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, including: the Departments of Civil and Environmental Engineering, Electrical Engineering and Computer Science (EECS), Materials Science and Engineering (MSE), and Mechanical Engineering (MechE); 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 MIT Sloan School of Management. Many LMP research projects collaborate with industrial companies, including Advanced Synergic Microsystems, Ltd., Chevron, GS1 US, Intel Corporation, Quantum Signal, and Raytheon Company. LMP government support, which is often coordinated with industrial support, comes from the Army Research Office (ARO), the Defense Advanced Research Projects Agency (DARPA), the Department of Energy (DOE), and the National Science Foundation (NSF). LMP also maintains a strong international presence—research sponsors include Daegu-Gyeongbuk Institute of Science and Technology (DGIST), King Fahd University of Petroleum and Minerals, the National University of Singapore (NUS), GS1 AISBL, Philip Morris International Management S.A., and Samsung Electronics.

LMP's total research volume was $5.33M for AY2011. The active programs of professors George Barbastathis, Tonio Buonassisi, Jung-Hoon Chun, Martin Culpepper, Stephen Graves, Timothy Gutowski, David Hardt, Emanuel Sachs, Sanjay Sarma, David Trumper, Kripa Varanasi, John Williams, and 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 and equipment: Professors Chun, Culpepper, Hardt, Trumper, Varanasi, and Youcef-Toumi are now actively engaged in this research thrust area. An SMA flagship research project on microfluidic device manufacturing is led by Professor Hardt, who is joined by MechE and EECS faculty members in the 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.
- Manufacturing systems and information technologies: 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, and works on wireless sensors and complex systems as well. Dr. Brock continues 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 on supply chain design and management. Dr. Iagnemma researches mobile robotic systems, and Dr. Anthony researches the application of information technology to improve the productivity of medical imaging systems.
- Renewable energy and environmentally benign manufacturing: Professor Buonassisi continues work in photovoltaics research, while Professor Chun continues work on fuel cells for mobile 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, Anand, Youcef-Toumi, Thorsen, and Boning and Dr. Anthony. Collaborators in Singapore include professors Chee Yoon Yue, Shu Beng Tor, Appa Iyer Sivakumar, Yee Cheong Lam, Soon Fatt Yoon, and Rohit Bhatnagar at Nanyang Technological University, along with professors Andrew Nee and Velusamy Subramanian at NUS.

Research in CPM has focused primarily 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 group has developed basic constitutive models for the polymers involved and has created numerical tools for full thermo-mechanical 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 continued work on two projects 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 design and realization of computational instrumentation, and his group creates 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. Research in freehand ultrasound instrumentation is directed to expand the productivity and diagnostic capability of medical ultrasound. His research in optical and photogrammetric metrology focuses on creating production-ready instruments capable of measuring three-dimensional micron-scale features distributed over a meters-scale area. This research is funded by General Electric and SMA.

In addition, Dr. Anthony, along with professors Charles Sodini of Microsystems Technologies Laboratories and Joel Voldman of Research Laboratory of Electronics, has cofounded and will codirect the MIT Medical Electronics Device Realization Center (MEDRC). The vision of MEDRC is to transform the medical electronic devices industries, to revolutionize medical diagnostics and treatments by bringing health care directly to the individual, and to create enabling technology for the future information-driven healthcare system.

With support from Samsung Electronics, the project conducted by Professor Barbastathis focuses on methods to further improve spot quality and compensate for the non-uniformity of the ablated spot by creating a beam with a flat-top profile. Such a beam would ensure that the entire ablation area receives the same energy and would improve the material deposition/ablation profile. This can be done primarily by using a holographic optical component, such as a Fresnel/grating or diffractive optical element, designed and optimized to achieve a flat-top beam output generation. As long as the non-uniformity can be assumed to be static in time, a test ablation structure profile without compensation can be used in the design algorithm. Professor Barbastathis has demonstrated that a uniform beam spot with diameters 2–30 μm can be generated by controlling the proposed system, which can be implemented as a static glass element or dynamic spatially tunable system.

The data interoperability technologies developed by MIT's data center program are supported and evaluated by the Department of Defense (DOD) Joint Chiefs of Staff as a means of integrating data, process, and planning within the United States Joint Forces Command. The program, led by Dr. Brock, is building the languages, protocols, and systems to integrate data and analytic models across the internet. With the ability to combine both structured data and unstructured natural language, the infrastructure addresses many real-world problems in planning, logistics, and communications. In cooperation with government and corporate sponsors, the program has developed and tested prototypes for various agencies within the US government.

Professor Buonassisi's research focuses on the field of photovoltaics, with projects specifically addressing the areas of defect engineering, next-generation materials, and nanoscale defect characterization. His group's most notable accomplishments this year include: (1) developing novel technologies to predict and reduce the impact of iron and dislocations on crystalline silicon solar cell performance; (2) inventing processes to sputter cuprous oxide (Cu_2O) earth-abundant solar cell materials with exceptional electronic properties; (3) solving process-property-structure relations in hyperdoped silicon, a promising material for intermediate band solar cells and infrared detectors; and (4) developing direct solar-to-fuel conversion using silicon-based solar cell devices. Professor Buonassisi also worked closely with a select group of industry-leading companies and promising start-ups to transfer his technologies into commercial manufacturing lines. In one instance of industrial collaboration with an industry leader, he reduced the phosphorus diffusion process cycle time by 75 percent, while maintaining or even improving cell performance.

Professor Chun continued to lead the copper (Cu) CMP research program under the auspices of Samsung Electronics. 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 CPM, focusing on modeling and control of rapid polymerization for the casting process, and he also led portable fuel-cell research. He has been a key participant in the Novartis–MIT Center for Continuous Manufacturing in developing a new manufacturing paradigm and enabling technologies for the pharmaceutical industry.

Dr. Coughlin continued his research collaboration with DGIST in the development of an on-road experimental platform to assess visual distraction and the validity of the DGIST driving simulator as a test-bed for the evaluation of visual secondary demands.

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 carbon nanotube-based force and displacement sensors that enable high-rate, in-process metrology for manufacturing, and equipment/instruments for mass nanomanufacturing. Professor Culpepper has also worked to define a major effort to enable mass manufacturing of enhanced surfaces for energy and optical applications, which will become the topic of an Environment Research Council proposal. 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 these 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: 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 continues to do research on the modeling of supply chains and production/inventory systems. With support from SMA, he has examined inventory management and order fulfillment in an online retail setting. The supply chain for an online retailer presents many new challenges because the online retailer will stock each item in multiple warehouses and will then dynamically decide how to assign inventory to orders and what shipment modes to use. Professor Graves's research focuses on how to provide high levels of service with the least amount of inventory and shipping costs. In another project, supported by an industrial sponsor, he has developed tactical planning models for three types of supply chains: a serial manufacturing system, an assembly system, and a job shop. In each case the tactical planning models allow for the optimization of the relevant tactics for each type of supply chain; these tactics include the optimal deployment of safety stocks, the frequency of production setups, and the level of production smoothing.

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. The latter includes the modeling of the recycling system and an analysis of alternative product designs. In collaboration with Professor Graves of MIT Sloan and Dr. Elsa Olivetti of MSE, and under the auspices of MITEI, his group investigates the effects of remanufacturing on energy use and carbon emissions. His new book, *Thermodynamics and the Destruction of Resources,* with professors Bhavik Bakshi (Ohio State University) and Dusan Sekulic (University of Kentucky), has recently been published by Cambridge University Press. In other work, Professor Gutowski and his students developed a method to model the environmental impacts associated with lifestyle in the US.

Professor Hardt's work focuses on novel equipment and control systems for micron-scale polymer processing. In the past year, his group has explored new methods for rapid and controllable bonding of polymer microfluidic devices. A new project has been started to explore the precise printing of conductive polymers as sensing and actuation elements in polymer devices. In addition, his group has begun an in-depth investigation of contact mechanics and control thereof for the process of continuous roll-to-roll micro-contact printing.

Dr. Iagnemma's research focuses on modeling, design, and algorithm development for mobile robotic systems. Much of his work is supported by DOD and has an emphasis on developing robotic systems for operation in challenging environments, which include difficult outdoor terrain, planetary surfaces (including the surfaces of the moon and Mars), and inside the human body. Current ARO-sponsored work focuses on designing and building a highly agile robot for inspection of improvised explosive devices. Another DARPA-sponsored program is dedicated 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 two areas: wireless sensors and sustainable water/energy. He has extended his work in RFID into the sensors arena. By leveraging physical changes to the antenna in a regular, inexpensive RFID tag, it is possible to create wireless sensors that cost only a few cents. Professor Sarma's group has also developed a mathematical framework for incorporating sensor data into a field reconstruction. This enables large-scale mapping and "hot spot" detection—for example, of the source of a pollutant leak—using large numbers of fixed and mobile sensors. Separately, Professor Sarma's group has developed a range of technologies for scanning cities and environments. One technology utilizes long-wave infrared images to analyze buildings using drive-by scanning from the street. The output of this system, which resembles Google Street View, can be used to automatically analyze and recommend repairs to buildings to minimize heat loss. The group is also developing a technology to analyze streetlights for lighting coverage, lighting quality, and light repair.

Professor Varanasi's research group aims to bring about transformational efficiency enhancements in various industries, including energy (from power generation, to oil and gas, to renewables), water, agriculture, transportation, and electronics cooling by fundamentally altering thermal-fluid-surface interactions across multiple length and time scales. His group has enabled this approach via highly interdisciplinary research focused on nanoengineered surfaces and interfaces, thermal-fluid science, and new materials discovery, combined with scalable nanomanufacturing for significant efficiency gains, reduction in CO_2 emissions, and the prevention of catastrophic failures in real industrial applications. Professor Varanasi's work spans various thermal-fluid and interfacial phenomena, including phase transitions (condensation, boiling, and freezing), nanoscale thermal transport, separation, wetting, catalysis, flow assurance in oil and gas, nanofabrication, and synthesis of inorganic bulk and nanoscale materials guided via computational materials design. His group's recent work on icephobic surfaces reducing energy consumption in the deicing of aircraft engines and wind turbines was highlighted in the *New York Times* and MIT News. The group also uncovered a new dynamic phenomenon of micro water-hammer effects on the stability of droplets during dynamic interactions with superhydrophobic surfaces, and this work was highlighted by NSF, MIT News, and MITEI.

Professor Williams continued his research collaboration with Philip Morris International to develop the electronic product code (EPC) network as the standard for tracking and tracing. The project provided a model and testing capability relative to the tracking of items in the tobacco industry, as well as enabling the development of software and a methodology to validate that EPC information services–compliant servers are able to handle the tobacco industry schema.

The achievements toward high-speed atomic force led by Professor Youcef-Toumi can be categorized into: (1) developments in atomic force microscope (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 recent work, the group demonstrates a new way to characterize the lateral scanner dynamics without the 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 per second. Furthermore, Professor Youcef-Toumi's group successfully tested an active vibration suppression technique to improve the bandwidth of a new generation of rigid AFMs. In this work, a piezo-based, feedforward controlled, counter actuation mechanism is used to compensate for the excited out-of-plane scanner dynamics. For this purpose, the AFM controller output is properly filtered via a linear compensator and then applied to a counter actuating piezo. An effective algorithm for estimating the compensator parameters is developed. The information required for compensator design is extracted from the cantilever deflection signal, which eliminates the need for any additional sensors. This imperative characteristic of the proposed approach makes it suitable for commercialization, and the group is currently working on preparing a patent disclosure on this invention. In addition to the control approaches, Professor Youcef-Toumi's group has employed novel mechanical design techniques to improve the dynamics and range of the AFM scanners. In this line, the 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, the 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 continued significant educational activities, including the graduation of the fifth 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 students to assume roles of technical leadership in the manufacturing industry. As of August 2011, the program will have over 100 alumni, and the AY2012 entering class will total 18. Students have been engaged in industry-based group projects for their project theses in companies that include Daktari, Konarka, Vicor, and Nano-Terra.

In AY2010, Professor Barbastathis was promoted to full professor and was named the Singapore research professor of optics. He was also elected as a fellow of the Optical Society of America. Professor Chun was on sabbatical leave in fall 2010.

New Initiatives

LMP has continued the renewal campaign that began in spring 2005. The Manufacturing and Productivity Seminar Series at MIT continued this year 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. In addition, LMP will hold the 2011 Manufacturing Summit at MIT in October; the 2011 summit will focus on manufacturing in an innovation economy.

Physical space upgrades continued as part of the renewal, and the renovation of Given Lounge was completed in early 2011. Further reorganization of laboratory and office spaces is planned to accommodate new students, staff, and faculty. To support these physical upgrades, LMP continued to build its fundraising efforts.

Jung-Hoon Chun
Director
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