MICROMANUFACTURING

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International Research and Development

by

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WTEC Panel on Micromanufacturing

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Abstract

This international technology assessment study has focused on the emerging global trend toward the miniaturization of manufacturing processes, equipment and systems for microscale components and products, i.e., *small equipment for small parts*. It encompasses the creation of miniaturized units or hybrid processes integrated with metrology, material handling, and assembly to create microfactories capable of producing microprecision products in a fully automated manner at low cost. The study has investigated both the state-of-the-art as well as emerging technologies from the scientific, technological, and commercialization perspectives across key industrial sectors in the United States, Asia, and Europe including medical, electronics, aerospace, and consumer products. This study does *not* include the lithographic-based processes common to the microelectromechanical systems (MEMS) community. The United States receives satisfactory marks for nanotechnology R&D, but its micromanufacturing R&D is lagging behind the rest of the world, particularly in technology transfer and ongoing development. This will undoubtedly have serious long-term implications since it is well-recognized that micromanufacturing will be a critical enabling technology in bridging the gap between nanoscience and technology developments and their realization in useful products and processes. While examples do exist where U.S. government programs are focused on industry-university-government collaboration, the scale of efforts both in Asia and Europe is significantly larger. On this latter point, Europe appears to be very strong, particularly as these partnerships work to refine and fine-tune developments for industry adaptation and commercialization.

WTEC MISSION

WTEC provides comparative assessments of international research and development in selected technologies under awards from the National Science Foundation, the Office of Naval Research, and other agencies. Formerly part of Loyola College, WTEC is now a separate nonprofit research institute. Michael Reischman, Deputy Assistant Director for Engineering, is NSF Program Director for WTEC. Sponsors interested in international technology assessments and related studies can provide support for the program through NSF, or directly through separate grants to WTEC.

WTEC's mission is to inform U.S. scientists, engineers, and policymakers of global trends in science and technology. WTEC assessments cover basic research, advanced development, and applications. Panels of typically six technical experts conduct WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in their labs.

The WTEC staff helps select topics, recruits expert panelists, arranges study visits to foreign laboratories, organizes workshop presentations, and finally, edits and disseminates the final reports.

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TABLE OF CONTENTS

1. Introduction
Richard E. DeVor and Kornel F. Ehmann

2. Design
Martin L. Culpepper and Thomas R. Kurfess

3. Materials
David Bourell and Kamlakar Rajurkar

D. Site Reports—Europe

FOREWORD

> We have come to know that our ability to survive and grow as a nation to a very large degree depends upon our scientific progress. Moreover, it is not enough simply to keep abreast of the rest of the world in scientific matters. We must maintain our leadership.[1]

President Harry Truman spoke those words in 1950, in the aftermath of World War II and in the midst of the Cold War. Indeed, the scientific and engineering leadership of the United States and its allies in the twentieth century played key roles in the successful outcomes of both World War II and the Cold War, sparing the world the twin horrors of fascism and totalitarian communism, and fueling the economic prosperity that followed. Today, as the United States and its allies once again find themselves at war, President Truman's words ring as true as they did a half-century ago. The goal set out in the Truman Administration of maintaining leadership in science has remained the policy of the U.S. government to this day. Dr. John Marburger, the Director of the Office of Science and Technology (OSTP) in the Executive Office of the President, made remarks to that effect during his confirmation hearings in October 2001.[2]

The United States needs metrics for measuring its success in meeting this goal of maintaining leadership in science and technology. That is one of the reasons that the National Science Foundation (NSF) and many other agencies of the U.S. government have supported the World Technology Evaluation Center (WTEC) and its predecessor programs for the past 20 years. While other programs have attempted to measure the international competitiveness of U.S. research by comparing funding amounts, publication statistics, or patent activity, WTEC has been the most significant public domain effort in the U.S. government to use peer review to evaluate the status of U.S. efforts in comparison to those abroad. Since 1983, WTEC has conducted over 60 such assessments in a wide variety of fields, from advanced computing, to nanoscience and technology, to biotechnology.

The results have been extremely useful to NSF and other agencies in evaluating ongoing research programs and in setting objectives for the future. WTEC studies also have been important in establishing new lines of

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[1] Remarks by the President on May 10, 1950, on the occasion of the signing of the law that created the National Science Foundation. *Public Papers of the Presidents* 120: p. 338.

[2] http://www.ostp.gov/html/01_1012.html.

communication and identifying opportunities for cooperation between U.S. researchers and their colleagues abroad, thus helping to accelerate the progress of science and technology within the international community. WTEC is an excellent example of cooperation among the many agencies of the U.S. government that are involved in funding research and development; almost every WTEC study has been supported by a coalition of agencies with interests related to the particular subject at hand.

As President Truman said over 50 years ago, our very survival depends upon continued leadership in science and technology. WTEC plays a key role in determining whether the United States is meeting that challenge, and in promoting that leadership.

Michael Reischman
Deputy Assistant Director for Engineering
National Science Foundation

PREFACE

Over the history of technological invention, we have seen many successful applications of the notion *larger is better*. The Boeing jumbo-jet 747, the SUV, large-screen TV and Nimitz-class super-carriers are good examples of this concept. But, with recent advances in basic sciences, the concept that *smaller is better* has been receiving increasing attention from researchers and practitioners. The entire balloon of nanotechnology is the direct outcome of this notion. However, it is interesting to note what is in the middle of these size ranges—the larger range on the order of 10 to 10^3, and the smaller range on the order of 10^{-8} to 10^{-9} meters. We refer to the size range of centimeters to micrometers as the meso/micro scale. This is about the size of the tiny robots in Steven Spielburg's science fiction film, *Minority Report*, in which tiny devices individually and collectively, in a distributed manner, monitored an entire human society.

Inspired by how ants work, the concept of *small equipment for small parts or even large parts* grew out of Japan in mid-1990s in which four discrete manufacturing processes were fit into a portable, less than 0.12 m^3 space, 34 kg suitcase. Imagine the efficiency and the effectiveness of a similar machine located in a hospital operating room where doctors could create a customized implant just right for your needs during the operation. Imagine such modular, but highly reconfigurable, equipment located in your neighborhood where a customized design could be realized from art-to-part with required precision and functionality. Imagine how such equipment could empower individual creativity, the underlying reason why the United States has dominated and grown in this very competitive global market. Perhaps it is as hard to imagine this much like it was hard to imagine the future of computers back in the 1970s.

Recognizing the enabling nature of small, highly flexible and reconfigurable equipment for the United States in the competitive global economy, the National Science Foundation (NSF) in partnership with the Office of Naval Research (ONR), Department of Energy (DOE), and the National Institute of Standards and Technology (NIST), commissioned a worldwide study on the status of micromanufacturing with particular emphasis on the United States, Europe and Asia to be conducted by the World Technology Evaluation Center (WTEC). In the context of this study, micro and meso-scale manufacturing refers to manufacturing processes and systems capable of fabricating parts with three-dimensional micro-scale features and high relative accuracy (10^{-3} to 10^{-5} meters) from a wide range of engineering materials, including stainless steel, titanium, brass, aluminum, platinum, iridium, plastics, ceramics and composites. This size range is a critical link between the nano and macro worlds.

During this project, I had the privilege to work with many dedicated program directors/managers at various government agencies who care deeply about how the U.S. is moving in terms of technological advances and how to best support our advancement in manufacturing and develop our young talent. Many thanks go to the following individuals for their continued support and participation in this WTEC study: Drs. Khershed Cooper and Ralph Wachter of ONR, Dr. Phyllis Yoshida of DOE, Dr. Amit Bagchi of NIST/ATP, Dr. Michael Reischman of NSF Directorate for Engineering, Drs. George Hazelrigg, Delcie Durham, Warren DeVries and Kevin Lyons of NSF/DMI (Division of Manufacturing and Innovations), Drs. Yip-Wah Chung, Masayoshi Tomizuka and Mario Rotea of NSF/CMS (Civil Mechanical Systems), Dr. Alfonso Ortega of NSF/CTS (Chemical and Transport Systems), Dr. Lynn Preston of NSF/EEC (Engineering Education & Centers), Dr. Bruce Hamilton of NSF/BES (Bioengineering & Environmental Systems) and Dr. Sreeramamurthy (Rama) Ankem of NSF/DMR (Division of Materials Research).

Any success attributed to this study and this book could not have been achieved without the intellectual contributions and the great devotion of panel members during this year-long study. As a government participant representing the National Science Foundation, I accompanied the group on site visits and participated with them in report writing and planning of events and can attest to the panel's dedication. At this moment, it is particularly important for me to thank Prof. Ehmann for his extraordinary leadership, Prof. DeVor for his unmatchable wisdom, Prof. Bourell for bridging materials to processes, Prof. Culpepper for his now famous quote on design at the micro/meso scale, "That which was not seen tells the story better than that which was observed," Prof. Hodgson for his expertise in operational systems, Prof. Kurfess for his in-depth knowledge of machine design and metrology, Prof. Madou for his breadth in many different fields, and Prof. Rajurkar for his broad insights on the landscape of manufacturing processes. Last, but not least, I would like to thank WTEC personnel and consultants for their excellence in managing this study under the leadership of Dr. Shelton, particularly, Roan Horning, Gerald Hane and Hassan Ali. All these people were so knowledgeable and so efficient that it has made the work extremely enjoyable.

Looking back, it has been quite an exciting journey from the encouragement of Dr. Delcie Durham—"Do something that you feel passion about and that you can enjoy along the way"—on a quiet day in early December at her NSF office, to the first one-hour meeting in the afternoon of Dec. 19, 2003 with Dr. Robert D. Shelton, President of WTEC, and Dr. Y. T. Chien, VP of Research at WTEC, to the interagency exploratory meeting on March 11, 2004, which led to the workshops and site visits in 2004 and 2005, and finally to the publication of this book now in 2006. During and after the WTEC study trips, the interest from the international community on this particular topic has been overwhelming. A striking example is Takashima Sangyo Co. Ltd.'s Desktop Manufacturing (DM) plant which consists of about 120 desktop-sized machines operating in a mere 300 m^2 factory developed since our December 2004 visit to Asia. Concurrently, numerous Japanese companies are starting to offer specialized products ranging from assembly, joining, metrology, to processing and other equipment, along with supporting component technology products such as sensors, actuators, and controllers that support the Desktop Manufacturing Paradigm. Foreign government activities include, but are not limited to: a) renewed funding by the Japanese government for AIST's efforts with a consortium of companies to develop the Desk Top Factory (DTF) concept and lines of supporting processes and equipment; b) the large national Microfactory Program in Korea, headed by the Korea Institute of Metals and Machinery (KIMM); c) the large scale project funded by the European Union on Evolvable Ultra-Precision Assembly Systems (EUPASS) focusing on micro-assembly headed by Philips Applied Technologies with participation from key European universities and leading companies; d) another large EU project, MasMicro, focused on developing various desktop machines for mass production of microparts. The funding level for each of these activities is in the tens of millions of dollars over a three to five year span.

Globalization has pushed manufacturing into an economically lean mode. This is the time to invest and to find the competitive edge with which the U.S. can lead and can excel. It is not time to abdicate our leadership position to others. A large nation like the United States should continuously contribute to the manufacturing science base and the technologies that transfer raw materials and energy into products that people can use to enrich their lives and that of the environment that surrounds us.

Science fiction frequently stimulates imagination long before the realization of physical inventions. In the famous Chinese traditional novel, "Journey to the West," written by Wu Chen-En circa 1590, Monkey King, in a single leap, could travel as much as 33,000 miles (more than enough to go around the globe), had eyesight like an X-ray, and many other superpowers that modern technologies are still trying to realize. In the fictional Star Trek universe, a *replicator* can convert energy into matter—any inanimate matter as long as the desired molecular structure is on file. Likewise, I hope that you will enjoy the rest of this book and allow your imagination to run unbridled as the future of manufacturing unfolds.

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August 2006

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Kornel Ehmann and Richard DeVor

PURPOSE AND SCOPE OF STUDY

In an effort to better understand the current status and emerging directions of R&D efforts in micromanufacturing worldwide, the National Science Foundation (NSF), the Office of Naval Research (ONR), the Department of Energy (DOE), and the National Institute of Standards and Technology (NIST) have commissioned a study by a team of U.S. experts. The team first organized a workshop in August, 2004 to survey U.S. activities in the field. The team then visited selected government, industry, and university sites in both Asia (Japan, Korea, and Taiwan) and Europe (Austria, Germany, Netherlands and Switzerland), conducted under the auspices of the World Technology Evaluation Center (WTEC). Detailed site visit reports can be found in Appendices C and D. The sponsors of this study selected a panel of experts to make the site visits and prepare the report. The expertise of the panelists spans the range of issues to be examined including design, materials, processing, metrology, applications, and business and economics. Detailed biographical information on the panelists can be found in Appendix A.

This international technology assessment study has focused on the emerging global trend toward the miniaturization of manufacturing equipment and systems for microscale components and products, i.e., *Small Equipment for Small Parts*. This trend is referred to with increasing frequency as the Microfactory Manufacturing Paradigm or Desktop Manufacturing Paradigm. It encompasses the creation of miniaturized unit or hybrid processes integrated with metrology, material handling and assembly to create microfactories capable of producing microprecision products in a fully-automated manner at low cost. The study has investigated both the state-of-the-art, as well as emerging technologies from the scientific, technological, and commercialization perspectives across key industrial sectors in Asia and Europe including medical, electronics, aerospace, and consumer products. This study does NOT include the lithographic-based processes common to the microelectromechanical systems (MEMS) community. This related topic was previously the subject of a similar WTEC study, “Microsystems Research in Japan,” published by WTEC in September of 2003.

In planning for the study, and in order to bring into focus the issues for which the panel sought answers, a series of questions were crafted by the panel and sent in advance to the hosts at each site to be visited. These questions can be found in Appendix B. The guiding principles driving the creation of this set of questions can be broadly classified into three categories that relate to miniaturization and for which answers have been sought. These are:

Scientific

- Impact of scaling laws on manufacturing processes/equipment
- State-of-the-science; gaps, deficiencies and needs in fundamental process knowledge
- Understanding of multi-disciplinary science-based requirements

Technological

- Driving forces for miniaturization needs
- State-of-the-art; gaps, deficiencies and needs for miniaturization of manufacturing
- Bridging between scales; nano to micro to macro
- Results from proof-of-concept testbeds

Commercialization

- Understanding principal current and future applications
- Economics of microscale manufacturing
- Societal benefits and broad-based impact of miniaturization
- Possibility of creating a disruptive manufacturing technology
- Results from proof-of-concept testbeds

SUMMARY OBSERVATIONS AND INSIGHTS

What follows is a synopsis of the findings of the panel given in terms of the state of worldwide R&D initiatives, specific technology trends and observations, and the interactions among universities, government institutes and labs, and private industry in the development of micromanufacturing technologies.

Worldwide Micromanufacturing Initiatives

1. Emerging miniaturization technologies are clearly driving developments in microscale processes, machines, metrology to meet needs re-

lated to part size, feature definition, accuracy and precision, and materials development. The study has revealed that there is a lot of activity in both Asia and Europe in this regard.

2. In both Asia and Europe, starting with MEMS, the approach tends to be more mechanics-centric rather than electronics-centric in nature. While 2D lithography-based technology development is present, it is not dominant, i.e., there is a more balanced approach. R&D tends to be very product-oriented with patient and sustained efforts aimed at refining the technology, i.e., more emphasis on *down-to-earth* as opposed to *blue-sky* initiatives.
3. The trend toward miniaturization of machines is evident in both Asia and Europe, with commercialization of desktop machine tools, assembly systems, and measurement systems well underway. The Microfactory Paradigm is more evident in Asia than Europe with several concept systems developed as far back as ten years ago. For example, in Japan, at the National Institute for Advanced Industrial Science and Technology (AIST)**,** strong efforts have been directed toward developing small-scale micromanufacturing machine tools and microfactories. In Europe, the focus is more at the machine/process level.
4. Both in Asia and in Europe, many of the issues under study and technical challenges embraced, were those identified at the U.S. workshop in August of 2004, viz., the need for smaller-scale machines, the need for multi-functional hybrid machines, attention to part handling and fixturing, the integration of metrology and processing, and the need for microscale process development.

Technology-based Trends and Observations

Summaries are provided in this section related specifically to the technology trends observed during the Asian and European site visits.

Design

1. The results of the assessment indicate the state-of-the-art in technologies that support the design of/for non-lithography-based micro/mesoscale parts is far from ready to provide adequate support for designers, due in large part to the nascent state of the technology and the fact that design researchers have yet to become aware of the design challenges in this field.
2. Both Asia and Europe show evidence of well-funded and focused efforts that are aimed at developing nanoscale and microscale design knowledge. There are a few efforts that are targeted at understanding how to simultaneously model and simulate multi-scale and multi-physics in engineering applications.

3. It was clear from the site visits in both Asia and Europe that standards for micro/mesoscale parts are currently in an early stage and require better definition. The standards for measurement and evaluation of part characteristics are of particular importance. Without these standards, it will be difficult for designers to talk with others (e.g. vendors, customers, etc.) about the specifications that drive the design and fabrication of their parts.
4. At present, the gap between the existing and the ideal in the application of stochastic techniques in micro/mesoscale design appears to be a *practice* gap. Designers simply are not using these powerful techniques. This was quite apparent from the visits to both Asia and Europe. The most important recommendation to be made here is to increase awareness of the benefits of stochastic methods and how they should be used during the design process.
5. In the area of design modeling tools, it was evident that European designers were focused upon generating accurate and robust modeling tools. The most successful designers were observed to have utilized a hybrid approach in which they augmented existing software. This indicates a technology gap that is probably best addressed by software vendors.

Materials

1. The visits to Asia and Europe revealed that typically, materials used for micromanufacturing are the same as those used in macromanufacturing. They encompass the full range of metals, polymers and ceramics/glasses. However, a feature unique to micromanufactured materials is the need for clean, inclusion-free materials.
2. Many efforts were found to be focused on improving the understanding of material behavior at smaller-size scales and how this would affect fabrication processes. In particular, grain size effects were found to be heavily researched, including effects of grain size on machinability, surface finish, and materials properties.
3. A major materials issue that was identified particular to micromanufacturing is the lack of an economic driving force for materials development, primarily due to small quantity needs.

Processes

1. The visits to industries, universities and research organizations in Asia and Europe revealed a broad spectrum of processing methods and equipment now in use for microscale manufacturing. It was observed that many microscale components/products are being manufactured using existing macroscale or reduced-size precision manufacturing proc-

esses and equipment. This approach is, however, exposing the difficulties related to the smallest unit of amount of material removal, addition and forming per cycle and achievable precision. In particular, issues such as material properties, generation and delivery of small amounts of energy, the effects of scaling on the process mechanism, process-material interactions, and related heat transfer issues are being revealed.

2. In both Asia and Europe the visits revealed a tremendous amount of activity on the miniaturization of processing equipment. Numerous examples could be found of both R&D activity and commercialization efforts in developing reduced-size and desktop/tabletop-size processing equipment and systems, with particular emphasis on multifunctional machines, e.g., processing, assembly, and metrology. This includes considerable evidence of interest and activity in the microfactory paradigm.
3. At the same time, the site visits revealed a great deal of activity in new process development to address specific needs and issues in microscale manufacturing. This was particularly evident in Japan, Taiwan, and Korea where such development frequently crosses the boundaries of mechanical, electrical, and chemical methods and encompasses technologies developed for both MEMS- and non-MEMS-related applications.
4. While the emphasis on new process development was found to be strong, activity directed at achieving a fundamental understanding of the mechanisms and performance characteristics of these new processes based on first principles and modeling efforts was proportionally less evident when compared to device development and experimentally based performance evaluation.
5. The Asian and Europe site visits revealed that issues related to process modeling and simulation, process-material interactions, monitoring and control, process capabilities, tool and equipment design, metrology, economics, and application, are yet to be fully addressed.
6. The visits demonstrated a belief that processes performed in a desktop factory environment could have a dramatic impact on society. Sankyo Seiki, for example, believes that its desktop factories (DTFs) might revive manufacturing in Japan and Korea. The Japanese Government has just started a new desktop factory project.
7. Although there is a great deal of past and continuing research on the directed assembly of small-scale parts (much of it driven by fiber optics and microphotonics), it was evident from the Asian and European

visits that there is a need for improved assembly and integration technology at the microscale.

Metrology, Sensors and Control

1. It was observed that there is a variety of metrology systems available for microcomponent inspection. However, few of these systems are three-dimensional in nature. Furthermore, all of the systems are relatively slow and expensive, making them reasonable choices for research and development but less than desirable choices for production lines from both a robustness perspective, as well as an inspection speed perspective.
2. Many of the standards that are applicable to macroscale metrology are not available for microscale metrology. Tools such as interferometers, ball bars and even gage blocks and gage balls are not available at the microlevel for testing and calibrating micrometrology systems. Thus, calibrating these systems and determining their capability is limited.
3. A variety of sensors for microcomponent metrology were observed during the visits. Many of them circumvent calibration issues, which are difficult to address, by either incorporating their own standards, or by employing procedures that generate data that can be interpreted without the need for precise calibration.
4. While machine control has progressed quite well, process control has not. This is primarily due to a lack of models, process understanding, and experience. Thus, significant efforts are needed in developing micromanufacturing process models and the controllers and control algorithms to utilize these models to improve the overall process and, ultimately, the product.
5. Controllers are also becoming more flexible to address the variety of processes that are being used in the microfactory. While they are becoming more reconfigurable, e.g., controlling a lathe and a mill, etc., major control system manufacturers in Asia are not looking toward open architecture controllers. These companies control the majority of the computer numerical control (CNC) market, and their customers are not requesting open architecture controllers. Thus, there is no great incentive to move in this direction.

Government Strategies and Funding Patterns

1. Research-to-technology refinement-to-commercialization appears more organized at the national government levels in Asia and Europe than in the U.S. in terms of both direction and government financial assistance for the long-term, resulting in more sustained efforts to refine and fine-tune new developments.

2. Both Japan and Korea support large, multi-year country-wide programs in micromanufacturing and microfactories, although in Korea this has been a very recent phenomenon. In Japan, the 10-Year Micromachine Program (1991-2001) constituted a major government investment that jump-started a number of initiatives with industry that continues today. Major successes include micromanufacturing and assembly systems at Olympus, Seiko, Hitachi, Fanuc, and Mitsubishi. In Korea, the Korean Institute of Machinery and Metals (KIMM) was awarded a major government contract for microfactory development.
3. In Japan, both the National Institute for Advanced Industrial Science and Technology and RIKEN (The Institute of Physical and Chemical Research) have missions heavily oriented toward R&D for industrial application, and both had major efforts directed toward micromanufacturing with very impressive results. In both labs, the R&D programs are producing very sophisticated, complex, and highly innovative processing methods.
4. In Taiwan, there is some institutional government investment, but it is mostly through large corporations with strong product focus, typical of Japan's *branding* strategy. The Industrial Technology Research Institute (ITRI) is the major government-supported laboratory conducting research in support of Taiwan's high-technology industries with a large segment being devoted to micromanufacturing research and development. Another government facility, the Metal Industries Research Institute (MIRI), is initiating a program in micro/mesoscale manufacturing methods (M^4).
5. In Europe, there has been much government investment in institutions at both federal and state levels. The emphasis seems to be on creating an enabling infrastructure to support the conversion of research results into technologies to the point that they are attractive to companies for application and commercialization. The major success story seems to be the Fraunhofer Institutes in Germany that are spread throughout the country. Each is focused on a particular technology, is co-located with major universities engaging students as staff members, and works closely with companies.
6. In Germany, the *Fraunhofer System* is a major driver of micromanufacturing research, technology development, and commercialization. With strong ties to the university system and industry, the Fraunhofers unite the three partners and the results are impressive. Efforts tend to be long-term, sustained, and lead to commercialization. State-based institutes are also common in Germany, again usually co-located with a local university.

Corporate Strategies and Observations

1. In terms of overarching corporate strategies, several points are worth noting:
    - *Large R&D Budgets:* In general, R&D budgets abroad can be larger than in the U.S. for both large and small companies. For example, in 2001 at Samsung, R&D investment was 4% of sales (about the same as the average U.S. company's R&D investment), but climbed to 8.5% in 2004, where it will remain for the future. At Kugler in Germany, a small precision machine tool manufacturer, the R&D budget is about 20% of total company expenditures.
    - *Sustained Efforts:* In both Asia and Europe, companies tend to be able to develop and sustain R&D projects over the long term. For example, FANUC’s ROBOnano (multi-purpose micromachine that sells for $1 million) was the realization of a 17-year effort involving dozens of researchers and engineers.
    - *Strong Government Partnerships:* The new Carl Zeiss microcoordinate measuring machine (CMM) was a joint effort with the German government, which funded 30% of the project.
    - *Close Institute/University Ties:* German companies provide significant investment and have staff located at Fraunhofer Institute and university locations to jointly develop technologies.
2. In Japan, the companies that have been strong over the past two to three decades in manufacturing leadership, e.g., FANUC (controls), Matsushita Electric (consumer products), Mitsubishi Electric (electronic products, devices) and Olympus (optics), seem to have invested heavily in micromanufacturing technologies continuously over the last fifteen or so years. Emphasis on robotics and mechatronics has driven this investment, which focuses on automated assembly of small devices and systems, and, application-driven new process development to meet specific part needs in terms of requirements related to geometric features, surface finish, relative accuracy, and materials properties. Notable examples are the microfactory concept developed by Olympus, primarily as a microlevel, automated assembly system and the ROBOnano machine tool developed by FANUC.
3. In Japan, it is interesting to note that the majority of the micromanufacturing equipment developed could be classified as somewhat exotic in nature, directed toward sophisticated, low-volume, high-precision needs of specific products and devices, and requiring a significant investment, with costs in the several $100K to $1M range. On the other

hand, there was little evidence found to support the notion that Japan might be considering the development of lower-cost, higher-volume commodity micromanufacturing equipment at this time.

4. In contrast, in Germany, there was abundant evidence of the desire to commercialize smaller micromanufacturing machine tools and accessories on a commodity basis, examples including Kugler's Flycutter and MicroTURN machines, the Carl Zeiss F25 small-scale CMM, and the Klocke Nanotechnik microscale robotic systems.

Institute/University Strategies and Observations

1. In both Asia and Europe, university research tends to be more device-development oriented with longer-term projects aimed at developing devices and associated integrated systems. Activity in the areas of process fundamentals, particularly, modeling and simulation, was less evident.
2. In Japan, university research programs tend to be more fundamental and professor-centric than in the United States. University/industry collaborations were less evident during site visits. Both Korea and Taiwan follow a similar pattern. In Japan, universities and government laboratories appear less connected.
3. In Germany, virtually all universities visited were associated with a Fraunhofer Institute and heavily engaged in industry-based research and development projects. Similar tendencies were seen in Switzerland and the Netherlands (e.g., ETH Zurich, Eindhoven). In all cases, laboratory facilities were excellent, based primarily on government funding, and faculty appeared to have more time to focus on research and less time on funding issues than in the United States.
4. In Japan, desktop manufacturing via micromachine tool and microfactory efforts were found at several university locations, including multi-functional machine and robotic devices. Perhaps the most important message gleaned from the university visits is that micromanufacturing in the context of this study will continue to see strong growth, and demand continuing research on a broad range of related topics, e.g., new materials, process understanding, new concepts for micromanufacturing equipment.
5. Regarding the relationship between the universities and companies in Japan, it was observed on several occasions that companies expect the universities to teach fundamental principles and provide broad scientific education, while the companies generally provide focused and application-oriented special training during the early years of employment. It was noted that government policy related to intellectual property seems to provide a favorable situation for industry regarding

university-based innovations and inventorship under government funding. Companies can purchase licenses from the government, which owns all such funded intellectual property (IP), to commercialize university-based inventions. The faculty involved can be required to work with the companies free-of-charge. However, the universities in Japan are in the process of adopting the U.S. model of funding research.

6. In Germany, the Fraunhofer Institutes are co-located with major universities, some of whose departments seem to mirror the institute structure. The focus tends to be on specific technologies at each location, e.g., laser, production methods, machine tools, etc. There is a mix of government and private/industry funding, and projects tend to be longer-term. Emphasis is on refining and fine-tuning technologies to make them commercially attractive and easily adapted. A wide range of services are available, including consulting, feasibility studies, basic research, technology transfer, systems integrations, and quality assurance/quality control (QA/QC). Links with universities seem to be very important to success. The Fraunhofer institutes are extremely well equipped with state-of-the-art facilities. It is noteworthy that a high percentage of staff, approximately 10%-15%, later start companies.

MICROMANUFACTURING R&D: A U.S., ASIA, AND EUROPE COMPARISON

Table ES.1 indicates that while the United States receives adequate marks for nanotechnology R&D, emphasis in the on micromanufacturing R&D is lagging far behind the rest of the world. This will undoubtedly have serious long-term implications, since it is well-recognized that micromanufacturing will be a critical enabling technology in bridging the gap between nanoscience and technology developments and their realization in useful products and processes. The Uniteed States gets particularly low marks for government funding of micromanufacturing R&D and the development and nurturing of industry, government, and university interactions and collaborations. On this latter point, Europe appears to be very strong, particularly as these partnerships work to refine and fine-tune developments for industry adaptation and commercialization.

Table ES.1
Summary of the Relative Status of International Micromanufacturing Technology Development

Activities	Japan	Taiwan	Korea	Europe	U.S.
Government funding in micromanufacturing	****	****	***	*****	*
State of the micromanufacturing technology	*****	****	***	*****	**
Industry/University/ Gov't partnership	***	***	****	*****	*
State of nanotechnology*	****	**	*	***	****

A PERSPECTIVE ON FORWARD PLANNING FOR THE U.S.

One overarching conclusion to be reached in reflecting on the observations made during this study is that MEMS and nanoelectromechanical systems (NEMS) advances are highly oversold in in the United States. While it is true that the U.S., over the last twenty years, has emphasized lithography-based MEMS with outstanding research results and a dominant market position, many MEMS products have become commodity products, and therefore, the Asian countries stand to reap more benefits in the near future from them. Perhaps there is an important lesson to be learned here.

Although less advertised, non-lithography micromanufacturing, practiced mostly in highly competitive, private companies such as Sankyo Seiki, Samsung, Olympus, etc., is more likely to continue to lead to more practical products faster. These products include lenses for cameras in telephones, flat panel displays, a myriad of automotive parts, microfuel cells, microbatteries, micromotors and, of course, desktop factories. Based on the state-of-the-art and current investment levels, Europe, especially Germany and Switzerland, and Asia, particularly Japan and Korea, will gain the most from developments in non-lithography-based micromanufacturing as they have a long tradition in it and have invested more heavily in this field.

We believe that to succeed in non-lithography-based manufacturing, a stronger-than-usual link between industrial partners and academia is required since micromanufacturing is very applied and product-driven. In this regard we are now behind in the United States, although it was here that the trend of academia/industry collaborations started. The links between industry and academia are now better in both Europe and in Asia. It

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* Reflects assumptions about relative level of funding for nanotechnology net qualitative assessment. This panel did not evaluate quality of nano research.

is a commonly held belief that technology transfer offices in U.S. academia have become so unwieldy that they prevent smoother and better collaboration with industry. This will need to change.

In some showrooms of the Asian visit, it became apparent that none of the products on display were manufactured in the United States anymore. New product demands are stimulating the invention of new materials and processes. The loss of manufacturing goes well beyond the loss of one class of products. If a technical community is dissociated from the product needs of the day, say those involved in making larger flat-panel displays or the latest mobile phones, such communities cannot invent, and eventually, can no longer teach effectively. Yet, a more sobering realization is that we might invent new technologies, say in nanofabrication, but not be able to manufacture the products that incorporate them. It would be naïve to say that we will still design those new products in the United States. For a good design, one needs to know the latest manufacturing processes and newest materials. We are quickly losing ground in developing new manufacturing processes and materials, and we must reverse this trend quickly.

To stem the hollowing out of their manufacturing base, the governments of many developed countries have made huge investments in the miniaturization of new products (MEMS and NEMS) and the miniaturization of manufacturing tools, for example DTFs. These efforts are intended to regain a manufacturing edge. To illustrate this point, Olympus' Haruo Ogawa, leader of that company's MEMS team, says that MEMS may help rebuild Japan's power as a manufacturing nation. Sankyo Seiki representatives believe that its DTFs might revive manufacturing in Japan. In Korea, the government just started a new DTF project. Finally, in some quarters in the United States, nanotechnology is seen as a means for the United States to remain a high-technology innovator.

An approach for the United States would be to launch a concentrated effort in advanced manufacturing techniques and re-introduce the societal merits and value of actually making things. With the information technology sector depressed, and high-paying jobs still scarce, this is a good time to launch such an effort. The current WTEC study could be a first attempt toward this goal. Hybrid manufacturing approaches, incorporating top-down and bottom-up machining approaches, could be key in attracting a new generation of motivated engineers and scientists into the science and engineering of manufacturing.