Guest Editorial
Exciting Trends for Automation in Manufacturing

FOR manufacturing of most goods, human labor has traditionally had three advantages over automation: flexibility, deployment speed, and capital cost. The pressure to produce large volumes of products that have a very short life cycle (e.g., digital cameras and smart phones) makes it difficult to establish automated or even flexible assembly lines in a time span that is small in comparison to the product life cycle. However, recent advances in computing, communication, and hardware technologies are rapidly changing the manufacturing landscape. Emerging innovations such as 3-D printing, the Industrial Internet, and open source software and hardware have enormous potential for the field of automation.

Three-dimensional (3-D) printing (also known as additive manufacturing) technologies are expected to be a disruptive technology. 3-D printing does not require any part-specific tooling or complex process planning, and greatly reduces set up time since instructions for driving a 3-D printer can be automatically generated from a 3-D CAD model. More importantly, a 3-D printer does not require any special skill to operate. Because of this and the fact that the setup time is minimal, the process of automatically going from a CAD design to manufacturing is straightforward, and 3-D printing has the potential of revolutionizing e-commerce in the manufacturing space. Indeed the ability of designers to buy 3-D printing services over the Internet is already driving down the cost of this technology and increasing its adoption and applications. While current applications are limited in terms of size, scale, and choice of materials, this technology is likely to become pervasive in all segments of the manufacturing industry.

The open source software movement has inspired similar movement leading to open source designs of 3-D printing machines, which has in turn to a drastic reduction in prices for low-end 3-D printers. Currently, there are 3-D printers in the market that cost less than USD 1000 making this technology accessible to a wide range of users. Currently, the open source movement is restricted to only certain types of 3-D printing technologies. While high end 3-D printers are still very expensive, there are significant opportunities for developing low-cost 3-D printers that work with metals and high strength polymer materials.

Computer-aided design (CAD) systems are the main tool for creating models to be printed on 3-D printers. Democratization of manufacturing via processes like 3-D printing is only possible if CAD systems become easy to use. Despite recent advances in 3-D CAD/CAM tools, people with limited technical expertise still find these systems hard to use. CAD system user interfaces have to improve significantly in terms of user friendliness for consumers to effectively utilize 3-D printers for in-home use (e.g., designing and 3-D printing a scaled model of their house). Improved interfaces will also enable the use of 3-D printing in K-12 schools in educational endeavors and also enable people with nontechnical background to participate in the invention process.

Another important trend relates to the complexity of manufactured products. The complexity of parts and products we are able to design and build, and what society wants is constantly increasing, while the useful lifetime for products and the lead time are decreasing, even as product variety is increasing. In the world of 3-D printing, increased geometric complexity of a part does not necessarily lead to increased cost. This has allowed designers to develop parts with intricate internal voids to enhance performance (e.g., increased surface area for heat transfer) and reduce weight. This has also allowed designers to look to biological structures for inspiration. Indeed structures in the natural world often utilize geometrically complex, multiscale structures. The reduction in the amount of material used in a part is also driven by our desire to achieve sustainability by minimizing the material usage. However, designing geometrically complex parts manually with current CAD systems is a very tedious and error prone task. We need to develop automated shape synthesis tools to work in conjunction with CAD systems that can automatically create new shapes from the functional requirements. As advances in nanotechnology make it possible to customize nano-composites to specific parts, we also need to develop new high-speed, multiscale automation technologies that can automate fabrication of parts to fully realize the potential of the 3-D printing revolution.

The price-performance ratio of 3-D vision systems are falling and algorithms for using 3-D vision technology have matured to a point that vision-guided inspection and assembly can now be used to automate manufacturing processes. It is also possible to scan 3-D environments to automatically create 3-D models with sufficiently high accuracy, providing an alternative path for creating models for 3-D printing and other manufacturing processes. Consumers can scan their bodies and design products like bicycle seats that conform to their bodies. Vision systems can automatically detect, identify and localize objects, monitor the performance of manufacturing operations, and benchmark the quality of finished products. New advances are needed in low-cost 3-D sensing technology to improve the accuracy and ensure that this technology works with highly reflective, translucent, or dark objects in a reliable manner. Further advances are also needed to develop low-cost 3-D CAT scanners that create a model of the internal structure of the objects being inspected.

Digital Object Identifier 10.1109/TASE.2013.2249711

The ability to buy 3-D printing services over the Internet provides a glimpse of how the Internet is affecting the manufacturing practices and business models. The ubiquity of computers including mobile devices and the increasing robustness of networking technologies has led to what GE calls the *"Industrial Internet"*[1] – the

> *convergence of the global industrial system with the power of advanced computing, analytics, low-cost sensing and new levels of connectivity permitted by the Internet.*

Machines used for manufacturing processes and for assembly are increasingly being networked for sharing information and for real-time coordination. Already there are many networking sites and brokering models to enable matchmaking between designers, engineering analysts, and manufacturers. These trends are changing business practices in manufacturing and enabling individual innovators and small companies to bring their product to niche markets that are typically ignored by large manufacturers. At a finer level, human workers and managers expect to be part of the manufacturing network and be able to access real-time information from factories independent of their physical location and the time of the day.

The convergence of networking and the availability of models and vast amount of digital data due to highly automated processes are making manufacturing a rich application area for the rapidly developing machine learning technologies. The emergence of standards for exchanging models and data is accelerating this trend. Machine learning technologies can enable new methods for process and quality control, diagnostics, maintenance, and robot programming. In particular, it is now possible, for example, to monitor and predict the tool wear and perform cutter path compensation to maintain part accuracy in operations such as water-jet cutting and milling. It also enables monitoring of vibrations in machining processes and the online adjustment of process parameters to avoid process instability. The emergence of cloud-based computing paradigms and new software architectures that support real time operation (e.g., for the Google Car or for Amazon/Kiva Systems warehouses) suggests that networks of machines can learn from each other and continuously optimize their performance leading to faster recovery from errors and increased robustness.

[1]http://www.ge.com/docs/chapters/Industrial_Internet.pdf

The push toward the development of open source software has finally reached the world of digital manufacturing consisting of networked machines, sensors and humans. There are many efforts to develop open source software infrastructure for design, simulation and integration, all derived from abstractions of sensors, actuators, and processes. This shift toward modularity in software and hardware will lead to a paradigm in which the role of expensive hardware is minimized, reducing the barrier to entry. We are already seeing inexpensive industrial robot systems such as Baxter (Rethink Robotics) with programming abstractions that allow users with minimal skills to quickly program machines for pick-and-place and assembly operations.

We believe manufacturing is at an inflection point. Increases in transportation costs, increases in global human wages, and increases in productivity fueled by advances in automation science and engineering have resulted in the fraction of product cost attributed to labor to fall steadily. However, with growth in product and part complexity, the cost of integrating manufacturing processes with robots, sensors and material handling equipment continues to rise. What if the open source revolution that has energized hobbyists in robotics and 3-D printing can also be brought to manufacturing? What if we are able to design hardware with well-defined interfaces and software abstractions, provide simulation environments for the hardware, and enable open-source development of software for integrating systems? These trends draw on talent from around the world and have enormous potential to greatly accelerate the rate of innovation in manufacturing.

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