EXECUTIVE SUMMARY

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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 institute 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 related to part size, feature definition, accuracy and precision, and materials developments. 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 being 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

In this section summaries are provided 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. Of particular importance are the standards for measurement and evaluation of part characteristics. 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 "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 as 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 Asian 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 processes 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 multi-functional 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 towards 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 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 continue 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/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 – costing 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 with research programs tending to be more professor-centric as in the U.S. 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 U.S.
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 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 end up starting companies: perhaps 10-15%.

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

The table below (Table ES.1) indicates that while the U.S. gets high marks for nanotechnology R&D, emphasis in the U.S. 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 U.S. 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 EC.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 U.S. 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, as micromanufacturing is very applied and product-driven. In this regard we are now behind in the U.S., although it was in the U.S. that the trend of academia/industry collaborations started. The links between industry and academia are now better in both Europe and in Asia. It 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 U.S. 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. A yet 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 U.S., 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 (the leader of their MEMS team) says that MEMS may help rebuild Japan's power as a manufacturing nation. Sankyo Seiki believes that its DTFs might revive manufacturing in Japan. In Korea the government just started a new DTF project. Finally, in some quarters in the U.S., nanotechnology is seen as a means for the U.S. to remain a high-technology innovator.

An approach for the U.S. would be to launch a concentrated effort in very advanced, new 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 towards this goal. Hybrid manufacturing approaches, incorporating top-down and bottom-up machining approaches, could be a key to attract a new generation of motivated engineers and scientists into the science and engineering of manufacturing.