POLYIMIDE V-GROOVE JOINTS FOR THREE-DIMENSIONAL SILICON TRANSDUCERS
– exemplified through a 3-D turbulent gas flow sensor and micro-robotic devices

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TRITA-ILA-0001
ISSN 0281-2878
ISBN 91-7170-568-6

Submitted to the School of
Computer Science - Electrical Engineering – Engineering Physics (DEF),
Royal Institute of Technology (KTH), Stockholm, Sweden
in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Stockholm 2000
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ISBN 91-7170-568-6

Printed by KTH Högskoletryckeriet, Stockholm 2000.

The front cover shows the first walking micro-robot with a Swedish wasp on its back. The out-of-plane rotation of the eight legs is obtained by thermal shrinkage of polyimide in V-grooves (PVG). The movements of the legs are obtained by sending heating pulses through integrated heaters that expand the polyimide joints. The size of the silicon legs that are rotated out of the wafer plane is 1000 x 600 x 30 µm³ and the overall chip size of the robot is 15 x 5 x 0.5 mm³. The walking speed is 6 mm/s and the robot can carry 50 times its own weight.

Photo: Per Westergård, Vetenskapsjournalisterna (published with kind permission).
Abstract

Today, we can see a fast growing interest in silicon micromachined transducers following the ongoing miniaturization trend around us. The sophisticated production methods associated with silicon technology offer the possibility for low-cost highly miniaturized electro-mechanical devices. However, the planar nature of the photolithography technique used in most silicon fabrication has a large drawback when three-dimensional (3-D) microstructures are needed. This thesis presents a new 3-D technique using polyimide V-groove (PVG) joints based on thermal shrinkage of polyimide in V-grooves to overcome the planar limitation. These polyimide joints have been carefully investigated and several important advantages compared to other techniques are demonstrated (i.e. very robust, self-assembly small radii joints for accurate out-of-wafer plane erection of silicon microstructures). Further the new micro-joint can be used both in a static mode for 3-D sensor applications and in a dynamic, actuator, mode. In the thesis two different applications are described.

The first application field is fluid dynamics and turbulence flows which are unsolved problems in physics. Measurement and active control of turbulent flow fields are key issues in many technical application areas. Miniaturized micromachined 3-D sensor with hot-wires in the same size as the smallest turbulence scales can help researchers to study physical phenomena that are not yet understood due to lack of sufficiently small sensors.

Development of a reliable fabrication process to fabricate the 3-D hot-wire sensors based on the PVG-joint has successfully been realized. Experiments showed that the fabricated hot-wire sensors have several important advantages over hand-made conventional metal hot-wire sensors. For example, the fabricated silicon hot-wires have higher flow sensitive, response times smaller than 30 µs, no drift over time, small hot-wire dimensions (500 × 5 × 2 µm³), potential for low cost fabrication and array configuration. Turbulence characteristics of free-standing hot-wires fabricated by micromachining have been investigated for the first time.

In the research field of micromechanics the focus has moved from single sensor and actuator devices to more complex and sophisticated micro systems. The manufacturing approach for these small micro-systems, consisting of assembly many small sub-components and micro-devices, is of great importance for future success and expansion of microelectromechanical systems (MEMS). In particular, micro-assembly is a key point for many micro-systems and one challenging technology is the used of MEMS-based micro-robotics devices. The thesis contains a general review on both micro-robotics and three-dimensional microfabrication.

Several actuator applications are feasible with the new PVG-joint. In this thesis they are exemplified by a micro-conveyor and the first MEMS-based walking micro-robot. The use of the PVG joint with integrated heaters allows dynamic stroke up to 340 µm for a 1 mm long silicon structure, using the large thermal expansion of polyimide. The lifetime exceeds 2×10⁸ load cycles under 5 weeks of continuous actuation. These polyimide joint actuators are used in asynchronously driven array configuration where each actuator can be operated individually with integrated heaters. Several different design in the form of micro-convoyers with maximum conveyance speed of 12mm/s and a load capacity of 3500 µg and a robot with measured walking speed of 6 mm/s and a static load capacity of 6000 µg are presented.

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ERRATA

I have found some errors in the papers included in this thesis (listed beneath). Although I have made my best to avoid any errors there are undoubtedly several others and I sincerely apologize for those that remain. I welcome hearing from readers about any factual errors or overlooked omissions in the papers and publications included in this thesis. All mistakes and shortcomings, in particular in language and style of presentation, are due myself as author.

Updates of this errata, and full information of the status of the submitted papers (i.e. Journal and page information when/if they get published) will be available at the web site for this thesis at: http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html

If you care to contribute to this errata, please send e-mail (for correct e-mail address see http://www.s3.kth.se/instrlab/staff/thorbjorne.html).

Thorbjörn Ebefors
Stockholm, 2000

ERRATA   ver 1.0 (2000-04-25)

Paper 3, p 14, line 9: reads error should be uncertainty.

Paper 3, p 15, Fig 11: Y-axis reads E (m/s) should be E (V).

Paper 3, p 15, Fig 11: Y-axis the scale reads 0.5 to 3 should be 5.5 to 8.

Paper 3, p 19, line 11: reads shielded should be electrically isolated.

Paper 5, p 2, Table 1: at row 3 the total area should be 5 x 5 mm²
at row 7 the author reads Soh should be Suh
the extension reads legs a should be legs b
the load capacity reads 250 µN mm² should be 250 µN mm².
at row 11 the total area should be ≈18 mm²
at row 12 the extension reads erected a should be erected b
the extension reads Hz b should be Hz h
the information at row 7 column 5 (Δx=20 µm ...) and row 11 column 5 (Δx=10 µm ...) should be switched.

The web address reads: http://www.s3kth.sc/instrlab should be http://www.s3.kth.se/instrlab/
To my wife Leena, and …

"Miniaturization by evaporation:
...What are the possibilities of small but movable machines?
They may or may not be useful, but they surely would be fun to make"
- Richard P. Feynman

Richard P. Feynman, Nobel Price winner in Physics 1965
in his talk "There's plenty of room at the bottom"
at the Annual meeting of the American Physical Society (APS)
at the California Institute of Technology, December 26 1959.
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Guide for multimedia enhancement

This thesis features multimedia enhancement related to some of the figures in the thesis. The symbol [M] is used to indicate that a figure is complemented with multimedia materials. These multimedia features are available from different Internet homepages. Immediate links to these URL sites are given, see the list below. When the external video materials are not protected by copyright these video clips, as well as the multimedia material for the experiments performed in this work, are available from the website for this thesis at:

The following figures feature multimedia enhancements:

**Figure 10.** Various movies on the heatuators and their use in micro-robotic applications presented by the MEMS research group at University of Colorado, USA. These movies are available at http://mems.colorado.edu/img/a.heatuator.html

**Figure 12.** Different movies on fabricated organic actuators which have been used to achieve intelligent micro-conveyance systems. These movies are available at: http://www.ee.washington.edu/research/mems/Projects/Video/

**Figure 14.** Different movies on the ECP active hinge and its use in micro-robotic applications presented by the MST-polymer research group at University of Linköping, Sweden, are available at http://www.ifm.liu.se/AppPhys/ConjPolym/research/micromuscles/CPG_micromuscles.html

**Figure 16.** Different movies on fabricated hinge devices by the MUMPs process are available at: http://www.memrsrus.com/cronos/sycsmumps.html

**Figure 30.** Animations of the dynamic operation principle for the PVG joint are available at http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html.

**Figure 32.** Videos showing the test set-up and the dynamic characterization for the PVG joint are available at: http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html.

**Figure 34.** A video showing the timed solutions of the FEM-model (i.e. the dynamic behavior for the PVG joint) is available at: http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html.

**Figure 47.** A video animation on the dynamic, asynchronous operation of arrayed out-of-plane erected legs for micro robotic applications is available at: http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html.

**Figure 50.** Photographs on a MEMS fabricated walking micro-robot prototype are available at the photo gallery of Rich Yeh at: http://www-bsac.eecs.berkeley.edu/~yeh/sems.html

**Figure 55.** Videos showing dynamic actuation test on the 500 µm long legs and various videos on the conveyance test performed are available at: http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html.
Figure 56. Videos from the various load tests that were performed on the micro-conveyor are available at: http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html

Figure 57. Videos from the various speed and load tests that were performed on the micro-robot are available at: http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html

Footnote 1 A large variety of Images and Movies on surface micromachined micro-systems consisting of mechanical linkage and gears for force transfer, driven by electrostatic comb-drive actuators are available from the Sandia National Laboratories micromachine gallery at: http://www.mdl.sandia.gov/micromachine/
List of papers

The presented thesis is based on the following six reviewed journal and conference papers:

1. **New small radius joints based on thermal shrinkage of polyimide in V-grooves for robust self-assembly 3-D microstructures**
   Thorbjörn Ebefors, Edvard Kälvesten and Göran Stemme
   Published in Journal of Micromechanics and Microengineering (IOP), vol. 8, no. 3 (Sept. 1998), pp. 188-194.

2. **Dynamic actuation of polyimide V-grooves joints by electrical heating**
   Thorbjörn Ebefors, Edvard Kälvesten and Göran Stemme

3. **Using Silicon Based Hot-Wire for Turbulence Measurement**
   F. Carlsson, M. Thunblom, P. Johansson, A. Bakchinov, L. Löfdahl, Thorbjörn Ebefors and Göran Stemme
   Manuscript submitted for Journal publication

4. **Three Dimensional Silicon Triple-hot-wire Anemometer based on Polyimide Joints**
   Thorbjörn Ebefors, Edvard Kälvesten and Göran Stemme

5. **A Robust Micro Conveyer Realized by Arrayed Polyimide Joint Actuators**
   Thorbjörn Ebefors, Johan Mattsson, Edvard Kälvesten and Göran Stemme
   To appear in *Journal of Micromechanics and Microengineering (IOP)*
   The paper version provisionally scheduled for September 2000.
   Electronic multimedia version available from the abstract page in the online journal; (see http://www.iop.org)

6. **A Walking Silicon Micro-robot**
   Thorbjörn Ebefors, Johan Mattsson, Edvard Kälvesten and Göran Stemme
   Presented at the 10th International Conference on Solid-State Sensors and Actuators (TRANSDUCERS’99), Sendai, Japan, June 7-10, 1999, pp. 1202-1205.

The contributions of Thorbjörn Ebefors to the different publications:

1. All design, fabrication and experiments. Major part of writing.
2. All design, modeling, fabrication and experiments. Major part of writing.
3. All design, modeling, fabrication and experiments on the sensor. Part of turbulence experiments and writing (mainly the sections about MEMS sensors and fabrication).
4. All design, fabrication, experiments. and writing. Major part of writing.
5. Parts of design, modeling, fabrication and experiments. All writing.
6. Parts of design, and fabrication. Major part of experiments and all writing.
The work has been presented orally at the following international conferences (with referee and reviewing procedure):

7 New robust Small radius joints based on thermal shrinkage of polyimide in V-grooves
Thorbjörn Ebefors, Edvard Kälvesten and Göran Stemme

8 Dynamic actuation of polyimide V-grooves joints by electrical heating
Thorbjörn Ebefors, Edvard Kälvesten and Göran Stemme

9 Dimensional Silicon Triple-Hot-Wire Anemometer based on polyimide joints
Thorbjörn Ebefors, Edvard Kälvesten and Göran Stemme

10 Three dimensional microstructures based on polyimide joints
Thorbjörn Ebefors, Johan Mattsson, Edvard Kälvesten and Göran Stemme

11 A Micro Motion System based on Polyimide Joint Actuators (key note paper)
Thorbjörn Ebefors, Johan Mattsson, Edvard Kälvesten and Göran Stemme

12 A Robust Micro Conveyer Realized by Arrayed Polyimide Joint Actuators
Thorbjörn Ebefors, Johan Mattsson, Edvard Kälvesten and Göran Stemme

13 A Walking Silicon Micro-Robot
Thorbjörn Ebefors, Johan Mattsson, Edvard Kälvesten and Göran Stemme

14 3D Micromachined Devices based on Polyimide Joint technology
Thorbjörn Ebefors, Johan Mattsson, Edvard Kälvesten and Göran Stemme

15 Teaching sensor technology and MEMS-processing using an in-house educational MPW-process
Thorbjörn Ebefors
Other conferences (without referee and reviewing procedure) where the work has been presented (presentations given by the people from TFD-CTH):

16 **Measurements using a silicon based single hot-wire**
   F. Carlsson, M. Thunblom, P. Johansson, A. Bakchinov, L. Löfdahl (CTH),
   T. Ebefors and G. Stemme (KTH)
   Presented at Svenska mekanikdagarna (SvMek), KTH, Stockholm, Sweden, June 7-8, 1999.

17 **Measurements using a silicon based single hot-wire**
   F. Carlsson, M. Thunblom, P. Johansson, A. Bakchinov, L. Löfdahl (CTH),
   T. Ebefors and G. Stemme (KTH)
   Presented at the 52nd Annual American Physical Society meeting of the division of fluid dynamics (APS/DFD’99), New Orleans, USA, November 21-23, 1999.

A selection of other publications where the work has been published or presented, mainly in popular science forums:

18 **3-D MST Using Polyimide Joints**
   Thorbjörn Ebefors

19 **Svenska forskare har byggt en supperstark pytterobot**
   Sus Andersson (reporter)
   Vetandets Värld, Vetenskaps redaktionen P1, Swedish radio (SR), 1998-10-05.

20 **Pytterobot med plastmuskler**
   Anders Wallerius

21 **Mikrorobot bär 30 gånger sin egen vikt**
   Matti Krank
   Forum för ekonomi och teknik (Finland), no. 2, Mars 1999, p. 32.

22 **Making Micromachines**
   Eric J. Lerner
   AIP-The Industrial Physicist, (USA), Vol. 5, No. 4, August 1999, pp. 18-22.

23 **Micro-robot**
   Sharon Jåma (reporter)
   NOVA, SVT-1, Vetenskaps redaktionen Norrköping, Swedish television 1999-10-04.

24 **Micro-robot**
   Staffan Erlandsson (research editor)

25 **Robot insects could ‘man’ factories**
   Mark Prigg
   Sunday Times (UK), Part 5 Innovation, p. 11, 99-10-17.
1 Introduction

1.1 Miniaturization of systems by micromachining - MEMS

Silicon microelectronics has revolutionized the world by allowing low cost integrated circuits (IC) to be produced in large quantities on silicon wafers. Integrated circuits are now used in most of our daily used electronic products like computers, coffee machines, dish washers, and cellular phones etc. The electronic revolution has given us a trend towards smaller and smaller products while not that much progress in miniaturization of classical mechanics has occurred (i.e. Swiss watch mechanisms). In the classic talk at the 1959 annual meeting of the American Physical Society, 1965 years Nobel price winner, Richard Feynman anticipated and gave the road map of how to extend the electronic miniaturization to mechanical devices and micromachines [1]. With this talk, Feynman “invented” a new field when he proposed miniaturization of systems as an almost boundless territory of scientific inquiry. Actually, he was searching for a new exciting field of physics (at that time physics at high pressure and/or at low temperature sparked much interest due to several discoveries when physical parameters were pushed to extremes). What Feynman came up with was that “There’s Plenty of Room at The Bottom” i.e. the physics in a very miniaturized world. In this talk as well in another famous talk in 1983 [2] Feynman described how it should be possible to build computers and mechanical micro-machines (as well as other devices that now have become a reality [3]) by using fabrication technologies adopted from the microelectronic industry, i.e. thin film deposition by evaporation together with photolithography and etching.

The excellent mechanical properties of silicon together with well established fabrication techniques from IC-industry has been used to manufacturing small low-cost sensors and actuators, so called micromachining, microfabrication or micromechanics. These terms broadly refers to the use of lithographic and other precision techniques to carry out fabrication of different micro-devices. Since the practical introduction of silicon micromachining in late the 60’s and early 70’s many different devices have been fabricated. The diversity of sensors and actuators means that no single technology can be used to fabricate these devices., but rather many different techniques are used. However, normally one can classify most of these techniques into three major categories: bulk micromachining, surface micromachining and micro-molding and/or replication. These techniques will be described more in section 3. For the interested reader, several different review publications have been published. The classic paper by Petersen [4] gives a good overview of early devices and fabrication methods used during the 70’s and early 80’s. Most of the developments in the field, both in terms of fabrication technology, devices as well as micro-systems, during the latest years are covered in the excellent textbook by Kovacs [5]. The most common devices include different types of sensors and actuators fabricated in a silicon substrate, but other materials such as quartz, silicon carbide and gallium arsenide have also been used [6].

Modifications to old techniques and the evolution of new fabrication techniques is still progressing, although the trend today is going towards a system paradigm. Due to the more system focused thinking of micromachining, the field is currently often referred to as Microelectromechanical Systems (MEMS), which is a term most used in North America, MicroSystem Technology (MST) or used mainly in Europe and Micromachines in Japan [7]. MEMS and MST can be defined as a set of microfabrication techniques for producing two- or three-dimensional structures or components featuring micrometer to millimeter dimensions with accuracy in the micrometer range (i.e.
dimensions smaller than classical watch-making parts) see Figure 1. These components can be either individual units (monolithic micro-system or sensors and actuators on a single chip), as illustrated by the surface micromachined micro-motor in Figure 1 a) or parts of a larger microelectromechanical system by assembling several mechanical structures and electronic devices into for example micro-optical or micro-fluidic systems. Another example is the assembled LIGA system illustrated in Figure 1 b). The assembling of small MEMS devices has led to a new and fascinating sub-field of MEMS: the micro-robotics [8].

By miniaturizing (i.e. by the use of silicon microfabrication) a classical macro robot to a chip like robot, some of the fundamental problems associated with the assembly of a micro-system seem solvable. The micro-gear in Figure 1 b) is a typical device which may be assembled automatically using various kinds of micro-robots. Further, micromachined robots open up new fascinating possibilities in other fields, for example medicine (Minimal Invasive Surgery-MIS) which is further described in section 7.3. However, the challenging task is to develop a suitable robot platform with robust out-of plane erected, movable arms and legs (i.e. 3D actuators having large force and displacement capability).

Figure 1. (a) A polysilicon rotating micro-motor compared with the diameter of a human hair (typically 100 µm diameter) for an indication of the size [9]. Thousands of these motors are fabricated parallel at wafer level and the rotating parts are released simultaneously by removing a sacrificial layer (by etching). Systems of impressive complexity using this kind of motor can be made without assembly of any kind, although the force/torque that can be generated is quite limited. 
(b) Top: A micro-motor together with individual parts of an epicyclic gear fabricated by LIGA. Bottom: the assembled micro-gear from the individual components shown above, with tolerances well under 2 µm [10]. The gear system assembly is done manually under a microscope. One of the application for this motor - gear system is for flying micro-robots (e.g. a micro-helicopter). Compared to the micromotor in a) the forces and torques generated by this kind of assembled motor-gear systems is much higher.
From having been a subject mainly of interest to scientists at universities and research institutes, today MEMS and microfabrication is beginning to establish itself in industry and several micromachined commercial products are being manufactured. Volume products existing today are sensors for measuring pressure and acceleration (e.g. as crash sensors in the air-bag system in your car) and different products in IT-peripherals such as printer-heads (e.g. ink-jet) and read/write heads for magnetic hard disk drives [11, 12]. MEMS has made a major impact in many disciplines (e.g., aerospace, mechanical, and electrical engineering as well as in biology, medicine, optics, and robotics).

During the last decade, microfabrication and microfabricated devices have also been incorporated into other research disciplines, for example, fluid dynamics (see chapter 5). Here, the researchers’ dreams or intentions are to use micro-systems consisting of arrays of sensors and actuators for measuring, manipulating and controlling, for example, different turbulence parameters (e.g. shear forces and vortices). The signals from cleverly placed sensor arrays are used in logical/computational circuits to calculate appropriate schemes to actuate the different actuators on the chip and thereby reduce drag and friction forces on an airplane wing, for example. Basic research result has been achieved on aerodynamic control based on MEMS devices. Again, the challenge is to develop three dimensional microstructures both for measuring the flow (i.e. 3D flow sensors) and out-of-plane working actuators [16]. The main motivation for using MEMS in fluid dynamics is the size aspects. The turbulence eddies are often extremely small and, therefore, requires miniaturized sensors (i.e.

Figure 2. a) A prototype of the M3 (Micro-sensors, Micro-actuators, and Microelectronics) chip with integrated shear stress sensors, micro magnetic 3-D actuators and CMOS control circuits. The shear stress sensors are based on polysilicon hot-wires [13, 14].

b) A close-up of the out-of-plane working actuator (magnetic flaps) [15].
MEMS-based) to resolve the small eddies. The turbulent boundary layer around, for example an airplane wing, is rather thin and, therefore, the out-of-plane actuators should only interfere with this layer. Therefore, micro-actuators (i.e MEMS-based) are most suited since they rely on low power consumption. Figure 2 show one of the first micro-systems used for active control of turbulence. Other types of out-of-plane folded microstructures both for actuation and for sensing of turbulent flows will be described later on in this thesis. Also, a new kind of micromachined 3-D flow sensor and investigations on its applicability for turbulence measurements will be presented.

1.2 Three dimensional microstructures

As can be concluded in the previous section, micromachined three-dimensional (3-D) sensors and actuators using micro-joints or hinges are essential in many applications. Two examples are the need for 3-D flow sensors and the out-of-plane working actuators for turbulence measurement and control in fluid dynamics. The turbulent flow field is three-dimensional in most practical applications and to better understand the complex physics and make theoretical models of such flows experimental results are necessary. Since the length and time scales of these kinds of turbulent flows are very small means that fast, miniaturized, closely packed sensor elements in all three directions are required. Micromachined (flow) sensors which have successfully been used in many other disciplines should be very well suited here as well. However, most MEMS-based flow sensors presented up to now are one-dimensional (only a few are sensitive in two directions, and none in all three dimensions). The reason for this is the planar nature of “standard” silicon micromachining, which makes it difficult to realize 3-D sensors. Several interesting techniques for 3-D MEMS has been presented, but most often they have drawbacks (i.e. lack of electrical interconnections, not very robustness, clumsy shape and size resulting in flow obstruction) which makes them less suitable for this kind of sensor and measurement application.

Micro-robotic applications exists in many different forms and could mainly be categorized into three groups, micro-grippers and micro-tools, micro-conveyers, and locomotive micro-robots (walking, swimming, flying). Some of these devices may not need out-of-plane folded structures, but most of them do. Again, the challenge is to design the folded 3-D structure sufficiently robust. However, a few technologies have been presented that can solve this problem but still there are large difficulties to obtain an actuator that can generate large forces and large strokes at a reasonably high speed and at the same time have enough power efficiency to carry the energy required to move and operate the robot [17]. In the MEMS field, which now has matured to such an extent that it is possible to obtain complex systems, assembly tasks have come more and more into focus. Several different aspects of the problems of micro-assembly have recently interested both industry and academic researchers. The first issue concerns the assembly of hybrid systems consisting of several micro-devices, which may be put together using MEMS-based micro-robotic systems. The second aspect concerns the assembly of the 3-D micro-robots themselves as well as other devices which need out-of-plane folded structures (true 3-D structures). Manual assembly is always cost and time consuming and, therefore, out-of-plane erected 3-D structures that are self-assembled (serial or parallel - batch) in some way are of great interest.

A lot of other applications, for example micro-optical-electro-mechanical systems (MOEMS), also rely on out-of-plane folded microstructures (mirrors, lenses, etc.) to achieve free-space optical benches [18]. However, this is beyond the scope of this thesis, which focuses on general techniques for out-of-plane erected microstructures and their application in micro-robotic systems and in fluid dynamic research tools.
2 Survey of the Thesis

The purpose of this thesis is to document the contributions made by the author to the development of MEMS devices for use in fluid dynamic applications in an interdisciplinary cooperation between the MEMS group at KTH and Thermo- and Fluid Dynamics at Chalmers University of Technology, Gothenburg. Further, the thesis will describe the results from a spin-off project on micro-robotics that has been established. The six papers included in this thesis together with the summarizing text give the details of the work.

2.1 Historical background

The project started in 1986 with the design and fabrication of a silicon gas flow sensor by Göran Stemme at the Department of Solid State Electronics at Chalmers University of Technology [19, 20]. This gas flow sensor uses polyimide as a thermal isolation material and is illustrated in Figure 3. Co-operation with Lennart Löfdahl at Thermo and Fluid Dynamics (TFD) at Chalmers was established and an improved generation of the silicon flow sensor was fabricated and tested for the

![Figure 3. (a) - (b) The first gas-flow sensor using polyimide for thermal isolation of the heated hot-film from the substrate [19]. (c) - (d) The compatibility of IC manufacturing, micromachined V-groove etching and polyimide processing was demonstrated by integration of CMOS electronics (15 transistors located on the base of the chip) with the flow sensor [20].](image-url)
measurement of mean and fluctuating velocities in a turbulent boundary layer [21]. The next step was to integrate the flow sensor together with a sufficiently small pressure sensor (microphone) for the measurement and calculation of the correlation between fluctuating pressure and wall shear stress at one "point". The fabrication of the integrated sensor as well as the obtained results were reported by Edvard Kälvesten in 1996 [22].

2.2 Motivation for a new micro-joint technology

So far the micromachined devices involved in the project have been two-dimensional (single sensors or small flat arrays of sensors). However, in experimental fluid dynamics there is also a strong requirement to measure in three dimensions and also to control the flow. Figure 4 illustrates a conventional triple hot-wire sensor which is most frequently used today for measurement of turbulent flows. However, these sensors are expensive and relatively large (wire lengths in the millimeter range with diameters of typically 5 to 10 µm [23-25]). Therefore, there is a need for smaller, faster and more accurate 3-D flow sensor probes for simultaneous measurement of the three perpendicular velocity components in the flow. There is also a strong requirement for robust out-of-plane working micro-actuators for controlling turbulent boundary layers [26]. The preliminary statement of objectives for this work was to design and fabricate robust “true” three-dimensional silicon structures useful for 3-D sensors and actuator components in general and for the realization of MicroElectroMechanical Systems used in fluid dynamic applications. The first idea was to make a 3-D version of the combined pressure / flow sensor presented by Kälvesten. The first theoretical design towards such a kind of 3-D flow sensor is shown in Figure 5. The out-of-plane rotation of the sensor elements could be obtained either by mechanical folding or by bimorph engineering (i.e. the curvature is obtained by two layer of polyimide having different thermal expansions which may allows for a self-assembly by heating the structures using integrated heaters between the two polyimide layers). The folded structures are kept in place by a locking mechanism.

Figure 4. A conventional triple hot-wire sensor with typical dimensions. The normal wire diameter is 5-10 µm and the wire lengths are in the order of millimeters which gives a measuring volume larger than 10 mm³. This kind of sensors are hand made and thus difficult to achieve good control of the wires.
The first ideas of a 3-D flow sensor (suggested by prof. G. Stemme in 1995). Two alternatives for the out-of-plane rotation seemed to be possible: 1) mechanical folding using external manipulators or 2) bimorph structures using for example polyimide with a large thermal expansion coefficient. The structure must be fixed by a interlocking mechanism. The flow sensing element could be either the hot-film technique used by Stemme / Kälvesten and illustrated in Figure 3 or free-standing silicon-wires. The important feature of this configuration is the compact arrangement of the sensor elements. Here, the measuring volume could be orders of magnitude smaller than the conventional hand-made flow sensor in Figure 4.

The long term goal for the interdisciplinary project collaboration between the fluid dynamic research group at Chalmers and the MEMS research group at KTH is to develop new techniques and devices based on microfabrication for miniaturized sensors and micro-systems which are suitable for extensive high-performance turbulence measurements and control in three dimensions.
2.3 Specifications

As described in the introduction section of this thesis, there are growing needs for 3D out-of-plane rotated structures in a variety of applications. In the 3D flow sensor application, shown in Figure 5 a joint or hinge is required for the out of plane rotation. This hinge or joint should meet the following specifications:

• The joint / hinge must be robust enough to withstand the forces generated by the flow and have a small bending radius for low chip area consumption and the possibility to fabricate a compact sensor with a minimized measuring volume.

• A batch and surface (or front bulk) micromachined compatible process (based on standard IC-materials) should be used for cost-effective production and good accuracy for the position of the out-of-plane standing structure.

• Batch (or serial) self-assembled structures with an easily controlled and accurate out-of-plane erection (possibility for trimming of the bending angle) must be produced to reduce manual fabrication steps and thereby obtain possibility for large scale fabrication at low cost.

• The out-of-plane erected structures must be fixed at a bending angle close to 90° / 180°, preferably without the need of interlocking mechanism or if necessary the avoidance of manual assembly of the locking mechanism is important.

• Several electrical interconnections to the sensor element on the out-of-plane rotated structure must be realized with low thermal and electrical cross-talk.

Both the robustness and the surface micromachined compatibility criteria (i.e. possibility to integrate the hot-film / hot-wire sensors illustrated in Figure 5) probably means that single crystalline structures (SCS) should be used and folded out-of-plane.

2.4 Objectives of the work

As with most doctoral investigations, the goals and objectives of the project are subjected to continual adaptation. In this work the primary focus has been on MEMS application in fluid dynamics. The initial goal in 1995 was to fabricate miniaturized 3-D sensors (triple hot-wire or triple hot-film) suitable for measuring the instantaneous velocity vector (i.e. magnitude and direction of the velocity of small eddies) in a turbulent gas flow.

During the project, the new micro-joint technology developed and used to solve the problems associated with the 3-D flow sensor, evolved and demonstrated other very attractive features, i.e. useful for large force and displacement out-of-plane actuation. This lead to a spin-off project on micro-robotics, starting in 1997. For this spin-off project, the goal was to develop a walking MEMS fabricated micro-robot platform and investigate its applicability for use in different micro-robotic applications such as micro-assembly and medicine.


2.5 Research methodology

The research field for this doctoral investigation, MEMS, is generally a practical and experimental research field which is very interdisciplinary. The MEMS field is also relatively young which allows for several different research approaches. In Figure 6 an attempt to illustrate two fundamentally different methodologies for (MEMS) research in a simplified way is given. Either a basic research approach can be used, i.e. study one of the inner circles in detail (complete) in combination with already published research results. Both theoretical (e.g. simulations) and experimental (e.g. material science investigations for new MEMS materials and processes) approaches are used. Since the field is experimentally oriented and young most research is about new devices and applications but to obtained that most often new processes and materials have to be developed. In the MEMS field very few groups use the classical research methodology to verify or reject earlier presented research results.

With a basic research (inside -> out) approach new knowledge which is based on the fundamental results obtained in the inner circle may allow for a quick jump, small segment or straight line, to the device point on the periphery of the outer most circle. A good example is the fundamental research on deep reactive etching conducted in the early 1990’s. When the fundamental problems of vertically etching through a whole silicon wafer were solved, many new devices in new applications fields were quickly developed. When starting graduate work using this inside-out research approach one have clearly defined sub-projects from the beginning where a certain circle or circle segment should be investigated from several different aspects. Focus can then be placed on the optimal solution within the circle of investigation. Another research approach is to focus more on a system level (so far this kind of academic research mainly focuses on simulation tools but is more common in industry). This

![Diagram](image)

**Figure 6.** An illustration of different research methodologies for MEMS in a particular application field. Some small segments have been investigated and research results from these are reported in literature (i.e. the gray segments). A simplified description of two research approaches that can be used are: 1) bottom-up or inside -> out basic research where one particular circle, most often close to the midpoint, is investigated in detail. New knowledge is gathered and the circle segment is extended. 2.) applied research (top-bottom or outside -> in) where small segments of already existing knowledge are put together in a new way to reach a particular device. This is illustrated by finding a way which combines the gray segments from the inner circle to the outer most with a certain application. Most often new small segments with new knowledge must be added to reach this point, but the focus is on putting together existing knowledge in a new way.
kind of research can be illustrated by the largest circle which illustrates the whole system and then the
research goal is to fill out small segments of missing knowledge so that a path with gray segments
can be created from the inner circle to the actual system and device of interest.

The methodology used for the work performed for this thesis can be categorized as the outside -> in
approach (i.e. the focus is to find the easiest or fastest way to the outer most circle and the specific
devices for solving or investigating the feasibility to solve an existing problem). No clear project
description was outlined when the work started, except that the work should be experimental rather
than theoretical. The focus was, to investigate MEMS technologies within fluid dynamics and to
achieve accurate turbulence measurement in all three dimension at a length and time scale smaller than
with present methods and sensors. This is illustrated by the left circle in Figure 7. The concrete
devices in focus on the periphery were to miniaturize the classical triple hot-wire sensor. By a quick
literature study the fundamental techniques and knowledge on how to fabricate free-standing silicon
hot-wires [27-32] and thermally insulated hot-film [19, 20] elements was already published and some
knowledge on flow sensors for turbulence measurement was gained through earlier work performed at
the department [21, 22]. However, all of these previous flow sensors were planar. Therefore, it was
obvious that the key point for this work would be on techniques for three dimensional out-of-plane
structures with detailed features in all three directions, illustrated as the inner purple, dark-gray,
colored circle. The basic methodology for this work was to use existing fabrication technologies as
much as possible and complement these with a few new key processing steps, which may be
investigated in more detail. The research deals with integrating different techniques and fabrication
processes into a functional device. In cases where none of the reported technologies in literature is
suitable, new solutions of more fundamental character are needed. Then the new ideas should be
investigated experimentally using simple test structures or macro models. In cases where the new
ideas could be useful in new application fields spin-off project may be started (i.e. same new circle

Figure 7. The methodology for the present doctoral investigation. Focus is on putting together
existing techniques with working devices in the fields of fluid dynamics and micro-robotics. The key
segment is 3-D out-of-plane structures where new techniques are needed to advance to the outer
circles.
PVG Joints for Three-Dimensional Silicon Transducers

A third, obvious, application area (i.e. a third circle not shown in Figure 7) is micro-optical-electro-mechanical systems (MOEMS) which also rely on folded microstructures (mirrors, lenses, etc.) out of plane to achieve free-space optical benches [18]. However, this is beyond the scope of this thesis, which focuses on general techniques for out-of-plane erected microstructures (the inner purple colored circle) and their applicability for use in micro-robotic systems and in fluid dynamic research tools (the two circles shown in Figure 7).

2.6 Outline of the thesis

The thesis started with an introduction on miniaturization of systems and a short background to the fields of fluid dynamics and micro-robotics with the focus on MEMS applications and how micromachining may be the solution to some of the basic problems associated with (system) miniaturization in these fields. In both of these fields, 3-D microstructures are an essential requirement to realize the key components needed to achieve a complete working device or a larger system. In chapter 3 a review of different micromachining techniques to obtain 3-D microstructures in silicon is given. Compared with Figure 7, this review corresponds to the whole inner, purple colored or dark gray circle. The features of the various reviewed 3-D techniques are compared with the micro-joint specifications (given in section 2.3) for the realization of a triple hot-wire sensor and the suitability of these techniques in micro-robotic applications is discussed. Most of the techniques reviewed could not fulfill the requirements for the 3-D sensor completely. Therefore, the development of the new polyimide V-grooved (PVG) micro-joint technique was developed and is described in chapter 4 (i.e. filling a new circle segment with new knowledge in the circle of 3-D technologies), illustrated by the yellow-light gray segment in Figure 7. Here the description of the novel PVG joint and some experimental results on both static and dynamic characteristics, obtained with fabricated test structures, are presented. Thereafter, a deeper introduction to MEMS in fluid dynamics (some of the segments in the whole fluid dynamic circle in Figure 7) and especially on micromachined flow sensors and hot-wire anemometry is given in chapter 5. The first device application based on the new PVG joint, the triple hot-wire sensor, is presented in chapter 6. First, different aspects of the manufacturing and MEMS processing of the 3-D flow sensor is presented, followed by the fluid dynamic experiments performed to study the applicability of silicon hot-wires for turbulence measurements. Chapter 7 discusses and defines the different terms in micro-robotics as well as highlighting some of the most feasible applications for micro-robotics (some of the outer segments in the micro-robotics circle of Figure 7). Special attention is paid to micro-conveyers and walking micro-robot platforms based on MEMS technologies. The PVG joint micro-robotic devices in the form of micro-conveyers and the first totally MEMS-based walking micro-robot are presented in chapter 8. Finally, chapters 9-10 include a summary of the appended papers, the conclusions and discussions of the work together with an outlook for future research are given. In the end of the thesis, six journal articles on the use of the PVG joints in various applications are appended.
3 Review of three-dimensional silicon technology

Batch and mass fabrication of truly three-dimensional (3-D) silicon structures is a key step in future micromachining technology that can enrich the MEMS field with new applications. As pointed out in the introductory chapters, many sensor and actuator applications require three-dimensional components. Before going into detail about truly 3-D structures, a brief discussion of the advantages and disadvantages of “standard” micromachining technologies, illustrated in Figure 8, will be presented. The basic technologies (backside bulk micromachining, frontside bulk and surface micromachining) used to create out-of-plane rotated 3-D structures are also introduced, as well as the two most common micromolding techniques.

Figure 8. Cantilever structures fabricated using a) back side bulk micromachining b) front side bulk micromachining and c) surface micromachining sacrificial layer techniques.

3.1 Quasi 3-D structures by standard micromachining technologies

During the past twenty years, the development of new silicon processes has been very successful. A wide variety of process techniques for quasi-3D MEMS (limited freedom for structure dimensions and thickness) have been used, including isotropic and anisotropic wet and dry etching (i.e. deep reactive ion etching, DRIE) and so called bulk micromachining (or subtractive micromachining) [33]. Using bulk silicon etching combined with wafer bonding [34] quasi 3D-structures such as pressure sensors, accelerometers, flow sensors, micro-fluidic devices and different resonators have been created [35]. Creative designs have demonstrated that it is possible to achieve 3-D sensors taking advantage of the anisotropic behavior of silicon. For instance, a 3-axis monolithic accelerometer has been fabricated with standard bulk etching technique [36]. However, sensing in three dimensions is not possible with most sensors. Alternatives to bulk micro machining exist.

Surface micro machining [37, 38] is another interesting technique where the silicon substrate is used as a support material rather than the structural material as in the case of bulk micro machining. Various thin films such as polysilicon, silicon dioxide and silicon nitride are deposited and etched, resulting in advanced microstructures. One commonly used technology is sacrificial layer etching where free-standing thin-film structures (e.g. polysilicon) are etched free by lateral etching of the underlying sacrificial layer (e.g. silicon dioxide or another polysilicon layer) while the structural layer is encapsulated by a protective layer. Surface micro machining results in structures ranging from a few microns to several thousands of microns in length but are limited to only a few microns in thickness or tens of micrometers with epi-poly [39] (for epi-surface micromachining the Europractice MEMS MPW-process no. 1 from Bosch is commercially available [40]). Material deposition
characteristics and current lithographic techniques generally limit devices to a planar geometry. During
the last ten years, much work has been done on surface micromachined devices. Despite the "two-

dimensional" nature of this technique, various complex structures are now used in commercial
applications such as pressure sensors for heart surgery diagnostics [41], the ADXL- airbag
accelerometers made by Analog Devices Inc. [42, 43], and the Texas Instrument Digital Mirror Device
(DMD™) for projection video displays [44, 45]. A variety of micromotors (see Figure 1) and
electrostatically driven comb-drive actuators have also been fabricated and used in several applications.
One important advantage of the surface micromachining technique is its relatively simple integration
with IC elements. Since surface micromachining results in quite thin and fragile structures, this
technique has been modified to achieve thicker structures either by depositing thicker structural layers,
epi-poly or by etching into the substrate, so called front-bulk micromachining. For front-bulk
micromachining the substrate can be used either as a part of the sacrificial layers and the structure is
made out of deposited thin film layers, as illustrated in Figure 8 b) and in the appended papers no. 3
and 4, or the substrate (i.e. single crystal silicon - SCS) can be used both as the structural material
and sacrificial material as in the SCREAM bulk-process [46].

Bulk micromachining gives access to the entire bulk of the wafer for the 3D structures, but this
still limits the structure height to approximately one millimeter. An alternative micromachining
 technique that has attracted some attention is the creation of miniaturized or microscale parts through
micromolding and / or replication. The most common process is known as LIGA which is a German
acronym for “Lithographie, Galvanof ormung, Abformung” (lithography, electroplating and molding)
developed by Ehrfeld et al. [47, 48]. The LIGA process, based on template-guided electroplating,
is capable of producing structures with extremely high aspect ratios (at least 100:1) thanks to the use of
extremely well-collimated synchrotron radiation (X-rays) to expose the template layer resulting in
nearly perfectly straight sidewalls. Although LIGA can be used to create 3D micro structures its major
drawback is that very expensive equipment (i.e. a synchrotron) is required. By modifying of the LIGA

technology using sacrificial layers (SLIGA [49]) it is possible to achieve movable structures for
actuator and micro-robotic applications. Besides the LIGA process, the HEXSIL process (further
described in next section) and plastic replication are interesting quasi 3-D technologies.

3.1.1 Micro-robotic devices based on quasi 3-D structures and in-plane actuation

Since the most common way to design MEMS devices is planar, the first presented micro-robotic
devices were based on in-plane actuation. The micro-gripper presented by C-J Kim et al. [50] has a
relatively thin gripping arms (i.e thin film deposited polysilicon). Other micro-grippers based on
 quasi 3-D structures with high aspect ratios (i.e. thin beams perpendicular rather than parallel to the
surface) have also been presented, see Figure 9. These grippers are formed by etched away the
substrate under the gripper, i.e. over-hanging gripping tools. One critical parameter of the in-plane
technique is how to achieve an actuator with large displacement and force generation capabilities.
Thermal actuators are known for their ability to generate high forces. A thermal actuator made from a
single material would be easy to fabricate, but the displacement due to thermal expansion of a simple
beam, for example, is quite small. This is a general drawback for in-plane actuators that occurs
independently of the fabrication technique used. However, by using mechanical leverage, large
displacements can be obtained as was demonstrated by Keller and Howe [51]. They used a
micromolding and / or replication technique, named HEXSIL, to fabricate thermally actuated micro-
tweezers made from nickel and later in polysilicon [52]. In the HEXSIL process [53] the mold is
formed by deep trench etching the silicon substrate. A sacrificial layer of oxide is deposited in the
silicon mold which is then filled with deposited polysilicon. Then the polysilicon structure is released
from the mold by sacrificial etching of the oxide. Afterwards, the mold can be re-used by a new oxide and polysilicon deposition process. One advantage of this process is the ability to make thick (100 µm or greater) polysilicon structures (i.e. quasi 3D structures) on which electronics can be integrated. Figure 9 (b) shows a close-up of the leverage design for the HEXSIL micro-tweezer, where a large beam is resistively heated by the application of current, and subsequently, expansion causes other beams in the link system to rotate and open the tweezer tips. When cooled, the contraction of the thermal element closes the tweezers.

Leverage and linkage systems (sometimes combined with gears for force transfer) is a very useful technique to for obtaining large displacements and / or forces and can be used for other than thermal actuation, e.g. electrostatic comb-drive actuators\(^1\) [54]. Several publications on design optimization schemes for various leverage techniques, applied to thermal actuators (so called compliant microstructures) have been presented by the MEMS group at MIC, Denmark [55]. Micro-robotic devices (a two-degree of freedom XY-positioner and a three-degree of freedom robot arm with a microgripper) have been fabricated using laser micromachining in nickel and compliant electrothermal microactuators [56]. Another way to achieve a leverage effect is to use clever geometrical designs for single material expansion. Such a method using polyimide filled V-grooves will be described in chapter 4. As an alternative to single material expansion actuators, bimorph structures could be used, see section 3.2.

Another approach to producing single-material (unimorph) in-plane thermal actuators (also known as heaters) for micropositioning applications was presented by Guckel et al. [57]. They used the LIGA process and an asymmetric structure (one “cold” and one “hot” side as illustrated in Figure 10 a), to generate large displacements (tenths of a millimeter) with relatively low power

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\(^1\) [M]: Multimedia Images and Movies on such systems are available from the Sandia National Laboratories micromachine gallery at: [http://www.mdl.sandia.gov/micromachine/](http://www.mdl.sandia.gov/micromachine/)
consumption. More recently, this approach was used by Bright et al. [58] for surface micromachined polysilicon thermal actuators. With this in-plane actuator they have successfully fabricated overhanging micro-grippers and several micro-optics devices. Howe et al. [59] have demonstrated that this kind of polysilicon thermal actuators has a long lifetime. By manually folding several heatuator structures out-of-plane in an array configuration, a micro-positioning device as well as a prototype for a walking silicon micro-robot platform were obtained [60]. The folded thermal actuator (heatuator) leg is illustrated in Figure 10 b). This kind of out-of-plane folding is very time-consuming and major improvements both on speed, yield and accuracy could be achieved by powered self-assembly using the thermal actuators or electrostatic comb-drives as micro-motors which folds the structure out-of-plane. This kind of 3-D structures and assembling approach will be described in detail in the following sections of this thesis.

![Diagram of heatuator](image)

**Figure 10.** a) Schematic illustration of a single-material asymmetric thermal actuator for in-plane actuation (also called heatuator). The actuator structure was originally made of nickel in a LIGA process although surface micromachined poly-silicon structures have also been used.  

b) An out-of-plane folded heatuator for micro-robotic applications [60]. The details concerning folded surface micromachined 3-D structures are presented in section 3.2.  

[M]: Related to this Figure are the various movies on the heatuators and their use in micro-robotic applications presented by the MEMS research group at University of Colorado, USA. These movies are available at [http://mems.colorado.edu/img/a.heatuator.html](http://mems.colorado.edu/img/a.heatuator.html)
PVG Joints for Three-Dimensional Silicon Transducers

As demonstrated above, bulk and surface micromachining etch techniques as well as the different molding / replication techniques can provide some quasi three-dimensionality in structures and they can also be used to fabricate in-plane actuators. Using standard surface photolithography technology results in high resolution structures in the plane, but due to processing parameters such as under-etching and etch uniformity over the wafer, the resolution of long structures in the direction parallel to the plane is much poorer. Even though it is fairly easy to achieve good control of etch depths down into the substrate, the fine structures on the walls or free hanging in the middle of these etched holes are difficult to realize. In general, conventional lithography techniques limit structures to two dimensions (although lithography has been used for gray-tone patterning [61] on sloped surfaces [62] as well as on curved structures [63] and on semiconductor balls™ [64]). Using other fabrication techniques such as laser-chemical writing [55] and electron discharge machining (EDM) [65, 66] results in larger geometrical freedom to create 3-D structures but, at the expense of serial manufacturing rather than parallel (batch) fabrication as for the other technologies discussed so far.

One way of realizing true three-dimensionality while still having the possibility of batch fabrication is to use out-of-plane rotation of microstructures, as described in Figure 10 b) complemented by controlled self-assembly. The great advantage of such an approach is that it uses conventional high-resolution surface lithography (with the possibility of producing sub-micron features) while providing access to the third dimension. Actuation of such an out-of-plane rotated structure with large displacements has several important application areas. Various interesting techniques for making 3D structures using the out-of-plane rotation approach by different hinge or joint techniques have been proposed; a review of some of these techniques are given later in this chapter. Since many techniques exists, the focus of this chapter will be to show the technologies that have been used or would be possible to use for 3-D sensors of various kinds as well as 3-D actuators (especially for micro-robotic applications and active control within micro systems for active fluid dynamic control). Special emphasis is placed on polymer based joints / hinges.

A pre-study of suitable techniques was done in early 1996 [67]. This study only focused on the applicability of the different techniques to the triple hot-wire sensor (i.e. the specifications given in section 2.3). However, in the following review other techniques are also included that have been used or have the potential to be used in micro-robotic and 3-D sensory applications.

For 3D sensory applications the focus is on the specifications given in Section 2.3. Parameters such as the angle’s accuracy of the erected structure (i.e. need for bending stops, interlocking mechanisms), robustness and interconnection of several metal wires to the out-of-plane rotated structure is of great interest for the triple hot-wire sensor. Self-assembly is another challenge, which is also a requirement for batch fabrication of a 3D structure. Self-assembly, could be obtained either in parallel (batch) or serial (powered) configurations and will be further discussed in section 7.1, [68, 69]. Most often the parallel approach and one-time folding is favored over the serial approach with built-in micro-motors for adjustable actuation. For the actuator application review the focus is on the displacements and force generation capability and the possibility for use in arrayed configurations with individual (asynchronous) actuation.
3.2 3-D structures based on bimorph structures

Different techniques using controlled stress engineering in a sandwich structure have been used for out-of-plane rotation of microstructures. The theory of bending sandwich structures consisting of two or more materials with different thermal expansion coefficients, so called bi-metals, was presented more than 70 years ago by Timoshenko [70]. In the MEMS field, different combinations of standard IC-materials have been used as illustrated in Figure 11. It is common to use aluminum (Al), chromium (Cr) or gold (Au) which have relatively high thermal expansion coefficients (i.e. 10 to 25 ppm/°C) in combination with silicon (Si), polysilicon, silicon dioxide (SiO₂) or silicon nitride (SiₓNᵧ) with low expansion coefficients (i.e. < 3 ppm/°C) [71]. Another attractive material combination is the use of different polyimide layers. Several different polyimides exist, both with very low thermal expansion coefficients (< 5 ppm/°C) and very high (> 50 ppm/°C) and its is fairly easy to use both kinds of polyimides in the same structure. Polyimide is also commonly used in IC fabrication and, therefore, most processing equipment already exists. A deeper discussion of polyimide processing and characteristics of polyimide is presented in section 4.1.

![Figure 11. Schematic drawing of a bimorph transducer. The layer two material is bulk silicon and layer 1 is a material which expansion is different than the expansion of layer two. The expansion may be obtained by for example thermal heating (different thermal expansion coefficients between layer 1 and 2) or piezoelectric where layer 1 is expanding due to a voltage over the piezoelectric material. From [71].](image)

Controlled static bending (out-of-plane erection) can be achieved by good control of the deposition condition of the different layers (i.e. thickness, deposition temperature, curing or annealing condition, thermal expansion coefficients, etc). Normally the deposition and/or the annealing temperature of the different layers are rather high which means that when a multi-layer structure is cooled down the differences in thermal expansion leads to built in stress and a static erection of the free-standing structure out-of-plane. The most important advantage of this approach is that the microstructure is self-assembled so that no external manipulators are needed to raise the structure out-of-plane. Among the drawbacks are the large radius of curvature for the folded structures and the poor control of their position [72, 73]. Smaller radii of curvature can only be achieved with very thin and fragile structures. By the combination of two different polyimide layers smaller bending radii and larger displacements used to control the position of the folded structures are obtained [74-78].

Several different methods, which show similarities in volume expansion characteristics [79], could be used to control the expansion for two material bimorph structures, i.e. dynamic and/or static folding. Some of them are described in the following sections.
3.2.1 Bi-morph effect using thermal expansion and electrostatic forces – bimetal joints

The classic way to achieve an actuator using a bi-morph structure has been to integrate a heater on a bi-metal [70] (or bi-morph) cantilever [71]. Electrothermal (electrical joule heating using resistors) heating is easy to obtain with MEMS technology. Figure 12 illustrates a surface micromachined microactuator achieved by utilizing the large residual stress difference between two different thin polyimide films. The out-of-plane curling can be controlled either with thermal actuation using an integrated heater and the bimetal effect or by electrostatic actuation [77]. Polyimide is compatible with IC manufacturing which makes it possible to integrate electronics, for example, for advanced control algorithms used in micro-conveyor systems with large arrays of bi-morph actuators that are individually controlled [80].

Figure 12. Surface micromachined 3-D structures using a bimorph structure consisting of two different polyimides with different thermal expansion coefficients. Control of the out-of-plane rotation can be obtained either with the integrated gold heater (i.e. bi-metal) or by electrostatic forces [77].

[M]: Related to this Figure are the different movies on fabricated organic actuators which have been used to achieve intelligent micro-conveyance systems. These movies are available at: http://www.ee.washington.edu/research/mems/Projects/Video/

To overcome the limitations of electrostatic actuation (which requires high driving voltages) [73] a solution with serially connecting several bending actuators was proposed [81]. The serial electrostatic actuator is illustrated schematically in Figure 13. Smaller bending radii were achieved with this arrangement. The radius of curvature is nevertheless quite large and smaller radii can only be achieved with very thin and thus weak structures.
Multi-layered surface micromachined bistable actuators for applications where the structure needs two stable positions (out-of-plane and into a cavity in the substrate) have been presented by C.-J. Kim et. al. [82, 83]. This device consists of a buckled cantilever structure (poly-Si / oxide / poly-Si) which is bent out-of-plane by a tension band of nitride. The great advantage of this device over the other bimorph structures presented above, is that two stable positions are obtained without any power consumption to keep the structure in each respective state. Other thermal bimorph structures need a DC-power supply (i.e. constant temperature) to keep the structure in the “on” position. The buckling cantilever by Kim et. al. can be switched between the two states by uneven thermal expansion as a result of unsymmetrical Joule heating. By heating either the upper or the lower polysilicon layer by a heat pulse, the cantilever structure can obtain a static position either out-of-plane or bent into the cavity in the substrate. A modified version of this device involves a second cantilever structure (tension-band-anchor) connected to the tension band. This solution allows for more reliable switching with low-voltage drive.

For applications where arrays of actuators are necessary the bimetal structures are very suitable since they can be used in compact configuration and addressed individually [75, 76, 78, 80]. As for all kinds of thermal actuators, bimetal actuators show large power consumption and are relatively slow compared to other actuation principles but on the other hand they have the potential to generate large forces and large displacements. Electrostatic actuation requires high voltages but relatively low power although the force generation capability is limited for such structures.

3.2.2 **Bimorph effect using electro active polymers EAP - Active polymer hinges**

In recent years, the field of electro active polymers (EAP) has gained much interest, especially since it is possible to integrate them with MEMS and microfabrication [84]. This research field is very wide both in terms of application areas (miniaturized and macro-sized actuators for robotics, loud-speakers, pumps, valves [85] and even artificial hearts and in terms of the materials used [86]. Many research groups are working on the idea of using EAP or Ionic Polymer-Metal Composites (IPMC) as artificial muscles and biomimetic sensors for macro and micro-robotic applications [87]. Different driving modes can be used, *Longitudinal EAP –* where the polymer responds with change in length (unimorph structures) or *Bending EAP –* polymer that responds by bending (it may be the result of use of multiple layers as bimorph or inherent property).
Figure 14. Out-of-plane rotation using active polymer [88].

a) Principle for the EAP-actuator. The poor adhesion between gold (yellow/light gray) and silicon (gray) is used as a differential adhesion technique to release the structure (an alternative to sacrificial layer etching as in most other surface micromachining). At the anchor point chromium (orange or intermediate gray) is used for adhesion. The active hinge part consists of a bimorph structure of polypyrrole-PPy (purple/dark gray) and gold. The rigid part of the structure consists of gold and a photopolymerisable plastic, photoBCB (benzocyclobutene) in green/intermediate gray.

b) A sketch of a three-electrode electrochemical cell with a microactuator as the working electrode (WE). RE is the reference electrode and CE is the counter electrode.

c) Photograph of the three electrodes. In the middle, the 20 x 70 µm² working electrode (WE) is shown. On the left, the microactuator lies flat on the substrate and, on the right, it is bent perpendicular to the substrate (90°).

Courtesy: Edwin Jager, MST-polymer research group, Univ. of Linköping (published with permission) [M]: Related to this Figure are the different movies on the ECP active hinge and its use in micro-robotic applications presented by the MST-polymer research group at University of Linköping, Sweden. These movies are available at http://www.ifm.liu.se/Applphys/ConjPolym/research/micromuscles/CPG_micromuscles.html
When an electrically conjugated or conductive polymer (ECP) is changed from insulating to conducting by applying a small voltage, the volume of the polymer is changed [89]. A bimorph structure consisting of the polymer and a gold layer (PPy-Au) will then curl. This effect can be used as a hinge. The polymer hinge is used to connect rigid plates to each other and to silicon substrates allowing precise three-dimensional positioning of the plates, as shown in Figure 14. Large reversible bending angles (from 0° to 180°) with small radii of curvature are obtained with applied voltages between +0.35 V and -1.0 V. The drawback is that the tuning requires an electrolyte (liquid) which is not compatible with most sensor applications. However, it has been stated that “dry” microactuators should be possible to construct in principle [88]. The polymer material is also more unstable than conventional IC-materials and has a large potential for degradation. Cycle lifetimes between 1,000 and 10,000, response times in the order of seconds and sensitivity to humidity has been reported [90]. However, by using Ti-PPy artificial muscles improved long term characteristics were obtained, which is a requirement for most micro-robotics devices. Various surface micromachined micro-robotic devices based on Au-PPy have been presented [90, 91]. Promising results on conducting polymers for active chateters and micro-surgery have also been reported [92, 93].

3.2.3 Bimorph effect using phase transformation expansion - shape memory alloys (SMA)

Similar to the EAP techniques mentioned above, volume changes resulting in either longitudinal expansion or bending of a bimorph structure can be achieved using controlled heating to obtain a phase change in a material (so called Shape Memory Alloys-SMA). An integrated heater is used to obtain the phase transformation of the SMA alloy. There exist many SMAs such as Ti-Ni, Cu-Al-Ni, Cu-Zn-Al, Ni-Al and Mn-Cu alloys which are more or less compatible with microfabrication. Among these, the most commonly used are Ti-Ni and Ni-Ti based alloys because these alloys are the best from a practical fabrication point of view [94]. The ability to deposit thin-film SMAs (i.e. sputter deposited) makes them suitable for 3D out-of-plane erected microstructures.

In the late 80’s and early 90’s a new class of untraditional materials, so called shape memory polymers (SMPs), were developed and became commercially available. The shape memory effect of polymers were first discovered in the late 60’s [95]. SMPs exhibit an elastic memory effect (i.e. their elastic modulus changes in a large and reversible way across the glass transition temperature ($T_g$)) similar to traditional SMAs. When the temperature increases above $T_g$ the material becomes more flexible, whereas when the temperature decreases below $T_g$ the material becomes harder and is able to sustain a new shape.

Micro-robotic devices in the form of micro-grippers [96, 97] and micro-robotic catheters for medical application [98-100] based on SMA have been demonstrated. For use in array configuration out-of-plane erection the SMA approach seem to be less suitable. Since a SMA actuator has inherent hysteresis there are no direct and simple relations between the temperature and the position or force. Therefore, accurate position or force control by SMA actuators requires the use of powerful controllers and the experimental determination of complex data. Many mathematical models are being currently developed by various research groups to overcome this important limitation. The reliability of shape memory devices depends on their global lifetime performance. Time, temperature, stress, strain, strain mode and the amount of cycles are in this respect important external parameters. Internal parameters that can have a strong influence on the lifetime are: the alloy system, the alloy composition, the heat treatment, and the processing technique. For general purposes, the maximum memory effect, strain and/or stress, will be selected depending on the required amount of cycles. For long lifetime applications only limited stress and strain values can be used [101].
3.2.4 Bimorph effect using piezoelectric expansion

A volume change or length expansion can also be obtained by applying a voltage across a piezoelectric material [79]. When the piezoelectric material (deposited on a thin cantilever) expands the cantilever bends due to the bimorph effect. Thus, it is possible to obtain a voltage controlled out-of-plane rotation. Because silicon is not a piezoelectric material, the most common method is to glue or deposit the piezoelectric material (usually lead-zirconate-titanate (PZT), zinc oxide (ZnO), aluminium nitride (AlN), lead-magnesium-niobate (PMN)) on a silicon cantilever or to use quartz which has a piezoelectric effect. Also, different polymers, such as poly-vinylidene fluoride (PVDF), show piezoelectric properties [102]. The piezoelectricity of PVDF could be several times higher than that of quartz under special treatments.

As for most bimorph structures it is easy to integrate several piezoelectric cantilevers in an array configuration. A prototype of a walking micro-robot based on piezoelectric (AlN) actuation has been demonstrated [103, 104]. However, this device is based on membrane / in-plane deformation to obtain the rotational motion of the robot legs, rather than a folded out-of-plane approach. The legs are attached to the membrane which is forced into rotational movements by three bimorph piezoelectric areas on the membrane which are actuated with a 120° phase shift. Piezoelectric bimorph cantilevers, i.e. out-of-plane working actuators, have been used for active turbulent boundary layer control in the fluid dynamics field [105].

The main drawback of all bimorph joints or hinges (bimetal, SMA and the piezoelectric techniques) is that the bending radii for out-of-plane structures are normally large. Small bending radii can only be obtained by thin beams, which result in fragile structures. For most 3-D sensors small bending radii (< 50 µm) is required. By using stress engineering, the control and accuracy of the out-of-plane erected structures are not very good. The great advantage is the easy integration of actuator functionality in the structure, which is implemented automatically, most often it is also easy to integrate a sensing element in the folded structures, e.g. piezoresistive strain gauges or piezoelectric films as force sensors.

3.3 3-D structures based on mechanical folding

The most straight-forward way to achieve out-of-plane bending of a microstructure is to use an external manipulator and fold a flexible or elastic joint or hinge, as illustrated in Figure 15. This was also the first idea for the design of the 3-D flow sensor (compare Figure 5). Because this technique requires the use of an external manipulator it is not batch compatible. To solve this problem different assembly techniques have been tested. Both parallel (batch) assembly using directed streams of air from a capillary tube and vigorous agitation in DI rinse water and serial assembly with integrated actuators on-board on the chip and used for manipulation have been presented. One common approach is the use of integrated actuators (for example the heatuator [106] or the electrostatic comb drive described in section 3.1) which pulls or pushes the mechanical structure out-of-plane. Both the parallel and serial assembling solutions tend to be quite complex and fragile. Sophisticated micro-techniques mimicking the function of a macroscopic hinge, first presented by Pister [107], is easy to fabricate and can be used both in static and dynamic applications. In the following parts of this section the micro-hinge principle as well as other micro-hinge or joint techniques based on mechanical folding will be described.
3.3.1 PolySi hinges

The surface micromachined polysilicon hinge was presented in 1992 [107]. This hinge is fabricated using surface micromachining with two layers of polysilicon and phosphosilicate glass (PSG) as a sacrificial layer, as can be seen in Figure 16. Recently, more sophisticated designs with improved performance and reliability based on four or even five layer polysilicon processes have been used [54, 108, 109]. With an increasing amount of commercially available multi-project-wafer (MPW) processes focusing on surface polysilicon micromachining (like Cronos’ MUMPs [110] and Sandia’s SUMMiT [111] processes with 4 and 5 polysilicon layers) these kinds of devices are available to everyone. A variety of micro-opto-electro-mechanical systems (MOEMS), i.e free-space micro-optical benches, corner cube reflectors for communication and bar-code scanners of impressive complexity using integrated actuators for serial self-assembling out-of-plane structures (mirrors, lenses etc.) have been presented [54, 112-119] as well as components for RF-MEMS [120]. The polysilicon hinge has also been proposed as a fabrication technique for 3-D sensors, micro-grippers and other micro-robot applications [107, 121].

The main drawback of the original version of the polysilicon hinge technique is that it is not suitable for batch production because manipulators are required for raising the structure. Different approaches using air streams and agitation in water to raise the structure out-of-plane have been proposed to solve the assembling problem [107, 109]. Even though it would be possible to obtain batch self-assembling, there are arguments on the accuracy and yield of these methods. The difficult task of assembling orthogonally oriented structures is partially solved by Howe et al. using pop-up structures rather than flip-up structures, although the reported yield and reliability are not particularly good. Alternative self-assembling solutions based on comb drive and thermal actuators (similar to the one described in Figure 10) were presented more recently [106, 116, 119]. At first sight, this serial self-assembling method seems complicated and somewhat fragile, but since the hinges are fabricated using commercially available and robust MPW processes, the complexity is maybe not a big issue. Although, it is possible to make adjustable assembling with the built-in motor-driven actuators, it is still a serial and time-consuming process and the drivers for the assembly consumes chip area. Another drawback is that these surface micromachined structures require some kind of interlocking arrangement to stay bent out of the wafer which complicates the assembly process. Different interlocking mechanisms for folded 3-D structures will be discussed and described in section 3.6. To be useful for 3-D sensor applications the difficulties in achieving several electrical interconnections to the assembled structure must be solved. Presently the electrical interconnection wires have been realized by a limited amount of serpentine folded springs as illustrated in Figure 10. Such an interconnection approach was also used to obtain a folded hot-wire structure in the original hinge.
paper by Pister, see section 5.1.1 for further details. This allows only two electrical interconnection wires to the folded structure. Electrical contact to a folded structure (plate) through the hinges that tie the structure (plate) to the substrate has been proposed [107], which would allow more interconnection wire. However, each interconnection wire requires one hinge to avoid cross-talk. Further, the contact resistance for such wires may be quite high and for some bending angles no electrical connection at all could be obtained [107].

**Figure 16.** (a)-(c) Cross sections of the hinge during fabrication.

(d) A perspective view of a hinged plate after release by external manipulators (from [107]).

(e) SEM-photo of a polysilicon hinge realized in MUMPS technology (from [122]).

[M]: Related to this figure are the different movies on fabricated hinge devices by the MUMP’s process. These movies are available at: [http://www.memsrus.com/cronos/svcsmumps.html](http://www.memsrus.com/cronos/svcsmumps.html)
3.3.2 Aluminum joints

An approach using the flexibility and softness of aluminum has been used to fabricate 3-D piezoresistive sensors using post-process XeF$_2$ etching of standard CMOS-wafers [123, 124]. External manipulators were used to rotate the structures out-of-plane with a flexible aluminum joint, as shown in Figure 17. The advantage is that 3-D sensors can easily be integrated on the same chip as the electronics and that the electrical interconnections to the folded structure are automatically obtained by the aluminum joint. The main drawback is the manual assembly which also requires interlocking braces. The structures also seem to be (extremely) fragile if used in real flow sensor applications.

In Figure 17 b), a test structure of out-of-plane folded hot-wires is shown. To keep the folded structure in place a manually assembled interlocking brace is used.

![Figure 17](image)

**Figure 17.** (a) Overview of a 3-D accelerometer design based on an aluminum hinge with piezoresistive detection [124]. The aluminum hinges are formed by front-bulk silicon etching of standard CMOS-wafers. The front bulk sacrificial etching is done through the pits using XeF$_2$ as a CMOS compatible etcher not attacking the aluminum. (b) SEM-photo of raised hot-wire test structures [123]. (c) Close-up of the aluminum hinge with an interlocking brace [124].
3.3.3 Polyimide joints

Polyimide, with its high flexibility (low Young’s modulus), and other elastic materials are good micro-joint materials. To obtain movable bulk micromachined mirrors, polyimide has been used to create the joint [125, 126]. The out-of-plane folding can either be obtained by manually using probes or by using external electrostatic forces (see also section 3.4).

Elastic joints in polyimide using surface micromachining were developed in an attempt to fabricate an insect based micro-robot [127]. Figure 18 shows a 3-D structure obtained with the elastic polyimide joint using surface micromachining (sacrificial etching of PSG). The structure is manually assembled into its final position just like paper folding (Japanese origami). Bending angles up to 70° were obtained, but the variation in the bending angle is large. These structures do not have integrated actuation but rely on external forces. For the locomotive micro-robot, a vibrating table was used to supply the robot with energy. By designing the different robot legs to have different resonance frequencies it was possible to actuate the different legs individually and thereby move the robot forward (and left-right). The leg is thin and fragile which means that the robot structure easily sticks to the surface it is shaking on. A similar method using nickel as the structural material has been used to create micro-wings for flying micro-robotic devices [129]. “Self-assembled” polyimide joints were obtained by relying on the residual stress in the polyimide. Uncertainty values, \( u_c \) (1 \(\sigma\)-level), for the bent angle variations in the range of 12 to 18 degrees for static bending angles between 20 and 50 degrees for different types of the joint could be calculated from the reported data. For most application the poor control of the assembling angle is not sufficient.

![Figure 18. To the left a schematic view of a 3-D structure using mechanical folding of an elastic polyimide joint [127]. The surface micromachine fabrication process with manually assembled 3-D structure is shown to the right [128].](image-url)
For 3-D sensory applications the poor control of the folded structure, the fragility of the structure, together with the fact that no electrical interconnections are integrated makes this surface micromachined polyimide joint technology less attractive both for the 3-D flow sensor and micro-robotics.

Most of the 3-D structures presented so far in this chapter have been used for actuators, but folded structures can also be used as sensors [130]. One example is the highly symmetric three-axis accelerometer shown in Figure 19. This accelerometer is based on a folded micromachined silicon cube, which is assembled manually using polyimide as joints. This cube houses a non-micromachined seismic mass (i.e. a tungsten mass fabricated with conventional fine mechanical tools) which are kept in place by polydimethylsiloxane (PDMS) rings. This rubber elastic material acts as a soft spring and by choosing a correct design a suitable damping can be achieved (i.e slightly sub-critically damped), where the acceleration forces move the mass enough to detect the movement capacitively. The capacitance, formed between the mass and the different walls on the cube, varies with acceleration. The three pairs of capacitors on either side of the seismic mass shown in Figure 19 d) are connected to differential capacitance to voltage converters (CVCs) to generate the output signals.

For actuator applications, the elastic type joints are preferable, since problems with wear caused by friction in a rotational bearing (like the polysilicon hinges described in section 3.3.1) are avoided using an elastic joint. This has been successfully demonstrated using in-plane structures actuated electrostatically [125, 126] and magnetically [131]. If the problems with cross-talk between actuators, self-assembling and controllability of the bending angle can be solved, this type of joint would be very interesting in both micro-robotics and as actuators in active control systems for fluid dynamics.
Silicon wafer partly oxidized, KOH etched from the back side

Aluminum deposited onto both sides of the wafer and annealed to obtain an ohmic contact

Chromium deposited on the back side of the wafer to obtain a good adhesion of the polyimide

Spincoating and patterning of polyimide (PI) on the back side (not to scale)

Spincoating and patterning of PDMS on the front side (PI layer on scale)

PI deposited and patterned on top of the PDMS as a protective layer for the RI-etching

RI-etching through the silicon wafer, to obtain separate capacitor plates and the foldable crosses

Removal of the protective PI layer and etching of aluminum and chromium, to avoid short circuits

Figure 19. a) The fabrication process used to create a cross-like structure on a mm-scale.
b) Photo of the etched silicon wafer before assembling.
c) The assembling procedure of the accelerometer using polyimide joints.
d) Topview showing the capacitive read-out. The soft PDMS acting as springs/dampers for the accelerometer structure.

(From [130], published with permission from Joost C. Lötters, Courtesy Dr. W. Olthuis, Univ. of Twente).
In 1995, a new reshaping technique using Joule heating to obtain (thermal) plastic deformation was presented for permanent 3-D polysilicon structures [132]. Figure 20 a)-b) illustrates the experimental procedure for the 3-D structure realization. To obtain self-assembling 3-D structures without the drawback of using external micro manipulators, a technique using an integrated scratch drive actuator (SDA) for folding was presented in 1997 [133, 134]. Figure 20 f)-i) shows the principle of the self-assembling process producing permanent 3-D structures using integrated SDA actuation and reshaping technology. Compared to the different mechanisms of an integrated actuator for assembling 3-D structures based on polysilicon hinges, the SDA is probably a more reliable self-assembly method [135]. Self-assembling of surface micromachined structures, primarily made of polysilicon, is still a problem. Hinged polysilicon structures are not being sold in large quantities yet. We can not say with complete certainty that it would be possible to use one of the existing techniques for high-volume low-cost high-yield assembly.

For micro-robotic applications, an inverted SDA has been used to move external objects in micro-conveyance systems [136]. By using arrays with SDA bushes turned upward, the output force could be transmitted to an object placed on top of it. To turn the bushes upwards, a bonding process using a silicon wafer with “standard” SDAs bonded to a glass wafer followed by a “dissolved-wafer” process (silicon ICP-etch) to etch away the bulk silicon wafer, were used.

**Figure 20.** a) An external manipulator is used to fold the structure and supply the structure with a reshaping voltage. The Joule heat raises the temperature of the arm high enough to cause annealing effects resulting in stress release and plastic deformation. b) After removal of the voltage the arm cools down and the structure retains its 3-D shape (from [132]). c) – e) Illustration of the scratch drive principle (SDA) f) – i) Illustration of a 3-D self-assembled polysilicon structure based on scratch drive actuators (SDA) [134]. Moving the polysilicon structure out-of-plane by scratching with the bushes. Joule heating results in plastic deformation and permanent 3-D structures.
3.4 3-D structures based on external forces

In the previous section, out-of-plane rotation of 3-D microstructures was obtained by manually assembly using probe needles or integrated, large area consuming actuators. However, it is also possible to achieve the erection of the structure in an automated way by applying an active external force on the structure instead of using the residual stress difference between two thin films or the mechanical manipulators. Thereby, more compact chips could be obtained. Electrostatic [125, 126], magnetic [137, 138], or pneumatic [139, 140] forces can be used to repel or attract the freestanding structure so that they bend out of the wafer plane. Figure 21 illustrates the external force principle using a permanent magnet to achieve out-of-plane motion and polysilicon beams as hinges.

Since the force is applied externally, this technique seems difficult to integrate in asynchronously driven arrays. However, micro-conveyers based on external magnetic actuation for locomotive tasks have been demonstrated. For externally powered actuators it is difficult to control each individual actuator in a large array of folded structures. Therefore, a synchronous jumping mode is used to convey the objects [137]. This jumping mode involves quick actuation of all the actuators simultaneously, which forces the object to jump. When the object lands on the actuators (located in their in off position), the object has moved a small distance and the actuators can be actuated again to convey the object further. In fluid dynamics applications, these magnetically actuated out-of-plane 3-D structures have been integrated with flow sensors for actively reducing skin-friction drag in turbulent flows [13], see Figure 2. Electromagnetic actuated structures using another hinge mechanism (serpentine springs instead of the beam-hinges) has been used for out-of-plane optical modulators and holographic data storage [141]. The polyimide joint described in section 3.3.3 has also been used for micro-optical mirror applications using external electrostatic forces [126].

Figure 2 b) showed surface micromachined magnetic actuators (magnetic flaps) for Active Fluid Control [15]. These surface micromachined 3-D actuators are fragile and not robust in most flow fields, therefore, a bulk flap actuator has been used, as well as other more robust actuators, i.e. pneumatic balloon actuators [139].

![Figure 21. 3-D structures obtained by applying external magnetic forces [137].](image-url)
Figure 22. a) Controlled folding of 3-D structures using an external magnetic field, \(B\), and current, \(i\), controlled resistance network to generate a Lorentz fold force. b) By changing the direction of the magnetic field, \(B\), and by proper design of the structure (i.e. resistance of the structure legs) complex structures such as boxes can be assembled simply by controlling the current in each structure (i.e resistance net). Permanently folded structures are obtained by deforming the polysilicon hinges beyond the yield point and thereby producing suitable plastic deformation [138].

A more controllable method for out-of-plane folded microstructures using external magnetic fields were reported in 1998 [138]. By the use of the Lorentz forces and a controlled currents (i.e a resistance net) more controlled erection was obtained, as illustrated in Figure 22. The hinge consists of a thin polysilicon layer ranging from 0.2 to 0.6 µm in thickness and the structure is made of electroplated copper. By deforming the hinge beyond the yield point, a plastic deformation occurs and the permanently fixed complex structures can be obtained. By controlling the direction of the magnetic field, \(B\), and the current, \(i\), passing through the structure, assembling of miniaturized boxes is easily realized (compare the boxes structure for 3-D sensors in Figure 19).

An attractive complement to the electrostatic and magnetic external force actuators is the use of pneumatic actuation for out-of-plane deflection of micro-structures. If one external pneumatic source is used it is quite easy to make array configurations where each actuator in the array is (electrically) controlled by micromachined valve(s) which open and close different flow channels on the chip [142]. With electrically controlled valves the power consumption of the whole system may be low since a closed fluid system with low leakage could be obtained, with actuators having large displacement and high force capability. Figure 23 illustrates the principle of a pneumatic balloon actuator (PBA) for out-of-plane rotation [140]. A macroscale prototype (16x16 mm²) was used for characterization of the
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However, miniaturization using batch micro-fabrication techniques is possible using liquid to gas phase transformation by Joule heating instead of external pressure support. With a small array (4x4) of PBAs a conveyance system was used to demonstrate the possibilities in micro-robotic applications using pneumatic out-of-plane actuators. Other micro-robotic (micro-conveyers) devices based on pneumatic actuation have been published [65, 143, 144]. The pneumatic actuation principle is also attractive in biomedical micro-robotics application (cell sorting etc.). The use of thermal, magnetic or electric micro-gripper actuation could easily kill or destroy the biological and living sample. The pneumatic micro-gripper presented by C-J Kim et al. [145] avoids such problems. In fluid dynamics, impressive results on active control of flying vehicles using pneumatically actuated micro-balloons have been presented [139].

Figure 23. Principle of a pneumatic balloon actuator (PBA) [140].

- a) Non-pressurized balloon.
- b) Pressurized balloon for out-of-plane deflections.
- c) Cross-section view of the pneumatic actuator consisting of a silicon rubber membrane and a polyimide film. The silicon rubber doesn’t support any bending load and largely expands while the polyimide film with silicon ribs support bends rather than expands.
- d) Photo of the out-of-plane erected structure. The size of the balloons are 16x16 mm².
3.5 3-D structures based on unimorph structures

In section 3.2 different methods using bimorph structures to achieve the out-of-plane rotation were described. It is also possible to use volume changes in just one material (unimorph) combined with clever geometrical designs, as will be described below, for static out-of-plane erection of micro-structures.

3.5.1 Resist, BSPG or solder hinges by surface tension forces

In principle, all of the different techniques described in sections 3.3-3.4 need either external manipulators or integrated push-pull actuators to raise the structures, i.e. serial assembly. To overcome this drawback, a parallel batch self-assembly technique for fabrication of three-dimensional microstructures was presented in 1995 [147]. This technique is based on the surface tension force of molten solder. The main drawback is that non-standard IC-materials (Pb:Sn solder) are used meaning that very accurate process control is required for controlled folding. Further, it seems difficult to achieve more than a few electrical interconnection (i.e Pb:Sn solder) to the out-of-plane rotated structures. To overcome the drawback the material incompatibility when using Pb:Sn solder, a solution using glass (borophosphosilicate, BPSG) as the meltable material was proposed in 1998 [146]. By using glass it was possible to achieve a more controllable assembly, but BPSG requires high temperatures to melt (1100°C) making it impossible to integrate metal interconnections and electronics together with the 3-D structures. Figure 24 shows the preparation of the 3-D structure based on surface tension forces. The structure after the out-of-plane rotation is shown in the photo of Figure 25. In 1999, a third material, resist, was used to create the surface tension forces and act as the hinge material [69]. Compared to the motor driven assembly for other hinged 3-D structures, a very small chip area is required for the batch - parallel self-assembled hinge mechanism when a resist pad and surface tension is used. Further, the resist method has advantages due its simplicity (two masks: one sacrificial and one for the mechanical structure) and low temperature processing allowing for CMOS electronics on-board. However, the electrical interconnection to the folded structure is no longer obtained since resist is an electrical isolator. To avoid instability problems, the melting is performed above the glass transition temperature, and the structure is encapsulated by sputtered aluminum after melting. In this way, resist’s instable nature (i.e. temperature and humidity sensitive)

**Figure 24.** Preparation of 3-D structures with Si mechanical parts (from [146]). Published with permission from prof. Richard Syms.

**Figure 25.** Photo of the 3-D structure based on surface tension forces, published with permission from prof. R. Syms [146].
is partially circumvented. No simple method for obtaining several interconnection wires has been realized yet. The resist hinge may cause problems since surface-micromachine processing (wet sacrificial etching) most often requires freeze drying to avoid sticktion. This kind of fabrication is most often not compatible with resist. Polymers such as BCB, SU-8 or various polyimides may be more suitable for the surface tension hinge technique since these materials have better stability. The polymer material polyimide is long term stable and exhibits high mechanical stability, has excellent hydrolytic stability against water and non-oxidizing acids. It is also thermally stable up to a few hundreds degrees and highly resistant against oxidative degradation in air after curing and imidization since all hydrogen atoms are bonded to atomic rings [148]. Further, the polyimide is a low temperature process (< approx 350°C) and thereby allows CMOS electronics integration in the same way as the resist hinges.

Over the years several technologies and the materials has been reported for self-assembly using the surface tension hinge method. In Table 1 the different versions of the process is described.

When the resist surface tension hinge is used, part of the folded structure can be actuated, which has been demonstrated by electrostatic comb-drives for a micro-mirror scanner device suspended in a permanent folded frame [69, 149]. However, the whole folded structure is difficult to actuate which is required in most micro-robotic applications. The surface tension technique was proposed by Bright et al. [60] as a method of obtaining a self-assembling erection of the thermal actuator leg in their micro-conveyor prototype device, illustrated in Figure 10 b). In this way, they may overcome the drawbacks of time consuming manual assembly.

Table 1. Material combinations for the different surface tension powered self-assembly processes.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Ni metal</td>
<td>Boron-doped Si</td>
<td>Boron-doped Si</td>
<td>Si (SOI)</td>
</tr>
<tr>
<td>Sacrificial</td>
<td>Si substrate (front bulk machining)</td>
<td>Si substrate (front bulk machining)</td>
<td>Si substrate (front bulk machining)</td>
<td>Thermal oxide (surface machining)</td>
</tr>
<tr>
<td>Melttable</td>
<td>Pb-Sn solder</td>
<td>Pb-Sn solder</td>
<td>BSPG</td>
<td>Photoresist</td>
</tr>
</tbody>
</table>

A new method for batch self-assembling using geometrical leverage of V-grooves and controlled thermal shrinkage of polyimide in that groove, has been developed. These polyimide V-groove (PVG) joints were presented for the first time in 1997 [67]. This techniques gives robust out-of-plane structures and has been used both for sensor [150-152] and actuator [153-156] applications. The PVG-joint technique is further described in section 4 and in the appended papers.
3.6 Locking mechanism for out-of-plane folded structures

Several of the techniques described in sections 3.3-3.4 do not result in permanent out-of-plane folded structures and therefore need some kind of locking mechanism to remain fixed out-of-plane. Most techniques for 3-D sensors also use time consuming manual serial-assembling for folding the structures [107, 123, 130]. However, parallel assembling using turbulent air streams or clever agitation in water, etc. have been proposed [107]. This technique seems to give poor accuracy and poor control of the position of the out-of-plane structures. To overcome the drawbacks of manual assembly or the low yield with the agitation technique, serial assembly powered through integrated actuators (i.e. electrostatic comb-drives or thermal actuators to fold the structure into place [106, 116, 119] can be used. The advantage of such an approach is that the assembly is not permanent (i.e. possible to unassembly), however, the actuators require large areas to function properly.

![Diagram of locking mechanism](image)

**Figure 26.** a) Layout of a geometrically controlled mechanical limiter for accurate out-of-plane rotation using photoresist hinge drivers (surface tension forces). b) SEM-photo of a partly assembled 3-D structure. c) Fully rotated structure. d) Detail of the mechanical limiters. (published with permission from prof. Richard Syms [69]). By the use of a surface micromachining process (i.e. two layer polysilicon) instead of the front bulk micromachining more sophisticated self-locking mechanisms are feasible [60].
To obtain permanent out-of-plane folded microstructures, a mechanical limiter or bending stop structure could be used to improve the accuracy of one-time assembly for most of the techniques presented earlier in this chapter. Thereby, it is possible to avoid problems associated with creep caused by, for example, temperature or humidity variations. For some of the out-of-plane techniques a interlocking mechanism is necessary to obtain a permanently folded structure. Syms [69] used an above-substrate limiter for the resist hinge, described in section 3.5. This method, illustrated in Figure 26, is self-assembled and works for special sets of geometries and jam conditions (i.e. a wide range of angular velocities, $\theta$, for the rotation of the different structures). The bending accuracy for an angle of $45^\circ$ was reported to be $\pm 3.75^\circ$. The process yield for the first batch was quite modest ($\approx 20\%$ of the parts were rotated and only $5\%$ rotate through $45^\circ \pm 1^\circ$). However, improved reliability and yield has been obtained by using deep reactive etching and optimization of other steps in the process. Thus, an alignment accuracy of $\pm 4$ minutes of arc and a yield greater than $70\%$ have been obtained [157].

More sophisticated solutions involve other types of locking mechanisms as illustrated in Figure 17 b) and c) and in Figure 27. However, these folded plates and interlocking braces are manually folded into place. Pop-up structures which are locked in place by clever designs in a self-assembly mode were presented recently by Howe et. al. [109].

**Figure 27.** A self-engaged locking mechanism. Notches in the tether lock into a narrow hole in the flip-up plate, locking the plate into position [106].
Polyimide V-groove filled Joints 2

Before going into detail about the polyimide V-groove (PVG) joint technique a short introduction to polyimide processing and typical characteristics of polyimide as a MEMS-material will be presented.

4.1 Background to polyimide processing and polyimide characteristics

Polyimide is commonly used in IC fabrication for isolation purposes, specialty coatings used as a protective and stress relief layer, or "buffer coat" applications before packaging of the chip and therefore most process equipment required for MEMS-polyimide processing already exists. A large amount of different polyimides are commercial available on the market, both with very low thermal expansion coefficients (CTE < 5 ppm/°C) and very high (> 50 ppm/°C). It is fairly easy to combine these different polyimides to form bimorph actuator structures, see Figure 13. Some polyimides are photosensitive which makes them easy to pattern (i.e. using UV-photolithography and solvent developer). They are also compatible with CMOS electronics since they utilize low temperature processes [20, 80, 158]. The polyimide is well suited for micro-joints / hinges due to its flexibility (i.e low Young modulus, 2-3 GPa). Besides various joints / hinges applications both for a static folded 3-D structures and out-of-plane working actuators, polyimide has also been used as a sensing element in several MEMS sensors [159].

A comprehensive overview of the fundamental chemical and physical properties of polyimides is given in [148]. Most polyimides are almost insoluble in common organic solvents and, in general, a soluble polyimide precursor is usually applied. This precursor is converted to the final polyimide by a subsequent thermal (curing) treatment. The heating is performed in an inert gas (in our case N2) and / or vacuum. Both types of curing have been tested in this work. As the imidization (i.e. crosslinking between the molecules in the polymer chain) proceeds, molecular rigidity and consequently the glass transition temperature increases. When the glass transition point, \( T_g \) (the definition of \( T_g \) is given by Kittel [160]) of the polymer reach the reaction temperature the imidization slows down. The curing process results in weight and thickness loss (i.e. shrinkage) of the polyimide caused by outgassing of the solvents in the polyimide as well as the crosslinking between the hydrocarbon molecules (imidization). For IC applications a low shrinkage is most often desirable since large shrinkage creates mechanical stresses. Most of the modern polyimides have a thickness shrinkage less than 30% between uncured and fully cured polyimide and a coefficient of thermal expansion, CTE less than 30-40 ppm/°C. Even though the shrinkage can be large the line width is remained (i.e. only thickness reduction) as illustrated in the two top graphs in Figure 28.

In this work, as well as for many MEMS applications, a polyimide with large thermal shrinkage is desirable for obtaining small radius joints for out-of-plane rotated microstructures. To obtain large dynamic movements for actuator applications a polyimide with a high CTE is also preferred. The polyimide that was used by Stemme and Kälvesten [22] in previous works in earlier stage of this project seemed to be the most suitable and was used for the new polyimide joint project.

---

2 To distinguish the polyimide V-groove joint technique from those presented in section 3.3.3, the abbreviation PVG (polyimide V-groove )-joints is introduced. When not specific expressed one should be able, from the content, to understand if the discussion refers to polyimide joints in general (including both those in section 3.3.3 and the PVG-joint) or the PVG-joint specifically.
The polyimide, is from Ohlin-Ciga-Gaily (OCG), Belgium and is called “Probimide® HTR-3-200” (formally called “Selectilux® HTR-3” when sold by Merck during the late 80’s) has been used. The "200" in “HTR-3 200” means the thickness (viscosity) of the polyimide. The “200” version of the polyimide results in about 20 µm thick layers on flat wafers (dependent on the spinning speed). Measured thickness shrinkage of the “HTR-3 200” polyimide on a flat wafer for curing temperatures up to 450-460°C resulted in values as high as 60% relative to the polyimide thickness when annealed (soft-baked) at 150°C. Another reason that the HTR-3 polyimide was chosen was because of the "easy" patterning procedure since the polyimide is photosensitive. Since 1999, the HTR-3 polyimide is sold by Arch Chemical Inc, Norwalk, Connecticut, USA [161] and the Probimide® tradename (Registered of Ciga Specialty Chemicals) has been changed to Durimide®.

4.2 Principle for the Polyimide V-groove (PVG) joint technique

The main disadvantage with all the different polyimide joint techniques described in section 3.3.3 is the poor control of the out-of-plane folding when manual folding is used. A new polyimide micro-joint technique for self-assembly has therefore been developed. The basic principle for this new polyimide joint is shown in Figure 28. The new polyimide micro-joint technique is used to create a

Figure 28. Illustration of two different polyimide shrinkage configurations.

Top: The polyimide shrinks (thickness reduction) during curing, the lateral dimension remains.

Bottom: Principle of the polyimide V-groove (PVG) joint. The curing causes the polyimide in the V-groove to shrink and for a freestanding structure the main shrinkage is in the horizontal direction and only a small thickness reduction occur. The absolute lateral contraction length of the polyimide is larger at the top of the V-groove than at the bottom ($\varepsilon \cdot a > \varepsilon \cdot b$) resulting in a rotation which bends the free standing structure out of the wafer plane. $\varepsilon$ is the relative shrinkage coefficient of the polyimide, defined by eq. (1).
well controlled out-of-plane rotation resulting in robust single crystal silicon (SCS) folded structures with possibility for detailed features in all three dimensions which is required to be able to realize a 3-D flow sensor (c.f. the specifications in section 2.3) The polyimide in the V-grooves shrinks when the polyimide is cured. The absolute contraction length of the polyimide is larger at the top of the V-groove than at the bottom \( (\varepsilon \cdot a > \varepsilon \cdot b) \) which results in a rotation that bends a free standing structure out of the wafer plane. The relative shrinkage, \( \varepsilon \), is defined as:

\[
\varepsilon = \frac{\Delta l}{l} = \frac{l_{uncured} - l_{cured}}{l_{uncured}}
\]

where \( l \) is the characteristic length in the shrinking direction. Depending on where the polyimide is applied, the main shrinkage can be either in the lateral direction (e.g. for the polyimide filled V-grooves) or in the vertical direction (thickness reduction) if the polyimide is applied to a flat wafer.

Large bending angles can be obtained by connecting several V-grooves in series. Figure 29 shows a schematic view of a PVG joint with three V-grooves. The PVG joint can operate in both a static and a dynamic mode. The static irreversible (one-time / non-reversible) bending angle is obtained

![Figure 29. Schematic view of a 3-D structure based on a PVG joint with three V-grooves. The metal lead wires through the V-grooves are used to realize electrical connections to the out-of-plane rotated structure. Using thermal expansion of the polyimide the metal can also be used as a heater in the V-grooves to obtain dynamic movements of the silicon plate.](image)
during the imidization (thermal curing) process when crosslinking between the hydrocarbon molecules occurs and various solvents in the polyimide are outgassed, which results in a reduction of the polyimide volume. The shrinkage is dependent on the curing temperature which makes it possible to control the permanent static bending angle very well.

Assuming that the relative shrinkage, $\varepsilon$, is uniform throughout the V-groove, and neglecting possible shrinkage effects in the vertical direction, an expression for the bending angle dependent only on the geometrical angles in the V-groove can be written. For an angle of $54.74^\circ$ between the $\{100\}$ and $\{111\}$-planes, resulting from KOH-etching of $\{100\}$-silicon, the bending angle is:

$$\alpha = 2 \cdot N \cdot \left[90^\circ - 54.74^\circ - \arcsin(\cos(54.74^\circ) \cdot (1 - \varepsilon))\right]$$

where $\alpha$ is the out-of-the-plane bending angle, $N$ the number of V-grooves used in the joint and $\varepsilon$ the relative shrinkage of the polyimide. Since the bending angle of the structure is independent of the thickness of the silicon, the thickness can be chosen to fit the purpose of the design. A thicker structure requires a deeper and wider V-groove at the top, which will result in a larger bending radius. For 30 $\mu$m thick structures the corresponding radii of curvature is about 60 $\mu$m. By scaling the V-grooves and the silicon beam thickness bending radii similar to those achieved by the surface micromachining technique using the surface tension forces techniques [69] are possible.

The dynamic and reversible bending angle is a result of the thermal expansion of the cured polyimide. The heating is obtained by integrated heaters (resistors). Two different versions of heaters have been used: i) serpentine metal heater as illustrated in Figure 29 or ii) polysilicon heaters, as illustrated in Figure 30. These resistive heaters are used to produce local power dissipation in the joint. The temperature increase results in expansion of the polyimide and a dynamic change of the bending angle. The dynamic bending is suitable for actuator applications as well as for trimming the static bending angle to compensate for undesired process variations in the bending angle.

The temperature increase and the resulting polyimide expansion gives a dynamic change of the bending angle:

$$\alpha = 2 \cdot N \cdot \left[90^\circ - 54.74^\circ - \arcsin\left(\cos(54.74^\circ) \cdot (1 - \varepsilon + \alpha_T \cdot \Delta T)\right)\right]$$

This expression is the same as that for the static bending angle (except that the thermal expansion, $\alpha_T \cdot \Delta T$, is now included), where $\alpha_T$ is the thermal expansion coefficient of polyimide, $\Delta T$ is the temperature increase caused by the heating, $\alpha$ is the out-of-the-plane bending angle, $N$ the number of V-grooves used in the joint and $\varepsilon$ the relative shrinkage of the polyimide during curing.

A detailed description of the processing of the test structures is found in paper 1 and 2 and in section 4.3. The more advanced PVG joint process used for the fabrication of the 3-D flow sensor is described in detail in paper 3.
Figure 30. Schematic view of a 3-D test structure based on a PVG joint with four V-grooves and a topview of the interconnection scheme of the heating resistors. Using thermal expansion of the polyimide in the V-grooves, a dynamic movement of the out-of-plane rotated structure can be realized. The metal in the V-grooves is used to connect the polysilicon heaters as shown in the topview. The metal lead wires through the V-grooves are also used as heat conductors for transporting away the heat from the joint to the silicon substrate (heat sink). By the parallel configuration of the polysilicon heaters a redundancy for failure is achieved.

4.3 Fabrication of PVG joints

During the evolution of the different devices reported in this thesis several different versions of the fabrication process have been tested, see papers 1-6 for a full description. Here is one of the basic processes described, which is used to fabricate 3-D test structures for the evaluation of the dynamic features of the PVG joints. It is based on a double-sided bulk micromachining process and polysilicon resistors (heaters). An overview of this basic fabrication process is described in four sections below. The sections relate to Figure 31 where the fabrication process for the polysilicon integrated heater based test structure is schematically shown.

(a) The process is based on a 10 cm 500 µm thick SOI-wafer with a top layer of 30 µm mono-crystalline silicon with an underlying 1.5 µm oxide layer. First, the heaters are formed using LPCVD deposited polysilicon. The polysilicon is then doped with boron. To protect the polysilicon during KOH-etching the structures are encapsulated using low stress LPCVD-deposited silicon nitride (Si$_x$N$_y$). The 30µm deep and 70µm wide V-grooves are etched in KOH using the buried silicon oxide as an etch stop. To obtain nice convex corners several different corner compensations techniques have been used [162].

(b) Silicon oxide is grown locally in the V-grooves (LOCOS) to insulate the metal conductors from the silicon. The nitride around the polysilicon resistors prevents any oxidation of the heaters. Aluminum is sputtered (1.5 µm) on to the wafer and contacted to the polysilicon via contact holes in the silicon nitride. The aluminum lead wires through the bottom of the V-grooves are patterned to connect the polysilicon heaters to each other using a two layer resist deposition process.

(c) The polyimide (HTR-3 200 from OCG) is spun on to the wafer and patterned using standard lithographic techniques to create the polyimide joint in the V-grooves. The polyimide is then soft baked at 150°C. The back side of the wafer is patterned using a double-sided mask aligner. To protect the structures on the front side, this side is covered using black wax and a protecting (111) silicon wafer during the 500µm back side KOH-etch. The buried oxide acts as etch-stop.

(d) The buried oxide (etch stop) layer is etched in a BHF solution to release the structures. The black wax is then dissolved to release the moving legs from the protecting wafer and they are then cleaned using acetone-propanol. The polyimide is then cured in a N$_2$ atmosphere at 250°C to 450°C depending on desired bending angle, to bend the structures out of the wafer plane. The test structures can then be evaluated using a probe station to supply the integrated heaters with power.

![Figure 31. Schematic of the fabrication process for the test structures with polysilicon heaters for dynamic evaluation. Note that the scales are distorted.](image-url)
Variations of this process has been used to fabricate the different structures and devices reported in this thesis. The description of the different processes are presented in the appended papers included in the thesis.

By using the fabrication technique described above combined with standard surface and front bulk micromachining fabrication techniques, various sensors (i.e. for flow, pressure, force and acceleration measurements) in the out-of-plane rotated bulk structure (SCS) can be fabricated. Several detector principles including polysilicon (piezo)-resistive detection, piezoelectric or capacitive “comb-drive” principle can be used. This combined process technique also enables sensor-actuator integration to measure the exerted force on the folded structure. This kind of tactile sensing is useful in micro-robotics, for example, to detect the location of an object placed on a micro-conveyer consisting of a large array of out-of-plane folded legs which can be actuated individually depending on the signal from the force sensors, see chapters 7 and 8. 3D sensors may also take advantage of micro scale folded boxes where the walls act as electrodes for detection, compare the 3-D accelerometer, shown in Figure 19.

4.4 PVG joint characterization

Different test structures were fabricated to evaluate the behavior of the PVG joint. The test structure consists of a 600x500x30µm³ silicon plate rotated out of the wafer plane using the PVG joint. PVG joints with different numbers of 70 µm wide and 30 µm deep V-grooves were studied. The number of V-grooves in each joint varied from one to seven and the bending radii of the PVG joint vary between 50 and 65 µm with different numbers of V-grooves. For testing the dynamic behavior both serpentine metal heaters and polysilicon heaters were used. The metal interconnection to the 3-D structures were used to study the effect on low resistance connections to folded structures. To characterize the behavior of the PVG joint both statically and dynamically an optical measurement set-up was used, illustrated in Figure 32.

![Measurement set-up for the bending angle. Both static and dynamic angles are measurable. Note that the scales are distorted.](http://www.s3.kth.se/instlab/research/dissertations/thorbjornedoc.html)
4.4.1 Static measurements

The static bending angles were measured with an optical system consisting of a visible laser light aligned parallel to the test structure, as illustrated in Figure 32. The reflected laser beam from the test structure was measured and the bending angle was calculated for different structures and different curing temperatures. The angle, $\theta$, between the incoming laser beam and the beam reflected from the silicon plate can be determined using simple trigonometry. The angle was measured to an accuracy better than 1° or 0.1° depending on the configuration of the used measurement set-up. A strong correlation between the polyimide shrinkage, measured on flat wafers according to the top illustration in Figure 28, and the bending angle was measured. The bending angle ranged from $0^\circ$ to $200^\circ$ depending on the curing temperature and the number of V-grooves in the joint with an average static bending angle of $31^\circ$ per V-groove for a polyimide curing temperature of 400°C (fully cured polyimide). This is in good agreement with the simple theory described by eq. (2) and further described in paper 1. However, it is important that the major part of the polyimide volume is located inside the V-grooves as in Figure 28. In a scaling test, where a 8 µm thick structures with a top V-groove opening of 30 µm was used, it was observed that the location of the polyimide volume is of great importance to achieve well controlled bending. With the down-scaled test structure the polyimide process was not optimized meaning that the polyimide thickness above the V-groove was larger than the actual polyimide within the V-grooves and therefore contributed to the bending in a way similar to the surface tension force technique described in section 3.5.1. Polyimide should be suitable material also for the surface tension technology. However, the in our tests the polyimide volume was not optimized to give controlled out-of-plane bending of the test structure. To use the surface tension forces a correct relation between volume, area, and thickness of the melted hinge material has to be fulfilled to achieve accurate bending. Further, the surface tension force technology should (can) not be used for bending angles above $90^\circ$ with a single hinge [157]. For the 8 µm thick PVG-joint test structure the relation ship of the thickness vs. volume was not fulfilled and therefore a poor bending accuracy of the folded structure occurred.

Force measurements showed that the polyimide in the PVG-joint can withstand large forces (up to 50-100 mN) before it deforms plastically (or breaks by bad adhesion). The out-of-plane erected structures can be forced almost down to original in-plane position (hundreds of micrometer deflection) without plastic deformation of the polyimide occur, although there is a risk that the metal interconnection wires breaks. For reliable electrical interconnections the structures should not be forced to bend more than 30-40° after the structure has been erected. Measurement on the resistance of the serpentine metal wires, illustrated in Figure 29, showed that the change of the interconnecting wire resistance (aluminum wires at the bottom of the V-grooves) to the out-of-plane erected structures was less than 1 Ω after the structure has been assembled. Typically the over all resistance of the serpentine metal wire (bonding pad to bonding pad) was 8 Ω.

4.4.1.1 Self-assembled folding for PVG-joints - accuracy and interlocking fixtures

As already pointed out, the PVG joint technique is self-assembled and the out-of-plane rotated structure remains in that position by itself. In the first test structure measurements the control of the position of the erected structures was not as good as expected. Bending angle variations up to $20^\circ$ between structures from different wafers were measured using the laser system shown in Figure 32. Therefore, a bending limiter mechanism similar to the techniques presented in section 3.6 was developed for the PVG joint technique to meet the specifications given in section 2.3. In later
versions of the process, much better control of the variation of the static bending angle between different structures have been obtained. With three to five V-grooves in the joint the variations after curing are within ±1.5° per V-groove over a whole wafer and less than ±3° from wafer to wafer. In the last batch of PVG joint structures the total uncertainty for the bending angle for a 90° out-of-plane erected structure with 3 V-grooves are less than ±1° without any interlocking mechanisms. This could be compared to the value of ±3.75° using an interlocking mechanism for the resist based surface tension hinges [69].

By the good control in the out-of-plane rotation obtained with PVG joints it is not necessary to use interlocking fixture to meet the requirements on the position accuracy for the out-of-plane erected structure (see section 2.3). Neither is a locking mechanism needed to keep the erected structure in place, but to improve the bending angle control of the structure an interlocking fixture can be used. In the experiments a single bending stop structures was fabricated and tested but a complete fixture has been proposed as shown in Figure 33. The advantage of this approach over the ones that were described in, for example, Figure 17 and Figure 27 is that the PVG joint interlocking fixture relies on batch-parallel self-assembled rather than serial or manual assembling. Further advantages using the locking approach is that the mechanical stability of the PVG joint increases and that it allows for a noncritical curing temperature for obtaining 90° bending. Using a bending stop structure allows for an increased curing temperature resulting in a pre-stressed PVG joint, which will not bend back due to polyimide creeping caused by, for example, humidity or temperature influences on the polyimide. However, it is worth mentioning that during all the PVG joints experiments that have been performed over the last three and a half years no tendencies for such creep have been observed. Assembled PVG-joint structures have been stored for more than a year under controlled climate conditions (approximately 40% relatively humidity) without any changes in the bending angles.

Figure 33. The principle for self-assembled interlocking braces based on PVG joints. A second stop-structure with five or six V-grooves with a bending angle, α₂=180°, stops the bending of the sensor structure with four V-grooves at a bending angle close to 90°. A third lock-structure with three V-grooves and a bending angle, α₃>90°, completes the interlocking arrangement.

Similar to the lock mechanism described in Figure 26, the PVG joint bending stop structure (i.e. the configuration shown in Figure 33 but without the third locking structure) is sensitive to dimensional errors. The experimentally measured accuracy of this method is typically in the range of ±1-3° and is good enough for 3-D flow sensor applications. One critical feature for achieving good control of the folding using the bending-stop structure shown in Figure 33 is that any remaining oxide or nitride at the edge of the V-grooves before the curing and out-of-plane erection must be removed (i.e. the nitride corner-compensations). So far, these corner-compensation structures has been
released manually in a probe station and rinsed away in DI water. This is a time and cost intensive task and should be avoided. One may use a dry (DRIE) etch to form the structure and thus avoid the corner compensations followed by a wet (or a partly isotropic dry) etch to form the V-grooves.

The better control of the bending obtained through out the process development of the PVG-joint technique in the latest fabricated batches would allow for another solution without the locking mechanism. Parallel-batch assembly of all structure on a wafer to an angle close to 90° is performed in the polyimide curing oven and then each structure could be adjusted into the correct position by using the integrated heater or heating on a hot-plate. In this ways very good accuracy could be obtained without any locking mechanism.

Most often parallel (batch) assembly of the interlocking fixture is the most favorable approach because it is fast. This is the normal function of the PVG joint. Most other techniques for 3-D sensors use time consuming manual serial-assembling, i.e. the 3-D accelerometer sensor shown in Figure 19 and the two test structures of hot-wires by Pister, Figure 17. But, as pointed out in section 3.3, serial self assembly is feasible with integrated micro-actuators. The advantage of using such an approach is that the assembly is not static (i.e. possible to un-assemble) but the actuators require a large area to function properly. For the turbulent triple hot-wire application these, actuators would probably also disturb the flow around the sensor body too much when used to erect out-of-plane standing hot-wires making it difficult to design compact probes.

Using the PVG joint technique to create interlocking fixtures, as the one shown in Figure 33, the design is limited to a certain range and set of configurations which are determined by the order that the structures could be folded into place. This is in agreement with other parallel assembled interlocking mechanisms [69]. However, a one-time serial self-assembling approach using PVG joints has also been experimentally verified using integrated polysilicon heaters inside the joint for local curing of the polyimide. Using this approach, an almost complete freedom to fold the different structures in any order is obtained. The two structures for stop respective locking, shown in Figure 33, could then be replaced with just one structure with a small slot for alignment. That configuration allows for smaller tolerances but to the price of long assembly times. Compared to the assembly times needed to melt the resist in the surface tension hinge technique (a few hours for 130°C and 5 minutes for 150°C), the time needed to cure the polyimide filled V-grooves are longer, typically more than 5 hours. However, the operating temperature of the PVG-joint could be as high as the curing temperature (most often 350-450°C) which is a great advantage compared with the resist hinge where the operating temperature is limited to 130°C. For serial PVG-joint assembly (i.e use of integrated heaters) it is favorable to use the polysilicon integrated heaters rather than the serpentine heaters since one has more local heating in the joint. The serpentine metal heaters, illustrated in Figure 29, have not been tested since it is believed that this method would give cross-talk to the joints close to the heated one since the entire chip is heated.
4.4.2 Dynamic measurements

The dynamic behavior of the PVG joint was studied using a minor modification of the laser system set-up. By the use of photodiodes for detecting the reflected laser beam from the dynamically actuated test structures, see Figure 32, the response time of the PVG-joint could be measured\(^3\). Dynamic bending angles larger than 5° per V-groove have been measured for power supplies around 375 mW for the metal serpentine heaters and 200 mW for the polysilicon heaters. For the 500 µm long structure this corresponds to stokes up to 175 µm. The cut-off frequency for the thermally excited structure was in the range of 1-10 Hz which corresponds well with the measured response times between 100 and 200 ms. No differences in response time between the serpentine metal heater and the polysilicon heater configurations were observed. The size of the polymide volume to heat and cool down is more important than the way the heating is performed. PVG joints with fewer V-grooves, equivalent to smaller thermal mass to heat and cool, respond faster than corresponding ones with more V-grooves. Full details of the dynamic characteristics for the serpentine metal heater configuration are given in paper 2. Characteristics of the test structures based on polysilicon integrated heaters are partially described in paper 5.

4.4.2.1 Simulation models

In paper 2 a model (simplified lumped heat capacity model) for simulating the dynamic behavior of the PVG joint with serpentine metal heaters is described \([163]\). The degree of thermal isolation determines how fast the heating and cooling occurs. Polyimide is an effective thermal isolator. The cut-off frequency is determined by the thermal mass, \(C_{\text{th}}\), and the thermal resistance, \(R_{\text{th}}\) of the PVG joint, which can be calculated from the discrete electrical components in the network by the lumped heat capacity electrical analogue model. PVG joint actuators with three V-grooves result in higher cut-off frequencies as compared to a four V-grooves joint, due to the smaller polyimide volume, but also have smaller stroke lengths, \(\Delta x\). To obtain fast cooling of the PVG joint the metal interconnections to the polysilicon heaters also are used as heat conductors, as illustrated in Figure 30. With wide metal wires in the bottom of the V-grooves a good thermal conductance to the silicon substrate (heat sink) and therefore fast cooling is achieved but to the price of higher power consumption during heating. This metal strip is also used to obtain redundancy for the polysilicon heater configuration. Each heating resistor is divided into separate parts connected by the short-circuiting metal strip, which allows for functional heating even if some part of the resistors (or the via contacts between the resistor and the metal) is not working. Further, a better distribution of the supplied power over the different polyimide filled V-grooves are obtained by such a parallel configuration. For the serpentine metal heater configuration, shown in Figure 29, most of the power dissipation is obtained in the outer most V-groove due to the thermal insulation of the polyimide in the inner polyimide filled V-grooves. Further experiments and simulations are needed to obtain an optimal design regarding the speed and force generation capability as well as the power consumption of the PVG joint actuator. By using the polysilicon heater configuration instead of the serpentine metal heaters, a reduction of the power consumption by a factor of two was obtained for the same generated strokes and forces. Further improvements on the design of the heaters is feasible. To improve the simulation model for more accurate design optimization a 2-D FEM-model has been used to simulate the polysilicon heater based PVG-joint. Preliminary results on the temperature

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\(^3\) [M]: Videos showing the used measurement set-up and the dynamic behaviour for the PVG joint are available at: [http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html](http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html)
distribution and the response time is shown in Figure 34. Further simulation on design optimization schemes is possible using the coupled multi-physic capability (thermo-electro-mechanical simulation) of the FEM program.

4.4.2.2 Failure mechanisms and lifetimes of PVG-joint actuators

The failure mechanism related to the PVG joint working as an actuator is described in paper 5. Besides the failure caused by thermal means, the structures could also fail due to mechanical reasons (creep or fatigue). It has been demonstrated that the structures could be exposed to high forces and very large displacements before the polyimide deforms plastically. Even though the structure in some lucky cases can be bent almost 90 degrees without any plastic deformation in the or losing the electrical connection, dynamic bending angles over 30-40° should be avoided after the structure has been erected (bending angles 0° to 200°) in order not to break the metal interconnection wires in the bottom of the V-grooves.

With the intention of degrade the PVG joint performance by fatigue, four actuators were run for five weeks while cyclically heating at various frequencies. All four actuators used in the fatigue test worked unaltered after more than $2 \times 10^8$ million load cycles (250 hours at 250 Hz), when the test was stopped. So far, none of the tested PVG joint actuators have ever lost their performance due to fatigue. Further details about the testing of the failure mechanism and lifetime of the actuator are presented in paper 5.

Figure 34. The steady-state temperature distribution within the PVG joint using a heating power of 160 mW simulated using the FEMLAB software package from Comsol [164]. To simplify the simulation geometries for the model the structure is drawn in-plane rather than out-of-plane rotated, but the dimensions of the V-grooves are the same as after the polyimide curing. The mesh size is so small that it is not shown in the figure. The structure bends downwards when heated. The maximum temperature in the joint is 179°C (red or dark gray at the outer most heater in the V-grooves) at steady-state resulting in a tip displacement of 110 µm and the minimum temperature (blue or dark gray) at the left corresponds to 33.7°C. (Courtesy: Per-Olof Persson, Comsol)

[M]: A video showing the timed solutions of the FEM-model (i.e. the dynamic behavior for the PVG joint) is available at: [http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html](http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html).
In other work using polyimide actuators, an encapsulation layer (e.g. silicon nitride) around the metal heater and interconnection wires was used as a precautionary measure to prevent corrosion of the metal that might occur due to the moisture permeability of polyimide [80]. For our applications we have not seen anything that indicates that normal moisture affects the performance of the devices even though the metal wires are in direct contact with the polyimide. For the polyimide V-groove joint actuator most of the power dissipation is obtained in the polysilicon heating resistors, which are encapsulated with low-stress silicon nitride.

As pointed out by Kovacs [165] it is favorable to have thin metal structures for long lifetime actuators. For thin metal layers (i.e. aluminum) no particular grain structure is dominating. Thereby, micro-scale thin film metal mechanical structures have much longer lifetime than normal macro-scale structures using the same material. This is used, for example, Texas Instrument Digital Mirror Device (DMD), where no gross failures have been observed after one trillion operations [44]. For the PVG joint actuators no indication that the resistivity or other electrical properties of the metal or the polysilicon heaters are affected by long term use has been seen. However, compared to the test of the aluminum hinges in the digital mirror devices by TI the number of load cycles in the PVG joint fatigue test were quite moderate. By using a small amount of copper and silicon in the sputter deposited aluminum layer, the metal diffusion processes into the polysilicon heaters are limited which improved the stability of the polysilicon heaters and also enhance the electromigration lifetime of the metal interconnections.

4.4.2.3 External work, energy density and power consumption for PVG actuators

For most micro-robotic application, at least locomotive micro-robots, the most critical parameter is the work generated by the actuator and the power consumption required to achieve locomotion of the robot. Several authors have discussed the scaling performance for different micro-actuators and commented on their applicability for locomotive micro-robots from an energy perspective [17, 95, 166-168]. As stated by Fearing [17] the most important features for a micro-robot actuator is long strokes, and high force at reasonable speeds. To obtain autonomous micro-robots the energy density and/or power consumption for the actuator is also of great importance.

The best way to evaluate the output work from the PVG actuator is by direct force-displacement measurements. However, the miniaturized system used to measuring the robustness of the PVG joint structure (i.e. the plastic deformation measurements described in paper 1) did not allow such direct measurements of the generated force. Instead, rough calculations on both the output work and the energy density of the PVG joint actuator (the polysilicon heater version) was obtained by measuring the lifting capability of any array of out-of-plane rotated structures. This approach has been used in several other actuator investigations, for example Smela et al. for the EAP-actuators [90] and Fujita et al. for SDAs [169], to calculate the efficiency of different actuators.

The results obtained for an array of PVG joint actuators (i.e. the conveyer configuration) are presented in paper 5. There we conclude that even though the power consumption is relatively high meaning a relatively poor efficiency, the thermal principle may still be better than most other actuation principles for micro-robotic applications. The PVG joint actuators gives large strokes, generate large forces and can be driven at a reasonably high frequency. Compared to other more power efficient principles, for example electrostatic and piezoelectric actuation which have been extensively investigated by Fearing [17], the PVG joint actuators has a great advantage due to its high output work (stoke x force). Typical energy densities and power consumption’s for a small selection of micro-scale actuators are given in Table 2. Electrostatic actuation both in linear (i.e. comb-drive) and
rotational (i.e. wobbler-motors) configurations usually are very power efficient but the stroke lengths and forces that can be generated are very limited. The high power density is obtained mainly because of the high speed of operation (kHz-range and above). But speed is not the critical parameter in most micro-robotic application and, therefore, complex solutions using chip (area) consuming gears to decrease the speed and increase the force/displacement are needed. The three thermal techniques described in the table show high power densities mainly caused by the high force generation capability. On the other hand, the thermal principle rely on high powers and are therefore less efficient. As stated by Fearing [17], actuators having reasonable speed, long strokes, and high force are best suited for micro-robotics applications. The PVG joint actuator meets these criteria quite well. However, the high power consumption of the PVG joint could probably be reduced by design optimization. The FEM-simulations that was described in section 4.4.2.1 is intended to be used for such optimization.

**Table 2.** Comparison of a small selection of micro-actuators (for micro-robotic applications). Partially copied from the different tables of electrostatic and magnetic actuators in [17] and Table 1 in [156].

<table>
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<tr>
<td>Linear electrostatic</td>
<td>400</td>
<td>5000</td>
<td>10⁻⁷</td>
<td>6x10⁻⁶</td>
<td>200</td>
<td>NA</td>
<td>C-J Kim et al. [50]</td>
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</tr>
<tr>
<td>Rotational electrostatic</td>
<td>π/4 x 0.5² x 3</td>
<td>40</td>
<td>-----</td>
<td>2x10⁻⁷</td>
<td>-----</td>
<td>900</td>
<td>NA</td>
<td>Nakamura et al. [170]</td>
</tr>
<tr>
<td>Rotational piezo electric</td>
<td>π/4 x 1.5² x 0.5</td>
<td>30</td>
<td>-----</td>
<td>2x10⁻¹¹</td>
<td>-----</td>
<td>0.7</td>
<td>NA</td>
<td>Udayakumar et al. [171]</td>
</tr>
<tr>
<td>Rotational piezo electric</td>
<td>π/4 x 4.5² x 4.5</td>
<td>1.1</td>
<td>-----</td>
<td>3.75x10⁻³</td>
<td>-----</td>
<td>90 x 10⁷</td>
<td>2.5 % efficiency</td>
<td>Johansson et al. [172, 173]</td>
</tr>
<tr>
<td>Linear magnetic</td>
<td>0.4 x 0.4 x 0.5</td>
<td>1000</td>
<td>2.9 x 10⁻⁶</td>
<td>10⁴</td>
<td>3000</td>
<td>NA</td>
<td>Ho et al. [174]</td>
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<tr>
<td>Scratch drive actuator, SDA</td>
<td>0.07 x 0.05 x 0.5</td>
<td>50</td>
<td>6 x 10⁻⁶</td>
<td>160 x 10⁻⁴</td>
<td>300</td>
<td>NA</td>
<td>Akiyama &amp; Fujita [169]</td>
<td></td>
</tr>
<tr>
<td>Rotational magnetic</td>
<td>2 x 3.7 x 0.5</td>
<td>150</td>
<td>-----</td>
<td>3 x 10⁻⁷</td>
<td>---</td>
<td>0.002 % efficiency</td>
<td>Teshigaraha et al. [175]</td>
<td></td>
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<tr>
<td>Rotational magnetic</td>
<td>10 x 2.5 x ??</td>
<td>20</td>
<td>-----</td>
<td>350 x10⁴</td>
<td>-----</td>
<td>3 x 10⁵</td>
<td>8 % efficiency</td>
<td>Dario et al. [176]</td>
</tr>
<tr>
<td>EAP (Ppy-Au bimorph)</td>
<td>1.91 x 0.04 x 0.00008</td>
<td>0.2</td>
<td>1.25 x 10⁻³</td>
<td>1.4x10⁹</td>
<td>0.2 % efficiency</td>
<td>Smela et al. [90]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal polysilicon heatuator</td>
<td>Approx. 0.27 x 0.02 x 0.002</td>
<td>2</td>
<td>1/96 x 30x10⁻⁷</td>
<td>3.75x10⁻⁶</td>
<td>2x10⁴</td>
<td>NA</td>
<td>Bright et al. [60]</td>
<td></td>
</tr>
<tr>
<td>Thermal bimorph polymide</td>
<td>Approx. 0.4 x 0.4 x 0.01</td>
<td>1-60</td>
<td>69x10⁻⁶ N/mm²</td>
<td>2.6-9x10⁻⁴</td>
<td>&lt; 10⁴</td>
<td>= 16.7 x 10⁻⁴</td>
<td>Suh et al. [78]</td>
<td></td>
</tr>
<tr>
<td>PGV-joint actuator</td>
<td>0.75 x 0.6 x 0.03</td>
<td>3-300</td>
<td>10⁻³</td>
<td>10-150 x10⁻⁶</td>
<td>10⁵</td>
<td>200 mW</td>
<td>0.001 % efficiency</td>
<td>This work</td>
</tr>
</tbody>
</table>
4.5 Discussion and conclusion

The main purpose for developing the new PVG-joint technology was that the out-of-plane erection techniques described in chapter 3 could not, in any easy way, fulfill the specifications for the 3-D flow sensor given in section 2.3. The investigation on the fabricated PVG-joint test structures showed that most of the specifications could be reached by the use of the new PVG joint. The PVG-joint gives robust, batch self-assembled 3-D structures. The bending radius of the PVG-joint was small enough to allow compact fabrication of three orthogonal free-standing hot-wire/hot-film elements for the application in mind. The criteria of well controlled position accuracy was only partially fulfilled in the first tests, which resulted in the development of a bending stop mechanism which was tested in the fabrication of the 3-D flow sensor, see section 6.1.1. Test structures intended for testing the feasibility of fabricating free-hanging polysilicon wires encapsulated in silicon nitride (Si$_3$N$_4$) using polysilicon as a sacrificial layer under the wires for free-etching were included. This fabrication technique was shown to be feasible and it was also possible to integrate it with the PVG-joint technique, although the yield of these wires was low in the initial tests. Therefore, improvements on the stress control of the layers were needed for realizing a suitable fabrication process for the 3-D flow sensor. However, the conclusion after the test structure evaluation was that a continuation of the project towards the realization of a 3-D turbulence flow sensor based on the PVG-joint technology seem most feasible. Further details about the PVG-joint based 3-D flow sensor are given in chapter 6 and in paper 3-4.

The requirement of trimmable bending angles was also met by the PVG-joint. Dynamic bending angle up to 20° or strokes up to 175 μm was possible to obtain with the 500 long test structures. This was better than expected and opened up new actuator applications. A spin-off project on micro-robotics could therefore be established with the goal of investigating the possibility of using the PVG-joint in configuration with arrayed actuators. Further details about the PVG-joint based micro-robotic applications are given in chapter 8 and in paper 5-6.
5 MEMS and Fluid dynamics

Measurement and control of the turbulent flow fields are key issues in many technical application areas, e.g. in the optimization of wing sections of aircrafts, designing streamlined vehicles for lower fuel consumption and minimization of noise generation. Further, the theory behind turbulent flows is one of the fields in Physics that is not yet completely understood. To improve the computer aided design tools used in fluid dynamics, more experimental data is needed which in some case has been impossible to obtain due to the lack of sufficiently small sensors. This field is therefore open for new interesting research, for example, by the use of MEMS sensors. The smallest scales of the fluctuating velocities in turbulent flow are of the order of 100 µm, which means that the sensors needed to resolve these phenomena have to be roughly the same small size. The introduction of miniaturized micromechanical silicon sensors, which in general are one order of magnitude smaller than conventional sensors, into fluid dynamics has made it possible for researchers to measure new flow parameters (correlation measurements, wall-shear stress etc) [16, 21, 22, 178-181]. Many principles to sense flow using micromachined flow sensors have been reported. An excellent review of the different kinds of microfabricated flow sensors is found in [182]. Miniaturization offers possibilities to circumvent the drawbacks of classical sensor principles (i.e. slow and power consuming thermal sensors). MEMS-based thermal sensors reveal some interesting properties which put them in a group of utmost interest for measurements of fluctuating quantities and steering parameters for control purposes. Normally, thermal flow sensors could be classified in three basic categories:

- Hot-wire or hot-film anemometry sensors
- Calorimetric flow sensors
- Time of flight sensors

Good overviews of thermal micro-scale flow sensor are given in the reviews by Tien and Elwenspoek [183, 184].

In the last decades, the interest in using numerical methods, i.e. computational fluid dynamics (CFD), has grown very fast. However, this growing interest together with the increased need of advanced turbulence model requires knowledge of more fundamental characteristics of the turbulent flow (cross-correlations $uv$, $uw$, $uvw$ (pu) and higher order moments $u^2$ & $u^3$ etc in the Navier-Stokes equations), which “only” can be obtained from experimental measurements. Therefore, new small multi-dimensional sensors preferably in array configurations for turbulence measurement are required.

The most commonly used flow sensor when studying turbulence is the Hot-Wire Anemometer (HWA). The thermal Hot-Wire anemometer measures fluid velocity by sensing changes in heat transfer from a small, electrically heated hot-wire exposed to fluid motion. Lately, Laser Doppler

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4 The “typical” size of the turbulent eddies is characterized by the Kolmogorov length scale defined as $\eta = (v^3 / \varepsilon)^{1/4}$, where $v$ is the kinematic viscosity and $\varepsilon$ is the dissipation rate [177]. For most experimental wind tunnels (e.g. the two low-speed tunnels at TFD-Chalmers) the Kolmogorov scale is in the range of 100 micrometer. Hereafter, this is called the smallest turbulence eddies in a technical interesting flows. However, for high flow speeds (i.e. high Reynolds number as in ultra-sonic flows) the smallest scales in the turbulent flow become much smaller than 100 micrometer.
Anemometer (LDA) measurement and Particle Image Velocimetry (PIV) have also frequently been used in experimental fluid dynamics. These two techniques have the advantage of not disturbing the flow. On the other hand, these techniques require particles in the flow to be useful. PIV is a technique developed by fluid dynamists to solve the problem of how to instantaneously measure these complex flow, over different kinds of surfaces, without interfering with the flow itself. In some applications (usually laboratory fluid dynamics research) these optical systems are very good. However, in other applications it can be difficult to have an optical set-up. Optical set-ups have the drawback of limited spatial and temporal resolution due to the need of particles in the flow. The hot-wire probes for turbulent measurements are much easier to use and allows for better resolution (point measurements and time series with random sampling intervals) and do not require particles in the flow.

One reason for the development of the LDA and PIV methods has been the difficulty in miniaturizing conventional hot-wires (spatial resolution) and use them in array configurations to measure flow distribution in the room. However, MEMS based hot-wires offer the possibility to fabricate large arrays of hot-wires without complicating the fabrication significantly. The parallel (batch) processing feature of the MEMS technology means that it is equally easy to make several hot-wires in an array as it is to make only one hot-wire. That is not the case for conventional hand-made hot-wire probes, which are very difficult to make in large quantities, especially if there is a need for compact arrays.

5.1 Hot-wire anemometry (HWA)

The literature contains numerous excellent studies describing various aspects of hot-wires anemometry, which have been accumulated over a century. The most important contributions are summarized in a number of excellent books and review papers [25, 185-192].

The conventional triple hot-wire sensors which are used today for measurement of turbulent flows are expensive and relatively large (wire lengths in the millimeter range with diameters of typically 5 to 10 µm [23]), see Figure 4. In fluid mechanics there is therefore a need for smaller, faster and more accurate triple hot-wire probes for simultaneous measurement of the three perpendicular velocity components in the flow. Micromachining is a promising technology to realize such miniaturized.

5.1.1 Micromachined hot-wire anemometers

Thin as well as thick hot-wires made of silicon or silicon carbide have been presented in literature, for example [27-32]. Most of them are not designed as conventional hot-wire probes for turbulence measurements, i.e. probe-like configuration with small prongs holding the wires. Such a prong-like configuration with freestanding wires is necessary to reduce chip induced flow disturbances. Jiang and co-workers presented a single silicon hot-wire with a prong-like configuration [14, 30, 31]. Successful stationary flow measurements were presented as well as extensive theoretical investigations, but no experimental results using that single wire sensor for turbulence measurements have been reported. In comparison with conventional hot-wires the advantages of silicon hot-wires can briefly be summarized as follows: possibility for mass-production at a low cost, easy integration into array configurations, miniaturized size with better accuracy of the dimensions since photolithography is used [14]. The high resistivity of silicon results in more sensitive sensors, reduced power consumption and faster response times (since the response time is inversely proportional to the resistivity [179]). Most of these parameters can easily be adjusted by the material properties as well as the actual size of the wires [193]. However, there are of course drawbacks as well (i.e. thin film
deposition, lithography and etching results in noncircular wires which are irreparable, etc.), and a big challenge is manufacturing 3D sensors using micromachining since it is basically a planar technology. Further, there are also some crucial questions on the applicability (i.e. accuracy, suitable calibration functions, angular dependency, noise levels, aging, drift and long-time stability) for turbulence flow measurements due to the non-circular wire cross-section. Could standard calibration techniques [25, 192] be used for silicon HWAs? A mandatory validation of polysilicon hot-wires for turbulence measurements is essential.

Pister and co-workers have presented two different techniques to fabricate silicon hot-wires that are folded out-of plane [107, 123]. The first uses the polysilicon hinge technique described in section 3.3.1 and the second is based on the Al hinges described in section 3.3.2. However, the anemometer performance of these structures have never been tested [135] so their ability to be used as flow sensors are still uncertain. The design of the hot-wire structure shown in Figure 17 b) is not suited for turbulence measurements due to the fragile prong structures used and the sensor body (silicon substrate) will constitute a blockage effect on the flow. This test structure design does not allow the flow to be measured in all three dimensions either. It is important that the out-of-plane structure is robust enough not to bend due to the forces the flow creates. This is one critical parameter for the folded structures presented by Pister et al. since surface micromachined structures may be too weak for the flow sensor application. The use of serpentine polysilicon springs which is the normal way to obtain electrical interconnection to the folded structures for the micro-hinge technology, as illustrated in Figure 10, could interact with and disturb the turbulent flow around the flow sensor.

5.1.2 Flow sensing principle for hot-wires

A hot-wire flow sensor is based on the thermal anemometer principle. The thermal anemometer measures fluid velocity by sensing changes in heat transfer from a small, electrically heated hot-wire exposed to fluid motion. A hot-wire sensor can be operated in several different modes depending on the way the sensor heating current or power is controlled. The two basic modes are the constant-current (CC) mode, where the current to the wire is kept constant and variations in the sensor resistance caused by the flow are measured by monitoring the voltage drop variations. Similar to the CC-mode is the constant-power (CP) mode [150, 194], where the power to the wire is kept constant (adjusting voltage) and variations in the sensor resistance (directly proportional to the hot-wire temperature) caused by the flow are measured directly. In the constant-temperature (CT) or constant-resistance mode, the wire is placed in a feedback amplification loop, which maintains the wire at a constant resistance and hence constant temperature. The current or power required to do this then becomes a measure of flow velocity. The constant-temperature is preferable because it exhibits a considerably higher frequency response due to the feedback amplification loop than the constant-current/power modes. The constant-current (CC) and constant-power (CP) modes are not used very much for turbulence measurement nowadays since it is fairly easy to build fast feedback electronics for the CT mode. The constant-current anemometer is primarily used for temperature measurements. When the hot-wire is supplied with a very small current the velocity sensitivity is negligible and the sensor acts as a simple resistance-temperature device (so called cold wire). Normally, a CTA rely on small temperature fluctuations in the flow media. It is clear that the ambient temperature changes the resistance of the hot-wire, so the change in ambient temperature gives a change in the detected signal without any flow variations. A combination of the CT- and CC-mode can be used for measuring the temperature variation of the fluid using a triple hot-wire sensor. Then two of the wires are aligned orthogonal to the flow and the third wire (in CC-mode for temperature sensing) along the main flow direction and, therefore, is not sensitive to the flow velocity, only to the temperature of the fluid.
Besides single hot-wires, several reports on multi-wire 1-D probes fabricated by micromachining have been published. The main purpose to use two or more elements is to get a differential signal to eliminate common disturbances, such as temperature variations in the flow. Further, multi-wire 1-D probes have the advantage of being directionally sensitive. Multi-wire probes could also be used as calorimetric flow sensors. Most calorimetric flow sensors consist of two temperature sensitive wires and one wire acting as a heater (which could be the same as one of the temperature sensing wires or a separate one). The sensing wires are usually located symmetrically up and down stream of the heater. The output signal is then the temperature difference between the upstream wire (which is cooled by the flow) and the downstream wire (which is heated). The heat that is transferred into the fluid is carried away by convection to the downstream sensing wire.

Calorimetric flow sensors can also be operated in a dynamic mode, so called time-to-flight sensors. A heat pulse from the heating wire will be transported by the flow (convection) to the downstream wire. The time between the pulse was sent at the heater and the detection is a measured of the flow. However, the heat pulse will deform by the velocity profile and broaden at the same time by heat diffusion meaning that careful design is necessary, since their exists a optimal regime (depending on the distance between the two wires, the flow velocity and the magnitude of the heat pulse) where the sensor works properly. Recently, Elwenspoek et al. presented a new concept, called temperature balanced anemometry (TBA), for two wire measurement [194].

### 5.2 Active control

Besides the use of miniaturized sensors there is also an increasing interest in reactive control of turbulent flow [16, 178, 179]. Miniaturized micro-systems containing sensors, actuators and/or logic circuits, similar to the system shown in Figure 2, for sensing and controlling (turbulent) flows are supposed to have deep impact on the fluid dynamic field in the future. Preliminary, small scale, studies have shown that such micro systems can reduce the drag of frictional forces up to 20% under certain circumstances [13, 105, 139, 195, 196]. By the use of out-of-plane micro-actuators it is feasible to perform fluid dynamic interactions since the length scales of the actuators and the boundary layer before separation at a leading edge of a wing is typically the same size. By the use of small surface perturbations large aerodynamic control moments (pitch, raw and roll) could be obtained through fluid amplifications. Future challenges include achieving significant actuation perpendicular to the plane (e.g. robust 3D actuators), and also unit cost reduction as well as energy expenditure of micro-actuators, and designing micro-devices that are capable of withstanding the harsh field environment of, for example, an aircraft. These are not easy tasks, but the payoff – if for example, air / water / land-vehicle drag could be reduced by a few percentage points would translate into fuel savings in the billions of dollars as well as tremendous benefits to the environment [16].

Among the many review articles on the topic of using MEMS in fluid dynamics that have been published, the articles by Ho & Tai [178, 179, 197] and the article by Löfdahl & Gad-el-Hak [16] are recommended for further reading. For a general introduction to the fluid dynamics field and to basic properties of turbulence, the book by Tritton [198] is recommended.
6 Three dimensional flow sensor based on PVG joints for turbulence measurement

As pointed out in section 5.1.1 silicon hot-wires are a good candidate for miniaturized hot-wires probes. A few different approaches to silicon HWA designs have been presented during the last ten years [27-32]. Most of them are not designed as conventional hot-wire probes, i.e. probe-like configuration with small prongs holding the wires. Such a prong-like configuration is necessary to minimize chip induced flow disturbances.

The first fabricated device using the 3-D PVG joint was a miniaturized 3-D hot-wire probe, schematically shown in Figure 35. Comparing this design with the original one, illustrated in Figure 5, one can see that the small bending radius achieved with the PVG-joint allows for simpler assembly, although the measuring volume is only marginally increased. For the PVG-joint based 3-D flow sensor the $x$- and $y$- hot-wires are located in the wafer plane and only the third $z$-wire is rotated out of the plane using the new robust small radius PVG joint. Also, other PVG-joint designs with all three hot-wires rotated out of plane, similar to the design in Figure 5, have been fabricated. The sensor in Figure 35 is designed to resemble the function of a conventional triple hot-wire for turbulence measurement. However, the microfabrication technique constitutes limitations of the wire configuration meaning that crossing wires, as in Figure 4, are difficult to obtain if the requirements of low thermal cross-talk should be fulfilled. For MEMS based hot-wires $V$ or $L$ wire configurations are better than $X$-wire configurations (or similar in three dimensions where one single origo is used with sensor elements only in positive directions not to cross the wires in-plane during fabrication as illustrated in Figure 35). Jiang and co-worker presented a single silicon hot-wire with a prong-like configuration but the thickness of the prongs were only in the micrometer range and therefore robustness problems occurred when their sensor was tested in real flows [14, 30, 31]. No experimental results using that single silicon wire sensor in turbulent flow fields have been reported.

![Figure 35. Schematic view of the 3-D hot-wire probe based on a polyimide V-groove joint. The silicon chip size is $3.5 \times 3 \times 0.5 \text{ mm}^3$ and the three wires are $500 \times 5 \times 2 \text{ µm}^3$. Compared to the measuring volume of a conventional triple hot-wire sensor like the one in Figure 4, this configuration results in reduction of the measuring volume by one to two orders of magnitudes.](image-url)
Flow sensor design and fabrication

The hot-wire sensor consists of three basic parts: the hot-wires, the prongs holding the wires and a sensor body where all electrical connection out from the sensor is done. The prongs should be long and thin so as not to interact with the flow cause any flow blockage. However, the prongs need to have a certain thickness to be robust enough to withstand the forces generated by the flow and simplify the fabrication process. From a normal MEMS fabrication cost effectiveness perspective, long prongs consume chip area and therefore should be kept short. Sharp corners and unsymmetrical structures of the sensor body should be avoided since these easily cause disturbances in the flow. To achieve good spatial resolution the hot-wire needs a length to diameter ratio larger than 100 \(^5\). Sensors with short response times are made by reducing the thermal mass of the hot-wire, e.g. by using thin and short wires. As a compromise between possibilities to manufacture the sensor (i.e. wire strength and accuracy in the photolithography process) and the desire for small size, the dimensions of the hot-wires were selected to be 500 \(\times\) 5 \(\times\) 2 \(\mu\)m\(^3\). For the latest versions of the fabricated hot-wire sensors, which were used in most of the measurements reported in this thesis, undesirable over-etching occurred during the polysilicon etch that defines the wire dimension. This over-etch resulted in dimension variations of the actual polysilicon wire. The thickness is typically in the range of 1.5 - 2 \(\mu\)m and the width between 3.5 and 4.5 \(\mu\)m with a slightly trapezoidal cross-section. From an aerodynamic point of view the hot-wires should be as symmetrical as possible to minimize the angle dependency when the flow reaches the wire (i.e. yaw and pitch angle calibrations).

Papers 3 and 4 describe the fabrication process of the flow sensor in detail, both with and without the PVG-joint needed for three dimensionality. A bulk micromachining process in combination with sacrificial etching was used to form the hot-wire probes. The hot-wires are made of 2 \(\mu\)m thick polysilicon encapsulated with silicon nitride. The silicon nitride around the hot-wires prevents oxidation during operation which makes it possible to use the sensor at very high temperatures (without burning off the wires or oxidizing them). The nitride is also necessary for the process itself. To underetch the wires and obtain free-standing wires a polysilicon sacrificial layer and bulk silicon KOH-etch are used and therefore the polysilicon wires need to be nitride encapsulated in order not to be etched or oxidized during the KOH-etching and thermal annealing steps in the fabrication process. The hot-wires are connected to 30 \(\mu\)m thick bulk silicon beams defined by double sided KOH etching. By the use of bulk silicon beams (prongs) instead of surface micromachined thin film shanks

\(^5\) For conventional circular hot-wire sensors the thumb rule is to have a length-diameter ratio of 200 [25]. For silicon wires, for which the fabrication is based on photolithography and etching, circular cross-sections of the wires are difficult to obtain. Wires with a square cross-section is feasible and preferred, but the use thin film deposition techniques (LPCVD polysilicon wires encapsulated with oxide or nitride) limit the vertical dimension (i.e. thickness) to be thicker than 3-4 \(\mu\)m and the use of (1:1 proximity alignment) lithography to pattern first the wire and then the encapsulation around the wire, limits the horizontal dimension of the wire to be smaller than approximately 5 \(\mu\)m. This sets the limit for the design in this work but sub-micrometer wires are possible with other lithography techniques (i.e. steppers). The resistivity of polysilicon-based wires are much higher than wires made of metal, commonly used in conventional hot-wires, and therefore allows for better temperature distribution over the wire and less thermal conductance to the prongs. These facts motivate the chosen length-diameter of 100 for the silicon wires.
PVG Joints for Three-Dimensional Silicon Transducers

[14] holding the wires, better mechanical rigidity can be obtained and also problems associated to bending of the prongs are avoided. However, the prongs have to be thin enough not to interact with the flow. The new PVG joint is used to obtain three-dimensionality. Seven or eight masks were needed to fabricate the 3-D flow sensor and the fabrication process is described in detail in paper 4. The fabricated out-of-plane erected wires are shown in Figure 36.

In the first tests of fabricated free-standing hot-wires problems associated with high mechanical stresses in the wires were observed. The result was low yield and crooked wires (i.e. large curved wires resembling a violin string). Special attention was paid to reduce the stress levels. Guckel et al. [199-201] showed that by using fine-grained silicon deposited at the amorphous-polysilicon (< 580°C) boundary and then thermally annealed to form polysilicon, the qualities (i.e. uniformity of the nominal strain field through the poly-Si layer) was better than for silane LPCVD-deposited silicon in the polysilicon (> 600°C) phase. The use of amorphously deposited polysilicon was used as the first step to reduce the stresses in the wires. However, the deposition rate of the amorphous silicon layer using a silane based LPCVD system was low, which means that a 13 hour deposition was needed to form the 2µm silicon layer. It has also been reported that the amorphously deposited polysilicon results in higher and more linear thermal coefficients of resistance (TCR) of the boron-doped resistors after the annealing step than for directly deposited polysilicon [14].

The other layers that contributed with high stress levels are the silicon nitride layers. “Normal” LPCVD deposited nitrides (Si,N) for IC-applications have large stress and limit the total nitride thickness on a wafer to approximately 0.2 µm. By using low stress (silicon rich) nitride (Si,N) films [202] these problems were avoided. A thick isolation material (i.e. the silicon nitride) is needed under the metal layer. This to minimize the capacitive coupling between the closely spaced metal lead wires used for the interconnection of the polysilicon hot-wires to the outside world.

Another approach tested to minimize the stress is the use of stress engineering with two different layers (i.e oxide having compressive stresses and nitride with tensile stress). Then we get more mechanical stress in the encapsulated wires than in the case of low-stressed nitride as well as a potential KOH leakage through the oxide film into the polysilicon hot-wire layer, shown in

Figure 36. SEM-photo of the x- and z- hot-wire resistances electrically connected through the PVG joint. The protecting silicon frame must be broken before measurements can be performed. The nitride corner compensation must also be taken away. Presently, this is done manually using a fine probe needle but modification of this process to avoid this manual fabrication step is feasible.
Figure 37 a). Such leakage is believed to destroy the hot-wires in some cases. However, it is not yet clear if a LPCVD deposited silicon oxide layer (i.e. TEOS- Tetraethyl Orthosilicate or LTO-Low Temperature Oxide) is worse than highly silicon rich nitride films where the high silicon content could lead to the $\text{Si}_n\text{N}_m$ may be etched in the KOH solution.

The combination of oxide-nitride layers has another advantage by having high etch selectivity in standard reactive ion etchers (RIE). Since most of the process equipment (i.e. machines for standard IC-manufacturing) requires flat wafer surfaces to achieve, for example, accurate resist spinning for the photolithography, possible problems are avoided by making all critical patterns before the front-side KOH etching. Compared with the fabrication process for the test structure chip outlined in section 4.3 it is preferable to form the via holes through the nitride-2 layer used for contacting the polysilicon layer (either the hot-wires or the heaters) before the KOH-etch. By patterning these via holes before the KOH-etch and then adding a third protective nitride layer, the patterning is simplified. However, when the third relatively thin nitride layer should be etched away (without any patterning) after the

Figure 37. Principles for encapsulating the hot-wires and making the via contacts.  
**a)** The principle for stress engineering using tensile nitride and compressive oxide to encapsulate the hot-wires. A potential KOH-leakage through the oxide layers at the edge of the polysilicon wire could occur. KOH leakage into the polysilicon layer will degrade or destroy the performance of the polysilicon hot-wires. The patterning of the via hole through nitride-2 and oxide-2 must be done after the KOH and LOCUS oxidation when the wires are free-standing and the surface is structured with relatively deep V-grooves. Compare the fabrication process described in paper 4.  
**b)** To simplify the lithography steps for patterning two additional layers (oxide and nitride-3) are used which allows for patterning of the via hole before the KOH etch (i.e. flat surface). The high etch selectivity between nitride and oxide and oxide-nitride respectively oxide-polysilicon means a simply way to etch a way the two top layers without affecting the hot-wires and the encapsulation around it.
KOH-etch no stopping layer is present to prevent etching of the nitride-2 layer used for encapsulation. However, this problem can be avoided by using two different layers having high etch selectivity, i.e. a silicon oxide between the nitride-2 and nitride-3 layers as illustrated in Figure 37 b). To minimize the potential for long term resistance drift they were encapsulated with nitride to prevent oxidation and a small amount of Copper (0.5%) and Silicon (1%) in the Aluminum interconnection wires were used. The Al/Cu0.5%/Si1% alloy was used to minimize temporal drift that may be caused by slow diffusion of dopants when the polysilicon hot-wires are operated at a temperature up to a few hundred degrees. The small amount of copper and silicon act as a diffusion barrier for such drifts and enhance the electromigration lifetime [203].

6.1.1 Bending stop structure

One problem associated with some polyimides is their tendency to creep (i.e. change its volume over time). It is well known that some kinds of polyimides can swell due to humidity [159, 204].

To overcome the potential drawbacks of the creep effect, successful tests on the use of bending stop structures to stop and lock the bending at particular angles were performed. The bending stop approach is shown in Figure 38 where a bending stop structure, having typically 5 or 6 V-grooves in the joint, is rotated almost 180 degrees and stops the rotation of the first structure at a bending angle of exactly 90°. The advantage of using a bending stop structure is that it allows a noncritical curing temperature to be used. The curing temperature may be increased, resulting in a prestressed structure which will not bend back due to polyimide creep. The higher curing temperature also reduces the proclivity to creep because this effect is considered to be a low temperature problem. A concept for a complete interlocking arrangement is described in paper 1 and in section 4.4.1.1.

**Figure 38.** SEM-photo of a z-hot-wire which has been out-of plane rotated by a three V-grooved polyimide joint. A bending stop structure rotated 180° stops the z-wire at exactly 90°. The curing temperature is noncritical since a bending stop structure was used. Thus it is possible to achieve a pre-stressed PVG joint which is less affected by humidity and the creep effect of the polyimide.
6.2 Measurement set-ups and electronic read-out circuits

As described in section 5.1.2, the hot-wire anemometer measures fluid velocity by sensing changes in heat transfer from the small, electrically heated hot-wires exposed to the fluid. Several different operation modes can be used. For the test performed by the PVG-joint based hot-wire sensor both the constant power (CP) mode and the constant temperature (CT) mode have been used (described in section 5.1). For conventional metal hot-wires which have a resistance in the range of 10 Ω commercial CTA-instrument and amplifiers are most often used for data acquisition. However, since there are no commercial instruments for the new silicon hot-wire sensors with wire resistance in the range of 1-100 kΩ custom made electronics must be used. Using the constant temperature mode means that the supplied power needed to maintain the temperature of the hot-wire at a constant level increases for increasing flow velocity. The temperature is held constant using a feedback amplification loop to balance the Wheatstone bridge. Special attention must be taken to obtain accurate and high gain through the whole frequency range of interest (1 Hz – 10 kHz) without resulting in resonance.

For conventional hot-wires, numerous methods to convert the anemometer output voltage into a velocity exist. The classical way has been to use King’s law,

\[ P = A + B \cdot U^{1/2}, \]

which was theoretically derived and experimentally verified by King in 1914 [185]. Here, \( P \) is the electrical power supplied to the anemometer (equivalent to the output voltage, \( E^2 \), for a CTA with constant wire-resistance), \( U \) the velocity of the fluid and \( A, B \) the constants determined by fitting King’s law to a calibration curve. A Pitot tube was employed as reference for the velocity, at the same time as the output voltage from the anemometer was recorded. For using silicon hot-wires in various turbulence measurements high accuracy of the sensor over a large velocity range is essential. Paper 3 demonstrates that the conventional calibration function (King’s law) is applicable to silicon hot-wires. However, by using a modified calibration function which also takes into account the effects of natural convection, which are important at low flow velocities, the silicon wires have an uncertainty of approximately the same magnitude as conventional wires over a relatively large interval of velocities. The nitride encapsulated polysilicon wires have better calibration stability in time than conventional flow sensors, which often need to be recalibrated. Further details on characteristics of the flow sensor is given in section 6.3.

In the initial state of the project where only simple demonstration of the flow sensitivity of the hot-wire were needed, the measurement set-up shown in Figure 39 was used. The triple hot-wire probe was mounted in the center of a flow channel. The cross section of the channel was 16x16 mm. A reference mass flow sensor (TSI 800630, TSI Inc.) together with an electrically controlled valve controls the flow in the channel. The valve regulates the flow by using a feedback control algorithm implemented in a personal computer. One wire at a time was characterized. To obtain the maximum flow signal the wire to be characterized was oriented perpendicular to the flow direction. A manual control of the supplied power (i.e. constant power mode) was used. This wind tunnel set-up could not generate high flows and controlled turbulent flows.

For the more accurate calibration and characterization needed for the turbulence investigations of the silicon hot-wires, the large wind tunnel at CTH-TFD in Gothenburg was used. This low-speed (1-50 m/s) temperature controlled (±1°C variations) wind tunnel has a measuring section of 1.25 x 1.8 x 3.0 m and a contraction ratio of 6.2. The transverse system in the wind tunnel allows for precise positioning of the sensor in the flow and also for calibration of the angular dependency of the wires to the flow. A conventional hot-wire acting as a reference sensor is placed on the same
transverse system. Grid generated turbulence and a turbulent wall boundary layer were used to estimate the turbulence characteristics of the silicon wire. The grid used consisted of a square cross-section 15x15 mm² and a mesh size of 80 mm. The solidity (projected solid to total area) of the aluminum pipe grid was 0.34. All grid turbulence measurements were performed at a location 25 mesh sizes downstream. The anisotropy measurements, the turbulent energy spectrum and the autocorrelation of the flow were determined with the use of the new polysilicon hot-wire probes. The turbulent characterization of the hot-wire sensor is presented in section 6.3.1.2.

![Figure 39. Measurement set-up for the initial flow sensor characterization.](image)

6.3 **Flow sensor characteristics**

To measure the time response of the hot-wire the resistance change caused by heating (i.e. squared voltage stimuli) without any flow passing the wires were studied. Time constants, $\tau$, of 120 and 330 $\mu$s were measured for the cooling and heating, respectively, in the open mode. This is approximately one order of magnitude faster than conventional metal hot-wires. The reason for the fast response time of the polysilicon wire is the relatively high resistivity of the boron doped wires and the shorter and thinner wire dimensions compared to the conventional metal hot-wires. By operating the sensor at constant temperature the response time of the sensor was measured to be in the order of 30 $\mu$s at zero flow and moderate gain in the feedback amplification (i.e minimal risk of resonance in the electronic circuits). Jiang et. al. have demonstrated response times in the order of 0.5 $\mu$s (corresponding to a bandwidth of 1.4 MHz) with extremely thin and short polysilicon hot-wires [14].

Similar to the response time measurements cross-talks measurements have also been performed by electrical excitation. A square wave electrical signal was supplied to the in-plane $x$-wire and the amount of cross-talk (electrical and thermal) to the other in-plane $y$-wire was studied. As illustrated in Figure 35 the $x$ and $y$-wires share one prong, where the spacing between the electrical interconnection wires are small, thus a strong electrical cross talk occurs by the low resistance through the substrate between the two capacitor elements formed between the two wires and the substrate. For turbulence measurements with high frequency content this cross-talk will affect the accuracy in the turbulence
parameters measured. Using the square voltage stimuli, (i.e. high frequency content) described in paper 3, constitutes the worst case. It is believed that the dominant cross-talk is caused electrically (by the capacitance) and only small a contribution by thermal cross-talk. The cross-talk could impose restrictions on the feasibility for turbulence measurements with more than one hot-wire. However, the capacitive coupling formed between the interconnecting wires can be reduced by proper shielding and grounding (extra metal strips and doped substrate surface for grounding). An alternative fabrication process allowing for a redesigned sensor could minimize electrical cross-talk. By using deep reactive ion etching (DRIE) the interconnection wire now located on the same prong could be separated to two different prongs with a small air cap in between and thus minimize the capacitive coupling. Such a prong separation solution have showed good results for conventional multi hot-wire probes [192, 205, 206]. This kind of prong separation is not possible when using the KOH-etching technique which gives sloped walls and imposed restrictions on how close the different prongs can be placed to each other. Further, by using DRIE instead of KOH, corner compensation such as the ones shown in Figure 36, is not needed. As discussed in the fabrication section (6.1) it is a time and cost consuming step to manually break and rinse the corner compensation remains away.

6.3.1 Flow sensor characterization in the wind tunnel

Initial tests were made to demonstrate the flow sensing capability for the out-of-plane z-wire. The simple measurement set-up shown in Figure 39 was used and the wire was operated in a manually adjusted constant power (CP) mode. The first flow measurement curve from that flow sensing configuration is shown in Figure 40 a). The equivalent hot-wire temperature is calculated from the resistance-temperature calibration curve shown in Figure 40 b). For this particular wire, which has been heavily doped with boron (2x10^{16} cm^{-2}) the temperature coefficient of resistance (TCR or \( \alpha \)) is positive and has a value of 800 ppm/°C. By low or moderate doping (< 1x10^{15} cm^{-2}) this coefficient is increased and also shift signs. However, the resistance of the wires then becomes large (above 100 kΩ) since the resistivity becomes high and therefore the voltage required for heating the wire becomes too large to be suitable for implementation with “standard” electronic components. Further, highly resistive hot-wires are most often electrically noisy.

![Figure 40](image)

**Figure 40.** a) Measured hot-wire resistance, \( R \), and average hot-wire temperature as a function of flow at a constant power supply for a hot-wire mounted perpendicular to the flow.  
b) Hot-wire resistance, \( R \), as a function of temperature for measurements performed in a temperature controlled climate chamber at zero flow.
The flow sensitivity for hot-wires operating in the CP (CI)-mode are much lower than for the constant temperature (CT)-mode. Therefore, a CTA was used for more accurate measurement and to characterize the turbulence behavior of free-standing silicon wires. Before turbulence characteristics can be determined elementary calibration of the new silicon hot-wires in non-turbulent flow is needed. The investigation was undertaken in order to clarify the impact of the unsymmetrical cross-section of the new hot-wires.

6.3.1.1 Characterization in non-turbulent flows

To test the flow sensitivity and the angular dependency of the hot-wire sensor, modified sensor chips with just one or two hot-wires (i.e. no out-of-plane rotated \( z \)-wire) were mounted and calibrated in the large wind tunnel at CTH-TFD. Photographs of a single hot-wire sensor similar to those used in the elementary tests, are shown in Figure 41. Compared to the photo shown in Figure 36 the protecting frame and two of the wires have been broken. The nitride corner compensations have also been dissolved manually to hinder flow disturbances. The sharp corners and short prongs holding the wire is not the ideal case for a flow sensor, but good enough for the first characterization of a silicon based free-standing hot-wire. The experimental arrangement is further described in paper 3.

\[ \text{Figure 41. a) A single hot-wire chip mounted on a printed circuit board. Chip size 4 x 3 mm.} \\
\text{b) Close-up of the sensor connected to the PCB by bonding wires.} \]

The hot-wire was operated in the constant temperature mode by being connected to a constant temperature anemometer feedback control instrument. The CTA instrument consisted of a Wheatstone bridge configuration and a feedback amplifier implemented on a printed circuit board close to the sensor. The electronic amplifier used the unbalanced voltage (error signal) from the Wheatstone bridge in a feedback loop to maintain the constant temperature of the hot-wire (i.e. balance the Wheatstone bridge). The average voltage (power), \( E \text{ [V]} \), needed to maintain the hot-wire at a constant temperature was used as a measure of the average flow, \( U \text{ [m/s]} \). Figure 42 shows the calibration curves obtained by a single polysilicon hot-wire. By using King’s law (or a modified version of that law) for calibrating the sensor, it was demonstrated that the uncertainty in flow measurement performed with the silicon hot-wire was approximately of the same size as for a conventional reference hot-wire over
a relatively large flow interval (0.5-50 m/s). At an overheat temperature of 80°C the silicon hot-wire showed twice as large flow sensitivity and one order of magnitude lower power consumption than the conventional hot-wire operated at a temperature of 220°C. Further, the silicon hot-wires showed very stable calibration behavior over time as can be seen in Figure 42.

**Figure 42.** Flow measurements performed in a wind tunnel using a single hot-wire oriented perpendicular to the flow. The hot-wire was connected to a constant temperature anemometer (CTA) instrument and operated at an overtemperature of 80°C. A Pitot tube measuring the reference average flow velocity was used as a reference. The calibration uncertainty of the silicon wires was approximately the same order as the conventional wires. The reproducibility between two measurements is better than 1%. Note the low operating temperature of about 100°C, which should be compared to 200-250°C that is the normal temperature for conventional wires. This implicit power consumption was one order of magnitude lower for the silicon even though the sensitivity is twice as high as a conventional hot-wire.

In paper 3 measurements on the angular dependency (i.e. pitch and yaw angles) of the nitride encapsulated silicon hot-wires were reported. Since the encapsulated hot-wires do not have a symmetric cross-section, proper calibration of the pitch angle is needed to achieve accurate turbulence measurements. One approach is the use of a look-up table. For the yaw angle a cosine dependency is expected. However, in the yaw angle measurements presented in paper 3 a small deviation from the cosine dependency was observed. This indicates a somewhat low aspect ratio (length to diameter) of the encapsulated silicon wires (i.e. the assumptions described in footnote no. 5 were not perfectly correct). Longer and / or thinner wires are needed for accurate measurements.

The characteristics of the 3-D hot-wire sensor are shown in Table 3.
Table 3. Characteristics of the fabricated 3-D flow sensor.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-wire</td>
<td>p⁺⁺ polysilicon (boron-ion implanted at 2x10¹⁶ cm⁻²)</td>
</tr>
<tr>
<td>Hot-wire encapsulation</td>
<td>low-stressed silicon nitride</td>
</tr>
<tr>
<td>Micro-joint</td>
<td>polyimide (HTR-3 200 from OCG)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow sensor dimensions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip size (without Si frame)</td>
<td>3.5 x 3.0 x 0.5 mm³</td>
</tr>
<tr>
<td>Chip size (with Si frame)</td>
<td>5.0 x 3.0 x 0.5 mm³</td>
</tr>
<tr>
<td>Hot-wire size</td>
<td>500 x 5 x 2 µm³ (excluding encapsulation)</td>
</tr>
<tr>
<td>Silicon beam</td>
<td>600 x 50 x 30 µm³ (x- and z- prongs)</td>
</tr>
<tr>
<td>(holding hot-wire)</td>
<td>1000 x 50 x 30 µm³ (x- and z- prongs)</td>
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<tr>
<td></td>
<td>600 x 80 x 30 µm³ (common x- y- prong)</td>
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</table>

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature dependency, TCR</td>
<td>+ 800 ppm/°C (hot-wire resistance)</td>
</tr>
<tr>
<td>Time constant, τ</td>
<td>120 and 330 µs (cooling resp. heating without electronic feedback at zero flow)</td>
</tr>
<tr>
<td></td>
<td>30 µs (with electronic feedback at zero flow)</td>
</tr>
<tr>
<td>Flow sensitivity</td>
<td>10.4 V²/(m/s)¹/² (at ∆T= 80°C)</td>
</tr>
</tbody>
</table>

6.3.1.2 Characteristics in turbulent flows

The new silicon hot-wire sensor, developed within one of the projects for this thesis, was aimed to measure turbulent flows. For all previously reported turbulent fluctuating flow measurements using MEMS sensors, the sensors have been based on flat membrane configurations [14, 178, 179, 197, 207]. These sensors have been wall-mounted and used to measure shear stresses in a turbulent boundary layer. However, for 3-D flow sensors another approach than the membrane configurations and wall mounting is needed, i.e. prong configuration with free-standing wires. Since, turbulence characterization on free-standing silicon wires has not been reported earlier basic tests were needed. Therefore, the modified and simpler versions of the new triple hot-wire consisting of either one single wire, as illustrated in Figure 41, or two orthogonal in-plane wires were used to clarify the possibilities to measure turbulent quantities with free-standing silicon hot wires. The obtained results are presented in paper 3 and are briefly summarized beneath.

In all experiments using different versions of the new silicon hot-wire sensors the captured data were compared to measurements using gold plated standard hot-wires (reference sensor). In a nearly isotropic turbulent flow field generated by a grid positioned in the wind-tunnel, the turbulent quantities obtained using the silicon sensor compared well to results from the reference sensor. A typical turbulent spectra obtained with a silicon hot-wire sensor is shown in Figure 43, for 0 and 10 m/s mean velocities. The spectra represent the energy at each frequency component. Good agreement between silicon hot-wires and the conventional reference sensor were obtained. The root mean square (RMS), including all frequencies of the stream-wise velocity signals were calculated. Compared to the conventional hot-wire result, the differences were small (less than 0.01 %).
Figure 43. Measured frequency spectra at free stream velocities of 0 and 10 m/s. The noise level is well below the signal level.

In the grid generated turbulence small velocity fluctuations are measured while the mean velocity remains constant. From the calibration curves, reported in paper 3 and Figure 42, it is clear that the silicon wires can measure mean velocities, accurately, over a wide range of velocities. To investigate the new silicon hot-wires ability to measure both large changes in mean velocity and turbulent fluctuations, the sensor was applied to a turbulent boundary layer. The acquired data for the silicon hot-wire and the reference sensor showed large deviations. The most probable explanation to this deviation is the blockage effect caused by the sensor. The short prongs holding the wire means that the sensor body (silicon substrate) need to be closely positioned at the wall. The result is that the fluid is accelerated in the gap between the sensor and the wall, which has a large impact on measured mean velocity and fluctuations. Improvements to the sensor layout, i.e. longer prongs holding the wire(s) and eliminating sharp corners on the sensor body could probably minimize this blockage effect. A few test structures using the PVG-joint technology to obtain a probe with all three wires out-of-plane, similar to Figure 5, has been fabricated but not tested for flow calibrations. Using this configuration the wires can measure turbulence quantities close to the wall but the sensor body does not need to be very close to the wall as in the case of in-plane wires. Another attractive feature of the design idea shown in Figure 5 is that the sensor element is erected inwards rather than out-of-plane (as for the PVG-joint technique), meaning that the bonding wires are located on the back of the chip. This is a desirable feature for all MEMS devices for fluid dynamic applications (especially the wall mounted ones) but most often it is difficult from a fabrication point of view to have the bonding wires on the back-side of the chip while the sensing elements are on the front-side.

Another aspect that may explain the deviation in the measured boundary layer turbulence parameters between the silicon sensor and the reference sensor, is the relatively large separation in the span wise direction between the two sensors. Due to the geometry of the probe holders for the sensors mounted on the transverse system, a separation of 100 mm was necessary. If the boundary flow is not perfect, e.g. due to acoustic interference disturbances from the wind tunnel itself, we can not be sure that the two sensors are subjected to the same types of flow.
6.4 Discussion and conclusion

Based on the new PVG-joint technology a functional and reliable fabrication process has been developed and tested for the realization of miniaturized triple hot-wire sensors. For the first time a 3-D MEMS based flow sensor tested in real flow has been presented. The characteristics of the new flow sensor is summarized in Table 3. To the best of our knowledge this was also the first successful experimental investigation on the applicability for use of free-standing silicon hot-wires in turbulent flows. All earlier investigation on MEMS-based sensors for turbulence measurements have been focused on membrane or wall mounted configurations not suitable for the realization of 3-D sensors. For nearly isotropic grid generated turbulence flows, accurate measurements were demonstrated for the new sensor consisting of a single silicon hot-wire.

The goal of this doctoral investigation, described in section 2.4, was to fabricate a miniaturized 3-D flow sensor and to enable turbulence measurements in all three dimensions (i.e. study the instantaneous velocity vector) in, for example, a turbulent boundary layer at relatively high Reynolds number and small turbulence eddies (small Kolmogorow scales) with such a sensor. It was believed that the accuracy of the fabricated flow sensors described here would not be good enough to put effort in such complicated measurements. 3-D turbulence measurement which requires a look-up table approach where calibration for a lot of wire angles (both the yaw and pitch angles due to the non-circular cross-section) and a large flow interval is needed. However, the turbulence flow investigation on single wires indicates that the MEMS-based 3-D hot-wire sensor had potential for such measurements. A redesign of the prong layout holding the wires and the sensor body itself, aimed to minimize flow blockage is the first step towards a sensor with capacity for measuring the instantaneous velocity vector in all three dimensions. For turbulent wall boundary measurements it is favorable to have all three wires rotated out-of-plane (or folded into the plane as for the sensor design shown in Figure 5) and thereby partially avoid the acceleration of the flow through the narrow gap between the wall and the sensor body. A wire length of 500 µm could remain but the beams sticking out from the sensor body must be much longer to avoid to have interference of the sensor body with the flow. The price for this is larger chip area for each sensor and thus higher manufacturing costs, but the price may be of less importance since 3-D hot-wire probes initially are intended as research tools and not as consumer products. Still it should be possible to fabricate the silicon hot-wire probes in low or medium sized quantities to a price comparable to conventional triple hot-wire sensors. Further, more attention must be paid to the fabrication issues focusing on how to fabricate wires with more symmetrical cross-sections. A symmetrical cross-section (preferably circular from a fluid dynamic point of view but most realistically square from a MEMS fabrication perspective) will simplify the calibration (flow intervals and pitch and yaw angle calibration) required to create the look-up table needed for accurate 3-D turbulence measurements. Further, improvements on the minimization of the capacitance induced cross-talk in multi-wire configurations are needed. This seems to be “easily” obtained by deep etched slots separating the different interconnection wires, doped substrate for grounding, and grounded dummy strips of metals between the “real” metal lead wires for “generalized shielding”.
7 MEMS and micro robotics

The MEMS field is traditionally dominated by silicon micromachining. As described in the introduction section the micromachining field is now focusing on the integration of various functions (sensors, actuators and processing capabilities) in miniaturized systems. Today, when the micromachining field has matured and grown from a technology where simple devices were made (MEM-MicroElectroMechanics) to a technology used for manufacturing complex miniaturized systems (MEMS-MicroElectroMechanics Systems) new problems emerge. For example: How does one assemble these very small devices into larger systems? As early as 1959 professor Feynman addressed “… the problem of manipulating and controlling things on small scale” in his famous APS talk. Feynman’s solution to the microassembling problems was the use of micro-machines which built or assembled other micro-machines consisting of different micro-devices. This approach can be regarded as the hybrid technology contrary to the monolithic approach where all integration is done on one single silicon chip preferably using wafer level assembly [68].

7.1 Micro-assembly for MEMS

The MEMS technology, especially surface micromachining (described in section 3), has the ability to batch fabricate mechanisms that are preassembled in situ and all structures on the whole wafer are released simultaneously by etching of sacrificial layers. This, together with the possibility of integration of CMOS or BiCMOS electronics is a remarkable feature. Micromechanical systems of impressive complexity like linear motors, rotating gears, and linkages between these components have been made with alignment tolerances in the micrometer range in parallel fabrication [54]. To fold mirrors out-of wafer plane several motors are used to achieve a serial assembling controlled externally by electrical signals. The impressive and complex systems achieved with surface micromachining can also be obtained using bulk micromachining where different kinds of wafer bonding [34] and packaging schemes have been used to assemble complete micro-systems of wafer level [35]. However, for many applications the use of lithography, etching and bonding alone could not fulfill the requirements on the system level. Monolithic integration of electronic and micromechanical functions is not always the most suitable. Combining microelectronics, micromechanics, micro-fluidics and/or micro-optics into a single fabrication process inevitably compromises all subsystems. Good examples of the different assembly approaches is found in micro-fluidic systems, as illustrated in Figure 44. Here different active and passive fluidic component such as pumps, valves, mixers, and reactor chambers are needed as well as various kinds of sensors, mechanical actuators and micro-thermal components to form the complex micro total analysis system (μ-TAS). In Figure 44 a) the monolithic approach is illustrated but sometimes it is advantageous to use serial assembly as in Figure 44 b) instead of trying to integrate everything on a single chip. Another aspect of wafer level assembling for micro-systems is the wafer size used for different applications (normally 100 mm or 150 mm wafers for MEMS while 200 mm or 300 mm wafers are or will be the most common for CMOS electronics). Even though the trend is to increase the wafer size for MEMS manufacturing (especially for commercial large volume products) the wafer size used in the IC-industry also increases constantly. This makes assembly by wafer bonding (flip chip etc.) unrealistic. Instead, serial assembly (i.e. “pick-and-place”) is better suited. Such micro pick-and-place systems can be achieved by micro-robotic devices in the form of micro-tweezers and micro-grippers [50-52, 145, 208, 209]. To extend this serial assembling approach further, other micro-robotic components such as conveyers and miniaturized robots (preferably fabricated using MEMS-technologies) are also required, see section 7.5 regarding the concepts on micro-factories and desk-top micromanipulation stations. General reviews of
the different assembly approaches for MEMS have been presented [68] [210]. These two references are recommended as an introduction to micro-assembly. Different aspects of micro-assembly using MEMS based micro-robotic devices will be further addressed in this thesis.

**Figure 44.** Different micro-assembly approaches illustrated by two examples from µ-TAS.

(a) Monolithic µ-TAS: assembly / integration on a single chip (Lab-on-a-chip) [211]

(b) Modular-Hybride µ-TAS: assembly of different micro-components / elements (H1-H4) [212].

Besides the serial “pick-and-place” assembling, parallel approaches are also possible. Pister *et al.* [213] presented a concept where folded boxes using 3D microstructures based on aluminum hinges (see chapter 3.3.2) were used to obtain wafer sized pallets for micro-parts assembly. The micro-parts (e.g. small diced MEMS or electronic chips) are supposed to be randomly transported on the pallet, by an external vibration field or by integrated micro conveyers (see chapters 7.4.1 and 8.3). The boxes with three walls, connected with micro-locks (see section 3.6) and one opening capture the conveyed objects and keep them in place for handling, testing or assembling tasks. Parallel sorting and assembling can also be obtained by other micro-conveyer strategies. Böhringer *et al.* have presented theories on programmable vector fields for advanced control of micro-conveyance systems [214]. Recently, these algorithms were experimentally tested using polyimide thermal bimorph ciliary microactuator arrays with integrated CMOS electronics [80].
Besides the assembling of complete micro systems also other types of assembling is required in MEMS. In section 3 a detailed description of different methods for creating 3D microstructures based on out-of-plane erection were presented. This type of assembling, powered self-assembling of 3-D microstructures, is of great interest since manual assembling is very time, labor and cost expensive. The out-of-plane micro-structure assembling can, in the same way as the system level assembling, be obtained either serially (built in actuation by micro-motors) or parallel batch self-assembling using built in mechanisms for the assembling or by the use of external manipulators (not self-assembly).

Depending on the application, both serial and parallel assembly approaches may be advantageous or disadvantageous. For example, for mass assembly 3D structures, a parallel, one time method is best, while for tracking and scanning devices (like the polyimide based out-of-plane rotated probe presented by Li et al. [215]), individual adjustability may be required.

### 7.2 Definitions of micro-robots

Today we can see a growing interest world-wide on the concept and possible applications for micro-robotic devices including micro-manipulations tools and micro-conveyers and / or micro-robots for locomotive mechanisms. Even though the micro-robotics field currently is an area of intensive research no clear definition of the term micro-robot exists. As stated by other authors reviewing micro-robots [8, 95] all these “micro”-terms, such as ‘micromechatronics’, ‘micromechanism’, ‘micromachines’ and ‘micro-robots’ which are used synonymously to indicate a wide range of devices whose function is related to the “fuzzy” concept of operating at a ‘small’ scale. However, ‘small’ scale is a relative term so a clearer definition is needed.

The definition of micro-robot refers to the features attributed to a robot in the macro world, i.e. a micro-robot should be able to move, apply forces, manipulate objects, etc in the same way as a ‘macro’-robot. The obvious difference between a macro-robot and a micro-robot is the size of the robot. One definition of a micro-robot is: a device having dimensions smaller than classical watch-making parts (i.e. μm to mm) and has the ability to move, apply forces and manipulate objects in a workspace with dimensions in the micrometer or sub-micrometer range [216]. However, it is important that the robot can move over distances much larger than that. Such a definition is quite wide and include several types of very small robots. Since the fabrication technologies used to fabricate these devices play an important role, another more precise subdivision is desirable in order to help identify the practical capabilities of the different technologies. Following the classification scheme of micro-robots used by of Dario et al. [95] and Fatikow et al. [217], one can divide the micro-robot in many different groups. In the definition made by Dario et al. the micro-robots were separated into three different sub-categories, each characterized by the fabrication technology used to obtain the robot and the size of the device, as illustrated in Table 4.
Table 4. Classification of micro-robots according to size and fabrication technology [95].

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) ‘miniature robots’:</td>
<td>having a size in the order of a few cubic centimeter and can be</td>
</tr>
<tr>
<td></td>
<td>fabricated by assembling conventional miniature components as</td>
</tr>
<tr>
<td></td>
<td>well as some micromachines (like MEMS based micro-sensors)</td>
</tr>
<tr>
<td>b) ‘micro-robots’ 6:</td>
<td>defined as a sort of “modified chip” fabricated by silicon MEMS</td>
</tr>
<tr>
<td></td>
<td>based technologies (like batch compatible bulk- or surface-</td>
</tr>
<tr>
<td></td>
<td>micromachining or the micromolding and / or replication method)</td>
</tr>
<tr>
<td></td>
<td>having features in the micro-meter range</td>
</tr>
<tr>
<td>c) ‘nano-robots’:</td>
<td>operating at a scale similar to the biological cell (in the order of a</td>
</tr>
<tr>
<td></td>
<td>few hundred nanometers) and fabricated by nonstandard mechanical</td>
</tr>
<tr>
<td></td>
<td>methods such as protein engineering.</td>
</tr>
</tbody>
</table>

Good examples of ‘miniature robots’ are those competing in the annually “Micro Robot Maze Contest 1992-99” at the International Symposium on Micro Machine and Human Science (MHS) in Nagoya, Japan [218, 219].

While MEMS based micro-robots consist of billions of atoms and are fabricated with the photolithography technology, nanorobots are built by assembling one individual atom or molecule at a time (often by self-assembling chemical means), which can not be done by conventional mechanical principles. Examples of these nanorobots (nano-machines or molecular-machines) and the proposed fabrication methods used to achieve the different components, like gears, bearings and harmonic drives, needed for the realization of a nano-robot are found in the textbook of Drexler [220]. In 1999, the first reports of successful molecular motors were presented [221]. That nano-motor, consisting of a 78-atom molecular paddle wheel, was able to rotate one third of a complete revolution in approximately 3-4 hours. Researchers in the field of theoretical physics are now pushing for further miniaturization and talk about Quantum Machines and Quantum computers which will consist of stretched parts of a single atom [222].

Beside classification by size, micro-robots can also be classified by its mobility [95, 223]. All robots, including the three different classes of micro-robots mentioned above, usually consist of sensors and actuators, a control unit and an energy source. Depending on the arrangement of these components, one can classify micro-robots by the following four criteria:

• locomotive and positioning possibility (yes or no)
• manipulation possibility (yes or no)
• control type (wireless or wires)
• autonomy (energy source on-board or not on-board)

6 To distinguish the true ‘micro-robot’ (i.e. MEMS based robot with micrometer sized components) from the whole class of micro-robots (including mini-, micro- and nano-robots), several more or less confusing notations have been proposed. In this thesis the term “MEMS based micro-robot” is introduced to separate the two similar “micro-robot” terms when that is necessary. Otherwise, one should be able to understand from the context if “micro-robots” is meant as a general term (including both miniature-, micro, and nano-robots) or as the specific MEMS based “micro-robots” term. The term MEMS based micro-robot differs from the notation used by Dario et al., but the content is the same.
Figure 45 illustrates 15 different possible micro-robot configurations by combining the four criteria. As depicted in Figure 45, the classification is dependent on the following micro-robot components: the control (CU), the power source (PS), the actuators necessary for moving the robot platform (i.e. robot drive for locomotion) (AP), and the actuators necessary for operation (i.e. manipulation with robot arms and hands) (AO). Besides the different actuation functions, sensory functions are also needed, for example tactile sensors for micro-grippers or CCD-cameras for endoscope applications (as in Figure 45. a).

The ultimate goal is to create a fully autonomous, wireless mobile micro-robot equipped with suitable micro-tools according to Figure 45 o). Since this is a very difficult task a good start is to investigate the possibility to make silicon micro-robots that are steered and powered through wires, like the one in Figure 45 c), and study their locomotion capability.

The majority of MEMS based micro-robotic devices developed so far could be categorized as movable links (i.e. micro- catheters [98, 99]), according to Figure 45 a) or micro-grippers [50-52, 145, 208, 209] as those in Figure 45 d). Among the research publications for locomotive robots several micro-conveyance systems (Figure 45 b) have been presented [60, 65, 75, 76, 78, 80, 90, 103, 137, 143, 144, 214, 224-229]. Robots using external sources for locomotion could be used (Figure 45 b, f, j n). According to Fatiokow [217] several researchers are working on methods to navigate micromechanisms though human blood vessels; however, these micro-robots are difficult to control. Examples on partially autonomous systems which may be classified as micro-robot systems (compare Figure 45 j) are the concept for smart pills. Centimeter sized smart pills for sensing temperature and / or pH inside the body have been presented [230, 231]. Then the pill is swallowed and transported to the part in the body where one wants to measure. The information of the measured parameter is then transmitted (telemetrically) out of the body. More sophisticated approaches also

*Figure 45. Classification of micro-robots by functionality (modification of earlier presented classification schemes [8, 95, 223]). CU indicates the control unit, PS the power source or power supply, AP the actuators for positioning and AM the actuators for manipulation.*
involving actuators (AM) have been proposed [231, 232]. The position of the pill inside the body is located by an X-ray monitor or ultrasound. As soon the pill is reached the infected area, the active drug included in the pill is released by the actuators onboard. The communication could be obtained by external radio signals, which do not hurt the patient. Different kinds of actuators (AM) are feasible for drug delivery.

Many research groups around the world are working on micro and miniature robots for locomotive mechanisms according to Figure 45 c), g), and k) (i.e. mainly walking robots). Several important results have been presented towards walking micro-robots, fabricated by MEMS technologies and batch manufactured. The surface micromachined robots from University of California at Berkeley, USA (prof. Pister & prof Fearing) [121, 233] and from the MEMS group at Univ. of Colorado, USA (prof. Bright) [60], and the piezoelectric DRI-etched micro-robot [104] from CSEM/IMT-Switzerland (prof. de Rooij) for which a suitable low power ASIC for robot control have successfully been tested [103] should be mentioned. The large European Esprit-project MINIMAN [234] with the goal of fabricate movable micro-robotic platforms with integrated tools with 6 degrees of freedom for application such as micro-assembly within a sweep electron microscope (SEM) involves different MEMS / MST research groups from Univ of Karlsruhe-Germany (prof. Fatikow), Univ of Pisa-Italy (prof. Dario) and Uppsala Univ.-Sweden (S. Johansson) etc. Further, miniature robot systems with MEMS/MST components [235, 236] have been developed at ETH-Zürich and the microengineering department at EFPL-Lausanne (prof. Clavel, prof Siegwart et al.) Switzerland, several research publications on gnat mini-robots and actuator technologies for MEMS micro-robots [237, 238] has reported by different research groups at MIT, USA (A. Flynn, prof. Brooks et al.) in the early 90’s and also several groups in Japan are involved in miniature robotics based on MEMS devices. In Japan an extensive ten year program on “micromachine technology”, supported by the Ministry of International Trade and Industry (MITI) started in 1991. One of the goals with this project is to create micro and miniature robots for micro factory, medicine and maintenance applications. Several micro-robotic devices including locomotive robots and micro-conveyers have been produced within this program. Miniature robot devices or vehicles [175], for locomotive tasks, containing several MEMS components has been presented, but no experimental results on MEMS batch fabricated micro-robots suitable for autonomous walking (i.e. robust enough to be able to carry its own power source or powered by telemetric means) have been presented. Besides the walking micro-robotic devices, several reports on flying robots [10, 239-241] and swimming [242, 243] robots have been published. The micro-motor and gear box shown in Figure 1 b) is used to build small flying micro-helicopters, which are commercially available as rather expensive toys. Besides the pure mechanical micro-robots, hybrid system consisting of mechanical and electrical components and living organisms have also been reported [244].
7.3 Micro-robotic Applications

From being only theoretical ideas in the 60’s and 70’s, new exciting practical results for building complex systems and “micromachines” on a chip started to emerge in the late 1980’s when spinning surface micromachined micromotors made of polysilicon were fabricated on a silicon chip, as illustrated in Figure 1 a), by researchers at the University of California at Berkeley [245]. Several papers on ideas for making MEMS based micro-robotic devices to be use in a variety of applications using such micro-motors were published in the late 1980’s and early 90’s [166, 237]. Now, ten years later one finds publications on micro-robotic devices for practical use (at least on a research level) in various fields. One of these application fields is medicine [98, 99, 246, 247]. In surgery the use of steerable catheters and endoscopes, as illustrated in Figure 46, are very attractive which may be further miniaturized by MEMS based micro-robotic devices which will allow advanced computer assisted surgery (CAS). Smaller and more flexible active endoscopes are needed which assist the surgeon and can react to instructions in real-time. They may enter into the blood vessels and enter various cavities (angioplasty) by remote control, where they carry out complex in-situ measurements and manipulations (gripping, cutting, applying tourniquets, incisions, suction and rinsing operation etc.) In order to meet these demands, an intelligent endoscope must have a microprocessor, several sensors and actuators, a light source and possibly an image processing unit integrated in it. These micro-robotic devices will revolutionize classical surgery, but their realization is still a problem because of friction, poor navigability, bio-compatibility etc.; they are also not small enough yet [8].

Figure 46. Example of a micro-robotic application. In minimal invasive surgery (MIS) MEMS based micro robotic devices for endoscopic application such as steerable catheters, micro-grippers and other micro-tools are expected to have a deep impact in the near future. (Illustration published with permission from Surgical Vision Ltd. Courtesy Graham Street).
Other interesting areas for micro-robotic devices are production (micro-assembly [68, 248], micro-factory [249, 250]), metrology [215] (automated testing of microelectronic chips, surface characterisation, etc.), inspection and maintenance [251], biology (capturing, sorting and combining cells [145]), bio-engineering [97], micro-optics (positioning of micro-optical chips, micro-lenses, and prisms [252]). Many of these applications require automated handling and assembly of small parts with accuracy in the sub-micron range.

7.4 Arrayed actuator principles for micro-robotic applications

For most micro-actuators the force that can be generated and the load the actuator withstands are limited. This constitutes a fundamental drawback for all miniaturization in the robotic field. However, by using microfabrication to fabricate the actuator it is easy to fabricate large arrays of actuators where the actuators are working together and thereby increasing the force and load capability. This approach, which better takes advantage of the lithographic fabrication, also have the potential for integrating electronics on the robot chip for more sophisticated tasks (e.g. autonomous micro-robots). The concept of array configuration of micro-actuators, where the cooperative work of many coordinated simple actuators generates interaction with the macro world, was introduced by Fujita and Gabriel in 1991 [253]. They called their technique for distributed micro motion systems (DMMS). The driving schemes for the actuators in the array can be either in a synchronous mode (all actuators are switched on and off at the same time) or by an asynchronous mode (different actuators are switched on and off at different times). Most often the asynchronous mode is favorable since it is more effective and smoother movements can be achieved. Intelligent control of the actuation schemes for the actuators can be achieved by integration of sensors in the system [78]. Based on information from these sensors (object weighing and / or location) advanced control of each actuator can be obtained for improved functionality of the micro-system.

As stated above, most micro-actuators generate relatively small forces and strokes, but this could partially be solved by array configuration. However, there are large variations between how different actuation principles scale to micro-scale, some principles scale more favorably than others. Several theoretical reports on the scale effects and the applicability of various actuation principles for micro-robotic devices, have been published [17, 95, 166-168]. Some actuators, for example, piezoelectric and electrostatic based actuators, have the advantage of low power consumption and can be driven at high speeds (kHz regime and above), but generally they also show low force capacity and small strokes while others such as magnetic and thermal actuation principles have potential to exert large forces and displacements. On the other hand, these actuation principles rely on significant currents and / or powers which may require forced cooling. During the design of a micro-robotic device, the trade-off between range of motion, strength, speed (actuation frequency), power consumption, control accuracy, system reliability, robustness, load capacity etc. must be taken into consideration. In the extensive actuator review focusing on micro-robotics presented by Fearing [17], the general conclusion was that actuators generating large strokes, and high forces are best suited for micro-robotics applications. The speed criteria are of less importance as long as the actuation speed is reasonably high (in the range of a couple of Hertz up to thousands of Hertz). In Table 2 some data on stroke and force generation capability as well as power densities and efficiencies for a small selection of actuators suitable for micro-robotic applications is given.

For locomotive micro-robotic applications such as conveyance and walking robots it is essential to have actuators which both can generate forces to lift an object or the robot itself out from the plane
(i.e. to avoid surface sticking) and also can generate forces that could cause movements in the in-plane direction. Two fundamental principles exist. First, contact-free (CF) systems can be used. Here different force fields, such as electrostatic, magnetic or pneumatic forces, are used to create a cushion to separate the object from the surface. To drive the device in the in-plane direction, these force fields could have a direction dependence, which forces the device forward (i.e. directed air streams for a pneumatic system [65] or the Meissner effect for levitation and orthogonal Lorentz force for driving a magnetic actuator system [225]). The other fundamental principle is contact (C) systems, where a structure is in contact with the moving object (e.g. legs for walking). To avoid surface stiction these structures must create out-of-plane movements. In Chapter 3 a review of different techniques to create such 3-D actuators were given. Most of those techniques described there could be arranged in array configurations for distributed micro-motion systems (DMMS).

For externally powered out-of-plane actuators, described in section 3.4, it is difficult to control each individual actuator in a large array of folded structures. Therefore, a synchronous jumping mode is used to convey the objects or move the device itself. This jumping mode involves quick actuation of all the actuators simultaneously, which forces the object to jump. When the object lands on the actuators (located in their in off position), the object has moved a small distance and the actuators can be actuated again to move (walk or convey) further.

Living organisms very often offer good models for designing micro robotic systems [75, 254]. Mimicry of the six legged insects gait [254] has been proposed for the design of multi-legged robots implemented using microfabrication techniques [60]. The first proposed [71] and realized [75] MEMS contact transportation system was based on the ciliary motion principle adopted from nature. The principle for a ciliary motion system (CMS) is illustrated in Figure 47. The CMS principles rely on an asynchronous driving technique which requires at least two spatially separated groups of actuators which are turned on and off at different times, alternately holding and driving the device. Higher speeds and smoother motions can be achieved with such asynchronous driving than with synchronous driving.
**Figure 47.** The ciliary motion principle.  
**a)** Conveyance system used in nature to convey objects from [253].  
**b)** The first micro-conveyor system based on the ciliary motion principle using bimorph polyimide legs, from [76].  
**c)** A two phase ciliary motion system (CSM) for a walking micro-robot platform when implemented using MEMS technology for out-of-plane working 3-D actuators. By using two rows of legs the robot is possible to steer in the forward-backward, left-right and up-down directions.  

7.4.1 Micro-conveyers

During the past recent years, a variety of MEMS concepts for realization of locomotive micro-robotic systems in the form of micro-conveyers have been presented [60, 65, 75, 76, 78, 80, 90, 103, 104, 137, 143, 144, 214, 224-229, 255]. Some of these concepts are summarized in paper 5 (see Table 1). There the micro-conveyers are classified in two groups: contact-free or contact systems, depending on whether the conveyer is in contact with the moving object or not.

Contact-free systems (denoted CF), have been realized using pneumatic, electrostatic or electromagnetic forces creating a cushion on which the mover levitates. Magnetic levitation can be achieved by using either permanent magnets, electromagnets or diamagnetic bodies (i.e. a superconductor). The main advantage of the contact-free systems is low friction. The drawback of these systems is their high sensitivity to the cushion thickness (i.e. load dependent) while the cushion thickness can also be quite difficult to control. Also, this kind of conveyance system often has low load capacity.

Systems where the actuators are in contact (denoted C) with the moving object have been realized based on arrays of movable legs erected from the silicon wafer surface. The legs have been actuated by using different principles such as thermal, electrostatic and magnetic actuation. Both synchronous driving [137] and the more complex, but also more effective, asynchronous driving mode have been used.

The magnetic [227, 228] and pneumatic [65] actuation principles for contact free conveyer systems has a disadvantage since they need a specially designed magnet mover or slider which limits its usefulness. With a contact system based on thermal actuators it is possible to move objects of various kinds (non magnetic, non conducting, unpatterned, unstructured etc.). However, the increased temperature of the leg in contact with the conveyed object may have limitations in some applications. The contactless techniques have been developed mainly to meet the criteria needed for cleanroom environment where the contact between the conveyer and the object, for a contact system, may generate particles which then could serve to restrict its applicability for conveyance in cleanrooms. Further details about different micro-conveyance systems are found in the introduction chapter of paper 5.

7.4.2 Walking MEMS micro-robots

In principle, most of the micro conveyer structures described in the previous section could be turn up-side-down to realize locomotive micro-robot platforms. For the contact systems that means that the device will have legs for walking or jumping. The contact free systems relying on levitation forces will fly over the surface rather than walk. Such systems seem more difficult to realize than the contact operating robots. The focus for the rest of this section is therefore on contact micro-robot systems for walking.

Even though it seems straightforward to turn a micro-conveyer up-side-down, most of the existing conveyers do not have enough load capacity to carry its own weight. Further, there are problems on how to supply the robot with the required power. As illustrated in Figure 48, power supply through wires may influence the performance of the robot operation range and the stiffness of the wires may degrade the controllability too much. On the other hand, telemetric or other means of wireless power transmission requires complex electronics on the robot. Since many actuators proposed for micro-robotics, see section 3, require high power consumption, the limited amount of power that can be transmitted through wireless transmission is a big limitation for potential application areas. To avoid the need for interconnecting wires, designs based on solar cells have been proposed and low-power
consuming piezoelectric actuators [103, 104], electrostatic comb-drives [121] or inch worm actuators [233] suited for such wireless robots have been planned to be used. For wire-powered robots a limited amount of wires is preferably which implicates that simply actuation schemes of the legs of the robot (i.e. on-off actuation) is required if complex onboard steering electronics should be avoided. Several proposals of how to make totally MEMS-based micro-robots with the possibility for locomotion (e.g. walking) have been presented either powered with wires or without wires.

Several different principles used to actuate the different legs on a walking micro-robot have been proposed. Most of them mimicking principles used in nature. Some of the most feasible principles for walking MEMS micro-robot platforms are listed beneath:

- **Ciliary motion** used by Ebefors et al. [155] for eight-legged robots, illustrated in Figure 47.

- **Elliptical leg movements** adopted from the animal kingdom have been proposed by Ruffieux et al. [103, 104], and illustrated in Figure 49.

- **Gait mimicry of six-legged insects** (similar to that of a crab [254]) have been proposed by several research groups, for example the six-legged micro-robot by Yeh et al. [121, 233] and the multi-legged micro-robot prototype by Kladitis et al. [60]. This concept is illustrated in Figure 50 (see also Figure 10 b).

- **Inch-worm robots** [168] or **Slip and stick robots** [235], mimicking an inchworm or caterpillar are attractive micro-robot walking principles since these techniques take advantage of the frictional forces rather than trying to avoid them. The scratch drive actuator, illustrated in Figure 20 works according to this principle, i.e. by firmly attaching the surface with only half of the robot or actuator body, then extending the spine (or middle part) of the body, before anchoring the other half, releasing the first grip, shortening the spine, swapping the grip and so on in a repeatable forward motion.

- **Vibration fields and resonating legs** used by Shimoyama et al. [128], illustrated in Figure 51.

Since friction always poses a serve restriction on micro-robots due to their small size, solutions that take advantage of this effect (i.e. inch worm robots) rather than trying to avoid it are the best suited robots for micro-gait. This trend can also be seen in the evolution of micro-motors. Nowadays, many researcher try to avoid bearings or sliding contacts in their motors, as in Figure 1 and Figure 50 and instead make use of friction in inch-worm motors [233] or actuators with flexible joints [127, 155] without the drawback of wearing out.
Figure 49. The rotational leg walking principle. A few hundreds of cells (shown at the right part) are arranged into a hexagonal array, inside a triangular grid frame that provides stiffness and room for interconnection. The simplest gait requires two phases so that half the actuators are in contact with the ground, where friction transmits their motion to the device, while the other half is preparing for the next step (compare the CMS-technique depicted in Figure 47). The bottom figure illustrates the serial interconnections of the actuators resulting in six independent groups of beams. From [104].

The main problem associated with the fabrication of silicon robots is to achieve enough strength in the movable legs and in the rotating joints. Most efforts to realize micromachined robots utilize surface micromachining techniques which results in relatively thin and fragile legs. Pister et al. [121] proposed the surface micromachined micro-hinges, describe in section 3.3.1 for joints, poly-Si beams for linkage to the triangular polysilicon legs and linear electrostatic stepper motor actuation for the realization of a micro-robot, as illustrated in Figure 50. A similar approach for walking micro-robots was used by Kladitis et al. [60]. They also used the micro-hinge technique to fold the leg out-of-plane but instead of comb-drives for actuation they used the thermal heatuators, as illustrated in Figure 10 b). To further improve the leg robustness and load capacity of their robot the used 96 legs arranged in 6 groups instead of using a six- legged robot. However, that robot structure could “only” withstand a load four times the dead-weight of the robot. That was not enough to obtain locomotion.

For both micro-robots described above, which were based on the micro-hinge, the polysilicon legs were manually erected out-of-plane. The use of a the micro-hinge technique may cause problems because of wearing. Miura, Shimoyama et al. [127, 257] introduced the concept of creating insect-like micro-robots with exoskeletons made from surface micromachined polysilicon plates and polyimide (friction less) joints, illustrated in Figure 18. These micro-robots were powered externally by a vibrating field (i.e. no cables were needed) as illustrated in Figure 51. By cleverly designed robot legs having different masses and spring constants and thus different mechanical resonance frequency, the leg to be actuated can be selected by applying a certain (resonance) frequency. The robot could then be shaken in a controlled way to walk forward and left-right as illustrated in Figure 51 b). The need for a vibrating table to achieve the locomotion strongly limits the applications for this robot. The thin legs also mean that the robot sticks easily to the vibrating table by surface forces. This means that the surface which the robot walks on needs to be insulating.
Figure 50. Top: First version of the micro-robot prototype based on surface micromachined micro-hinges (see section 3.3.1) for joints, each leg has three degrees of freedom and is comprised of two 1.2 mm long rigid polysilicon links and electrostatic step motors for movements (not included in the SEM-photo).
Bottom: Concept for a new design based on a solar-powered silicon micro-robot. Various components will be made separately and then assembled. Surface micro-machined hinges are used for folding the legs. Each leg has two links and each link will be actuated by an inch worm motor. (Published with permission from Kris Pister).
[M]: More photographs on the micro-robot prototype, in relation to this figure, are available at the photo gallery of Rich Yeh at: http://www-bsac.eecs.berkeley.edu/~yeh/sems.html
Figure 51. (a) The principle for a selective power supply through a vibrating energy field. The micro-robot has several resonant actuators with mutually exclusive resonance frequencies. The power and control signals to the robot are obtained via the vibrating table. (b) The four possible kinds of actions. (c) Photograph of the 1.5 x 0.7 mm² sized surface micromachined micro-robot. The different legs have different spring constants and masses resulting in different resonance frequencies. Polyimide is used for the soft springs and polyimide joints are used to create the erected leg (see Figure 18). From [128].

For robots based on ciliary motion systems, the robot is easily steered forward and backward by changing the phase-shift between $x^+$ and $x^-$, as illustrated in Figure 47 b). By designing the robot like an ant with two rows of legs, the robot could be steered in the right-left directions by driving the left and right legs at different speeds or stroke length (in the same way a caterpillar does).
There are four different approaches to steer a micro-robot to the left and right by imitating a caterpillar:

- **phase**: one side is driving forward and the other side is driving backwards (or is turned off).
- **power**: longer stroke lengths ($\Delta x$) on one side by increasing the power (also means higher steps ($\Delta y$) => the robot walks with a stoop).
- **frequency**: increasing the number of steps on one side (means smaller steps ($\Delta x$ and $\Delta y$) => the robot walks with a stoop).
- **combination of frequency and power**: (equal stroke length but faster on one side => “smooth” robot movements).

Another approach to obtain steerable walking robots is the use of large 2-D arrays [60, 103, 104] with several rows of legs oriented both in x- and y- directions. For these systems, onboard electronics is probably required for minimizing the amount of wires required for the steering signals.

Further aspects on different locomotive micro-robots are found in the introduction chapter of paper 6.

### 7.5 Micro-factories and micromanipulation desktop station

In his famous APS-presentation, Feynman anticipated the use of small machines building smaller machines or systems [1]. However, this has not been realized yet. Rather, we use larger and larger machines to achieve miniaturization and to study physics at a very low scale (e.g. the huge accelerator facilities, like the one in CERN, Switzerland used to study the smallest particles in the atom).

From the perspective that MEMS is just the next step in the silicon revolution in that silicon integration breaks the confines of the electrical world and gives it additional dimensions for interacting with its environment through sensors and actuators, Feynman’s ideas are not exactly accurate today. Today, the equipment’s used for silicon manufacturing are very large and expensive but have the very attractive feature of batch fabrication. This allows the possibility to achieve lowcost devices in large quantities. However, there are manufacturing concepts other than the IC inspired batch silicon MEMS fabrication, which most often have the drawback of requiring large volumes to be cost effective since the equipment is large and expensive. During the last decade, efforts have been made on the concept of micro-factories, especially in Japan [249, 250]. In this concept miniaturized versions of traditional tools typical for local processing (like drilling, milling etc. [66]) are used rather than the parallel (batch) approach used in the IC industry. The idea with the **micro-factory** approach is primarily to allow small devices to be made. Often aspects such as possibilities to save energy, space and resources are also addressed. It is still impossible to predict if these techniques will ever be competitive with standard parallel batch processing, but two important advantages have already been demonstrated: flexibility and geometrical freedom. The main challenge is the slow processing time associated with high precision machining. One potential solution to this problem might be to use micro-factories where a great number micro-robotic devices (conveyors and robots) are working in parallel supporting the micro-tools with material [258-260]. In this multi-robot system the challenge is to obtain autonomous communication between the different micro-robots. Very few research publications have been presented in this field. In nature, the ant creates an odor trail to guide fellow ants. Shimoyama *et al.* have been working on hybrid systems consisting of mechanical parts and living organisms. By using “living sensors” in the form of insect antennae they were able to steer and control a mobile robot by pheromone stimulation [261]. Aoyama *et al.* [262] have presented inch-sized robots who leave behind a magnetic footprint which can be detected by other robots for communication and motion guidance, as illustrated in Figure 52. These footprints are fade out with time allowing continous and advanced motion involving several miniature robots.
Similar to the micro-factory concept is the “Automated Desktop Station Using Micromanipulation Robots” proposed by Fatikow et al [248, 263, 264] and is illustrated in Figure 53.

**Figure 52.** Communication between miniature robots. The following robot follows the leader by a magnetic trace. (Published with permission. Courtesy of prof H. Aoyama, University of Electro-Communications, Tokyo)

**Figure 53.** Concept of the flexible microrobot-based microassembly station (FMMS). (Courtesy prof S. Fatikow, University of Karlsruhe).
8 Micro-robotic devices using PVG-joint actuators

A variety of actuator applications are possible using the PVG joint in the dynamic mode. Since the 3-D flow sensor uses the PVG-joint the natural continuation of that project would be to integrate actuators for flow control. Actuator systems for active control and drag reduction in fluid dynamic [26] using the PVG-joint may be possible. The drawback for the 3-D actuator structures obtained with the PVG-joint is the difficulty to obtain a “flat” surface profile. The permanently out-of-plane erected structure may cause unwanted disturbances into the flow. This static bending can be limited by modifications in the curing process of the polyimide or using other materials with lower thermal shrinkage coefficient. However, the structures would probably still be bent out of plane due to the stresses in the material used to fill-up the V-groove. Further, the power consumption is rather high resulting in that the power required to obtain a drag reduction may be larger than the gain from the reduction. Some of the other out-of-plane actuation techniques described in chapter 3 seem to be more suitable for active control applications and therefore no further investigation has been made on the applicability for use of the PVG-joint technique for active flow control. However, there are other actuator applications where the PVG-joint is more suitable, for example micro-robotic (e.g., micro-grippers, micro-conveyers, micro-robots, micro-manipulators). One of the advantages of using the polyimide based micro-joint is the possibility to generate large forces and large displacements as well as easy integration in array configurations. In micro-robotics these are important parameters while the actuation speed for the out-of-plane actuator is of less importance. For other applications such as micro-optical systems (e.g., bar-code readers and deflectable mirrors for display systems) the requirements on force and displacements are not very important but instead high actuation speed for the erected structure is the critical parameter. With this in mind, a spin-off project with the goal of fabricate a walking micro-robot platform was established to demonstrate and exemplify the possibilities for the PVG-joint in actuator applications. The results from that project are described in this chapter as well as in paper 5 and 6.

From a fabrication perspective a walking micro-robot platform and a micro-conveyor is very much the same device but from an evaluating perspective these two devices show large differences. Several publications on successfully tested micro-conveyor systems has been reported [60, 65, 75, 76, 78, 80, 90, 103, 104, 137, 143, 144, 214, 224-229, 255]. Successful realization of walking micro-robots by flipping a conveyer structure (i.e., from a conveyer position lying on its back with the leg struggling in air to a walking position standing on its leg) has not been presented. The two fundamental reasons to this is the lack of sufficiently protruding structures, i.e., not long enough out-of-plane erected legs, since both mechanical and electrical interfaces for most designs have to be on the same side of the substrate as the erected legs (i.e., on the robot belly). Further, the robustness and load capacity of the erected legs for most fabricated conveyers have been relatively poor. In many cases the conveyer structure could not withstand its own weight when turned up-side-down but also the strokes obtained during actuation of these conveyer chips were small. Therefore, the structures stick to the surface when turned up-side-down as a robot. With this in mind we started to do the necessary fundamental tests for distributed PVG-joint actuators in array configuration on a conveyer structure instead of the walking robot chip because of the simpler experiment set-up. However, the conveyer chip is almost the same as the robot chip and they have been fabricated in the same batches. After the batch fabrication steps the conveyer is ready to be tested while the micro-robot need some more critical fabrication steps.
The fabrication steps for the micro-conveyer is much simpler than for the robot, since no chip dicing and bonding of wire interconnections were needed as in the case of the micro-robot realization. Thus the starting point was to carefully evaluate the micro-conveyer (described in section 8.3 and paper 5) before starting with the walking robot. The experiments on the first walking MEMS micro-robot will be described in section 8.4 and paper 6.

8.1 Arrayed PVG-joint actuator principles for micro-robotic applications

Several different approaches for conveyance and walking micro-robot systems were feasible for the PVG-joint technology. A simple device with few interconnection wires seems to be most suited for a walking micro-robot. Since the PVG-joints allows separate actuation of the structures on a chip, the asynchronous ciliary motion principle used by Fujita et al.[75, 76] were chosen because of its easy “on”-“off” actuation scheme and effective motion. This technique was first tested for a 1-D micro-conveyer based on the PVG-joint actuators, as illustrated in Figure 54. Depending on the static bending angle (“off” position) different features for the motion could be achieved. As shown in Figure 30, the PVG-joint results in both a horizontal, $\Delta x$, and vertical, $\Delta z$, displacement when the joint is heated. Most often fast and accurate conveyance in the in-plane direction is desirable, then the best situation is to have the legs rotated slightly below 90°. In this way smooth movements and the maximum load performance are obtained. Most of the energy goes to transport the object laterally with only minor vertical movements. To obtain as large displacements as possible it is advantageous to have as many V-grooves as possible in the joint. However, the present fabrication process which completely imidizes the polyimide using a curing temperature above 350°C only enables a few V-grooves, when the bending angle should not exceed 90°. A smaller thermal shrinkage and, thereby, a smaller static bending angle is achieved when the polyimide joint is cured at lower temperatures. This means that more V-grooves could be included in the joint and the static bending angle would still not exceed the critical 90° bending. However, for not fully cured polyimide joints there is a risk for ageing and drift. As discussed in paper 5 there are possible solutions to get around this problem. Another feasible design is to have the legs rotated approx. 115° or more out-of-plane as “off” position, illustrated in Figure 54 a), and then make sure that the legs in the “on” position do not bend back more than to the critical 90° position.

For most of the presented research results about micro-conveyer systems up to today the focus has been on the in-plane conveyance function (i.e. $x$- or $x$- and $y$- conveyance). The relatively large displacements obtained with the PVG joint technology also provide a big advantage in applications where the vertical position, $\Delta z$, of the moving object must be controlled (e.g. micro-optics and microscopy). This is done in-phase heating of all the legs simultaneously. In this case it is favorable to have the static bending angle close to 180° where much of the energy goes to transport the object vertically with only minor horizontal movements, as illustrated in Figure 54 b). The levering effect for micro-optic applications such as focus adjustment is easily controlled by the heating power.

Since the device originally was designed to achieve a walking micro-robot the arrayed actuators just consist of 2 rows. This allows for steering the robot like a caterpillar, as described at page 96. For a conveyance system it is enough to test the possibility to rotate an object on the leg, but advanced 2-D conveyance will require actuators oriented in both $x$ and $y$ directions [80]. The conveyer should therefore be regarded as a good and easy platform to test fundamental functionality for the walking micro-robot and not as a complete conveyer system. However, the results from the test on the “1-D” conveyer can easily be used for realizing 2-D conveyers.
Both micro-motion systems consist of a 15 x 5 mm$^2$ chip. The micro-conveyor has two rows of six legs with a length of 500 µm namely 12 legs per chip. The micro-robot has two rows of four legs with 1 mm length namely eight legs per micro-robot.

![Diagram of micro-conveyor and micro-robot](image)

**Figure 54.** a) Operation principle for the 1-D micro conveyor in conveyor mode. The legs have been erected to 135° as the steady-state position. A displacement equal to $2\Delta x$ is obtained during one period due to the fixed phase difference of +90° between the two sets of legs. For –90° degrees phase-shift between $x^+$ and $x^-$ the result is displacement in the opposite direction. b) Operational mode for the micro-conveyor in lifting (levering) mode. The actuation of both sets of actuators are done in-phase.

### 8.2 Fabrication of the PVG-joint based micro-robotic devices

The fabrication scheme for the micro-conveyor is basically the same as for the test structures described in section 4.3, but several legs are fabricated close to each other on the same chip. To limit the amount of external wires needed to supply the device with power and control signals, parallel interconnection of the arrayed legs is used on the chip, with the result that only three (or five) wires have to be externally connected to the chip. A critical aspect of micro robotic systems based on arrayed actuators and distributed (or collective) actuation is the problem associated with the need for very high yield of the actuators [103]. Even one single non-working actuator could destroy the whole motion principle. For the PVG-joint based micro-robotic devices this is partially solved by the used of parallel interconnection scheme, since not all actuators/legs then need to have perfect functionality. If one leg is broken all the others are still functional, since the power supply line is connected in parallel (see Figure 55) instead of the serial connection which is the most often used design for distributed micro-systems.

In the initial test structure fabrication the control of the bending angle was quite poor ($\pm 2^\circ$ variations per V-groove over a whole wafer as described in section 4.4.1.1). For micro-robotic application the position of the legs is a critical parameter. Any divergence of leg position means that one or more of the legs are sticking up above the others, thus reducing the efficiency of the motion
since the leg must overcome both the surface roughness and the variations between the different static leg positions before any motion occurs. Throughout the process developments large improvements of the bending angle variations have been achieved. These variations are caused both by static variations, for example fabrication process inhomogenities such as non-perfect thickness control of the polyimide when spinning on structured wafers etc., as well as dynamic variations caused by differences in, for example, the heating resistors and the polyimide behaviour. For the conveyer test structure with twelve legs on the same chip, these bending angle variations were measured to be less than 0.3° (equal to 3 µm variations in height between the legs) for both three and four V-groove polyimide joint actuators.

Figure 55. (a) Photograph showing different non-diced conveyer (and robot) structures used to demonstrate the function of the PVG-joint based micro-conveyer. One conveyer consist of 2 rows of legs (12 silicon legs in total). The two set of legs (6 each of x+ and x-) are indicated in the photo. For the conveyer with 5 bonding pads, the right and left rows of can be controlled individually resulting in a possibility for rotational conveyance motions. (b) SEM photos of 500 µm long legs.

[M]: Related to this figure are videos showing dynamic actuation test on the 500 µm long legs shown in the SEM-photos above and the various conveyance test performed. http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html.

Several different versions of the combined micro-conveyer and micro-robot chips have been fabricated as well as some test structures for micro-grippers. The different conveyer and robot versions are:

- Polyimide joint actuator variants: with 3 and 4 V-grooves
- Leg versions: 2x6 with a length of 500 µm (for conveyance) and 2x4 with a length of 1000 µm (used for the walking robots)
- Steering versions: two groups of four or six legs (3 bonding pads for back and forth) and four groups of two or three legs (5 bonding pads for back and forth + right and left)
- Two DOF-legs (both knee and ankle joint) for walking up/down steps or on rough surfaces.
The polysilicon heaters are used instead of the serpentine metal heaters (see Figure 29 and Figure 30) since then both a lower power consumption and a lower thermal cross-talk between different legs in the array is obtained.

The micro-robot is more complicated to fabricate than the conveyer structure since each individual robot needs to be separated from the wafer. Several processes (dicing, etching, and mechanical breakage) have been tested to separate the different chips with erected 3-D structures. The best solution found so far, which also was used for the triple hot-wire sensor fabrication described in paper 4, is to dice the robot-chip from the backside while the front-side (leg side) is protected with a "dummy" wafer. This means that the robot is diced before the legs have been erected out-of-plane and problems associated with breakage of erected 3-D structures close to the dicing track is avoided. The price to pay is that the polyimide curing has to be done on individual robot chips. Quasi-batch fabrication could still be used in the last fabrication steps (i.e. solvent-cleaning and polyimide curing). Finally, the micro-robot chip is electrical connected to the out-side world by long (10 cm) and very thin (25-30 µm) gold wires attached to the bonding pads using common wire-bonding technique.

8.3 Micro-conveyers using PVG-joint actuators

Paper 5 describes experiments on moving flat "medium sized" objects in the millimeter range on a one-dimensional demonstration conveyer primarily fabricated as a walking micro-robot and therefore not allowing true 2-D conveyance since all actuators are oriented in only one direction. Load, speed, robustness, simple steering (rotational movements as well as forward-backward motions) and power consumption tests have been performed to characterize the micro-motion system. Figure 56 shows the fabricated one dimensional micro-conveyer during a load test. The weight of the moved object is 2 g. The characteristics of the micro-conveyer are summarized in Table 5 and further details are given in paper 5.

Figure 56. The fabricated micro-conveyer during a load test. The 2 g weight shown in the photo is equivalent to 350 mg on each leg (or 16,000 times the weight of the legs).

[M]: Related to this figure are videos from the various load tests that were performed on the micro-conveyer: http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html
Table 5. Characteristics of the fabricated micro-conveyer.

<table>
<thead>
<tr>
<th>Materials</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Legs</td>
<td>bulk silicon</td>
</tr>
<tr>
<td>Micro-joint</td>
<td>polyimide (HTR-3 200 from OCG)</td>
</tr>
<tr>
<td>Heating resistor</td>
<td>p⁺⁺ polysilicon (boron-ion implanted)</td>
</tr>
<tr>
<td>Heat and electricity conductors</td>
<td>aluminum</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions / Configuration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip size</td>
<td>15 x 5 x 0.5 [mm]</td>
</tr>
<tr>
<td>Leg</td>
<td>500 x 600 x 30 [µm]</td>
</tr>
<tr>
<td>Number of legs</td>
<td>2 sets of legs (⁺⁺ and ⁻⁻) with 6 legs in each</td>
</tr>
<tr>
<td></td>
<td>4 sets of legs with 3 legs in each</td>
</tr>
<tr>
<td>Conveyance objects</td>
<td>Silicon chips (polished 2 x 10⁻³ µm surface roughness)</td>
</tr>
<tr>
<td></td>
<td>Silicon chips (unpolished 2.5 µm surface roughness)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum convey velocity, ( v )</td>
<td>12 mm/s (@ ( f = 250 \text{ Hz and } P_{\text{mean}} = 1.3 \text{ W} ))</td>
</tr>
<tr>
<td>Maximum out-of-plane lifting</td>
<td>30 µm (for the 90° erected leg)</td>
</tr>
<tr>
<td>Position accuracy</td>
<td>Better than 5-10 µm</td>
</tr>
<tr>
<td>Conveyance distance</td>
<td>± 3 mm (or ±45° for rotations)</td>
</tr>
<tr>
<td>Load capacity</td>
<td>&gt; 3500 mg dynamically</td>
</tr>
<tr>
<td></td>
<td>&gt; 6500 mg statically (possible for conveyance when released)</td>
</tr>
<tr>
<td>Power denisty (whole conveyer)</td>
<td>≈ 2000 W/m³</td>
</tr>
</tbody>
</table>

Intelligent control of the actuation schemes for the actuators can be achieved by integration of sensors in the conveyer system. Suh *et al.* [78] have investigated the use of capacitive sensing of the moved object in a micro-conveyer system. Mimicking the functionality used by many insect, *i.e.* resistive strain gauges located on the leg [254] is easy to integrate in a thermal actuator system were the heating resistors already are fabricated. For the PVG-joint based micro-conveyer, no additional fabrication steps are needed to realize piezo-resistive strain gauges on the legs to extract the weight and/or location of an object on the legs. The polysilicon layer used as heaters in the PVG-joint are very well suited for piezo-resistive sensing. Preliminary tests have shown that it is possible to use such leg located resistors as force sensors together with the PVG-joint. However, further investigation on how the piezo-resistors act when the PVG-joint actuators are used in dynamic mode is needed to clarify the impacts of the relatively high temperature variations on the piezo-resistors. By optimization of the doping level used to ion implant dopants into the piezo-resistors very low temperature sensitivity can be achieved (*i.e.* TCR=0 ppm/°C [200]) which in combination with a full Wheatstone bridge configuration could eliminated most disturbances from the temperature variations on the leg caused by the actuation and heating of the PVG-joint. Based on information from these piezo-resistive tactile sensors, advanced control of each actuator can be obtained for improved functionality of the micro-conveyer system. Among other approaches for feed-back information is the use of CCD-camera(s) as illustrated in Figure 53 one of the most suitable.
8.4 Walking MEMS micro-robots

The goal for the micro-robotic project was to obtain a walking MEMS micro-robot. The tests performed for the conveyer described in the previous section were a first step towards this goal. From the conveyer test the required external steering electronics were fabricated and optimized.

8.4.1 Additional fabrication steps for the micro-robot

Before the polyimide curing step in the fabrication process (see section 4.3) the micro-robotic batches were split into two parts, one for processing micro-conveyers (similar to the process described in section 4.3) and one for manufacturing micro-robots. After the backside KOH-etch and the oxide etch the micromachined wafers were diced by sawing from the backside. The protective wafer on the front-side was only partially sawed. The robot chips are released from the protecting wafer using a standard solvent cleaning (trichloroethylene or toluene, acetone and 2-propanal) to remove the black wax and resist. These solvents do not attack the polyimide. After this cleaning, which can be done in a partially parallel way, the polyimide is cured in a curing oven with nitrogen purging for 3 hours at a temperature of about 380°C. This curing, done on individual chips, reduces the volume of the polyimide and the legs are erected out-of the wafer plane. Then the robots are wire-bonded. The resulting device is a micro-robot capable for walking, as can be seen in Figure 57.

![Figure 57. The micro-robot during a load test. The load of 2500 mg is equivalent to maximum 625 mg/leg (when standing on only four of the eight legs, see Figure 47 c) or more than 30 times the weight of robot itself. The leg length is 1 mm and the legs are connected to the robot body by PVG-joints which consists of three V-grooves and a static bending angle just below 90°. The power supply is achieved through 30 µm thin gold wires, approximately 100 mm long. The micro-robot walks on a non-polished silicon wafer with a surface roughness of approximately 2 µm.](http://www.s3.kth.se/instrlab/research/dissertations/thorbjornedoc.html)
8.4.2 Walking experiments for the PVG-joint based micro-robot

The measurement set-up to control the robot walk consist of two (or four) signal generators which are driven with a phase difference close to 90°. These signals were connected to a switch that controls whether the phase shift should be +90° or −90° and then two (or four) saturated FET-transistors to achieve the right control power and control signals (squared voltage of approximately 20 V). Two other switches are used to steer the robot to left, to right or straight forward. The polysilicon heating resistors for each set of robot legs are typically in the range of 500 Ω. With this configuration both powers and frequencies as well as the phase shift between the two (or four) separate sets of actuators can be controlled, which allows for walks in both the forward-backward direction and turns to left and right according to the steering principles described on page 96.

The velocity was measured at different powers, loads and frequencies, as shown in Figure 58. The maximum measured walking speed was 6 mm/s at an applied squared voltage of 18 V (approximately 1.1 W) and a frequency around 100 Hz. This speed limit was set by the maximum supply voltage allowed by the electronic circuits we used and not by the polyimide joint actuators. Higher speeds are therefore possible to achieve by increasing both the heating power and the frequency. During the first measurements the walking distance was limited to a couple of centimeters by the length of the gold wires used for the power supply.

Temperature variations in the polyimide during the actuation cycle are dependent on the frequency as illustrated in Figure 59. For frequencies above the cut-off frequency, $f_c$ (where the stroke length $\Delta x$ is reduced by −3 dB), the thermal mass of the polyimide counteracts fast heating and cooling which reduces the maximum temperature (and increases the minimum temperature). Therefore, it is possible to compensate for the small displacements at higher frequencies by increasing the heating power without going over the maximum temperature at which the joints are destroyed. The walking speed
increased with increased power as illustrated in Figure 58. The walking speed also increases with frequency up to a specific frequency where the maximum speed is achieved. Due to small variations in the static leg position, the robot could not move at all at very high frequencies due to the small displacements of the leg. The leg has to overcome both the surface roughness and the variations between the different static leg position.

By increasing the load to 25 times the dead-weight of the robot itself, an unwanted reduction of the stroke length for each leg resulted. This translates into a lower walking speed and a lower top frequency at which the robot stops to walk.

The bonding wires limit the miniaturization of the robot to approximately 10x5 mm$^2$. For smaller robots the stiffness of the bonding wire affect the motion too much. This is in agreement with the results of other micro-robots. Therefore, this is believed to be the size limit for micro-robots steered and powered through bonding-wires. However, the challenge and the possibility of making smaller autonomous wire-less (i.e. battery powered and telemetric steered) robots still remains.

The various speed and load tests that were performed on the micro-robot (see Figure 57) are further described in paper 6 and the results are summarized in Table 6.

**Figure 59.** Frequency dependence of the polyimide joint temperature and horizontal stroke lengths, $\Delta x$, for a 500 µm long leg with a four V-groove joint. The cut-off frequency, $f_c$(-3dB) is 3 Hz. The same behavior is obtained for the 1000 µm long micro-robot legs and then the maximum stroke is 340 µm for 180 mW/leg power supply. The predicted minimum and maximum temperatures during the oscillation cycle are also plotted.
Table 6. Characteristics of the fabricated micro-robot.

<table>
<thead>
<tr>
<th>Materials</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Legs</td>
<td>bulk silicon</td>
</tr>
<tr>
<td>Micro-joint</td>
<td>polyimide (HTR-3 200 from OCG)</td>
</tr>
<tr>
<td>Heating resistor</td>
<td>p⁺⁺ polysilicon (boron-ion implanted)</td>
</tr>
<tr>
<td>Heat and electricity conductors</td>
<td>aluminum</td>
</tr>
<tr>
<td>Power supply</td>
<td>gold wires (standard bonding wires)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions / Configuration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot size</td>
<td>15 x 5 x 0.5 mm³</td>
</tr>
<tr>
<td>Robot weight</td>
<td>75 mg</td>
</tr>
<tr>
<td>Leg</td>
<td>1000 x 600 x 30 µm³ erected 85-90° from the robot-body</td>
</tr>
<tr>
<td>Number of legs</td>
<td>2 sets of legs (x+ and x-) with 4 legs in each</td>
</tr>
<tr>
<td></td>
<td>4 sets of legs with 2 legs in each</td>
</tr>
<tr>
<td>Walking surface</td>
<td>Silicon, silicon dioxide, wood, glass, metal, etc. (conducting and non conducting), surface roughness 2x10⁻³ µm to 25 µm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum walking speed, v</td>
<td>6 mm/s (@ f = 85 Hz and P_{mean}=1.1 W)</td>
</tr>
<tr>
<td>Maximum out-of-plane lifting</td>
<td>60 µm</td>
</tr>
<tr>
<td>Walking distance</td>
<td>Maximum: 30 mm (limited by the power supply wires)</td>
</tr>
<tr>
<td></td>
<td>Minimum: ≈ 5 µm (limited by the leg variations)</td>
</tr>
<tr>
<td>Steering</td>
<td>forward - backward</td>
</tr>
<tr>
<td></td>
<td>left - right</td>
</tr>
<tr>
<td>Load capacity</td>
<td>&gt; 3500 mg dynamically</td>
</tr>
<tr>
<td></td>
<td>&gt; 6500 mg statically (possible to walk afterwards)</td>
</tr>
</tbody>
</table>

8.5 Discussion

Compared to other used and proposed approaches to realize micro-robotic devices (micro-conveyers and micro-robots), the main advantage for the PVG-joint technique is the robustness of the actuators, which gives high load capacity. Besides the robust actuator function achieved, the polyimide joint principle also has the advantage of being self-assembled. Other proposed robot approaches need time- and cost-consuming manual assembly to erect the leg from the wafer. The large strokes of the silicon legs when using PVG-joint actuators result in a fast devices which is relatively insensitive to the topography of the surfaces it moves or walks on.

The walking micro-robot platform described here has demonstrated the possibility for locomotive MEMS-based micro-robots, but to be practical it needs to be equipped with tools of various kinds. One example of micro-tool equipped micro-robot was described in Figure 53. However, the integration of a micro-gripper on the PVG-joint based micro-robot is an easy task from a fabrication
point of view. In Figure 60 a conceptual drawing for a walking PVG-joint micro-robot equipped with micro-grippers is outlined. Preliminary tests on such fabricated micro-grippers have been done, but further investigations are needed on the design and the behavior of the force sensors before integration with the robot-platform can be made. As can be seen in Figure 60 the integration of the tactile force sensors on the gripping-arms results in an increased amount of interconnection wires. As already discussed this may influence the walking and steering capability of the robot too much. Hence, integration of some kind of electronics to reduce the amount of wires is probably needed. This complicates the fabrication but as demonstrated by the flow sensor fabricated by G. Stemme (see Figure 3) it is possible to integrate CMOS electronics and driving circuits for the heaters on-board on the chip using a V-groove filled polyimide fabrication process.

The main drawbacks using the thermal excitation principle are the relatively low cut-off frequency (i.e. slow systems), high power consumption and the possibility that the surrounding is heated which is not acceptable for most medical applications, for example the MIS applications mentioned in section 7.3. By FEM-simulation for design optimizations this problem may be solvable. Alternatively another actuation mechanism than heating may be used to produce the expansion of the polyimide in the V-grooves. The relatively high power consumption also constitutes a limiting parameter for the realization of wire-less micro-robots (i.e. autonomous systems).

Figure 60. Concept for a movable micro-robot with micro-grippers based on polyimide joint actuators. Please note that the drawing is not to scale. For a real device the dimension of the metal interconnections are much smaller than the legs and gripping arms.
9 Summary of appended papers

In the appended papers design, fabrication, simulation and measurements of different 3-D micro-structures are presented. The papers are given in chronological order. Papers 1 and 2 present the basic theory behind the polyimide joint and measurements on test structures. Paper 1 focuses on the static behavior and paper 2 on dynamic aspects. Paper 3 presents the experiments performed on silicon hot-wires investigating its applicability for turbulence measurements while paper 4 describes the first device, a 3-D flow sensor, based on the PVG-joint and the silicon hot-wires examined in paper 3. Paper 5 and 6 describe two different micro-robotic (a micro-conveyor and a walking micro-robot) devices where the actuation functionality of the polyimide joint is investigated. Both these devices use arrayed actuation.

Paper 1

This paper contains an overview of different 3-D techniques together with a motivation for the work of 3-D structures. A new and simple technique for making robust self-assembled 3-D silicon structures was presented for the first time. The principle of the polyimide joint is thermal shrinkage of polyimide in V-grooves producing accurately controlled bending angles over a wide range. A simple theory for the static bending angle dependency on the curing temperature was presented. With the fabricated test structures static bending angles between 0° and 200° were achieved with a maximum bending angle of 35° per V-groove. Bending radii smaller than 60 µm for a 30 µm thick out-of-plane rotated silicon plate were measured. It was shown that the aluminum conductors crossing the V-grooves in the polyimide joint are not affected by the out-of-plane rotation. Stress-strain measurements showed that the polyimide withstands high forces and large displacements before the polyimide joint deforms plastically. A description of a self-assembled interlocking fixture for accurate alignment of out-of-plane erected structures for 3-D sensor application was also presented.

Paper 2

An investigation of the dynamic characteristics of the polyimide joint presented in paper 1 was made. The dynamic mode of the polyimide joint was obtained by local heating, using integrated heaters, resulting in thermal expansion of the polyimide in the V-groove joint. To obtain a physical understanding of the polyimide joint behavior a lumped heat capacity model (electrical analogy) describing the equivalent thermal circuit was used. The results of the theoretical analysis showed good agreement with experimental data. Dynamic bending angles up to 3° per V-groove and cut-off frequencies up to 5 Hz (response times between 140 and 210 ms) were measured with the fabricated test structures. The dynamic mode can be used both for actuator applications and for trimming the bending angle to compensate for undesired process variations when the joint is used for 3-D sensor applications.

Paper 3

For the first time a flow sensor consisting of one and two perpendicular free-standing polysilicon hot-wire(s) has been fabricated and successfully tested for measurements of turbulent gas flows. The sensor was designed for turbulence measurements and the sizes of the two perpendicular polysilicon hot-wires have to be very small (500x5x2 µm³) to resolve the small eddies in a turbulent flow. The small size also results in fast response times. Special attention was paid to clarify the impact of a noncircular wire cross-section on measured flow parameters (i.e. yaw and pitch calibration).
Various measurements such as, flow sensitivity calibrations in CTA-mode, signal to noise ratios, thermal and electric cross-talk between two wires, time constants (open and closed-mode), power consumption, angle dependancy of the non-circular wire (yaw and pitch angle calibrations) were made and compared with conventional hot-wires. Turbulence parameters in the form of frequency spectras and correlation measurements in both grid generated turbulence and turbulent boundary layer were done to determine the accuracy for the new silicon sensor when these quantities are measured. From the measured parameters we could conclude that the sensor may be used for turbulence measurements. A double hot-wire sensor was used in order to investigate the possibility of measuring the instantaneous two component velocity vector in a grid generated turbulent flow field. Some of the parameters showed better performance and stability for the silicon wire than the conventional reference hot-wire sensor. However, the probe-like configuration with small silicon prongs holding the wires should minimize sensor-induced disturbances, but still a large blockage effect was measured in wall boundary turbulence. Therefore a redesign of the sensor is needed before high accurate turbulence measurements in boundary layers can be done.

**Paper 4**

The first functional micromachined 3-D flow sensor is presented. The sensor was designed for turbulence measurements so the measuring volume defined by the three perpendicular polysilicon hot-wires must be very small to resolve the small eddies in a turbulent flow. The focus of this paper is on the fabrication issues. A bulk micromachining process in combination with sacrificial etching was used to form the hot-wire probes. The fabrication process is extensively described in the paper. Two wires are located in the wafer plane and the rotation of the third z-wire out of the plane was obtained using self-assembled polyimide micro-joints. Locking fixtures for the z-wire were fabricated and successfully tested to ensure a bending angle of exactly 90°. High flow sensitivity was measured for the anemometric hot-wires. Simple characteristics (static flow measurement, temperature characterization, etc.) were done to prove the function of the 3-D sensor.

**Paper 5**

The first actuator application using the polyimide V-groove joint was presented. The article starts with an extensive overview of different micro conveyer systems (both contact and contactless). The micro-motion system (i.e. a conveyance system) consists of arrays of robust erected silicon legs arranged in two sets of groups where the legs work in different directions. With this chip we were able to obtain bi-directional transverse and rotational motion using electrical heating and the dynamic mode of the polyimide joints (described in paper 2). Successful experiments on moving flat objects in the millimeter range with high load capacity were presented. The conveyer consists of a 15x5 mm² chip with 12 silicon legs each 500 µm long. The maximum load conveyed on the structure was 3500 mg. Conveyance speeds up to 12 mm/s were measured. Accelerated lifetime measurements demonstrated the long-term stability of the actuators. The function of the polyimide joint actuators was unaffected after more than 2x10⁶ load cycles. Extensive results on the failure mechanism for the PVG-joint actuator were presented. Measurements were also done on position accuracy and mechanical/thermal failure mechanisms.
The first walking silicon micro-robot able to carry loads has been developed and investigated. The robot consists of arrays of movable robust silicon legs with a length of 1 mm. The motion is obtained by thermal actuation of robust PVG-joint actuators using electrical heating. Successful walking experiments over centimeter distances have been performed with the 15x5 mm² sized micro-robot. Walking speeds up to 6 mm/s with high load capacity have been achieved. The maximum external dynamic load the robot could carry on the back was equal to 50 times the dead-weight of the robot. The robot could still walk after withstanding static load up to 100 times its dead-weight.
10 Conclusion and Outlook

Micromechanics and microfabrication of sensors and actuators have witnessed phenomenal advances in a mere ten-year period. The 1960s and 1970s were arguably the decades of the transistor, ten years after its discovery, the 1980s and 1990s were the decades for electronic miniaturization and for the electronic system integration into more and more complex and smaller and smaller electronic systems (integrated circuits (ICs) and application specific ICs (ASIC)). Miniaturization is the basis for improving performance through integration: Combining thousands or even millions of individual components into a system with a total new functionality only really makes sense for miniaturized structures. Miniaturization saves space, materials and energy. It is a decisive factor to preserve our resources and a really promising access to a sustainable development. It is forecasted and also most likely that the first few years of the third millennium would be the microelectromechanical system-MEMS decades. MEMS is just the next step in the silicon revolution in that silicon integration breaks the confines of the electrical world and gives it additional dimensions for interacting with its environment through sensors and actuators. In this chapter where the results obtained for this thesis work are concluded, I will give my opinion on what I believe is the contribution to the research society with this thesis and how my results can be gained for future advancements to system miniaturization and integration.

Today we see increasing interest in micromachined products. The new PVG-joint can be used both for 3-D sensor and for actuator applications. This thesis has focused both on the basic behavior of the PVG joint and on the realization and evaluation of two different applications based on the joint: the turbulence triple hot-wire flow sensor and the two micro-robotic devices.

Three-dimensional sensors have a large potential in a lot of applications from medical, house-hold and military equipment to pure research tools such as the 3-D flow sensor. The same is true for 3-D actuator applications. I believe that the micro-robotic field based on MEMS fabrication, now in its very early stage, will have a deep impact on the whole MEMS field in the near future when more and more complex micro-systems must be assembled. Also in the medical field the use of miniaturized steerable catheters and endoscopes with flexible joints and equipped with micro-tools of various kind will revolutionize the classic surgery and allow for minimal invasive surgery (MIS) and computer assisted surgery (CAS). The idea most often associated with micro-robotics and medicine, is when an autonomous micro-robot is swallowed swimming around inside our bodies repairing damage parts as in the classical film, Fantastic Voyage (Sv. Den fantastiska resan) by Isaac Asimov's form the 1960's. That idea I think is still far from being realized but I think that MEMS based micro-robotic devices that are steered by wires will soon be on the market. Other applications where the polyimide joint technique can be used are accurate alignment of optical and electrical components (e.g. the use of micro-grippers and micro-manipulators positioning lasers, lenses, etc. for telecommunication systems) and micro-optical devices (mirrors for displays and bar-code readers etc.). The advantage of the PVG-joint technology (robust structures that can generate large strokes and forces) could be used for accurate micro-positioning since the technology also allows for well-controlled small displacements.
10.1 Conclusion – Fulfillment of the objectives

The initial goal of this doctoral investigations was to fabricate miniaturized triple hot-wire sensors suitable for measuring the instantaneous velocity vector (i.e. magnitude and direction of the velocity of small eddies) in a turbulent gas flow. This has not yet been done, but several important steps on the road towards such a sensor have been taken as will be described below. The spin-off project in the field of micro-robotics has also resulted in some important new knowledge about locomotive micro-systems. The micro-robotic field based on MEMS fabrication technologies is currently an area of intense research, basically because of the need for micro-assembly of different micro-devices into larger and more complex micro-system. Therefore micro-robotics is a key field for all kind of system miniaturization.

The work presented in this thesis can be divided into three parts: test structure for static and dynamic evaluation of the new micro-joint, fabrication and testing of the flow sensor and finally the micro-robotic devices. Among the important results from these different parts are the following:

- This thesis presents the first micro-joint based on thermal shrinkage of polyimide in V-grooves, which allows for self-assembly 3-D single crystalline silicon structures. The work has proved that the principle is useful for both sensor and actuator applications.

- The PVG-joint technique works (very well) both in the static and the dynamic mode. Long-term stability of the joints has been demonstrated. No degradation like due to creep or humidity and temperature dependence during storage and use of the joint in static and dynamic applications has been shown. For actuator devices a lifetime exceeding 200,000,000 load cycles was demonstrated without any degradation or failure. So far, none of the devices has ever been broken due to fatigue.

- The PVG joint gives robust, batch self-assembling, small radius joints with well controllable and trimmable bending angles. With the polyimide technique it is also easy to realize several electrical interconnections to the out-of-plane rotated structure. The fact that it is a single crystalline bulk material that is erected out-of-plane rather than surface-micromachined structure as in most of the earlier presented solutions opens up a range of different sensors that could be obtained. Surface micromachined sensor elements for flow, force, pressure, acceleration or other parameters may be produced in the bulk structure. The bulk structure combined with the flexible polyimide joint results in robust structures. The out-of-plane erected structure can be pushed by an external force almost down to the surface without breaking or plastically deform. When the force is released the structure goes back to its original position. The new polyimide joint technique also allows braces to be used for accurate out-of-plane positioning, which could be self-assembled either in a parallel-batch or a serial configuration. The uses of braces for interlocking also simplifies the fabrication process since the polyimide curing temperature then is not critical.

- A first device, the 3-D flow sensor, based on polyimide V-groove joints has been fabricated and tested. The fabrication process has been modified and improved several times and with the latest version a high yield was obtained. Special attention was paid to reduce the stress levels in the wires. The critical part is the mounting and packaging of the sensor. The main advantage of the new polysilicon hot-wire flow sensor is its small wire size and high resistivity resulting in fast response times, high sensitivity, and low power consumption. By the use of thin film deposition, photolithography and etching based batch fabrication there are possibilities for low cost, accurate
dimensions, and thin and short wires with easy integration into array configurations. The measuring volume defined by the three wires is small enough to measure the velocity of the small eddies in a turbulent flow. However, the tested layouts constitute some limitations since the hot-wire cross-section is not symmetrical.

- For the first time, results on turbulence measurement using free-standing micro-fabricated hot-wires in probe-like configuration have been presented. Even though the experiment demonstrated that the new micromachined silicon based hot-wire sensor has the ability to accurately measure different turbulence parameters, at least in some of the tested cases the goal of performing advanced turbulence studies in all three dimension (i.e. measurements on the instantaneous velocity vector) has not yet been realized. The influence of the sensor body to the flow (i.e. a large blockage effect) means that the accuracy for turbulent boundary layers is poor. One other performance reducing factor is the non-circular cross section of the hot-wire which means that careful considerations must be taken when calibrating the wire. By further investigations on calibration schemes (look-up table approach) and turbulent measurements on a more optimal designed triple hot-wire sensor (new layout but with the same fabrication process as the one presented in this thesis, i.e. paper 4) the initial goal to perform accurate experimental studies on small scale turbulent eddies (i.e. medium high Reynolds numbers) in all three dimensions of the flow field seems most realistic to achieve in the near future. With such a miniaturized 3-D silicon sensor arranged in array configurations, the fluid dynamic researcher can study physical phenomena which have not yet been possible to measure. Thereby, a better understanding of the complex turbulent flow could be achieved.

- The robustness of the PVG-joints has been demonstrated with the two micro-robotic devices which were able to move millimeter sized objects and carry large loads. The walking micro-robot platform is believed to be the first batch fabricated MEMS based micro-robot that can walk. Various devices and micro-systems using the high force generation and large stroke capability of the PVG-joint actuators are feasible. In the near future, when more and more complex micro-systems are expected and need to be put together by various types of micro-components the field of micro-assembly (e.g. micro pick-and-place stations) using micro-robotics will be very important. The walking micro-robot platform presented in this thesis may be used in this, micro-assembling, application field. The large strokes and forces that the PVG-joint actuators produce are attractive features in micro-robotics but also the easy integration of several different individually controlled actuator functions on the walking platform is important. (i.e. gripping arms with integrated force sensors). In some applications such as medical micro-robotics (i.e. steerable catheters for minimal invasive surgery) attention need to be paid to bio-compatibility since the thermal principle used for the PVG-joint actuators may cause damages on living tissues. In other applications the relatively high power consumption for the PVG-joint technique may cause limitation, for example. for autonomous wireless micro-robotic applications.
10.2 Outlook for future research

As is common when going into detail with a research project, one answers some questions and fabricates operating devices, but when the time comes for writing the thesis several new question have come up as well as inspiring ideas for new devices as well as improvements of the existing devices. Above I gave my opinion on what I think is the contribution to the research society with and the conclusions of this thesis. In the following, I will try to address some critical issues related to the PVG-joint technology which future research will need to focus on and solve before the PVG-joint technology could contribute with different application that may be commercially interested.

The starting point of this research project was to support the fluid dynamic researchers at Chalmers with miniaturized sensors suitable to perform extensive high-performance turbulence measurements in three dimensions. At the moment, as described in the chapter 6, the silicon hot-wires could be used for measuring turbulence. However, to be useful as a new research tool a redesign of the 3-D flow sensor must be made to minimize the influence the sensor has on the flow. The sensor itself is not allowed to create new turbulence eddies or increase the flow velocity. Also, a new and better packaging solution is necessary for measuring wall boundary turbulence. I believe research in general packaging solutions for MEMS sensors today has not been focussed on at university around the world. To be a successful alternative to manufacturing commercial products in the future I think the MEMS community needs to do more research on packaging solutions. The packaging problem with my flow sensors is only one example among many more that illustrates this need.

For turbulent wall boundary measurements it is favorable to have all three wires rotated out-of-plane (or folded into the plane as for the sensor design shown in Figure 5) and thereby partially avoiding the acceleration of the flow through the narrow gap between the wall and the sensor body that occurred in the experiments performed with the present hot-wire sensor. Further, more attention must be paid to the fabrication issues focusing on how to fabricate wires with more symmetrical cross-sections. A symmetrical cross-section (preferably circular from a fluid dynamic point of view but most realistically square from a MEMS fabrication perspective) will simplify the calibration (flow intervals and pitch and yaw angle calibration) required to create the look-up table needed for accurate 3-D turbulence measurements. The third issue of concern relates to cross-talk. Improvements on the minimization of the capacitance induced cross-talk in multi-wire configurations are needed. This seems to be “easily” obtained by deep etched slots separating the different interconnection wires, doped substrate for grounding, and grounded dummy strips of metals between the “real” metal lead wires for “generalized shielding”. However, this have not yet been tested and is therefore suitable tasks for future research.

An interesting area of research which has just recently got any attention is the study of turbulence flows a cryogenic temperatures (e.g. 0–20 K). Silicon hot-wires have a great potential there since one can make extremely temperature sensitive low-doped hot-wires which operate at a low resistance level (in the range of kΩ). That kind of measurements is difficult to do at room temperature because of problems associated with noise and building anemometer electronics that could handle wires with extremely high resistivity.

For the micro-robot platform to be useful for micro-assembling tasks it will need actuators for manipulation – AM (i.e. gripping tools), compare Figure 45 g) and Figure 53. A concept to realize such a walking micro-robot was shown in Figure 60. Micro-grippers with integrated tactile piezo-resistive sensors have been fabricated but these have not yet been completely tested. Further improvements and investigations on the reduction of the amount of wires needed for such robots have
to be solved. Another aspect for the PVG-joints that just briefly has been addressed in this thesis is the use of simulations for design optimizations. Such simulations may be used for, for example, optimal design of the heaters requiring a minimized amount of power consumption for a certain output work. Simulations and experiments on temperature distributions within the PVG-joint and the surrounding structures are also important. The temperature increase of the structures during actuation of the PVG-joint is important for medical micro-robotic devices. Also other bio-compatibility aspects, such as the material used, are of great importance.

Today we still do not even come close to comprehending microtechnology's potential, forecasted by Feynman back in 1959. But one thing is certain: Microtechnology will lead to an overwhelming multitude of products, devices, components and systems, a wide spectrum comparable in view of diversity only to that of living nature. Let us be fascinated by nature and build advanced micro-systems and micro-robots.
11 Acknowledgments

Now I have come to the long awaited moment to write the last part of the thesis, the acknowledgments (which is probably the most read part in the whole thesis). Five years of inspiring research which have felt like a short time in my life have been summarized in this thesis during half a year of writing which sometimes has felt equally long as the research itself. But at some occasions like now when the thesis should go to press within a few days, it feels to have been a too short time. However, none of the work presented would have been possible to achieve without the help of others. Many persons have been involved in this work and I am very grateful for their help. To avoid putting people in some special order, I will say a collective thanks to you all.

This work has been financially supported by the Swedish Research Council for Engineering Sciences (TFR) and the Swedish Foundation for Strategic Research (SSF). The work in this thesis has been carried out at the Instrumentation Laboratory, Department of Signals, Sensors and Systems (S3), Royal Institute of Technology (KTH), Stockholm, Sweden. There are some people that I would to personal acknowledge for their contribution to my work.

First of all, I want to thank my supervisors Dr. Edvard Kälvesten and Prof. Göran Stemme for support, encouragement and professional guidance. It has been a great pleasure to work with both of you.

My next thanks go to my colleagues at the Instrumentation Laboratory (both the present and former ones) for valuable help and discussion during the work. At Elmät there are a relaxed and fresh atmosphere, which makes it fun to go to work. A special thanks to Kjell Norén for all his help with different mechanical and electrical set-ups. I also want to thank Johan Mattsson who based his Master’s thesis on the micro-conveyor (micro-robotic) project and have been the co-author for all the micro-robotic publications and Jessica Melin for her help in correcting the English in the thesis and publications.

I would like to thank the staff at the Semiconductor Laboratory (HLB) in Electrum, Kista, and the MST group(s) at IMC/ACREO for help with the silicon processing. Special thanks to Margareta ”Maggan” Nilsson for always being helpful with my never ending questions about silicon processing. I also want to thank Christian Vieider for clever ideas about out-of-plane rotation of silicon structures.

I wish to thank Fredrik Carlsson, Peter Johansson and prof. Lennart Löfdahl at Thermo and Fluid Dynamics, Chalmers, for fruitful collaboration on the turbulent flow sensor. They have carried out most of the work on the flow characterization of the new flow sensor in their wind tunnels.

All research colleges around the world which I have been in contact with regarding the topics of this thesis are greatly acknowledged. A lot of you have favorably let me have access to your photos and other material to be used in the thesis and also kindly answered my many questions.

My last thanks goes to my family for support and understanding. Most of all, I would like to thank my wife, Leena, for her unlimited support and encouragement, especially these last stressful months. We will have a calm, relaxing summer all three of us, I promise!

The reference list will hopefully be formatted automatically so this should be the last thing I write in this thesis. Thank you all!

Stockholm, Valborgsmässoaftonen, 30th of April 2000, Thorbjörn Ebeffors
12 References


PVG Joints for Three-Dimensional Silicon Transducers


Kris Pister, private communication, February 2000.


PVG Joints for Three-Dimensional Silicon Transducers


PVG Joints for Three-Dimensional Silicon Transducers


[210] MSTnews, “MATAS: A modular assembly technology for hybrid µTAS,” no 1/00, 2000, special volume dedicated to “Packaging and modular microsystems”.


