

## Laboratory for Manufacturing and Productivity

The [Laboratory for Manufacturing and Productivity](#) (LMP) is an interdepartmental laboratory within the School of Engineering that is devoted to exploring new frontiers in manufacturing research and education. Its primary goals are the advancement of the fundamental principles of manufacturing processes, machines, and systems; the application of those principles to the technological innovation of manufacturing enterprises; and the education of engineering leaders. With 15 faculty and senior research staff and more than 90 students, the laboratory conducts research in the areas of design, analysis, control, and innovation of manufacturing processes, machines, and systems.

Research is funded 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, precision machine elements and systems, nanomanufacturing, nanoengineered surface and coating technologies, modeling and design of supply chain and production systems, radio-frequency automatic identification, sensor networks, information technology, robotics, photovoltaics, and 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 (ME); the Institute for Medical Engineering and Science (IMES) and the Singapore–MIT Alliance for Research and Technology (SMART); the Deshpande Center for Technological Innovation; the DuPont–MIT Alliance; Leaders for Global Operations; the MIT Energy Initiative (MITEI); the Novartis–MIT Center for Continuous Manufacturing; Lincoln Laboratory; and MIT's Sloan School of Management. Many LMP research projects are conducted in collaboration with industrial companies; these include Boston-Power, Inc., Chevron Corporation, General Electric, GS1 US, and Quantum Signal, LLP. Federal government support for LMP, which is often coordinated with industrial support, is provided by the Army Research Office, the Defense Advanced Research Projects Agency (DARPA), the Department of Energy (DOE), the Department of Transportation, the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Office of Naval Research (ONR). LMP also maintains a strong international presence; international research sponsors include Alstom, Ltd., ASML Holding N.V., Ferrovial S.A., GS1 AISBL, Jaguar Land Rover, King Fahd University of Petroleum and Minerals (KFUPM), the National University of Singapore, Samsung Electronics Company, Ltd., and Shell International Exploration and Production, Inc.

LMP's total research volume was \$6.6 million for AY2014. The active programs of Professors Tonio Buonassisi, Jung-Hoon Chun, Martin Culpepper, Sylvija Gradecak, Stephen Graves, Timothy Gutowski, David Hardt, Alexie Kolpak, Sanjay Sarma, David Trumper, and Kripa Varanasi, and Research Scientists Brian Anthony, Stanley Gershwin, and Karl Iagnemma, all contributed to this research volume.

## Research Highlights and Awards

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

- Micro- and nano-scale manufacturing processes and equipment: Professors Chun, Culpepper, Hardt, Trumper, and Varanasi are now actively engaged in this research area. A SMART flagship research project on microfluidic device manufacturing is led by Professor Hardt, who is joined by ME and EECS faculty members in the Center for Polymer Microfabrication. Professor Hardt has also begun a new project on micro-contact printing sponsored by the Center for Clean Water and Clean Energy in collaboration with Dr. Anthony. Professor Chun works in the area of continuous manufacturing of pharmaceutical dosage forms, while Professors Culpepper and Trumper focus on precision engineering, on both equipment and instruments for micro- and nano-scale technologies. Professor Varanasi works in the area of nano-engineered 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 Sarma, develops identification technologies, including radio-frequency identification (RFID) to enable the “internet of things.” Professor Sarma also works on wireless sensors and complex systems. 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. Professor Chun collaborated with Professor Giesla Lanza’s group at Karlsruhe Institute of Technology on establishing the concept of technology multipliers.

### Dr. Brian Anthony

Dr. Anthony’s new collaborative research activities include work with Dr. S. Rutkove at Beth Israel Deaconess Medical Center under an award from the National Institutes of Health (NIH). They are using ultrasound image-based biomarkers to track the progression of Duchenne muscular dystrophy. Dr. Anthony is also working with Dr. A. Samir at Massachusetts General Hospital under an MIT/MGH Grand Challenge Grant Award; they are working to enable optical tracking of transducer positions and ultrasound transducers in three-dimensional space, thereby permitting spatial tagging of sonographic data. The target clinical application for this project is the serial tracking of nephron mass for the risk stratification of patients with chronic kidney disease or renal parenchymal volumetry. In collaboration with Professor Lempitsky of the MIT–Skolkovo Institute of Science and Technology (Skoltech) and Professor H. Herr in the MIT Media Lab, Drs. Anthony and Samir have developed a low-cost volume-scanning ultrasound imaging solution that will provide three-dimensional limb shape reconstruction for patients who require fitted prosthetics. Dr. Anthony’s research is funded by General Electric, NIH, NSF, KFUPM, and Skoltech.

The MIT Medical Electronics Device Realization Center that Dr. Anthony co-founded and co-directs is now part of IMES. In this role, it has expanded its mission beyond medical electronics and acts as the industry engagement interface for IMES.

### **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.

Ongoing collaborative research center activities include an NSF-sponsored Engineering Research Center (Buonassisi co-leads one research thrust) with Professors Gradecak and Kolpak; the Energy Frontier Research Center with Professors Gerd Ceder and Kolpak, sponsored by the Department of Energy-Basic Energy Science (DOE-BES); a number of DOE-sponsored grants, including SolMaT II in collaboration with local company Technic and Foundational Program to Advance Cell Efficiency II (F-PACE II) with Arizona State University and the California Institute of Technology; Bay Area Photovoltaic Consortium grants with Stanford University and consortium companies from across the full range of US manufacturers; a Next Generation Photovoltaic Technologies III grant with DuPont and Stanford University; and projects with Professor Roy Gordon (Harvard University) and Dr. Steve Hegedus (University of Delaware). All are focused on photovoltaics. A MITEI seed fund grant with Professor Yang Shao-Horn focuses on solar-to-fuel conversion. Other collaborative activities include a SMART activity (Low Energy Electronic Systems Interdisciplinary Research Group) that is focused on developing high-efficiency photovoltaics for mobile devices.

Professor Buonassisi and his group generated several newsworthy research highlights. They demonstrated a 10% solar-to-hydrogen conversion efficiency using all Earth-abundant elements, a record for silicon-based solar-to-hydrogen conversion and they demonstrated the first four-terminal and two-terminal tandem perovskite-silicon solar cells (in collaboration with colleagues at Stanford University). These were the most downloaded papers that appeared in *Energy & Environmental Science* and *Applied Physics Letters* for months following their publication. The Buonassisi group published perspective pieces in *Nature Photonics* and *MRS Communications* that highlighted properties of defect-tolerant thin-film materials; and, working with two manufacturers, they demonstrated high electronic quality in novel solar cell materials.

On July 1, 2014, Professor Buonassisi was promoted to associate professor with tenure.

### **Professor Jung-Hoon Chun**

Professor Chun has been a key participant in developing a new manufacturing paradigm and enabling technologies for the pharmaceutical industry with the Novartis-MIT Center for Continuous Manufacturing. His team successfully demonstrated a new method of producing pharmaceutical dosage forms by applying a coat of molding followed by overmolding. Professor Chun and a team from Karlsruhe Institute of Technology worked on future manufacturing scenarios in the automotive industry, using the scenario technique to discover potential future value chains. This study also discussed the role of manufacturing knowledge in innovations in the established fields of powertrain and body-in-white and the impact of the big information and communication technology companies on the automotive industry. Moreover, they defined the term "technology multiplier" – an effect that underlines the importance of enabling manufacturing technologies such as additive manufacturing, aluminum-aluminum resistance spot welding, and resin transfer molding, to industrialize advanced

materials such as carbon fiber and reinforced plastics. Its multiplying effect is based on the assumption that companies that keep a high share of their own value creation (have deep production depth) are able to assimilate information and act on innovation more quickly. As a consequence, they are able to shorten the time to market of new technologies and to produce complex products with higher accuracy or at lower cost.

### **Professor Martin Culpepper**

Professor Culpepper's research has 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 nano-scale patterning; CMP; precision meso-scale tooling, equipment, and devices for defense; and instrumentation for nano-scale biomedical specimen fabrication and measurement. Professor Culpepper has worked to initiate dedicated fellowships for mechanical engineering and manufacturing research with the Draper Laboratory. He has also been in discussions with [Draper Laboratory](#) about a possible LMP-wide, multi-faculty program in advanced design and mass manufacturing of small-scale, precision components and systems.

### **Dr. Stanley B. Gershwin**

Dr. Gershwin continued his research on complex manufacturing systems models and analysis. His research areas included 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, real-time scheduling and material flow control, and the design of separation systems for recycling. His recent work has included the probability distribution of lead-time in manufacturing systems and the analysis and design of maintenance policies for production machines and manufacturing systems.

Dr. Gershwin has maintained a long-standing collaboration with colleagues at the Politecnico di Milano. His course, Introduction to Manufacturing Systems, has been added to the curriculum of the Skolkovo Institute of Science and Technology. He will be a keynote speaker at MIM 2016, the 8th International Federation of Automatic Control (IFAC) Conference on Manufacturing Modeling, Management & Control, to be held in June 2016 in Troyes, France.

### **Professor Stephen Graves**

Professor Graves continued to do research on the modeling and analysis of supply chains and production/inventory systems where most of the funding for the research comes from industry collaborators. One recent project involved the modeling and optimization of safety stocks in a semiconductor supply chain, supported by Samsung Electronics. Another project considered the management of the supply chain that supports warranty claims for consumer electronic devices. One focal issue is how

much inventory of refurbished devices to maintain, and when to start to dispose of this inventory into side channels, in light of the short life cycles for these devices.

The current project, supported by Ferrovia, is in collaboration with Professor Tim Gutowski, with the goal of developing models and analyses for improved design and operation of recycling facilities that receive and sort single-stream municipal waste. Student projects include an examination of new operational issues that arise with the introduction of robotics into the order fulfillment facilities, and developing models and methods for determining the best ways to deploy inventory across multiple facilities in an online retaining supply chain.

### **Professor Tim Gutowski**

Professor Gutowski's research group, Environmentally Benign Manufacturing (EBM), continued to do 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. This 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 included the Boeing Company, Ford Motor Company, Northwestern University, Pennsylvania State University, and MIT. The project will focus on the development of flexible sheet metal forming technologies for low energy.

### **Professor David Hardt**

Professor Hardt's work focuses on scaling up micro- and nano- processes with an emphasis on novel equipment and control systems. His most recent work has included the demonstration of closed-loop statistical process control for a microfluidic device manufacturing cell. This method can maintain process specification even with significant material and machine variations. A similar goal is being pursued in the area of roll-to-roll microcontact printing. The latter technology is not now well developed when scaling up is considered; in addition to novel measurement and control methods, his group has contributed unique methods for micron-scale soft lithography tools, contact imaging methods, and the demonstration of continuous printing using thiol-based self-assembling molecular inks. This large-area, high-rate, micron-scale patterning method is being explored for several promising applications. In collaboration with Professor John Hart's group, a method for creating patterned carbon nanotube forests is being developed that could be scaled to very large areas and high rates of production. Such arrays could greatly improve battery electrodes, for example. A second application is large-scale printing of micron-scale comb electrodes to remove dust from large surfaces, such as photovoltaic devices, electrostatically.

### **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 emphasizes developing robotic systems for operation in challenging

environments, including difficult outdoor terrain, planetary surfaces (the moon and Mars), and inside the human body. Recent Samsung-sponsored research focused on the design and development of miniaturized, articulated manipulators for next-generation minimally invasive surgery. Other NASA-sponsored research into robot–environment interaction is being performed in support of the Mars Science Laboratory rover mission, where Dr. Iagnemma serves as a collaborating scientist. Other DARPA-sponsored research is leading to the development of passenger-vehicle operator assistance algorithms to reduce or eliminate accidents. Dr. Iagnemma is also developing novel robotic systems that rely on the adhesive properties of magnetorheologic fluids and the jamming of granular materials.

### **Professor Sanjay Sarma**

Professor Sarma’s research in the area of RFID with sensors and antenna design has continued; he is also applying RFID technology to assist in computationally expensive processes, such as vision-based object identification. By combining RFID with vision technology, the search space for image processing can be reduced. Professor Sarma’s group has also expanded previous work in city streetlight scanning to monitoring of road conditions and city assets. The new efforts continue earlier work with sensors and imaging to quickly and automatically survey city infrastructure with vehicle-mounted mobile sensing equipment. Research directed to the “internet of things” includes CloudThink-connected car technology; this has been augmented with research into mobility as a service to provide data on multimodal transit. Professor Sarma’s group is also expanding CloudThink beyond connected vehicles into home and office technologies.

### **Professor David Trumper**

Professor Trumper’s research is focused on precision mechatronics for manufacturing systems. His group has been studying the design of high-linearity iron core actuators for precision motion-control systems, including magnetically levitated stages for semiconductor manufacturing. In collaboration with MITEI and Lincoln Laboratory, they have been studying novel types of motors and magnetic suspensions for high-speed machinery and flywheel energy storage. Professor Trumper’s group is working with Lincoln Laboratory on the design of a novel electromagnetic nano-imager that can use electromagnetic fields to create high-resolution images of the near-vicinity of a surface rapidly. Professor Trumper’s group is also working with a doctor at Boston Children’s Hospital to create a new type of treatment for esophageal atresia, using magnetic and fluidic devices to create stretching forces on an incomplete esophagus of a newborn. This approach has the potential to eliminate the need for invasive surgical procedures, which are required by current treatments.

### **Professor Kripa Varanasi**

The mission of Professor Varanasi’s research group is to bring about transformational efficiency enhancements in various industries, including energy (power generation, oil and gas, 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 through interdisciplinary research

focused on nanoengineered surfaces and interfaces, thermal-fluid science, and new materials discovery. This approach, combined with scalable nanomanufacturing, offers significant efficiency gains, reduction in CO<sup>2</sup> emissions, and has the potential to prevent 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 the synthesis of inorganic bulk and nanoscale materials guided by computational materials design.

The completion of the second Varansi Laboratory space has been a tremendous opportunity, allowing the ability to pursue more projects. The research group accomplishments over the past year include the founding of Dropwise, the second startup company to come out of technology developed in the Varanasi Research Laboratory. In July, Professor Varanasi became a tenured professor.

### **Degrees Awarded**

This year, LMP accomplished significant academic goals, including the graduation of the eighth class of the new master of engineering in manufacturing (MEngM) degree program; although this is not an LMP activity, LMP faculty and staff contribute substantially to the program. 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 2014, the program had more than 150 alumni who engaged in industry-based group projects for their theses. The companies involved include New Valence Robotics Corporation, Waters Corporation, and Varian Semiconductor (acquired by Applied Materials). In the 2016 academic year, there will be 13 MEngM students.

### **New Development**

As of June 30, 2015, LMP will no longer operate as an interdepartmental laboratory within the School of Engineering.

**Jung-Hoon Chun**

**Director**

**Professor of Mechanical Engineering**