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

Note: Response Requested

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

Brian Carlisle, Adept Technologies, Inc.:

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

<u>Ralph Hollis, Carnegie Mellon University:</u>
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>

<u>Robert A. Weller, Vanderbilt University:</u>
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>

<u>Mark Beranek, Boeing:</u>
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.

<u>John Stephen Smith, University of California, Berkeley:</u>
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'

<u>Donato Cardarelli, Milli Sensor Systems and Actuators Company:</u>
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

<u>Murilo Coutinho, USC Information Sciences Institute:</u>

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

William Tolles, Consultant:

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

Link to DARPA P.O.C Information

Link to Workshop Attendee P.O.C Information

Link to Speakers' Biographies