National Institute of Standards and Technology

Manufacturing Engineering Laboratory

Final Report on Micro-Meso Scale Manufacturing Exploratory Project

Fiscal Year 1999

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Executive Summary

Micro and Meso-scale devices are a very exciting new arena for many research groups and companies around the world. Meso-scale devices, defined as things between the size of a sugar cube and the size of one's fist, include small chemical process systems, air and water purifiers, refrigerators and air conditioners that weigh only grams, small robotic devices for military uses, and all manner of electronics and sensors and mechanisms that are tiny and light weight. This is a domain where electrostatic actuation works well and there are significant advantages in heat transfer, kinetics, and high surface to volume rations in building highly parallel systems from simple unit processes at the meso level. DARPA is pushing this area very hard, for small, lightweight devices for the individual soldier to carry; a huge new consumer electronics industry deriving from this work is just over the horizon.

Manufacturing is constantly pushing toward smaller and smaller scales. This is not a consistent continuum, and in fact micro-manufacturing is a larger field than meso-manufacturing because of exploitation of microelectronics fabrication technologies and the large markets for data storage devices, but there is activity at all scales and there is a pressing need for NIST and particularly MEL services at all scales. ***Making things at smaller and smaller scales is one of the most exciting frontiers of manufacturing.***

The future of meso-scale manufacturing operations will be strongly influenced by a new breed of assembly and manufacturing tools that will be intelligent, flexible, more precise, include in-process production technologies and make use of advanced part design, assembly and process data. The flexible manufacturing tools of the future will be a system integration effort of all the best MEL has to offer**.**

The needs of U.S. manufacturing industries in the area of meso-,micro-, and nano-manufacturing have been identified by: (1) FY99 industry visits and workshops aimed specifically to the area of meso/micro-manufacturing; and (2) FY99 and prior year industry visits and workshops aimed at micro/nano-manufacturing, including MEMS.

Industry needs were established during the Meso/Micro Manufacturing Exploratory project by:

- Visiting some 20 companies and laboratories and asking about the technology and about the specific measurements, standards, and data needs;
- Running two workshops, one cosponsored with DARPA and one with NSF, to establish the technology base and the prioritized needs and opportunities for NIST efforts in this area;
- Attending courses and lectures and conferences in MEMS and Nanotechnology;
- Organizing a NIST-wide coordinating group to inventory base efforts and needs; and
- Carrying out a literature search.

The ***prioritized needs*** for NIST efforts in meso and micro manufacturing were identified ***by industry*** during our visits and at our workshops to be:

- Dimensional and Mechanical Metrology

- Assembly and Packaging Technology and Standards

- Providing a Science Base for Materials and Processes, emphasizing materials testing methods and properties data.

The needs for NIST efforts at the nanoscale were grouped into four catagories for the FY2001 budget initiative:

- Nanocharacterization
- Nanomanipulation
- Nanodevices
- Magnetics Industry Support

A key issue at the nanoscale for MEL, not highlighted in the initiative but where we have a substantial base effort, is nanometrology, which in part fits into nanocharacterization and in part fits into nanomanipulation. Including nanometrology in the proposed strategic program positions MEL to opportunistically pursue the FY2001 initiative and other possibilities for program expansion; we all see this as, eventually, a continuum of scales for macro to nano, and we believe we have to be involved at all scales to meet industry needs.

Technical Opportunities for NIST Program

The needs identified above and prioritized by industry at our workshops are specifically NIST mission roles: ***measurement, standards, data and infrastructure technology***. More than 100 issues that NIST and NSF should address were rank ordered; the above are a composite of the top ranked issues that are specifically NIST issues.

NIST outputs and services are needed at meso-, micro-, and nanoscales just as they are needed by industry at macroscales.

We are talking specifically about manufacturing technology for discrete part manufacturing; that is the mission of MEL.

Business Case

Meso- and micro- manufacturing techniques are important for producing micro-sensors, fuel nozzles, and fiber optics, along with other devices used in medicine, telecommunications, and satellites. An estimate of the size of mesoscale industries is approximately $20 Billion; that is predicted to double in the next 3 years, a growth rate of about 25% per year (source: Nexus study). At the microscale, semiconductor electronics adds $150 Billion to the GNP. In terms of MEMS, as distinguished from microelectronics, the sole success stories are the air bag crash sensors and the TI deformable mirror devices, accounting for possibly $25 Million in sales per year, but a new generation of devices is about to reach the market that will increase that 10 fold and more over the next decade.

In the Micro-Meso Manufacturing project, the needs of U.S. manufacturing industries in meso- and micro-manufacturing have been identified by: (1) FY99 industry visits and workshops aimed specifically at the area of micro-meso manufacturing; and (2) FY99 and prior year industry visits and workshops aimed at micro-manufacturing, including MEMS. Specific activities included:

- Visiting some 20 companies and laboratories and asking about the technology and about the specific measurements, standards, and data needs;
- Running two workshops, one cosponsored with DARPA and one with NSF, to establish the technology base and the prioritized needs and opportunities for NIST efforts in this area;
- Attending courses and lectures and conferences in MEMS and Nanotechnology;
- Organizing a NIST-wide coordinating group to inventory base efforts and needs; and
- Carrying out a literature search.

The ***prioritized needs*** for NIST efforts in meso and micro manufacturing were identified ***by industry*** during our visits and at our workshops to be:

1. Dimensional and mechanical metrology

2. Assembly and packaging technology and standards

3. Providing a science base for materials and processes, emphasizing materials testing methods and properties data.

The needs identified above and prioritized by industry at our workshops are specifically NIST mission roles: *measurement, standards, data and infrastructure technology*. Altogether, more than 100 issues that NIST and NSF should address were rank ordered; the above represent a composite of the top ranked issues specific to the NIST mission and expertise. These issues are also central ones for discrete part manufacturing technology, that is the mission of MEL.

Specific needs related to these areas are discussed below:

In metrology:
Maintaining our leadership in global markets requires conformity with ISO uncertainty standards and other threatening barriers to trade, faster transfer of technology from laboratories to production, and higher quality products. The industries we are addressing here produce approximately $20 Billion output per year (which in turn leverages much larger portions of the GNP by providing key components for much more expensive macro-scale discrete part products). This is growing at something like 20-25% per year, several times faster than overall discrete part manufacturing ($1.1 trillion growing about 7% per year). So we are addressing a real "sweet spot" with high leverage for impact over the next decade.

It should be noted that Japan and Germany are investing very heavily in these areas; one indicator, cited by Al Pisano of DARPA, is the number of organizations working in the MEMS field. In 1994 the US was well in the lead; in 1997 the US was behind both Germany and Japan (150 in US, 270 in each of the others). Before 1990 there were never more than 10 MEMS Patents issued in the world in any year; in 1997 there were 150, of which only 50 were US Patents. The US must invest to stay in a leadership position; NIST will play a small but key role.

In assembly and packaging:
At the meso and micro level, successful automation would save $7B (estimate by Gordon Day, Chief of NIST Office of Optoelectronics Programs, Boulder) to $12 B (estimate by Brian Carlisle, CEO of Adept Technology, leading US manufacturer of robots for assembly and member of ATP funded Precision Optoelectronics Assembly Consortium--POAC) in the U.S. economy in photonics alone. NIST is co-sponsoring, with IEEE and NSF, a workshop on photonics manufacturing in September which will further delineate the needed outputs and their expected impacts.

Further, assembly and packaging is ***the*** essential problem for MEMS devices, one subset of microscale manufacturing. According to one expert:

> System Planning Corporation accomplished a market analysis for DARPA's MEMS effort. They estimated that the market potential for MEMS was ~13B in the year 2000. The market has never developed due to the price of the MEMS products. The current market is mainly automotive and is about $400M/year. This is air bag deployment sensors. The two main players are Analog Devices and Motorola. The main issue is packaging. Plastic packaging is critical for low cost. No one to date has a viable plastic packaging concept or capability. The other issue is more challenging. MEMS devices cannot be handled by normal die handling tools due to the mechanical structure. This makes not just the package cost expensive but the act of packaging very expensive.
>
> --Jeff Bullington, DARPA

There are no solutions here at the moment; NIST's microstage work for POAC, for example, has been enthusiastically received by industry. We have the capability to make a significant contribution. Our interaction with industry during the ATP program and during the Meso/Micro study have indicated that NIST can have a positive impact here through information exchange, demonstrations, performance measures for quantitative evaluation of components, development of key microrobotics and microsensing technologies, providing for metrology and calibration support, and proactive pursuit of interim and defacto standards.

In process technology:
Proper materials test methods (process metrology) will allow transitioning of technology from the laboratory to production. Individual manufacturers are able to establish repeatability but not real process control. Process metrology and standardization of materials test methods are basic NIST mission issues

and were identified as needs in every lab we visited. The 20 to 25% growth rate cited will not happen without infrastructure technology, standards, and measurement technology.

One specific need for NIST attention is MEMS (Micro Electro-Mechanical Systems) which is the use of semiconductor fabrication techniques to make sensors and actuators rather than integrated circuits. McGroddy of IBM, the head of NIST's VCAT, notes that this field has been a major disappointment, with only the air bag sensors and TI deformable mirror devices commercial successes after twenty years of work. This is true, but Pisano of DARPA points out that it has taken that time to develop an understanding of problems and that there are many new applications that will be major successes within a few years. Pisano also points out that MEMS requires better process control than microelectronics. For example, a 5% change in film thickness is within spec for conductivity of an interconnect, but that is a 15% change in resonance frequency if that film is made into a resonant beam (stiffness goes as the cube of thickness) which is totally unacceptable for making RF filters. Similarly, a 0.5% astigmatism in stepper optics is fine for microelectronics but is unacceptable for making gyro rotors that will turn at several hundred thousand RPM. Discussions with DARPA, Sandia, UC Berklely, and with CSTL and EEEL in NIST all indicate significant problems with process metrology, process control, and process control software in trying to build MEMS devices. All agree that NIST should be leading the attack on these problems.

In integration technology:
Creating a real, working, distributed manufacturing test bed will dramatically accelerate the development and diffusion of this technology into the marketplace by allowing large numbers of users to access centers of specific process expertise. Al Pisano of DARPA has started work on this concept and has Berkeley, Cornell, Sarnoff, and Stanford under contract, with four industrial fabs in negotiation. They believe quality control, and remote supervision or even remote operation of metrology equipment to monitor process operation and quality are the keys to making this concept work from a business standpoint. Pisano is seeking our involvement, citing problems with interoperability of software and data exchange, problems with process metrology (since MEMS fabrication needs better process control than microelectronic fabrication as noted above), and problems with remote testing and monitoring.

Conclusions

Micro and Meso-scale devices are a very exciting new arena for many research groups and companies around the world. The future of meso-scale manufacturing operations will be strongly influenced by a new breed of assembly and manufacturing tools that will be intelligent, flexible, more precise, include in-process production technologies and make use of advanced part design, assembly and process data. The flexible manufacturing tools of the future will be a system integration effort of all the best MEL has to offer**.**

Intelligent Integrated Microsystems has a tremendous growth potential expected to reach $30 billion in the first part of the next century, with applications in industrial areas like machinery and plant manufacturing, production control, power systems, and home and building control. And, this is just a projection for the Integrated Circuit Industry. Many more exciting and important discoveries and applications are on the horizon.

Based on our industrial visits and workshops, which provided prioritized inputs, certain minimal elements for a new program have been defined by those working on the MEL exploratory project, which would be:

♦ Dimensional Metrology: The "magic measuring machine", a suite of measurement technologies at meso and micro dimensions (PED)

♦ Force and Torque Measurement and Calibration Services to micro and nanoNewton levels (APTD)

♦ Assembly and Packaging: information exchange, microrobotics and microsensing technology, perfomance measures, interim and defacto standards to accelerate commercialization (ISD, PED, PL, EEEL)

♦ Process Technologies and Materials Properties (APTD, ISD, MSEL, EEEL)

♦ There are additionally information technology issues for MSID to address, and a definition of other OU roles in a NIST wide effort is still emerging. For example, a facility that would support all NIST labs for MEMS and 3D micromachining is under discussion; FTD is a candidate to assume that responsibility. The idea of further expanding that support to a virtual regional technology and fabrication center, with cosponsorship from DARPA, NSF and other funding agencies has also been raised.

Research and development is moving rapidly in this field. We can have some impact if we move slowly, we will have a major impact if we move rapidly. For example, in basic metrology, the need is chronic. Hutchinson Technology, manufacturer of 75% of the world production of suspension arms for disk drive read heads, needs force and torque calibration (at μN and nN-m resolution) now; they will have even more stringent needs five years from now (Note: NIST calibration services stop at 44N).

AMP needs to inspect location and form of 125 μ holes in fiber optic connectors which have 1 μ tolerances, the tolerances for single mode fibers will by 1/10 that. This is one of many examples of the need for a micro-CMM or “magic measuring machine” that is not one instrument but rather a suite of measurement techhnologies applied to 3D mechanical parts and devices and systems that fall in the range between classic CMM metrology and SEMs, STMs, and AFMs.

In providing measurement technology and calibration services, we are supporting a $20 Billion industry growing 25% per year. If we provide proper support, the U.S. will continue to dominate these markets. If we fail, the dominance will erode in favor of European and Asian competitors.

For assembly and packaging, process technology, and materials data, the other priority areas identified for NIST attention, if NIST does not respond the world will still move ahead; if we are proactive we can have a major impact, benefiting U.S. industry in particular. No one else in the U.S. has the mission of achieving economic growth through advanced manufacturing technology, and Europe and Japan are aggressively investing here, so technology will be developed and applied elsewhere if not here.

We can definitely play a major role, but we have to commit and focus adequate resources if we are to do so, and we need to partner with industry. Everyone we have visited has supported a strong NIST role; we currently have in place or are in the process of defining cooperative work with Boeing, Adept, New Focus, Corning, Hutchinson, Honeywell, Potomac Photonics, AMP and Optomec. We will leverage our resources through cooperation with other agencies and Government Labs such as Sandia and with universities including UNCC, Minnesota, San Jose State, Stanford, Berkeley, Vanderbilt and UCLA.

Appendix

Trip Reports

Nanospace 98 - to the Planets and Beyond

http://nanospace.systems.org/
The International Conference on Integrated Nano/Microtechnology for Space Applications
(Proceedings available on CD-ROM and detailed notes available from Ed Amatucci)

Executive Summary – Ed Amatucci

Nanospace 98 was an interesting and exciting conference, which brought together leading Nano scientists and NASA engineers and scientists. The research topics included MEMS (Micro Electromechanical Systems), Nanoelectronics, Nanoscience, Space Applications (current nanosystems in development phase) and some material science. The main theme and goal was to look at "where are we today and where do we want to go?"

The first day was dedicated to general overviews of nanotechnology from government, university and industry perspectives. The problems of manufacturing seemed to echo throughout the talks. There seemed to be a breakdown between the research and implementation of useful devices on a large and reliable scale. Also, the field is struggling to find useful applications, which have acceptance from industry and NASA engineers. This meeting hoped to help close that gap and educated the researchers on the developmental and manufacturing issues and also educate the developmental and industry engineers on the possibilities of nanotechnology. Also, a soft focus of the integration aspects of nanodevices with large systems was discussed. One NASA official explained the amusement of a wonderful MEMS device, which is then attached crudely with a _-20 screw – "sort of defeats the purpose."

Ken Cox, one of the NASA organizers, gave an excellent talk on "A Futurist's Perspective of Space". He stressed that NASA over the last six months has now viewed nanosystems as mission critical technology.

Another highlight of the week was a keynote address by Dr. Richard Smalley who received the Nobel Prize in Chemistry in 1996. He gave a very entertaining talk on the possibilities of graphite buckytubes. Excellent possibilities for the future exist. The Keynote Address and evening dinner was held at Space Center Houston.

Overall, it was a good conference and address the NASA needs very well. It only hinted at the needs for manufacturing processes, materials, and assembly systems. The researchers are still working on new and novel devices and little work seems to be focused at manufacturing issues past the fabrication of one device. Some are looking at material science issues which I feel will be a very significant aspect of our manufacturing research. Another way of looking at this field is that they are still building the building blocks in which we will use to develop complete manufacturing systems. Sensors, mechanical systems (including metrology), electronics, and computer system interfaces need to be further developed to build manufacturing systems for high-end production of MEMS and Nano-devices. By focusing on Meso-scale instruments, we will help this effort by working down towards the smallest possible systems we can fabricate, position accurately and assemble.

List of useful web sites related to material presented at conference:

- Government Perspectives on NanoTechnology - Gernot Pomrentie (DARPA Program Manager) Program manager for:
  1. Ultra Electronics: DARPA Nanoelectronics
     http://www.darpa.mil/ETO/ULTRA/index.html
  2. Terahertz Technology Sensing & Satellite Communications
     http://www.darpa.mil/ETO/Terahertz/index.html

- Web site for related NSF announcements-
  http://www.nsf.gov/nano
  http://itri.loyola.edu/nano/
  http://itri.loyola.edu/nanobase/ – Nanotechnology database

- ***Nanotechnology at NIST - Dean Collins - Information Technology Laboratory, Chief Vu-graphs*** *http://www.itl.nist.gov/div895/mems_nano*

- ***MEMS research for space applications at the Berkeley Sensor and Actuator Center Richard S. Muller*** ***http://www.berkeley.edu/***

- Web Site:
  http://www-bsac.eecs.berkeley.edu (formed under NSF 1986)- Berkeley Sensor and Actuator Center
  Kristofer, S.J. Pister - Robotics, systems, UCLA
  Albert P. Pisano - Columbia - Mech. Design, materials (Now at DARPA)

- Micro-elevator by self-assembly (MESA technology)
  Has developed micro XYZ stage using this technique
  Realized a 2D scanning device - rotates about the x and y axis.
  Large area mirror (400μm x 400μm)
  http://www.photonics.ucla.edu

- Advances toward molecular-scale electronic digital computers: A review and prospectus The Mitre Corp. James C. Ellenbogen
  http://www.mitre.org/technology/nanotech

- ESA (European Space Agency) sites on the www:
  http://www.esrin.esa.it/

- European MEMS/Nano Technology Ayman El-Fatary, Nexus
  http://www.nexus-emsto.com
  http://www.europractice.com
  http://www.eureka.be

Remmele Engineering
Micro Machining Division
17701 U.S. Highway 10
Big Lake, MN 55309
612-263-2636
Contact: Jeff Hillesheim, Manager
www.remmele.com

Date of Visit: 2/10/99
Attending: Clayton, Matt, John Evans, Nich and Brad
Recorder: Brad

Company Background
Remmele Engineering is a privately owned (family) job shop founded in 1949 and is considered one of the best in the United States. With gross sales over $100 million a year, it is certainly one of the largest job shops. Their customer's range from government (NAVY Agesis radar dishes) to the small companies (Professional Instruments, slideway components). It's a company that reinvests 15% of gross sales back into the company in terms of new equipment and facilities each year. Employing more than 500 people in six plants, Remmele manufactures parts sized from 30 feet in diameter (large rocket parts) down to 0.020" cubed (brain surgical device parts). Every two months, a company wide engineering meeting and a quality control meeting takes place. One full time engineer is tasked to find new machines, processes, or innovations from around the world and to integrate the promising new technologies into the plants. The company is structured into four divisions:

Micro Machining Division
Manufactures complex, difficult to produce items for the medical, aerospace, telecommunications and other high technology companies. This division offers production of sub-meter components using qualified statistical process controls

Automation Division
Designs and builds custom automated machines and manufacturing systems for medical, electronics, automotive, and consumer product manufacturers. This division specializes in applications involving assembly and testing, web handling and converting, metal removal and fabricating, and packaging and filling.

General Machining Division
Manufactures a wide range of complex, high quality and close tolerance parts and assemblies, including: low-quantity manufacturing and prototyping: large-part repetitive batch - ranging in size from 2 foot (600 mm) to 100 feet (30 m) in length, and design and build of tooling.

Repetitive Batch Machining Division
Provides precision machining and assembly services in batch quantities for complex, close tolerance components up to 24 inches (600 mm). Flexible Machining Systems (FMS) are employed to deliver consistent quality while responding quickly and efficiently to customers' changing requirements.

Micro machining activities
The Micro Machining Division was formed only 2 years ago. In looking at new markets to enter, Remmele identified the $500 million micro device market as lucrative. In particular, the retiring baby boomers will drive double digit growth in the medical device market. Currently, 60% of Remmele's micro parts are manufactured for the medical industry and medical devices are typically used only once and are the smallest parts Remmele produces. The pricing pressures within the medical industry is similar to the hard drive industry – medical devices start out large and expensive, but will turn into small, commodity, competitively priced devices. The second biggest market is fuel nozzles for jet engines.

Additional long-term markets to move into are the satellite, telecommunications, and semiconductor industries, since the demand for information exchange will only grow. With satellites, the part sizes are fixed and limited by the microwave frequency. Even though part size reduction is limited, there are over 160,000 10mm pin connections to be manufactured on a single communication satellite. Also, Remmele identified fiber optic connectors and devices as growth markets. Also, a long range goal is to work with customers who produce MEMS parts. Since the MEMS process is good to +/- 5 μm, the goal would be to remachine the device to tolerance.

It’s typical for micro device customers to ask for part tolerances beyond the capability of Remmele’s micro machines. A dedicated Swiss machine is available for quick turn around prototype work. If the prototype part works and the customer is satisfied, the extreme part tolerances are scaled back. Once in production, the typically lot size for the micro parts is 2500 pieces and each must be inspected quickly, so the results can be used to affect the machining process. After a part is machined, it must be taken off the machine, not necessarily easy, since you may not be able to see the part. Each part must be cleaned and inspected, the medical parts subject to specific Food and Drug Administration requirements. Finally, the micro parts are packaged. All this without loosing them.

Categorized below are specific discussions and observations:

Measurement and Inspection

Optical microscopes and vision systems are the primary tools used for inspection. In particular, a very sophisticated vision system from Microna (German) was recently installed. This system fitted curves, lines and circles to the part features measured with the CCD array. From these fitted curves, lines and circles, dimensional metrology is possible. The system has 1 μm pixel spacing and can measure 4 to 6 inch parts. In addition, the system has a touch probe and can be fitted with a laser scanner.

Other inspection processes being looked into include holography. Also, vision systems are used on many machines to view the machining process and spot problems such as tool breakage, part or tool deflections and tool wear. An acoustic emission system was tested for use in detecting tool breakage within the Swiss machines. But the high ambient noise, in particular from the live tooling gear drives, made detect impossible. Frequently, it is impossible to even inspect some micro parts. In cases like this, the part is manufactured and given to the customer for testing. If part works well, the manufacturing process is documented, since the inspection process can’t be documented.

Fixturing and Assembly

The smallest parts are made on the Swiss machines in one shot – the parts cannot be refixtured on another machine because of their size. These parts are manufactured through skill only since the tolerances and features called for exceed the machine’s specifications. The skill comes from the operator knowing the limits of his machine.

In order to reduce assembly time, parts are designed monolithically. Also, the parts could be left attached to a stick, giving the customer a jig to hold or fixture the part, during their assembly processes. The stick is snapped off at the end.

Machines and Facility

A 60,000 square foot facility houses over 20 Citizen Swiss 5 and 8 axes turning centers. In addition, the following machines are located in this plant:

5 axes micro milling machines
5 axes micro grinding machines
EDM machines (wire and electrode)
Micro laser cutting, drilling and welding
Conventional CNC turning and milling
Precise calibration through an environmentally controlled gage lab with laser capability
Multisensor measuring technology, automated 3-D vision system.

The high production machines are the Swill turning centers. When outfitted with live tooling, the machine is capable of milling operations, thought the gear drives are thought to be the primary limitation. Another limitation is a bar stock feed design. The bar stock is fed through the spindle, but also rotates. The dynamics of the centerless ground stock, up to 12 foot in length, rotating can cause vibration problems within the machine structure. Also, variations in diameter of the stock causes bar feeding problems. These machines are leadscrew driven with rotary encoders. Linear scales are not used because the small work space does not permit them.

Furthermore, Eiowa chucks, from Switzerland, are used extensively on the various milling machines. The chucks are repeatable to +/- 0.0001" and are used to move part fixtures in and out of machines.

Tooling and Processes
Tooling is very important and very difficult to find. Most micro tooling is hand made and suffers from dramatic variability as different craftsmen make each tool individually. Tools are obtained from Kennametal and other niche vendors. The tools from Europe were thought to hold a better edge.

With micro machining, the text books for conventional machining are thrown out. For instance, you would never recut surfaces as the tool rubbing wears prematurely. The approach taken at Remmele is to sacrifice the tools and recut the surfaces to remove burrs. All burrs are removed in this way, because it is impossible to debur the part once it is outside the machine (impossible to do by hand).

Most medical parts are made in titanium or stainless steel. Since the dry machining of brass is very similar to the wet machining of stainless steel, brass is used to set up machines and test processes prior to loading the stainless steel.

Applications
The part features produced include:
0.004" thin walled
0.002" lands
0.005" holes to 0.060" deep
working on 0.002" holes

Laser machining ranges from 0.020" down to 0.002" and fills hole in the capability of the Swiss machines. Looking for improvements by 10x in either direction.

An interesting application was the manufacturing of a 100,000 rpm impeller for clearing plaque from inside veins.

Company needs
The top priority is characterization of their Swiss machines. Further help is needed in inspection, part fixturing and tooling.

Comments
At the batch manufacturing plant, Remmele used woods metal to fixture satellite wave guides in position for subsequent milling processes. Afterwards, the woods metal was melted away in boiling water. Also, five axis thin wall/floor (0.020" thick) parts with 0.5" over hangs were in production for an aerospace company.

A potential joint project would be tele-presence video inspection over the internet with NIST or actual customers.

Honeywell
February 11, 1999
Plymouth, Minnesota

Attendees from NIST: Clayton, John, Matt, Brad, and Nich (Recorder)
Attendees from Honeywell:

- Dr. David Arch, Section Head, Microstructure Technologies
- Dr. Dave Zook, Principal Research Fellow
- Dr. Thomas Ohnstein, Sr. Principal Research Scientist, Sensors Dept.
- Dr. Burgess Johnson, Research Scientist, Sensors Dept.
- Dr. Bob Horning
- Dr. Cleopatra Cabuz, Principal Research Scientist, Sensors Dept.

Honeywell Technology Center (HTC) Review by David Arch:

The Plymouth, Minnesota center is one of several (HTC) facilities located in the US Europe and the Pacific ream countries. The number of technical staff of the HTC is approximately 600. Approximately 50% of the HTC budget is covered by external funding.

NIST presentations by Clayton and John:

The purpose of the Micro Meso Manufacturing project was explained and the desire to obtain information on metrology, standards and other needs from the US industry.

Honeywell activity in Micro and Meso Machines (MMM)- Brief Overview by Cleo Cabuz:

This is an important activity of the HTC in Plymouth. The center shares a micro manufacturing facility with another Honeywell department, which allows for the local fabrication of the MMM devices. Honeywell has worked on sensors for pressure, acceleration, temperature, and flame and on pumps, valves and actuators. One particularly interesting design was a pressure sensor that worked by measuring change in resonant frequency of MEMS flexure (diaphragm?).

Microvalve and LIGA Tunable Filter by Tom Ohnstein:

Honeywell and the Univ. of Wisconsin are developing Micro Electro Mechanical (MEMs) tunable filters for IR spectral analysis applications. These are transmission low pass filters, where the cutoff wavelength can be scanned or tuned. The filter structure is based on MEMs-LIGA fabrication techniques. The filter consists of an array of parallel metal plates joined by spring flexures. The distance between the metal plates is controlled by either a single pole electromagnetic drive or a three-phase linear stepper motor.

Mesopump by Cleo Cabuz:

Described diaphragm pressure meso pumps without valves. These are conical cavities with electrostatically actuated diaphragms. Three cavities in series are needed for the pumping action. The cavities are arranged in a rectangular array of approximately 1 in^3. Questions were asked regarding sticktion and surface roughness. Any spikes on the cavity wall surface could act as charge concentrators. It was suggested that diamond turning be considered for the machining of the pump surfaces.

PolyMEMs actuator by Burgess Johnson:

A MEMs stepping motor based on rotary switched reluctance stepping motors was described. Three toothed stators are coplanar with a toothed slider. The teeth of each stator are displaced by one-third of a tooth period. The teeth of the slider try to align with the teeth of the active stator. By activating and deactivating the stators sequentially it is possible to move the slider by +/- 1 mm.

Polymer Actuator by Burgess Johnson

A variation on the pump design was a linear actuator that was a series of cavities in series; the actuator would be actuated electrostatically. This would provide a pulling force against a spring. The system would be smooth over some range and then quantized since the cavities tend to snap shut at some voltage level.

Hutchinson Technology
February 12, 1999
Summarized by: Brian Boudreau

Objective:
Conduct discussions with NIST personnel on the verification of the torque error budget and development of the torque sensor calibration procedure.

Attendees:
NIST:
Dr. Clayton Teague, Chief Automated Production Technology Division
Dr. Matt Davies, Automated Production Technology Division
Dr. Brad Damazo, Automated Production Technology Division

Dr. John Evans, Chief Intelligent Systems Division
Dr. Nic holas Dagalakis, Intelligent Systems Division

Dr. Ted Vorburger, Group leader, Surface Metrology, Precision Engineering Division

HTI:
Betty Stras, Director, Advanced Measurement Development (AMD)
Brian Boudreau, Precision Engineer, AMD
Satish Pragalsingh, Precision Engineer, AMD
John Buttress, Corp. Standards Engineer, Corporate Standards & Measurement Sciences
Daniel Calhoun Supervisor, Suspension Development Lab
Todd Krinke, Engineer, Advanced Product Development
John Larson, Purchasing

Not Present:
Greg Hetland, Manager, Corporate Standards & Measurement Sciences, HTI

Presentations/Activities:
- HTI Overview
- NIST Department Overviews and Missions
- Fly Height Hierarchy/Error Budget and Discussion
- HTI's Prior and Current Torque Measurement Activities
- Plant/SDL Tour
- Torque Uncertainty Budget Review
- Torque Sensor Calibration Review

Significant Topics:
<u>NIST Overview Presentations</u>:
- Brad gave a presentation outlining some of NIST's activities/progress in developing the Maltese Cross force/torque sensor. He showed several slides that demonstrated NIST's capabilities in machining thin walled (0.001 in/25 µm) features in a number of different materials. He highlighted their capabilities by showing us an actual sensor prototype that they had fabricated.

<u>Prior and Current Torque Activities</u>:
- Brian presented a series of overheads that outlined our past and present activities in the development of a torque sensor. This presentation included a timeline showing that we need a usable calibration methodology in the May/June time frame. Our intentions to distribute the technology throughout the Rigid Disk Drive (RDD) industry and the potential problems that could be encountered if we don't have an externally verified calibration methodology and/or artifacts were also highlighted.

Calibration:

- NIST has proposed a Maltese Cross torque sensor concept that could be used in place of our current design. NIST is currently working on the sensor for another internal project that is scheduled to finish in September 1999. Their efforts in this area will require them to develop a calibration methodology for a deflection based torque sensor.

- Matt presented an evaluation of the Maltese Cross torque sensor design. He showed that the sensor could be made with adequate resolution to meet our published requirements. The analysis, however, also showed there is an imbalance between the nominal gram load and our desired torque requirements. He said we probably would have to make a trade off between the large nominal gram requirement and the torque resolution. There was some discussion of potential ways to offset or reduce the effects of the nominal gram load while retaining the sensitivity to the torsional forces but a final consensus was not reached.

- The group brainstormed four potential techniques that could be attempted for torque sensor calibration. The four techniques are fixed-weight artifacts, integrated motor coil on the load platform, fixed-spacing force actuators and the dual spring method. The following sections provide more details and a brief discussion of each technique.

  - ♦ Fixed Weight Artifacts - Clayton recommended we use fixed-weight artifacts that contact the load platform at two or more different locations. The primary advantage to this technique is that the artifact loads are fairly well known and constant. However, there is a small concern about the uncertainty of the constant point separation in this technique. The weight of the artifact can easily be determined but the position where it contacts the load platform and its relative position to the other contact points will be more difficult to determine and could potentially be subject to change.

  - ♦ Integrated Motor Coil - Matt proposed a calibration concept that would use an integrated coil on the underside of the load platform to create a torsional load on the sensor. The technique would require the sensor to be placed within a known magnetic field while a current was being passed through the integrated coil. Under proper conditions the coil would act like a motor and induce a rotational moment to the load platform. The technique would require a different orientation of the magnetic field for both the pitch and roll calibrations but that would not be difficult to implement. The sensor also would have to be fabricated from a nonferrous material such as aluminum, silicon, etc.
  - ♦ Fixed Spacing Force Actuators/Air Jets - Brad envisioned a dual force technique that could be used to apply a couple to the torque sensor's load platform. Brad's technique would require the simultaneous application of two forces to the load platform. The torque would be induced through an imbalance in the two loads. The important thing about this method is that the distance between the two forces would be fixed and known. The capability of the technique then would be limited by how well you knew what the input forces are. Brad recommended a fixture with jeweled air nozzles.
  - ♦ Dual Spring Method - Nicholas describe a possible technique that would use two wires or springs that would be attached to opposite sides of the load platform. A torque would be induced by pulling on one spring while pushing on the other. Nick proposed this could be done with the ends of both springs being connected over a pulley. The required forces then would be created by rotating the pulley by a known amount.

- Clayton made a point to highlight the fact that the sensor should use only three measurement points instead of the four that we are currently using. John Evans agreed with using only three, but noted the benefit of the fourth input as a confidence barometer.

- The group couldn't find any obvious faults in the evaluation of the current HTI calibration procedure and its application to the deflection based torque sensor. There was some discussion over whether the sensor model needed some additional components to represent the external gimbal or not. An agreement was finally reached that the additional terms wouldn't change the conclusion so the model was sufficient for this purpose. The group couldn't say for sure whether the proposed calibration methodology would work on a force restorative sensor.

Uncertainty Budget:

- Clayton opened the discussion with a compliment on our progress and dedication to the use of uncertainty principles in understanding our measurement systems.

- Discussion on this topic was limited due to time constraints.

General Topics:

- Clayton mentioned that Honeywell is/has been working on a resonance-based gram sensor. We mentioned that we knew about this development but hadn't had any contact with them in some time.

- John Evans asked, in a hallway discussion, if we could supply him with some micro-actuated suspensions for gripper experiments. (Brian will inquire about availability and discuss it with Greg and Betty.)

External Discussions:

- Joel Millett and Yiding Wang had a detailed discussion with Dr. Ted Vorburger on the Micro-CMM and white light measurement instruments

- John Buttress had a lengthy discussion with Clayton on the Fly Height Uncertainty Budget. Clayton agreed with the finite solutions approach, but suggested adding a discussion of the governing equations (from the fly height simulation software, CML Air). John conceded that a general overview of Reynolds equation would be beneficial, even if partial differentials were not used in the uncertainty model.

- Satish demonstrated our resonance tester to Matt and discussed the measurement issues with him. Matt mentioned that NIST potentially could build a frequency bar artifact for us. (Satish will prepare the artifact requirements and submit them to Matt.)

General Impressions:

- NIST is not directly working on any projects to address the torque related measurement issues in the RDD industry.
- There is some confusion as to the targeted application and use of the Maltese Cross sensor design.

Information to Request:

- Copies of the transparencies that Clayton, Brad, Nicholas and Ted presented at the meeting. (Greg)
- An organization chart for Rick Jackson's group at NIST and a list of the key projects and project leaders within the group. (Greg)

Summary of Action Items:

- Satish will prepare a requirements list for a resonance artifact and submit it to Matt.
- Greg will contact Ted to explore any potential relationship between HTI and NIST concerning NIST's efforts in using whitelight microscopy for 3D geometry measurement.
- Greg is to ask Clayton on the status of the torque calibration procedure evaluation.
- Ted will let Joel know of NIST's whitelight microscope choice when they make a decision.
- Greg will ask Clayton what strategies and tactics that he is considering for torque measurement going forward.
- Brian will work with Greg to organize a conference call to answer any unresolved questions and set future direction.
- Brian will inquire about the availability of some Actuated TSA suspensions and discuss with Betty and Greg.

Professional Instruments

Location and date of visit: Hopkins Minnesota
Recorder: Matt
Company Background: Professional Instruments Company is a privately-owned family business that was founded in 1946. The owners are sons of the founder and have worked many years in all areas of the company's operations.

PI currently operates six plants; five in Minneapolis, and one in Rochester, Minnesota. PI's total manufacturing floor space is ore than 100,000 square feet.

Host and points of contact: Mel Leibers
Chief Metrologist
7800 Powell Road
Hopkins Minnesota 55343 USA
(612)933-1222
<pico.airbearings.com>

Technology Development: In addition to PI's product line of air bearing spindles and slides, it does a wide range of subcontract manufacturing including tools, gauges, prototype parts, precision cams, special machines and production parts. The company actively works in the field of diamond machining and makes a strong effort to handle a wide variety of work which enables us to do jobs that many firms cannot handle without subcontracting.

Primary Customers: IBM, SVG Lithography, Rosemount, Moore Tool, Nikon, Dover, Carl Zeiss, Cranfield Precision, Allergan Medical Optics, 3M, Timken, Seagate.

Standards, measurements, and data needs of Micro-Meso-Manufacturing identified:
Precision Manufacturing and Metrology for Precision Components and Machines

General description of visit and particular points of note from discussions and presentations:
Although PI is not directly involved in micro-manufacturing many of the components they develop and market are enabling technologies for high-precision micro-machine tools. Thus, the visit centered around a tour of PI's facilities and laboratories and a discussion of the various components (such as air-bearing spindles and precision slides) that they now produce.

Our tour included an overview of:
Air Bearing Technology, Bearing Analyzers, Precision Machining Facilities and Air Bearing Repair Facilities.

Microfab Technologies, Inc
March 15, 1999
Recorder – Clayton Teague

Microfab Technologies' plant location is:
1104 Summit Ave.
Suite 110
Plano, Texas 75074

Our primary host was: Dr. David Wallace, Vice President; Technology Development. Others from Microfab at the meeting were: Scott Ayers, Director of Product Development; Dr. Hans-Jochen Trost, Senior Scientist; David Taylor, Staff Scientist (later found that he concentrated on biomedical applications; Royall Cox, Project Leader in Optics; Michael Grove, Chemist in Displays.

Microfab Technologies is a company about 14 years old and has since its founding concentrated on developing capabilities for direct write microdeposition of a wide variety of materials using piezoelectric demand mode ink-jet printing technologies. They have developed the capability to deposit a wide variety of paricle-laden fluids including dyes, organo-metallic liquids for depositing gold, silver and ferrites; many polymers; solder; epoxies; and biologically sensitive reagents. They have applied this technology to a wide variety of fields including; DNA diagnostics; blood typing; microlense arrays for coupling to GRIN fibers; matching GaAs microlasers and photodetectors; formation of resistors, capacitors, and inductors for passive electronic devices; drug delivery; and laser surgery by locally depositing materials to absorb laser light. This latter application is particularly effective since one can just deposit absorptive materials rather that varying the laser wavelength to get effective absorption by the desired substrate. The method alternatively deposits the absorptive material and fires laser pulse.

John Evans gave an overview of NIST and ISD's work in optoelectronic assembly highlighting MEL's new exploratory project in micromachining, microassembly, and micrometrology; Carol Handwerker's Division work on solder bonding; EEEL's work on micro-hotplate sensor arrays with CSTL's high speed chemical assaying and sensing; MSEL's work on micro and nano tribology; PL's work on self-assembly and SPM assembly of atomic structures; and finally, MEL's development of single-atom step-height artifacts.

Brad presented an overview of the micro/mesoscale exploratory project with emphasis on work to develop microsensor for millinewton force and nanonewton-meter torque measurements using high precision machining with small cutting tools.

Nich presented overview of ATP funded project, "Calibration and control of deformable structure micro positioners." Adept Corporation is the lead on this ATP project, with NCMS as the program manager. The project is being coordinated through the Precision Optics Assembly Consortium (POAC) with members of Adept, Boeing, New Focus, Dresser Industries, Corning, and New Jersey Institute of Technology. NIST participation is by ISD, PED, and soon APTD in MEL and MSEL.

Microfab is very interested in this area and will be submitting an ATP proposal on methods to reduce alignment constraints through deposition of microlenses on the end of fibers.

Dr. Wallace then presented an overview of MicroFab Technologies. His presentation overheads are attached. Several points raised in his overview were summarized in the opening paragraph in this report. Other points of interest were:

- Basic method used in all their micro-droplet dispensers was a piezoelectric driven acoustic –mode resonator cavity with the "quality" and size of the droplets being dependent on the waveform shapes used to drive the PZs.
- Properties of the droplets dispensed were monitored using pulsed light emitting diodes synchronized with the electrical pulses to excite the dispensing of each droplet. By varying the phase between these two events, the complete evolution of a droplet could be monitored from the ejection from the jet to the final coalescence into a high quality sphere. If the

waveforms or properties of the ejected materials were not chosen properly “tails” on the ejected jet could be observed which would in turn produce “satellites’ on the deposited droplet or bump.

- Direction of the ejected droplets was highly repeatable. They had monitored droplet direction and had found that at distances of up to one millimeter from the nozzle positional variations were less than one micrometer.
- Surface migration after deposition on substrate surfaces is the greatest source of uncertainty in positioning depositions. Surface variations could be positional variations in wetting, scratches or roughness in the surface, or some dust particle on the surface.
- For many applications modulation of the drop size is as effective and more economical than increasing the spatial density of the jets.
- Needs for NIST help were indicated carefully in copies of overheads Dr. Wallace provided.

M-Dot
3418 South 48th Street
Suite 3
Phoenix, AZ 85040
602-921-4128
Contact: Bryan Seegers , President

Date of Visit: 3-18-99
Attending: Clayton and Brad
Recorder: Brad

Company Background

The company name, M-DOT, is the first derivative of mass, or mass flow. Formed ten years ago as an Allied Signal spin off, M-DOT was founded specifically to develop and manufacture aerospace components and systems with specialization in gas turbine engines and related hardware. In addition to their engineering capability, M-DOT has a complete machine shop equipped for prototyping and production work. The company has over 30 employees with 23 being engineers. Income is derived from SBIR's, consulting, manufacturing and the DARPA microturbojet project. The president was the first in the world to design and build a micro jet engine for model airplanes. Their customers range from Georgia Institute of Technology (gas turbine for studying surge properties of combustion chambers), Allied Signal (design/build inlet and outlet exhaust manifolds), Gulf Stream (power resistors), to the Navy (tactical missile turbojet engine) to name a few.

Their engineers use extensively Solidworks for complex structural design and analysis, Algor for finite element stress analysis, and rapid prototyping techniques for molding complex shapes. In addition, M-DOT has low-cost, quick turn around sheet metal stretch forming capabilities and CNC machine capabilities. Custom fiberglass parts and assemblies are also produced. Other capabilities include hot formed titanium structures, composite panels for aircraft cowlings and production facilities for manufacturing test stands.

Micro machining activities

The DARPA microturbojet project drives M-DOTs micro machining activities. The project will produce a gas jet engine the size of an egg with 1.43 lbs of thrust and spins at 350,000 rpm. The engine components are made from molded parts using rapid prototype techniques such as the compressor with turbine blades. Other parts are micro laser welded, micro mechanically milled and turned. There goals are to see the turbines made from silicon carbide, use electroformed nickel for the combustion chambers, be able to cast thin walled parts.

Company needs

The needs are micro scale material properties, micro scale machining process parameters. Stress rupture test data for thin walled micro parts.

SandiaMicroelectronics Laboratory
Sandia National Laboratories
Microsystems Business Office
PO Box 5800 MS 1078
Albuquerque, NM 87185-1078
(505) 844-5947
(505) 844-7833 fax
Contact: Donald F. Rohr
rohrdf@sandia.gov

Date of Visit: 3-16-99

Company Background

Sandia is a DOE weapons lab run for DOE by Lockheed Martin. There are two Sandia sites, Albuquerque and Livermore. Sandia provides the engineering for the "physics packages" of nuclear weapons, whereas the theoretical and basic scientific work is done by Los Alamos and Lawrence Livermore Labs.

Sandia is involved in all manners of technology, but ultimately it is focused very tightly on DOE missions and particularly on nuclear weapons, environmental remediation, and safeguards.

Meso/Micro Manufacturing Activities (MEMS)

The microelectronics lab probably cost of the order of $100 M to build and has a budget of $100M per year. They have class 10 capability and recent 6" wafer equipment, which is beyond what any university facility would have. They are one of the leading MEMS labs in the country and have developed motors and gear trains beyond what anyone else has been able to achieve. The focus of this work is safe trigger systems for weapons and for sensors and detectors for various safeguards projects.

The key technology that they have developed is five level polysilicon surface micromachining, with which they are able to produce complex gear trains, comb motors, pin-in-maze discriminators, pop-up mirrors, and other mechanical components, with proper release and surface coatings to insure operation. The gears run to 500,000 rpm and are good for millions of revolutions; they are trying to get to billions of revolutions. They are now spinning this technology off to industry by offering training courses and design tools. They currently offer fab services and were negotiating with private foundries at the time of our visit.

Company needs

Few needs in a well-funded program like this, but materials properties and materials testing were of general interest. They also expressed interest in collaboration in any effort that NIST undertook.

UC Berkeley

Berkeley Sensor and Actuator Center
University of California, Berkeley
Department of EECS
497 Cory Hall
Berkeley, CA 94729-1770
510-643-6690

Founded in 1986, the mission of the Berkeley Sensor and Actuator Center (BSAC) is to develop a science, engineering, and technology base for microsensors, microactuators, mechanical microstructures, and microdynamic systems. The Center builds upon a well-developed arsenal of design and fabrication tools, which make possible today's microelectronic devices and integrated circuits, to create tomorrow's integrated microelectromechanical systems. Achieving this goal depends heavily on research advances in electrical, mechanical, chemical and biomedical engineering and materials science.

NIST Boulder Optoelectrionics Divison

Location and date of visit: Boulder, CO, March 15, 1999
Recorder: Nich
Laboratory Background:
  Age: Approximately 100 years old
  Size: Approximately 3,300 employees
Host and points of contact: Dr. Gordon W. Day, Chief
Dr. Alan F. Clark, Deputy Chief
Dr. Robert K. Hickernell, Group Leader, Optoelectronic Manufacturing
Technology Development: Optoelectronic devices metrology and standards
Primary Customers: Optoelectronic devices manufacturers
Standards, measurements, and data needs of Micro-Meso-Manufacturing identified: Automated assembly and packaging of optoelectronic devices
General description of visit and particular points of note from discussions and presentations:
John: Talked about the MEL Micro-Meso-Manufacturing (MMM) exploratory project.
Nich: Talked about the ATP Precision Optoelectronic Assembly Consortium (POAC) and the Intelligent Systems Division (ISD) intramural project on the same subject.
Gordon: Indicated that the assembly and packaging of optoelectronic devices is a significant component of their cost. The lack of automation has moved most of the assembly work to Pacific Rim countries.
A significant assembly problem is the alignment of optical fibers with sensors, light sources or optical components, like lenses. DARPA has funded Mark Lowery of the U. C. Berkeley to develop an optical fiber alignment machine. Unfortunately the machine costs approximately $500,000.
Nich: Adept robotics, the leader of POAC, used to build such a machine, but could not find many customer due to its cost. The POAC companies are developing an automated optoelectronic devices assembly robot, which will cost $50,000 to $100,000. New ideas might reduce that cost by an order of magnitude. The reduction of the assembly cost could bring jobs back to the US. Adept is estimating that automation could reduce each alignment operation from 60 to 30 minutes to just a few seconds. If we assume that the use of these devices will spread to automobiles, and every phone and computer that is manufactured in this country we can estimate a saving of $12 to $15 billion in a period of ten years.
Gordon: The savings will be significant but perhaps closer to $7 billion.
An alternative alignment technique is passive, where groves are used to guide optical fibers to the right position.
Nich: The groves can be used for coarse alignment. Fine resolution translation and rotation is required for the final positioning of the fibers. Most groves and fibers are coated with metal and electrostatic actuation is used for the final positioning of the fibers and to hold them in place while the glue or soldering is solidifying. The positioning and control unit must be very inexpensive because it goes into every single optoelectronic device manufactured.
Gordon: The Optoelectronics Industry Association (OIDA) has compiled a list of needs. Here is their prioritized list:

- Semiconductor Materials.
- Packaging.
- Modeling.
- Metrology.

A while ago representatives from this association met with the NIST director and demanded that NIST establishes a program on opto electronics. NIST submitted an initiative proposal, which was not funded this year, but it might be funded next year.
Plug in to IEEE LEOS (Lasers and Electro Optics Society) and CPMT (Components Packaging and Manufacturing Society) to keep track of the latest developments in the field. CPMT has an annual meeting, which is usually held in May.
The current trend is to move towards single mode, multi fiber packages with an ultimate goal of 10 Gb/s transmission rates.
Matt Young has developed SRMs for optical fibers and Ted Doiron has calibrated fiber gripping load cells.

Fanuc Berkley Research Center

Location and date of visit: Union City, CA, March 18, 1999
Recorder: Nich
Laboratory Background:
Age: Approximately 3 years old
Size: Approximately 10 employees
Host and points of contact: Dr. Hadi Akeel, General Manager
Dr. Albert G. Yee, Assistant General Manager
Dr. Salah E. Feteih, Senior Research Engineer
Technology Development: Industrial Robot Sensors
Primary Customers: Users of Industrial Robots
Standards, measurements, and data needs of Micro-Meso-Manufacturing identified: Micro-Meso scale load cells calibration tools. MEMs packaging.
General description of visit and particular points of note from discussions and presentations:

Hadi: Our parent Japanese company is a member of the Micromachine Center in Japan. This is a government-funded program, which promotes the development of Micro-Meso devices and manufacturing techniques. As part of this effort our parent company has build a 200 mm to 50 mm serial robot arm. A picture of this arm may already be displayed in FANUC web page.
Nich: I searched the FANUC and Micromachine Center web pages before the trip and it is not listed there yet.
What is this robot going to be used for?
Hadi: It will probably be used for the development of a table top manufacturing capability. The Berkeley facility will be used for the development of Micro-Meso scale sensors for our robots.
A recent Academy of Engineering report on MEMs concludes that the reason for the lack of commercial success of MEMs devices is due to the lack of a good packaging capability.
Tour of the facility: Brand new and small, but with a very impressive collection of expensive MEMs fabrication equipment. The most strange thing we saw was a machine shop facility next to a clean room. It underscores the company philosophy for quick interaction between the macro world and the micro world. They told us that they have not used the clean room yet and thus do not know if it can function properly next to a machine shop.
Albert: Asked permission from Hadi and then showed us two small load cells they have built. The first is a Stewart mechanism shape structure, that could fit in a cube of approximately 10 mm size. The second one was a 1 mm force sensor of unknown (proprietary) design. The Stewart shape load cell had semiconductor strain gages attached to all six struts and could measure six components of force and torque. The mechanical structure of the load cell was built by FANUC but the stain gages were attached by Micro ???. One problem with this load cell is that it has significant cross talk (5%).
Clayton: How do you calibrate this load cell?
Albert: We hung weights. This is not a very good way to calibrate them. We need standard loads of a few mN and we need to know the point of the application of the load.
Nich: You might need pure uniaxial, well characterized loads, which you may use to estimate the elements of the load cell calibration matrix. The calibration matrix can decouple the outputs to their individual Cartesian axes components.
Clayton: Perhaps you can use Lorenz electromagnetic force and a printed circuit coil to apply standard loads.

Adept Technology

Location and date of visit: Livermore, CA, March 19, 1999
Recorder: Nich
Laboratory Background:
Age: Approximately 18 years old
Size: Approximately 400 employees
Host and points of contact: Brian Carlisle, CEO
Carl Witham
Technology Development: Manufacturer of Industrial Robots
Primary Customers: Users of Industrial Robots
Standards, measurements, and data needs of Micro-Meso-Manufacturing identified: Database of NIST requests for possible applications of MMM. Products for micro assembly and material handling. Stereo vision for microscopic parts. Analytical tools for Design For Flexible Assembly (DFFA). Micro Assembly Techniques. Analytical tools for Feeding, Fixturing, Mating, and Fastening Processes. Better Sensors. U.S. Manufacturers Should Design for Automation.
General description of visit and particular points of note from discussions and presentations:
John, Clayton: Talked about the MEL Micro-Meso-Manufacturing (MMM) exploratory project and the capabilities and interests of ISD, APTD and PED.
Brian: You should generate a database of NIST requests for possible applications of MMM.
John: Packaging of MM devices is a big issue. Getting power and mechanical connections to these devices is difficult.
Brian: There is need of products for micro assembly and material handling. The traditional clearance for assembly is 1 m-in, and the workspace is 10 to 20 times the size of the parts. Part feeding and orientation has to be considered.
Clayton: Why do we need these large mass robots to move small light parts?
Brian: Ralf Hollis is trying to reduce the size of robots, but still has to use part feeders, etc. Adepts main product is Adept1, which weights 400 lbs and with good calibration achieves an accuracy and repeatability of 1m-in. We are developing a small robot of approximately 10 cm size.
Clayton: Can robots do machining. I have heard of an ABB robot that can do that.
Brian: Robots are not stiff enough for that kind of operation, they are very good for assembly operations. Automated assembly today includes flexible part feeders, new linear axes robots, vision systems, control products and Rapid Deployment Automation (RDA) knowledge products. RDA can reduce preparation time from 12 months to 8-12 weeks.
System design products are virtual environment animation products. New capability is the product design tools, which include the tolerances and can tell the designer if parts can be assembled. A suite of software will be developed for micro assembly applications.
Most of our customers are in the electronics market. Today the vision market is growing fast. The vision products market is approximately $5 billion strong and the robots market is approximately $5 billion strong too.
The pressure to our customers is for:

- Shortening product life cycles.
- Miniaturization.
- Demand for quality.
- Rising cost of labor.
- Return on capital investments.

The infrastructure cost overseas (Asia) is lower than that of the U.S. For technically sophisticated products they still have to be assembled in the U.S.
The new appliance concept is:
Simple, cheap, small, short life.
Cell phones, HP ink jet printers have a product life of 6 months. Some products have a life of only 3 months. Whatever MMM technology is put together it must support product lives of 6 to 12 months.
A challenge for U.S. manufacturing:

- No U.S. manufacturing of VCRs, Camcorders, SLR Cameras, Disk Drives.

- Either offshore labor or home automation.
- Miniaturization will challenge labor.
- U.S. manufacturers need to learn automation.

Key processes in micro assembly:

- Part Feeding.
- Part Grasping (Reliable Grasping and Releasing).
- Part Mating.
- Part Bonding.
- Sensing and Verification (Pin in, Lid flat, Gears engaged, Glue properly dispensed, How do you mate things).

Clayton: Can slurry assembly do all that?
Brian, John: Eventually you have to do serial assembly.
It is important to Design For Flexible Assembly (DFFA):

- Feeding, Fixturing, Mating, and Fastening Processes.
    - Robustness of these processes determines system yields.
    - Debugging these processes shows production ramps.
    - No analytical tools presently available.
    - Little or no thought during product design.
    - Little or no thought during system design.

A discussion on part, gripper, and mating tolerances followed.
Software tools, like SILMA, will give you the probability that the part will land on one state or the other. This information can be given to our flexible feeder to make it pulse the part appropriately. Proper gripper design can then exert stable kinematic constrain on the part.

Conclusion- There is need for the following:

- Micro Assembly Techniques.
- The Designer Needs Models of These Techniques.
- Better Sensors.
- U.S. Manufacturers Should Design for Automation.

Demo #1: An Adept robot grasped an optical fiber and inserted it through a metal box long neck opening and the tiny hole of a solder preform. The robot picked up and positioned a preform. Ordinary and microscopic vision system inspection of the fiber and the preform.
Clayton: Why do you need stereo microscopic vision?
Brian: The optical fiber comes wrapped in a spool and we would like the vision system to be able to identify the position and orientation of the end of the fiber.
Demo #2: Alignment of two optical fibers.
Demo #3: Intelligent part feeding.

Johns Hopkins/ Applied Physics Lab

Ed Amatucci
May 25, 1999

Invited by Dr. W. N. Sharpe of JHU, edward Amatucci and Nicholas Dagalakis visited the Applied Physics Laboratory in Laurel, Maryland. We gave a talk on the Meso-Manufacturing project and received feedback about our project and learned of their concerns in this field.

Attendees: Edward Amatucci, Nicholas Dagalakis, W.N. Sharpe, Jr., Scott Ecelberger, Richard Benson, Dale Wison, and others from their group. We also meet Dr. Harry Charles who leads a Micro-Medical effort at APL.

The visit was short and then we had a lab tour of their machining area and some of their production facilities.

Their feedback to us and interests that need to be addressed include:

- Understanding the limitations of Meso/Micro Designs and Development – how o use the tools and how to develop techniques to utilize existing tools not designed for this size analysis.
- Appropriate techniques to measure the micro/meso performance of designs
- What materials are better for the machining of meso-scale components
- New fabrication technology and machining, tolerancing issues
- Partnering issues – commercial sector

Attendees:

Ergin Atalar	Johns Hopkins University
Patrick Jensen	Johns Hopkins Microsurgery
Gregory Chirikjian	Johns Hopkins Engineering Robotics, computational (ME)
Nitish Thaker	Thrust Leader - Interfacial Tech. (BME/EE) – nthakor@bme.jhu.edu Biomedical Devices/Medical instrumentation, heart, brain, sensors
Ralph Etienne-Cummings	VLSI Chips – Image on the fly, sensors (ultrasonic/optical) (EE)
Pat Jensen	M surgery; force/actuators; sensing (eye…) (EE/ME)
Dan Stoinovich	(Kavoussi) Robotics “builds” – Percutaneous, steady hand robot (ME)
Larry Wolff	Optical spectroscopy/polarization (CS)
Louis Whitcomb	Controls, robotics (ME)
Carl Riviere	Precision, dexterity of hand, redundant (CMU)
Rob Howe	Sensing geometry (touch, haptic) (Harvard)

Thrusts
- Testing
- Imaging
- Devices

Patrick
- Microsurgery
- Surgical augmentation, extend capabilities of surgeries

Greg
- Planning & visualization of systems
- Probes, etc.

Dr. Sharpe
- Mechanical properties of MEMS, test specimens 2 microns

- Sensors, computer with UV or other low power sensors, applied to robotic control
- Clinical issues
- Carnegie Mellon – CMU, human perf. Dexterity institute
- Harvard (Rob) – "haptec" feedback
- Small MRI probes to get high resolution images.

RWS Taylor
- ERC director, systems origut.

Dan S.
- Urological cathador applications

Surgically accuracy's of the surgeon, manipulator built with sensing actuators, small multi-degree of freedom actuators – 1mm hole access, 1 micron precision. 10 micron limit – on based visual resolution is the limitation. www.madlab.jhu.edu

MRI images – based RF antenna blood vessel imaging in cathador…
- Endoscopy devices, needles – hardware to make the probe. Miniaturized automation? Coaxial cables suitable for these devices.
- Connectors dealing with the body tissue "surgery vision" – APL collaboration
    - Harry Charles
- 3D sensor processing on the chip
- Computational structure.

ERC – collaboration
- Engineering research center
    - Computer – integrated surgical systems & technology
    - Microsurgery, neurosurgery, needle surgery ??
- Interfacial technology

Needs
- Smaller & smaller probes
- Control devices
- Independently guided

Integration standard of medical devices
- ISG, LEICA, …

Ken Fahancoh – Industry partners

Spine surgery meetings

"Core Technology" – ERC, standardize integration of devices
- Adaptive to human environment
- Sensors, integrates

ERC needs to standardize & move to dissemination.

Dr. Sharpe
- Testing of small patterns of MEMS materials
- Using optical techniques to do reassuring
- Need better metrology of device.

Only 4 doing the studies.

Lowell Howard
- Image section

Joe Fu

- Wyco or Zygo   M. Gaihan, Janet Marchall

Technical services

- May 19th – 28th

Papers given to us:

Measurements of Young's Modulus, Poisson's Ratio, and Tensile Strength of Polysilicon
By William N. Sharpe, Jr., Bin Yuan, Ranji Vaidyanathan, and Richard L. Edwards

Mechanical Properties of LIGA-Deposited Nickel for MEMS Transducers
By William N. Sharpe, Jr., David A. LaVan, and Richard L. Edwards

Potomac Photonics

Ed Amatucci
April 14, 1999

We visited Potomac Photonics lab and taked about our Meso-Manufacturing project. We also heard about their needs. Matt was very interested and pursued a CRADA with them in Laser Machining. Our contact there is Sidney Wright. We meet:

Lori Beer, President. Ph.D., Engineering, Unv. Of Utah. Over the last 35 years he has started, run, or assisted companies with management and market development.

Sidney Wright, North American Sales Manager. MS Physics, Univ. of Tenn. 20 years experience in laser sales and engineering including time with the largest laser company.

Paul Christensen, Chief Technical Officer. Has worked with lasers, laser applications, and project management for 30 years; developed first waveguide excimer laser; Ph.D. EE, UC Berkeley.

Michael Duignan, VP for Research. 25 years experience in laser applications and new technology development. Ph.D. Physical Chemistry, Brandeis.

Check out their website at: www.potomac-laser.com

The needs they indicated include:
- Metrology issues – precise alignment of parts
- Robots – needs better automation
- Precision mechanical machining
- Systems integration issues
- Machine vision limits
- Quick turnaround is very important (commercial oriented)
- can work be directed to specific problems
  - example: brightness issue – metrology with a bright illumination source ("193" source)
  - price needs to be reasonable

General information:
- 21 full-time employees
- 4.2-4.5 million per year
- machine center they sell costs about $700K
- they do systems support 1.5 million , OEM lasers about 900K
- service support – feed and fixture systems (one their major research needs)

vision software for calibration and orientation of part – micro"Inspect", "micro inspector" and "microview" combined with machine vision. This maybe a new product for them. Uses Visual Basic.

Intuitive Surgical, Inc.
1340 W. Middlefield Rd.
Mountain View, CA 94043

Dr. Kenneth Salisbury
Fellow and Scientific Advisor
(650) 237-7185
(650) 526-2060 fax

Company

Intuitive Surgical makes telerobotic surgical systems for endoscopic surgery. The company slogan is "taking surgical precision and technique beyond the limits of the human hand."™. The product is a three-arm robot (two hands plus 3D video) that is placed over the patient. The arms are all tendon driven with kinematics that provide spherical coordinate system centered at the point of entry into the patient. The end effectors are interchangeable instrument packages with three axis wrist (roll-flex-roll, very reminiscent of Goetz' work at Argonne for nuclear handling that became CRL manipulator line, on a much smaller scale) plus grip actuation. The surgeon sits at a control console that has vide and two master controls with force feedback.

Based on DARPA funded telesurgery work at SRI. Some 100 procedures have been done in Mexico and Europe, many animal surgeries in US. Hoping to get FDA approval by end of year and go public. Easier to get approval for man-in-the-loop systems than for completely automatic robot systems (e.g. Integrated Surgical Systems RoboDoc has been held off the market for years with approval pending).

Supposedly much better in safety and effectiveness than standard minimally invasive surgery, very positive feedback from doctors.

Very impressive engineering.

Meso Manufacturing

The instruments are mesoscale parts and assemblies, with a complete robotic wrist and tooling being a few cm long and less than 1 cm in diameter. Very nice work. Potentially a razor blade business with the instruments the blades (at $1500 a pop delivered to the operating room).

Needs

Machining of small parts and assembly were reported to be difficult, manageable in prototype quantities. Cost was not an issue at the moment. Providing 100% inspection and test will undoubtedly be necessary for surgical instruments.

Trip Report to Bremen, Karlsruhe and Mainz Germany

From: Brad Damazo

Purpose: To present paper at euspen conference and visit the Karlsruhe Research Center, Institute of Microtechnology Mainz and the University of Karlsruhe.

Trip Summary: I attended the 1st international conference and general meeting of the European Society for Precision Engineering and Nanotechnology (euspen). The conference started on May 31st and was held through June 4th. The euspen conference replaces the IPES and UME conferences and will expand on the topic of precision engineering with future seminars, special topic meetings and training workshops to be held in locations throughout the European Union. This new society is unique in that the European Commission has funded the start up phase for three years, the funding level is approximately $500,000. During the conference, I presented a poster paper entitled "A Summary of Micro-Milling Studies" and had the opportunity to interact with numerous other researchers who are also working in the field of micro machining. In particular, I visited the Karlsruhe Research Center, University of Karlsruhe and the Insititute of Microtechnology Mainz to view their micro machining research programs.

Monday, May 31st

The conference organized visits to three laboratories on the University of Bremen campus, which I participated in. We visited the Fraunhoffer Institute of Manufacturing and Applied Materials (IFMM), the Bremen Institute of Applied Beam Technology (BIAS) and the Laboratory for Precision Machining (LFM). Each laboratory was impressive with highlights listed below:

Fraunhoffer Institute of Manufacturing and Applied Materials

The IFMM is performing research into non-traditional manufacturing areas. One such area of research is near net shape manufacturing using powdered metals. The target applications are for automotive parts (i.e. piston rod) and mm sized micro parts for the medical industry, using steel and titanium powders. The entire manufacturing process is under study including computer simulation of the casting process and powdered metal metallurgy. The on site equipment includes a powdered metal press, sintering/vacuum chambers and both optical and SEM microscopes to measure the micro parts. The actual molds are machined elsewhere.

Another program focuses on developing adhesives using molecular modelling. The target applications are for adhesive bonding of lightweight components such as micro systems and for developing metal bonded foam structures. This unique application uses an aluminum foam core bonded to aluminum or steel plates, forming a lightweight, stiff, highly damped structure for use in the automotive industry. The intended use is that of a structural member in engine compartments and rear seat areas for the Audi all aluminum car. The aluminum foam is 7.5 mm thick, with 0.5 mm pores and a density of 0.4/0.5 grams/cm^3.

Other work in progress, is surface analysis techniques inside a ultra high vacuum (10^{-10} torr). The vacuum chamber is fitted with an AFM, and SFM for measurement capability. The environment is variable through its multiple sources of inert gases and over a wide range temperature. Grain boundaries, fracture, adhesion, and friction and wear are studied using diamond tools, and various ferrous and non-ferrous materials. A magnetically coupled motor drives a diamond coated wheel for the wear test.

Lastly, the IFMM has a resource center in Newark, N.J.

Bremen Institute of Applied Beam Technology

The founders of the BIAS were the original inventors of the laser welding process in 1968. The staffing is composed of 34 scientist and engineers with 36 support staff, performing research in:

- Laser-Assited Microtechnology
- Laser Manufacturing Processes
- Coherent Optics
- Optical 3D-Sensing

Our tour was through the Microtechnology laboratories where research into laser assisted photochemical etching and laser ablation processes were used to produce micro-structures on ferrous, and nickel plated materials. The machining processed produced aspect ratios of 0.5 to 10 with no heat added to the material. During the photochemical etching, the point of focus causes a reaction to remove material. The process can not produce straight, 90 degree, walls, but only 85 to 89 degrees. Holes can be bored as small as 8 μm in diameter and 50 μm deep. The stated throughput was 100,000 of these tiny holes in 10 minutes. The type of laser used is a "green" laser and many of the experimental machining setups were controlled with the PMAC motion control board. The final application of the micro-structures are for mold tools or hot embossing tools.

Laboratory for Precision Machining
The laboratory is headed by Prof. Ekkard Brinksmeier and has become, in the last ten years, a leading research center for advanced ultra-precision machining technology. The work ranges from diamond machining, precision grinding, polishing, measurements to molecular dynamics simulation. One of the more interesting projects completed recently was that of finishing 18 off axis mirror segments for a 3 meter radio telescope reflector with a newly develop 3 axes fly cutting process. In addition, several micro machining projects were recently completed including the machining of fresnel lens for a focusing screen for Leica cameras, diamond milling of fresnel microsturcures on freeform surfaces for rear taillight lenses, and molds for intraocular lenses with diffractive optical elements.

The laboratory is well equipped with four ultra high precision machines for diamond turning, diamond milling and grinding. In addition, the measuring capability is covered with the lab's AFM, STM, EFM, white light interferometer, two CMM's and a phase shift interferometer. The laboratory building itself was complete 6 months ago for a cost of $7,000,000 and the laboratories are temperature controlled to ±0.1°C while sitting on 1000 tons of concrete. The city of Bremen has invested heavily into this building and many other high technology research institutes while trying to create a high technology research infrastructure for the city. In the past, Bremen was known for its shipbuilding, but this industry has been a victim of the economy.

Tuesday, June 1st through Thursday June 3rd
The oral and poster presentations were presented over the next three days. Over 260 papers were presented approximately 60 oral presentations and the balance as poster papers. From this collection of papers, 55 of them were on the topic of micro machining, inspection of micro devices, and processes for manufacturing micro devices. Also, there are over 12 different universities performing research in micro devices within Germany. Listed below are several papers of particular interest:

"Fabrication of Precision Molds" by E. Brinksmeier et al
"Sub-Newton Cutting Force Measurement for Mciro Machining Processes" by B.K.A. Ngoi et al
"Investigations on Capillary Action Microcasting of Metals" by K. Mohwald et al
"Review on Laser-Micro Structuring" by H. Tonshoff et al
"A Review on Micro-Electro Discharge Machining of Metal and Silicon" by D. Reynarerts et al
"Fibre-Optic Supervision for the Micro-Assembly Process" by B. Brocher et al
"Development and Characterization of New Probes for Dimensional Metrology on Microsystem Components" by T. Kleine-Besten et al
Listed below are vendors of particular interest:

IBS (from the Netherlands) is offering a machine tool characterization service. The volumetric accuracy of a machine would be measured with a ball bar by the customer and the data sent to IBS for analysis. Compensation models and software are then supplied to preprocess and modify the toolpath correcting for the geometric errors of the machine. IBS also builds specialize machines and using an in house developed PMAC motion control board based controller.

Physik Instrumte showed a 6-degrees of freedom micro positioning stage based on a Stewart Platform design. This little hexapod used gearmotors and leadscrew actuators to position the stage's platform with 70 mm travel and 50° of rotation. Physik Instrumte stated they had two other smaller hexapod designs in the works that used PZT actuators.

Lion Precision displayed an airbearing probe with 25 mm of travel. The probe can be preloaded with by adjusting a small needle value to obtain 2 mN to 200 mN of force. Such a probe could be used in force calibration of micro devices.

Nanotechnik has been developing a nanomotor for the last 9 years. This motor is a PZT device with nanometer resolution but with mm travel. The nanomotor itself is 4 mm in diameter and 15 mm in length and is shown side by side with a match stick. It can lift up to 3 grams in the director of its movement. The nanomotor is operated in two modes, course and fine, and has been used in scanning tunneling microscopes to study atomic structures. An unique application combines four nanomotors and a gripper to make a 4 degree of freedom (x,y,z and gripper) robotic gripper for fiber optic placement during assembly as shown below. In addition, tiny positioning tables with 5 mm of travel and nm precision are offered.

Monday, June 7th
Visited the Institute of Machine Tools and Production Science, Univerisity of Karlsruhe and was hosted by Dr. V. Huntrup. Dr. Huntrup works in a group performing analysis on cutting processes. Their work focuses on milling applications only, including dry cutting, milling hardened steel, high-speed milling and micro milling and model simulations. An interesting comment was dry machining (without coolants) is driven by money only (an estimated saving of 16%) not by saving the environment.

Dr. Huntrup's work is in micro mechanical milling of steel. After completing a literature search and finding numerous researchers micro cutting aluminium, brass, and nickel, he determined that micro cutting steel would be a good research area. In fact, micro cutting steel molds for injection molding micro devices is a fast growing field within the medical industry. His work spans three years and includes designing and building his own three axes milling machine (0.01 μm scales, 1mm pitch ball screw, a Precise 160,000 rpm spindle, controlled by the PMAC motion control board, and typical feed rates of 1500 mm/min).

Two years of research went into finding the right process parameters, parameters that include the hardness of the material. Their findings show that the material determines the work piece reproducibility. Since the grain boundaries cause discontinuities during the micro cutting process, much effort was focused on material heat treatment techniques. Ductile steel is not good for micro cutting, but harder steels are - the burrs are worse, but the geometry machined is more accurate and surface finish improves with hardness. The typical hardness is 52 Hc. In addition, during the cutting process, they found that carbon grain collisions with the endmill tool, causes tool vibrations. The smallest end mill used successfully, has been a 100 μm diameter carbide ball endmill.

Visited the Karlsruhe Research Center and was hosted by T. Schaller. The Karlsruhe research center was formed in the early 1950's, by the German Government, for the purpose of developing commercial nuclear power capability. This government research center, during the process of looking for ways to separate uranium isotopes, developed a micro nozzle design concept (a centrifuge separation process was later found to be more practical than the micro nozzle concept). A new process had to be developed to manufacture the micro nozzles and that process is now known as LIGA. The LIGA process comprises the steps of X-ray deep lithography, electroforming and molding to produce micro components with almost any lateral geometry (smallest lateral dimension 0.2μm) and structure height up to 3 mm in polymers, metals and ceramics.

As the center's research shifted away from nuclear power, to more commercial research, the LIGA process was found useful in producing micro components and the Microsystem Technology Program (PMT) was formed. The PMT is current performing micro component manufacturing research in the following areas:

Laser micro machining
The laser micro-machining process is influenced by the laser's wavelength, pulse, duration and energy density. Typical uses are for precision cutting, welding, engraving, drilling, abrading or laser beam supported etching. With a Nd:YAG laser, the lateral structural accuracies presently attainable is about 20 μm. The structure depths extend into the mm range. Aspect ratios of up to 10 have been achieved. With excimer lasers, the lateral structural dimensions presently attainable are in the submicrometer range. The structure depths so far achieved in polymers are in the mm range and in ceramics, below 100 μm. Lasers can be used to manufacture micro patterned molds for polymer molding, hot embossing and injection molding. In addition, lasers are used to machine coronary artery stents. Research topics include expansion of materials available for mold inserts to include tool steel, patterning of thin films and multilayers, minimization of attainable structure size and 3D structuring of polymers and ceramics.

Mechanical micro-machining
Mechanical micro-machining is drilling, turning and milling at the micrometer scale using diamond and hard micro tools to structure mainly steel, brass and other non-ferrous surfaces with accuracies down to 1 μm. In particular, mechanical micro-machining is used to make molds, as an example, a 3D micro structure mold was manufactured for growing liver cells. The smallest structure size attainable depends on the material and the diameter of the tools available. Research topics include developing and testing milling cutters with diameters below 50 μm, manufacturing micro-structures with improved surface finish and without burrs.

Electro-chemical deburring
Electro-chemical etching is a process to remove material with a chemical reaction, where ever a mask has not been placed. Electro-chemical deburring uses the same chemicals, but the intention is to remove the burrs left by the mechanical micro-machining processes only. The research topic is how to remove the burrs and not any additional material.

Hot embossing
In the hot embossing process, a micro-structured die (mold insert) in an evacuated chamber is pressed into a thermoplastic polymer film under great force, the film having been heated beyond its glass transitions temperature. The polymer fills the mold insert, in this way creating a detailed image of the micro-structures. A benefit of the short flow length in this process, and the use of very low molding speeds (μm/s), this embossing process allows void free micro-structures with very high aspect ratios (above 500). Applications include micro optics, microfluidics and medical technology. Research topics are enlarging the embossing area, introducing a wider ranges of materials i.e. at temperatures below 280°C, improving process cycle times and double sided embossing. Furthermore, this process can be referred to as compression molding. Much higher aspect ratios can be achieved with hot-emboss as compared with injection molding.

Injection molding

Micro injection molding allows microstructured components to be molded out of polymer, metal or ceramics. Applications are medical and biotechnology (micro pumps), micro optics, and micro process engineering (gears). Research topics are injection molding components with two micro structured sides, development of micro powder injection molding, and reduction of cycle times.

Micro reactors, mixers, and heat exchangers
Research into manufacturing microstructure reactors, micro heat exchangers, micro mixers for chemical mixing and reacting of hazardous materials in very small quantities safely, yet can could produce 6000 tons per year. The maximum thermal power of the devices ranges from 20 kW to 200 kW. Maximum water flow rates ranges form 700 kg/h to 7000 kg/h at pressure drops of 6-8 bar. The cross sections of the micro channels are in the range of 50 to 300 μm with thousands to ten thousands micro channels per device.

Micro electroforming deposition
Micro components made of nickel, copper, gold, permalloy, and electroless nickel can be made by electro-deposition into a micro-structured polymer mold. The polymer mold can be produced by UV or X-ray deep lithography and by replication techniques. The metals can be deposited into minute cavities (μm gaps) and over large areas (up to 150 cm^2). Applications include production of mold inserts, and micro mechanical components such as electrostatically driven linear motors. Research areas include making larger components, specific setting of internal stresses of the metals deposited (spring tensions) and development of mass production techniques using embossing or injection molding lost molds.

X-Ray Deep Lithography
The first step in the LIGA process. X-ray deep lithography comprises mask technology, coating of substrates with the resist, exposure, and development of the micro-structures. The parts are also used in the electro-deposition process as lost molds. High aspect ratios and less than 50 nm roughness on side walls are possible. Research topics included developing facilities for mass production, development of beryllium mask techniques, expansion of range and quality of structures and development of simulation tool for resist development.

Micro component inspection
The following methods for inspecting of micro components is available:

Analyses of surfaces and micro-regions by auger spectroscopy
X-ray micro-analysis
Materials testing by photo thermal methods
Micro-tensile testing
Surface analysis by atomic force microscopy
Electron microscopy
Integral elemental analysis

LIGA process
The LIGA process as mentioned above is comprised the steps of X-ray deep lithography, electroforming and molding of polymers, metals, silicon, and ceramics. Hot embossing mold/dies and injection molds are produced with the LIGA process and LIGA parts can be subsequently mechanically micro machined to add features not possible in the LIGA process. Structure heights up to 3 mm can be achieved with the smallest lateral dimension down to 0.2 μm. LIGA is a proven process used as a tool for research into the areas mentioned above. The LIGA process is very expensive when compared to micro mechanical milling, but the process produces submicrometer features where as micro milling can only produce one micrometer features. The micro mechanical milling can produce tapered (sloped walls) which the LIGA process cannot (only vertical walls). But, combining the two processes together allows for a wider feature set to be manufactured.

Tuesday, June 8th
Visited the Institute of Microtechnology Mainz (IMM) and was hosted by Dr. T. Paatzsch. The IMM was founded in 1990 by the stated government and is a non-profit institute. The IMM is an institute for applied

research and development in the field of micro technology and has over 230 employees. The objective of the IMM is to partner with industry for the research and development of innovative micro technology: leaving it to the industrial partner to commercialize the work.

The research and development activities cover a wide spectrum at the IMM, the activities include:

With immense bandwidth and the absence of EMI effects, optical fibers will eventually be used in computer backplanes for data interchange between the various processor boards. The IMM is developing a star coupler that has six 4x4 coupler elements on it and is built to manage the interaction of four processor boards via six optical channels. All star coupler units are fabricated in parallel on the same substrate, resulting in a high density package. In order to fabricate these devices, the LIGA process is used to form a mold and by using a micro replication process, 50 μm by 50 μm grooves are molded into a polymer substrate. Filled with UV- curable resin of higher refractive index, these grooves act as optical waveguides. Currently, such a coupler cost $5000, the goal is refine the process in order to lower the price to $2. Four years of research has gone into the process, the last remaining problem is the epoxy absorbs a very small amount of moisture during environmental (humidity) tests and swells, losing alignment.

The LIGA process was invented by Dr. Wolfgang Ehrfeld while at the Karlsruhe Research Center, and is the founder of the IMM. The LIGA process at the IMM, is used to manufacture molds and structures necessary for the production of miniaturized motors and gears, waveguide components, switches for fiber optic applications, micro-optical components, micro fluidic components such as pumps, heat exchanger structures and micro-reactors.

Their machine shop recently purchased a three axis Precitech ultra high precision milling machine. This will be used for micro mechanical milling of molds. Their edm shops uses AGIE machines and have successfully machined 10μm diameter holes, 0.4 mm deep using 10μm electrodes. The smallest diameter wire used on the wire edm machines is 30 μm. The AGIE machines have 0.1 μm resolution positioning and use small PZT micro stages, mounted on the machine, for even finer work.

In addition, the IMM has a laser welding and cutting laboratory used for mold making or part assembly. Also, a hot embossing and injection molding laboratory is used to make the micro components from the LIGA molds.

The IMM could not afford a marketing campaign to advertise their services, so the concept was born to go out to the local schools and work with kids to develop micro toys based on the kid's ideas. They developed and built the worlds smallest flying helicopter, a motorized micro ship, the worlds smallest digger, a micro bicycle and micro race car. The television media picked up the story and the IMM received loads of free publicity.

Talk Summary
Integrated Silicon Microsystems

Don DeVoe
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Institute for Systems Research
University of Maryland
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March 4, 1999

Executive Summary: Dr. DeVoe came to the University of Maryland as an Assistant Professor in 1997 to begin a program in MEMs. The focus of his work is on the construction of three-dimensional MEMs components using a combination of three processing steps: (1) Deep Reactive Ion Etching and Oxidation as a means of creating a "glue layer"; (2) Si Fusion bonding; and (3) a final etch to remove the SiO_2 glue leaving a released three-dimensional structure. Dr. DeVoe's goal is to use this technique to create three-dimensional MEMs devices with the following characteristics:

- $(500\mu m)^3$ workspace
- 1μm positioning accuracy
- Parallel fabrication
- Multi-DOF
- Integration
  - VLSI
  - surface micromachining
- Mechanically robust
  - couple macro-forces to micro-motions
  - survive extreme loading conditions

To achieve this he is focused on the development of parallel link manipulators. The talk was very well organized and informative. It especially illustrates that both the types of structures that can be manufactured and the length scales associated with MEMs devices are beginning to overlap significantly with so-called conventional manufacturing techniques.

Detailed Summary:

Introduction

The talk began with a description of the goals and applications of this work. The goals are to create three-dimensional MEMs structures with:

- $(500\mu m)^3$ workspace
- 1μm positioning accuracy
- Parallel fabrication
- Multi-DOF
- Integration
  - VLSI
  - surface micromachining
- Mechanically robust
  - able tocouple macro-forces to micro-motions
  - able to survive extreme loading conditions.

According to Dr. DeVoe the applications of such devices include:

- microrobotic dexterity and locomotion
- microrobotic end effectors
- arrays for parts positioning or transport
- microassembly tools
- arrays for smart skin (MAFC)
- probe positioning (data storage, materials analysis)
- microphotonics (3D mirror positioning)
- surgical / biosample manipulation.

Current MEMs fabrication techniques include: bulk micromachining; surface micromachining, LIGA and deep reactive ion etching and Silicon bonding. The types of techniques that are now used to fabricate MEMs devices cannot by themselves achieve the stated goals due to the lack of certain features summarized by the Table 1 below.

Next the some of the current technologies and some representative results were given. The fabrication technologies included: (1) hinged structure fabrication (UC Berkeley); (2) through plate masking; (3) sacrificial metallic mold (KAIST); (4) Ni diffusion bonding (Sandia); (5) Electrochemical fabrication (EFAB, USC); (6) Si Multi-layer bonding (MIT). The first type has mainly been used for demonstration. The second, third and fifth techniques are similar and use plating techniques. All require plane by plane fabrication but are not limited to extruded structures. Type 6, Si multi-layer modeling is interesting. This technique involves the bonding of patterned Si plates. Support tabs are fabricated into the structure and removed using lasers to burn them out through planned access ports.

These techniques have some major disadvantages, not allowing the integration of VLSI and MEMs, not allowing the fabrication of arbitrary geometry and not allowing for the fabrication of interconnects.

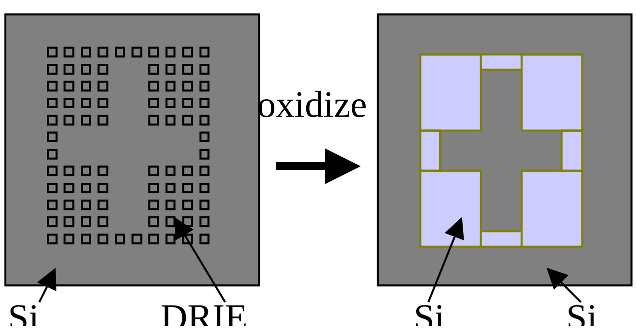
Table 1: Summary of the techniques for fabrication of MEMs.

Process Category	Technique	parallel process	no assembly	VLSI integ.	mech. robust	large range	true 3D
Serial	laser/ion etching						
	laser deposition						
	Focussed ion beam						
	micro stereo litho.						
Assembled	component bonded						
	pick-and-place						
Parallel	Hinged						
	bulk Si etched						
	deep-RIE						
	LIGA						
	3DMEMS						

The 3D MEMs Fabrication Process

Dr. DeVoe proposes to use a new combination of processes to create structures with arbitrary geometry, to allow VLSI integration and the integration of interconnects. The process involves three key processing steps:

(1) Deep Reactive Ion Etching (DRIE) and Oxidation



(2) Si-Bonding
(3) Etch and release

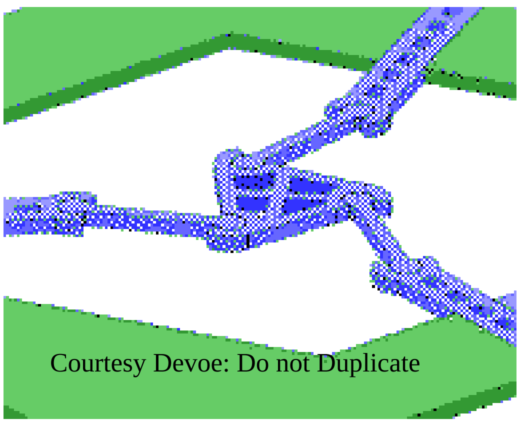
Step 2 is a critical and often problematic step in the 3D MEMs fabrication process. This step is done by Hydrophobic bonding and includes three steps:

- surface activation (O_2 plasma)
- pressure wave contact
- high-T anneal.

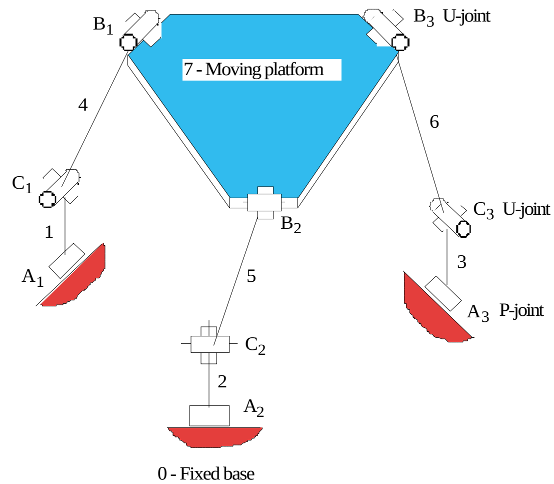
Devoe has made void measurements using IR and surface acoustic wave microscopy, and has measured bond strength using mechanical test methods.

The Focus of Devoe's Work

Devoe has focused his new fabrication technique on the development of micro-parallel-link mechanisms. Examples from the talk are shown below.



Planar



Three Dimensional

Similar to the macro-scale, these systems can be fabricated from combinations of different joint types. The combinations that are feasible using the fabrication techniques outlined are: RRR, RRP, RPR, PRR, RPP, PRP, and PPR.

Much of the remainder of the talk described the mathematics necessary to describe the mechanics and kinematics of such mechanisms.

Actuation techniques were then discussed. The table below describes the positive and negative aspects of the different actuation techniques.

actuation technique	fractional stroke (%)	max. Pressure (MPa)	energy density (J/cm^3)	efficiency	speed
electrostatic	N/A	0.025	0.004	high	fast
electromagnetic	N/A	0.1	0.025	low	fast
electrostrictive	4	0.21	0.032	high	fast
piezoelectric	0.2	35	0.035	high	fast
magnetostrictive	0.2	70	0.07	low	fast
SMA	8	400	16	low	slow
thermal	50	10	25.5	low	slow

The talk ended with acknowledgements of:

- DARPA/ETO
- Prof. Lung-Wen Tsai (co-PI, UMd)
- Zhixiong Liu (fabrication)
- Lan Ma (actuator design)
- Chris Kimball (mechanism analysis)
- Zhongzhou Tang (mechanism synthesis)
- John Maloney (process development)

Adam Cohen

MICROMACHINING EXPLORATORY PROJECT
SEMINAR SERIES
SPEAKER: ADAM COHEN, University of Southern California
DATE: JANUARY 22, 1999
Summary By: M. A. Davies, March 2, 1999

Title: EFAB: Batch Production of Arbitrary 3-D Microstructures and MEMS using a Low-Cost Automated Desktop Machine

SummaryDr. Cohen discussed a new method for fabricating micro-devices that utilizes selective electro-depostion, a process he called *Instant Masking*, and a *planarization* process such as polishing. The entire process is called EFAB which stands for **E**lectrochemical **FAB**rication.

INTRODUCTION

He began the talk by summarizing the current methods for manufacturing MEM's devices. These include:

- Bulk micromachining
- Surface Micromachining
- LIGA

The general limitations of these processes are:

- They only produce simple 2D to so-called 2 _ D structures
- The facilities are costly (electronics class clean room is $5M to $10M)
- The devices are often not IC compatible
- The processes are not standardized; everyone has their own customized tricks
- They require many manual operations
- There is a long lead time for device fabrication
- Standard micro-machining methods require hours or days per layer

There is a need for true 3D microfabrication capable of producing

1. Hollow regions
2. Overhanging devices
3. Features suspended from above – so-called *chandelier structures*.

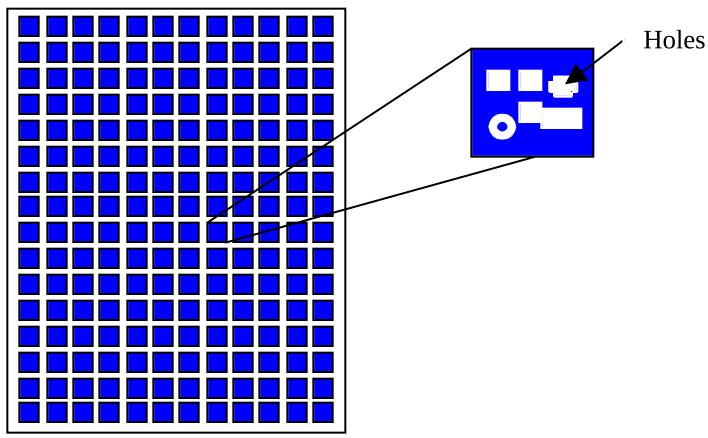
This new method is capable of producing these types of structures.

DISCUSSION OF THE NEW METHOD – EFAB

Steps

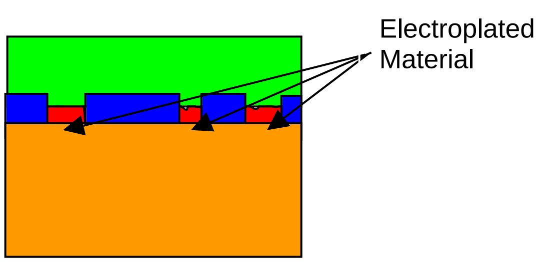
The method uses specially designed masks, selective electro-deposition, blanket electro-deposition, planarization of the blanket layers, and etching of sacrificial layers to create three-dimensional structures using 2-D layers. It reminded me a lot of rapid prototyping techniques. The Steps are described below.

Step 1: Develop a series of Masks to make a particular part. This involves using a CAD/CAM system to break a three-dimensional object into a series of layers, and then using etching to make the masks. The masks will be sandwiched between the anode and the cathode in step 2 to produce selective electro-deposition. The masks are large and complex because a different one must be made for each different laer in the final part. The lead time on the masks is approximately 3-4 days, but they can be used repetitively once they are fabricated.

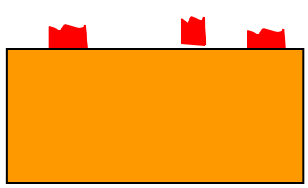


Step 2: The masks are alternately pressed to the substrate by the anode, with the substrate acting as the cathode for the electroplating process.

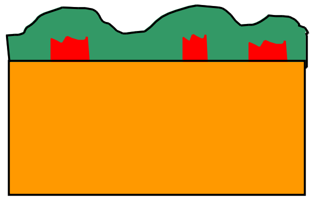
Step 3: A current is Applied for Specified time to deposit the desired amount of material.



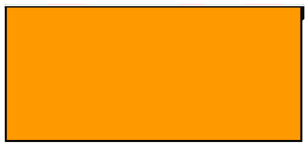
Step 4: The mask is released leaving the electroplated material.



Step 5: A Blanket Layer of Sacrificial Material is applied



Step 6: Both layers are planarized by polishing.



Step 7: The Next Layer is applied (Steps 2-6 repeated with a different mask)

Step 8: After all layers are applied the sacraficial layer (green) is etched away leaving the suspended structure.

Advantages

Dr Cohen discussed some of the advantages of this proceedure over traditional techniques. These included

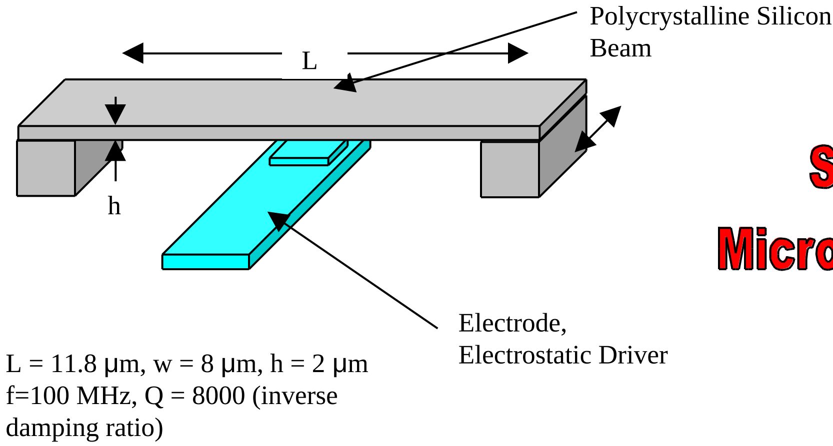
1. Potentially fast layer building time (goal: 2 layers per hour)
2. Can make three dimensional structures
3. The accuracy is very high because of the inherent accuracy of the planarization/polishing step.
4. The procedure is standardized; there are no custom steps.
5. He envisions the fabrication of cheap desk-top machines and *instant mask making houses*.
6.

Memorandum
To: Meso/Micro Manufacturing Team
From: John Evans, Matthew Davies
CC:
Date: 10/27/99
Re: RF MEMS Course, October 13 Session

Speaker**: Gabriel Rebeiz, University of Michigan**
Topic**: Integrated Front Ends using RF MEMS.**
Summary**: Rebeiz talked about various MEMS techniques for building resonators, filters, diplexers, switches, phase shifters, and antennas. General comments: very high Q, low insertion loss devices, competitive or superior to discrete or other approaches.**
TI, Honeywell, TRW, Hughes and others are working very hard with DARPA and other DOD money. Potentially low cost in volume production, but all experimental at this point, nothing is in commercial production.
Applications are filters and switches from 10 KHz to 10 THz, mostly Rebeiz talked about two domains, polysilicon electromechanical resonators for less than 100 MHz, and electromagnetic devices for up to 100 GHz.
Rebeiz notes that this is true multi-disciplinary work combining EE, ME, and Materials Science. He notes that EEs have to learn mechanical and materials sides, or MEs have to learn RF and circuit theory or you have to have very tightly coupled teams to make any progress.

1. Electromechanical Resonators (<100 MHz)

High Q (100-1000 or more), potentially low cost, repeatable, low insertion loss, so better than current practice.
Idea: build a polycrystalline silicon beam as shown in fig. 1, clamped at both ends and suspended over an electrode at a gap of 0.1μ to 3 μ. Takes 10-40 V to drive. Beam dimensions of 11μ by 8μ by 2μ give a mechanical resonance at 100 MHz (in vacuum).
Application: 3% filter, few dB insertion loss, Q of several hundred or several thousand [note: if could do single crystal, the Q could be 100,000]. Specific example was 7.8 MHz, Q of 6000, 2 dB IL, 30 dB rejection.



Surface Micromachining

Fig. 1: SDOF Polycrystalline Silicon Bridge

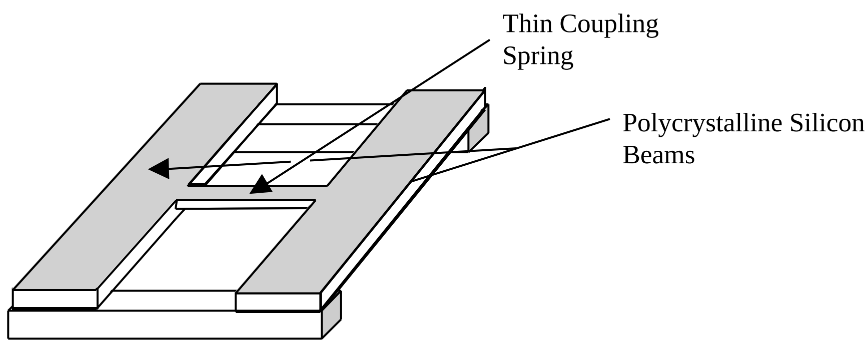


Fig. 2: Two Degree of Freedom Polycrystalline Silicon Bridge

Can sequence more than one with mechanical coupling, to give the equivalent of Chebychev filters. The bridge in this case is a mechanical resonator.

2. Electromagnetic Resonators

Rebiez presented various stripline structures, where a conductor is suspended in an air filled cavity on a membrane as shown in Fig. 3. Made 50 Ohm filter, conductive loss limited, permittivity near air, Q of several hundred at 50-60 GHz, IL 2 dB.

Comparison of MEMS Resonator and Waveguide Resonator:

Transmit IL	**0.3 dB**	**0.2 dB**
Receive IL	**0.95 dB**	**0.5 dB**
Isolation	**40 dB**	**60 dB**

So MEMS is comparable, not quite as good, but a very small fraction of size and weight.

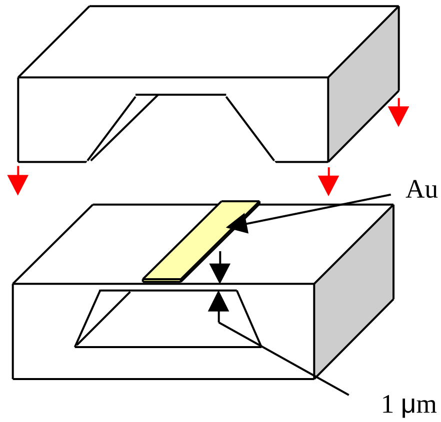


Fig. 3: Electromagnetic Resonator

Use: LMDS, 28 and 30 GHZ. See FCC web page.
Can use resonators to build oscillators.

3. Switches

Make a metal bridge, clamped at both ends and suspended over electrode as shown in Fig. 4. At some relative potential the bridge snaps down. There is an insulating film on the bottom electrode, so the key parameter is the ratio of on capacitance to off capacitance. The snap is quite pronounced. Before the snap, there is some motion, so this can be used for changing capacitance to tune a filter. The bridge is maybe 200-300μ long and the switch gap is 0.5-3μ, so this is well within the elastic limit of Al or Au or various alloys. Actuation voltages in the 10-40V range depending on gap. Bridge must be run with some residual stress so there is an adequate restoring force, since this is unidirectional field and there will be charge migration and an eventual permanent bias.
At some power level the switch will unconditionally close and stay closed, so this is also a fuse.
Application: low loss microwave switches to 60 GHz, eg for phones. IL 0.1dB at 10 GHz, around 10 μsec switching time.
Can use as distributed phase shifter by sequencing these in a transmission line, adjusting phase with voltage less than actuation voltage. End up with several mm lines, 100's or 1000's of degrees of phase shift up to 100 GHz. Steered arrays, missiles, etc.

4. Antennas

Lay down a conductor in an etched cavity, etch holes through one wall, dielectric constant goes from 12 for surrounding material to about 3, so end up with more efficient antenna, efficiency goes from 20% to 60%. Around 100 GHz.
[Notes got pretty sparse toward the end.]

$$F = \frac{\varepsilon_0 W w}{2g^2} V_{bias}^2 \qquad k = \frac{32Et^3w}{L^3} + \frac{8\sigma(1-\nu)tw}{L}$$

Due to Residual Stress σ

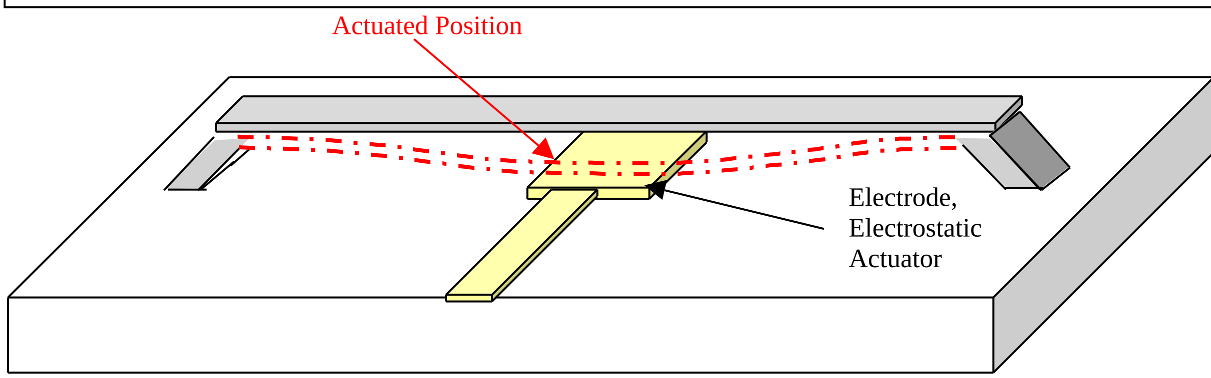


Fig. 4: Bridge Switch. When a voltage is applied to the electrode, the force is given by the above equations. The stiffness is given by the formula for k. Setting F=kg, a cubic equation for the equilibrium equation is obtained. When the voltage reaches a critical activation value the system becomes unstable and the beam snaps down in order of 5 μs.

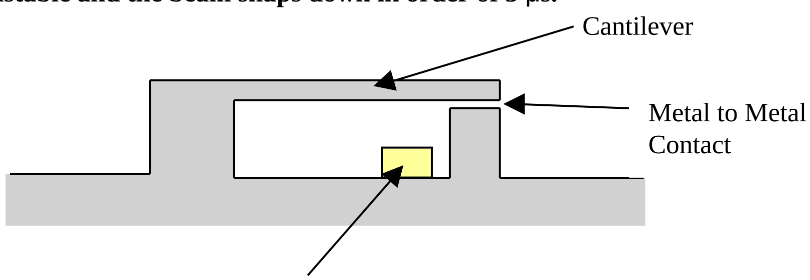


Fig. 5: Cantilevered switch

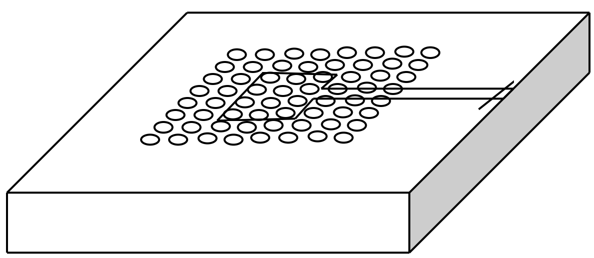


Fig. 6: Polysilicon based antenna with micromachined holes to decrease the effective permeability and thereby increase the efficiency of the antenna – don't know quite how this works.

MEMORANDUM

To: MMM Study Team
From: John M. Evans
CC: JSAlbus, Dave Coombs
Re: RF MEMS Course November 10 Session

The second session of the University of Maryland RF MEMS Course (arranged by the IEEE MTT Society) was this past Tuesday evening.
The speakers were all from Raytheon, Charles Goldsmith (TI-Raytheon, Austin, TX), David Hinzel (Raytheon E-Systems, Falls Church, VA) and Bob Streeter (Hughes/Magnavox-Raytheon, Ft. Wayne, IN). Vivid demonstration of rationalization among defense contractors.
Raytheon is working on exactly the same stuff that was presented at the October session: RF filters and switches, particularly using bridges (Al and Au, 300 µ long x 150 µ wide x 3 µ stand-off actuated by 30-50 V) that provide variable capacitance, and cantilevered ohmic contact switches. Same kinds of performance, same kinds of results. Interesting unique idea was a parallel array of variable capacitors that give a digital programmable capacitance with 6 bit resolution (parallel 16, 8, 4, 2, 1, and _ pF caps) for radio tuning.
Goldsmith talked about TI components work. Hinzel talked about using those components in DARPA Advanced Digital Receiver program, which is part of their Ultra Comm communications systems development (see attached flyer) which will cover 20-2800 MHz. The basic architecture is RF MEMS front end filters, an RF ASIC downconverter, a high speed ADC (developed by DARPA), and a DSP (TI C60), all on a SPCI/PCMCIA format card. So one analog intermodulation stage and then all digital processing. Each card will be able to cover four channels with sw selectable tunable filters. Neat. To be available mid-99 (Note for TMR).
Streeter talked about domains of application of RF MEMS filters, and how to cover the full 20-2800 MHZ range. MEMS stuff is on the higher end. Also talked about MEMS, non-MEMS, and hybrid inductors.
All the results to date have been on R&D devices, tested on wafer. Packaging is proposed at wafer-level, bond a matched micro-machined cover over wafer, then saw into individual filters. Still to be explored is good low-insertion loss connections. THIS IS A VALID SUBJECT FOR n2m workshop. I asked Goldsmith who should attend, he said they were all on a Raytheon-wide MEMS committee, if we send him or any of them an invitation, they would see that the right person attends.

MEMORANDUM

To: MMM Study Team

From: Nicholas G. Dagalakis

Date: Dec. 10, 1998

Subject: RF MEMS Course, Tue. Dec. 8 Session Summary

At the beginning of the session it was announced that there are plans to organize a workshop in late April 1999, preferably on a Tuesday. The organizers of the RF MEMS Course are looking for sponsors and speakers.

The first speaker of the session was Dr. Richard Gale of Texas Instruments (TI) Digital Imaging Technology Development Division. The subject of his talk was "Principles and Applications of the Digital Micro mirror Device (DMD)."

Gale explained that TI got out of the microchip memory business and is now concentrating on Digital Processing, Digital Light Processing, Digital Imaging Vision, etc. A key component of the last two areas is the DMD, which is described, in the attached paper. The DMD is available and sells for $10K to $20K.

The second speaker of the session was Peter van Kessel of Texas Instruments (TI) Digital Imaging Technology Development Division. The subject of his talk was "Digital Light Processing (DLP) Technology System Overview."

Kessel described several current and future applications of DMD. He described Digital Display Engines (DDE) (digital projectors) with one two or three DMDs. For the presentation they used a DDE with a single DMD and a rotating RGBW wheel.

Future applications include printing, 3-D imaging, holographic storage, digital lithography, digital movies, etc.

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Books and Reports:

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Madou, Marc, “Fundamentals of Microfabrication,” ISBN 8493-9451-1, CRC Press, 1997.

Nof, Shimon Y., “Handbook of Industrial Robotics,” John Wiley & Sons Inc, 1999, Sections 4.3, 10, 11.

Thakoor, Saita, Cutts, Jim, “Flexible Actuators for Small, Mobile, Special-Purpose Robots,” NASA Technical Report, NPO-20019.

Trimmer, William S., “Micromechanics and MEMS Classic and Seminal Papers to 1990,” IEEE Press.

Journals and Magazines:

“Journal of Micromechanics and Microengineering, Structures, devices and systems,” Published quarterly by the Institute of Physics Publishing, Bristol, UK.

“Journal of Micromechanical Systems,” A joint IEEE/ASME publication.

“Micromachine Devices,” Published monthly by Cahners Publishing Co.

“Micromachine,” Quarterly magazine published by the Micromachine Center, Tokyo, Japan.

Conference Proceedings:

“Proceedings of the Micro Electro Mechanical Systems Conference,” This conference is organized by the IEEE Robotics and Automation Society in cooperation with the ASME Dynamic Systems and Control Division annually in the US.

“Smart Materials Technologies,” Proceedings of the Conference on Smart Structures and Materials 1997, Organized by the International Society of Optical Engineering (SPIE).

“Special Issue: Integrated Sensors, Microactuators, & Microsystems (MEMS),” Proceedings of the IEEE, August 1998.

“Precision Fabrication and Replication,” Proceedings of the American Society for Precision Engineering, 1999 Spring Topical Meeting, Chapel Hill, NC.

“Microrobotics and Micromanipulation,” International Symposium on Intelligent Systems and Advanced Manufacturing, Organized by the International Society of Optical Engineering (SPIE), Boston, MA, November 1998.

"Proceedings of the IEEE Conference on Robotics and Automation," This conference is organized by the IEEE Robotics and Automation Society annually in the US, Look for sections on Micro/Macro Robotics, Micro Manipulation and Actuation.

"Proceedings of the Workshop on Microtechnologies and Applications to Space Systems," NASA Jet Propulsion Laboratory, Pasadena, CA, N9429767, June 1993.

"Proceedings of the International Conference on Integrated Micro/Nanotechnology for Space Applications," NASA Johnson Space Center, Houston, TX, 19960054083, 1995.

"Proceedings of the 1998 International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators," Organized by IEEE et. al., Santa Clara, CA, April 1998.

"Proceedings of MICRO SYSTEM Technologies 98," 6th International Conference on Micro Electro, Opto, Mechanical Systems and Components, Sponsored by the Fraunhofer Institute for Reliability and Microintegration (IZM), Potsdam, Germany, March, 1998.

Web Sites of Prominent Research Institutions:

Sandia National Laboratories Intelligent Micromachine Initiative, Albuquerque, NM, http://www.mdl.sandia.gov/Micromachine.

Berkeley Sensor & Actuator Center, Berkeley, CA, http://www-bsac.eecs.berkeley.edu.

Micromachine Center, Tokyo, Japan, http://www.iijnet.or.jp/MMC/.

Institute for Microstructure Technology (IMT) of the Karlsruhe Research Center and the University of Karlsruhe (Mechanical Engineering Faculty), Karlsruhe, Germany, http://www.fzk.de/imt/.

Ecole Polytechnique Federale De Lausanne, Department de microtechnique, Institute de microtechnique (IMT), Lausanne, Switzerland, http://dmtwww.epfl.ch/imt/.

Institute of Microtechnology, University of Neuchatel, Switzerland, http://www-imt.unine.ch.

Acknowledgement:

We would like to express our appreciation to Mr. Harry Brooks of the NIST Information Research Center for his prompt and courteous help with the literature search. We would also like to thank Ms. Rose Estes of the ILL office of the NIST Information Research Center for locating numerous very difficult references.

Meeting Minutes

Minutes of Kick-Off Meeting for MEL Exploratory Project on
Meso/MicroScale Manufacturing

Time/Place: October 1, 1998; 9:00 am / ISD Conference Room; Metrology Building

Present: Clayton Teague, John Evans, Eddie Amatucci, Nick Dakalakis, Brad Damazo, Matthew Davies, Lowell Howard.

Recorder/facilitator: Clayton Teague

1. C. Teague proposed an agenda which was followed roughly during the meeting:
   - Introductions to background of project
   - Brief introductions of each person present
   - Overview of proposal and project
     - Goal
     - Objectives (Tasks)
     - Criteria for Success
     - Budget
   - Followup Actions for next meeting. PLEASE READ ACTION ITEMS DECIDED UPON AT END OF MEETING.
   -

2. Based on discussion by the group, the recorder proposes the following goal for the project – readily admitting that it is open for modification based on feedback from participants:

   Project Goal: To assess industrial needs in the technology, measurements, and standards in the arena of meso and micro-scale manufacturing carefully and thoroughly, so that MEL and/or NIST can determine the opportunity for initiating an MEL-wide or a NIST-wide effort to address these needs.

3. The group discussed at some length possible criteria by which this project would truly be judged a success by management and by members of the team. We found this very difficult and postponed final decisions but did tentatively agree upon following rough criteria:
   - Obtain sufficient ATP interest that they would initiate meso/micro-scale manufacturing as a focus program area and fund some intermural projects in MEL/NIST.
   - Successfully conduct a workshop (successful to be defined) which clearly identifies the problems being faced by industry and identifies how NIST should be involved.
   - Completing a really “wow” demo project
   - Deliver a solid, well-written report on outcomes of our findings and the outputs of the workshop.

4. The proposed budget agreed to by Clayton Teague and John Evans and given below was passed out and briefly discussed.

	ISD	APTD	PED	Other
Task 1. Internal Needs	40	10		
Task 2. External Needs	40	35		
Task 3. Demo Project		35	15	
Task 4. Lit. Research	25	25		
Conduct Workshop				25 (ISD/APTD)
TOTALs	105	105	15	25

5. The group then brainstormed about means by which each of the four tasks outlined in the proposal could be accomplished producing the following ideas.

Task 1. Assessing Internal Needs and Capabilities

- Establish a task force, parallel or joint with this group, with members
- from all OUs – John Evans has already discussed this with Ric Jackson and made some efforts toward this end.
- Query FTD about what meso/micro-scale components and systems they have been asked to fabricate and/or assemble.
- Also query FTD about what things of this nature they have had to outsource
- Discuss same question with Chris Evans and Mike McGlauflin
- Get solid historical information about what has been done in this area at NIST and about what conclusions were reached.
- Find out who is investigating the relationship between function and materials properties for meso/micro-scale components
- Make sure that we really determine what is going on in MEL in this area
- What can NIST/MEL really do to address the great and well-identified need for a "meso-scale CMM;" determine the real needs/ likely time-scales and true needs for such a machine.
- What is the real need for a NIST fabrication facility for meso/micro-scale manufacturing? Or does NIST just need to have some critical parts of such a facility?
- What is NIST doing in rapid prototyping or solid free-form fabrication that can be applied to this project?

Task 2. Assessing External Needs/Capabilities and Industrial Partnerships

- John E. passed out information and discussed opportunities presented by:
  - an upcoming course at UofMD on Micromachined Components for RF systems,
  - a letter of interest from MciroFab Technologies, Inc responding to BAA 98-28; DARPA's MICE program and has a file of others sent to DARPA
  - a draft solicitation from DARPA on virtual reality for micro-system assembly,
  - copies of the program for an upcoming DARPA program review for meso-scale machines, and
  - copies of a presentation on n2m (nano to millimeter) Assembly Technologies.
- Identify companies that are "good" at meso/micro-scale manufacturing:
  - Remmele, National Jet, SGS, Ghuring, Microcut, (two companies in Pennsylvania)
  - Need to identify companies in ink-jet wax, and other types of rapid prototyping and solid free-form fabrication
- Identify companies that are "good' at meso/micro-scale measurement
  - Zygo, Brown and Sharp, Zeiss, Veeco/Sloan, whoever measures minature precision bearings- rolling elements, races and fuel injectors and components.
- Identify companies that are "good" at assembly of meso/micro-scale systems
  - Adept Robotics (and their use of vision systems)
  - Companies from the sensor industry
  - AMP (electrical and optical connectors and connector assemblies)
  - Teledyne
  - Dresser
  - New Focus
  - Bodine (assembly machine division)
- Track conferences and workshops that have taken place and planned for FY99
- Identify work underway in other government laboratories which would be collaborators:
  - NASA/JSFC
  - General Atomics/LANL
  - IFMM in Mainz, Germany (not exactly another US agency but very important international work)
  - SANDIA

- LANL

Task 3 and Task 4 were not addressed due to time limitations; the meeting had already extended to two hours. These two tasks and followup actions to ideas for Tasks 1 & 2 will be the subjects of the next meeting.

Meeting was adjourned with an agreement that the **following actions** would be taken before and in preparation for the next meeting:

Develop ideas/concepts/proposals for a demo project that is within the resources for this project that will "make the cover of our favorite trade magazine/ professional journal."

Give Clayton Teague feedback on possible amendments on these **fabulous** (just testing to see if anyone really reads this far!) minutes of the meeting.

The next meeting will be held in the Sound Building Conference Room on October 8th at 9:00 am; John Evans to be recorder/facilitator.
THAT's All Folks!

October 8, 1998
Second Meeting Minutes
Meso/Micro-Scale Manufacturing

Present**:** **John Evans, Clayton Teague, Nich Dagalakis, Brad Damazo, Matt Davies, Ted Vorburger**

Facilitator: John Evans

1. **Agenda** is attached.

2. **Revised Minutes** were distributed for the last meeting.

3. **Ted Vorburger** will be the participating for PED, anyone from PED is welcome at any time. Ted described surface probe measurement work and other dimensional metrology work relevant to this study.

4. **Criteria for success** were revisited, and the difference between outputs and outcomes was discussed. The following outputs and criteria for judging those outputs were agreed to:
   - **Report**
     - Clear definition of Meso/Micro scale, distinguish from MEMS
     - Clear definition of state of the art, projection of where the field is going, definition of key problems and key players in this field
     - Clear definition of NIST role
   - **Workshop**
     - Participation: 10/20 top companies; 10/20 top researchers; 10 NIST
     - Identification (by industry and research community) of key problems
     - Identification of possible solutions to those key problems

   [A third output will be a demonstration; discussion of criteria for success for the demo was deferred until that topic was brainstormed.]

5. General Info/Literature/Meetings

- IEEE has published a MEMS report that Matt found; Nich, as an IEEE member, will order for all.
- Nich passed out announcement of Micromachine conference and exhibition in Tokyo, October 28-30. Looks of interest, no one able to go.
- Nich discussed upcoming POAC meeting.
- DARPA will get us at least one invitation to Mesoscale Device kick-off; waiting to hear on number of openings.
- Clayton will propose ASPE Spring Topical Meeting session on MMM
- Matt and John (and Dave Coombs) will be taking U of Md course in macromachined RF devices, starting next Tuesday, others want to attend at least some lectures.

6. Brainstorming on **Task 3: Demonstration Project**

Micro-6 axis force sensor

The company that makes linkages for disk heads wants to measure six axis forces, assembly needs force sensing, other applications could use.

There is a wealth of knowledge in this area for robot wrist force sensors. Most use foil strain gages on Maltese cross (see attached article). Three orthogonal forces and three moments are computed using the Jacobian. Other geometries have been used, and DASA used photocells rather than strain gauges, but the general prinicipals are the same.

For a micro sensor, MEMS beams and capacitance sensors will likely be the best choice.

Very good possible project, to be discussed further.

Linear Actuator

Building a small Stewart platform for micro assembly has been proposed before. To obtain large angular motion, each linear element must have a range of motion comparable to the scale of the top platform.

It is proposed to investigate the design of a linear actuator with a 1 mm range of motion and 0.1 micron resolution. No one could come up with force requirements off the top of their heads, but the forces for assembly would be low.

Clayton discussed polymer “artificial muscles” as an actuator; the problems are bandwidth and the requirement for a liquid bath. Lab demos have gotten to 100 Hz, more than enough for a micropositioning stage, and the liquid could be handled with a closed bellows enclosure. Essentially we are talking about arthropod designs.

Stereo Camera Calibration

Nich presented the problem of calibrating stereo microscope cameras for 3D vision for microassembly. A target grid is used to calibrate the cameras; the grid must be moved linearly and held perpendicular to the linear motion. The range of motion required is 1”. Nich presented two designs, with three linear elements and three laser interferometers, and a Stewart platform design.

General discussion ended with the recommendation that the design should have a single linear actuator, with angular orientation corrected by piezo actuators, making the system a Fabry Perot to provide both orientation and position feedback.

Walking Machines

Nich presented several microleg designs for small mobile mechanisms for micro fabrication and assembly.

Time expired at this point and discussion was halted.

7. **Next meeting**: B121 Metrology, 9 AM, October 15, 1998.

October 15, 1998
Third Meeting Minutes

Meso/Micro-Scale Manufacturing

Present: John Evans, Clayton Teague, Nich Dagalakis, Brad Damazo, Matt Davies, Ted Vorburger

Facilitator: Clayton Teague

Recorder: Brad Damazo

Agenda: is attached

Review of Minutes for October 8th meeting: completed

Closure on proposals for "Criteria for Success" from last two meetings: Under the criteria for success, ATP involvement is a desired outcome, but is beyond the project's control. In addition, Clayton was pleased with the task 1 and task 2 descriptions as outlined in the minutes from October 1.

News Items: Nich ordered 8 copies of the IEEE "Special issue on Integrated Sensors, Microactuators, and Microsystems (MEMS)." Also, Nich provided everyone with a paper on a 6 DOF torque/force sensor entitled "Multisensory Robots and Sensorbased Path Generation," IEEE Int. Conf. On Robotics and Automation, Apr. 1986, San Francisco, Calif.

The recorder for subsequent meetings will rotate weekly.

John presented a space ball design using four 2-D photo-detectors. The detectors measure X-Y displacements and are insensitive to z displacements in this design. The detectors are equally spaced around the peripheral of the ball and are mounted on the same horizontal plane that goes through the center of the ball.

Matt presented the idea of using a layered approach to building micro assemblies with embedded electronics and sensors. The approach is to bond the electronics and/or sensors between metal plates and then machine away the excess material to yield a monolithic composite structure. The concept presented is - it's far easier to attach the electronics and sensors to large plates, than it is to small flexible structures.

Clayton brought up that he is listed as the point of contact for the micro-factory concept in the latest online issue of Manufacturing Engineering News. The reporter mistakenly assigned Clayton this role.

Continuation of brainstorming for Task 3 and Task 4: Nich presented lengthy descriptions of 12 different conceptual designs to be considered for demo project. The designs are summarized below:

List of potential demo project

1. Linear actuator
2. Stereo camera calibrator
3. Walking machines
4. Micro-Vision system
5. Six DOF micro-robot
6. Micro positioner
7. Micro machines

Ted presented a fiber optic connector measurement problem from AMP. Drawings are attached. Ted will investigate stitching white light interferometer images together to produce the equivalent of CMM measurement data. This is not a demo project, but research opportunity that will be used to measure parts manufactured for the demo project

Clayton summarized for the group the criteria for demo project:

1. "Wow" impact on our audience

2. Utilizes NIST capabilities for micro/meso fabrication
3. Involving metrology
4. Real customer with real problem
5. Problem we can really solve on this project

Action Item: Each project member is to picked one of the above potential demo projects and prepare to advocate his project to the group during the Nov. 9th weekly meeting.   For each potential project, design details and hard numbers must be presented in order for the group to evaluate the project's merit.

Items 4 and 5 were not covered in the meeting and were postponed the next meeting.

Notes for Meso-Meeting
October 22, 1998

Meso/Micro- Scale Manufacturing

Presents: John Evans, Clayton, Nich, Brad, Song, Eddie, Matt

Agenda: Handout

Nich:
· POAC, discussed meeting next week.
· Visit Adept and new focus.
· Demonstrate tunable diode laser assembly
· Discussions of linear robot

John:
· DARPA program n2m discussed
· Nich will ask Brian to come to the DARPA meeting. Any ideas for attendees would be helpful.
· DARPA Meso Scale- Matt went to the meeting, smaller, lighter and cheaper. Example, detectors, air conditioners… Clayton discussed "Soldier of the Future". Prepare the soldier for the urban environment, lightweight and stop bullets…. M-Dot and Flow ink. Flow meters 1.2hp 300,000rpm- turbine fuel engine.
· DARPA mice first meeting in January. U of M notes circulated
· NASA, JSE, NASA meeting first week of November, MEMS and NANO meeting Namotube Applications.
· Send web site to Clayton-Swiss MicroRobots – **see next line**
http://dmtwww.epfl.ch/imt/HighPrecRob/index.html
· Puerto Rico meeting Handout. Big name Sponsors.
· Peter will give talk at DARPA. I8M-HP-USC electroplating mask of Ni, plate with copper parallel construction; need CAD work, diamond turning/lapping
· Handout, Taylor, UNC-Chapel Hill, "Components of Nanomanipulator". Still have problem of "seeing " and "feeling" at the same time. "PHANTOM" controller- out of MIT

Matt:
· Mini-refrigerators discussed "diaphram pumps". Clean room suits, etc… will write up notes of meeting.

Task 1- discussion internal contacts FTD, get view graph, from kickoff meeting.

· Clayton - Holography possibilities for 3D metrology
♦ SEM- for metrology is difficult
♦ Clayton and Matt will talk with Mike Postek.
♦ Ed will look into the Rapid Prototyping
♦ Nich will look at assembly at a small-scale level.
♦ Prepare notes/memo and bring to the meeting.
♦ Electronic copy of minutes should be circulated
♦ Made assignments

Task 2- discussion external contacts first week of June-workshop at NIST and contacts while assessing external needs Tuesday, Wednesday (25-30 people), 10 researchers, 10 industry
· Bad list of job shops for machining
· Mike Philpott- speakers from Europe, etc…
· PED- who in metrology
· Assy- workshop

Goal: Good identification of who and what are the needs.

- Assessment of level of effort right now
    New initiative or established.

Demo Project Selection- November 9th

Vu-graphs

Meso/Micro Manufacturing
October 22, 1998

1. General information items (POAC, DARPA n2m, DARPA Meso, DARPA MICE, U Md/IEEE RF Mems course, NASA meeting, Puerto Rico meetings)

2. Assignments for Task 1: internal contacts

3. Assignments for Task 2: external contacts

Idea: invited speakers

4. Task 3: Demo Project proposals

Task 1: Internal

OU's - (John Evans)	November 19
FTD - jobs - (Brad and Matt) Outsource - (Brad and Matt)	November 12
Same? To Chris Evans and Mike McGlauflin (B&M)	November 12
History at NIST (J&C)	November 19
Fen and Matls (Brad)	November 19
MEL (J&C)	November 12
MESO CMM (PED - Ted and Johns) APTD - M & C	December 15
Need for NIST MESO/M Fab? (See 2)	
Rapid Puerto and SFF Eddie - MSID (Kevin Owens) Al Wavering	November 12
Assembly. (Nich)	November 19

TASK 2: External APTD

Companies that are "good" at Mfgr

Remmele
Nat Jet
SGS
Ghuriz
Mcat
Honeywell
Raytern
Exdredethme
Parasmic
Mdot
Mesoscopic Devices
Analog

Researchers

MSC
MicroFab
U Ill
MIT
→Europe←
→Japan←

Task 2:

Companies that are good at <u>Measurement</u>

Zygo
BTS
Zerss
Veeco Sloan

<u>PED</u>

Meso Micro-manufacturing Project Meeting
November 5, 1998

Attendees: Brad Damazo, Clayton Teague, John Evans, and Ted Vorburger (recorder)

A number of information items were distributed at this meeting. These included:

- SEMI's MEMS Technology Roadmap – distributed by John
- Calculations on sub-pixel averaging in metrology - Ted
- An announcement of the upcoming DARPA Assembly Workshop in February 1999 - John
- A discussion of a successful meeting at the Precision Optoelectronic Assembly Consortium regarding the NIST flexure stage – John reporting for Nich
- A Survey of NIST Activities in MEMS - John
- A report on the Laser MMT discussed at the Executive Forum in the American Society for Precision Engineering (ASPE) Conference - Clayton
- A report on the PTB Fiber-optic touch probe, also presented at the ASPE Conference - Brad

A quantitative review of individual project proposals was set for the subsequent meeting to be held on November 13, 1999.

Micromachining Minutes
November 13, 1998

1. Discussion of Minutes from other meetings/workshops
   (a) DARPA Mesoscale Device Kick-off meeting – minutes distributed
   (b) University of Maryland RF MEMs course – minutes distributed
2. Matt reported on NSF Activities
   (a) Ming Leu in DMII at NSF is considering a focus program in Micromachining
   (b) Ming Leu has asked Bob Hocken to host a workshop at Charlotte in June
   (c) Matt told Ming Leu about NIST exploratory project, Ming Leu offered that we combine the two workshops
   (d) Bob Hocken is considering a micromachining proposal to DARPA, He is ammenable to a NIST-Charlotte collaboration in that effort.
   (e) Professor Devoe at MD is doing interesting things in 3-D MEMs at the University of MD, Matt proposed that we invite him for a talk

Actions: Contact Hocken, contact Devoe.

3. Discussion of June Workshop
   (a) Dates available for NIST conference facilities are any Thursday and Friday in June
   (b) Idea: NSF brings academic participation and NIST will bring the industry participation
   (c) We should offer to have the joint workshop here

4. IEEE MEMs Meeting January, Orlando Florida

5.

Micro-machining Minutes
December 3, 1998

Facilitator: Clayton Teague
Note Taker: Matt Davies

Opening Comments by All of The Attendees

Clayton: Discussed a visit with Kang Lee to Wilcoxon Research on Dec 2. Wilcoxon makes vibration sensors for Turbines, helicopter rotors and Motors. Thurston Brooks, Director of Research and Development at Wilcoxon Research and was one of the originators of the Maltese Cross force sensor design at Lord Corp. Wilcoxon currently has an ATP award and is involved with a MURI (Multi-University Research Initiative) centered at Penn State. They are interested in working with us on this project.

John: Talked to Dennis Swyt about MEMs

- Effort was 3 years ago
- Reasonable pitch
- Lab council wasn't interested
- Ric did not make a strong pitch
- SPIE series
- Mike Postek

Japanese presentation

- NRLM, Elec. Tech Lab
- Mech. Eng. Lab

Another interesting MESO scale problem

- Radioactive seeds
- 1 _ mm test device necessary

Ed Amatucci

- Attended NanoSpace 1998 NASA JPL for Kevin Lyons
  - Trip report MEMs Nanotech
    - There were two different sorts of people present
      - Researchers
      - Implementers
    - Manufacturing issues not adequately addressed

Matt

- Hocken is interested
- Mote papers on 300 micrometer MEMs Maltese cross
- Need to invite Don Devoe to give a talk

Ted

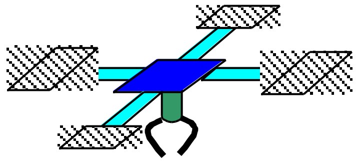
- Handout
- Will investigate near field optics program in the physics lab

General Comments

3. Clayton arranging the mailing list
    - Email to mesmic@nist.gov
    - Readable by any NIST employee

4. Demonstration Project Discussion

A. APTD: 6 DOF Force Sensor made to HTI Specifications
B. PED: Metrology for opto-electronic connectors
C. ISD: Hexapod with base points on x-y platform
D. ISD: Gripper at the end of arm with force sensor and metrology



E. ISD: Four axis robot for ADEPT

Specifications

- 50 μm total range
- Angle ???

ATP project – x,y, rotation only

F. New Ideas: Mini Sawyer Motors

Speakers

A. Don Dovoe
B. Adam Cohen
C. Exitec
D. Penn State
E. MCNC MEMs Center
F. SAIC
G. Illinois Mesoscale Pump People
H. U of W Meso-scale Assembly
I. Analog Devices
J. D.B. Wallace
K. Hocken, Zygo or someone else in Metrology

External Visitis

A. Remmele
B. National Jet
C. SGS
D. Ghuring
E. μCat
F. Honeywell
G. Raytheon
H. Panasonic
I. Mdot
J. Mesoscopic Devices
K. Analog Devices
L. Companies that are good at Metrology (PED will look into this)

Researchers

A. USC
B. MicroFab

C. U Ill
D. MIT
E. Europe
F. Japan

Tours

A. Remmele, PI, Honeywell etc.
   Time: Early February
   Person: Brad
B. National Jet
   Time: Early January
   Person: Brad
C. Micromachining, APL Baltimore job shop
   Time: February
   Person: Eddie
D. Wilcoxin
   Time: January
   Person: Clayton
E. Sarcos, Sandia, Microfab, Mdot, Raytheon
   Time: Mid-March
   Person: John

Workshop

Places and Times

- DARPA Mesoscale N2M (Late Feb)
- NIST/NSF/UNCC
  - ❑ Clayton will call Bob Hocken
  - ❑ NIST availability limited
  - ❑ 30 people

Meso Meeting Minutes
December 10, 1998

Attendance: John Evans, Matt Davies, Clayton Teague, J. Song, Ted Vorburger, Nich Dagalakis, Ed Amatucci

Handouts (Brad, I will send you copies.):
Matt's vu-graphs
Ted's project update
Nich's vu-graphs
Eddie's vu-graphs (I will distribute)

Went around the room:

Ted - Thanked john for an e-mail about vision research, etc.

Nich - MD meeting attended, he will distribute notes

Ed - Nanospace Conference, will circulate CD-ROM on NASA Exploration and latter the proceedings on CD-ROM, trip report will also be forwarded

John- Spoke about Dennis Swyt's study of MEMS, he will place a copy in B121 for anyone to make copies and study.

Clayton - Modeling and Simulation of MEMS will be publishing a journal, he had circulate a call for papers for their conference at an earlier meeting.

John - FY00 Budget Initiative, Division Chiefs are working on a Micro-Meso Manufacturing Initiative. Has a lot of support and momentum. Ted suggested that we get DOC Technology Office interested and supportive of our effort. Clayton thought this was a good idea. John emphasize we would need this lined-up by this summer. Gary Bachula maybe the contact at DOC.

DEMO Ideas:

Matt - gave a talk and explained APTD's ideas for a force sensor. John mentioned something about a disk height interferometer made by Zygo which maybe of interest. Matt says he needs to do more literature searchs. Strain gages are available and Clayton feels they will have the resolution - "off the shelf".

Ted - Reviewed proposal and had a handout with updates.

Nich - presented the 6D microrobot and an idea for a possible testing tool for meso-devices.

Ed - showed barrel grabber idea, would like to scale down. Also, explained goals of POAC consortium in flexible and fast production of fiber optic components. Suggested two possible demo projects:
1. Micro-grabber with incorporation of a force sensor
2. Microstage refinements

John - discussed the possibility of multiple efforts and a demo combining all of our efforts.
1. Force Sensor
2. AMP part metrology demo
3. Microstage development and demo with possible integration of a gripper and force sensor in the future.

Reviewed assignments for setting up trips and speakers. See the handout.

Micro-Meso-Manufacturing Meeting
Dec. 17, 1998

Note Taker: Nicholas Dagalakis

Clayton: Informed the group that a new office of Optoelectronics (OOEPS) has been established in EEEL. Gordon Day from NIST, Boulder will be the head of OOEPS and Mike Daum his deputy. Clayton is the MEL representative to this office. Phil Perconti of ATP is a member of this office too. It was suggested that the group prepare a write up, which describes its work in optoelectronics. Ed indicated that he is preparing something similar for the ISD optoelectronic assembly projects. APTD is involved with the measurement of the flatness of wafers and might prepare something too.

Ted: Asked whether there are plans to include nano technology to the initiative proposal. He explained that PED is planning to use nano tubes for its projects. He urged that if this technology is included it should be a focus area.

Nich: Distributed the summary of the U. of MD last MEMS lecture and a related paper. He also distributed copies of a CNN article on a Carnegie Mellon project on tiny robots and tabletop manufacturing.

Clayton: Indicated that he knows Prof. R. Hollins who is the leader of this project.

John: Met Kevin at the MEL party who told him that he has not set a date and location for the DARPA workshop, which might be held in NIST.

Mat: Mentioned that he was visited by Mike Sharp from John Hopkins who is interested to test the micro load cell. Mat also mentioned that he is building a micro pyrometer for the Physics Laboratory.

John: Boulder is interested in the development of micro bolometers.

Brad: Distributed the copy of a paper on laser machining.

Brad and Mat: Gave a brief report on the progress that they have made with the design and construction of the load cell. They have selected the MIT Maltese Cross design.

Clayton: Contacted Hutchinson who has indicated his desire to test the load cell.
Clayton: Could not find information on the electronic notebook.
Clayton: Discussed meetings to various Minnesota companies, like Honeywell, etc.
Clayton: Has found a seminar speaker from Wilcoxin and will arrange for a tour of their facilities.

Ed: Inquired about a contact from Penn state University.

Visits to Facilities Involved with Manufacturing and Research of Meso Scale Devices:

- January (week of 18) → schedule visit to?
- February → Minnesota
- Mid March → Utah, Colorado, New Mexico
- February or March → John Hopkins and APL (Bill Sharp and micro surgery)

The next meeting is scheduled for Thursday Jan. 7, 1999.

Happy Holidays

Meso/Micro-Scale Manufacturing Meeting Minutes
December 17, 1998

Present: John, Clayton, Nich, Brad, Matt, Eddie, Song

Facilitator: John Evans

Recorder: Brad Damazo

Review of Minutes for December 10th meeting: completed

News Items: A new NIST Office of Opto-electronics Programs ("OOPS") within EEEL was setup by Ray Kammer. Clayton is a representative.

Action/Warning: OOPS is looking for really cool photos of opto-electronics with in the next several months along with a write up.

Ted made contact with AMP. A January visit to NIST is planned.

Action Item: Kevin Lyons will be contacted by ISD once per week – see action items from previous meetings.

Action Item: Clayton will contact Bob Hocken and Ming Lou concerning workshop.

Nich passed out summary of RF mems course

Matt knows a Bill Sharp who is measuring micro cantilevers on a NSF grant. Bill has invited us to visit Hopkins. Perhaps he would be able to measure the dynamometer. He would also be a good candidate for the NSF NIST workshop. Also, a micro pyrometer for micromachining operations by Carol Johnson of the Thermal Physics group ???

Clayton handed out to the MEL management council his ASPE Executive Forum notes.

Demo Project: Micro dynamometer
Matt states there is Makino time available the end of January
Clayton states HTI is interested in using the dynamometer.
Brad is working on the manufacturing plans for the flexure.

Demo Project: Flexure Stage Assembly
Nich is working on a parameter model of the flexure stage
First ATP award was looking at two dimensional flexure stages
Second ATP award is looking at three-dimensional 6-dof stage using three of the two dimensional bases.
Math models and cad models to be developed.

Tours
Clayton will set up Wilcoxin tour after the holidays. Tour length would be about 1.5 hours. Also, a talk will be scheduled, anticipated 25-30 people attending.

Brad will set up tour of National Jet week of January 18th.

Brad will set up tour of Honeywell, Remele 1st week of February.

Talks
Eddie is tracking down PSU contact
Action Item: for next meeting, January 7th, come with calendar.

Meso-Micro Manufacturing Meeting Minutes
January 28, 1999

Attendees: John Evans, Clayton and Brad
Recorder: Brad

News Items:
Clayton, Brad and John Song visited National Jet last Thursday. A trip report is being put together and will be posted.

Adam Cohen, gave a talk on his USC EFAB work which is funded by DARPA Meso-machine program last Friday. We need a volunteer to write up a summary of Adam's presentation.

Current efforts under way and action items
Dapra Workshop on Meso-scale assembly
March 11^{th} and 12^{th}
The workshop will be located in Arlington and we are invited to attend – details latter. The speaker's list has been formulated.

NSF – NSIT – UNC Micro Manufacturing and Micro Metrology Workshop
Dates: Week of May 17, Brad is currently working with MESLA to get the shops conference room. The Workshop will be two days, most likely Tuesday /Wednesday or Wednesday/Thursday. Number of participates to shoot for is 30, 10 from industry, 10 from academia, 10 from Government (there is 8 of us from MEL).

Our focus will be on micro machining and micro metrology. As a strategy, we should aim to have a mix of industrial attendees present their problems and the metrology companies present their capabilities, with the hope that in one years time, a second workshop would produces solutions to the original problems. Each subsequent year's workshop participates should therefore increase. The lists of potential attendees were listed in previous minutes.

Action item: Brad will search the library for any work done on micro cmm's.

Trip up North
An agenda follows for the trip to Minneapolis:
Feb. 10, depart 6:30 am Dulles airport, arrive at Remmele Engineering approximately 10am.
Feb 11, visit Honeywell Technology Center 8:30 am, and Professional Instruments 1:30 p.m.
Feb 12, visit Hutchinson Technology 9am, and return on a 6:45 p.m. flight, arriving at Dulles at 10pm.
The flight cost is $592 and the trip is limited to six people:

Clayton
Brad
Matt
PED
John
ISD

Please contact Brad immediately if there are conflicts or problems. And yes we are leaving at 6:30 am. The next flight arrives in at 10:32 making it a bit late getting to the plant.

Trip out West
John is coordinating this trip with Clayton to find Berkley MEMS contact and pass on to John.

On or about March 1^{st} a table of contents will be formulated for the project's final report. We are effectively halfway through this project.

Contacts:
John will work on formulating, within NIST, support for a NIST wide program.

Meso-Micro Manufacturing Meeting Minutes
February 26, 1999

Attendees: John, Clayton, Matt, Nich and Brad
Recorder: Brad

News Items:
March 10- 11th Darpa workshop
March 15- 19th Westward MMM Trip
March 22nd Competence proposals due

April Wilcoxin

May 9 – 14th Paris Tool Show and CCM meeting (Clayton and Brad)

May 18 – 20th MMM workshop at NIST????????

May 26th CIRP Manufacturing Meeting
June 25th 1st draft MMM report due
July 15th Finish MMM report
July 22-23rd MEL MC Summer Planning Meeting

Action Item: Please send Brad info on scheduled events, he will keep a calendar and distribute it weekly.

Current efforts under way and action items
Dapra Workshop on Meso-scale assembly
March 10th and 12th
The workshop will be located in Arlington , John, Clayton, Nich and Ed have invitations. Matt and Brad are closed out.

Propose Table of Contents for Project's report

Table of Contents for MMM Report

- Abstract – half page
- Executive Summary –one page
- Technical Opportunities for NIST Program
  - Part measurement
  - Micro force measurement
  - Micro mass artifacts
  - Micro assembly
- Business Case
  - $500 million in yearly micro device sales
  - What would it mean to the follow markets?
    - Medical
    - Telecommunications
    - Satellite
    - Semi conductor
    - Fuel nozzles
    - Fiber optic
- Conclusions

Appendix for MMM Report

- *Trip reports*
- National Jet – Brad and Clayton
- Remmele - Brad

Honeywell - Nich
Hutchinson - Clayton
Professional Instruments - Matt
Future trips
 Westward
 MicroFab
 MDOT
 Sandia
 UC Berkley
 Fanuc
 Adept
 APL and job shop in Baltimore - Eddie
 Wilcoxin – Clayton (April)
Bibliography – Nich
Meeting Minutes - Group
NSF-NIST-UNCC Workshop report - Group
DARPA –Annapolis Workshop report John and Matt
DARPA – Assembly Workshop report – John, Nich, Eddie, Clayton
Survey of what's happening within NIST and MEL – Clayton and John
Summary of Talks and Course
 Dan DeVoe
 Adam Cohen
 UM MEMS
 Future speakers
 Gukel from Wisconsin
 Warren- date needed
Description and summary of demo project – Nich and Brads
Business case for ongoing program – Clayton and John

Action Item: Brad will generate a formal and in depth table of contents

NSF – NIST – UNC Micro Manufacturing and Micro Metrology Workshop
Dates: Week of May 17, shops conference room is reserved for May 18th 0 20th. The desired number of participates is 30, 10 from industry, 10 from academia, 10 from Government (there is 8 of us from MEL).

Workshop Agenda
Key words: Materials properties, electrical properties, optical
 Instrument manufacturers
 Users
 NIST measurement standards
 Design
 Manufacturing
 Assembly – Packaging MEMS
Workshop Theme
<u>Research in data, standards, measurement and technology needs at the meso/micro scale</u>

Potential Workshop Participates
Optical, Opto electronic, Fiber optic, Optical Device community
 AMP
 Boeing Electronics
 New Focus
 Corning
 Honeywell
Magnetic: read write heads and disk drive company's
 Hutchinson

Seagate
IBM
Read-Write

Aerospace

Hughes
Boeing
Lockhed Martin
Honeywell
Northup
Harris

Medical

Sarcos
Remmele
Johnson and Johnson
Medtronics
Boston Scientific

Mechanical

Analog Devices
GM
Wilcoxin

Technology Suppliers

Optical Metrology – Zygo
Micro hardness
Mycrona
Heidenhain
HP
Fanuc
Adept
Professional Instruments
Nova Sensors

Action Items: For workshop, ask presenters for 2 page abstract for proceedings.
Let Hocken find Academics

Trip up North

Action Items: Get you trip reports completed ASAP

Action item: John will work on formulating contacts within NIST, to support for NIST wide program.

Note: not minutes available for meeting on 2-19. Brad's notes showed no new information that wasn't included above.

Micro-machining Minutes
April 1, 1999

Note Taker: Matt Davies

ACTION SUMMARY:

ACTION: Call Ming Leu and discuss workshop agenda (Clayton, Matt).

ACTION: Our intent to invite academics and have Ming Leau and Bob Hocken lead that effort should be clarified in the phone converstion with Ming Leu. (Clayton, Matt)

COMMENTS REQUIRING FUTURE ACTION: NIST is interested in having some professors added tot he list of academics that Ming Leu and Bob Hocken will be Developing. These are:

1. Bill Sharpe (JHU)
2. Henry Guckel (UWis)
3. Weller
4. Ty Ram Tsu (sp?) (UC San Hose) (Eddie)

ACTION: Proceed to invite the attendees as assigned. (All)

ACTION: Determine how many people will fit comfortably in the shops conference room. Take other action as necessary. (Clayton and Brad)

ACTION: All assigned trip reports due Thursday April 8, 1999. (All)

ACTION: Please notify Nich about your preferences for the format of the JHU tour. (All)

ACTION: Notify Nich about your intent to attend the Potomac Photonics tour on Wednesday April 14. (All)

MEETING CONTENTS
Facilitator: John Evans

ITEM 1: Discussion of Correspondence with Ming Leu

From the e-mail sent to Clayton, each of Ming Leu's comets was addressed in turn:

Comment 1: The title of the workshop should be "Manufacturing of 3-Dimensional Components and Devices at the Meso and Micro Scales".
The title change was accepted.

Comment 2: The objective should be clearly stated.
We agree. Our suggestion is To identify research, data and standards needs to enable 3D manufacturing at the Meso and Micro Scales.

Comment 3: A prefered organizational structure is as follows: presentations in the morning and discussion in the afternoon on both days. The first day will address enabling technologies for manufacturing and the second day should address assembly, instrumentation, measurements, etc. Specificially:

DAY 1
Presentations
Use of meso and micro manufacturing by industry

Enabling technologies for meso and micro manufacturing

Group Discussion

Break out groups to discuss the presented and related topics

Summary of the discussion result by each group.

DAY 2

Presentations

Instrumentation needs for meso and micro manufacturing

Assebly and packaging for meso and micro manufacturing

Product measurement testing and calibration

Group Discussion

Break out groups to discuss the presented and related topics

Summary of the discussion result by each group.

This prompted a lot of discussion. A full half day of listening to presentations might be too long. There was concern that the topics of the discussion would be lost due tot he length of the presentation session. It was agreed however that our original arrangement might be too choppy. An alternate plan was suggested. In this alternate plan a long lunch would be used as a first discussion session, followed by more presentations after lunch and then a second discussion after lunch.

ACTION: Clayton and Matt Call Ming Leu and discuss.

Comment 4: It is essential to a lot enough time for each presentations: 20 minutes plus 5minutes for questions.

We agree.

Comment 5: There need to be more presentations by academics – at least 1/3 of the total.

It was felt that maybe Ming Leu misinterpretted the comment in Clayton's email "NIST has identified at least 18 people from industry and 18 people from government that we will be inviting" as implying that we weren't intending to invite any academics.

ACTION: Our intent should be clarified in the phone converstion with Ming Leu.

COMMENTS REQUIRING FUTURE ACTION: NIST is interested in having some professors added tot he list of academics that Ming Leu and Bob Hocken will be Developing. These are:

5. Bill Sharpe (JHU)
6. Henry Guckel (UWis)
7. Weller
8. Ty Ram Tsu (sp?) (UC San Hose)

ITEM 2: The Dates of the workshop.

The Dates fo the workshop are finalized**. They are May 18 and 19 in the shops conference room.**

ACTION: Proceed to invite the attendees as assigned.

ACTION: Determine how many people will fit comfortably in the shops conference room. (Clayton and Brad). Take other action as necessary.

ITEM 3: Ted proposed inviting additional industrial participants: (1) Cyberoptics; (2) Pratt and Whitney. It was decided that either of these could replace AMP. Thus, Ted will proceed to invite in order of preference: (1) Pratt and Whitney; (2) Cyberoptics; (3) AMP until he receives an acceptance.

ITEM 4: Trips, previous and future.

ACTION: All assigned trip reports due Thursday April 8, 1999. (All)

ACTION(S): The following trips are being planned.

(1) Johns Hopkins/APL (Nich, Eddie)

The visit to the JHU Center in Computer-Integrated Surgical Systems and Technology has been set for Wednesday 21st.

As far as the format of the visit is concerned we have two choices:

1. Go straight in to meetings with the faculty members of the center.
2. Give a seminar, which will be advertised and be open to all, and then have a meeting with the faculty members of the center.

ACTION: Please let Nich know what do you think will be more appropriate. (All)

(2) Potomac Photonoics (Nich)

Wednesday April 14 at 10:00 AM.

Draft of the proposed meeting agenda:

1. Manufacturing Engineering Laboratory (MEL) Objectives and Capabilities.(NIST)
2. The MEL Micro-Meso-Manufacturing (MMM) Exploratory Project. (NIST)
2a. The Intelligent Systems Division (ISD) MMM Objectives.
2a. The Automated Production Technology Division (APTD) MMM Objectives.
2a. The Precision Engineering Division (PED) MMM Objectives.
3. Near Term and Long Term Needs and Research Opportunities. (PP)
4. How can NIST and Industry Collaborate. (NIST, PP)
5. The NSF-NIST-NCUC (May 18 & 19) Workshop on MMM. (NIST, PP)
6. Conclusions. (NIST, PP)

ACTION: Notify Nich about your intent to attend.

(3) Wilcoxin (Clayton) Still TBD.

MMM **Meeting minutes**
April 22, 1999

Attendance: Clayton, Ted, Matt, Ed, Nich and John Evans

Reviewed attendance list (confirmed to speak *):

1. Zygo – confirmed (confirmed to speak) *
2. Hutchinson – confirmed (willing to speak)
3. Wilcoxon – confirmed
4. PI – confirmed
5. Kevin Lyons – confirmed
6. Bil Warren – confirmed
7. Pat Eicker (Sandia Robotics) – confirmed 1 _ days (will talk)
8. Potomac Photonics – confirmed (need to be asked – verbal OK)*
9. JHU (Thakor) – confirmed

Clayton needs/suggests for us to work on logisitics as he needed to depart.

Not confirmed / contacted:

1. Honeywell
2. New Focus
3. Adept
4. Sandia – MEMS
5. Pratt and Whitney
6. KLATencorAmray – SEM
7. Alumax – Winterbottom
8. Microfab

No discussion of Potomac Photonics trip or JHU trip.

Action Items:

1. John Evans- Talk to Honeywell Monday
2. Nich – New Focus – e-mail to Clayton clarifying contact
3. Matt- Contact Potomac Photonics – ask them to speak
4. Matt - E-mail to Brad – ask for addresses for Medtronics and Panasonic
5. Matt – contact Medtronics and Panasonic
6. Matt – Call Bob about Digital Optics Corp.
7. John Evans – Follow-up with Adept, Microfab and Sandia-MEMS
8. Ed – E-mail NSF about Dr. Sharpe and update of academic list invitees
9. John Evans – Four Groups of 15 Approximately, need rooms:
    - NAMT Lab
    - Shop Conf. Room – two groups
    - Coffee / Break Room (John will ask Dick Rhorer)
    - Conference Room in Materials
    - Conference Room in Polymers
10. Ed – Arrange for Coffee in Morning and after Lunch Coffee / Soda
11. Shirley – Reservations for dinner about four places groups of 12, suggestions: Chevy’s, O’Donnell’s, Hunter’s, Il Costello, Bugaboo Creek, Chris’s Steak House.
12. Shirley,Debbie, Ed – Staffing for Registration, Signage, Badges.
13. Matt / Nich – Video/Audio/ (Lisa/Rob) ? Stenographer ?
14. John Evans/Clayton – Proceedings
    - Ask Ric to speak at Meeting – intro.
    - Viewgraphs PP on disk

- Q and A summary
- Breakout summaries – PP slides on laptop
- Facility and staffing needs (work with us on item #12 as well)
- Final wrap-up

John Evans – Mentioned Clayton and he will be discussing meso-micro initiative with management

Discussion of medical community needs – 10 microns to several mm for most surgeries, smaller for brain, eye and nervous system surgeries.

Ed and others will make trip minutes for the Potomac Photonics Trip and the JHU trip and report to group for editting.

Meso-Micro Manufacturing Meeting Minutes
May 20, 1999

Attendees: John, Clayton, Matt, and Brad
Recorder: Brad

As a follow up to our short meeting last Thursday, please note the due dates on the final report. Also, the shared directory is up and running. Please deposit your documents in the appropriate folders listed below:

- Meeting Minutes
- Trip Reports
- Summary of Talks
- Workshop Documents (such as list of attendees)
- Inter Lab Report
- MEL Report

Final Report Deadlines
June 25th 1st draft MMM report due
July 15th Finish MMM report
July 22-23rd MEL MC Summer Planning Meeting

As a reminder, the proposed table of contents the final report follows:

Table of Contents for MMM Report

- Abstract – half page
- Executive Summary –one page
- Technical Opportunities for NIST Program
  - Part measurement
  - Micro force measurement
  - Micro mass artifacts
  - Micro assembly
- Business Case
  - $500 million in yearly micro device sales
  - What would it mean to the follow markets?
    - Medical
    - Telecommunications
    - Satellite
    - Semi conductor
    - Fuel nozzles
    - Fiber optic
- Conclusions
- **Appendix for MMM Report**
  - *Trip reports*
    - National Jet – Brad and Clayton
    - Remmele - Brad
    - Honeywell - Nich
    - Hutchinson - Clayton
    - Professional Instruments - Matt
    - Westward
    - MicroFab
    - MDOT
    - Sandia
    - UC Berkley
    - Fanuc

Adept
Johns Hopkins
Potomac Photonics

Bibliography – Nich
Meeting Minutes - Group
NSF-NIST-UNCC Workshop report - Group
DARPA –Annapolis Workshop report John and Matt
DARPA – Assembly Workshop report – John, Nich, Eddie, Clayton
Survey of what's happening within NIST and MEL – Clayton and John
Summary of Talks and Course

Dan DeVoe
Adam Cohen
UM MEMS
Future speakers
Gukel from Wisconsin
Warren- date needed

Description and summary of demo project – Nich and Brads
Business case for ongoing program – Clayton and John

Meso-Manufacturing Meeting
June 3, 1999

Attendees: Clayton, Matt, John, Nich, Ed
Recorder: Ed

13 Strategic Programs are being evaluated in management council – along with existing programs.

Need trip reports

Need Business case Bullets (Needed in Two Weeks)
- customer needs
- NIST role
- 5Yr plan
- expected impact
- bibliography

Strategic programs
- 1 or 2 will be chosen

common directory on MELSA server to put writing

workshop
-recorder still working on workshop minutes
-Hocken's student will make CD of vugraph's
-would be good to get just vu-graphs and data

Nich discussed micro-grippers

NIST wide Nano, micro scale activities
- chaired by Clayton and John, Research and facility
-NIST wide facility for nano, meso, production activities
    -need a new model to run the facility

Meso/Micro/Nano Manufacturing Meeting Notes
July 1, 1999

Attending: Clayton, John Evans, Ted, Nich and Brad
Recorder: Brad

Discussions centered on our strategic program proposal and are summarized below:

Current activities within MEL

ISD:	Micro/Meso assembly and sensing	ATP and DARPA funding
PED:	Micro/Nano metrology	STRS, ATP, OMP(EEEL) funding
APTD:	Mechanical micro/nano metrology Micro mechanical machining Fabrication processes	STRS, OA funding
MSID	Interoperability standards for fabrication Tools (Semitech/SEM Framework) CAD-CAD, CAD-CAE, CAD-KBE, CAD-CIM, CAI-CAPP	

Overall Program – Meso/Micro/Nano Technologies

1. Efficient development of nanotechology will be through development of enabling technology across all scales.

2. In short-term, Meso/Micro
   Fill in holes in dimensional and mechanical (properties) metrology
   Work with industry on assembly and packaging
   Develop science base for materials and processes

3. In longer-term, Nanotechnology
   - Nano characterization
     Materials characterization, spectroscopy
   - Nano manipulation
     Manipulating atoms and molecules
     Bottom-up
   - Nano devices
     Enabling Technologies
     Top-down
   - Magnetics

Strategic Program Proposal Topic

Title: Micro NAMT
Alternatives: Factory for micro fabrication
Meso fabricating factory

A. Develop a factory to fabricate one of the "Darpa" things, such as the micro power generator or to develop the micro force/torque transducer for data storage industry.
Enabling Technologies
1. Laser micro-machining processes
2. Micro mechanical machining
3. Assembly
4. Metrology (dimensional and mechanical properties)
5. Material and process science
6. Micro edm

7. Micro grinding
8. Solid free form fabrication

B. Develop regional micro technology center and manufacture Darpa MEMS thing.

Thoughts: Deal closely with Wilcoxin (ATP funded to develop MEMS accelerometer)

C. Nanofabrication

Thoughts: nano lithography, nano characterization – Standards for electrical current

Meso/Micro Meeting Minutes
July 8, 19999

Ed Amatucci

Attendees: John Evans, Nich Dagalakis, Dennis Swyt, Mike Postek, Steve Ray, Lowell Howard, and Ed Amatucci

Handouts: Meeting Minutes from July 1st, Interferometric Microscopy Status and Task Report, Meso/Micro Scale Measuring Machine, MSID Meso-Scale task proposals, Needs vs. Efforts chart and Micro-Meso-Manufacturing Flow Chart.

THESE NOTES ARE NOTE COMPLETE – I DID MY BEST TO CONVEY WHAT WAS DISCUSSED.

John – Discussion of last meetings minutes.

Lowell – Question about MEL's interests in Nano-technology. PED has 5 or so projects in nanoscale metrology, how is this included?
Response – MEL is trying to merge programs into a coherent "nano-technology" effort for the lab. And, this may mean a new strategic program.
Steve – commented about a "mother of all programs", etc…

July 14th – Strategic program proposal needs to be completed.

Discussion of merging skills of MEL into a strategic programs, not merging projects.

Two possibilities – Start new or merge existing techniques and R & D and expand.

Mike – commented about "metrology needs" – material characterization and test structures

Lowell – "organized body of users" – clue that there is a need for NIST's help

Mike – Need involvement from DARPA to fund a collaborative effort for program to be stronger.

Steve – Kevin Lyons has a program at DARPA….

NOTES from John's white board discussion:

Phase 1
Study, Industry Visits, Workshops, Literature survey, Lab projects

Phase 2
MEL MESO/MICRO
1) Metrology
    - Magic Measuring Machine
    - Micro force (also funded through competence)
2) Assembly and Packaging
    - Micro robotics
    - Micro sensing
    - Associated metrology and standards
3) Science Base and Processes
    - Micro materials
    - Test structures
    - Simulation
    - Knowledge base for nanotechnology

Dennis's charts:

1[st] chart:

	MEL		NIST	
	Meso/Micro	Nano	Meso/Micro	Nano
99	Lab work	nanotech SEMA Cellota's work Dagata, Lowell	Gaitan Reed Steve Hsu	nano-science
2000-1	Strategic Program?		Sold Directly !	
2001 +	? → "Enabling Technologies"? →		FY 2001 Nanotechnology Initiative	

Industry Needs Mes/Micro   Industry Needs "Nano"

2[nd] Chart:

Scale of Project 1 – 1.5 million

Project size 250 , 4-6 projects

Program	enables	Technology		
Micro/meso	→	Nano Problem	→	Need
Nano	→	Meso/Micro Problem	→	Need

Comment from someone:

Maybe move Macro technology to micro.nano technology directly.

Meeting was concluding and then we discussed a possible concept for funding and program responsibilities. This doesn't include "cross-lab" stuff.

Concept for possible program:

ISD 250, 250
APTD 250 + competence micro-force
MSID 250 + Darpa ?
PED 250, 250

Need a page on each to John Evans by close of business Friday.

Demonstration Project report

Interferometric Microscopy for Meso- and Micro-metrology

T.V. Vorburger, J. Fu, R.G. Dixson, and J.F. Song (PED)
B. Damazo (APTD)

Introduction

In this task we aim to apply the newly developed technique of scanning white-light interferometric microscopy to the measurement of small parts and features with dimensions ranging from 10 mm to 10 μm. The interferometric microscope was developed to perform surface metrology of smooth components. As a surface metrology tool, the resolution and accuracy requirements of interferometric microscopes have been much more critical for the z-direction than for the lateral (x,y) directions. The extension of these tools to coordinate metrology of small components will require research into the issues of x- and y-calibration and x- and y-resolution, as well as imaging quality, software capability, and data exchange.

The first type of interferometric microscope used the phase shifting interferometry technique [1-3] and was capable of measuring optical surfaces with resolution close to 0.1 nm. However, this technique was limited to smooth surfaces with rms roughness less than about 150 nm. The scanning white-light feature was added to interferometric microscopes in 1992 in order to overcome this limit in the z-range. Such microscopes are now capable of measuring surfaces with a z-height range close to 1 mm and a z-resolution close to 0.1 nm. These measurements are non-contacting and can be performed at high speed. The principal limitation is that surface areas having high slope with respect to the optical axis can fail to reflect or scatter enough light into the detection system to produce a measurable signal. Hence the instrument is limited to measurements of surfaces with modest slopes.

Nevertheless, the capability of the scanning white-light interferometric microscope for measurement of surface locations in all three coordinate axes raises the possibility that it can be used as a versatile dimensional metrology tool, capable of measuring width, diameter, spacing, pitch, straightness, angularity and other dimensional and geometrical parameters of small components. Two companies, Hutchinson Technology Inc, and Potomac Photonics already use these tools for a limited number of dimensional measurements, and the connector company AMP has approached NIST with problems in the measurement of sub-millimeter features on fiber optic connectors.

The scanning white-light interferometric (SWLI) microscope [4,5] is an area profiling technique that produces measurements of topography z(x,y). A typical SWLI microscope is shown in Fig. 1. A wide band source of light is collimated and then focused on a beam splitter in a cone of angles around normal incidence. Part of the light proceeds to the sample and part is reflected to the reference surface. The two reflected beams recombine at the beam splitter and produce optimally strong, interference fringes on the camera when the optical path difference between the two beams is zero. The topographic data are recorded as follows. The reference mirror is scanned vertically and the equal path condition is found for each pixel in the camera. The z-positions for the equal path condition are a function of the sample surface topography. The z-position data for each pixel (x,y) yields the topographic map z(x,y). This is a digital representation in which the x,y positions are linked to pixel elements in the camera of the microscope, which are equally spaced in x and y. Therefore, the point (x,y) can be represented by ($i\Delta x$, $j\Delta y$) where i and j are the pixel indices and Δx and Δy are the sampling intervals.

Status of Measurements

The following tasks for interferometric microscopy were completed in FY99:

- Contacted users of meso-measurement technology and discussed measurement needs in this field. These users included AMP, Hutchinson Technology and Potomac Photonics.

- Specified and ordered an interferometric microscope (IM) with:
  - Stitching capability to acquire large-scale data sets,
  - Phase shifting capability for independent z-axis calibration in certain ranges,
  - Scanning white light capability for measurement of z-dimensions up to 500 μm.

- Developed data files in the defacto standard, the universal data format (udf), which were read successfully by the IM vendor.

- Received the interferometric microscope on June 28, 1999. Testing and acceptance took place on June 30 - July 2. Three capabilities specified on the purchase order are not fully operational. These are the control of the x,y table for building up images of large components, control of tip-tilt of the component, and the software capability for reading and writing data in the udf format.

- Performed preliminary measurements of two millimeter-scale components supplied by Brad Damazo of APTD.

Discussion

The two components were a Maltese cross force-torque sensor and a small-scale circle-diamond-square (CDS) machining standard. Both components were machined in aluminum by the Makino 855 Delta machining center in FTD. Figures 2 and 3 show results for initial three-dimensional measurements of the two components with the interferometric microscope. Figure 2 shows the image of the central pad of the cross. Other data, not shown, were taken for the four arm, and all five sets of data will be stitched together to form one composite image. In the initial demonstration, we aim to measure the length and width of the central square pad, the squareness of the sides with respect to one another, and the width, thickness, and sidewall straightness of the webs. For the CDS we aim to measure the dimensions of the large square, the circularity of the circle, and the angle of the sides of the inner square with respect to the sides of the outer square.

Many areas of these specimens are well imaged using the interferometric technique. Features, such as vertical step heights, may be measured with these data. However, there is significant signal loss at the edges of the various prismatic elements due to burrs and other topographic imperfections on these components. The lost data points prevent accurate measurement of the width parameters and edge straightness. In order to improve the quality of the topographic images sufficiently to obtain accurate measurements of the width parameters, we plan to have electrochemical polishing performed on the components. This will be the first step in the plan to address the conditions of the

surface that allow high quality topographic imaging for dimensional measurement. After that, we will research the issues of calibration, resolution, software capability, and data formatting.

References

[1] B. Bhushan, J.C. Wyant, and C.L. Koliopoulos, Measurement of surface topography of magnetic tapes by Mirau interferometry, *Appl Opt* **24**, 1489 (1985).

[2] K. Creath, Comparison of phase-measurement algorithms, *Proc SPIE* **680**, 19 (1986).

[3] T. Doi, T. Vorburger, and P. Sullivan, Effects of defocus and algorithm on optical step height calibration, *Prec Eng* **23**, 135 (1999).

[4] P.J. Caber, Interferometric profiler for rough surfaces, *Appl Opt* **32**, 3438 (1993).

[5] L. Deck and P. deGroot, High-speed noncontact profiler based on scanning white-light interferometry, *Appl Opt* **33**, 7334 (1994).

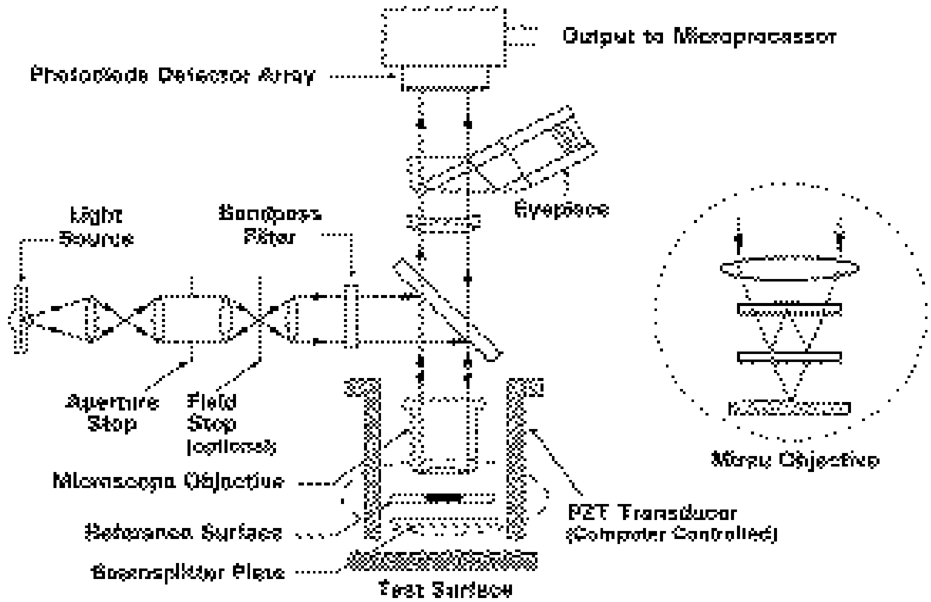


Figure 1. Schematic diagram of a typical interferometric microscope [3]. The interferometer configuration is a Mirau type.

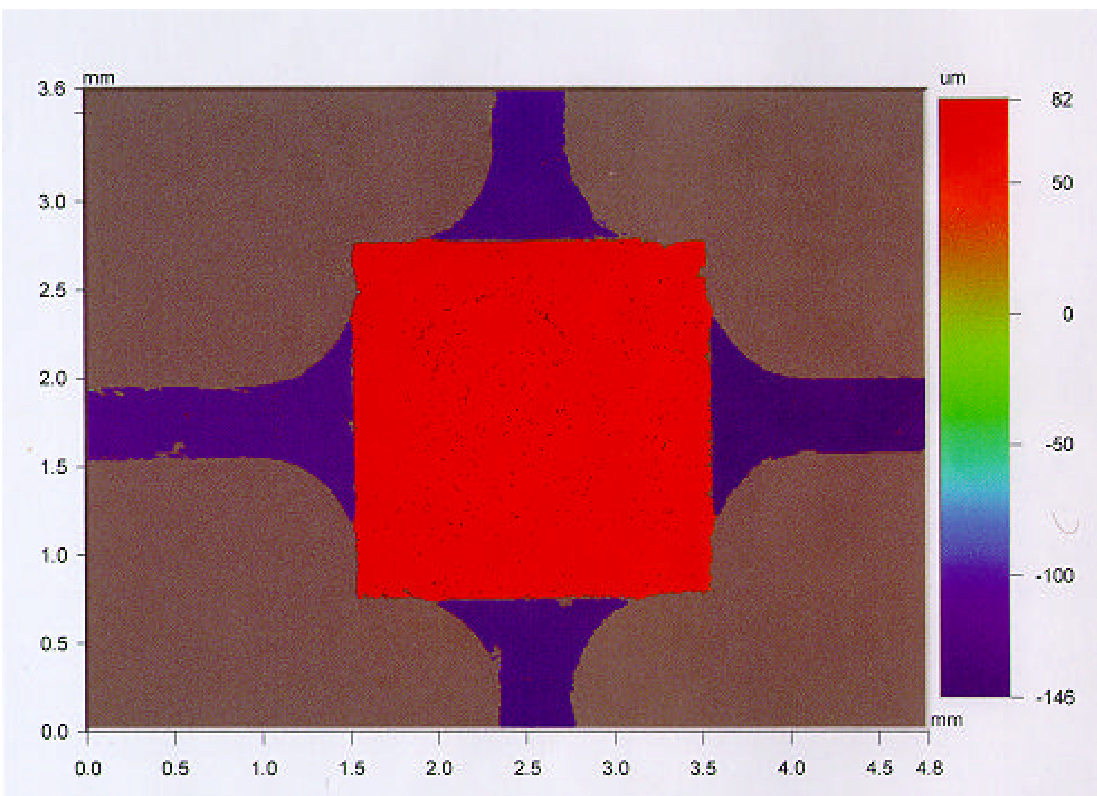


Figure 2. Topographic image of a Maltese Cross force-torque sensor measured by interferometric microscopy.

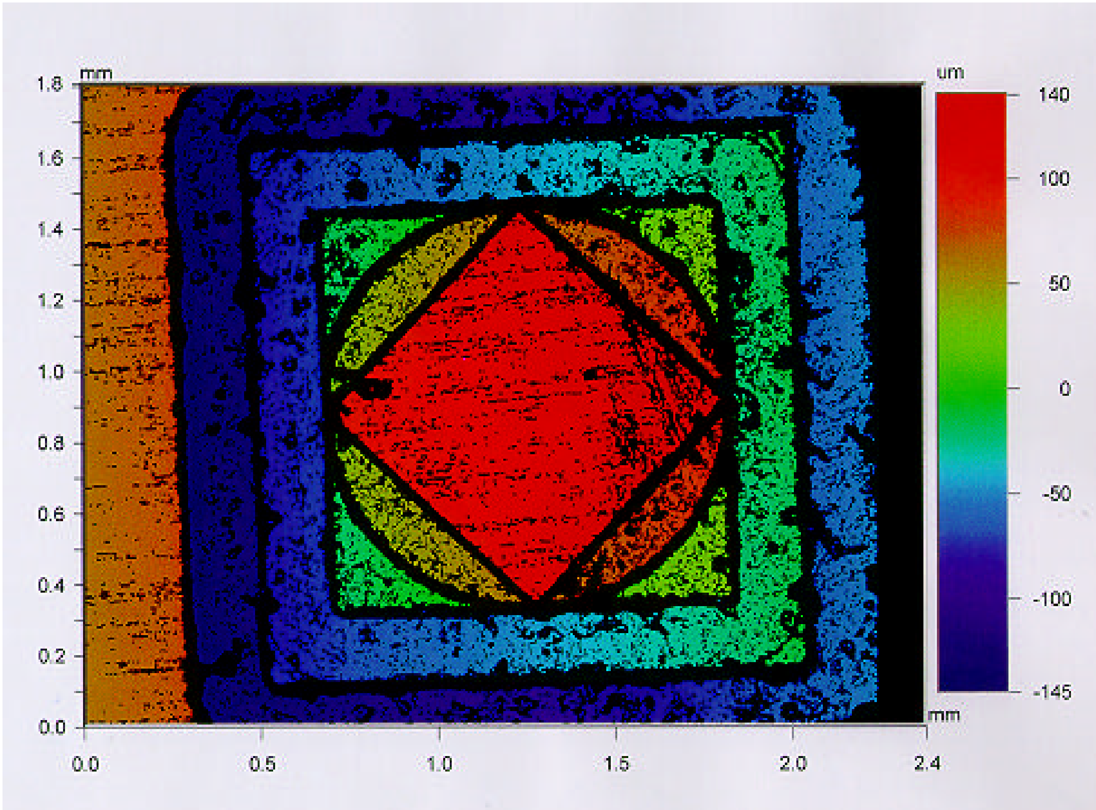


Figure 3. Topographic image of a circle-diamond-square meso-scale machining standard measured by the interferometric microscope.

A Machinable Device for Measuring Small Forces and Moment

Matt Davies, Brad Damazo, Clayton Teague

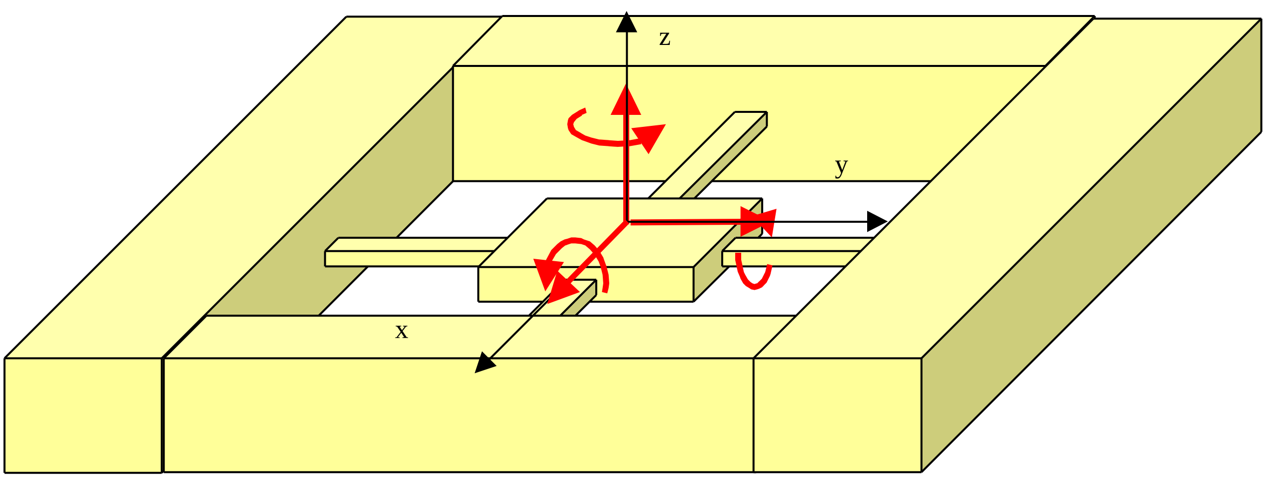
Section 1: HTI Design Specifications

Maximum Load : ~40 mN
Maximum Torque: 1.5 μN-m
Pad Size: 2mm square
Resolution: ~10 μN/15 nN-m

Section 2: A Proposed Design: Maltese Cross Configuration

A sketch of a maltese cross configuration is shown below. This configuration has the following advantages:

(1) It is likely to be "machinable"
(2) It is simple to analyze
(3) It is simple to instrument (i.e. the locations of the instrumentation are obvious and accessible.
(4) It has been used in numerous other applications
(5) Wilcoxin has an employee who is an expert in Maltese Cross design



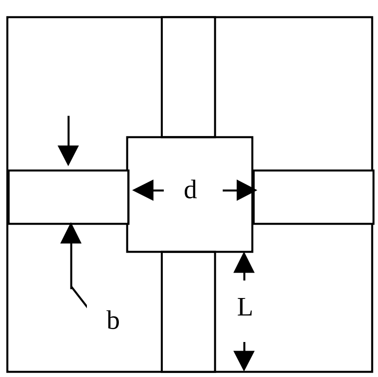


Figure 2: Definition of the dimensions of the maltese cross.

The thickness of the members (into the page) is denoted h.

Section 3: A simple size scale analysis using a cantilever beam

As will be shown in section 4, if we assume that the center pad of the cross is rigid and that the arms behave as beams with clamped ends, a cantilevered beam with a length equal to L/2 is the basic element needed to analyze the full cross under a downward load.

The size scale proposed for the prototype model is 2L+d = 1 10mm. To see where this size scale puts us relative to the maximum loads and resolution in HTI's specifications, let's start with a simple cantilevered beam 2 mm long with a width and thickness to be determined[**] such that they give us the desired specifications.

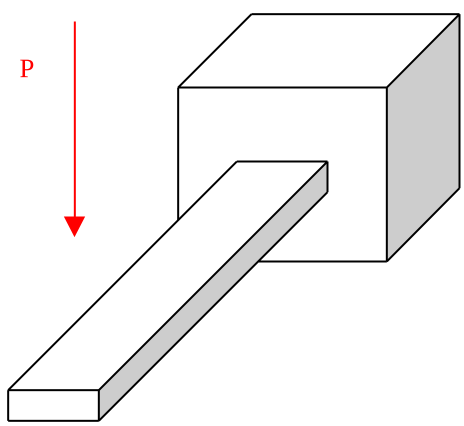


Figure 3: Cantilevered beam that carries _ the load of the full cross.

Now suppose P is _ of the maximum desired load of 40 mN or P=10 mN; this will be the load carried by each of the four members of the cross. The goal is to make the maximum load P produce the maximum desired strain in the member. The maximum desired strain is the elastic strain at yield divided by some safety factor. The strain at yield in aluminum or steel is approximately 1000 με (i.e. σ_y/E 70 MPa/70 GPa for aluminum or 200 MPa/ 200 GPa for steel) so taking a safety factor of 2 let the maximum allowable strain be 500 με. This is very rough and needs to be refined, but it's good enough for a first shot.

Analysis of this beam proceeds as follows (see Gere and Timoshenko, Strength of Materials for formula derivation of the formulas). First the maximum moment on the beam is given by:

$$M_{max} = P(L/2) \qquad (1)$$

The maximum stress, experienced on the outer surface of the beam at the built-in end, is given by:

$$\sigma_{max} = M_{max}C/I = P(L/2)/S \qquad (2)$$

where I is the area moment of inertia of the beam, C is the distance from the neutral axis to the outer skin of the beam, and S = I/C is the section modulus ($S = bh^3/(12(h/2)) = bh^2/6$).

Now using Hooke's law the maximum strain is given by:

$$\varepsilon_{max} = \sigma_{max}/E = PL/(2SE) \qquad (3)$$

Solving for the unknown, S, we get:

[**] The constraint on the ratio of length to thickness and width is approximately 5:1. This ensures that we can treat the members with a simple beam-bending analysis.

$S = PL/(2\varepsilon_{max}E)$. (4)

Putting in P = 10 mN, L = 4 mm (i.e. L/2 = 2 mm), E = 70 Gpa (for aluminum), and $\varepsilon_{max} = 500 \times 10^{-6}$, we get $S = 5.7 \times 10^{-13}\ m^3$.

So, consider the case of measuring only F_z, M_x and M_y (see Figure 1) so that we need strain gages only on the top and bottom surface of the beams. In this case only b needs to be large enough to accommodate a gage and h can be smaller. Taking b to be reasonably large, say 200 μm, and solving for h to give the necessary section modulus S, we get:

$h = (6S/b)^{-} = 130\ \mu m$ (5)

This might even allow for a gage on the h surface of the beam. Making b = 400 μm to allow even more room to mount a gage gives h = 92 μm. We have to be careful here however, because making b this large may make the beam look more like a pate than a beam. If necessary we can replace this beam analysis with a more thorough plate analysis in the future. An FEM analysis could also be used, but given the other uncertainties present in the problem this is probably overkill.

If we just use a cantilevered beam as a baseline, then for a given maximum load and maximum strain (defined by the yield) we can calculate the length of the beam as a function of the thickness and width as follows.

So suppose P_{max} = 1 mN, $strain_{max}$ = 1000 με and the E is the Young's Modulus of steel, then if t = 25 micrometers and w = 25 micrometers the length would be 520 micrometers. This is reasonable.

Maltese Cross Analysis

In order to analyze the moment measurement capability we have to look at the full cross configuration.

To do this we make the following assumptions:

(1) The central platform is rigid
(2) The arms of the cross behave as beams with built-in ends.
(3) The corner radii of the beams s zero[!!]
(4) The frame is rigid.
(5) Others that I have forgotten

. Each member acts like a double cantilever (ignoring corner radii for now) as shown in Figure 4. The load P experienced by each arm may come from either a force or a couple on the central platform. Thus, the cantilever analysis is sufficient to understand the full cross with a proper choice of P.

For a downward load F_z on the central platform,

$P = F_z/4$,

And the analysis in section 3 can be directly applied with $(F_z)_{max}$ = 40 mN and P = 10 mN.

[!!] Obviously, this will not be the case since the radii will be determined by the radii of endmills used to fabricate he device, but we have to start somewhere, and we can use a more accurate analysis later if things look promising.

Now consider an applied moment M_x on the central platform of 1.5 μN-m. A positive M_x moment would produce a force P in the positive z direction on the right arm of the cross in figure 1 and an equal and opposite force P in the –z direction on the left arm. The

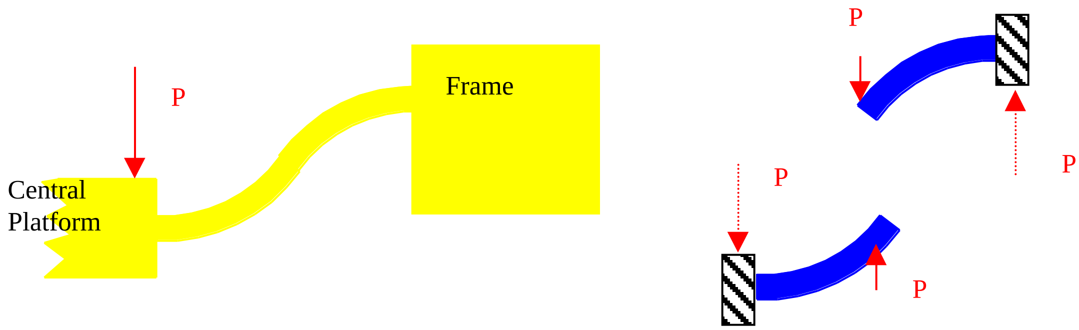


Figure 4: A single arm of the Maltese Cross with deflections obviously exaggerated for clarity. The load P may come from a force or a couple on the central platform.

magnitude of these forces is:

$P = M_x/d = 0.75$ mN.

This is much smaller than the load required to plastically deform the beam. However, it is also about 13 times less than the maximum measured load and so, while it is measurable, either moment resolution or maximum z-load will have to be sacrificed. Making the platform smaller (if possible) will improve the situation.

Section 5: Resolution

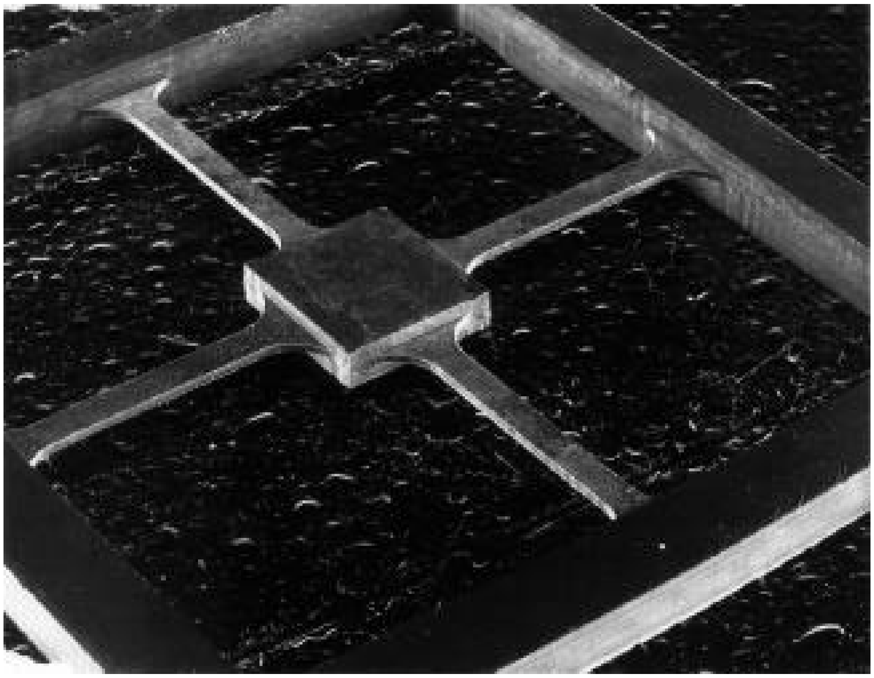
The resolution of a strain gage system is bout 1 part in 10000[++]. Thus for a maximum force of 10 mN we should get a resolution of 1 μN in the F_z force measurement. This meets the specification with conventional bridge circuitry. For the M_x moment measurement, the load produced by the specified maximum moment is 0.75 mN. If we measure moments and forces simultaneously, the resolution on the measurement of this force is still 1 μN or about one part in 750. This gives a resolution of 2 nN-m which also exceeds the specification.

Section 6: Conclusion

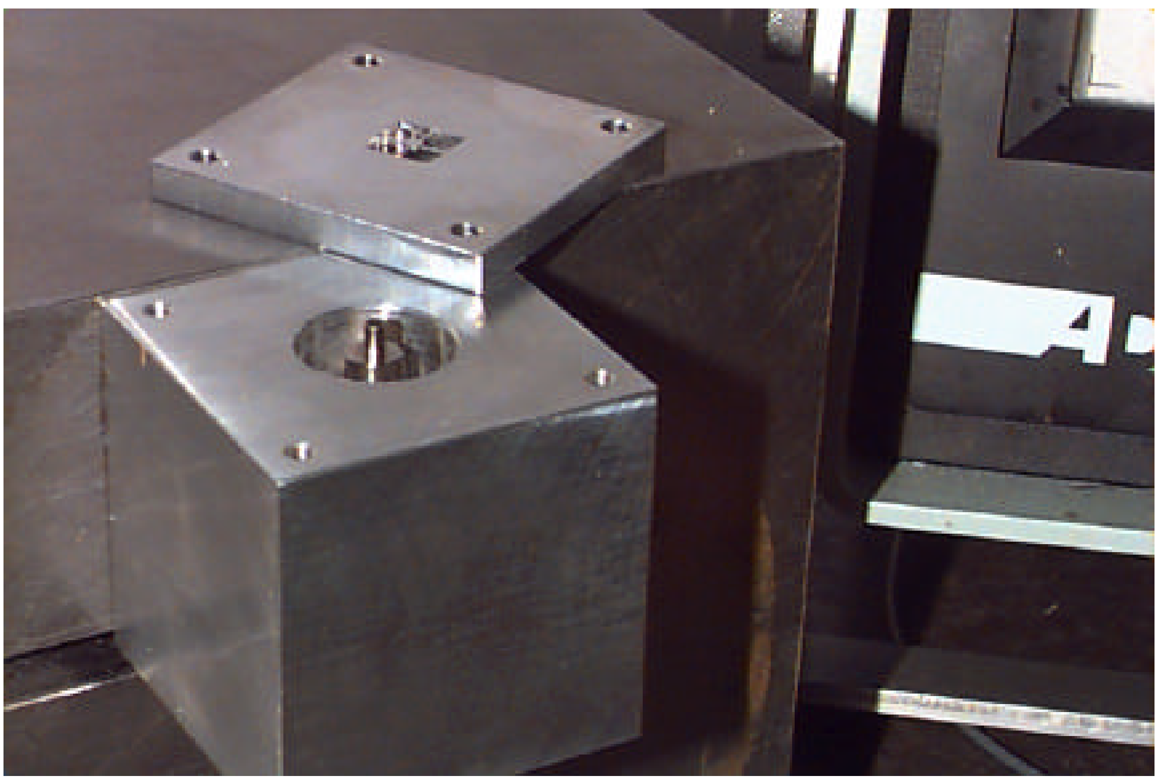
If my calculations are correct and we can think of a way to fabricate the fictitious device analyzed here, it should work!!!

The analysis should carry over to 6 dof although analysis of tension compression stresses in the elements will have to be done. I am assuming that all of the measurements are separable – i.e that the matrix relating the forces and moments to the sensor outputs can be made full rank with proper sensor placement.

[++] Conversation with Clayton Teague. According to Clayton, good electronic circuit design and noise reduction techniques might be employed to get 1 part in 100000 or 1 part in 1000000 in extreme cases.



Actual device as machined.



View of test fixture and capacitance probe to measure deflections of the flexure.

Motion Control and Testing of Deformable Structure Micro Positioners

Intelligent Systems Division

1. Summary

The objective of this task was to develop a simple motion controller for a planar micro-positioner, then use the motion controller to develop a quick and simple defect detection test. To visualize the motion of the micro-positioner stage we purchased and installed a microscope video imaging system and a micro-scale target, which is attached to the moving stage.

The defect detection test has been used for several months and it has proved to be very useful, because it was able to detect slipage in one coupling of the micro-positioner. This was induced by overloading or extensive performance testing and it would have been difficult to detect without this test. We also discovered that this test could be used to easily measure the transmission ratio of the micro-positioner couplings.

To better understand how this task fits in to the overall project and program goals we first explain the project background. The motion controller, the defect detection test, the video imaging system and the test results further explain this project task.

2. Background

Programmatic Goals

The long term goals of this project are the following:

- Develop optimum design specifications for superior performance monolithic planar micro-positioners.
- Develop calibration and testing procedures for monolithic planar micro-positioners.
- Interact with industry experts involved with the manufacture of opto-electronic devices to learn about their micro-positioner needs.

Calibration of the Kinematic Equations

Special care was taken to design and fabricate the micro-positioner so that it is symmetrical about two orthogonal axes and the dimensions of the parts correspond to the design model. In reality perfect symmetry is impossible and the lengths of the parts are slightly different than those desired. The objective of the kinematic equations calibration is to develop a mathematical model of the kinematic mechanism, perform appropriate calibration tests and develop identification algorithms, which will estimate the values of the unknown mathematical model equation parameters.

A matrix representation of the kinematic equations gives,

$$\begin{bmatrix} X_o \\ Y_o \\ \Theta_o \end{bmatrix} = \begin{bmatrix} -\frac{L_{1x}}{2H_{1x}} & -\frac{L_{2x}}{2H_{2x}} & 0 & 0 & 0 & 0 & -\frac{L_{1y}}{2H^2_{1y}} & \frac{L_{2y}}{2H^2_{2y}} \\ 0 & 0 & -\frac{L_{1y}}{2H_{1y}} & -\frac{L_{2y}}{2H_{2y}} & -\frac{L_{1x}}{2H^2_{1x}} & \frac{L_{2x}}{2H^2_{2x}} & 0 & 0 \\ \frac{L_{1x}}{W_x H_{1x}} & -\frac{L_{2x}}{W_x H_{2x}} & \frac{L_{1y}}{W_y H_{1y}} & -\frac{L_{2y}}{W_y H_{2y}} & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} X_{1i} \\ X_{2i} \\ Y_{1i} \\ Y_{2i} \\ X^2_{1i} \\ X^2_{2i} \\ Y^2_{1i} \\ Y^2_{2i} \end{bmatrix}$$

The motion controller was used to position the stage of the micro-positioner to a grid of calibration points and the input and output position and orientation of the stage was measured. Various least square identification algorithms are being used to estimate the values of the parameters of the kinematic equation.

Micro-positioner prototypes
Beginning with the concept originally conceived by Fred Scire with the PiezoFlex[1] microstage we have made significant improvements and we are pushing to provide superior performance and low manufacturing cost for industry to use this technology for Meso-Manufacturing Automation. We have gone through three designs so far. The first design prototype was fabricated approximately six months ago and it is being tested since then. The second and third design prototypes are currently being fabricated. Their design is based on experience obtain from the first design and are expected to enhance its performance and capabilities.

Insertion Tool
An insertion tool has been developed to install the piezo actuators with the proper loading and also to determine the spring rate of the micro-positioner stage. The insertion tool is used with a load cell that is coupled to the stage. As the stage is moved or piezo actuator installed, the force being applied to the piezo actuator can be monitored. The loading on the piezo actuator is limited and it is critical to stay under a factory value to achieve proper range performance of the stage as well as prevent damage to internal flexures within the actuator housing.

Safety Stops and Z-axis Actuator
Working with the Precision Optoelectronics Assembly Consortium as an ATP intramural partner allowed us to receive feedback as to how our research could be utilized in industry. Their feedback included adding safety stops to protect the stage, adding more degrees of freedom, reducing the size of the stage, developing parametric models of the stage and evaluating the machining cost of the stage. Their list mirrors what could be an impossible task considering current technology, but we have worked towards applying our research to address their feedback.

Safety stops have been integrated in the next version of our micro-positioners. The issue is to not limit or affect the travel of the stage and also to protect the stages flexures from a strong hit from a robot or other automation device. We chose to pursue a plastic rod approach and have made provisions for safety stops in the new designs.

Actuator Coupling
During the testing of the first actuator stage, we determined that there was a significant loss of actuator travel due to the poor coupling of the PZT actuator with the input block of the microstage. The coupling was made with epoxy similar to the original Piezoflex stages. We had two issues. First, how to solve the 50% or so coupling loss for the next generation stage; and, then how to “fix” the coupling for better efficiency in the existing stage.

Beginning with the new coupler design for the next version of the X-Y stage was the first step since we hoped the solution could be adapted to the existing stage. We first looked at alternative methods for developing a monolithic coupler which would only transmit axial motion into the stage input block. The coupler would also need to be small in physical size and be clamped securely to the input block. A variety of design iterations were explored and discussed amongst the team. A new coupling, the Universal Perpendicular Flexure Joint Coupling, attached to a kinematic v-groove clamp, will be tested when the new micro-positioner design prototypes become available.

Measure performance
Several performance tests were conducted to evaluate the new micro-positioner design. These include cros-talk, linearity, coupling and frequency response tests. The most important of them is probably the cross-talk test. This test measures the translation and rotation error induced in a direction orthogonal to the

[1] PiezoFlex is a trademark associated with Wye Creek Instruments design of a flexure stage. Certain commercial products, are identified in this paper to specify experimental procedures adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the products identified are necessarily the best available for the purpose.

commanded motion direction. Results indicate that this error does not exceed 0.5 micrometers of translation and 0.4 arcseconds of rotation in a range of 100 micrometers. The small error in rotation is important because that type of error is difficult to compensate with external means.

3. Motion Controller Design

A simple motion controller of the micro-positioner has been developed. Figure 3.1 shows a schematic block diagram of the controller. The controller is running on a PC and issues motion commands to the controller of two piezoelectric PZT actuators, through a serial line connection. The actuators are Queens Gate[2] (QG) 15 micrometers capacity PZTs (Q1 and Q2 in Fig. 3.1) and they are mounted into properly machined holes within the structure of the micro-positioner. The actuators are equipped with embedded capacitive gauges, which measure the change in the length of the PZT stacks. The QG controller closes the feedback loop using the data from the capacitive gauges. Our controller monitors and displays the actuator elongation information. The micro-positioner is equipped with two capacitive gauges (C1 and C2 in Fig. 3.1), which monitor the absolute position of the moving micro-positioner stage along its two orthogonal axes. The outputs from these two gauges are digitized, by a data acquisition card (DAQ) and plotted on the control panel of the controller. The controller is not using these signals for feedback information. The operation of the controller is open loop in order not to mask the performance of the micro-positioner.

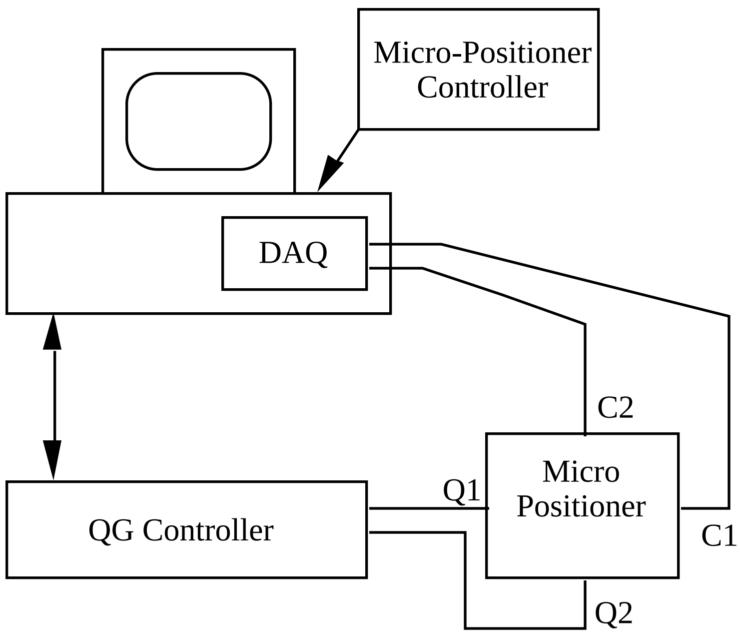


Fig. 3.1

Several versions of the controller have been developed in order to serve the needs of the performance testing and calibration work:

- Basic Motion Operation: This version allows the operator to specify any desired output X-Y position and to monitor the operation of the PZT controller.

[2] Certain commercial products, are identified in this paper to specify experimental procedures adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the products identified are necessarily the best available for the purpose.

- Rectangular Grid Operation: This version of the controller commands the moving platform of the micro-positioner stage to move sequentially to a rectangular grid of points, within the workspace of the stage.
- Square Motion Operation: This version of the controller allows the operator to command the stage to move along a square trajectory, of any desired size and to plot the output trajectory on the screen.

Figure 3.2 shows a picture of the control panel of the controller running the square trajectory test. This is a simple test that can easily spot problems with the operation of the micro-positioner. The micro-positioner is commanded to move its stage equal displacements sequentially along the X and Y orthogonal axes directions. The output displacement along the X and Y directions is measured, scaled and plotted on the controller monitor screen.

Fig. 3.2

The lengths of the sides of the trajectory plotted on the screen must be equal to the commanded displacement, times the transmission ratio of the coupling, times the micro-positioner gain. For example if the commanded input displacement is 10 micrometers and the gain is 10 the measured output displacement will correspond to 100 times the corresponding coupling transmission. This is a simple test to perform and can provide an easy measurement of the micro-positioner couplings transmission ratios. Figure 3.3 shows the output from such a test.

This type of test can be performed as a baseline and then used to monitor the operation of the micro-positioner. Figure 3.4 shows the result from a test when one of the couplings of the micro-positioner was defective. This particular design of the coupling was not capable of transmitting high actuation forces. Overloading or repeated rapid changes in the direction of motion resulted in deformation and slipage. As can be seen from Fig. 3.4 the output displacement along axis #2 is much smaller than that expected from the base line test. This defect would have gone undetected if it was not for the square trajectory test.

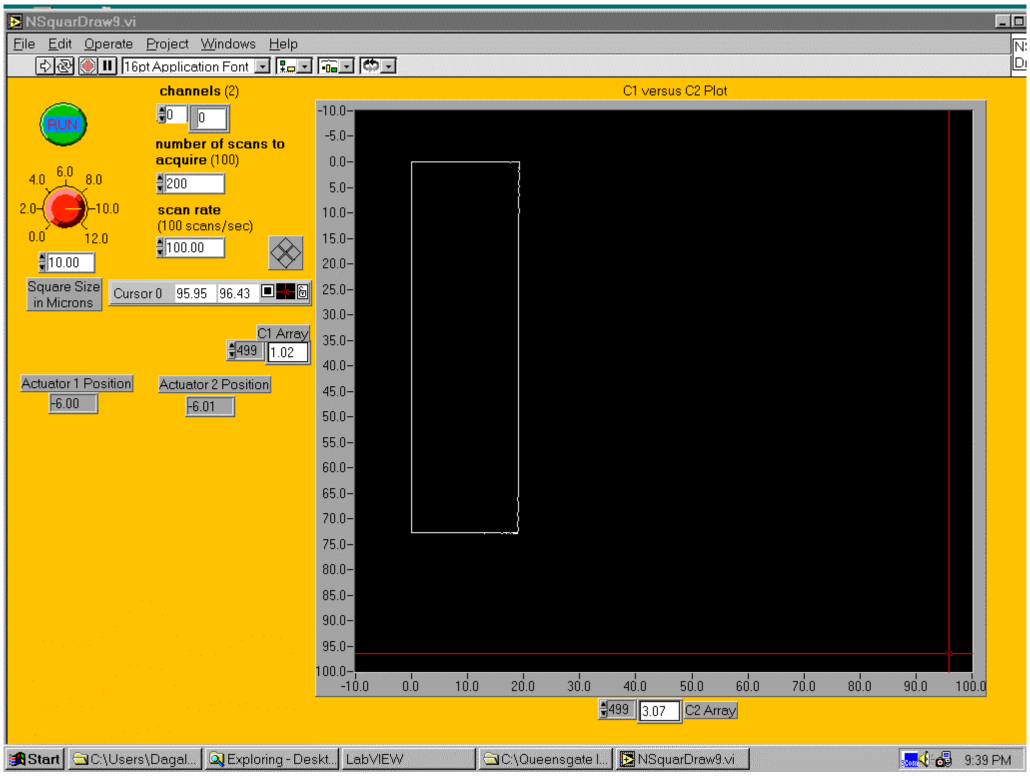


Fig. 3.4

4. Visualization System

To visualize the motion of the micro-positioner stage we purchased and installed a microscope video imaging system and a micro-scale target, which is attached to the moving stage. Figure 4.1 shows a picture of this system.

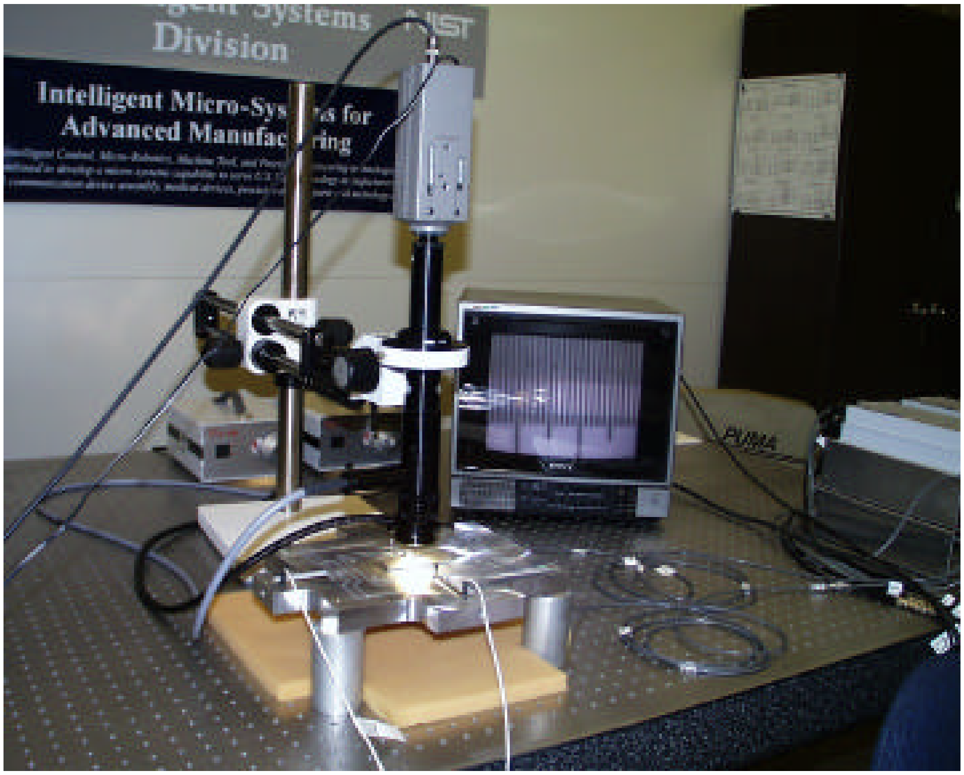


Fig. 4.1

Proceedings of
The Integration of Nano- to Millimeter Sized Technologies (In2m) Workshop

Held on March 11 – 12, 1999
George Mason University
Arlington, VA

Sponsored by DARPA/NIST

Table of Contents

TO: Invited Guests

FROM: Kevin W. Lyons, Program Manager
DARPA Defense Sciences Office

SUBJECT: Invitation to Participate in the DARPA/NIST Workshop on:

Manufacturing Technologies for Integrated nano-to-millimeter (In2m) Sized Systems: The State of the Art, and Opportunities for Further Advances

<u>Note:</u> <u>Response Requested</u>

I would like to invite you to a study on " Manufacturing Technologies for Integrated nano-to-millimeter (In2m) Sized Systems: The State of the Art, and Opportunities for Further Advances." This workshop will take place March 11-12, 1999, in Arlington, Virginia. The meeting location will be at George Mason University, located within walking distance of DARPA. The objectives, overview, focus questions, and agenda for this study are provided at the end of this message.

The meeting will be comprised of seven main talks and a series of panel discussions centered around particular "Questions." For each Question there will be a Chair and three panel members, each of whom will be asked to share their views through a few viewgraphs. All Questions will be discussed with the entire group and then a final plenary session will summarize the findings. If there is an interest on your part in participating as a panel presenter I would request that you reply back to Ms. Heather Heigele by February 25th. Please indicate which Question/s you would like to address and provide a brief description of your approach to the question. Plans are to select the panel presenters by March 1 to allow adequate time to complete your prepared comments.

On February 15th a more detailed agenda that includes the main presentation topics and speakers will be distributed by email. This will be followed by a final agenda and confirmed list of participants one week prior to the study.

I very much hope that you will be able to join us and appreciate your considering this request. The administrator for the meeting is Ms. Heather Heigele at Strategic Analysis, Inc. Please let Ms. Heigele know as soon as possible whether you plan to attend. Further details on hotels, directions, and other logistical information will be sent to all those that confirm their intention to attend.

With best regards,

Kevin W. Lyons

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Manufacturing Technologies for Integrated Nano-to-Millimeter (In2m) Sized Systems: The State of the Art, and Opportunities for Further Advances

Sponsored by:
Defense Advanced Research Projects Agency
National Institute of Standards and Technology

March 11-12, 1999
George Mason University, Room 318
Arlington, VA

OBJECTIVE: The objective of the workshop is to identify key requirements for realizing integrated nano-to-millimeter sized systems. The workshop will provide a forum for the interaction of different research communities in identifying innovative research aimed at overcoming the barriers in integrating components that are fabricated by multiple processes and span in size scale (nano through millimeter dimensions). The results of this study will contribute toward the development of a plan that will be used to guide future research funding by DARPA and NIST.

OVERVIEW: There has been considerable interest and funding expended in developing nano, micro, and millimeter scale technologies. This has resulted in some exciting prototype systems that clearly demonstrated that a certain functionality could be achieved through the novel application of a particular process technology. This work has evolved to encompass the development of more complex devices that are comprised of multiple components. At the present time, the successful development of these prototype nano-to-millimeter sized devices is highlighting the need to develop the associated precision assembly and manufacturing processes required to produce them. Effective use of In2m systems in commercial and defense applications will require that the community meet constraints such as affordability, reliability, durability, and repeatability and stability of processes. Success in these areas will require a heightened focus on developing and maturing advanced assembly and manufacturing technologies/methods that address the issues and barriers seen at this small scale. Further, the successful deployment of effective In2m systems and enabling technologies will require a multi-disciplinary approach that addresses issues in design, materials synthesis, micro-machining, assembly, integration (multi-scale/multi-process), and packaging of In2m components.

QUESTION #1: Are current equipment and practices able to meet the expected demands for part presentation, staging, placement, and fastening? Are these systems adaptable, and if so, will they be affordable? Are revolutionary solutions required to meet the demands expected by In2m?

QUESTION #2: Are there particular processes currently being used in industry or research centers that might be suitable, through design of novel extensions/modifications of process, for achieving massively parallel status. What are the expectations regarding affordability, quality, and performance.

QUESTION #3: What are the major issues with the transfer of energy and data between boundaries of nano, micro, and millimeter sized systems. How can these issues be addresses through attention to assembly technologies?

QUESTION #4: Can the functionality and design constraints of complex In2m systems be adequately characterized and utilized such that the most appropriate mix of technologies can be chosen for a particular application? What technical barriers have to be overcome to enable this? Are suitable simulation tools available? Are the fabrication processes and tolerances for In2m scale components of sufficient accuracy and repeatable to support assembly operations?

In2M Workshop Agenda:Thursday, March 11, 1999

8:00AM - 8:30AM	Breakfast and Registration	
8:30AM - 9:00AM	Welcome & review of agenda Topics of interest in DoD	Kevin Lyons, DARPA
9:00AM - 9:15AM	NIST Manufacturing Engineering Laboratory	John Evans, NIST

Session 1: Are current equipment and practices able to meet the expected demands for part presentation, staging, placement, and fastening? Are these systems adaptable, and if so, will they be affordable? Are revolutionary solutions required to meet the demands expected by In2m?

Moderator: John Evans, NIST
Scribe: Ed Amatucci, NIST

9:15AM - 10:15M
Brian Carlisle, Adept Technologies, Inc.
"Meeting the challenges of micro-assembly"

10:15AM - 10:30AM ---- BREAK

10:30AM - 12:00PM
Panel presenters
Ralph Hollis, Carnegie Mellon University
Robert A. Weller, Vanderbilt University
Robert Beranek, Boeing

12:00PM - 1:00 PM ---- WORKING LUNCH (brought in)

Session 2: Are there particular processes currently being used in industry or research centers that might be suitable, through design of novel extensions/modifications of process, for achieving massively parallel status? What are the expectations regarding affordability, quality, and performance?

Moderator: Peter Will, USC Information Sciences Institute
Scribe: Daniel Madey, Strategic Analysis, Inc.

1:00PM - 2:00PM
John Steven Smith, University of California, Berkeley
"Precision component placement using slurry-based methods"

2:00PM - 3:00PM
Donato Cardarelli, Milli Sensor System & Actuator Company
"Flat-pack gyro: A novel hybrid approach"

3:00PM - 3:30PM ---- BREAK

3:30PM - 5:00PM
Panel presenters
Murilo Coutinho, USC Information Sciences Institute
John Feddema, Sandia National Laboratories
Cleopatra Cabuz, Honeywell Technology Center

5:00 PM End of formal program for day; small-group dinners.

In2M Workshop Agenda: Friday, March 12, 1999

7:30AM - 8:00AM   Breakfast

Session 3: What are the major issues with the transfer of energy and data between boundaries of nano, micro, and millimeter sized systems. How can these issues be addresses through attention to assembly technologies?

Moderator: Peter Will, USC Information Sciences Institute
Scribe: Daniel Madey, Strategic Analysis, Inc.

8:00AM - 9:00AM
Don VerLee
Micro-fluidic devices - Challenges in Integration

9:00AM - 10:00PM
James Ellenbogen, MITRE
"Designs for Molecular Electronic Computer Circuits and for their integration into Micron-Scale and Millimeter-Scale Mechanisms"

10:00PM - 10:30PM ---- BREAK

10:30AM - 12:00PM
Panel presenters
William Tolles, Consultant, former NRL
David Wallace, MicroFab Technologies, Inc.

11:30AM - 12:30PM ---- WORKING LUNCH (brought in)

Session 4: Can the functionality and design constraints of complex In2m systems be adequately characterized and utilized such that the most appropriate mix of technologies can be chosen for a particular application? What technical barriers have to be overcome to enable this? Are suitable simulation tools available? Are the fabrication processes and tolerances for In2m scale components of sufficient accuracy and repeatable to support assembly operations?

Moderator: John Evans, NIST
Scribe: Nicholas Dagalakis, NIST

12:30PM - 1:30PM
Michael Pecht, University of Maryland
Physics of Failure for Complex Systems

1:30PM - 3:00PM
Panel presenters
Phil Kuekes, Hewlett-Packard Laboratories
William D'Amico, US Army Research Laboratory
Robert Reeber, Army Research Office

3:00PM - 3:30PM
Summary of Discussions on Questions, Opportunity for input: John Evans

3:30PM - 3:45PM

Discussion of Ideas for Follow-on Activities and Closure: Kevin Lyons

3:45PM Depart for the Airport

Session 1: Thursday morning, 3/11/99

Overview

Kevin Lyons, Defense Applied Research Projects Agency (DARPA):

ABSTRACT: This workshop will focus on technologies that support systems which span size technologies (nano, micro, meso, millimeter), multiple processes/materials (monolithic, SFF, plastic injection molding, direct write, etc.), and/or multiple functional regions (i.e., fluidics, optical, electrical, thermal, structural). To make small-scale systems a reality, a comprehensive, well-orchestrated research thrust must address a variety of issues that will serve to "integrate" these technologies from a systems level perspective. A unique opportunity exists to bring together competing yet potentially complementary technologies, thus accelerating the deployment of systems that are comprised of nano/micro/meso/milli-sized technologies.

The results of this workshop will assist in identifying key assembly process technologies that will enable more optimal system performance while conforming to schedule, quality, and affordability requirements. These issues are important to defense, as well as commercial industries. The results will also be used to accurately gauge where future research should be focused by identifying defense and commercial applications that drive this integration requirement.

<LINK TO LYONS SLIDE PRESENTATION>

John Evans, National Institute of Standards and Technology (NIST):

NIST Programs Relevant to In2m

ABSTRACT: The National Institute of Standards and Technology promotes economic growth by working with industry to develop and apply technology, measurements and standards. NIST carries out that mission through the Advanced Technology Program, the National Quality Program, the Manufacturing Extension Partnership and the Measurement and Standards Laboratories. Within the Laboratories, NIST carries out research, develops standards and measurements, provides standard data and reference materials, and provides measurement calibration services. NIST is involved in nanotechnology, microtechnology and mesoscale technology in research, technology, measurements, standards and data. An overview of NIST and examples of projects across these multiple scale domains are provided. The overview slides are accessible from the link below; the n2m project examples may be accessed at www.itl.nit.gov/div895/mems_nano

<LINK TO EVANS SLIDE PRESENTATION>

QUESTION #1: Are current equipment and practices able to meet the expected demands for part presentation, staging, and placement? Are these systems adaptable and if so, will they be affordable? Are revolutionary solutions required to meet the demands expected by In2m?

Moderator: John Evans, NIST

Scribe: Ed Amatucci, NIST

<u>Brian Carlisle, Adept Technologies, Inc.:</u>

ABSTRACT: Manufacturing processes that allow automated assemblies of small parts are rare in this country. As a result, no VCRs, camcorders, SLR cameras, or disk drives manufactured in the U.S. Recently, however, domestic advances in precision placement has been driven by miniaturization, rapid development of new product models, demand for quality, and the rising cost of labor. To answer these demands, Adept Technologies employs a philosophy called Design For Flexible Assembly (DFFA) which enables increased automation of precision assembly while minimizing cost. This process employs computational modeling and sensors to control and execute part feeding, grasping, mating, bonding, and verification. Initially, Adept Technologies concentrated on robotic placement of parts ranging from 1”-15” but they’re now considering precision placement of parts down to a micron. Some major challenges faced when one assembles parts of decreasing dimension are tolerance ‘stack-up’, joining of parts, and challenges associated with robot design and control. Some major robotic challenges are optimizing gripper design so that a single gripper can pick objects of widely varying sizes and shapes, optimizing gripper force so that the gripper can lift heavy objects but not crush fragile objects, and using sensor technology to determine part location and orientation.

<LINK TO CARLISLE SLIDE PRESENTATION>

Panel Presentations

Ralph Hollis, Carnegie Mellon University:

ABSTRACT: Current automated assembly systems have inadequate precision and agility for viable production of In2m products. For In2m assembly, there must (1) be precise means for aligning parts with workpieces, regardless of scale, and (2) means for handling very tiny parts. Typical flexible automation robots in use today have about 50 microns of precision, and handling of small parts subject to electrostatic charging and surface tension effects remains a problematic art form. An extremely important consideration is how to link together multiple and diverse individual micro-assembly operations into a designable, programmable, and deployable system. For the past 4 years, we have been developing, under an NSF Multidisciplinary Challenges grant, a hardware/software architecture that will enable manufacturers to rapidly develop automated assembly systems that are about 100 times more precise than today's state of the art, while occupying less floor space. I will discuss our present work in rapidly reconfigurable tabletop precision assembly systems (NSF Agile Assembly Architecture / Minifactory HPCC Multidisciplinary Challenges project).

<LINK TO HOLLIS SLIDE PRESENTATION>

Robert A. Weller, Vanderbilt University:
ABSTRACT: Complex microsystems of the future will of necessity comprise components and subsystems which are fabricated by diverse technologies. Assembly of these into functional units poses unique challenges not only in handling of parts but also in the delivery of the materials and energy to effect finishing operations. Many complementary techniques will be required. My remarks will center on direct-write approaches using finely-focused ion beams and pulsed-laser deposition of materials for joining, coating, bonding, interconnection of electronics, and direct-deposition of thin-film sensors, especially on high-aspect-ratio mechanical components.

<LINK TO WELLER SLIDE PRESENTATION>

Mark Beranek, Boeing:

Military/Aerospace Fiber-Optic Micro-to-Millimeter-Size (I2m) Systems

ABSTRACT: First generation fiber-optic components are being deployed in datacommunication networks onboard our nation's newest and most advanced military/aerospace platforms including the Boeing 777 commercial airplane, Air Force F-22 Raptor fighter, Air Force AWACS, Army RAH-66 Comanche helicopter, NASA International Space Station, NASA Space Shuttle, and NASA Earth Orbiter-1 satellite. At the heart of these networks are micro-to-millimeter-size (I2m) fiber-optic components that transmit, receive, distribute, connect, and switch light signals through optical fiber cable routed within the various platforms. First generation I2m fiber-optic components were qualifed via a rigorous packaging development path to meet difficult environmental requirements (hermeticity lifetime, alignment lifetime, pressure cycling, vibration, mechanical shock, thermal shock, acceleration, and humidity) imposed by the various military/aerospace systems. Significant investments were made and innovative packaging solutions were realized to meet these requirements. Despite achieving technological success, little commonality or standardization arose from the efforts and costs still remain high. Unfortunately, I2m precision fiber-optic component design and manufacturing has yet to be fully optimized or streamlined by the industry.

Further advancements in photonic device and fiber-optic network technology will continue to challenge the imagination of today's packaging and manufacturing engineer. Second generation military/aerospace fiber-optic components are still on the drawing board. Forecasted requirements indicate higher precision, higher density, and more compact packaging will be needed. For the next generation of components, the greatest assembly and packaging challenge will likely continue to reside at the optical interface. Light must be efficiently coupled between dissimilar components and materials with micrometer (and possibly sub-micrometer) assembly precision in a cost-effective, stable, and manufacturable way. Another sizeable packaging and manufacturing development cycle will likely be witnessed before next generation photonics technology is qualified for use in future military/aerospace networks. The interdisciplinary nature of photonics packaging and manufacturing problems will surely require expertise and investment in a variety of technological fields including materials, materials processing, mechanics, optics, optoelectronics, robotics, and vision.

<LINK TO BERANEK SLIDE PRESENTATION>

Panel Discussion

QUESTION 1: Are current equipment and practices able to meet the expected demands for part presentation, staging, placement, and fastening? Are these systems adaptable and if so, will they be affordable? Are revolutionary solutions required to meet the demands expected by In2m?

- Phil Keukes: Error correction codes are known
- Packaging: current costs are prohibitive but if we take IC fabrication as a model, with work and product volume, prices will drop (for example a Pentium takes 12 weeks and 500 production steps to make)
- Parallel operations decrease costs
- The parallel manufacturing used in Si fabrication plants should be emulated to spread benefits to other production areas.
- To currently build an IC at 2 micron resolution, plant costs would be about $50M. To build at 1micron resolution, plant costs are $2B.
- The real drawback of certain manufacturing techniques is their serial nature.
- MEMS technology is poised to exploit parallel manufacturing techniques.
- Interconnects are a huge source of cost.

Working Lunch Summary, Question 1:

We recommend initiation of a program in *micro-assembly* to focus on developing a solid foundation of theory and practice for sensing, part interaction, mating, fastening, packaging and testing, and overall system design tools including automated assembly system design tools, process modeling tools and design for micro-assembly tools. Mesoscale and microscale devices and products are rapidly approaching the point of commercialization; micro-manufacturing technology is a critical near-term need to address both military and commercial markets.

Nano-assembly will remain the subject of laboratory research for the foreseeable future; the needs for manufacturing technology will emerge from that research and should be revisited in 3 or 4 years as working devices are realized in the laboratory.

Discussion:

Question 1: Are current equipment and practices able to meet the expected demands for part presentation, staging, placement and fastening? Are these systems adaptable, and, if so, will they be affordable? Are revolutionary solutions required to meet the demands expected by In2m?

Answer: No, no, yes. The formal presentations, the panel discussion, and the luncheon working group all emphasized the shortcomings of current technology and the urgent need for new approaches to meet near term problems in industry as well as longer term problems.

The near term problems are in the micro range, from 0.1 microns to a few millimeters. Problems with managing small parts (examples: nano-block LEDs, hard disk sliders, parts for mesomachines) and problems with mating larger (mm or cm scale) parts with very tight (micron) tolerances were discussed (gyro parts, fuse parts, single mode optical fibers).

The micro domain presents unique problems that cannot be solved by simple scaling. At the top of this range (mm size parts) gravity and classical physics determine part behavior and part/tooling interaction; at the lower end (micron scale) chemical and electrostatic forces dominate. New strategies are needed through this transition region. There are no good theoretical foundations for guidance and no widely available infrastructure technologies to draw on, and laboratory solutions are in most cases not suitable for transition to the manufacturing floor. Manufacturing practice at the moment is highly labor intensive, working under stereo microscopes; addressing commercial markets requires cost-effective automation which in turn requires design tools and implementation technologies that are not now available.

Self-assembly and new process technologies of solid freeform fabrication, including focused ion beam, pulsed laser deposition and ink-jet printing techniques, are all promising, but serial assembly of parts (or self-assembled sub-assemblies) will always be required, and a basic technology infrastructure for micro-assembly is needed.

Sensing technologies for automated closed loop control and for inspection are considered the highest priority need in enabling micro-assembly. At the lower end of the domain under discussion this may include electron microscopy, UV stimulated electron beam imaging, and ion beam imaging. It is easy to imagine that fragile components, for example parts employing organic materials, could be damaged by simply “looking” at them, so appropriate passivation, encapsulation or other protection may be a design requirement. This emphasizes the need for a well understood technology base and systems perspective.

Specific Needs/Research Topics (as ranked by participants):

1. **Sensing.** 3D machine vision (note: DARPA has dropped the ball in this area), visual servoing, part pose identification, part acquisition. Depth of field and imaging of features at or near the wavelength of light are significant problems. Sensors for continuous closed loop control (rather than iterative sensing/acting). UV stimulated electron beam imaging, smaller portable SEMs. Force and touch sensing. Inspection integrated with fastening. Near and far IR sensing for micro-thermal feedback, e.g. for monitoring welds or solder joints. Sensors must be robust and easy to program for specific parts and ideally should be integrated with grippers and/or process tooling.

2. **Part Interaction.** At the micron scale electrostatic and chemical forces dominate interactions between parts and grippers and between parts and other parts. It may be easy to pick up a part and hard to let go of it. Need tactile feedback to monitor problems. Design tools for fixtures and grippers are needed.

3. **Material Delivery.** Controlled delivery and presentation of parts, and understanding interaction forces including surface tension and bonding forces.

4. **Fastening and Packaging.** New methods of joining parts including pulsed laser deposition, welding, soldering, adhesives, “snap-fit” based on surface chemistry and thin film chemistry.

5. **Intelligent End Effector.** Integrating gripping, sensing for location, sensing for mating, and sensing for quality control. This would become a micro-robot to be carried by a macro-robot.

6. **Process Modeling and Simulation.** Including scaling laws and understanding of new fastening materials, current fastening materials used on the micrometer scale, and current and new fastening methods.

7. **Theory of Design for Micro-Assembly.** DFA has been very important at the macro scale; similar tools based on different techniques and different laws are needed at the micro level.

8. **Materials Science.** Materials properties are needed for part design (design for micro-assembly), for tooling and gripper design, and for fastening technology. Surface science is very important in this domain and adhesives in particular need study. A detailed understanding of materials properties (mechanical, metallurgical/chemical) on the micrometer scale (thin/thick film regime) over temperature, stress/strain, and pressure (as opposed to the millimeter and larger scale) is also in particular need of study.

9. **Systems Engineering.** We are behind the Japanese and Europeans on systems engineering—we need tools to plan the transition of microassembly processes and equipment from the lab to the factory floor.

10. **Test Methods.** Testing procedures for thermal, shock, vibration, humidity, and electromagnetic susceptibility are needed, and must be validated against process models.

11. **Design Verification.** Tools are very good at the macro level but not at the micro level.

Benchmarking and Curriculum Development. NSF will handle curriculum development. Benchmarking and performance measures to evaluate relative performance of different strategies are needed, regular demonstrations of Best of Class techniques would help diffusion.

Session 2: Thursday Afternoon, 3/11/99

QUESTION #2: Are there particular processes currently being used in industry or research centers that might be suitable, through novel extensions/modifications of process, for achieving massively parallel status? What are the expectations regarding affordability, quality, and performance?
Moderator: Peter Wills, USC-ISI
Scribe: Dan Madey, Strategic Analysis, Inc.

John Stephen Smith, University of California, Berkeley:
Massively parallel assembly using SOFT (Self Oriented, Fluidic Transport)
ABSTRACT: **SOFT assembly allows the placement of millions of microscopic objects with +/- 1 micron accuracy in minutes. Objects are micromachined with a trapezoidal cross section, and held as a slurry. Matching recesses are micromachined in a target substrate, and the assembly takes place randomly, but with very high yield and accuracy. The assembly is planar, and conventional metalization and photolithographic patterning techniques are used to electrically interconnect the structures. This technique enables the tight integration of incompatible technologies, with nanochips as small as 30 microns on a side, and small interconnection pads giving extremely low parasitics for high frequency devices, orders of magnitude less than wire bonds or solder bumps. This talk will discuss the current state and capabilities of the technology, future directions, and applications which include active matrix displays, smart antennas, and optoelectronic integration. A videotape of an assembly taking place will also be shown.**

<LINK TO SMITH SLIDE PRESENTATION>

Questions and discussion following talk:

- Is the process ‘reworkable’ once a defect has been found? No, but defects are rare particularly when compared to wire interconnect technology. Another way to deal with this is to apply the technique to technologies which are defect tolerant.
- How does the SOFT process compare to ink jet? With regard to the nanochips being made by Alien now, gravity is a strong force and electrostatic charge wasn’t necessary for assembly. Their size is great enough that gravity dominates and the chips’ sharp geometry brings about self alignment. At smaller scales, charge may be required for assembly. Or even charge and geometry could be required, as it is in many biological interactions.
- Friction plays a large role in the SOFT process. The coefficients of friction of the substrate and the nanochips and the slope of the mating cavity help determine the probability of successful self-alignment. Given a certain cavity angle, there’s an optimal coefficient of friction. Also, the nature of the fluid in the slurry will alter the coefficient of friction. If a hydrophilic coating is used on the nanochips, the coefficient of friction can be decreased to near zero.
- A speaker is used to cause the vibration – ‘beaker on a speaker’

Donato Cardarelli, Milli Sensor Systems and Actuators Company:

ABSTRACT: The Flat-Pack Gyro was the first instrument to which MSSA applied the Millimachining approach to enable the manufacture of high performance instruments using batch processes to reduce cost, size and power consumption. Its development was funded by a Phase II SBIR award from the Phillips Laboratory/VTEE, KAFB over a two year period ending in January 1998. The conceptual development of Millimachining began with the start of MSSA in 1993.

This talk will describe the gyro, the Millimachining approach, component designs and fabrication technologies pursued. The Flat-Pack Gyro combines micro, milli and macro technologies to form constituent layers with integrated subcomponents.

A high performance pendulous accelerometer called the POGA has also been pursued under Navy funding over several years. The POGA is an example of the more mature state of fabrication technologies at the present. Its construction is enabled by silicon plasma etching through the wafer. Silicon is its primary material. The prospect of reducing the cost of this class of accelerometers (including strategic grade) by an order of magnitude is very realistic.

<LINK TO CARDARELLI SLIDE PRESENTATION>

Questions and discussion following talk:

- What was the final size of the gyro? 1” x 5/8”
- What’s sensitivity of the accelerometer? ~1 micro-G
- Target price was $100 per device.
- The rotors are not treated for touch down. Opposing surfaces are steel and nickel. Stator will wear before the rotor.
- Self-pumping rotor is nice feature. It facilitates air bearings and pressurizes with rotation of the shaft.

Panel Presentations

Murilo Coutinho, USC Information Sciences Institute:

ABSTRACT: In this talk we address the use of Intelligent Motion Surfaces (IMS) as a feasible micro-assembly process that scales with the VLSI technology, and is capable of achieving massively parallel planar assembly of micro and possibly nano structures. The talk starts providing a brief introduction to what is an IMS. We then move on to current state-of-the-art hardware/software implementations, focusing on quality and performance issues. We finalize the talk addressing technological barriers that need to be overcome, as well as new ideas and possible directions to be explored in future research work.

<LINK TO COUTINHO SLIDE PRESENTATION>

Questions and discussion following talk –

- How many of these assemblers have been built? Several chips have been built – rotator, conveyor belt, chips for study of energy transfer problem
- How does the assembler handle the problem of flipping parts over? No solution yet. However, energy dissipation can make friction work for you. For example, if a moving object experiences an abrupt change in coefficient of friction, it will flip – like the ice skater who suddenly skates onto asphalt.
- What sort of sensor feedback is being used? None right now. Therefore, very robust software/modelling is required.

John Fedemma, Sandia National Laboratories

Parallel assembly of high aspect ratio microstructures (by LIGA*)*

ABSTRACT: This presentation summarizes a three year effort to develop an automated microassembly workcell for the assembly of LIGA (Lithography Galvonoforming Abforming) parts. Over the last several years, Sandia has developed Processes for producing LIGA parts for use in weapons surety devices. Some of these parts have outside dimensions as small as 100 micron, and most all have submicron tolerances. Parts this small and precise are extremely difficult to assembly by hand. During the first two years of this project, we investigated the assembly of individual components using an extremely precise Cartesian assembly workcell. In particular, we concentrated on micro-grippers, visual servoing, and micro-assembly planning. We came to the conclusion that assembly of individual parts is too time consuming and expensive. Therefore, during the last year, we focussed our efforts on parallel assembly techniques. We tested the ability to assemble an array of LIGA components attached to two 3 inch diameter wafers. In this way, hundreds of parts can be assembled in parallel rather than assembling each part individually. In the experiments, the Cartesian robot is used to press 386 and 485 micron diameter pins into a LIGA substrate and then place a 3-inch diameter wafer with LIGA gears onto the pins. Upward and downward looking microscopes are used to locate holes in the LIGA substrate, pins to be pressed in the holes, and gears to be placed on the pins. This vision system can locate parts within 3 microns, while the Cartesian manipulator can place the parts within 0.4 microns. Combined with a diffusion bonding process, we believe that this parallel assembly technique is a very promising technology for building multi-layered high aspect ratio microstructures.

<LINK TO FEDEMMA SLIDE PRESENTATION>

Questions and discussion following talk:

- Have many of the fabricated structures been tested for functionality? Yes. For example, the gears have been used in the gearbox of a motor.
- What materials were you working with? The posts are stainless steel; gears are nickel.
- Do pins need to be located manually? No they need to be chamfered manually.
- 100 devices in the array, currently.
- What is the limitation on # of devices? Limited by size of wafer 3”.
- How long does it take to do the alignment of the pins and gears? This is automated and it takes a three minutes.

Cleopatra Cabuz – Honeywell, Inc.

Polymer Based, Highly Parallel Arrays of Electrostatic Actuators Produced Through Conventional Fabrication Methods

ABSTRACT: Low power actuators are highly desirable in today's computer controlled world. Electrostatic and piezoelectric actuation are the solution of choice for such actuators. The displacements and the forces provided by such actuators are, however, too low to be useful in real life. Multiplying the work through highly parallel arrays of actuators is an attractive solution. However, silicon based MEMS technology is unfit for the job. On the other side, the freedom provided by plastic manufacturing technologies is a perfect match to the fabrication of large 3D arrays of actuators. The paper will present a way of combining conventional manufacturing technologies such as injection molding, die cutting, mechanical assembly with advanced materials, thin film deposition techniques and innovative device concepts to produce low cost, high performance actuators. – C. Cabuz

<LINK TO CABUZ SLIDE PRESENTATION>

Question and discussion following talk:

- What about the Westinghouse MEMS pump that was being built? They didn't succeed. It never worked.
- Could you briefly describe the Honeywell chemical muscles which you mentioned? Similar to pump – actuated membranes that relax and contract.
- What pressure differential can the pump create? The main result of this type of pumping is throughput, not pressure.
- Is this a low power device? It's low power compared to other state of the art.
- Are there fatigue failure problems associated with the actuating polymer pieces? After 1 billion cycles, there were no failures. This was with the metallization. The metallization (aluminum) protected the membrane from battlefield gases. 100-micron depression by 10 mm causes subtle stress states.
- What's the voltage drop across membrane seating? 75 to 100 V. Membrane is Kaptan.

** No Panel Discussion this day due to late finish.*

Session 3: Friday Morning, 3/12/99

QUESTION #3: What are the major issues with the transfer of energy and data between boundaries of nano, micro and millimeter sized systems? How can these issues be addressed through attention to assembly technologies?

Moderator: Peter Wills, USC-ISI

Scribe: Dan Madey, Strategic Analysis, Inc.

Don VerLee, Abbott Laboratories

Microfluidic Systems

ABSTRACT: *waiting for abstract*

<LINK TO VERLEE SLIDE PRESENTATION>

Questions and discussion following talk:

- Where are these applied today? Very few places. There's no marketing motivation for these to be sold because of the large cost of new products. It's also a cultural issue: manufacturers are used to employing robotics to move fluids around. However, microfluidics is getting close to application in drug delivery systems.
- When machining and assembling microfluidic circuits, how are proper registry and tolerance ensured? Dial pin alignment is used
- Can one make bonds that are selectively active? It's really a surface chemistry issue, not a microfluidics issue. This is the topic of a lot of patents and research.
- What's a major main stream application motivating this work? Overcome cost and throughput issues on traditional analyzers.
- Modeling efforts? Off the shelf models work for macro level but microlevel models need to be developed.
- Will microfluidics ever be commercial? Of course, but it will take the competitive pressure. Abbott has a patent portfolio on the topic and is waiting for the right time.

James Ellenbogen, MITRE Corporation

Designs for Molecular Electronic Computer Circuits and for their Integration into Micron-Scale and Millimeter-Scale Mechanisms

ABSTRACT: **The speaker will describe briefly specific MITRE designs for molecular-scale electronic switches and circuits, parts of which presently are being synthesized and tested in the new DARPA Moletronics Program. Then, he will focus the main part of his talk on several strategies for connecting these processor, memory, and control circuits electrically to larger, micron-scale structures. These integrated nanometer-scale/micron-scale structures are designed and intended for two specific applications: (a) control of micro-sensors and (b) control of millimeter-scale robots.**

<*Ellenbogens slides are not cleared for publication*>

Questions and discussion after talk:

- What sort of switching speeds are expected? If we assume 100 electrons/bit, roughly 10^9 bits/sec. However, at this rate, the circuit would run at a temperature that is too high. One of these circuits needs to run at speeds below about 10^4 bits/sec to remain cool.
- What types of packaging are required? Don't really need any. Low vapor pressure. Probably just put a polymer film over it.
- What software is used for modeling? A combination of codes – GAMESS (used for molecular modeling), Spartan
- Who does the synthesis? Jim Tour
- What's the stability like? Very stable. More heat sensitive than silicon but
- DNA computing vs. this approach: they surveyed areas and put results in the bluebook. He thinks that the nanoelectronic route is the way to go because we have 50 years of microelectronics experience. Science and engineering builds on what exists. For purposes of integration, nanoelectronics will be more convenient than DNA. Whatever one builds needs to be incorporated into micro computing. Keukes: Quantum computing is also promising. In all nanoelectronic devices, electrons are still the mode of transport

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Panel Presentations

<u>William Tolles, Consultant:</u>

Issues with Data/Energy Transfer at the Nanoscale

ABSTRACT: Performance of a classical microelectronics chip is considered as the dimensions are reduced by several factors of two beyond one micron. This exercise points out the critical factors involving information and energy transfer as dimensions decrease. Progress in today's fabrication units balance the critical breakdown electric fields against other design parameters to extend miniaturization. As reduction continues, interconnect complexity, energy dissipation and Poisson statistics represent significant near-term problems. Issues involving single electron transistors and molecules proposed for information storage and logic are addressed. Methods of reducing power dissipation involving new materials are introduced. An example of new materials for a massively parallel bus line indicates one innovative solution to the interconnect problem. The performance of practical systems for storage and retrieval of information follow a relationship that might indicate limits due to thermal dissipation relative to the limit of nkT for the storage of information.

<LINK TO TOLLES SLIDE PRESENTATION>

Questions and discussion after talk:

- At a molecular level, Ohm's law is a statistical law. When we think of molecular electronics, we can probably design molecules to develop an advantageous ohmic state. Tolles responds that this will not happen due to the various excited states of a

molecule. Molecules will probably not be made any more or less conductive than they currently are.
- What about using ionic energy transfer, as done in biological systems? Tough one.

David Wallace, MicroFab Technologies, Inc.:
Ink jet printing used for interfaces between electronics and opto-electronics

ABSTRACT: Demand mode ink-jet printing technology is capable of producing and placing 15-125µm diameter droplets at rates up to 8,000 per second. Ink-jet based deposition as a manufacturing process would be low cost (no tooling required, expensive material is conserved), non-contact (allows deposition onto assemblies that are already populated with devices or other features), data-driven (no masks or screens are required because the printing information is created directly from CAD information), and environmentally friendly (it is an additive process with no chemical waste). MicroFab is currently developing ink-jet based processes and equipment for electronics manufacturing applications (solder, passive components, interconnects),[1,2] photonics (sensors, lenslet arrays, switches, displays),[3,4] medical diagnostics (DNA and antibody arrays),[5] and medical procedures.[6]

1. D.J. Hayes and D.B. Wallace, "Solder Jet Printing: Wafer Bumping and CSP Applications,"
Chip Scale Review, Vol. 2, No. 4, pp. 75-80, September 1998.
2. D.J. Hayes, D.B. Wallace and W.R. Cox, "MicroJet Printing of Solder and Polymers for
Multi-Chip Modules and Chip-Scale Packages," *Proceedings, IMAPS International Conference on High Density Packaging and MCMs*, Denver, April 1999.
3. W.R. Cox, T. Chen, C. Guan, D.J. Hayes, R.E. Hoenigman, B.T. Teipen and D.L. MacFarlane, “Micro-jet Printing of Refractive Microlenses,” *Proceedings, OSA Diffractive Optics and Micro-optics Topical Meeting*, invited paper #I-00002, Kailua-Kona, HW, June, 1998.
4. D.J. Hayes, W.R. Cox and M.E. Grove, “Low-Cost Display Assembly and Interconnect Using Ink-Jet Printing Technology,” *Proceedings, Display Works ‘99*, San Jose, Feb., 1999.
5. D.B Wallace, H.J. Trost, and U. Eichenlaub, "Multi-fluid Ink-Jet Array for Manufacturing of
Chip-Based Microarray Systems," *Proceedings, Second International Conference on Microreaction Technology*, March 1998.
6. D.B. Wallace "Ink-Jet Based Fluid Microdispensing in Biochemical Applications," *Laboratory Automation News*, Vol. 1, no. 5, pp 6-9, November 1996.

<LINK TO WALLACE SLIDE PRESENTATION>

Questions and discussion after talk:
- What’s natural scale for size of drops? How much can you control it? When you get small, wall effects are strong. It’s hard to clean it. Drops are typically 10-200 microns (smallest water was 9 micron, metal was 24 micron). By varying parameters of the system, real time modulation of the system can be achieved.
- What materials are dispensable? Liquid metal, liquid polymers, organic solvents; viscosity must be below certain value.
- Why not use electro-hydrodynamic control of the droplet size and position? Easier said than done.

- Is the 300^{o}C limit that you mentioned your top end? For now, it's a materials problem that needs to be solved.

Panel Discussion

Question #3: What are the major issues with the transfer of energy and data between boundaries of nano, micro and millimeter sized systems? How can these issues be addressed through attention to assembly technologies?

- Although computers may be able to be made so small, do we really need them so small? Is the demand there?
  - Yes! We do need them smaller! Instead of data transmission, we'll have information transmission. There's no limit. We'll push it as far as we can to get better information trans.
  - Cost will play a huge role. Go as small as people will pay for it.
  - History saw migration from main frame to pc. This may continue to the point that many things will contain very small computing devices.
- Yes, but are we even making proper use of the ones that exist??
- Biological systems are more efficient. Use less power, carry more weight. Computers in the future will have actuators and sensors. This shows the need for transference of energy and data across interface.
- How far away is a molecular circuit?
  - A logic gate is basically made already. An element of an electrical memory will be made in 2 years through a darpa moletronics program.
  - Tolles concurs that within a few years, this will be done – main problem will be interconnects.
  - Verlee points out that transistors follow moore's law but not sensors or actuators. This is because of demand.
- Mechanical motion of molecules fuels much of the human body.
- With the advent of nanoelectronics, for the first time, we'll make machines that are on the same size scale as biological beings. The pharmaceutical industry is currently researching the workings of some of the most elequent molecules out there. What's the best way for computer scientists and EE's to benefit from the knowledge of microbiologists?
  - Verlee – the educated will have to be re-educated
- What is the one most important issue with regard to data and energy transfer?
  - Wallace – embedded systems; seamless communication
  - Ellenbogen – 4 points made in his talk
  - Tolles – cultural divides; finding ways for biologists and genetisists to talk to EE's
  - Verlee – cultural divide; so much low hanging fruit is there for profit right now. This is very difficult stuff that isnt currently required to make a profit. Another problem is mass transfer.

Session 4: Friday Afternoon, 3/12/99

Can the functionality and design constraints of complex In2m systems be adequately characterized and utilized such that the most appropriate mix of technologies can be chosen for a particular application? What technical barriers have to be overcome to enable this? Are suitable simulation tools available? Are the fabrication processes and tolerances for In2m scale components of sufficient accuracy and repeatable to support assembly operations?

Moderator: John Evans

Scribe: Nicholas Dagalakis

Dr. Michael Pecht, University of Maryland:

Physics of Failure of Complex Systems

ABSTRACT: *waiting*

<LINK TO PECHT SLIDE PRESENTATION>

Questions and discussion after talk:

- Is temperature or temperature gradient the main cause of failure? Temperature, temperature gradient and the rate of change of temperature can create problems. In the case of surface mounted devices, moisture in the mold compound activated by the temperature rise of the reflow process could bulge, delaminate and sometimes crack the device.
- Have failure models be developed? Yes for some target applications, which are understood.
- Don't you have to see a failure in order to predict what is causing it? If you understand the materials and structures you can predict that.
- Sometime it is impossible to predict failure even if you study your design well. -- I would argue that you did not do your work diligently enough.

Panel Presentations

Dr. Robert Reeber, US Army Research Office

The Factory-After-Next Manufacturing at the Mesoscale

ABSTRACT: I have recently started two Army SBIR's aimed at improved desktop manufacturing. One utilizes focussed laser beams, the other a microscale computer controlled plasma torch. The objective is to reduce the size of a "manufactured byte" so as to control microstructure. At the same time we want to provide a computational means to calculate important properties of the mesoscale component that has a finite element model with materials science inputs relating to optimizing performance criteria. I think what is needed is effectively the following three legged stool: An integrated approach unifying multi-disciplinary materials science, solid state theory, mechanical engineering is required. Topics of interest include:

1) Property Predictions, Theory: Extend available theoretical tools and materials databases to predict properties of a wide range of advanced material systems. Theoretical approaches should include semi-empirical and first principle materials/mechanics modeling, i.e. iterative finite element homogenization theory, anisotropic materials, anharmonicity effects, property modeling and other algorithmic developments with predictive capabilities. Current capabilities need to be supplemented with additional physical property data, such as molar volume and thermal expansion to adequately treat interphase misfit and thermal stress in heterogeneous systems. General computational models are needed for simulatling microstructural evolution, solid-state precipitation, phase transformations and mechanical behavior. Simulation tools should include modern non-local continuum models for treating heterogeneous structures.
2) Microstructural Optimization: Develop new experimental capabilities that provide adequate resolution for optimizing the microstructure. These should have sufficient process step resolution to afford microstructural control during part fabrication. Ion beam, laser ablative, sol gel inkjets etc. have the capabilities to provide " pixel by pixel " or "process byte" resolution sufficient to optimize the microstructure. In addition, field effects (e.g., electric, magnetic and acoustic) that can influence microstructual evolution and residual stress should be investigated. Simple mechanical test specimens, and later functional meso/microscale ceramic and metal components should be predesigned with specific microstructural features (initially 0.1 to 1000micron sizes), processed and tested. Results obtained will provide directions for refining and improving the original algorithms/models/theories employed.
3) **Experimental Prediction Verification: Test mechanical and physical properties of prototypes and provide an interactive framework between modelers/theorists/ designers for seamless integration of materials and process data into reliable processing approaches that produce components with optimized microstructures and performance. A reasonable objective would be the preparation of specific microstructures and gradient materials systems that either validate or lead to improvements in existing theory. Design tools to be provided should have a pixel by pixel predictive capability over extended ranges of temperature, pressure and life-cycle conditions. – R. Reeber**

<LINK TO REEBER SLIDE PRESENTATION>

Questions and discussion after talk:

- What is the cost of inexpensive interferometers from Whiteside? A few cents. They are made of polymer.

<u>Phillip Kuekes, Hewlett-Packard Laboratories</u>

Molecular Manufacturing Beyond Moore's Law

ABSTRACT: Our approach particularly relates to the question: Are the fabrication processes and tolerances for In2m scale components of sufficient accuracy and repeatable

to support assembly operations? The end of expensive manufacturing tolerance is coming. It will be replaced by smart subsystems that are able to report their state and to respond to instructions for making corrections. We have already built a special purpose supercomputer, Teramac, with over 220,000 known manufacturing defects. We have been able to electronically find and correct these defects. The Teramac custom computer can be thought of as a giant FPGA with a half billion configuration bits. The large number of configuration bits and the two million wires available for routing make it very easy to place and route logic designs onto the physical network without depending on an unbroken symmetry in the physical network. . If you have enough wires and switches you can first build an imperfect machine and then design a perfect one.

As part of the DARPA Moletronics program, we will be extending these defect tolerance methods to the molecular level of assembly by building a 1,047,400 circuits in a space 100 by 100 nm. Literally molecular space. Once the nano-level has some inexpensive defect tolerance then all the levels above can benefit. Instead of " Design - Build", the manufacturing paradigm will become, "Build -Measure- Design- Repair." The ability of a reconfigurable architecture to create a functional system in the presence of defective components may well change the style of manufacturing in the coming century. The industrial revolution started with inexpensive labor assembling capital intensive interchangeable precision parts. Two centuries later we may switch to supercomputer labor assembling inexpensive chemically produced imperfect parts.

<LINK TO KEUKES SLIDE PRESENTATION>

Questions and discussion after talk:

- What about the massive amount of wires? You may use quantum dots to make the contacts.
- How many defective FPGAs were in the refrigerator? There are 864 FPGAs and within +/-1 3/4 of those chips were bad.
- How long before we see a working device? 2 to 3 years for a 100nm device.

William D'Amico, US Army Research Laboratory

Experiences in the Integration of Nano-Scale Devices to 155mm Projectiles

ABSTRACT: Automotive grade MEMS accelerometers have been demonstrated for use in gun-launched projectiles. COTS devices have been launched on spin-stabilized artillery projectiles by the US Army Research Laboratory's Weapons and Materials Research Directorate. The accelerometers were ground tested using shock tables and air guns in powered and unpowered states to shock levels of 75,000 g's. Typically, the devices maintained calibration and operational capabilities up to 30,000 g's when powered and 60,000 g's when unpowered. These COTS devices have also been flight-tested. In one test, the accelerometer was used to measure axial force (drag). The acceleration telemetry data were compared very favorably to a Doppler radar history. Other flights have used higher frequency response accelerometers as vibration sensors. Typically, a magnetic sensor is also used to correct for spin and centrifugal bias effects of the DC accelerometers.

<LINK TO D'AMICO SLIDE PRESENTATION>

Questions and discussion after talk:

- What are your work objectives? Understand where we can take these new technologies and use them with cheap ammunition.
- Where did you have difficulties with these tests? Integration of instruments with fuses.
- How many devices did you test? More than 1 and less than 100. ONR had a testing program on this subject called "Commercial Technology Assertion." You really have to worry about shock and cold temperatures.
- What parameters did you calibrate? We calibrated accelerometers for misalignment because they have cross axis sensitivity.

Panel Discussion

Question: Can the functionality and design constraints of complex In2m systems be adequately characterized and utilized such that the most appropriate mix of technologies can be chosen for a particular application? What technical barriers have to be overcome to enable this? Are suitable simulation tools available? Are the fabrication processes and tolerances for In2m scale components of sufficient accuracy and repeatable to support assembly operations?

Could you talk about the CAD on the fly concept?
P. Kuekes: Taking a set of measurements you can redo your CAD design subject to new constrains. The CAD on the fly could be done by a subcontractor, because it is a computation, which could be done anywhere in the world, through the net.

I like this idea of self healing when something goes wrong and you find it. I wonder whether health monitoring before and after [the healing] would be useful.
P. Kuekes: I suppose I agree. In all our publications we are careful to make a distinction between defect tolerance and fault tolerance. By defect tolerance we mean essentially [defects which are] part of the manufacturing process or infant mortality. I am convinced, this is a theoretical argument, that we should [be able to] get the vast majority of those [defects] and they won't reoccur later.
The argument is that the mechanism we use to construct these nano structure, which is essentially a harsh process, it effectively occurs at a higher temperature, with more energy involved. There should be higher probability for defects to occur at those temperatures and fewer at operating temperature after construction.
Cosmic rays and photons could cause errors to molecular nano structures. Quite separate from the defect tolerance algorithms there is an entire discipline, that a lot of people are working on, on fault tolerance error correction code type of architecture. That [architecture] is rarely put on what we are talking about. I believe it is easier to put it (the fault tolerance error correction code type of architecture) logically to our architecture, because of its cheap parallelism error correction capability.

Integration of Nano- to Millimeter Technologies (In2m) Workshop

Notes on Working Lunch: Friday afternoon, 3/12/99

QUESTION #4: Can the functionality and design constraints of complex In2m systems be adequately characterized and utilized such that the most appropriate mix of technologies can be chosen for a particular application? What technical barriers have to be overcome to enable this? Are suitable simulation tools available? Are the fabrication processes and tolerances for In2m scale components of sufficient accuracy and repeatable to support assembly operations?

ANSWERS: No. Improved simulation and design approaches. Suitable simulation tools are available for macro-design but they break down at a certain level. In general, no.

Approaches to improve simulation and design of In2m systems:

- Simulation packages must become more physically and chemically correct at very small scales. Computational codes must consider the dominant interactions occurring at the smaller scales - e.g. wall interactions, non-continuum flow, and surface chemistry in the case of microfluidics; the diminishing importance of gravity and the increasing importance of electrostatics and chemical interaction during dry assembly. Computational materials science inputs to design codes must concentrate on engineering properties such as strength, thermal expansion, fracture and degradation resistance and results should be robust and verifiable.
- Accurate tests methods are needed to verify and provide feedback to improve simulation codes.
- Defect engineering architectures for defect tolerance and utilization. Flexible designs which allow a certain degree of failure without affecting overall performance. In particular, expensive precise mechanical tolerances must be replaced with inexpensive distributed intelligence, possibly implemented in nanoscale electronics. This includes both sensors and actuators that are incorporated in the object being manufactured, and nanoscale sensors incorporated in the tooling used for manufacturing.
- New design paradigms must be considered, e.g. simulation – fabrication – test – redesign – fabrication – test – redesign – fabrication … The issue of redesign at the time of manufacture is a strategy to leverage the exponentially decreasing cost of computation in CAD systems. The new design paradigm is: Design (leaving open several locally optimal possibilities in design space) – Simulate (including design alternatives) --Fabricate (possibly imperfectly) – Test (find fabrication defects) – Redesign (around fabrication defects) – Repair (around defects) – Retest.
- Open architecture CAD/FEA capability that will allow the introduction of new data into the analysis software.
- Plug and play CAD modules.
- Internet availability of CAD modules.
- Open architecture plug-in capability.
- Common CAD/CAM interface to manufacturing equipment? (No clear yes response.)

Approaches to improve fabrication and assembly:

- Practice of flexible manufacturing where CAD and CAM are intertwined. This includes “just in time” CAD, that allows minor design changes to be made at fabrication time depending on defects found resulting from an imperfect self assembly process.
- Focus more resources on finding new methods of self-assembly. Self assembly with electrical and magnetic field controls is promising. Self assembly is very important. It is our greatest hope for highly parallel fabrication methods to dramatically reduce the cost of In2m systems.
- Focus resources on developing more versatile catalog of materials for use with established techniques, particularly polymers, templated materials systems
- Use of haptic feedback and scaling in virtual environments integrated with CAD/CAM to allow the user to better understand the process/assembly/interaction issues
- Improve microstructural controls by improving fabrication resolution limitations
- Develop more micro-production techniques, e.g. soft lithography which is a set of techniques that relies on a molded elastomeric element to transfer patterns, enable curved surfaces to be patterned, and provide new routes to complex structures with feature sizes as small as 30nm
- Devices made to mate with an object must be programmable and versatile in some way so that they can be utilized for a variety of applications.
- Optimized design and use of embedded systems

To Be Included

Memorandum

To: MMM Study Team
From: John M. Evans and Matthew Davies
CC: Jim Albus, TMR team
Date: 10/27/99
Re: DARPA Mesomachine Program Meeting

The kick-off meeting for the subject program was held October 20-21 in Annapolis. NIST was allowed one registration; Matt Davies attended Tuesday and John Evans attended Wednesday. The agenda is attached. Overall, the emphasis is on chemical devices for cooling and water purification and the quality of the projects was somewhat disappointing, particularly the meso-scale robots, but there are some excellent individual projects.
Vugraphs will be copied and sent to all registrants, so we should have a set in a week or two.
Note: Bill Warren, the project manager, is also still looking for the "WOW!" demo and would like to keep in touch with us. First MICE meeting is going to be early next year, we will be invited.
Day 1: Introductions and Systems for the Individual Warfighter
QUOTE OF DAY 1 FROM BILL WARREN'S TALK TRYING TO ENCOURAGE PEOPLE TO WORK TOGETHER.

"It is amazing what you can accomplish if you do not care who gets the credit"
Harry Truman

8:10 am Welcome and Opening Remarks
(1) **Larry Dubois (DARPA/DSO**)
Rough discussion of why we want to work in the area of mesomachines.

Definition of Mesoscale: Between conventional manufacturing and MEMs (sugar cube and a fist). Why?:

- Multiple Smaller Machines Operating in Parallel
- Greater reliability
- You gain from the physical scaling laws
  Increased stability
  Inertia/Gravity – similar
  Efficiency – low
  Strength/Weight – high

Surface Tension/Weight – high
Power/Weight – high
Inertia/viscosity - intermediate

Examples form History

- Warner (1845) Miniature steam Engine (1”x1”x2”)
- Miniature Duck (1700)

Micro-Assembly – Kevin Lyons

- Positioning in 3D
- High Strength, High-speed, High-acceleration
- Combined electromechanical devices

(2) **Bill Warren DARPA/DSO**

- “There is lots of room in the middle”
- Five Thrust Areas for the Military
  (1) Water Purification
  (2) Air Purification
  (3) Climate Control
  (4) Biological Weapon Protection
  (5) Micro Control

8:30 am: ***Dr. Jay Duesenbury***
WATER PURIFICATION SYSTEMS AND FUTURE REQUIREMENTS

Jay discussed the needs for purifying, supplying or even producing water for use in a military operation. These must be possible in all environments. The possibility of a majority of future wars being fought in URBAN ENVIRONMENTS is of great concern. Water is needed for drinking, laundry, bathing, cooking, hospitals. There is a need for rugged, mobile light weight purification systems, ranging from personal units capable of 5-15 liters per day to large units that produce 3000 gallons per day. Units should be able to purify water from ocean water to brackish water to fresh water. Small power supplies for these units is a critical concern.

Soldiers typically carry 4 quarts of water on their person.

There are a number of R&D initiatives currently ongoing
(1) 1500 gal per day Tactical water Purification System
(2) Packaged water system – ship water to the field and then package it
(3) Canteen contained water purification system

There are also a number of initiatives including:
(1) Water production system using exhaust from combustion engines
(2) Post-treatment of waste
(3) Individual purification system that is lightweight, capable of desalinization and purification. This will require a *technology breakthrough*.

** Desalinization is energy intensive 1-6 kWhrs/liter ????

9:15 am ***Major Tom Hartshome USMC***
MARINE REQUIREMENTS AND NEEDS

Tom was quite a character. He was a marine through and through. He gave a very entertaining talk describing the needs of the marines including concerns about an increased number of future amphibious operations and urban wars. In future amphibious operations, the mode of operation will be to leave supplies on the ships and send them in to the field JUST IN TIME (JIT supplies). Some other highlight were:

(1) Total weight of supplies carried by a marine currently is 65 lbs.
(2) The weakest points are water and communications.
(3) Communication equip. (7lb radio with 1 lb battery)
(4) Army is Looking at having heads-up display over the eye and computer in backpack – marines do not buy into this approach – TOO BIG
(5) Efforts being lead by the Office of Science and Innovation accessible at www.usmc.mil
(6) Portable power is a problem in terms of both battery weight and disposal.
(7) NEEDS ARE: Target Acquisition, Computers, Radios, PLRS and Weapons.

A basic message was Batteries, Batteries, Batteries.

- Integrated Combat System
  PHASE 1:
    - Climate Control for Mission Oriented Protective Gear
    - Power for Weapon Systems and Target Acquisition
    - Power for Personal Computers, radios, etc..

  PHASE 2:
    - Power for EXOSKELETON
        - Strength and Climate Control
        - Power for Weapon Systems
        - Power transmission by Inductive Coupling ??
        - Power for personal computers and radios
    - Robo SKELETON, Enhanced human capability
    - Body Armor
        - Climate Control
    - Mine Detection, fast and use robotic devices
    - Urban Reconnaissance
    - Water Purification and desalination
    - Remotely Piloted Vehicles, 500 meters to 2000 meters real time intelligence, possibly miniature spi planes.

9:35 am ***Dr. Eugene Wilusz, US Army Soldier Systems Center, R&D Natick MA***
MILITARY REQUIREMENTS/NEEDS

Problem: A soldier in Chemical/Bio gear in a hot environment will succumb to heat stress in 60-90 minutes depending on activity level. Therefore, we need microclimate control systems.

Several systems already exist. He discussed some in detail. Power sources and ruggedness are again the main problem.

The needs are: quiet generators and other power sources, water purification, and lightweight systems.

9:50 am ***Dr. Eric Syvrhd, Office of Special Technology***
SOCOM TECHNOLOGY PROGRAMS

Dr. Syvrhd discussed the special needs of the Special reconnaissance forces (SRF). These forces must operate 300-400 km behind enemy lines with up to 100 lb of personal equipment. They must leave with everything that they carry in. They must also be deployable by air, water or land, and must have advanced target finding and communications equipment. Equipment includes: radio, laser range finder, M90 binoculars, spotting scope and limited night vision ability. Also they utilize quick hide-sight or camouflage kits. Batteries are heavy and their life is unpredictable.

The objectives of the SRF is to (1) inform, (2) collect, (3) Demo., (4) participate and (5) document.

Critical technologies include:
- Hydrogen Fuel Cells
- Intrusion Sensor Systems that trigger a camera (for example) to take a picture of an intersection when a truck signature is detected.
- Hasty Hide Shelters
- Communication headgear for high noise environments
- Head mounted thermal vision systems
- Tactical PC's

11:15 am MESOSCALE POWER SYSTEMS
Bob Nowack
DARPA/DSO

Dr. Nowack gave a very informative overview of DARPA programs now being funded. He began by defining the problems that have motivated this work. He implied that the biggest problem facing the modern soldier is power. Again it seems that the battery size and weight problem is of prime importance.

- ❑ The Soldier Power Problem

  - Computer/Radio 45 W
  - Helmet sighting systems 5-6 W
  - Microclimate cooling >100 W

For small sensors *energy harvesting* from the environment seems to be a promising approach. However for larger devices this s not possible. The physical reality of currently available power storage systems is summarized in the following chart.

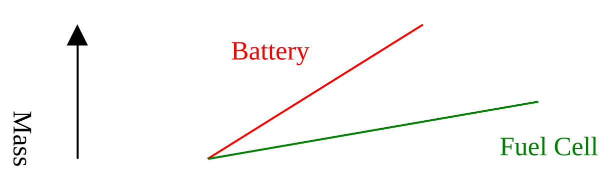
System	Theoretical Specific Energy (W-hr/kg)	Realizable Specific Energy (W-hr/kg)
Rechargeable Batteries	1200	200
Primary Li/SO_2		
.		
.		
Diesel	13200	1320
.		
.		
Nuclear	2,800,000	190,000

[Note: one row of numbers is missing. Best guess: 1200/200 apply to Li/SO2]

The Issues Are:

- Energy Conversion
- Energy Storage
- Energy Harvesting

For shorter missions the mass of batteries is lower than fuel cells. However, for longer missions, fuel cells are much better. He showed an interesting graph like the one sketched below.



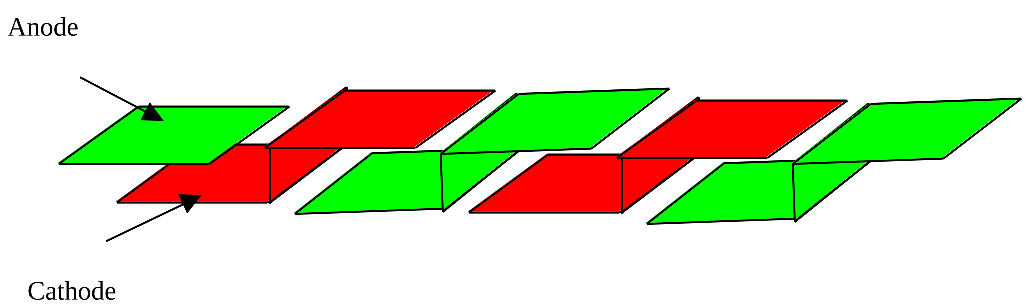
Current hydrogen power systems have a mass of about 10 lbs and produce 24kW-hrs of energy at 75 Watts maximum output. This makes them a very attractive energy source. [Editing note from JME: Battery pack for HelpMate mobile robot used deep discharge sealed gelled lead acid batteries, weighed 250 lbs, provided 2.7 KW-hrs of energy, probably produced 500 W max and 200W average power)]

- Hydrogen Power Sources

Storage	Production
Glass Microspheres (3M)	??
Fullerenes	??
Nanotubes	Ammonia
Cyclo-alkaline (??) Dehydrogenation	Direct Methanol
Metal Hydrides	Hydrocarbon Reforming
Pressurized Hydrogen	Bioreforming***

*** From what I could gather bioreforming means "plugging in" to a biological organism like a rat [This sound like a strange idea but was so far out I thought I should note it down.]

- H_2/PEM fuel cell stack – cool mesoscale device. I've attempted to sketch it below.



- Thermo Photo-Voltaic Power Systems (TPV systems)

These devices function from a low-level source of continuous power plus a battery for storage. The source is usually an infrared radiator with a thermo-electric device for power conversion. These devices are not efficient in that they give off a lot of waste heat, but for long duration missions, they can apparently be made small and light. Also the implication was that these devices work better on the mesoscale, but I didn't catch the details. Probably, it is a volume to surface area argument, although at first thought this argument would seem to favor larger devices ???

- Micro-turbine Systems

MIT micro-turbine – the goal is 2M rpm, 50 W, 175W-hr, 50 gram device the size of a shirt button.

Now in development by MDOT a 400,000 rpm micro-turbine with 1kW of power output in a 1.5" diameter package (see Day2 notes below).

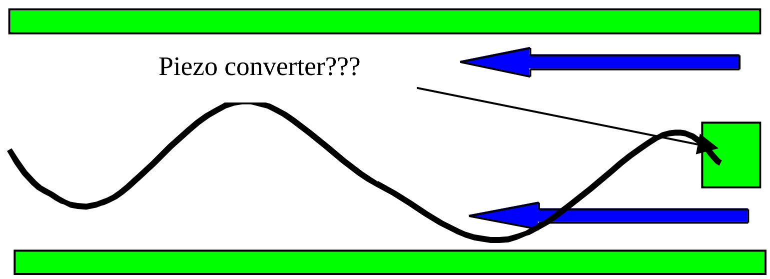
- Mechanical Storage Devices

  Kinetic Energy Watch

  Wind up radio – 30 sec wind time for _ hour of run time, being distributed to nations without power or batteries available with the goal of having them listen to VOA.
  See Web site www.freeplay.com.
-
- Solar Power
- Energy Harvesting

The Eel system harvests energy from water flow by coupling to the flutter (flow-induced vibration) of a mesoscale device as shown below.

1.5 m/s flow
produces 844 mW
of usable output



MIT – N. Heygood is developing solid-state hydrogen power harvesting system the size of a button.

Heel Strike Power generation/storage systems are also under development. These make sense for things like boot-worn GPS systems for soldiers.

- Thermoelectric systems – Stew Wolff at DARPA. TE Microdevices. Thermoelectric leg arrays??

- The BIG CHALLENGES
  - Thermodynamic limitations – how close can we get?
  - Scaling laws and using the physical phenomena. Don't assume that we should do things on the MESO-scale the same way we do things on the MACRO-scale. Understand the scaling laws and use them to your advantage.
  - Hybrid electromechanical systems
  - Power management, consumption, generation, storage.

Day 1: Coffee and Lunch (Informal Conversations)
I [Matt] talked to Dr. Jerry L. Martin, President of Mesoscopic Devices who has worked on high-speed microturbines in the past. He wanted to explore the possibilities of an SBIR to examine new designs of high-speed micromachines.

I [Matt] ate lunch with Professor John Georgiadis from the Mechanical Engineering Department at the University of Illinois, and Dr. Thomas Schwalbe from the Institute for Microtechnik at Mainz Germany. Professor G. was very impressive. He is working on a mesoscale desalinization device that uses freezing of water on a mesoscale to reject salt. He was fairly closed mouthed about the technique, since they are in the process of obtaining a patent. A far as I could gather from the conversation and his talk later in the day, they are using some type of dynamic excitation of a salt water flow to create small regions of desalinated water while simultaneously draining the brine with high salt concentration. They claim to have a device with the following specifications:

- Weight less than 2lbs
- Compatible with canteen mounting
- 0.5 liters per hour of 1000 ppm salt-water from 20000 ppm salt water.

Day 1: Cooling Systems and Water Purification Systems
1:30- 2:15 ***Dr. Mike Philpott, University of Illinois U-C***
INTEGRATED MESOSCOPIC COOLER CIRCUITS

Professor Philpott is leading a large, multidisciplinary group comprised of 15 professors with backgrounds in Mechanical, Electrical and Materials Engineering. The focus of the group is to devise a mesoscale cooling system with the following specifications.

- 100 mm x 100 mm x 2.5 mm
- Mechanical flexibility so that it can be used as a patch on clothing
- Temperature difference of 10 degrees C
- 1 W cooling capability per patch
- Reverse-Rankine Vapor Compression Cycle.

The applications of this device are:

- Environmental suit for soldiers
- Personal cooling tanks
- Hospital use
- Food Cooler for automobiles
- Micro-electronic system heat management
- Reduction or elimination of thermal signatures that can be detected on the battlefield

Another application that occurred to me is the production of suits for laboratory use in thermally sensitive experiments where we don't want the researchers to heat up the equipment when they enter the laboratory.

The major technical challenge of this work is the production of a substantial pressure gradient in a small compressor.

The design of the compressor they are using is below. It works with a donut shaped, micro-machined chamber with a capacitively activated metal-polymer-metal sandwiched diaphragm. The device is made with a small gap in the center to begin the collapse of the diaphragm, which then is zipped to one side or the other by a controlled activation of the electrodes.

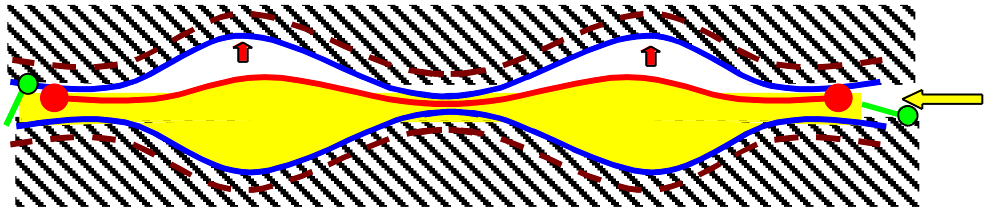


Fig: Drawing of a Meso-compressor

The meso-compressor is approximately 80 mm in diameter and the gap at the center s only 20 micrometers. This is necessary for fast actuation of the diaphragm.

They can apparently develop pressure differentials of several tens of kPa across this device. This would mean several Newtons on the diaphragm which I guess is feasible (e.g 50,000 N/sq m * 1e-02 m * 1e-02 m = 5 N). Dielectric breakdown limits the pressure currently.

The coolant runs through cooling channels that are 12.5 micrometers deep and 200 micrometers wide. **These are currently prototyped by micro-mechanical machining.**

They expect to manufacture the full cooler patches at $5-$15 per device. Pretty good!

2:15 pm ***Dr. Kevin Drost, Batelle, Pacific Northwest National Laboratory (PNNL)***

HEAT ACTUATED PUMP FOR COOLING

Dr. Drost discussed an absorption desorption pump that was 4 cm x 8 cm x 8 cm and could produce 400 W of cooling power. **They are making microchannels for the coolant flow in the heat exchangers that are 25 micrometers wide using laminated shim stock. The method is " dirt cheap". They also have a need to make many 5 micrometer holes and would like to talk to anyone who knows how.**

Other than these few items, I didn't get much else out of this talk. Although he was a dry speaker, Drost did seem to be quite good at his work.

3:15 pm, ***Dr. Charles Call, Mesosystems Technology Inc.***

AIR FILTRATION/WATER PURIFICATION WITH HIGH-TEMPERATURE MESO-SYSTEMS

Dr. Call discussed thermo-catalytic air and water purification. They also use meso-scale heat exchanger channels. This device uses combustible fuel, not batteries. They claim that 2 oz. Of fuel purifies 1 liter of water in five minutes. **They fabricate the device by NC –Machining but it didn't look particularly challenging from this perspective.**

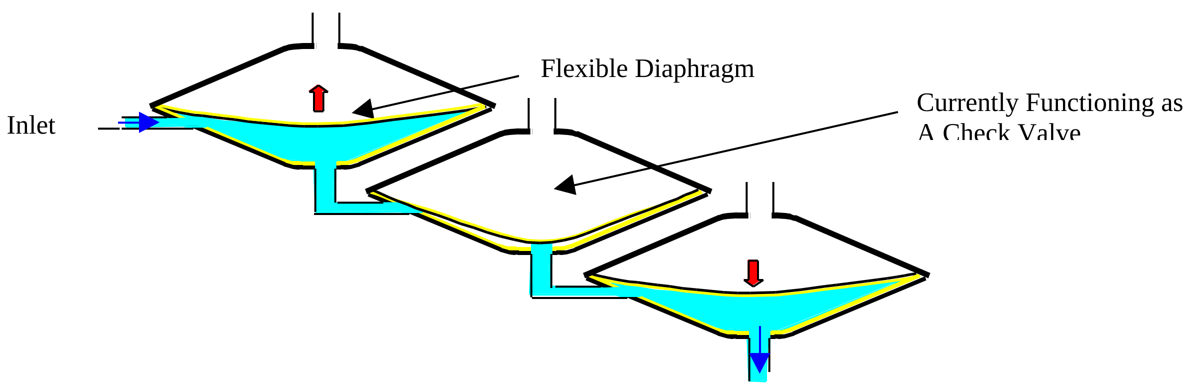
*4:00 pm, **Mike Robson, Miox Corp.***
MESOSCALE WATER PURIFICATION SYSTEM

In general this talk was more of the same. However, they do have a unique device they call a purification pen that produces a mixed oxidant solution that can be poured into water. **They also discussed briefly the idea of designer membranes – i.e. membranes designed at the** nano-level for specific purposes.

*4:15 pm **Dr. John Georgiadis, U. Illinois***
MESOSCALE THERMO-MECHANICAL WATER PURIFIER

Discussed above (lunch).

Day 2: Meso Pumps and Turbines and Manufacturing
Honeywell**. Diaphragm pressure pumps, without valves. More or less conical cavities 7 mm in diameter, inlet on the periphery and outlet at the base of the cone. Essentially a capacitor, 4-5 nF, driven at 40-50V. Uses the progressive motion of the diaphragm from the circumference to the center to close the inlet and then force gas out the outlet. Multiple staging avoids need for valve on the output, the architecture is three pumps in series, which gives two compression stages and a check valve for the output.**
Overall 3x3x30 array, which gives 90 parallel pumps, can do 5-10 l/min in 1 in^3 with 1 watt of power. Max pressure out 1 atm. [Note: 10 l/min is with no output pressure].
Manufacturing problems: surface roughness from EDM when making molds, need 10 nm surface finish to make good capacitors. Overall assembly is stack-up and screw together, no apparent sealing problems.



Sarcos**. Vacuum pumps, two stage, for medical and instrumentation applications. They note that you also need valves and manifolds to make complete instruments. Working on two different designs, a wobble/vane pump followed by a piston pump, and a molecular drag pump followed by a piston pump. Both designs are impressive. The vane design runs at resonance to minimize work in moving the vane.**
Resulting pressure 20-30 Pa. Expect to run for 8 hours on 0.3 kg Li ion battery. Target 1000 hours life. Micro-machining and hand assembly. Very nice work.

M-DOT**. This is a small company located in Pheonix. Connected with Flow, Inc., which is the company partner in CSTL NAMT project.**
Microturbine for UAV power or, coupled with a generator, for electrical generation. Single stage, cast turbine, laser welded sheet stainless steel for housing. 1.5" diameter, 1.2 Hp at 300,000 rpm. Fairly quiet operation since contained, most acoustic energy is ultrasonic. Exhaust after regenerator several hundred degrees. Will run 1 hour on 0.7 lbs of fuel. For low speed UAV need to have bypass or fan for maximum coupling efficiency to air.
Very nice work, very attractive power source for extended high power operations, e.g. for TMR.

USC**. Electrochemical Fabrication (EFAB). They represent this as ultra-precision solid free form manufacturing of functional meso machines, but the ultra precision is questionable.**
Idea is to use electroplating to do SFF, Ni for structure and Cu for sacrificial material. Make masks for each layer ahead of time, mask is reused instead of sacrificed. Key advantages: all points on a given layer are done in parallel (vs scanned serially for laser driven SFF techniques), and process is at 50 C and can build mechanical structures right onto silicon without damage.
Sequence: build a layer in a mask, remove from mask, overcoat with copper, planarize (lapping, get some smearing of metals, want to try diamond fly cutting or something like that), repeat.
Good resolution with stuctures to as small as 25 microns, layers 3-4 microns. Have done 4-5 layers so far, plan on hundreds. Expect 10-15 vertical microns per hour in production with 1-2 micron acuracy. Target: parts of 100 μ - 10 mm scale. Potentially very inexpensive technique in production, e.g. integrated coil and spring actuator for motion sensor or mirror steering estimated at $0.18 in 1 M qty. and $0.07 in 10 M qty.
Need better planarization techniques, need software for doing masks.
Note: head of this project is Peter Will, who got IBM into robots in late 70's/early 80's and then was at HP.
Day 2: Robotics
This was pretty awful stuff.
LANL **Biomorphic robots, nano-satellite robots. This is Tilden's work (see http://sst.lanl.gov/robot and biosat.lanl.gov). Tilden is engaging speaker, but this is very simplistic hobby stuff. Adaptive analog controls is his main claim to fame. Control theory is in term of Petri nets.**
Sandia **Hopping robots using hydrocarbon fuel combustion (read Bang!) for energy. One atmosphere ignition and adiabatic expansion. Record to date is 11 ft. altitude. Planning on 1 m hops, 200 gm robot, many km range with 10-20 gm of fuel. Working on handling misfires, ignition, and self-righting.**
Vanderbilt**. Piezo vibrating robots. This was slightly better, running quadruped skeletons at structural resonances with a single actuator. Will add forelegs. Cute but probably pretty useless, won't be able to cope with significant surface irregularities, can't change form factor very much. Most interesting idea: make right legs and left legs with slightly different resonant frequencies. Drive at the average and you get straight line motion (with some lack of efficiency). Change the frequency and you turn left or right as on side moves toward resonance and lengthens the strides and the other side movees away from resonance and reduces the strides. Obvious trade off between range and turning radius.**
Georgia Tech **Flying robots (with flapping wings). Again exploiting structural resonances. Will probably run two rigid wings in opposition (kind of looks like a dragonfly). Target: ability to fly into and through a building, land and move around on surface or transmit info. When flying all energy will be used for flying, max range 10's of meters. They point out that some things are not scalable, specifically communications wavelengths or gps wavelengths are not scalable, so you need certain antenna dimensions.**
None of these projects are going to produce much other than tv clips and National Enquirer stories. Sandia approach is the most interesting, one could use that power source for a Spring Flamingo drive and have a pretty interesting design for running machine (eg decoy).
Comment from Jim Albus: DARPA is repeating the Marvin Minsky fallacy, or the Fallacy of the First Step: an engaging spokesperson promises all sorts of wild things for the future based on some (ultimately dead end) approach, then works on some trivial first step, and says that you just need to let things evolve, all we need is more money. Eventually someone will realize the emperor has no clothes and the funding gets cut, but the well will be poisoned for others who might be working on the same problems with better approaches.