda/4) |

**Table 1: Characteristics required for LBP application**

## Theory of Operation

A vertical comb actuator is capable of large angle operation because it can generate large electrostatic torque in a relatively long stroke compared with a parallel-plate actuator [3]. However, the characteristics of a comb actuator can change significantly in that the electrostatic torque decreases rapidly and quickly becomes negative if a pair of movable and stationary comb-teeth completely overlaps. In addition to this, due to the one-way electrostatic force, the acceleration of a comb actuator essentially occurs during only half the period of a cycle of vibration unless it has some special mechanism like a push-pull structure of the parallel-plate actuator [4]. To realize large-angle scanning, full-time acceleration using either positive or negative torque corresponding to the vibration is required.

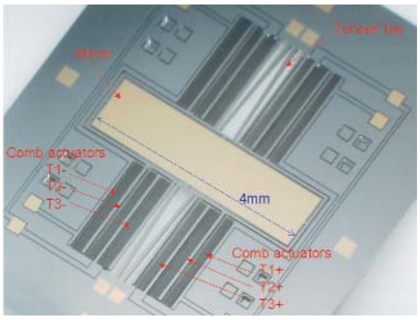



**Figure 1: Photograph of fabricated scanning mirror**

We propose a new structure for scanning mirrors fabricated from SOI wafers using bulk micromachining, as shown in Figure 1. The mirror has multi-level comb actuators, called T1, T2 and T3. Each actuator consists of 2-layer stationary electrodes and is positioned on a different radius.

Figure 2 shows the principle of the 2-layer comb-actuators for four different periods corresponding to the rotation of the comb-driven mirror. At the moment of the initial state , torque in both directions of rotation can be generated by applying a voltage between the movable and bottom stationary electrodes of Tx+ and Tx. Neither of the top stationary electrodes can generate torque. When the mirror rotates at a small angle, the bottom stationary electrode of Tx+ generates positive torque and both the top stationary electrodes generate negative torque. If the moving electrodes completely overlap with the lower stationary electrodes so that the displacement z reaches the same value of thickness as the comb teeth $T_{COMB}$, the torque generated by the bottom stationary electrodes decreases to zero. When the moving electrodes move past the overlap with the bottom stationary electrodes, so that z is larger than $T_{COMB}$, the torque generated by the bottom stationary electrodes changes to negative.

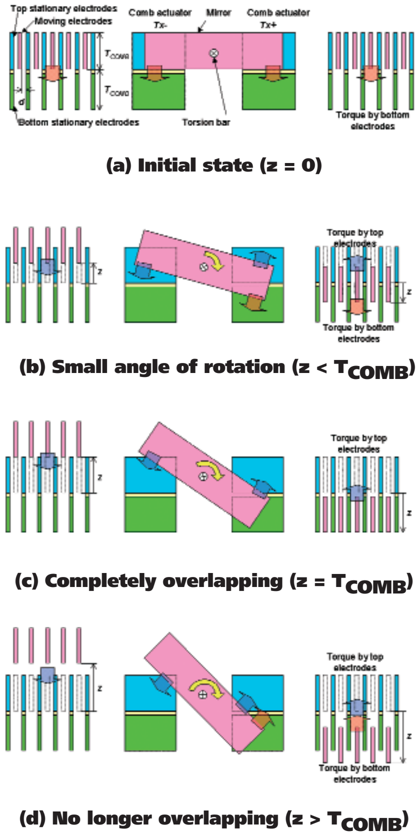



**Figure 2: Principle of full-time accelerated comb-driven mirror**

From simple calculations of the generated torque by the 3-level actuators of our proposed micromirror., both the top and bottom of T3 show constant torque over +/- 15 degrees, but this is insufficient. Both of T2 show constant torque up to 8 degrees, decreasing to zero up to 13 degrees. Similarly, both of T1 show constant torque up to 6 degrees, decreasing to zero up to 7 degrees. Only the bottom of T1 shows reversing polarity and increasing negative torque at more than 11 degrees.

Based on these results, the top of T1, T2 and T3 are electrically connected and the bottom of T2 and T3 are connected. The bottom of T1 is isolated from the others and has the same voltage applied as the bottom of T2 and T3 up to 7 degrees, but at over 7 degrees, the voltage applied as to the bottom of T1 must be cut or the same voltage must be applied as to the top of T1, T2 and T3. By appropriately controlling the three different comb actuators, positive/negative torque can be generated at every angle, thus achieving full-time acceleration.

**Fabrication of Mirror**

An N-type (100)-oriented SOI wafer with a 100-µm-thick top layer, 1-µm-thick BOX layer, and 200-µm-thick bottom layer was used. First, a gold/chromium layer and a 1.5-µm-thick CVD oxide layer were deposited and patterned on the top and bottom surfaces. The top silicon was etched with DRIE until the BOX for the top layer was exposed, and then the bottom silicon was also etched with DRIE to a depth of 200µm. Finally, the BOX and patterned CVD oxide were etched using buffered-HF. Each comb actuator consists of 7-µm-wide, 200-µm-long comb-teeth with an air gap of 8 µm. A V-shaped torsion bar was applied to suppress the pull-in motion of the comb-teeth actuators [3]. Figure 3 shows an SEM image of the bottom of a comb-teeth actuator in the fabricated mirror; 200-µm-thick stationary bottom comb-teeth, and 100-µm-thick movable and stationary top comb teeth were fabricated.

**Experimental Results**

Using a half-wave rectifier and a 2-channel pulse generator with power amplifiers, voltage was applied to a pair of comb actuator, for example, T1+ and T1-, alternately. Figure 4 shows the response of the mirror with acceleration by the bottom electrodes (a) and top electrodes (b) at a resonance frequency of 3.3kHz. Sine-shaped resonance of the mirror, caused by both the top and bottom electrodes and a 90-degree-phase between them, was observed. Vibration accelerated by the bottom electrodes can be easily controlled even with open-looped driving. However, the vibration phase accelerated by only the top electrodes cannot be precisely controlled because it is only excited by the unbalancing of the fabricated mirror [5]. Figure 4-(c) shows the response of the mirror with full-time acceleration. An increase in the rotation angle from that driven by each stationary electrode and the controlled phase of vibration was observed.

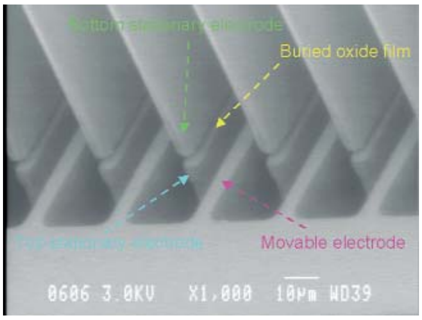
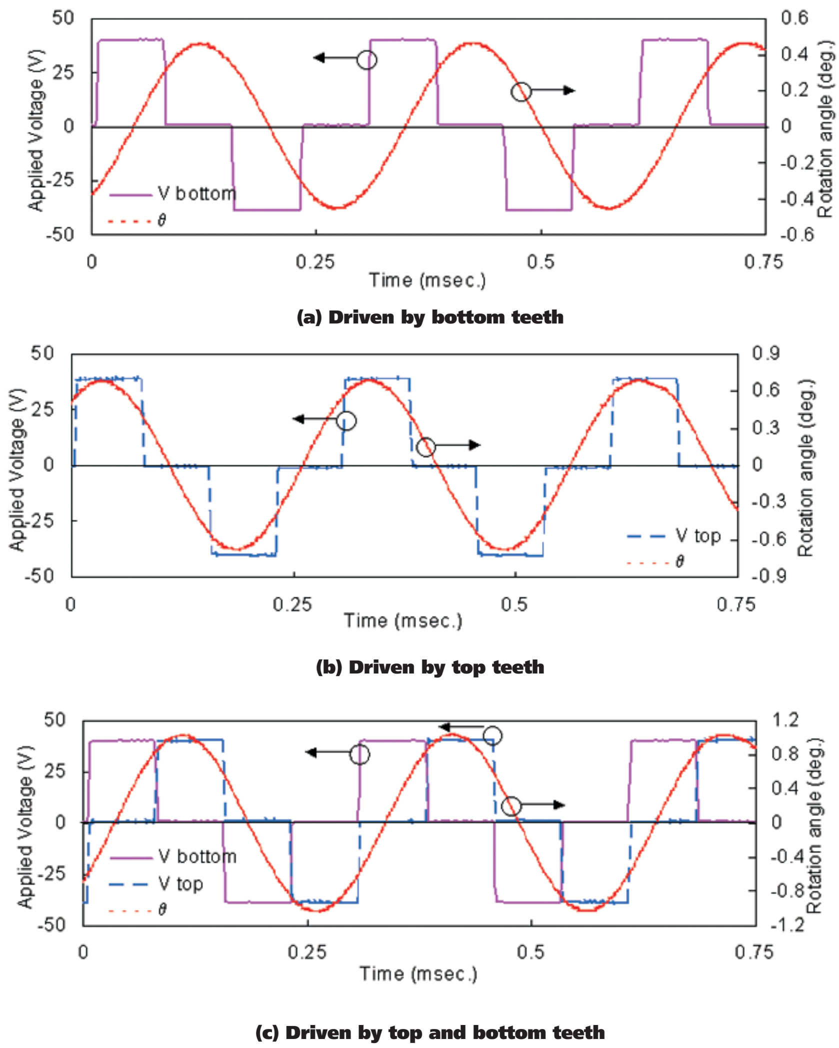



**Figure 3: SEM photograph of the comb-teeth electrodes of fabricated mirror from the bottom view**




(a) Driven by bottom teeth

(b) Driven by top teeth

(c) Driven by top and bottom teeth

**Figure 4: Measured response of mirror at resonance frequency of 3.3 kHz**

Figure 5 shows the experimental results for each comb actuator at its resonance frequency. Driving by the top electrodes enables a +/-5.8-degree-rotation and driving by the bottom electrodes realizes a +/-6.5-degree-rotation. A +/-10.9-degree-rotation was observed with full-time acceleration, although a +/-12.3-degree-rotation would be expected if both were used appropriately. This difference can be explained by the fact of reversing polarity to negative torque generated by the bottom T1. An optical scanning angle of almost 45 degrees was achieved using fulltime acceleration. If the bottom T1 was switched off at the appropriate sequence using close-looped driving with rotation sensing, a large rotation angle such as 15 degrees would be expected. A large scanning angle and low drive voltage were demonstrated using full-time acceleration of the comb-driven micromirror.

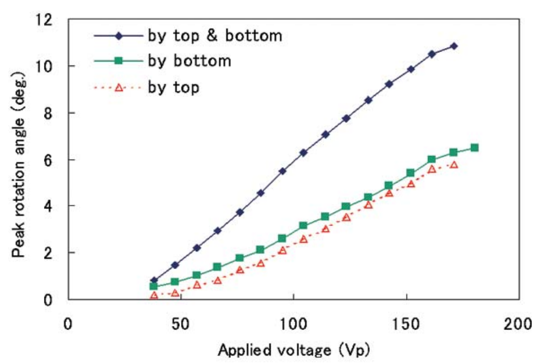



**Figure 5: Experimental results of rotation angle at resonance frequency versus applied voltage**

## Conclusion

Using multi-level and 2 layer comb actuators, the full-time acceleration on the mirror was obtained and the optically 45-degree-scanning at 3.3 kHz was realized. A remarkable high speed corresponding to 66,000 rpm of hexagonal polygon-mirror was obtained.

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# Micropyrosystems for Generating a Mechanical Force

*Danick Briand, Carole Rossi, Manel Puig-Vidal, Josep Samitier and Johan Köhler*

*In 2000, the EC funded MicroPyros* project was initiated to develop technology to merge energetic materials, MEMS devices and electronics in order to realize new performing micropyrotechnical systems. During the project models and simulations tools were developed for the combustion at the micro-scale level, different designs and processes were evaluated to optimize the propellant ignition, the electronics and a 2D addressing process were developed to control and command an array of pyrotechnical cells, the characterization tools were set-up, and finally, the technology was demonstrated through the fabrication and characterization of arrays of solid propellant thrusters. In this article, the outcome of the Micropyros project will be described with an emphasis on potential applications.*

## Introduction

Beyond the traditional applications exploiting their propelling character, the pyrotechnical materials constitute a substantial and compact source of energy and gas that can be integrated into MEMS. Typical solid propellants feature an energy density of around 5J/mm$^3$. Hydrocarbonated fuel contains 10 times more. If we can simply convert the pyrotechnical energy into heat or work -even with a conversion yield of 10%- pyrotechnical systems remain competitive versus any micro actuator or micro batteries. The Micropyros project aimed at exploiting pyrotechnical energy for micro actuation by integrating pyrotechnical material with a silicon micromachined system to realize a class of PowerMEMS devices called MICROPYROSYSTEMS. The concept is simply based on the combustion of a solid pyrotechnical material stored in a micromachined chamber. Micropyrosystems benefit from MEMS technologies and the large quantity of energy contained in pyrotechnical materials. The use of only one solid pyrotechnical material offers two main advantages:

- There is no moving part eliminating frictional force and making technological fabrication easier.
- There is no liquid fuel, no leakage can take place and the material remains stable over time.

In the following, the realization and characterization of the micro-thrusters array developed during the Micropyros project are described. A review of the application of Micropyrosystems is given with examples of concrete developments.

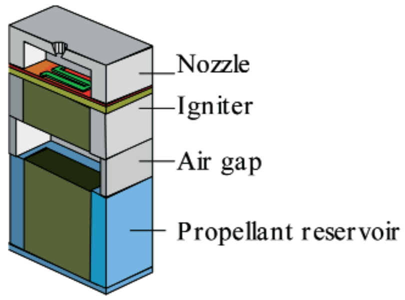


**Figure 1: Schematic view of the millimeter scale DEMO architecture.**

## Design and manufacture

Today, the state-of-the art of the thrusters systems for nanosatellite are cold gas systems or µFEEP for fine pointing and very precise manoeuvre. Besides, there is a lack in miniature, safe and low cost, 1mN-10mN range thrusters for micro and nano spacecraft to realize the station keeping, orbital manoeuvre, etc. The demonstrator to be developed in the Micropyros project was therefore chosen by the consortium to be an addressable array of 16 pyrotechnical microthrusters fabricated and tested with the electronics needed for communicating, addressing and powering. The design of the demonstrator was mainly based on the knowledge acquired from previous projects carried out at LAAS, Toulouse, France [1] and supported by IMTEK, Freiburg, Germany, which has developed a simulation tool adapted to Micropyrosystems [2]. The chamber section of each thruster is of 2.25mm² and the width of the nozzle throat has been calculated to be 250µm and 500µm. It consists of 4 parts of silicon (see Figure 1):

- A silicon micromachined igniter with a polysilicon resistor patterned onto a thin dielectric membrane (micro-hotplate), the heater area ranges from 540×540µm² to 720×720µm².
- A propellant reservoir made in Foturan and used as the combustion chamber.
- A silicon nozzle part added over the igniter and structured using bulk silicon micromachining.
- A glass seal wafer.

Adhesive bonding was chosen for the assembling of the device because it is a low temperature and simple process, compatible with surfaces contaminated with the propellant. At first the nozzle part is bonded to the igniter part by a thermal epoxy and the Pyrex seal wafer to the chamber wafer by a UV sensitive. Then the igniter part is filled with the ignition propellant (GAP or ZPP) and the combustion chambers filled with the GAP based propellant. Finally, the two wafer stacks are again bonded using thermal epoxy.

## Ignition and thrust characterization

Reliable ignition and combustion, being a main problem area in micropyrotechnics research, has been specifically addressed. The ignition success rate of the GAP-filled devices was not perfect; the ignition success is ~70% without preheating and can reach 90% with a preheating procedure. The GAP material ignition energy is 11mJ for a resistor size of 540×540µm². Preliminary ignition results using a more sensitive material (ZPP) are more promising, especially targeting further miniaturization. ZPP material reaches 100% of ignition success.

A millinewton thrust balance has been developed and used in the thrust characterization of the microthruster arrays and the propellant selection. Thrust measurement gave results between 0.1mN and 3mN and deduced impulse is ranging from $10^{-4}$Ns and $10^{-3}$Ns. Micropyrosystems feature a maximum yield of 20mN/W that places them among the most efficient micro actuator devices.

A method to evaluate thrust vectors from the microthruster array in the millinewton range has also been set up by combining MEMS technology and modal analysis. The sensor structure is made of monocrystalline silicon and consists of a solid plate which is suspended by a set of slender beams. Piezoresistors in 12 Wheatstone bridge configurations on the spring beams evaluate the momentary stress introduced by an applied thrust.

## Electronics circuit

Each thruster could be addressed independently using silicon PN diodes in series with each heater. A specific electronic system has been designed to optimise the ignition of the propellant. A closed loop temperature control system is implemented with a pre-heating temperature introduced as reference temperature. This temperature is compared to the real measured temperature on the polysilicon heating resistance. A PI regulator reduces the error temperature and modifies conveniently the output current value to deliver to the microthruster. A portable electronic circuitry (6 dm³) has been developed with as main performances and functions:

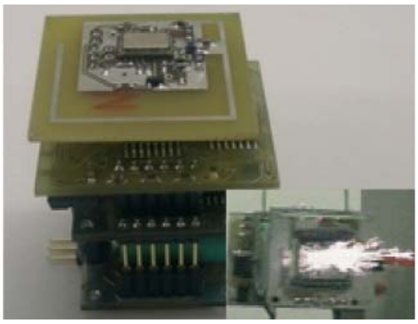

**Figure 2: Photo of the Microthruster DEMO assembled with the electronics and under operation.**

- Totally autonomous microsystem: battery powered with RF wireless communication.
- Reprogrammable microprocessor based system for ignition optimisation process.
- R & T measurement at any time for any micropyrosystem in the array.
- Preheating of a selected micropyrosystem with a fixed current or up to a fixed temperature during a certain time.

Electronic feedback control can greatly improve the reliability of the propellant ignition and combustion; for the GAP material, ignition success has been improved by a real-time monitoring of the ignition power delivered in the propellant and by launching the ignition when the propellant is at the proper temperature. Figure 2 shows the flame produced during the propellant combustion in a microthruster integrated with the electronics.

## Applications

Beside micro propulsion for space, micropyrosystems find application in numerous fields of application depending if the heat or gas produced by the combustion are used:

1. The pressure generator.

High pressure actuation using a micropyrosystems could replace pressurized cartridge for drug injection [4]. The micro gas generator is used as one shot low pressure pneumatic actuator for pharmaceutical and civil application.

2. Selective gas generator.
By integrating the appropriate propellant, Micropyrosystems can generate selective gas as $N_2$ to drive flow in micro channels or $H_2$ for fuelling µ-fuel-cell or $O_2$ for health [5].

3. The micro initiator and others.
Micropyrosystems can also be used to produce heat, gas and particles to initiate a pyrotechnical charge [6]. Compared with classical mechanical micro baiting, micropyrotechnics enable the realization of smart, safe, low energetic and miniature micro initiators for military needs and space application.

**Conclusion**

The broad perspective in the development of solid propellant micropyrosystems arrays has given a reliable line of production, including microfabrication of parts, filling of propellant, electronics design and implementation, and assembly. Future developments will aim at demonstration in space and further optimization of the performance of these systems.
Moreover, Micropyrosystems are generic systems: from the same Si-based technology, just changing the design and pyrotechnical material, we can either generate a force or/and heat or/and gas or/and particles. Without any additional cost, it is possible to integrate electronic security functions in the micropyrosystems that improves the robustness and the reliability of the system. Micropyrotechnic presents a growing interest for the realization of high energetic and controlled devices not only in Europe but also in the USA and Asia [7,8].

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