An Overview of Nano-Micro-Meso Scale Manufacturing at the National Institute of Standards and Technology (NIST)

Edward Amatucci, Nicholas Dagalakis, Bradley Damazo, Matthew Davies, John Evans, John Song, Clayton Teague, Theodore Vorburger

Abstract

The future of Nano, Micro and 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. To prioritized NIST efforts in Nano, Micro and Meso manufacturing, several visits to industrial and government research laboratories and two workshops were organized. The identified needs at the Meso and Micro Scale include: Dimensional and Mechanical Metrology, Assembly and Packaging Technology and Standards, and Providing a Science Base for Materials and Processes emphasizing materials testing methods and properties data. Nanocharacterization, Nanomanipulation, Nanodevices and Magnetics Industry Support have been identified at the Nano Scale. Nanometrology and Nanomanipulation have a substantial base from which to expand within the Manufacturing Engineering Laboratory (MEL). Therefore, MEL is initiating a new long-term Strategic Program in Nano-Manufacturing to conduct research and development, to provide the measurements and standards needed by industry to measure, manipulate and manufacture nanoscale discrete part products. The program will address the measurement and standards issues associated with the manufacture of both nano scale products themselves, as well as with the development of the production systems required for their manufacture.

Keywords: nanomanipulation, nanocharacterization, nanodevices, nano-manufacturing, discrete part manufacturing, measurement standards, dimensional metrology, assembly and packaging, meso manufacturing.

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Introduction

Nano-Micro-Meso (NMM) Scale Manufacturing measurement capabilities, standards development, and performance measures are emerging as critical needs for various manufacturers. Leveraging a history of dimensional metrology, nanotechnology, sensor calibration and development, controls and automation, and systems integration for manufacturing enterprises, the Manufacturing Engineering Laboratory (MEL) of the National Institute of Standards and Technology (NIST) is poised to meet these new challenges while working with our partners in government, academia and industry. This overview will review the MEL exploratory project and share with you our findings of the industrial needs and motivations in Micro and Meso Manufacturing. Furthermore, strategic programs being organized to meet new challenges in nano scale manufacturing will be discussed.

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 ratios in building highly parallel systems from simple unit processes. The Defense Advanced Research Projects Agency (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 which includes semi-conductor manufacturing, wafer and chip manufacturing processes, etc. is a larger field than meso-manufacturing because of exploitation of microelectronics fabrication technologies and the large markets for data storage devices. There is activity at all scales and there is a pressing need for NIST and particularly MEL services at all scales. ***Making devices at increasingly smaller scales is one of the most exciting and challenging 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, and precise will include production technologies with in-process control and sensor capabilities to produce parts quicker and more accurate; and will make use of advanced part design, assembly and process data.

Nano-manufacturing is a growing area for MEL and we have initiated a strategic program that will provide the measurements and standards needed by industry to measure, manipulate and manufacture nano scale part products.

Manufacturing Engineering Laboratory Exploratory Project

The needs of U.S. manufacturing industries in the area of meso-,micro-, and nano-manufacturing were identified by [Reference 1] :

- Visiting some 20 companies and laboratories and asking about the technology needs and about the specific measurements, standards, and data needs;
- Running two workshops, one co-sponsored 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 (Microelectromechanical Systems) MEMS and Nanotechnology;
- Organizing a NIST-wide coordinating group to inventory base efforts and needs; and
- Carrying out a literature search and review.

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 categories:

- Nanocharacterization
- Nanomanipulation
- Nanodevices
- Magnetics Industry Support

A key issue at the nanoscale for MEL, not highlighted through the study yet where MEL has a substantial base effort, is nanometrology. This in part fits into nanocharacterization and in part fits into nanomanipulation. MEL sees this as eventually addressing a continuum of scales from macro to nano, and MEL has to be involved at all scales to meet industry needs.

Technical Opportunities for NIST Program

The needs identified above and prioritized by industry at MEL 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. Specific needs related to these areas to be addressed by MEL are discussed below:

In metrology:

Maintaining U.S. leadership in global markets requires conformity with existing standards (e.g. International Standards Organization (ISO)) as well as addressing faster transfer of technology from laboratories to production, and higher quality products. The manufacturing industries we are addressing here produce approximately $20 Billion output per year (which in turn leverages much larger portions of the Gross National Product (GNP) by providing key components for much more expensive macro-scale discrete part products). Current growth is 20 % - 25 % per year, several times faster than overall discrete part manufacturing ($1.1 trillion growing about 7 % per year). So MEL is addressing a real and important need with high leverage for impact over the next decade.

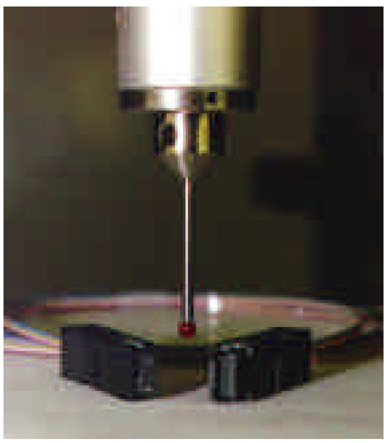

Figure 1. Demonstrates large size of probes used on CMMs compared to small meso-scale components needed to be checked.

New and innovative approaches to metrology need to be address as represented by Figure 1. The size of the critical features on the fiber optic connector needed to be checked are much smaller then the size of conventional probes on the Coordinate Measuring Machine (CMM). These parts have small diameter holes and the tolerances between the holes are critical for optical alignment of components. How manufacturers measure these internal features and the distance between these features accurately and reliably is a major concern. New tools and methods need to be developed and expanded from the current capabilities at the macro and in the micro and nano scales. These meso components fall within a gap in the most current expertise.

It should be noted that Japan and Germany are investing very heavily in these areas. One indicator, cited by Al Pisano, formerly of DARPA and currently at Berkeley, 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 the United States, 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 U.S. Patents. The United States must invest to stay in a leadership position; NIST will play a small, but key role in measurement and standards.

In assembly and packaging:
At the meso and micro level, successful automation in photonics alone would save approximately $7 B[1] to $12 B[2] in the next 10 years in the U.S. economy. [Reference 1.]

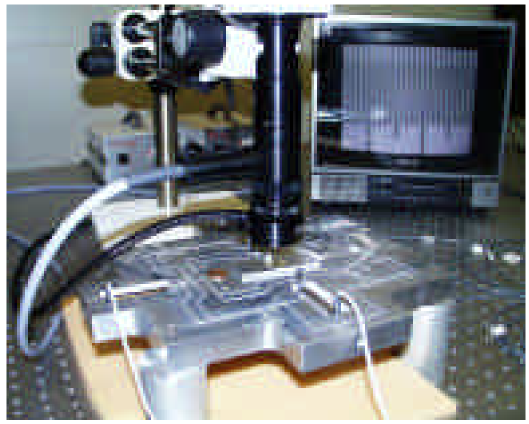

Figure 2. Calibration and Control of Micro Positioners – Microstage used for testing to demonstrate concepts to Precision Optoelectronics Assembly Consortium. Fall 1999.

Furthermore, assembly and packaging are ***the*** essential problems for MEMS devices, one subset of meso manufacturing. According to one expert:

> System Planning Corporation[3] 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

NIST is actively moving to try to address these issues; NIST's microstage work (Figure 2.) for POAC, for example, has been enthusiastically received by the photonics industry. We have the capability to make a significant contribution to positioning and automation of meso scale components. Our interaction with industry during the Advanced Technology Program's (ATP) POAC effort and during the exploratory study has indicated that NIST should have a positive impact in the photonics industry. NIST expects this impact to exhibit itself through information exchange, demonstrations, performance measures for

[1] Estimate by Gordon Day, Chief of NIST Office of Optoelectronics Programs, Boulder.
[2] 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).
[3] Any mention of specific companies or their products does not imply endorsement by the National Institute of Standards and Technologies.

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. Researchers have even advanced the state of the art in microstage capabilities in pursuit of measurement and standard capabilities, as illustrated in Figure 3.

NIST Prototypes
for 6 degrees of freedom
micro positioners.

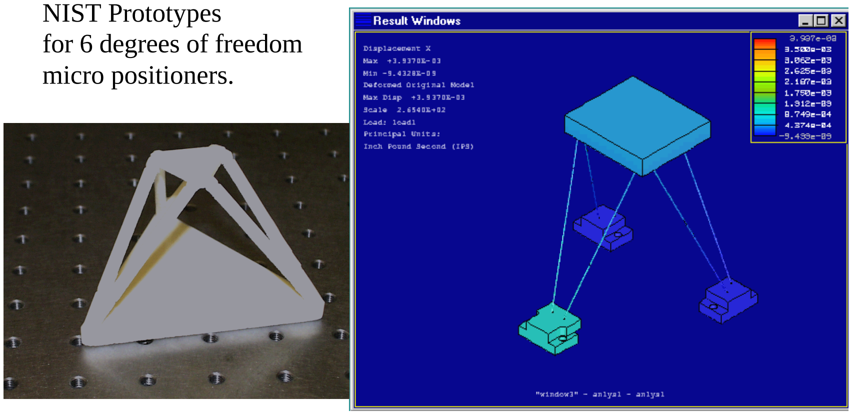

Figure 3. NIST prototype micro positioners.

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 is MEMS which is the use of semiconductor fabrication techniques to make sensors and actuators rather than integrated circuits. Several observers have noted that this field has been a major commercial disappointment so far, with only the air bag sensors and deformable mirror devices commercial successes after twenty years of work. This is true, but others point 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. Another reason for the delay is that MEMS requires better process control than microelectronics. For example, a 5 % change in film thickness is within specification for conductivity of an interconnect, but a 15 % change in resonance frequency would result if that film were used in a resonant beam (stiffness changes as the cube of thickness). This 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 revolutions per minute. Discussions with leading organizations in the field indicate significant problems with process metrology, process control, and process control software in trying to build MEMS devices. All agree that NIST should be a major contributor in leading the attack on these problems.

Another important measurement need is for developing much better force measurement capabilities to support calibration and manufacturing of meso and micro scale components used in current products. For example, Figure 4 shows an early prototype of a force transducer to help investigate force measurement and calibration of suspensions used in electronic disk drives.

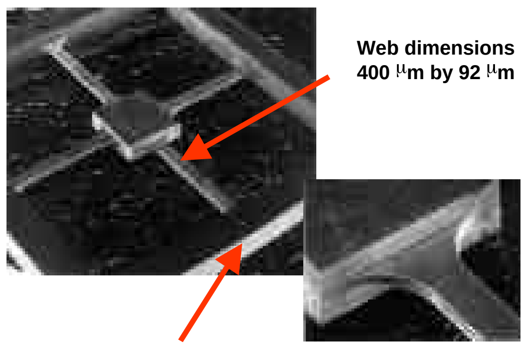

Figure 4. Example of research force measurement capabilities.

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. DARPA has funded work on this concept and has Berkeley, Cornell, Sarnoff, and Stanford under contract, with four industrial applications in negotiation. These organizations and universities 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. DARPA sought NIST's 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.

Nano Manufacturing Strategic Program

MEL is initiating a new strategic program in Nano-manufacturing to provide the measurements and standards needed by industry to measure, manipulate and manufacture nano-discrete part products. The program will address issues associated with the manufacture of both nano-discrete-part products themselves, as well as with the development of the production systems required for their manufacture.

Some key concepts that will be addressed in this program are defined below:

- ***Nano-discrete part products*** is defined as a product having critical part features with dimensions of <= 100 nm for either a single discrete part or an assembly of discrete parts. Product classes are being drafted that further clarify what is meant by a discrete part. These classes include a single discrete part, assemblies and complex assemblies.
- ***Measure*** refers to “the mechanical properties of product features with accuracy at the sub-atomic scale (e.g., dimensional accuracy better than 0.1 nm)”.
- ***Manipulate*** is defined as “tools that can grasp, position, and assemble to sub-nanometer accuracy”.
- ***Manufacture*** is defined as “the fundamental production and assembly processes of material removal, addition, reshaping, and transformation for producing large lot sizes of nano-molecular discrete parts at and below the nanometer level.”

A key point in understanding nano-manufacturing is to realize that at some point nano scale devices have to interface to the macro world. This is a significant technological barrier to adopting nanotechnology to commercial uses.

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 real time process control production technologies and make use of advanced part design, assembly and process data. The field of Intelligent Integrated Microsystems has a tremendous growth potential expected to reach $30 billion in the first part of this century, with applications in industrial areas like machinery and plant manufacturing, production control, power systems, and home and building control. [Reference 1] 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 research considerations have been defined. These are:

♦ Dimensional Metrology: A suite of measurement technologies at meso and micro dimensions to handle metrology requirements as shown in Figure 1.

♦ Force and Torque Measurement and Calibration Services at micro and nano Newton levels.

♦ Assembly and Packaging: information exchange, microrobotics and microsensing technology, perfomance measures, interim and de facto standards to accelerate commercialization

♦ Process Technologies and Materials Properties

Research and development is moving rapidly in this field. For example, in basic metrology, the need is chronic. A leading manufacturer 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. Current NIST calibration services stop at 44 N. [Reference 1.]

Another requirement of a major electronic manufacturer is the need to inspect location and form of 125 μm holes in fiber optic connectors that have 1 μm tolerances. Future needs will push the tolerance requirement by 10 fold. This is one of many examples of the need for a micro-CMM that is not one instrument but rather a suite of measurement technologies applied to 3D mechanical parts and devices and systems that fall in the range between classic Coordinate Measuring Machine (CMM) metrology and Scanning Electron Microscopes (SEM), Scanning Tunneling Microscopes (STM), and Atomic Force Microscopes (AFM).

The following summary from our workshop, co-sponsored with NSF and well represented by industry, academia and government, helps to capture the importance and necessity of pushing technology development, measurements and standards at all scales:

" In the not-too-distant future, it is expected that fabrication on an even smaller scale—the nanoscale—will yield functional components, devices, and systems that employ atoms and molecules as their building blocks. The ultimate objective, of course, is to link the enabling technologies across all scales—nano, micro, meso, and macro—accounting for such factors as materials and device characterization methods, fabrication technologies and processes, measurement and test methods, and modeling and simulation tools.
Experts in the broad field of manufacturing research and development agree on the urgent need to address the challenges posed by any factors that might inhibit progress toward further ultraminiaturization. The implications are significant not only for society at large, but also for the commercial sector. Given that significant growth is expected especially in the near-future demand for and availability of micro- and mesoscale applications in medicine, communications, defense, aerospace, and consumer products, it follows that the makers of products in those ranges must develop cost-effective manufacturing techniques. Thus, there is a pressing need to focus research attention on enabling process technologies,

packaging and assembly technologies, standards, measurement methods and instruments, and data and tools for engineering." [Reference 3]

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  - Dr. Ming C. Leu, Program Director of NSF's Manufacturing Processes and Equipment program
  - Dr. John Evans, Chief of the Intelligent Systems Division, MEL, NIST
  - Dr. E. Clayton Teague, Chief of the Automated Production Technology Division, MEL, NIST

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