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, education, and innovation. Its primary goals are: (1) the advancement of fundamental principles in manufacturing processes, machines, and systems; (2) the application of those principles to the technological innovation of manufacturing enterprises; and (3) the education of engineering leaders. With 18 faculty members and senior research staff and more than 90 students, LMP conducts research in the areas of design, analysis, control and innovation 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: (1) polymer microfabrication, (2) chemical-mechanical polishing (CMP), (3) precision engineering, (4) precision machine elements and systems, (5) nanomanufacturing, (6) n anoengineered surface and coating technologies, (7) modeling and design of supply chain and production systems, (8) radio-frequency automatic identification, (9) sensor networks, (10) information technology, (11) robotics, (12) photovoltaics, and (13) environmentally benign manufacturing. In addition, LMP works closely with many other departments, laboratories, and programs, including the Departments of Electrical Engineering and Computer Science (EECS), Materials Science and Engineering, and Mechanical Engineering; the Singapore–MIT Alliance; the Deshpande Center for Technological Innovation; Leaders for Global Operations; the MIT Energy Initiative; Novartis–MIT Center for Continuous Manufacturing; Lincoln Laboratory; and the MIT Sloan School of Management. Many LMP research projects collaborate with industrial companies, including Robert Bosch LLC, Boston-Power, Chevron, General Electric, GS1 US, Quantum Signal, and Shell. LMP government support, which is often coordinated with industrial support, comes from the Army Research Office, the Defense Advanced Research Projects Agency (DARPA), the United States Department of Energy, the Department of Transportation, the National Aeronautics and Space Administration (NASA), and the National Science Foundation. LMP also maintains a strong international presence. Research sponsors include ASML, Samsung Electronics Company, Ltd., Ferrovial S.A., GS1 AISBL, King Fahd University of Petroleum and Minerals, and the National University of Singapore (NUS).

LMP's total research volume was $9.8 million for FY2014. The active programs of professors George Barbastathis, Tonio Buonassisi, Jung-Hoon Chun, Martin Culpepper, Nicholas Fang, Silvija Gradecak, Stephen Graves, Jeffrey Grossman, Timothy Gutowski, David Hardt, John Hart, Alexie Kolpak, Sanjay Sarma, David Trumper, and Kripa Varanasi, as well as research scientists Brian Anthony, 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. These are described below.

Micro- and nanoscale manufacturing processes and equipment. Professors Barbastathis, Chun, Culpepper, Fang, Hardt, Hart, Trumper, and Varanasi were actively engaged in this research area. Professor Hardt, joined by Mechanical Engineering and EECS faculty members in the Center for Polymer Microfabrication, led a SMA flagship research project on microfluidic device manufacturing Professor Hardt's group now has an operating research factory for microfluidic devices. Professor Chun worked on the CMP, while Professors Barbastathis, Culpepper, Trumper, and Fang worked on precision engineering, which focused in part on processes equipment and instruments for micro- and nanoscale technologies. Professor Hart continued research in manufacturing and applications of carbon nano-materials. Professor Varanasi worked in the area of nano-engineered surface and coating technologies for transformational efficiency enhancements in energy and water use.

Manufacturing systems and information technologies. Led by Professor Sarma, the Auto-ID Laboratory continued to develop identification technologies to enable "the internet of things." Professor Sarma also worked on wireless sensors and complex systems. Dr. Gershwin was active in factory-level manufacturing systems design and control, while Professor Graves focused on supply chain design and management. Dr. Iagnemma researched mobile robotic systems, and Dr. Anthony researched the application of information technology to improve the productivity of medical imaging systems to reduce the cost of medical care.

Renewable energy and environmentally benign manufacturing. Professor Buonassisi continued to work in photovoltaics research in collaboration with Professors Gradecak and Kolpak. Professor Gutowski was engaged in research projects focusing on the interaction between manufacturing and the environment.

Dr. Brian Anthony

The focus of Dr. Anthony's research is computational instrumentation. His research combines multiple approaches, including mathematical modeling, simulation, optimization, and experimental observations to develop instruments and measurement solutions for problems that are otherwise intractable.

His group developed a controlled-force platform compatible with any ultrasound imaging system that can simultaneously image and apply precise, operator-controlled force to tissue accommodating for both patient and sonographer motion. His group developed an optical-based position-and-orientation-controlled ultrasound imaging system that precisely measures and/or maintains the relative orientation and positions of a US transducer with respect to the patient without markers or emitters. Ongoing clinical projects include imaging required in treating the liver, kidney, thyroid, and muscles in clinical collaborations with Massachusetts General Hospital, Boston Children's Hospital, and Beth Israel Deaconess Medical Center.

Dr. Anthony's research in optical and photogrammetric metrology focused on creating production-ready instruments capable of measuring 3D micron-scale features distributed over a meters-scale area. His group has developed a high-speed 3D profilometer for the inspection of transparent parts in micro-scale and is now developing high-throughput inspection techniques for the monitoring and control of roll-to-roll manufacturing processes for continuous high-rate production of flexible electronic systems.

Professor George Barbastathis

The project conducted by Professor Barbastathis focused on the detection of defects at hundreds nanometer scale on a fourth-generation thin film transistor (TFT) glass panel. Defects as small as 100nm on an initial glass plate may grow as big as several micrometers during the multilayer deposit process of TFT glass fabrication. Professor Barbastathis proposed a detection method based on an off-axis holography with an attenuated reference field. With the proposed method, the optical fields scattered from defects are projected to a charge couple device camera to make a hologram with a reference field the intensity of which is attenuated comparable to that of the scattered field. Simulations over particles as small as 100nm in diameter were performed under experimental noises, such as shot and Gaussian, and they showed the validity of the scheme.

Professor Tonio Buonassisi

The mission of Professor Buonassisi's Photovoltaic Research Laboratory (PVLab) is to develop the next generation of photovoltaic materials and processes by focusing on core strengths of defect engineering, characterization, and simulation.

This year, Professor Buonassisi's group made several contributions: (1) through defect control, they helped a partner company create kerfless silicon wafers with Czochralski silicon-equivalent performance; (2) in novel thin-film materials, his team was involved in generating two world-record solar-cell efficiencies—thin-film cuprous oxide and tin sulfide—demonstrating that a principled approach can be used to accelerate efficiency improvements in solar-cell devices; (3) in foundational science, his team demonstrated sub-bandgap photo-response in silicon hyper-doped with gold, and re-defined the diffusivity of interstitial nickel in silicon.

Professor Jung-Hoon Chun

Professor Chun continued to lead the copper (Cu) CMP research program in collaboration with Dr. Nannaji Saka. Since various low-*k* dielectric materials (mechanically softer than silicon dioxide (SiO2)) are introduced into ultra large-scale integrated electronics replacing SiO2 as the insulator, his research involved investigation and mitigation of scratching by pad asperity during Cu CMP. Based on a scratching regime map developed by his group, a new pad conditioning protocol was invented to maintain optimum topologized properties of CMP pads, which will reduce the use of consumables during conditioning. In addition, Professor Chun 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. He was instrumental in launching the Hong Kong University of Science and Technology-MIT Research Alliance consortium and was also involved in initiating a research program on technology multiplier effects with colleagues around the globe.

Professor Martin Culpepper

Professor Culpepper's research focused on the design of mechanisms, equipment, and instruments that are required to make, manipulate, and measure parts for precision measurement and manufacturing. His group has tackled the challenges that are associated with the design and manufacturing of equipment and tooling for precision manufacturing, including tooling for nanoscale patterning; CMP; precision mesoscale tooling, equipment and devices for defense; and instrumentation for nanoscale biomedical specimen fabrication and measurement. During AY2014, Professor Culpepper focused on initiating a new research thrust in the manufacture of nano-level precision of neurological specimens for medical instrumentation and the creation of rapid prototyping and maker spaces for undergraduate and graduate fabrication and manufacturing education. He is also creating a hands-on summer professional course, Rapid Prototyping, to complement the latter item; it will be held for the first time in summer 2015.

Professor Nicholas Fang

Professor Fang has developed a large-area solid electrolyte by embossing Nafion membrane from preformed master. A solid electrolyte can be used as a stamp for solid state super-ionic stamping (S4). S4 uses a patterned solid electrolyte as a stamp and etches a metallic film by an electrochemical reaction to directly reproduce metallic features. In previous works, focused ion beam milling was used to create the nano-pattern in the stamps (silver sulfide (Ag_2S) and copper sulfide (Cu_2S)) due to the highest resolution possible, even though this method does not easily scale up for large area patterning over square micrometers. In contrast, embossed Nafion membrane allows fabrication of stamps of several square centimeters as quickly as small stamps given a master pattern. This single-step, high-throughput, high-resolution, large-area manufacturing technology for metallic nanostructures may potentially lead to groundbreaking solutions for the semiconductor industry.

Dr. Stan Gershwin

Dr. Gershwin continued his research on complex manufacturing system models and analysis. His research areas included: (1) quantitative analysis of the interaction between quality and quantity measures in production systems; (2) mathematical modeling and analysis of systems with loops (for material control information or for pallets/fixtures); (3) mathematical modeling and analysis of systems with multiple part types; (4) analytical solutions of single-buffer systems with general arrivals and service; (5) real-time scheduling and material flow control; and (6) the design of separation systems for recycling. He has maintained a long-standing collaboration with colleagues at the Politecnico di Milano with support from the Rocca Foundation, and he has joined the MIT Skoltech Initiative to develop a manufacturing system course for the Skolkovo Institute of Science and Technology.

Professor Stephen Graves

Professor Graves' research group focused on the modeling and improvement of supply chains and production/inventory systems. Current projects include: (1) optimization of inventory placement and order fulfillment in an online retail setting; (2) modeling and analysis of a semi-automated fulfillment center, addressing storage and retrieval decisions; (3) modeling and optimization of safety stocks across a semiconductor supply chain; (4) analysis of a reverse logistics system for consumer electronics, including failure forecasting, inventory management, and warranty matching; and (5) modeling and analysis of a material separation system for waste recycling.

Professor Tim Gutowski

Professor Gutowski's research group, Environmentally Benign Manufacturing (EBM), continued to conduct research on the interaction between manufacturing and the environment with special attention to energy usage and carbon emissions. Current research efforts by EBM are at all levels for the manufacturing enterprise, including the development of new processing technologies, design methods, factory-level energy improvements, and an environmental assessment of the manufacturing sector at the global level. Last year the EBM group was part of a successful team that won a $7.6 million research contract from the US Department of Energy. The group also included Boeing, Ford, Northwestern University, and Pennsylvania State University. The project will focus on the development of flexible sheet metal forming technologies for low energy. This year the group started a new project with Ferrovial of Spain on modeling material recycling systems. This project is done in collaboration with Professor Graves.

Professor David Hardt

Professor Hardt's work focused on novel equipment and control systems for micron-scale polymer processing. During AY2014, the microfluidics manufacturing cell project was completed. This was the culmination of a multi-year integration of basic results into a working manufacturing cell producing microfluidic devices at production rates with full product and process monitoring. This system generated real production data for use in novel process control research, and next year will be key to a new project on rapid prototyping combined with production scale up for the microfluidics industry. His other work on the scale up of micro-contact printing has recently demonstrated in-process control of the critical contact region in a pilot scale roll-to-roll configuration. This combines a high-precision print roll actuation system with a novel transparent impression roll-sensing system. In addition, the work on direct-write patterning of micron-scale printing cylinders has mapped this novel process completely and developed the ability to control both print feature size and cross-section morphology. The latter has important implications for enhancing the robustness of printing at the micron-scale since it can be exploited to enhance the mechanical stability of print roll features.

Professor John Hart

During the past year, Professor Hart completed the transition of his research group to MIT, continuing research in manufacturing and applications of carbon nanomaterials (including carbon nanotubes and graphene), and beginning new research in additive manufacturing and origami-inspired manufacturing. Professor Hart's Mechanosynthesis

Group focuses on the synergy of new materials, mechanical design, and computational models to enable the realization of scalable manufacturing processes for applications such as composite structures, electronics, energy storage systems, and bio interfaces.

Professor Hart established a 3D printing teaching laboratory with support from LMP and Mechanical Engineering; this is currently housed at the International Design Center (building N52). During summer 2014, Professor Hart oversaw a five-day MIT short program that was attended by 45 industry participants. At the 2013 American Society of Mechanical Engineers International Design Engineering Technical Conference, Professor Hart received the 3M nonTenured Faculty Award.

Dr. Karl Iagnemma

Dr. Iagnemma's research focused on modeling, design, and algorithm development for mobile robotic systems. Much of his work was supported by the US Department of Defense 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. Other NASA-sponsored research into robot-environment interaction was performed in support of the Mars Science Laboratory rover mission. Other DARPA-sponsored research led to the development of passenger vehicle operator assistance algorithms to reduce or eliminate accidents. Dr. Iagnemma also developed novel robotic systems that rely on the adhesive properties of magnetorheological fluids and jamming of granular materials.

Professor Sanjay Sarma

Professor Sarma's research has focused on wireless sensors, city scanning, battery optimization, and cloud computing. He has continued his work in radio frequency identification (RFID) in the sensors arena, leveraging physical changes to the antenna in a regular, inexpensive RFID tag 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 to enable large-scale mapping and "hot spot" detection (e.g. of the source of a pollutant leak) using large numbers of fixed or mobile sensors. Also in the RFID area, Professor Sarma's group used RFID data to speed up image recognition and has been looking at how linked data can be used to improve vaccine tracking in developing countries. Professor Sarma's group continued its work investigating a range of technologies for scanning cities and environments. The group expanded its analysis of streetlights for lighting coverage, lighting quality, and light repair to include other city infrastructure concerns such as road conditions and city asset monitoring. Professor Sarma's research into battery optimization has looked at algorithms for optimizing hybridized battery packs, thermal management, and battery pack design for high-performance electric vehicles. Professor Sarma's group also continues its new research front called "Cloud Think," with over 100 vehicles around the world now being tested with new hardware developed for a sub-project focused on a CloudThink-connected car.

Professor David Trumper

Professor Trumper's research centers on the design of novel mechatronic systems. In the area of actuation, Professor Trumper's group studied the design of high-linearity iron core actuators for precision motion control systems, with a particular application to magnetically levitated stages.

In joint research with Lincoln Laboratory, Professor Trumper's group investigated novel magnetically suspended reaction wheels for spacecraft altitude control. These reaction wheels are driven using a new configuration of magnetic hysteresis motor.

Professor Trumper's group also collaborated with researchers at the Brigham and Women's Hospital to study the effect of mechanical deformation on angiogenesis in tissues. In addition, he recently started a new project focused on mechatronic aspects of concentrated solar power collection and thermal energy storage. This is a joint project with professor Alex Slocum in Mechanical Engineering, professor Charles Forsberg in Nuclear Engineering, and with a group at the Masdar Institute Cooperative Program in the United Arab Emirates.

Professor Kripa Varanasi

Professor Varanasi's group vision is to bring about transformational efficiency enhancements in various industries (energy, water, oil, gas, agriculture, transportation, medicine, 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: (1) interfacial thermal-fluids phenomena; (2) wetting and adhesion; (3) phase transitions (condensation, freezing, crystallization, boiling); (4) nano-engineered surfaces; (5) surface chemistry; (6) multi-scale surface materials; (7) manufacturing, and (8) energy efficiency.

Research accomplishments over the past year include design developments on lubricant-impregnated and textured surfaces that are resistant to scale formation and ice adhesion, fog harvesting, and electrostatic precursor films. These surfaces also promote an increase of Leiden frost temperature, which prevents frost formation, and stable dropwise condensation to enhance heat transfer and reduction of contact time for a bouncing drop.

New Appointments

Dr. Brian Anthony was appointed the deputy director of the MIT Skoltech Initiative, and has been deeply involved with MIT's leadership role in the Advanced Management Program. Dr. Anthony was also appointed as principal research scientist as of January 1, 2014.

Professor John Hart joined LMP as associate professor of mechanical engineering in July 2013 and was selected for the MIT Mitsui Career Development Chair.

New Initiatives

Construction on the new Hart and Varanasi lab spaces began in Spring 2014 and is scheduled for completion in late August 2014. This construction is part of the Institute's space improvement effort to create new advanced engineering spaces on the fourth floor of Building 35. The new Hart Lab will provide key resources for Professor Hart's research in carbon nanomaterials, additive manufacturing, and origami-inspired manufacturing. The new Varanasi lab is located across the hall and supplements Professor Varanasi's existing lab in Building 35. The new space is key to the Varanasi Lab's growth and expansion and the achievement of full research potential.

In spring 2014, LMP also initiated an evaluation of the potential to create a unified lab space for several faculty labs in the basement of Building 35. This shared space would maximize the efficiency of existing resources and provide a framework to advance lab functionality and collaboration.

Jung-Hoon Chun
Director
Professor of Mechanical Engineering