Laboratory for Manufacturing and Productivity

The Laboratory for Manufacturing and Productivity (LMP) is an interdepartmental laboratory in the School of Engineering devoted to exploring new frontiers in manufacturing research and education. Its primary goals are: (1) the advancement of the fundamental principles of manufacturing processes, machines, and systems, (2) the application of those principles to the innovation of manufacturing enterprises, and (3) the education of engineering leaders. With 18 faculty and senior research staff and 102 students, the laboratory conducts research in the areas of innovation, design, analysis, and control of manufacturing processes, machines, and systems.

Research is conducted through sponsored research projects, government grants, industrial consortia, and international collaborations. LMP's major areas of interest include: polymer microfabrication, chemical-mechanical polishing (CMP), precision engineering, machine elements and systems, nanomanufacturing, nanoengineered surface and coating technologies, production system design, radio-frequency automatic identification, sensor networks, information technology, photovoltaics, fuel cells, and environmentally benign manufacturing. In addition, LMP works closely with many other departments, laboratories, and programs at MIT, including the Departments of Civil and Environmental Engineering, Electrical Engineering and Computer Science, Materials Science and Engineering, and Mechanical Engineering; Singapore–MIT Alliance (SMA); Center for Transportation and Logistics; Deshpande Center for Technological Innovation; DuPont–MIT Alliance; Leaders for Global Operations; MIT Energy Initiative (MITEI); Novartis–MIT Center for Continuous Manufacturing; Lincoln Laboratory; and Sloan School of Management. Many of its research projects collaborate with industrial companies, including Advanced Synergic Microsystems Ltd., Chevron, GS1 US, Intel Corporation, NanoInk, Quantum Signal, Raytheon Company, and Semiconductor Research Corporation. Its government support, which is often coordinated with industrial support, comes from the Army Research Office, the Defense Advanced Research Projects Agency (DARPA), the Department of Energy, and the National Science Foundation (NSF). LMP also maintains a strong international presence—research sponsors include Daegu Gyeongbuk Institute of Science and Technology, King Fahd University of Petroleum and Minerals, National University of Singapore, GS1 AISBL, Philip Morris International Management S.A., and Samsung Electronics.

LMP's total research volume was $5.93M for 2009–2010. The active programs of MIT professors George Barbastathis, Tonio Buonassisi, Jung-Hoon Chun, Martin Culpepper, Timothy Gutowski, Stephen Graves, David Hardt, Emanuel Sachs, Sanjay Sarma, David Trumper, Kripa Varanasi, John Williams, Kamal Youcef-Toumi, and research scientists Brian Anthony, David Brock, Joseph Coughlin, Stanley Gershwin, and Karl Iagnemma contributed to this research volume.

Research Highlights and Awards

In the past year, LMP continued to develop research programs in three major thrust areas:

- Micro- and nanoscale manufacturing processes
- Manufacturing systems and information technologies
- Renewable energy and environmentally benign manufacturing

Professors Chun, Culpepper, Hardt, Trumper, and Youcef-Toumi are now actively engaged in the micro- and nanoscale manufacturing processes research thrust area. An SMA flagship research project on microfluidic device manufacturing is led by Professor Hardt, who is joined by Mechanical Engineering and Electrical Engineering and Computer Science faculty members in the new Center for Polymer Microfabrication (CPM). Professor Chun works in the area of CMP, while Professors Barbastathis, Culpepper, Trumper, and Youcef-Toumi work in the area of precision engineering, which focuses in part on equipment and instruments for micro- and nanoscale technologies. Professor Varanasi works in the area of nanoengineered surface and coating technologies for transformational efficiency enhancements in energy and water use.

In the manufacturing systems and information technologies research thrust area, the Auto–ID Laboratory, led by Professor Williams, develops identification technologies, including radio-frequency identification (RFID), to enable "the internet of things." Professor Sarma contributes to RFID research, as well as works on wireless sensors and complex systems. Dr. Brock continued the expansion of MIT's data center to develop the languages, protocols, and technologies required to integrate data and models across global networks. Dr. Gershwin is active in factory-level manufacturing systems design and control, while Professor Graves focuses his research on supply chain design and management. Dr. Iagnemma researches mobile robotic systems.

In the research thrust area of renewable energy and environmentally benign manufacturing, Professor Sachs has been joined by Professor Buonassisi in his photovoltaics research. Professor Chun continues his work on fuel cells for mobile devices, while Professor Culpepper has launched a new effort to enable energy efficient, mass manufacturing of carbon nanotubes (CNTs) for energy storage/conversion devices. Professor Gutowski is engaged in research projects focusing on the thermodynamic analysis of manufacturing processes and the analysis of recycling and remanufacturing to save energy.

CPM comprises a broad spectrum of research related to the science and engineering of creating commercially viable methods for manufacture of micro- and nanoscale products from polymers. The current focus is on microfluidic products in both the biomedical and computational fields.

Participants in CPM include Professors Hardt, Chun, Youcef-Toumi, Thorsen, Lallit Anand, and Duane Boning, and Dr. Anthony. Collaborators in Singapore include

Nanyang Technological University professors Chee Yoon Yue, Shu Beng Tor, Appa Iyer Sivakumar, Yee Cheong Lam, Soon Fatt Yoon, and Rohit Bhatnagar, along with National University of Singapore professors Andrew Nee and Velusamy Subramanian.

Research in CPM has primarily focused on the basic understanding of the processes of embossing, reaction casting, and thermal bonding, along with implementation in a manufacturing system. For the former, the CPM group has developed basic constitutive models for the polymers involved and has created numerical tools for full thermomechanical simulation of the embossing process, as well as reaction-distortion models of elastomer reaction casting. The group is now building on this base to create novel methods for device manufacture and to realize these in an automated production cell. The goal is to produce functional devices in high volumes with consistent quality using the embossing process. This has involved the development of a precision robotic handling system and novel measurement methods capable of large-range, high-resolution measurements.

In addition, CPM initiated two new projects this year dealing with continuous, or roll-to-roll manufacturing of enhanced surfaces. One project deals with the printing of self-assembling molecules using micro contact printing, and the other considers real-time, on-web measurement and control of nano-embossed patterns. The latter project is conducted as a subcontract to the University of Massachusetts Center for Hierarchical Manufacturing.

Dr. Anthony focuses on the development of computational instrumentation, creating computational systems to sense and control physical systems. His research combines mathematical modeling, simulation, optimization, and experimental observations to develop instruments and measurement solutions for problems that are otherwise intractable. Two research projects are funded by SMA. His research in freehand ultrasound instrumentation is directed to expand the usability and functionality of freehand ultrasound instruments, and his research in optical and photogrammetric metrology is focused on creating production-ready instruments capable of measuring three-dimensional micron-scale features distributed over a meters-scale area. His new initiative is to define and build an MIT center with focus on medical device realization. This endeavor brings together faculty not only from LMP and the Microsystems Technology Laboratory, but also from throughout the Institute.

Under the support from Samsung Electronics, the project conducted by Professor Barbastathis focuses on the design and experimental verification of a high-resolution multi-spot laser repair system for semiconductors. Mainly, two types of defects were considered: open defects (open circuits) and closed defects (leftover residue-redundant circuits). For the open defect type, the missing patterns are deposited by means of a laser chemical vapor deposition process, and for the closed defect type, the residual material is eliminated by means of an ablation process. The optical system has been designed and its detailed analysis has been conducted according to manufacturing requirements for the system to be implemented by the sponsor. A test setup has been built including the blazed grating array fabricated with microfabrication technology, which is the critical component to produce high-efficiency multiple laser spots. The system was tested to produce laser ablation as well as multiple laser spots by the gratings.

The data interoperability technology developed by MIT's data center program is evaluated by the Department of Defense as a foundation for data communications within the United States Joint Forces Command. The program, led by Dr. Brock, builds the languages, protocols, and strategies to integrate data and analytic models across the internet. With the ability to combine both structured data and unstructured natural language, the infrastructure developed by the data center program addresses many real-world problems in planning, logistics, and communications. In cooperation with corporate sponsors, the program has developed and tested prototypes for various defense and intelligence agencies within the US government.

Professor Buonassisi's research is focused on the field of photovoltaics, with projects specifically addressing the areas of defect engineering, next-generation materials, and nanoscale defect characterization. Significant results were achieved in defect engineering and modeling in silicon-based solar cells.

Professor Chun continued to lead the Cu CMP research program under the auspices of Intel Corporation and Cabot Microelectronics. Since various low-*k* dielectric materials (mechanically softer than SiO_2) are introduced into ultra large-scale integrated electronics replacing SiO_2 as the insulator, his current research involves investigation and mitigation of scratching by pad asperity during Cu CMP. His group recently developed a scratching regime map, the first of its kind. In addition, Professor Chun has been participating in research at CPM, focusing on modeling and control of rapid polymerization for the casting process, and he led portable fuel-cell research in collaboration with MIT professor emeritus Nam Suh. Professor Chun also worked on a supply chain issue in manufacturing of photovoltaic panels in collaboration with Professor Graves. He has been a key participant in the Novartis–MIT center in developing a new manufacturing paradigm and enabling technologies for the pharmaceutical industry.

Professor Culpepper's research focuses on the design of mechanisms, equipment, and instruments that are required to make, manipulate, and measure parts for small-scale manufacturing. His group is tackling the challenges that are associated with the design and manufacturing of: (1) CNT-based force and displacement sensors that enable high-rate, in-process metrology for manufacturing of enhanced surfaces in energy devices; (2) the equipment and tooling that enables the directed "printing" of CNTs and other small-scale features to create energy devices; and (3) equipment/instruments for the mass nanomanufacturing of biomedical devices. The overarching goal of the research is to generate the tools, technologies, and techniques that enable precise and directed fabrication of parts that bring the unique characteristics of nanoscale features to bear on pressing medical and energy problems. Professor Culpepper has also worked to define a major effort to enable mass manufacturing of enhanced surfaces for energy and optical applications. This endeavor brings together many LMP faculty to investigate the many problems whose solutions are required to further the science of enhanced surfaces, and to then optimize/apply the resolutions in practical applications.

Dr. Gershwin continues his research on complex manufacturing systems models and analysis. He also continues to teach and do research in SMA and the MIT–Portugal program, both in course development and research collaboration. Specific research areas include a quantitative analysis of the interaction between quality and quantity measures in production systems; mathematical modeling and analysis of systems with loops (for material control information or for pallets/fixtures); mathematical modeling and analysis of systems with multiple part types; analytical solutions of single-buffer systems with general arrivals and service; and real-time scheduling and material flow control.

Professor Graves has continued to do research on the modeling of supply chains and production/inventory systems. With support from SMA and MITEI, he completed a collaborative project with Professor Gutowski to study the effects of remanufacturing on energy use and carbon emissions. He also continues work on supply chain modeling and optimization with focused projects examining the supply chains for office supplies, computers, and electronic chips. In a continuing project, he has examined inventory management in a retail setting with the objective of identifying how to allocate inventories to reduce out-of-stocks and transportation costs, and to maximize revenues. In a new project with a manufacturer of industrial systems, he has been developing tactical models for optimizing internal supply chains and manufacturing systems.

Professor Gutowski's research focuses on the environmental aspects of manufacturing and the role of manufacturing and product design in a sustainable society. His current work is supported by NSF in the areas of manufacturing process analysis and product design for recycling. This latter area includes the modeling of the recycling system and an analysis of alternative product designs. In collaboration with Professor Graves of the Sloan School and research scientist Elsa Olivetti of Materials Science and Engineering, and under the auspices of MITEI, his group investigates the effects of remanufacturing on energy use and carbon emissions. Currently he is writing a book with two colleagues on applying thermodynamics to the analysis of resource use and the sustainability of manufacturing systems. In other work, Professor Gutowski and his students developed a method to model the environmental impacts associated with a person's lifestyle in the US.

Professor Hardt's work is focused on novel equipment and control systems for micron-scale polymer processing. In the past year, his group has developed a low-cost, high-rate embossing and boding machine design paradigm that makes this process very competitive with conventional injection molding while leading to more precise parts. His group has also developed some fundamental tools for understanding the critical step of demolding embossed parts, and the rapid degassing of thermosetting elastomers for large-scale production of small devices. Several new projects are focusing on the design and control of equipment for large-scale, micro-contact printing of sub-micron features on various substrates.

Dr. Iagnemma's research focuses on modeling, design, and algorithm development for mobile robotic systems. Much of his work is supported by the Department of Defense and has an emphasis on developing robotic systems for operation in challenging environments. This includes difficult outdoor terrain, planetary surfaces (including the surfaces of the moon and Mars), and inside the human body. Current Army Research

Office-sponsored work is focused on designing and building a highly agile robot for inspection of improvised explosive devices. Another DARPA-sponsored program is devoted to developing small, deformable mobile robots that could perform diagnostic tasks inside the human body. His future work will continue to explore novel robotic designs and algorithmic methodologies.

Professor Sarma's research has focused on three areas: wireless sensors, RFID, and sustainable water/energy. In RFID, he has worked on new protocol concepts for radio-frequency security and on the network layer. He is also working on the application of RFID with robots and in warehouses that can be mapped automatically by wandering "RFID-bots." Professor Sarma has recently started a research program in wireless sensing, focusing particularly on sampling theory as related to multiple mobile sensors. The applications of this research range from unmanned aerial vehicles sampling chemical fields to pinpoint a chemical leak, to unmanned buoys in the ocean detecting tidal waves. Finally, Professor Sarma has worked on the detection of water leaks and on energy efficiency using techniques ranging from robots to infrared thermography.

Professor Trumper's research efforts center on the design of novel precision electromechanical systems. He is engaged in an active collaboration with professor Robert Hocken of the University of North Carolina at Charlotte and research scientist Mark Schattenburg of the MIT Kavli Institute for Astrophysics and Space Research in projects for precision motion systems in support of accurate measurement devices for use in semiconductor fabrication and nanotechnology. These projects are also investigating the fabrication of extreme accuracy gratings for use as reference artifacts in nanometrology systems. In a project supported by Advanced Synergic Microsystems Ltd., Professor Trumper's group is investigating novel actuation and control approaches for high-accuracy motion in lithography systems. Professor Trumper's group is also collaborating with professor Christopher Love of Chemical Engineering to design new instruments and processes for rapid cell assays. These assay techniques hold promise in identifying rare cells that secrete compounds of interest in treating diseases such as HIV and malaria.

The primary focus of Professor Varanasi's research is the development of nanoengineered surfaces and coating technologies that result in transformational efficiency enhancements and avoidance of CO_2 emissions in multiple industries, including energy, water, agriculture, oil and gas, transportation, electronics cooling, and buildings. His group conducts research at the interface of nanomanufacturing, thermal-fluid science, and materials science for the discovery of new industrially robust materials, surface structures, and scalable surface and coating nanomanufacturing techniques that can fundamentally alter thermal-fluid-surface interactions for efficiency enhancements.

Professor Williams is leading a new collaboration among MIT, the University of Colorado at Boulder, the National Renewable Energy Laboratory, and SAP Research on smart grid technology. Research scientist Abel Sanchez and postdoctoral associate Christian Floerkemeier have continued to lead the Auto-ID Laboratory open source initiative, which allows other universities and researchers access to the latest developments in RFID and electronic product code (EPC) standards, such as e-Pedigree and EPC Information Services.

The achievements towards high speed atomic force led by Professor Youcef-Toumi can be categorized into: (1) developments in atomic force microscopy (AFM) control schemes, and 2) improvements in mechanical design. On the former, Professor Youcef-Toumi's group has designed and implemented several control approaches to high-speed AFM on both commercially available and custom-built AFMs. In a recent work, his group demonstrates a new way to characterize the lateral scanner dynamics without addition of lateral sensors, and to shape the commanded input signals in such a way that disturbing dynamics are not excited. This approach has enabled an order of magnitude increase in the scan rates of unmodified commercial AFMs and has been successfully applied to a custom-built high-speed AFM-enabling imaging at more than 10 frames/second. Furthermore, Professor Youcef-Toumi's group recently successfully tested an active vibration suppression technique to improve the bandwidth of a new generation of rigid AFMs. In addition to the control approaches, his group has employed novel mechanical design techniques to improve the dynamics and range of the AFM scanners. In this line, his research group has presented a novel methodology for generating flexure-based topologies that can meet performance requirements leading to the desirable imaging range and speed. Based on this methodology, his group has designed and built a high-speed AFM, successfully imaging dry samples such as silicon wafers, as well as samples in liquid to monitor biological processes at very high imaging speeds.

This year, LMP also continued significant educational activities. AY2010 saw the graduation of the fourth class of the new master of engineering in manufacturing degree program, which, while not an LMP activity, occurs largely through the efforts of its faculty and staff. This highly focused, one-year professional degree program is intended to prepare the student to assume a role of technical leadership in the manufacturing industry. As of August 2010, the program will have more than 100 alumni, and the entering class for AY2011 will total 15. (It is important to note that the AY2011 entering class is the first after the expiration of the SMA fellowship program, which funded some 15 fellowships in prior years.) Students have been engaged in industry-based group projects for their project theses in companies that include BD Medical, Merck, Philips Domestic Products, Schlumberger, and Tetra Pak in Singapore, and Instron Corporation and Nano-Terra in the US.

Over the past year, Professor Sarma was promoted to full professor and became the collaboration director of the MIT–Singapore University of Technology and Design. Professor Varanasi was named d'Arbeloff assistant professor of mechanical engineering. Professor Sachs was on leave.

Professor Varanasi received the 2010 Best Paper Award at the Institute of Electrical and Electronics Engineers–American Society and Mechanical Engineers ITherm Conference. He also received NSF's Faculty Early Career Development Award and DARPA's Young Faculty Award. At the annual manufacturing summit at MIT, Jonathan David Smith, Thor Eusner, and Anjuli Appapillai received best poster awards. This year, graduate students David Fenning, Katherine Hartman, Christopher J. Love, Adam

Paxson, Katherine Smyth, Joseph Sullivan, and Maria Telleria received NSF fellowships; Fernando Tubilla was awarded a Legatum fellowship; Michelle Vogl received a MITEI fellowship; and Sourabh Saha and Malima Wolf were named Martin Fellows.

New Initiatives

LMP has continued the renewal campaign that began in spring 2005. The Manufacturing and Productivity Seminar Series at MIT continued this year, and was held through fall 2009 and spring 2010 as an intellectual forum within the MIT community to present and exchange emerging ideas on manufacturing and productivity developed at LMP, MIT, and in industry.

Physical space upgrades continued as part of the renewal. Several basement offices have been consolidated and a new common office for graduate students was built. Planned upgrades include renovation and modernization of the Given Lounge and further reorganization of laboratory and office spaces to accommodate new students, staff, and faculty. To support these physical upgrades, LMP continued fundraising efforts aimed at LMP alumni with the support of the School of Engineering dean's office and the alumni association office.

In April, LMP held the 2010 Manufacturing Summit at MIT. The summit included presentations from all research areas within the lab, and a presentation from NSF senior advisor for engineering Bruce Kramer. Following the conclusion of the two-day conference, the LMP industrial advisory board met. The event was a great success, with over 100 participants, and contributed to LMP's ongoing efforts to build relationships with alumni and industry.

Jung-Hoon Chun
Director
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More information about the Laboratory for Manufacturing and Productivity can be found at http://web.mit.edu/lmp/.