Feature

Assembly of 3D micro-components: a review of recent research

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Abstract

Purpose – The purpose of this paper is to review recent developments in micro-scale assembly technologies, primarily in the context of microsystems based on three-dimensional (3D) micro-electromechanical systems (MEMS) and micro-opto-electromechanical systems (MOEMS) technologies.

Design/methodology/approach – Following a brief introduction, this paper first discusses the problems associated with the assembly of micro-components and then considers the role of robots and self-assembly technologies. This is followed by a brief summary and conclusion.

Findings – Experimental robotic systems have been developed and used for the assembly of a wide range of MEMS and MOEMS components. Various self-assembly technologies offer prospects for massively parallel microassembly but have yet to achieve the success of the robotic approach. Some work has sought to combine the best feature of both approaches but as yet, no technologies have been developed that can rapidly, accurately and cost-effectively assemble micro-components into hybrid 3D MEMS/MOEMS devices in a true production environment.

Originality/value – This paper provides a detailed review of recent progress in the robotic and self-assembly of micro-components.

Keywords Assembly, Microassembly, Self-assembly, Robotics, Microtechnology, MEMS, MOEMS

Paper type Technical paper

Introduction

Reflecting the desire for ever-increasing functionality, recent years have seen a proliferation of products that are more complex yet far smaller than their predecessors and good examples are consumer electronic products, such as cell phones, digital cameras and music players. A range of industrial products have emerged based on micro-electromechanical systems (MEMS, see *Assembly Automation*, Vol. 29, No. 4) and micro-opto-electromechanical systems (MOEMS, Figure 1) technologies which take miniaturisation to a further level, where most active parts have micron-sized dimensions. Most are essentially two-dimensional (2D) and are produced by a range of planar micro-fabrication methods involving multiple and often complex lithographic, deposition and etching processes. However, three-dimensional (3D) devices could allow the further exploitation of MEMS and MOEMS technologies but assembling micron-sized components into more complex, 3D products poses all manner of technological challenges. There is, therefore, a need for highly automated, flexible and cost-effective micro-assembly techniques. The cost issue is particularly critical, as assembly can often represent well over 50 per cent of the total cost of a MEMS device. This article discusses a selection of recent research activities concerning the assembly of micro-scale components and considers two radically different approaches: robotics and self-assembly.

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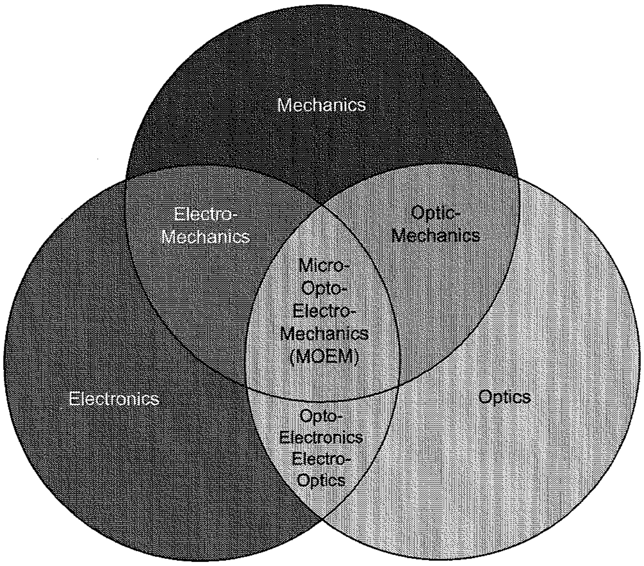
Complex microsystems and the problems with assembly

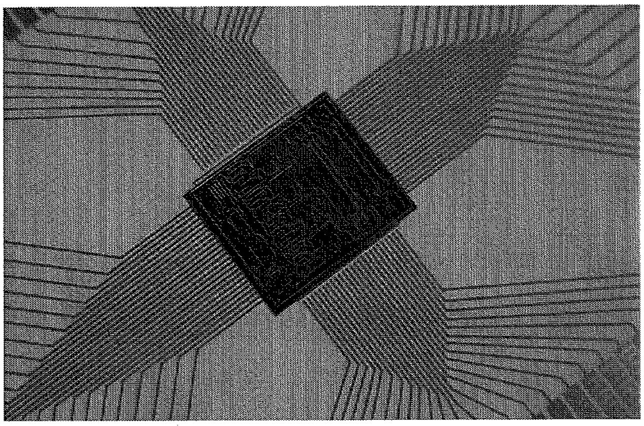
Since the widespread adoption of conventional MEMS devices such as sensors and ink-jet nozzles, more complex micro-devices have started to exert a commercial impact. These frequently combine differing materials, such as silicon and other semiconductors, polymers, adhesives, metals and glasses and merge disparate technologies which may include electronics, optics, fluidics and mechanics. Examples include various classes of advanced sensors, miniature actuators such as micro-motors and pumps, lab-on-a-chip (LOC) devices (Figure 2) and other micro-analytical systems, microfluidic products, micro-robots (Figure 3), miniaturised medical devices and MOEMS such as microspectrometers and telecoms components. While some products are readily available, many more are under development and the materials and technologies used are generally incompatible with the techniques employed to fabricate conventional MEMS. A further problem with objects whose sizes are significantly below 1,000 μm, irrespective of the materials involved, is that that are often exceedingly fragile, posing severe handling problems. These problems are compounded by the fact that many micro-scale physical effects differ significantly from those at the macro-scale. For instance, surface and intermolecular forces, such as adhesion originating from surface tension, van der Waals forces and electrostatic forces, become more significant than gravitation, resulting in further difficulties in manipulation. In many cases, releasing a micro-component from a griper is particularly problematic.

Figure 1 MOEMS involves the combination of three differing technologies



Source: Wikipedia

Figure 2 An LOC device



Note: These typically combine disparate technologies
Source: Wikipedia

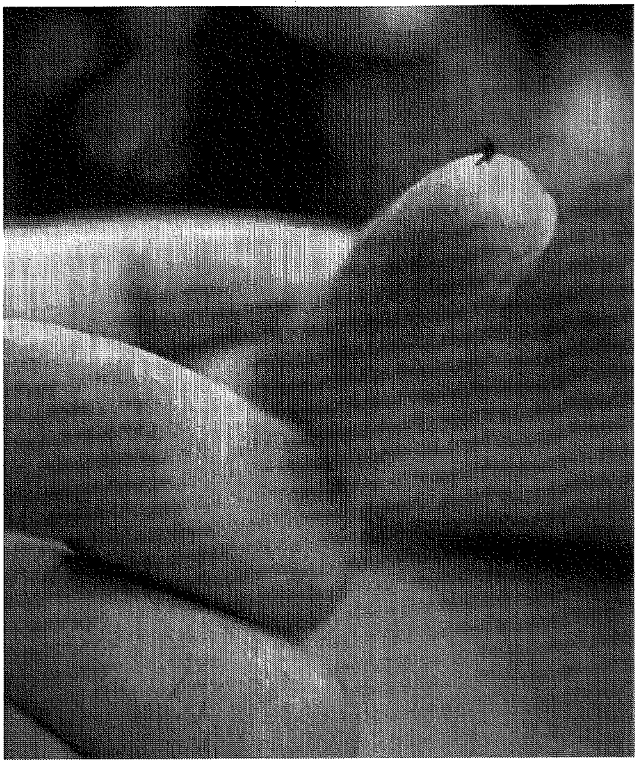
It is widely recognised that techniques that could assemble disparate micro-parts into 3D structures on an industrial scale would be of immense benefit and create all manner of new products and applications.

Robotic solutions

Robotic solutions to these problems are attracting great interest but some of the difficulties of this approach are well illustrated by a comparison between the requirements for macroscale and micro-scale robotic assembly, as shown in Table I. Critical components requiring further development include microgrippers, high-precision positioning systems and accurate and often micro-scale 3D imaging technology.

It is clear that the robotic assembly of micron-sized components remains a challenge but research groups from around the world are developing systems which aim to accomplish this task. Research at the well-known Automation and Robotics Research Institute at the University of Texas at Arlingtion (UTA) has led to the development of the "μ^3" microassembly system. This is based on three robotic end-effectors with nanometre levels of positioning, motorised stages (including servos and piezoactuators) with a total of 19 degrees of freedom (DOF) and a high magnification, stereo vision system. This is used to assemble devices with mm to μm part sizes with nanometre tolerances such as those based on MEMS and MOEMS technologies. An example of the latter application is the assembly of a microspectrometer which comprised a 1 cm^2 die, three 500 μm-tall mirrors, a 400 μm ball lens, a 3 mm^2 beamsplitter and a MEMS scanning mirror. The system has also been used to investigate the assembly of MEMS components designed with snap connectors. This technique has successfully assembled micro-optical benches and a silicon microrobot. Research by Texas A&M and Texas State universities involves the development of a microassembly system aimed at components with sizes in the range 100-500 μm. It is composed of a micro-robot, micro-grippers, an infrared (IR) imaging system and a microscopic visual feedback system. In order to make the system functional, a three-DOF mini robotic hand is utilised which features fingers fabricated from the piezoelectric polymer polyvinylidene difluoride (PVDF). Both the vision system and the micro-grippers are integrated into the system to recognise, grasp and then manipulate a micro-scale object. The image processor converts the captured 2D IR image to 3D geometry, followed by template matching for object localisation. During the matching process, the geometry

Figure 3 Microrobots, such as this flea-sized example developed at UTA, could be assembled with robotic technology



Source: University of Texas at Arlingtion

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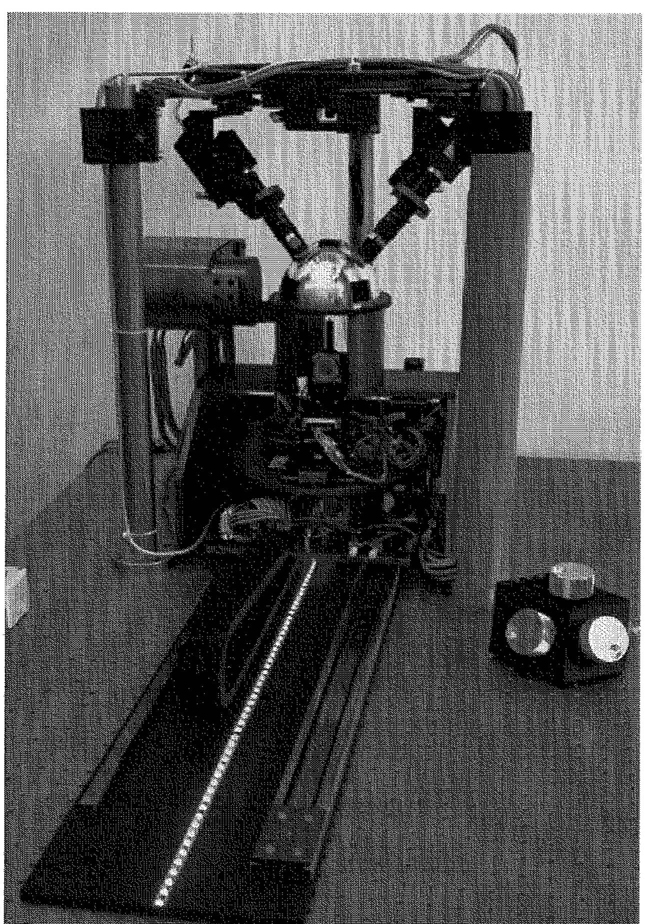
Table I Comparison between robotic assembly of macroscale and micro-scale components

Feature	Macroscale	Microscale
Dominant forces	Gravity, friction	Electrostatic, Van der Walls, stiction, capillary, friction
Positioning	Simple	Complex, very high resolution required
Velocity	Rapid: cm/s, m/s	Slow: μm/s, mm/s
Fore sensing	Simple	Difficult, forces can be as low as a few μN
Grippers	Mechanical, well established	Micromechanical, suction, vacuum, etc. others under development
Fixturing	Mechanical, well established	Micromechanical, subject of further development
Handling	Simple	Complex, parts are very fragile and subject to micro-scale forces
Vision system	Simple, well established	Complex, costly, require further development
Throughput/manipulation	Serial	Parallel preferred

obtained from the IR image is compared to the reference template in a database from which incremental changes are calculated, thereby determining the exact position and orientation of the object to be manipulated. The system has been evaluated with micro-gears, fabricated by MEMS technology.

Several years of research at the ETH Zurich have led to the development of the "microassembly system V2" (Figure 4) which is aimed at the assembly of hybrid MEMS parts and other micro-components. This has six DOF: a four-DOF base unit and a two-DOF gripper and uses nine DC motors and three stepper motors. The base unit consists of a large backlash-free, high-precision rotation table, providing rotation around the z-axis. The x-, y- and z-axis motion has a range of $\pm$12.5 mm, a resolution of 0.04 μm and a speed of 2.9 mm/s. The vision system is based on three pan and tilt CCD cameras equipped with microscopes offering from 0.75X to 3X magnification which measure laser light reflected off the gripper. Illumination is by three high power LED-based systems offering high incidence, low incidence and indirect lighting. Two types of grippers are used: a conventional tweezer-type microwire gripper powered by a DC motor that can grip objects with 200-800 μm sizes and an electrostatically actuated MEMS gripper with integrated capacitive force feedback sensing which can accommodate objects with sizes down to 5 μm. Amongst other uses, the system has been used to assemble a hybrid acoustic transmitter developed by the group. As noted above, gripper performance is critical when handling micro-components and the MEMS gripper used here has a range of $\pm$2,000 μN, a sensitivity of 1,000 μN/V and a resolution of between 0.3 and 0.5 μN. This technology has been spun-out of ETH and a range of grippers, high sensitivity force sensors, some of which can resolve down to 50 nN, and complete microassembly systems, is now available commercially from FemtoTools GmbH. These have been used to assemble a range of products including sensors and a microrobot based on sub-miniature electroplated components, developed at the ETH. Figures 5, 6, 7 and 8 show, respectively, an SEM of the microgripper and force sensing probe, an SEM of a microgripper in action, a microgripper positioning a component into a sensor and the "FT-G1000" micro-handling system.

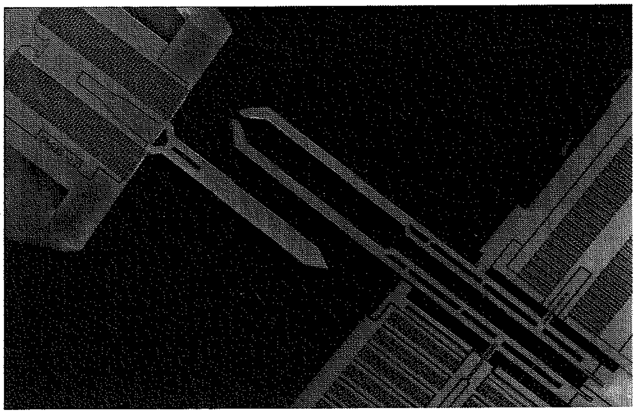
Figure 4 The "Microassembly system V2" developed at the ETH Zurich



Credit: ETH Zurich

The French Franche-Comté Electronique Mécanique Thermique et Optique – Sciences et Technologies (Femto-ST) is a joint research unit which arose from the merging of five separate research laboratories. It has long been involved with microassembly technologies and has developed two robotic systems covering different component sizes. The "SAMMI" comprises a five-axis robot (three linear axes and 2 rotational) and is equipped with a piezoelectric microgripper and a motorised binocular microscope. It is used for the assembly of micro-components whose size is between 100 μm and few mm. The "PRONOMIA" workstation arose from a three-year, government-funded research project and is conceptually similar but aimed at smaller parts with sizes ranging from 10 μm to a few hundreds of microns. Importantly, it differs from other devices in that assembly is

Figure 5 SEM of a microgripper and a force sensing probe with μN resolution

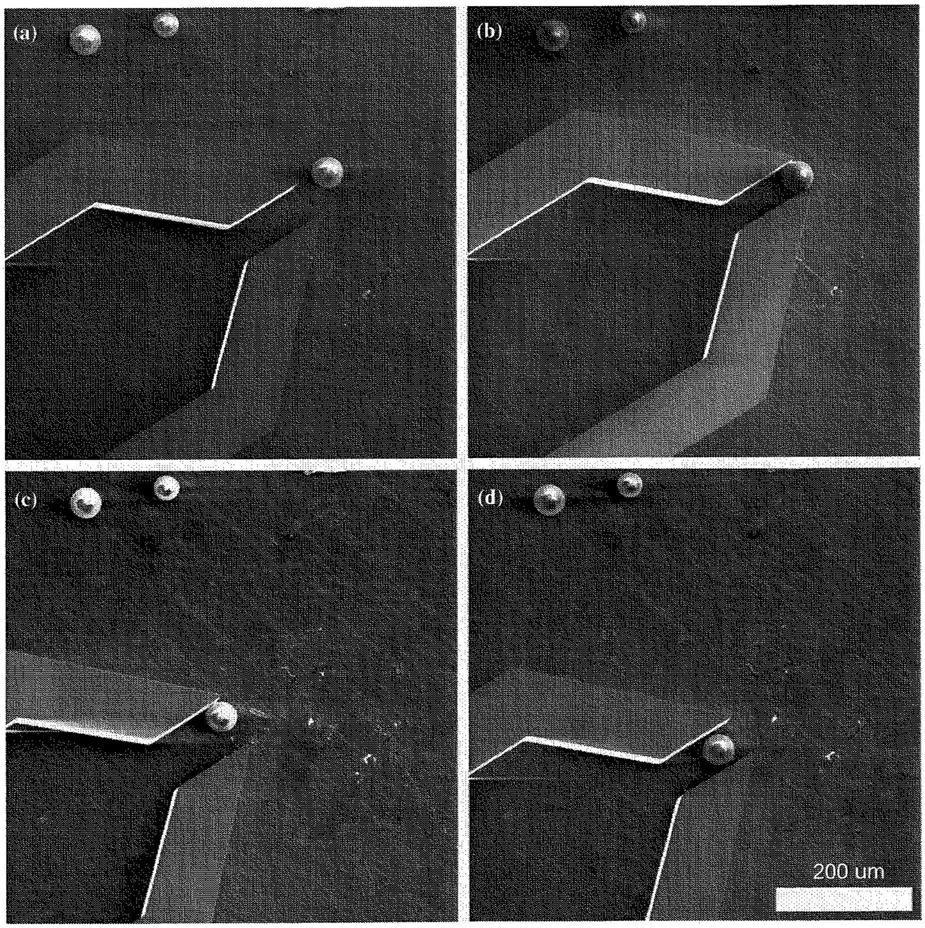


Source: FemtoTools GmbH

conducted in a liquid medium with the aim of eliminating electrostatic and other forces which hinder handling in air. The project succeeded in quantifying the benefits and limitations of this approach but further work is required to ascertain its true potential. Recently, reported work by the group involves the robotic microassembly of hybrid MOEMS devices based on a so-called "reconfigurable free space micro-optical bench" (RFS-MOB) which is a microengineered silicon substrate with V-grooves and a central runner. The 3D workstation has two manipulators with eight-DOF offering nanometre resolution. It uses an active, piezoelectric microgripper with two fingers, each having two DOF, which allows generic MOEMS components to be assembled into the optical micro-benches and can compensate for the tolerances of the parts. The RFS-MOB system has been demonstrated with a MOEMS comprising a mirror and a lens holder and the group proposes its use on more complex devices such as microspectrometers, miniaturised 3D confocal microscopes and a miniaturised goniometer.

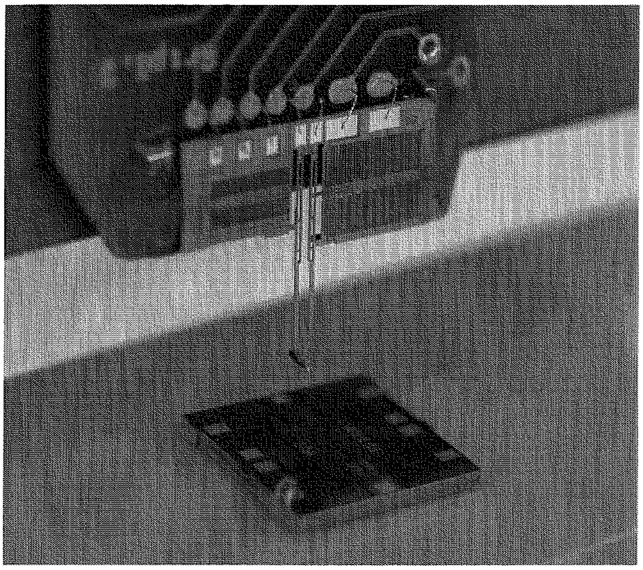
The approach being taken in a collaboration between workers from the Canadian universities of Victoria and Waterloo involves fabricating micro-components by surface micromachining which feature-specific elements to aid handling and assembly. As such it is conceptually similar to the previously mentioned UTA work in that it involves a "design for assembly" principle. The parts are designed with tether features protruding from their sides which allow them to be securely held and accurately located on the surface of a silicon chip. They also have a joint feature used for connecting them to other micro-parts during assembly and third, and most importantly, they have an interface feature which allows them

Figure 6 SEM of a microgripper handling micron-sized spheres



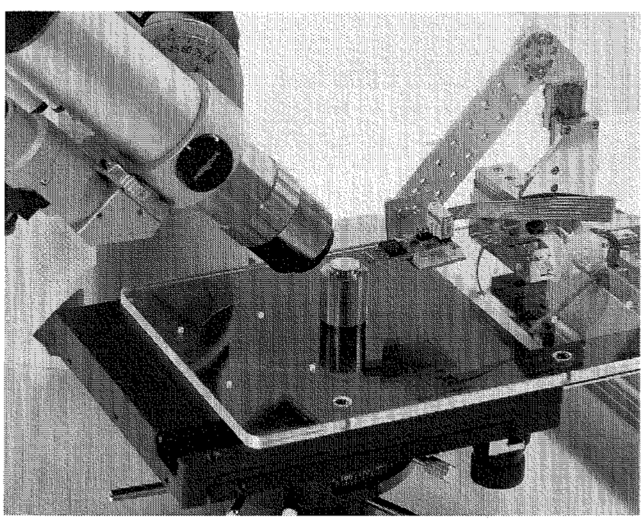
Source: FemtoTools GmbH

Figure 7 The microgripper inserting a magnetic component into a sensor



Source: FemtoTools GmbH

Figure 8 The "FT-G1000" micro-handling system



Source: FemtoTools GmbH

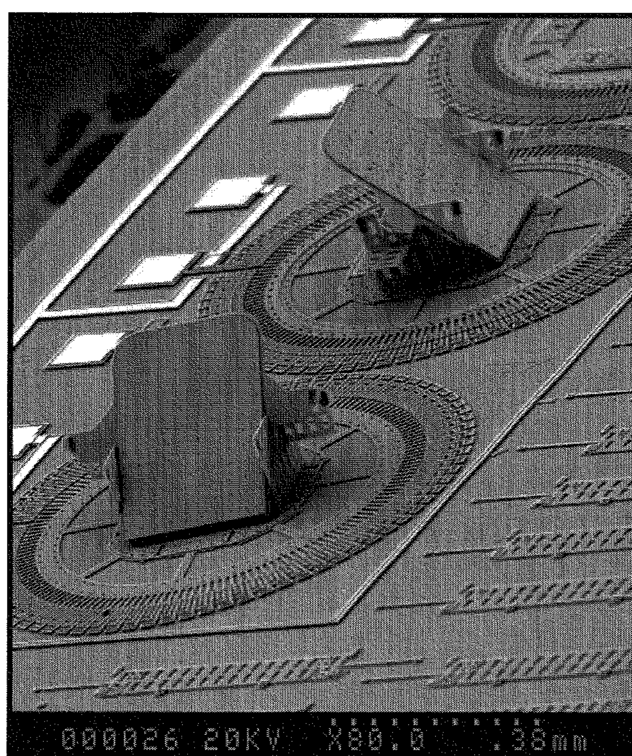
to be grasped by a handling system. This consists of a microgripper attached to a six-DOF robotic micromanipulator. The microgripper tips are specifically designed so as to grasp a part by the interface feature. A novel aspect of this work is that the microgrippers are fabricated alongside the parts to be assembled on the same chip. Prior to performing a microassembly task, the microgripper is first removed from the chip by bonding it to the end effector of the robotic micromanipulator. Next, the microgripper is used to grasp the parts and remove them from their original fabricated locations. The micromanipulator then translates and rotates the parts to the target assembly site and joins them at that site. Examples of 3D MEMS/MOEMS devices that have been successfully assembled using this system include micro-coils and motorised 3D micro-mirrors mounted onto an electrostatic micro-motor for optical cross-connect switches (Figure 9). It is important to note that, since an assembly process is used, it is possible for the electrostatic motor and the various parts of the 3D micro-mirror to be fabricated on different chips, by different methods.

Self-assembly technologies

Self-assembly technology has been proposed as an alternative means of assembling micro-components into hybrid MEMS/MOEMS products and has been considered in some detail in an earlier issue of this journal (Vol. 28, No. 4). In broad terms, self-assembly refers to bottom-up processes in which a disordered system of components forms an organised structure as a consequence of specific, local interactions among the components without external direction. The potential benefits are huge in this context: the process is massively parallel and dispenses with the need for complex robotic systems. It has been the topic of extensive research, particularly in the microelectronics context and there is an extensive literature. Most work concerns the self-assembly of electronic components conducted in liquid media, generally water-based solutions or ethylene glycol. This avoids the effects of friction and stiction and provides efficient mass-transport and mixing of the components. However, many "dry" approaches have also been investigated, as summarised in Table II.

Work at the University of Washington is representative of the liquid medium approach and has been used for the assembly of multiple batches of micro-components onto a single substrate. The substrate is prepared with hydrophobic alkanethiol-coated

Figure 9 SEM of the assembled 3D micro-mirrors on the electrostatic micro-motors



Source: Universities of Victoria and Waterloo

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Table II Non-liquid self-assembly technologies

Technique	Application
Vibration and triboelectric attraction	Location of hinged polysilicon plates on silicon nitride or polysilicon substrates
Magnetic	Positioning ferromagnetic microstructures
Stiction	Positioning a vertical comb drive actuator
Centrifugal forces	Assembly of hinged microstructures
Thermal	Release of hinged microstructures from a substrate

gold binding sites and to perform the assembly, a hydrocarbon oil, which is applied to the substrate, wets exclusively the hydrophobic binding sites in water. Micro-components are then added to the water and assemble on the oil-wetted binding sites. Moreover, assembly can be controlled to take place on specific binding sites by using an electrochemical method to deactivate certain substrate binding sites. By repeatedly applying this technique, different batches of micro-components can be sequentially assembled on a single substrate. As a post-assembly procedure, electroplating was incorporated into the technique to establish electrical connections for the assembled components – surface-mount LEDs. Building on this type of earlier research, a collaborative Swiss self-assembly project, SELFSYS (fluidic-mediated self-assembly for hybrid functional micro/nanosystems), commenced in 2009. This is being conducted under the auspices of Nano-Tera, a Swiss federal programme which is funding 19 four-year research projects. SELFSYS aims to develop techniques which allow free-floating MEMS building blocks in a liquid to be self-assembled and deployed on a variety of surfaces. The project is aimed at two specific applications: the self-assembly of MEMS to a micron-scale RFID tag and the assembly of liquid-containing micro-capsules, or "smart pills", that can be triggered to release liquids into the human body.

A large body of work is investigating self-assembly involving liquid solder. In 2005, workers from the University of Minnesota successfully demonstrated the self-assembly of micron-sized LEDs and CMOS circuits by using shape recognition and surface tension effects between the components in liquid solder. Researchers from the University of Western Ontario have since taken this concept further by patterning solders with different melting points to designated binding sites on the components and to activate them separately and sequentially with appropriate processing steps at differing temperatures. Thus, it is argued that this approach to self-assembly is programmable.

However, despite these and many other efforts, little real progress on MEMS/MOEMS self-assembly has been reported and none compares to the achievements of the robotic approach. Perhaps in recognition of this, a four-year, EU-funded project, HYDOMEL (hybrid ultra precision manufacturing process based on positional- and self-assembly for complex micro-products), aimed to investigate a hybrid approach to micro-assembly which combined robotics with self-assembly. This involved 22 organisations from nine European countries and was completed in 2010. Two strategies were investigated: robotics assisted by self-assembly, where a primary robotic process is supported and optimised by self-assembly and second, self-assembly assisted by robotics, where the self-assembly or self-alignment process is augmented by robotics. Results have been mixed but the work suggests that there is some merit in combining these disparate microassembly technologies. In experiments involving MEMS components, coarse robotics has been combined with precision self-alignment to achieve high production throughputs and the highly accurate alignment of a MEMS components and a PCB. The MEMS component was a microgripper with an integrated force sensor produced by FemtoTools (see above). Self-alignment resulting in mechanical and electrical contact of the MEMS parts was achieved by using capillary forces from molten low-temperature solder. The project has demonstrated the feasibility of combining precision robotics with self-assembly but whether this strategy offers genuine commercial prospects appears to remain uncertain.

Summary and conclusions

It is widely recognised at novel techniques are required for the assembly of hybrid 3D MEMS and MOEMS devices. These would allow these technologies to be further developed and open up all manner of new applications. Many groups have developed robotic system to assemble micron-sized MEMS and other components which rely on a range of differing strategies and some exploit the "design for assembly" concept. As yet, none have emerged which satisfy all of the requirements of micro-part assembly in a true production environment. Self-assembly opens up the possibility of massively parallel assembly but results so far suggest that far more research is required before its potential can be realised. Combining both of these concepts appears to have some merit. To conclude, much progress has been made but a technology that can rapidly, accurately and cost-effective assemble disparate micro-components into hybrid 3D MEMS/MOEMS devices remains elusive.

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