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Getting Smart About Manufacturing

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THEME: SMART MANUFACTURING

ON THE COVER: Make way for the rise of smart manufacturing.

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DEPARTMENTS & COLUMNS

FEATURES

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EDITORIAL

Manufacturing the future

by Davis George Moye

Sometimes I get to look at (but never touch) the big manufacturing machines at work: one, in particular, is 3 m tall and at least 5 m long, yet it makes a product that we measure in micrometers. Why does it take something so big to manufacture something so small? I often want to touch this machine, the three-dimensional (3-D) printer, and many other fascinating things at work. But after what happened to the last laser lithographer (which really did set paper on fire), the head machinist has promised me that I will find myself at the forefront of bioelectronics research as a test case for a prosthetic epidermis should I lay another finger on any of his equipment again. I hope he does not realize I am borrowing his uninterrupted power supply for my own workstation.

On a not-so-recent trip to an important history museum, whose name utterly escapes me, I learned about ancient Roman sculpture. In producing a bust of the emperor's head, the ancient Romans melted and poured bronze into a mold in a foundry. Like ancient Greeks, and other people before them, the Romans would hand carve an impression of the emperor's face and sculpt out of clay or stone. Then they would pour molten bronze inside, hoping it turned out right. The yield rates were not very good back then.

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My own experience as a newly hired project management engineer at an electronics manufacturing company has come with a steep learning curve or at least can be likened to drinking water from a fire hose.

We have come a long way with smart foundries. Now that our mechanical engineer designs the part on a computer-aided design program, converts the file to a stereo lithography format, and then the head machinist sometimes lets me stand at least 2 m away to watch the 3-D printer additively manufacture layer upon layer of directly deposited metal to reproduce the latest broken part of some big, impressive-looking machine (that I was unaware was out of commission), as it serves to make more micrometer-long electronic components.

I have not even mentioned the people who numerically model our products or the others who ensure that the supply chain keeps raw materials inbound so that the salespeople can keep revenue inbound. My own experience as a newly hired project management engineer at an electronics manufacturing company has come with a steep learning curve or at least can be likened to drinking water from a fire hose. If you are considering a manufacturing job or career, we hope you find this special edition of *IEEE Potentials* useful. If not, modern manufacturing touches on many fields; we at least hope to make your learning curve a little flatter.

About the author

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THE WAY AHEAD

Seek out your Section events and leaders

by Pablo Herrero

By the time this issue reaches your hand (or tablet), the IEEE-USA-organized Future Leaders Conference in New Orleans, Louisiana, will be nearing its kickoff on 28–30 July 2016. While I write this article (prior to the event being held), I would like to take the time to congratulate the team who put the tireless effort into making the event a reality. It is important for many reasons but mainly because it is the first official IEEE all-student event in Regions 1–6. While these student gatherings are very popular (with a huge turnout) in other Regions, it is a tremendous logistical and financial effort to congregate six Regions for the first time in the United States. If you were part of it, we would love to hear about your experience. If you were not able to attend, I encourage you to look for the many pictures and testimonials available on the Internet.

Events like this are the essence of IEEE student activities. It's all about interaction, networking, and learning. Imagine if you could "import" activities that were successful in a university from a different state. What if you could replicate the same success at your university? This is the place to learn how. Believe it or not, many other universities and IEEE Student Branches suffer from the same issues as your branch, whether it's decreased engagement, low membership, or not enough interest in your meetings or activities. These types of events are the place to collaborate to solve such problems.

Sometimes it is not possible to attend an event or you have more specific problems that need closer attention. In these cases, seek guidance from branches in your area by contacting your IEEE Section. These entities have the right contacts to help you locally (and in most cases, those at the Section level possess past experience as student leaders). They can help you seek funding for an event or endorse your support petition with a university or with a particular company that you want to sponsor your next event. Moreover, I encourage you to take part in the Section itself. Find out what kind of Chapter meetings they have and what interesting activities they organize. In many cases, Sections are seeking volunteers, and you can take the first steps of a fruitful relationship.

I always tell branches that is impossible for other people to know if you need help if you don't ask for it, so publicize and promote yourself within the Section.

It is important that you let your Section know about the awesome activities are you organizing. I always tell branches that is impossible for other people to know if you need help if you don't ask for it, so publicize and promote yourself within the Section. It will pay off in the long run.

I want to wrap up my comments with a follow-up to the careers/graduate education theme from the May/June 2016 issue of *IEEE Potentials*. You may have been watching the news reports of large IT giants announcing cuts in staff. Remember when I was telling you how important is to keep learning? Well, large companies need to keep learning as well, and they rely on people like you, the student leaders, to take the first steps. The engineering field runs quite fast: don't let yourself lag behind. The IEEE is a great tool to stay up to date on the latest trends in technology and groundbreaking research. Stay connected, keep on learning, and you (and your company) will win.

About the author

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GAMESMAN SOLUTIONS

Solution #1: It's All Natural

By using the pattern of all natural numbers, we can find the difference between the square of a number and its consecutive number. For example, the difference between 4^2 and 5^2 is 9. And $4+5=9$. So knowing that 4^2 is 16, we can find 5^2 by adding 9 to 16.

This works for every consecutive natural number (and any two numbers that differ by one). That is, the difference between $(n+1)^2$ and n^2 is the sum of $n+1$ and n.

So for the problem, knowing that 5552 = 308,025 and 555 + 556 = 1,111, then 5562 = 308,025 + 1,111 = 309,136.

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Solution #2: Going Ballistic

The rocket will be in the Pacific Ocean. It will fall into the sea in a little over 2 min at about 1,500 km to the east. Its speed is nowhere near enough to keep it in orbit. Although the rocket's speed will increase the falling time slightly, its speed is too small to make much difference.

Solution #3: High-Altitude Stories

Satellites travel above the atmosphere, so they do not make sound.

Yes, if it is in a near-polar orbit. The Earth may have rotated to a position where the satellite happens to be in a part of its orbit that is in the direction opposite to that in which it was first seen.

No, since in two hours the Earth moves only 30°, and the satellite, even though in a near-polar orbit (which would be necessary for "direction-reversal"), will have had time to go around the earth no more than twice and will look much the same. It will take about 12 h or more for the Earth to rotate to a position where the satellite, viewed from the same place on the Earth, will be observed going south. If the satellite seems to be moving quickly, it is in low orbit, and, however quickly it seems to be moving, it will almost certainly be daylight before this reversal happens for the first time.

Solution #4: Pólya's Orchard

The nearest visible trees to the origin are those at $(\pm 1, 0)$ and $(0, \pm 1)$.

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Between two adjacent nearest trees, say (1, 0) and (0, 1), the next nearest visible tree is (1, 1). Between the trees at (1, 0) and (1, 1), the next closest visible tree is at (2, 1). In general, it's possible to show that, for a pair of "bracketing" closest visible trees recursively defined in this way at (h, k) and at (h^r, k^r), the next closest visible tree between them is at $(h + h^r, k + k^r)$.

Our orchardist sets a path to the left of (1, 0) but to the right of (1, 1). Beyond those trees, the next nearest visible tree is at (2, 1), which he determines he will walk to the left of it. According to our rule above, the next nearest visible tree between (1, 1) and (2, 1) is at (1, 1) + (2, 1) = (3, 2), of which he will pass to the right. It becomes clear that the sequence of trees he will pass to the left of and to the right of, alternately, is (1, 0), (1, 1), (2, 1), (3, 2), (5, 3), (8, 5), … . The $(n + 1)$th tree in this series is determined from the previous two according to the recurrence relation $(h_{n+1}, k_{n+1}) = (h_n, k_n) + (h_{n-1}, k_{n-1})$. This is a Fibonacci sequence. The well-known closed-form solution of the recurrence relation is that

$$h_n = K_{n-1} = \frac{\gamma^n - (-\gamma)^{-n}}{\gamma + \gamma^{-1}},$$

where $\gamma = (\sqrt{5}+1)/2$ is the *golden ratio*.

The bearing to each of these trees, with (0, 1) serving as north, is $\arctan h_n/k_n$. We see that

$$\lim_{n\to\infty} \frac{h_n}{k_n} = \gamma.$$

Therefore, the bearing on which the orchardist sets out is $\arctan \gamma$.

Solution #5: Norden's "New Invention"

Let **A** be the matrix of squared distances. The element $a_{ij} = \|\mathbf{x}_i - \mathbf{x}_j\|^2$, where $\mathbf{x}_i$ and $\mathbf{x}_j$ are the coordinates of points i and j, respectively, and $\|\cdot\|$ represents the Euclidean norm. So $a_{ij} = (\mathbf{x}_i - \mathbf{x}_j)^T(\mathbf{x}_i - \mathbf{x}_j) = \mathbf{x}_i^T\mathbf{x}_j - 2\mathbf{x}_i^T\mathbf{x}_j + \mathbf{x}_j^T\mathbf{x}_j$. If we define a column vector $\mathbf{r}$ such that the elements are $r_i = \mathbf{x}_i^T\mathbf{x}_j$, then we can write the matrix **A** as

$$\mathbf{A} = \mathbf{r}\mathbf{1}^T - 2\mathbf{X}^T\mathbf{X} + \mathbf{1}\mathbf{r}^T,$$

where **X** is the matrix formed by stacking the vectors $\mathbf{X}_j$ side-by-side together, and **1** is the column vector of all ones. Observe that $\mathbf{A}$ is therefore the sum of two rank-one matrices, $r1^T$ and $1r^T$, and a rank-three matrix, $\mathbf{X}^T\mathbf{X}$ (assuming that the points of interest are not coplanar). Therefore, the rank of $\mathbf{A}$ cannot exceed five and, except in contrived cases, will be precisely five. If there is an error in one of the recorded distances, the decomposition of $\mathbf{A}$ into low-rank matrices will be invalid, resulting in $\mathbf{A}$ having higher rank. In conclusion, the test for determining whether one of the distances is in error is to calculate the rank of $\mathbf{A}$. If the rank is greater than five, then an error exists.

Suppose a mistake has been made in recording the squared distance between points m and n and only between these two. Then the decomposition of $\mathbf{A}$ is now

$$\mathbf{A} = \mathbf{r}\mathbf{1}^T - 2\mathbf{X}^T\mathbf{X} + \mathbf{1}\mathbf{r}^T + \epsilon \boldsymbol{e}_m \boldsymbol{e}_n^T + \epsilon \boldsymbol{e}_n \boldsymbol{e}_m^T.$$

Here, $\mathbf{e}_m$ and $\mathbf{e}_n$ are the mth and nth columns of the identity matrix and ϵ represents the error in the recorded squared distance. So, $\mathbf{A}$ has now had added to it another two rank-one matrices. Except in exceptional circumstances, we expect its rank would be seven. Observe that $\boldsymbol{e}_m$ and $\boldsymbol{e}_n$ are in the range space of $\mathbf{A}$. The approach, then, is to test which of the columns of the identity matrix lie in the range space of $\mathbf{A}$. This can be done efficiently using the compact singular value decomposition of $\mathbf{A}$, that is, $\mathrm{A} = \mathrm{U}\boldsymbol{\Sigma}\mathrm{V}^T$. If $\boldsymbol{e}_k$ is in the range space of $\mathbf{A}$ then $\boldsymbol{e}_k^T\mathbf{U}$ must have unit length like $\boldsymbol{e}_k$. Note that $\boldsymbol{e}_k^T\mathbf{U}$ is simply the kth row of $\mathbf{U}$. In summary, we first calculate the sum of squares of each row of $\mathbf{U}$. The pair of rows in which the squares sum to one correspond to the points whose distance has been recorded erroneously.

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Advanced/smart manufacturing: From nanoscale to megascale

Sharad Sinha

In continuation of our efforts to bring you thematic issues centered around interesting and hot topics, this issue of *IEEE Potentials* focuses on advanced and smart manufacturing technologies. Increasingly, industry segments are facing the challenge to decrease the manufacturing cost per unit of a product. A number of different measures have been adopted by companies including moving factories to places with lower labor costs, improving production processes and manufacturing technologies, and designing better products.

With information technology (IT) playing an increasing role in almost every sphere of our lives and the cacophony around the "Internet of Things," which aims to interconnect devices, processes, and human beings to optimize certain goals, there is a growing interest in the manufacturing industry toward greater incorporation of IT technologies in the manufacturing sector.

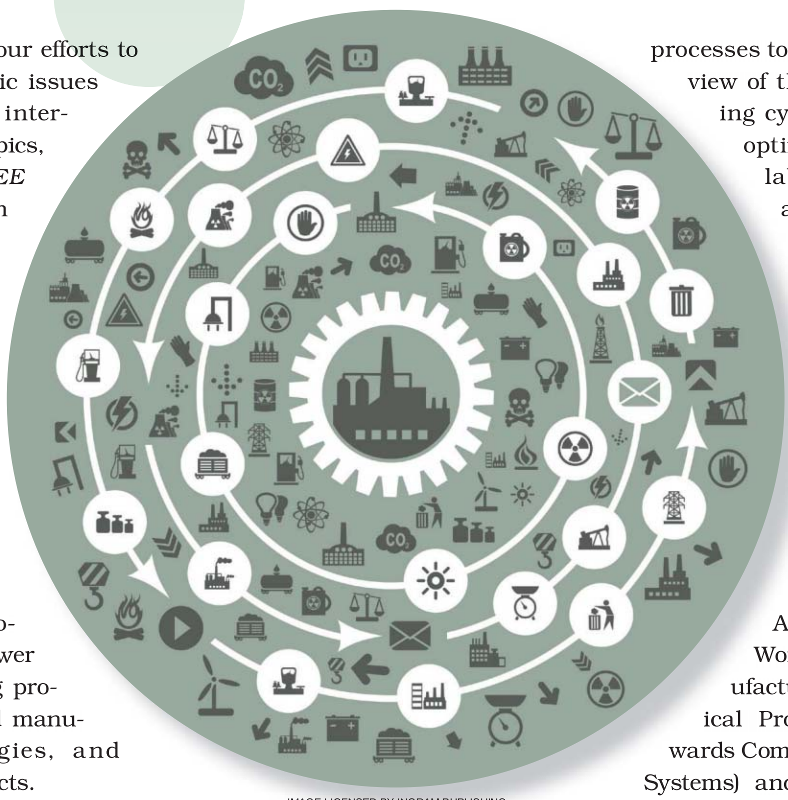

IMAGE LICENSED BY INGRAM PUBLISHING

This IT-oriented view of production and manufacturing is now referred to as *smart manufacturing* or *industry 4.0* (if you are from Europe). The goal is to interconnect machines, labor, materials, and processes to gather a better overall view of the entire manufacturing cycle so that it could be optimized with respect to labor, material, energy, and cost efficiencies.

It is believed that this approach would bring about the next industrial revolution and a number of summits (such as the Fourth Annual Smart Manufacturing Summit and the National Institute of Standards and Technology and the Open Applications Group Inc. Workshop on Smart Manufacturing and Cyber-Physical Production Systems—Towards Composable Manufacturing Systems) and research plans have been dedicated for this purpose (the National Science Foundation National Network for Manufacturing Innovation, United States, and the Smart Foundry 2020, India, among others).

A number of companies are moving toward adopting the interconnected view of factories and their automation. In comparison to other industrial position papers and blogs that focus exclusively on the IT-oriented view of

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smart manufacturing and examine the production and the manufacture of products, in this issue we take the liberty to explore manufacturing advancement at both the product level as well as at the technology level that would enable some of these products.

The articles in this issue cover approaches extending from nanoscale fabrication to megascale production. We hope you gain valuable insight into the manufacturing and fabrication challenges existing at both scales, as essentially some of the nanoscale devices would be turned into products sold at the megascale.

"Smart Assembly for Soft Bioelectronics" by Chee Hwan Lee focuses on the smart assembly of soft bioelectronics. These and related approaches to assemble bioelectronic devices may prove critical to the production and adoption of biocompatible structures in medical devices of the future.

Many of us played with LEGO blocks when we were kids. Following this lead, "LEGO-Like Microassembly Using Reversible Dry Adhesion" by Seok Kim presents the concept of LEGO-like microassembly to discuss advances in micromanufacturing. This has enabled him to produce teapots and motor-like three-dimensional (3-D) microstructures on silicon. The method can be extended to research and develop different kinds of structures at the micro- or the nanoscale, which could be used in different devices (for instance, the accelerometer in your smartphone uses a similar microsensor).

Three-dimensional printing is a fascinating topic, and different kinds of 3-D printers for home use are being developed and promoted on different platforms, including crowdfunding sites such as Kickstarter. In "An Overview of 3-D Printing in the Manufacturing, Aerospace, and Automotive Industries," Choon Wee Joel Lim et al. present a discussion of how 3-D printing is going to play an important role in manufacturing components in the aerospace and the automotive industries.

We hope you gain valuable insight into the manufacturing and fabrication challenges existing at both scales, as essentially some of the nanoscale devices would be turned into products sold at the megascale.

Siwei Jiang et al. discuss modeling, simulation, and optimization methods for manufacturing operations and supply chain networks. Their article, "Complex and Intelligent Systems in Manufacturing Operations and Supply Chain Networks," includes various ideas related to memetic computation and computational intelligence that could be used to understand and improve the many different complex processes involved in large-scale manufacturing—from supply chain management to factory assembly line.

In "SMART Foundry 2020," B. Ravi focuses on a concept that presents an IT-oriented view of manufacturing being worked on by a consortium of educational institutions and companies under the sponsorship of state and national governments in India. His article covers the basics of manufacturing and extends to the sensor-enabled and cloud-based data analytics necessary for making manufacturing smart. At the same time, this is discussed with a perspective on the role of smart manufacturing in economics and job creation in countries like India.

The final article is dedicated to semiconductor manufacturing technologies, a prime mover of consumer electronics market. In "Exposure Optimization in Scanning Laser Lithography for Semiconductor Manufacturing," Andrew J. Fleming, Adrian G. Wills, and Ben S. Routley discuss the challenges in lithography for integrated circuit design and associated optimization methods. The decreasing feature size of transistors (from the old 180 nm to the present 14 nm and beyond) has made lithography more challenging.

We hope that you will learn from the breadth and the depth of these smart manufacturing articles and provide us with feedback so that we may continue to bring you topics dedicated to subjects that most interest you.

About the author

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Smart Manufacturing

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Smart assembly for soft bioelectronics

Chi Hwan Lee

Biology is soft and curvilinear, whereas wafer-based electronics are rigid and planar. The mechanical mismatch impedes the effective integration of electronic systems with biological tissues or skins, paving the way for the construction of device materials (i.e., semiconducting composites) onto soft, biocompatible elastomers with the ability to be stretched, bent, and twisted. Advances in mechanics allow the rather brittle device materials to accommodate large levels of strain ($\gg$1%) and therefore retain their functionality under repeated mechanical deformations in use.

A large array of emerging products ranging from skin-like wearable health-monitoring systems to stretchable, bioresorbable electronic implants exist at a prototyping or commercializing phase. This article reviews recent developments in advanced assembly techniques to integrate various device materials with bio-related soft substrates and their applications in emerging biomedical devices.

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Advanced assembly techniques

A set of techniques has become available for the assembly of device materials with soft, biocompatible elastomers. A representative strategy, often referred to as a *transfer printing technique*, uses a series of pick-and-place processes in a deterministic manner in which arrays of device materials are picked from a native substrate by using a viscoelastic stamp, such as polydimethylsiloxane (PDMS), and then printed onto a receiver substrate. Various classes of device materials in the forms of membranes, ribbons, or wires are available for the process to

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serve as active semiconducting components.

The basic mechanism of the process relies on the intrinsic viscoelastic behavior of the stamps, where the adhesion forces strongly depend on peeling rate; when the stamp delaminates quickly (>~10 cm/s), the adhesion energy at the interface between stamp and device materials is larger than its counterpart at the interface between the donor substrate and device materials and, thereby, the stamp can "pick-up" the device materials. Similarly, the opposite occurs when the stamp delaminates slowly (<~10 cm/s) for "printing" step. To further enhance the efficacy of the pick-and-place process, several techniques exploit the modified viscoelastic stamp configured with carefully defined microstructures.

Figure 1 shows an example that uses a viscoelastic stamp with pyramidal microtips at the corners, allowing pressure-modulated adhesion controls in high- and low-adhesion states for picking and printing successively. The compressed stamp, when in full contact (Fig. 1, top panel) has a strong rate-dependent behavior while the adhesion forces decrease when the stamp retrieves its original shape (Fig. 1, bottom panel). The large differences in contact area allow for the high levels of adhesion switching between the high- and low-adhesion states.

Advances in mechanics allow the rather brittle device materials to accommodate large levels of strain (≫1%) and therefore retain their functionality under repeated mechanical deformations in use.

The commercial grade of completely automated tools for the adhesion-controlled pick-and-place processes over wafer-scale exist with the capabilities of printing rates more than millions of device materials per hour, nearly 100% yields, and placement accuracy better than 1 ∓m. Many of the emerging electronic systems described in the following sections exploit these techniques and serve as test bed applications of the reliable assembly capabilities.

Other classes of transfer printing techniques also exist in which the basic working principles rely on different phenomenon. A representative example includes the environment-assisted transfer printing technique that exploits a controlled interfacial delamination phenomenon by using water in manipulated environments in terms of temperature, pH, and chemical surfactants.

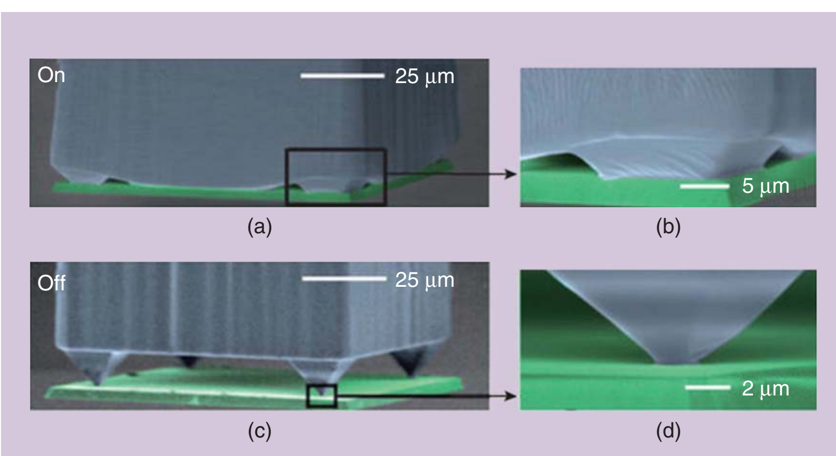

FIG1 Scanning electron microscope (SEM) images of a viscoelastic stamp bearing pyramidal microtips in high- and low-adhesion states [(a) and (c), respectively], in which the transferring object appears green. (b) and (d) show high magnification images of individual microtips in each state.

Here, a layer of ductile metals such as nickel or copper (~300 nm thick) serves as the separation layer at the interface between the growth/fabrication substrate and the prefabricated device on top. In the presence of water, the applied mechanical peeling forces deforms the chemical bonds of the metal (separation) layer and the surface of the growth/fabrication substrate (i.e., a silicon wafer), causing induced electrostatic charges to attract water molecules.

Chemical reactions happen between the attracted water molecules and the mechanically strained chemical bonds at the debonding tips, thereby significantly reducing the energy release rate (up to ~75%) to readily generate the interfacial delamination. The phenomenon is referred to as *water-assisted subcritical debonding*. The resulting interfacial delamination liberates the device layer from the growth/fabrication substrate and then prints onto a receiver "target" substrate to complete the entire process. No post-fabrication steps are required, so the choices of receiver substrates can be extended to almost arbitrary materials ranging from paper, rubber, plastic, and bio-related soft materials. Demonstration devices enabled by the technique include flexible thin-film solar panels, ultrathin nanosensors, wearable memory devices, and water-dissolvable electronic systems. No effective biomedical devices have yet appeared.

One disadvantage involves the fact that the metallic separation layer (nickel or copper) prevents the growth of monocrystalline semiconducting materials, impeding the construction of commercial-grade products. Efforts to overcome this limitation are being exerted.

Skin-like wearable electronics

Wearable electronic systems that typically consist of an array of sensors, data acquisition modules, and remote control stations have evolved for several decades in diverse forms by exploiting wrists, shirts,

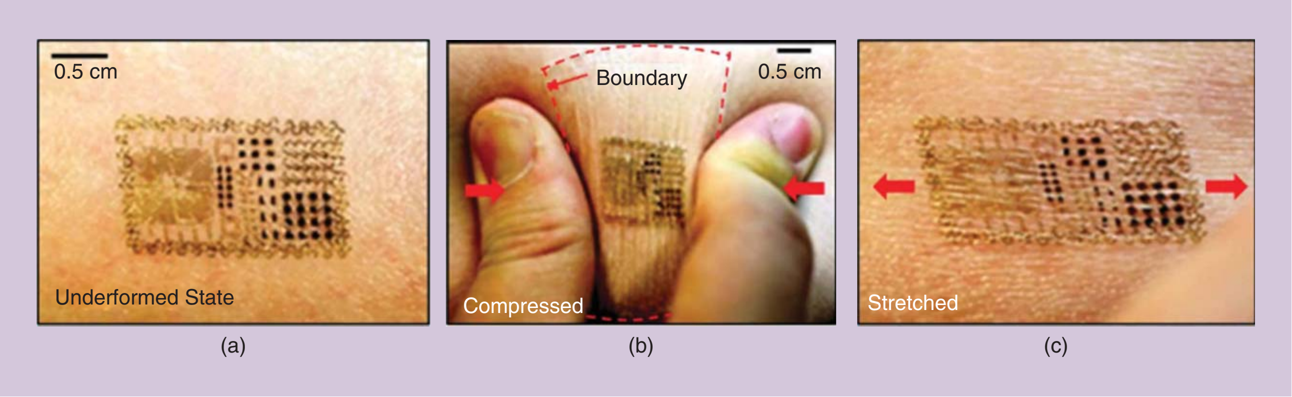

FIG2 A series of optical images of a demonstration platform for skin-like wearable electronics (a) attached on the skin, (b) compressed, and (c) stretched. (Images reprinted with permission from AAAS/Science.)

bands, socks, or adhesive patches. These devices have many important capabilities for applications in at-home health-care systems, but a key challenge remains in the discomfort of unsuitable sizes, weights, and shapes for practical applications during prolonged use.

Recent advances in materials, mechanics, and manufacturing technologies have led to ultrathin, lightweight, and stretchable "skin-like" wearable electronics that can conformably laminate onto the surface of the skin and are mechanically invisible to the user. A representative example device appears in Fig. 2, in which the device platform is equipped with a broad collection of electronic sensors for temperature, strain, pH, and electrophysiological signals to monitor electrical, chemical, and mechanical activities through the skin. Here, the printed arrays of semiconductor nanomaterials (i.e., silicon nanomembranes) that are configured with serpentine (stretchable) interconnectors serve as active sensing components. The stretchable design configurations that typically comprise device islands connected by serpentine interconnects allow the entire device structure to accommodate large deformations without fracture, yielding high levels of stretchability. These strategies aim to isolate the mechanical deformations to the elastomers, thereby significantly reducing principal strains in the rather brittle device materials.

The design configurations can also combine multilayer neutral mechanical plane layouts to offset the induced tensile/compressive strains in the device materials under bending. Clinical utility of these types of devices exists for skin-mountable biomedical applications that need to run in a rapid, mechanically flexible, and noninvasive manner. Examples include those for real-time monitoring of temperature, pressure, stiffness, and vascular blood flow rate through the skin.

The products are equipped with various electronic modules, such as accelerometers, gyroscopes, and physiological sensors, allowing to wirelessly provide first-hand data to medical researchers. The technology is expected to play an important role in future monitoring systems for motion disorders such as Parkinson's disease or neurodegenerative disorders, as a representative example.

Soft core/shell packages

Many clinical applications involve the mounting of such electronic systems on the surface of the skin, which requires an efficient packaging system to protect the devices from environments as well as to minimize the interfacial stresses

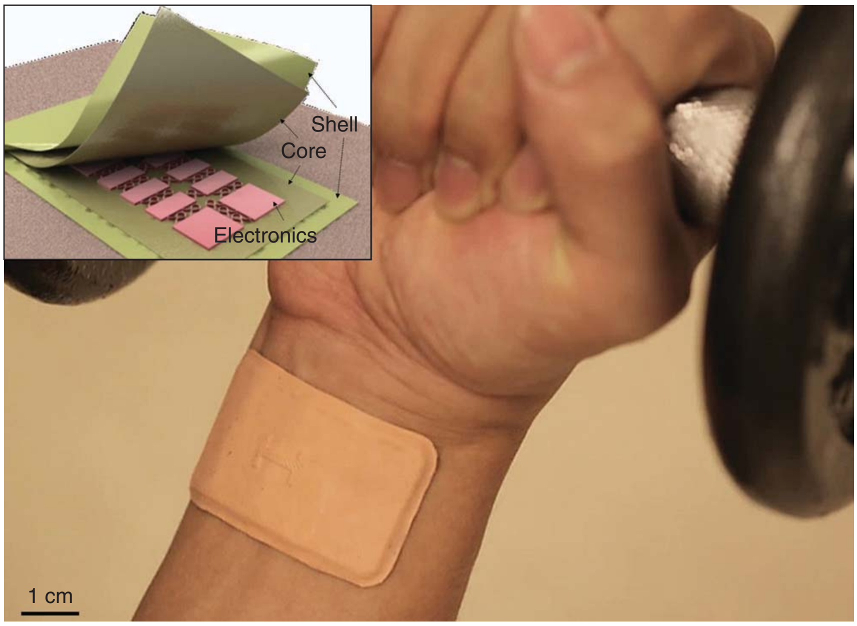

FIG3 An optical image of a core/shell packaging structure applied on the wrist during dumbbell lifting. The inset shows a cross-sectional illustration of the representative layers in a core/shell structure with embedded stretchable electronics. (Images reprinted with permission from Wiley-VCH.)

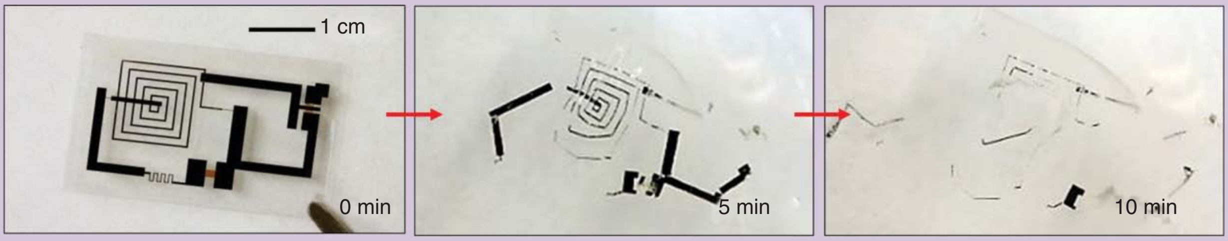

FIG4 A series of optical images of a demonstration platform for bioresorbable (transient) electronics dissolved in deionized water in time sequence. (Images reprinted with permission from AAAS/SCIENCE.)

with the skin. Recent approaches have developed core/shell structures (Fig. 3, inset) where the core contains the functional devices surrounded with either extremely soft liquid or solid materials, while the shell involves a thin enclosure using a different elastomer to provide a robust interface for handling and laminating onto the skin.

Efforts toward mechanically unusual forms of electronic systems have established the foundations to advance the technology for even more challenging materials and devices.

A demonstration example exploits microfluidic spaces filled with dielectric fluids (i.e., silicone oligomer without curing agent) for the core and supporting elastomeric substrate/encapsulate layer (i.e., Ecoflex) for the shell. Devices and associated stretchable interconnectors are suspended in the microfluidic space, where each electronic component is selectively anchored to the bottom surface. The configuration allows for the decoupling of the mechanics of the free-floating interconnectors from the shell, enabling large-range motions with little constraint in response to externally imposed deformations, such as bending, stretching, and twisting.

A disadvantage, however, exists in this structure for the possibility of fluid leakage from the damage to the shell. To resolve this issue, an alternative strategy exploits an ultralow modulus solid silicone elastomer (i.e., Silbione, Young's modulus (E) = ~5 kPa) for the core material to capture the favorable mechanics and to eliminate any possibility for the leakage. Here, the thickness of the core material plays a critical role in the mechanical isolation of the devices where the effective tensile modulus of the core/shell package can significantly decrease as the thickness of the core material increases. The optimized layout of the core/shell package yields mechanically imperceptible systems to the wearers for normal skin sensitivity (~20 kPa) with abilities of reversible responses to large strain deformations (up to > ~30%).

As shown in Fig. 3, the package structure can also incorporate a human skin-like color by applying a commercial coloring pigment to provide aesthetics for the skin-mountable units. The resulting device can intimately mount onto the surface of the skin without delamination, simultaneously allowing for the monitoring of physiological signals or sense motions of the wearer by exploiting the built-in functionalities.

Bioresorbable electronic implants

Efforts toward mechanically unusual forms of electronic systems have established the foundations to advance the technology for even more challenging materials and devices. Paradigms of the device platforms can shift from wearable, stretchable to implantable, bioresorbable formats. The latter presents the electronic devices with the ability to physically dissolve via resorption in the body in a programmable manner.

The devices, often referred to as *transient electronics*, consist of entirely biocompatible and bioresorbable materials, as well as nontoxic end products, such as magnesium/molybdenum for conductors, silicon dioxides/magnesium oxide for dielectrics and passivation layers, single crystalline silicon nanomembranes for semiconductors, and silk/poly(lactic-co-glycolic acid) for substrates and encapsulating materials. The resulting outcome presents the integrated circuits that can temporarily provide diagnostic and/or therapeutic functions, followed by complete dissolution in the body at a prescribed time frame, thereby eliminating the unnecessary load for surgical extraction of the implanted hardware.

Figure 4 shows the first proof-of-concept device, pioneered by Prof. John A. Rogers' group at the University of Illinois at Urbana–Champaign, that comprises a set of electronic components, ranging from inductors, capacitors, resistors, diodes, transistors, and metal interconnects, to substrate/encapsulate, all in a completely dissolvable format by deionized water at room temperature. Mechanical stretchability for these classes of devices is also important, especially when they serve as implantable systems by integrating with the curvilinear surfaces of biological tissues.

For this purpose, the devices can incorporate the stretchable design configurations, such as device islands connected with serpentine interconnects to accommodate various levels of strains. Example devices show stretchability up to ~30% without degradations in performances, where portions of the device structures begin to delaminate when further stretched.

The demonstration examples involve stretchable, bioresorbable pH monitors where the chemically functionalized silicon nanoribbons serve as an active sensing element to detect the change of pH of surrounding aqueous solutions. Here, dissolvable metals such as magnesium serves as the electrodes and interconnects, silicon dioxide serve as the interlayer dielectrics and encapsulant, and biodegradable elastomer (poly-1,8-octanediol-*co-citrate*) serves as the substrate. Each component completely dissolves within hours to days in physiological conditions (i.e., phosphate buffer saline, pH: ~7.4 at 37 °C) via reactive resorptions (hydrolysis). In the same condition, the conductance of sensing materials (i.e., doped silicon nanoribbons) is changed by only ~1% or less during immersion for five days. The dissolution behaviors are tunable depending on materials, thicknesses, morphologies, and encapsulation strategies. Essential concepts, basic materials, and fabrication techniques are now available for these types of technology.

Conclusion

Advanced materials, assembly techniques, soft core/shell packaging strategies, and stretchable mechanics designs have established a route to build new classes of soft bioelectronics with capabilities that cannot be achieved by conventional electronic systems. Emerging electronic systems enabled by these technologies were reviewed including skin-like wearable electronics and bioresorbable electronic implants. The monolithic integrated systems equipped with wireless power suppliers and data communications are continuously improving. Interesting future topics in the relevant research includes the investigations of possible interactions through the effective interface between the soft bioelectronics and the surrounding biology.

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Smart Manufacturing


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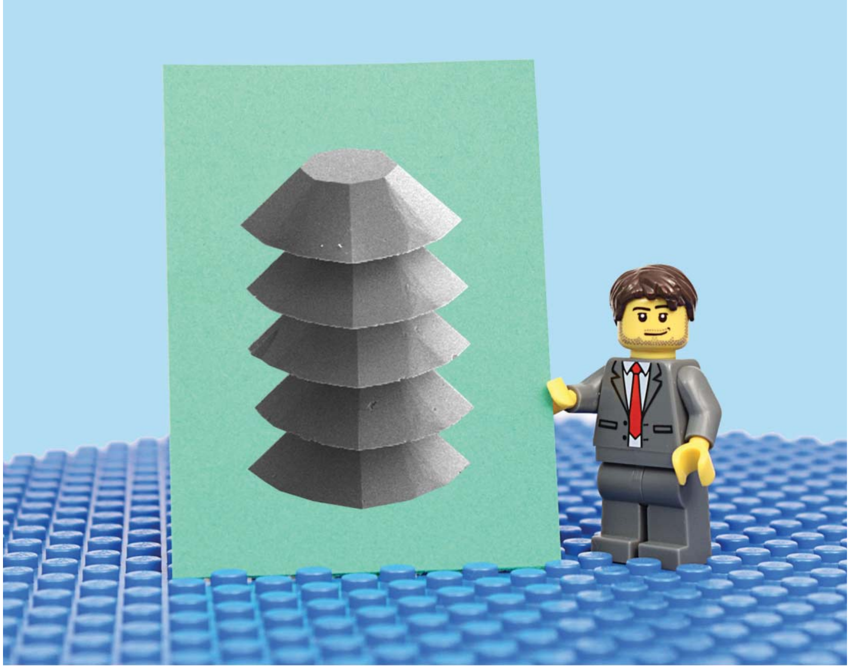
LEGO-like microassembly using reversible dry adhesion

Seek Kim

When I was a kid, I was fascinated by watching water striders glide on the water and would wonder: why do they not drown but instead play, standing effortlessly on the water? This is undoubtedly a common question among curious children. The simplest answer would be "because the insect is very small and light." So then, why are smaller things better able to float on the water? An aircraft carrier can easily float on the sea too, although it is extremely large.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As I got older, I gradually learned that things in different sizes are governed by different external forces. For example, a water strider floats dominantly due to surface tension, while buoyancy lifts and allows an aircraft carrier to cruise. Indeed, surface tension is one of the most dominant and often the most troublesome force at the micro- or smaller scale, unless things are so small that classical mechanics are no longer valid.

Consider the following example: Body weight or buoyancy is linearly proportional to body volume, i.e., its length cubed. In the same way, surface adhesion or friction increases linearly as surface area, or length squared, increases. Surface tension is just directly proportional to length. Thus, if a body is doubled isometrically, its length, surface, and volume would increase by factors of two, four, and eight, respectively. This implies that buoyancy or body weight would be more dominant than surface tension or surface adhesion at larger scale, and vice versa.

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Different scales need different manufacturing methods

Once this conclusion is reached one may imagine that common macro world manufacturing methods may not necessarily be suitable for small-scale manufacturing. At the microscale, sawdust or drill debris would tend to stick to saws or drill bits because of the vanishing ratio of inertia to surface adhesion, and as a result, cutting or coring would be more difficult at smaller scale. This is why common manufacturing approaches at the microscale rely on a diverse set of electrochemical process sequences to build microscale structures.

Microfabrication is a popular, all-encompassing name to describe

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these many processes. Typical microfabrication involves multiple process cycles starting with a thin film (from submicron to a few micrometers) of material deposited on a flat substrate under vacuum conditions. Since the target material film covers the entirety of the substrate, a lithography step follows to form a patterned photoresist layer that acts as a masking layer for the subsequent thin-film etching step, thus defining the thin film's desired shape. This may be the first of many similar process cycles to be conducted sequentially on the substrate until an intended structure is completed.

As all processes are done on a single substrate, this form of microfabrication can be defined more specifically as *monolithic microfabrication*. Microfabrication has been a very successful high-precision micromanufacturing method for mass production of integrated circuit (IC) chips and microelectromechanical systems (MEMS) devices, which are composed of micro- or nanoscale constituents.

Nevertheless, microfabrication inherently suffers from a variety of challenges, such as the high cost originating from vacuum processes; difficulty with the recycling of etched materials, which often constitute a majority of a deposited film; complications with creating three-dimensional architectures; and significant limitations when attempting to combine different classes of materials. These challenges originate from the layer-by-layer thin-film processing of a single substrate and the fact that dissimilar materials often require different and incompatible techniques to process. Consequently, the development of novel micro-devices with improved performance or new functionality often requires independent fabrication of constituents followed by microassembly, rather than monolithic microfabrication.

Microassembly combined with microfabrication advances micromanufacturing

Microassembly is generally classified into two categories: 1) robotic pick-and-place including contact and noncontact modes and 2) self-assembly relying on the principle of minimum total potential energy. Robotic pick-and-place commonly uses microgrippers, such as mechanical tweezers or other end effectors operated by electrostatic, magnetic, capillary, optical, or vacuum effects. This approach can perform very complex handling tasks utilizing machine vision, force sensing, and feedback control. However, it is very difficult to release a micro-object once gripped with a contact mode microgripper, since surface adhesion dominates over body weight at the microscale. Without proper strategies to overcome surface adhesion between a micro-object and microgrippers, releasing processes are very tedious and time-consuming, if not impossible.

The development of such novel microsystems with improved performance or new functionality often requires independent fabrication of constituents followed by microassembly, rather than monolithic microfabrication.

Moreover, microgrippers may damage micro-objects, and such manipulations are not easily preformed in parallel, thus scaling the approach to allow for mass production is generally not feasible.

Self-assembly is performed by designing the system with the desired assembling positions of micro-objects that correspond to the minimal potential energy of the system. Therefore, the assembly naturally forms using gravitational, capillary, or electrostatic forces as the driving potential. Since self-assembly uses the minimum total potential energy principle, it can be done in parallel for higher throughput. While self-assembly is well suited for multibatch processes, it suffers from poor design flexibility and often poor yield due to the misassembly of parts when the system is stuck in its local potential energy minimum.

Each approach has different advantages and disadvantages so that each one can be used for different needs or purposes. However, the need remains for a manufacturing approach that can allow for both strong flexibility of design and scalable manufacture.

Transfer printing using reversible dry adhesion

To enable deterministic and parallel manipulation of micro-objects, transfer printing, involving the use of smart dry surfaces with highly reversible adhesion (i.e., reversible dry adhesives) has been studied in many different forms for the last several years. Among these, a microstructured elastomeric surface designed using strategies of biomimetic dry adhesives provides extreme, reversible levels of switchability of nonspecific, generalized adhesion. This design turns out to be highly effective for controlling surface dry adhesion to pick and place micro-objects and possibly in parallel mode for process scalability.

This microstructured elastomeric surface can repeatedly switch its dry adhesion as a function of drastic contact area change upon mechanical loading. Figure 1 presents the surface with a microplatelet in its strong and weak adhesion states (i.e., adhesion ON and OFF), which corresponds to pick and place modes, respectively. When the microplatelet is in contact with a receiving surface and their intermolecular interaction is sufficient, the microstructured surface in its adhesion OFF state can release the microplatelet.

How to join adjacent micro-objects

While transfer printing has shown enormous potential toward highly scalable heterogeneous materials integration, it natively addresses

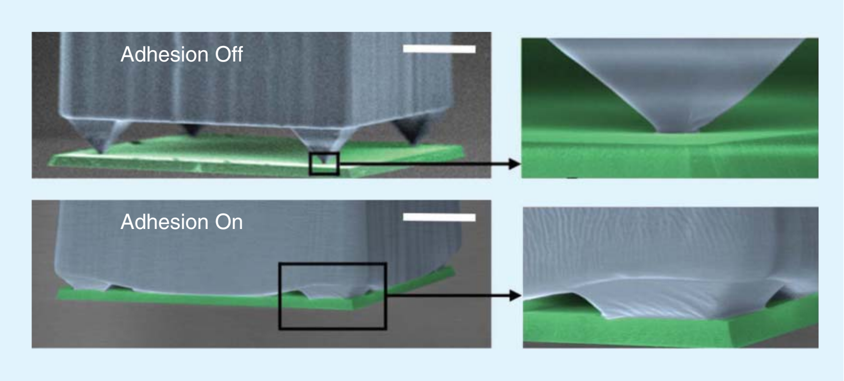

FIG1 The colored scanning electron microscope (SEM) images of a microstructured elastomeric surface representing its strong and week adhesion states (i.e., adhesion ON and OFF), in which microplatelets appear green. Scale bars are 20 μm. (Reproduced with permission from S. Kim et al., 2010.)

only manipulation of micro-objects from the microassembly point of view. Microassembly-enabled functional devices may only be considered complete when the manipulated objects are finally joined together, not only mechanically but also electrically, thermally, and optically, as each application requires. Strategies of material joining have been extensively studied in the MEMS field, where two wafers of homogeneous or heterogeneous materials are brought together, pressed to enhance their intimate contact, and annealed to cause direct bonding that forms covalent bonds at the atomic level.

Similarly, micro-objects may be joined based on covalent or metallic bonds simply by annealing after transfer printing. Whereas the bonding of large wafers is highly sensitive to surface defects, which ruin intimate surface contact and therefore bond quality, the likelihood of surface defects tends to decrease as an object becomes smaller, particularly when its surface is small compared to the surface defect density. Once micro-objects are placed, they can be annealed and joined without any pressing step to enhance intimate contact in most circumstances. Intermolecular force between the micro-object and substrate is enough to form their intimate contact.

Microassembly of heterogeneous materials relying on transfer printing and thermal annealing, so called *micro-LEGO*, is a new approach that complements monolithic microfabrication.

Different joining mechanisms are adopted for different material pairs at the interface of two micro-objects. For example, two silicon objects are joined through fusion bonding, while a silicon-to-gold interface is formed through eutectic bonding, each process involving its own processing conditions of temperature and duration.

LEGO-like microassembly

Microassembly of heterogeneous materials relying on transfer printing and thermal annealing, so called *micro-LEGO*, is a new approach that complements monolithic microfabrication. This assembly is referred to as *micro-masonry* or *micro-LEGO* due to the similarities in the aspects of stacking and joining of disparate classes of building blocks while at different scales. Target materials are processed into transferrable micro-objects, assembled into spatially organized three-dimensional (3-D) architectures via reversible adhesion-based transfer printing and thermal annealing-based material joining.

Figure 2 depicts the general procedure of micro-LEGO, where micro-objects are first formed such that they are weakly tethered to a donor substrate and they can be retrieved by a microstructured elastomeric surface, i.e., a reversible dry adhesive. Those micro-objects are repeatedly retrieved, delivered, and placed onto a receiving substrate, then joined through thermal annealing. This approach has allowed not only the construction of teapot-, pagoda-, and motor-like 3-D silicon microstructures, but also the assembly of a micromirror device with silicon platelets and conductive elastomers as demonstrated in Fig. 3. These 3-D heterogeneous

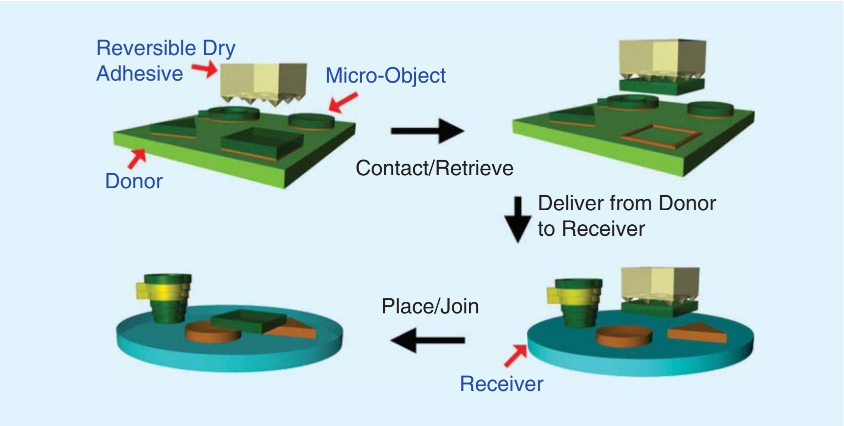

FIG2 The procedure of LEGO-like microassembly including micro-object retrieval using a microstructured surface with reversible dry adhesion, delivery to the target location of a receiver, and placing and joining of the micro-object on the receiver.

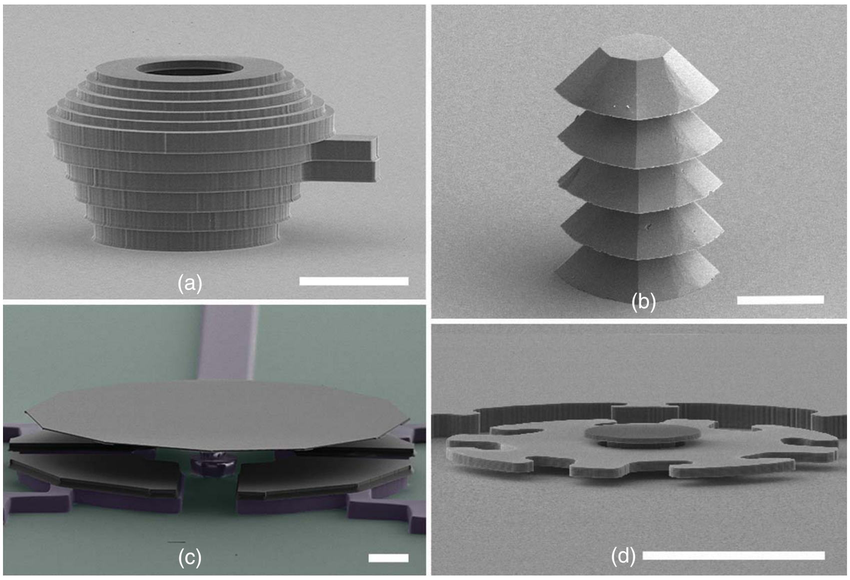

FIG3 Exemplary microstructures and a microdevice fabricated by LEGO-like microassembly. Micro-teapot, (b) a micro-pagoda, (c) a micro-mirror device, and (d) micromotor structures. All are made of silicon (gray) and conductive (purple) or nonconductive (green) elastomers. Scale bars are 100 μm. (Reproduced with permission from H. Keum, et al., 2012; J.D. Eisenhaure, et al., 2016; and Z. Yang, et al., 2015.)

architectures of assembled structures and devices are extremely challenging, if not impossible, to reproduce via conventional monolithic microfabrication or other microassembly techniques, such as those based on robotic pick and place and self-assembly.

question of transfer printing is how to achieve process parallelism and selectivity simultaneously.

In addition, quick and selective material joining processes must also be developed to enable scalable and flexible microassembly. The use of reversible dry adhesion of responsive materials, such as shape memory polymers, in place of elastomers, and local thermal annealing techniques including laser raster scanning are being actively researched to meet these needs.

While miniaturized electronic device manufacturing has and will continue to rely on monolithic microfabrication, further advances to enable 3-D integration of active and passive components, 3-D architectures for MEMS, and others necessitate alternate manufacturing methods.

Future of micro-LEGO

Transfer printing natively supports mass production since it involves an elastomeric surface that may deliver micro-objects in parallel or roll-to-roll fashions, yet micro-LEGO based on transfer printing has yet to be demonstrated with any significant degree of parallelism. Furthermore, for the improvement of process flexibility selective manipulation of micro-objects is desired. In this regard, the grand

While miniaturized electronic device manufacturing has continued and will continue to rely on monolithic microfabrication, further advances to enable 3-D integration of active and passive components, 3-D architectures for MEMS, and others necessitate alternate manufacturing methods including deterministic robotic pick and place and stochastic self-assembly. In addition, transfer-printing-based microassembly, i.e., micro-LEGO, would be the third axis to complement monolithic microfabrication due its potential for assembly scalability and flexibility.

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An overview of 3-D printing in the manufacturing, aerospace, and automotive industries

Choon Wee Joel Lim, Kim Quy Le, Qingyang Lu, and Chee How Wong

Additive manufacturing (AM), also known as three-dimensional (3-D) printing, is the process of joining materials to make objects from 3-D model data, usually layer upon layer. Contrary to conventional manufacturing techniques, parts are built up by the addition of materials one layer at a time, corresponding to the cross section of the sliced 3-D model. Due to the nature of AM's layer-wise fabrication process, the need for fixtures and cutting tools are eliminated. Furthermore, computer-aided design (CAD) tools have allowed design optimization on demand, enabling the production of customizable parts readily.

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To discuss the impacts of AM, we describe the AM process, in general, before examining its contribution and potential challenges in the manufacturing, aerospace, and automotive industries.

Additive manufacturing

AM, which is referred to as the "the third industrial revolution" in recently published articles, is a manufacturing process that fabricates a 3-D object by adding materials layer by layer. Applications include the building of houses, complex engineering mechanical parts, medical implants, and even food.

Generally, as illustrated in Fig. 1, 3-D-printed objects can be created following the eight steps in an AM process. First, users create a 3-D model with the use of CAD software, before converting it into a stereolithography (STL) file. The user inputs the parameters and the STL file into the AM system, after which slices of the digital mock-up are generated before transferring into the build sequence. Next, the machine builds the part, layer by layer. Upon completion, the user will then remove the part from the substrate and perform the post-processing necessary for use as a functional product or prototype. Most importantly, to facilitate easy assembly and serve its purpose, it is necessary that these printed parts satisfy the three Fs—form, fit, and function.

AM for engineering applications

Metal AM, mainly powder based, is more commonly used in the manufacturing, aerospace, and automotive industries. Specifically, direct metal laser sintering (DMLS), electron beam melting (EBM), and selective laser melting (SLM) are technologies

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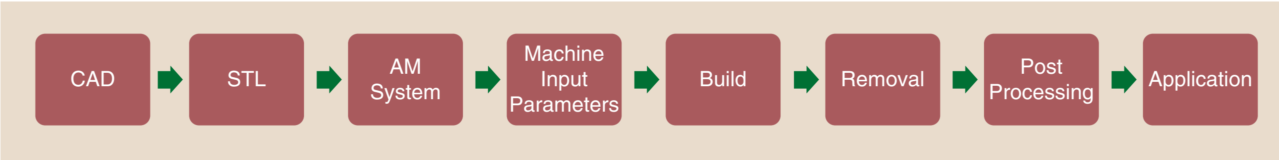

FIG1 The general AM process steps.

under the ambit of powder bed fusion (PBF). Another category that uses powder materials, directed energy deposition (DED), consists of direct metal deposition (DMD) and laser metal deposition (LMD).

The PBF processes involve material deposition onto the build area before the energy source (either laser or electron beam) heats the cross-sectional area of the sliced 3-D model, while the DED processes involve concurrent material and energy deposition through a nozzle to the desired area. These processes fully melt the powder particles in an inert gas atmosphere or under shield gas, which is capable of producing high relative density as-built parts (≥99.5%). In addition, rapid cooling during the fabrication produces parts with fine microstructures, improving the mechanical properties.

Most studies focus on metallic alloys due to their excellent mechanical properties. However, the mechanical properties of these parts produced vary across different AM processes. As an example, Table 1 compares the reported tensile strength of Ti-6Al-4V parts produced by various AM processes. From this table, the tensile strength of the parts manufactured generally falls between 900 MPa and 1,400 MPa.

Moreover, among these processes, SLM and LMD produce parts with higher tensile strength (≈1,250 MPa) while EBM produced the weakest (946 MPa). Next, the yield strengths reported for DMD (1,105 MPa) and LMD (1,100 MPa) show that the stresses at which the parts began to deform plastically are rather similar. Similarly, EBM and DMLS produced parts with a lower yield strength of approximately 800 MPa. However, it is worthwhile to note that there are several other factors that will affect such properties. These factors include powder characteristics, energy source type and settings, and built environment.

AM in the manufacturing industry

AM, an enabling technology, has significant impacts on manufacturing. It changes design concepts and provides more leeway for the user to create interesting and complex parts. Parts can be fabricated as a single piece rather than being assembled from several pieces made by conventional methods. For example, in the automobile industry, cars that are traditionally built on assembly lines can be now fabricated within a machine. A 3-D-printed car can have several parts fabricated as one piece instead of a few, in contrast to the cars manufactured today.

Being a subtractive process, computer numerical control (CNC) machining of parts with internal cavities is a tall order. In contrast, this is not a problem for AM due to its additive nature. This method of fabrication opens possibilities like the fabrication of internal cooling chambers for aerospace components as single bodies without the need for fasteners. Additionally, lesser parts that are mechanically joined together will require lesser inspections and therefore improve workflow efficiency.

AM also prevents excessive material wastage. In conventional manufacturing methods, materials are gradually removed from the bulk to achieve the desired features. This process will lead to the wastage of any excess material. The excess material, usually in the form of chips, has to be recycled or discarded, incurring extra costs. Material wastage is reduced drastically in AM, as there are no issues associated with material removal. Processes like DMLS may not have any form of waste material, except when support structures are required.

Injection molding is another conventional manufacturing method that requires a cavity and a core. The downside of injection molding is the difficulty in manufacturing undercuts and blind holes. In contrast, AM can easily build complex parts without a need for the tool mold to create a particular desired shape.

Recently, E. Atzeni and A. Salmi conducted a study to compare the cost of high-pressure die-cast and SLS produced parts. Results revealed that the total cost per assembly by high-pressure die-casting is €21.29 + 21,000/N, where N is the number of parts. For instance, the cost per assembly of ten pieces is €2121.29, while the cost is €231.29 for fabricating 100 pieces. In comparison, the total cost per assembly by SLS is €526.31 for all production volume. Therefore, this study shows that AM is preferable for small-to-medium batch productions.

Potential challenges of AM in manufacturing

Although AM provides several benefits to the manufacturing industry, there are persistent challenges that hinder its wide adoption. One challenge is to achieve the desired strength of the part through design

TABLE 1. The tensile properties of Ti-6Al-4V parts produced by various AM processes.

MECHANICAL PROPERTIES	AM PROCESS				
	DMD	SLM	LMD	DMLS	EBM
Tensile strength (MPa)	1,163±22	1,200–1,400	1,211±31	1,043.3	946
Yield strength (MPa)	1,105±19	—	1,100±12	797.7	848

optimization. The other challenge lies in understanding the microstructure and mechanical properties of the AM-produced parts. This understanding is important so that the mechanical properties of the AM parts, such as density, tensile strength, and hardness, can meet the application requirements.

AM in the aerospace industry

AM has significant impacts in the aerospace industry, given that there are many opportunities that it can provide—design, material, and fabrication methods. Through AM, it is possible to fabricate near-net shape functional parts in a short span of time, increasing reliability and reducing cost. Furthermore, as AM is capable of building lattice structure parts, the weight of an aircraft can be reduced, improving fuel efficiency.

With an increased use of unmanned aerial vehicles (UAVs) to replace manned aircrafts, there is a heavier reliance on the cost-effective production of prototypes and small production runs. For space applications, engineers can design more sophisticated rocket propulsion systems that can carry a higher payload or even printing parts in space for future missions.

Advantages of AM in commercial aircraft

AM is viable for printing rarely replaced parts that have a high buy-to-fly ratio and producing parts that are no longer in production. This will save time and costs for producing these parts, especially those that are made by molding or casting. AM also reduces material wastage in comparison to an estimated 90% of wasted bulk material in conventional machining. For example, a study on the critical analysis of 3-D printing technologies for aerospace applications has shown that for every 1 kg of titanium part produced, a total of 10 kg of titanium is wasted and has to be recycled for further use.

Airbus, an aircraft manufacturer, recognizes that AM will be a game-changing process in its production line. Through AM, it is able to produce aircraft parts that are 30–55% lighter, while saving up to almost 90% of the material. Peter Sanders, director of Emerging Technologies and Concepts at Airbus, noted that the technology reduces energy consumption by up to 90%.

Additionally, nonstructural, noncritical, out-of-production parts can be produced on demand with minimal cost. For example, Airbus recently printed a small plastic crew seat panel used in Canada's Air Transat A310, as the part is no longer in production. Airbus also estimated that cost savings of 10–30% is achievable through the use of AM in the long run.

As mentioned previously, AM can produce complex parts with ease. New designs, which can improve the aerodynamics of the aircraft, can be manufactured at a lower cost compared to conventional methods. AM also reduces the need for the joining of several parts. Instead of having multiple components that require fastening by bolts and nuts to form an assembly, AM can manufacture the assembly as a single piece, increasing reliability and reducing the need for more inspection.

A good example is the T25 sensor housing produced by General Electric (GE). This sensor measures, records, and provides pressure and temperature measurements for the aircraft engine control system. Furthermore, this housing is one of the first 3-D-printed parts that is certified by the Federal Aviation Administration (FAA) to be installed on commercial GE Leap jet engines. The approval of this 3-D-printed part by the FAA has become a milestone in AM for the aerospace industry. In addition, GE will open a new assembly plant in Indiana to fabricate and assemble the new engines with 3-D-printed parts.

Aerospace material interest for AM

In the aerospace industry, most aircraft utilize titanium alloy for its high-strength to low-weight properties. These alloys are used in structural components within the aircraft to withstand high-stress conditions during operation. As a result, research on AM-produced Ti-6Al-4V parts is gaining wide attention. As these mechanical structures are not produced in large amounts for an aircraft, stocks may not be readily available for replacement when required. AM ensures that these parts can be easily fabricated just in time for aircraft repairs.

One company that focuses on researching and improving the design of these mechanical structures is Lockheed Martin, an aerospace and global security company that engages in the research, design, development, manufacturing, integration, and sustainment of advance technology for the aerospace sector. They experimented with 3-D printing and successfully optimized structural designs that resulted in a reduction in weight, material, waste, and fuel consumption.

AM for space applications

The National Aeronautics and Space Administration (NASA) recently conducted a test on a 3-D-printed marshal engine propulsion injection plate. Due to its highly intricate design, conventional machining is not possible to produce this part. AM, however, is able to produce the part with an aerospace-grade alloy that is capable of withstanding extreme space flight conditions. As these propulsion systems require special flow configuration for maximum performance, AM is able to produce parts that allow unique interior flow configuration not possible for conventional methods.

NASA also developed AM systems for use in the International Space Station. In the event that a tool is damaged, the replacement can be fabricated immediately without waiting for resupply from Earth, saving time and money in the process. In addition, certain tools used by NASA in space programs are mission specific. Producing these tools with conventional methods would be costly and time consuming. However, with AM, these tools can be fabricated on-demand allowing the missions to be completed timely.

AM for UAV application

AM for UAVs is first developed for military purposes, and they are usually built as prototypes, after which a small quantity is produced for deployment. Prototypes are usually subjected to countless testing and revisions to improve the design. Therefore, many companies fabricate UAVs by AM in the interest of production time. UAVs are also gaining traction in the hobbyist industry. An increased number of hobbyists are fabricating their own UAVs and are turning to AM as the fabrication method to acquire their prototypes at a cheaper cost.

UAVs, such as quadcopters, usually have propellers outside of their bodies. This design increases the risk of propeller damage. To mitigate this design flaw, AM can be utilized to fabricate propellers inside the UAV body, which will help to lengthen the lifespan of the UAV. In addition, AM can also reduce the weight of the parts required in a UAV. Components can now be printed as one hollow piece, or with internal lattice structure, giving it lightweight and high-strength properties to provide for longer flight time and higher payloads.

Potential challenges of AM in aerospace

AM development for aerospace has been sluggish due to the need for the certification and qualification of parts before they can be implemented for commercial use. Although AM can provide many benefits to the aerospace industry, the risk that comes with its implementation must be mitigated. There are many variables to be considered, and, unlike conventional manufacturing, the lack of understanding and knowledge on effects on AM processes and alloys raise concerns.

One area of interest, due to the harsh environment to which an aircraft is subjected, is the understanding of fatigue and aging in AM alloys. Parts that are used in aircraft today have undergone extensive testing and certifications to ensure that a certain confidence level is met. In contrast, due to insufficient information regarding how AM-produced parts will perform, especially on their mode of failure, they are not suited for use as load-bearing structures in an aircraft. Currently, most AM-printed parts in the aerospace industry are usually restricted to nonstructural and noncritical use.

AM in the automotive industry

In the automotive industry, AM has opened doors for lighter, safer, and environmentally friendly cars with shorter production lead times at reduced costs. AM is also used in the reproduction of hard-to-find parts.

The main aim in the design of automobiles is to minimize the weight of the car while ensuring safety. By employing AM techniques, the production of intricate cross-sectional areas, such as the honeycomb cell or cavities in the parts, is made possible.

Influences on the automotive industry

AM has an influential contribution in achieving competitiveness among automakers. Compared to conventional manufacturing processes that often restrict design, AM can produce parts with a higher degree of design freedom. This versatility is significantly beneficial in the production of custom features, allowing for the addition of enhanced functionalities. For instance, integrated electrical wiring and reduced weight can be achieved through the use of hollow and lattice structures, respectively. Moreover, novel AM technology has made the production of multimaterial-printed parts with independent properties including electrical conductivity and variable strength possible. All these AM processes have taken on a crucial role in the creation of lighter, faster, safer and more efficient cars for the future.

In addition, AM is a driver in the transformation of the supply chain. Currently, original equipment manufacturers (OEMs) have to collaborate with thousands of suppliers to source for the different components in cars, which often result in long lead time. As supply chain management is an intensive planning and logistics exercise that is both time and cost consuming, OEMs are continually seeking ways to compact their supply chains. AM has the potential to reduce the costs of moving and distributing mid-process and end-usable components, as these components can be produced on-demand, thereby reducing the overall lead-time and shortening the automotive supply chain.

With the various advantages of AM, companies are able to propel significant change within the supply chain. These changes include a decrease in costs and the simplification of the supply chain. Moreover, the combination of product innovation and transformation of the supply chain will influence the modification of business models of automobile corporations.

Applications in automotive

Currently, cooling vents and dashboards made by AM technology have already been adopted in some vehicles. With continuous improvements in AM processes and materials technology, it is likely that AM-based produced parts will be widely used in automobiles in the near future. Future applications may include engine components and suspension springs.

AM has also been used as the primary production technology for the manufacturing of electric cars. For example, a team of U.S. engineers manufactured URBEE-2 with approximately 50 AM-fabricated components.

Potential challenges of AM in the automotive industry

Although substantial advantages are offered by AM, several challenges have to be taken into consideration. Low volume production of AM-produced car components is not economical, as profitability is volume driven. Approximately 86 million automobiles were manufactured globally in 2013. With the immense volume, the low production speed of AM is hindering its entrance to the direct part-manufacturing market. Research on high-speed AM is therefore essential.

The production of large AM-based components has proven to be demanding. Parts like body panels that are produced by AM processes will still have to be joined together through conventional methods such as mechanical joining. Low-cost AM processes with the capability to produce large metal components have been explored, and significant progress has been made.

Conclusion

AM is a manufacturing process that fabricates a 3-D object by adding materials layer by layer. As such, the fusing or depositing of materials, specifically at areas defined by the sliced 3-D model, prevents material wastage. In addition, the layer-wise manufacturing process allows for the fabrication of complex parts, such as lattice structures. Due to these advantages of AM, there are several studies conducted to develop AM-built parts for different applications, such as in manufacturing, aerospace, and automotive industries. In these industries, metal AM processes, such as PBF and DED, are more commonly used.

In manufacturing, AM has allowed designers to create parts that were previously deemed impractical via conventional methods, such as CNC or injection molding. For instance, CNC is unable to fabricate parts with internal cavities because it is a subtractive process. Therefore, it requires the assembly step to obtain the desired part. Similarly, it is very challenging to manufacture parts with undercuts and blind holes by injection molding. In contrast, these parts can be manufactured readily by AM. In addition, a CNC machine is considered a multistage manufacturing process, while an AM machine supports building multiple parts in a single stage. Hence, this manufacturing flexibility also benefits the aerospace and automotive industries.

AM brings many opportunities to the aerospace industry—commercial, space, UAV, and new-material development. It is able to achieve the needs of this industry through the production of complex parts with ease, and just in time. Designers will also be able to implement designs that will improve the aerodynamics of aircrafts, and, in turn, increasing fuel efficiency. If the challenges of AM can be overcome in the aerospace industry, there will be a higher adoption rate of parts produced by AM.

In the automotive industry, AM technology has propelled competitiveness among automakers as it drives product innovation and transformation in the supply chain. Thus, there is an upward trend in the use of AM-produced parts in automobiles. However, low volume production and the manufacturing of large AM-based components are some of the challenges hindering the adoption of AM in the automotive industry.

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Complex and intelligent systems in manufacturing

Siwei Jiang, Chi Xu, Abhishek Gupta, Liang Feng,
Yew-Soon Ong, Allan Nengsheng Zhang, and Puay Siew Tan

The scientific landscape of manufacturing systems continues to change hand in hand with the evolution of the field itself. It is anticipated that new scientific insights will impact further growth in this area. However, the number of personnel with major specialization in complex systems, those that get hired by academia and industry, remains small; yet, the professional requirements are high and include a thorough education in one or more of the following:

- mathematics and operations research
- memetic computation
- data analytics
- deep learning
- manufacturing sciences.

Since various real-world manifestations of complex systems often demand the cutting edge of technical know-how, professionals in the field are required to have credible research experience.

For sustained research contributions at the frontiers of manufacturing operations and supply chain (SC) networks, two research institutes, Singapore Institute of Manufacturing Technology (SIMTech) and Nanyang Technological University Singapore (NTU), through the School of Computer Science and Engineering, have come together to establish the SIMTech-NTU Joint Laboratory on Complex Systems.

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The main motivation behind the formation of the Joint Lab is the development of competencies in the fields of manufacturing execution complexity management and complex SC network management, through fundamental research.

The backbone of our research agenda is proposed to comprise two core scientific capabilities: 1) modeling, simulation, and optimization, and 2) big data in complex systems. Details of the two capabilities will be discussed in the following sections.

Modeling, simulation, and optimization

A complex system is composed of interconnected subsystems or entities that, as a whole, exhibits potential (or emergent) properties that may not exist at the individual subsystem level. Stemming from a bottom-up paradigm, complex system modeling and analyses facilitate understanding of how local changes at the individual or micro level could lead to emergent behaviors at the macro level. Taking this cue, it is noted that traditional optimization techniques have been known to provide suboptimal performance for complex systems in manufacturing operations and SC networks. In an attempt to fill this lacuna, two major concepts will be discussed in this section:

1) "complex adaptive systems and agent-based models" for mitigating risk in SC networks
2) "memetic computation and evolutionary multitasking" for automated extraction, adaptation, and incorporation of knowledge across silos for improved optimization and decision making in complex multi-echelon SC networks.

Complex adaptive systems and agent-based models

The vulnerability of an SC has been accentuated due to internal weakness and outside disruptions, such as supply risk, demand risk, process risk, control risk, and environment risk. Although the conventional methods, such as risk matrix, value at risk (VaR), and supply chain operations reference model (SCOR), have been adopted in industry, they have the shortcoming of being nonmeticulous and insufficient for capturing the complexities of an SC.

To identify the most critical risks, an extended risk matrix approach (ERMA) is proposed to make the right mitigation decisions with limited resources (Z. Li et al., 2015). The key characteristics of ERMA is to add detectability and recoverability dimensions to the basic metrics in a traditional risk matrix approach (RMA) to enable SC organizations to create more comprehensive risk profiles of their SCs. Based on an industrial case study, disruption risks with high severity and low probability are found to be more risky due to low detectability.

On the other hand, the supplier selection problem can be quite complex as it usually involves numerous variables and uncertainties. In (Z. Li et al., 2015), a new approach based on agent-based simulation (ABS) is proposed to select suitable suppliers. In ABS, profit and customer service level (CSL) are used as key performance indicators (KPI) to rank the suitability of the selections. The results reveal the impacts of supplier profiles on KPIs, which will help firms to make the right decision on supplier selection.

Memetic computation and evolutionary multitasking in complex multi-echelon supply chain networks

With the aim of achieving advanced optimization and decision support tools, researchers at the SIMTech-NTU Joint Lab have identified the emerging science of memetics as being a key ingredient for driving future technological breakthroughs. Over the last decade, the meme-inspired notion of memetics, which represents the mind-universe analog to genetics in cultural evolution, has been successfully applied to a variety of real-world scenarios, including multi-agent systems and vehicle routing problems (VRPs), among others.

For instance, a coadaptive memetic algorithm (CAMA) has been proposed to measure the correlation of memes (i.e., local search operators) to VRP variants at different stages of the search process. Experimental results on benchmark VRP instances have shown that CAMA obtains competitive or often superior results in comparison to other state-of-the-art methods of the field. To elaborate, much like the concept of genes in genetics, which form the instructions for building proteins, memes in memetics are described as building blocks of cultural evolution that are stored in the brain and prescribe instructions for carrying out behavior. Buoyed by several success stories, in recent years, the meme-inspired computing methodology has become a rapidly expanding area of research progress in computer science and engineering.

In the literature, memetic computation has been defined as a paradigm that uses the notion of meme(s) as units of information encoded in computational representations for the purpose of improved problem solving. The memes are captured from recurring information patterns and can be evolved to form more complex higher-level structures.

In our recent work, a novel memetic computation approach for intelligent evolutionary optimization of problems has been proposed based on the aforementioned concept. The paradigm attempts to mimic the salient features of human cognition by learning higher-level knowledge abstractions, in the form of memes, from previous problem-solving experiences, which can subsequently be applied to related problem solving exercises in the future. Several noteworthy demonstrations of the efficacy of the paradigm have been presented in various practical domains, including last mile logistics (which refers to the last leg of the supply chain and is typically modelled as the VRP), arc routing, and a real-world case study on a package collection/delivery problem.

Our research endeavors in the field of memetic computation have also given birth to the intriguing concept of evolutionary multitasking, which has recently been formalized under the label of multifactorial optimization (MFO). In contrast to traditional optimization algorithms that focus on efficiently solving only a single task at a time, MFO was conceived as a paradigm that can harness the implicit parallelism of population-based search to handle multiple optimization problems (or tasks) concurrently. Given an integrated solution representation scheme that encompasses the search spaces of all constitutive tasks, the unification serves as a kind of meme space wherein building blocks of encoded knowledge are processed and spontaneously shared across different optimization tasks.

In contrast to the works in (L. Feng et al., 2015) the transfer of knowledge during evolutionary multitasking occurs in an implicit manner without the need for explicit knowledge extraction and injection. While there potentially exist manifold real-world applications of this concept, among them, of particular interest, has been its realization in the domain of complex multi-echelon SC networks. It is noted that in SC and manufacturing systems, there usually exist several subsystems that must execute different tasks at the same time, where each task can often be modelled as a classical combinatorial optimization problem. Thus, in such settings, there naturally emerges the scope for effective multitasking.

To this end, by allowing our proposed evolutionary multitasking engine to take over, it becomes possible to autonomously exploit the underlying commonalities between multiple optimization tasks at once, thereby facilitating faster and, consequently, improved decision making. Several computational studies in continuous as well as discrete optimization substantiate our claims and encourage future investigations of this exciting new paradigm.

Among the diverse research initiatives undertaken at the SIMTech-NTU Joint Lab, one that has attracted much industrial attention in recent times is that of improving the efficiency of solving large-scale problems in last mile logistics. It is noted that city logistics systems are generally faced with a multitude of solution quality indicators and practical constraints that are imposed by growing social, economic, and environmental concerns of all relevant stakeholders, the shipper, carrier, residents, and administrators.

Our research endeavors in the field of memetic computation have also given birth to the intriguing concept of evolutionary multitasking, which has recently been formalized under the label of multifactorial optimization (MFO).

In this regard, we have successfully surmounted several pressing challenges by incorporating state-of-the-art techniques from a number of allied disciplines, including that of large-scale global optimization and multi-objective evolutionary computation, among others. In particular, a fast hypervolume-based multi-objective evolutionary algorithm (FV-MOEA) has recently been proposed in (S. Jiang et al., 2014), showing notable performance enhancements on a variety of benchmark instances involving two to five objective functions. Furthermore, based on the FV-MOEA, a library of meta-heuristic solvers has been built for better handling multi-objective VRPs.

As depicted in Fig. 1, we demonstrated the efficacy of the library on a complex industrial case formulated as a multidepot capacitated vehicle routing problem with pickup, delivery, and time windows (CVRPPDTW). The results show that the optimal solutions found by our optimizer result in significantly improved routing solutions as compared to current industrial practices, bringing down the service delay experienced by customers by more than 11%.

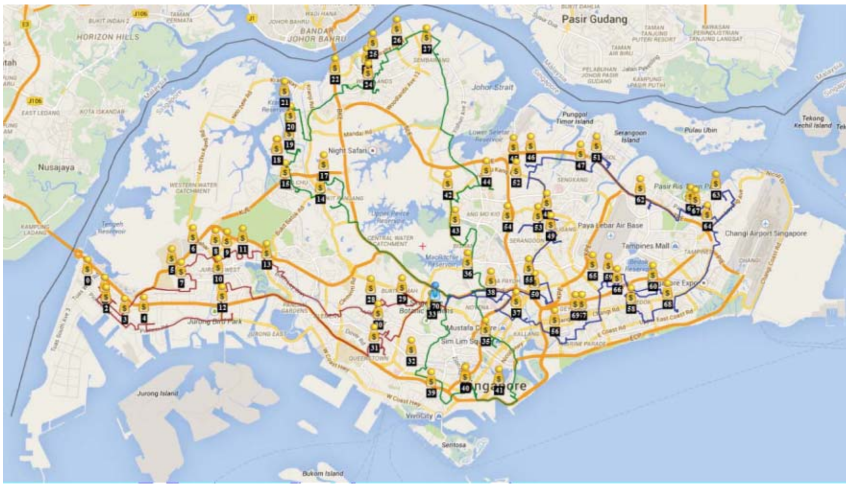

FIG1 A screenshot of the last mile logistics for a multidepot CVRPPDTW.

Big data in complex systems

The general modeling and optimization techniques developed in the first core competency serves as a basis for complex systems studies.

Conventional exploratory analysis and data visualization techniques for demand forecasting focus on one or a few time series at a time and has the scalability issue in a big data environment.

Big data analytics forms the second core competency to complement the first. Advanced methodologies, technologies, and tools are developed for this competency to allow us to discover useful hidden knowledge and system behavior patterns in manufacturing operations and SC networks, which are used to enhance the performance of the general modeling or optimization solutions. The research for this competency has two major topics of emphasis: 1) heterogeneous data preprocessing, data mining, and machine learning and 2) large-scale dominant feature mining and reduction. The first topic addresses the variety problem in big data, while the second topic aims to resolve the curse of dimensionality and the associated volume problem.

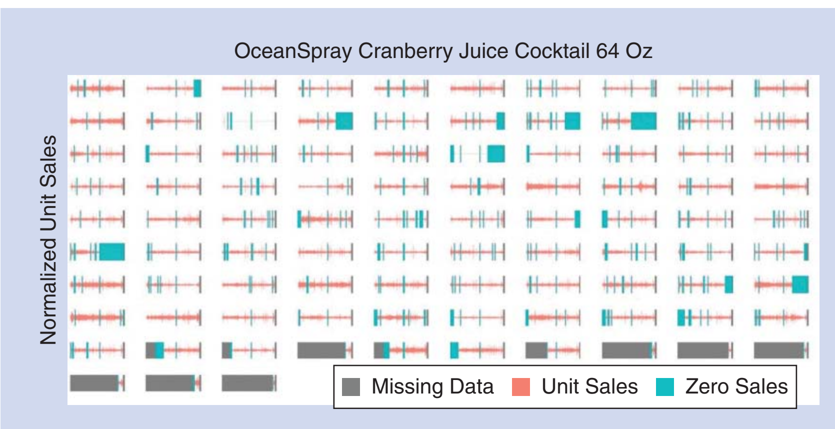

FIG2 A kite diagram for a particular UPC sold at 93 stores.

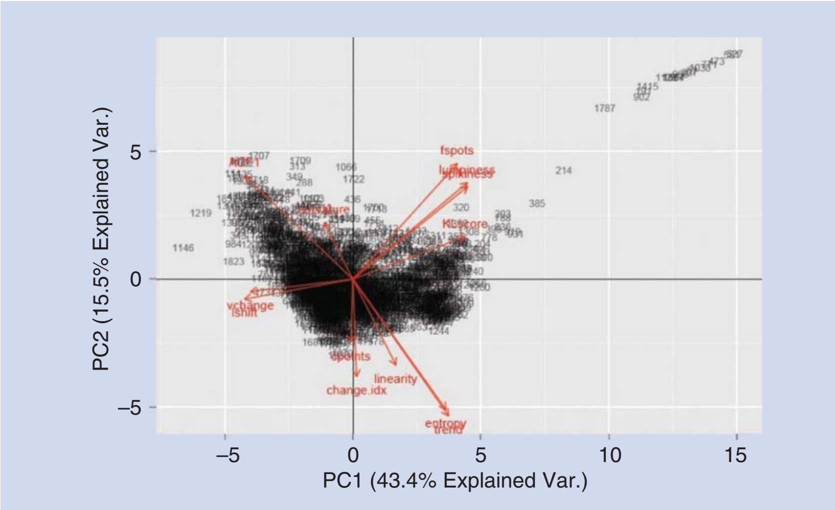

FIG3 A biplot of results of principal component analysis for the 1971 time series.

Heterogeneous data preprocessing, data mining, and machine learning

Currently, the data collected from complex manufacturing processes and SC networks can come from a variety of internal or external data sources across different locations. As a result, it is common that the data is multimodal in nature, bearing different spatio-temporal context, varying in quality, format, and representation forms. For shop floor applications, we are developing data-driven methodologies using data mining and machine learning to help in-situ process and energy efficiency monitoring and predicting performance in complex manufacturing processes to achieve excellence in quality control and energy efficient production. For supply chain applications, the aim is to develop methodologies and techniques to clean the heterogeneous data in a scalable way, fuse and unify the heterogeneous data from both internal and external data sources, as well as mine the information from the fused data to support decision making.

A segment of the SC network that can benefit from this study is demand forecasting in fast moving consumer goods (FMCGs), where the demand data can be collected from thousands of point-of-sales or consumers with various levels of quality. Discovering data outliers with problems such as missing data and wrong records from various sources through exploratory analysis is crucial for the performance of demand forecasting as these outliers can deteriorate the forecasting accuracy significantly.

Conventional exploratory analysis and data visualization techniques for demand forecasting focus on one or a few time series at a time and has the scalability issue in a big data environment. To overcome this issue, we developed exploratory analysis and visualization techniques in (D. Yang et al., 2015) to help preprocess big FMCG time series. The developed techniques include colored multivariate time series plots, kite plots, and principal component plots, which can help improve visualization for one, a few and many time series, respectively.

Figure 2 shows a kite diagram for a particular Universal Product Code (UPC) sold at 93 stores. The strictly nonnegative store-level sales time series is flipped about the *x*-axis to form closed glyphs. Figure 3 shows the principal analysis results of a 1971 demand time series characterized by 13 key features like lumpiness and spikiness. These proposed techniques enable a fast discovery of missing or spurious data from a large amount of raw data in the preprocessing stage, and eliminate them from inputs to demand forecasting in order to improve forecasting speed and performance.

In another study targeted at applying machine learning for dairy supply chains, a milk yield prediction and analysis tool (PAT) is developed in the lab. Figure 4 shows a GUI of the tool for individual cow milk yield prediction. The tool is able to consolidate milk yield data of cows spreading in various spatial locations and farms, and perform hierarchical predictions for milk yield from an individual cow level up to a country level. Various prediction models, including empirical models, time series models, regression analysis models, and four machine learning models: artificial neural network (ANN), support vector machine (SVM), genetic programming (GP) and Gaussian process regression (GPR), have been developed. With these models, the tool is able to provide insights into milk production and facilitate a "what-if" analysis for future milk supply.

Large-scale dominant feature mining and reduction

Researchers have largely reached a consensus that the explosion of data volume causes scalability issues for data analytics in manufacturing and SC applications. The big volume problem for data analytics has two aspects: big instance size and big dimensionality. Much of the current studies focus more on the instance size, largely overlooking the issues related to dimensionality.

FIG4 A GUI of a PAT tool for individual cow milk yield prediction.

To fill in the gap, we aspire to develop feature reduction techniques for both structured and unstructured data by exploring the syntactic and semantic relationships between features, utilizing the inherent data characteristics and exploring the domain knowledge of data. Our ongoing studies include the development of nonlinear dimensionality reduction algorithms for anomaly pattern detection of shop floor operation data, and effective feature reduction schemes for unstructured or semi-unstructured data including customer feedbacks and comments.

In (B.Y. Ong et al., 2015), we have developed an improved feature selection metric known as sparsity-adjusted information gain (SAIG), which modified the conventional information gain metric and aimed to adjust the feature ranking scores according to the sparsity of the data. SAIG is a filter method and attempts to utilize all of the information (i.e., term frequency, document frequency and sparsity/density) that can be obtained from the sparse matrix to improve the feature selection. Furthermore, noteworthy research headway has recently been made in the realm of feature grouping, where (Zhai et al., 2016) have proposed a novel framework named "group discovery machine" for seeking correlated feature groups that are informative and representative of data sets characterized by big dimensionality.

Conclusion and future work

To handle the emerging problems in advanced manufacturing systems, the key techniques in complex systems are identified in this article. The SIMTech-NTU Joint Laboratory on Complex Systems has developed novel algorithms in two major directions. First, "modeling, simulation, and optimization" contributes

In the future, we plan to apply the developed algorithms in collaboration with industrial partners.

to decision support in SC management by providing high-quality solutions that autonomously incorporate knowledge from previous and/or related problem-solving exercises. In this regard, the emerging fields of memetic computation and evolutionary multitasking are identified as the major torchbearers for future research advancements. The second direction of "big data in complex systems" plays a crucial role in detecting broken data in supply chain networks and in selecting meaningful features for enhancing classification accuracy.

In the future, we plan to apply the developed algorithms in collaboration with industrial partners. In addition, the joint lab will extend its core competencies with new directions that include but are not limited to:

- further development of human cognition-inspired memetic computing

technologies for real-time complex problem-solving
- advancement of effective computational analogs of cognitive multitasking with application to large-scale integrated supply chains
- exploiting big data for driving contextual intelligence.

Read more about it

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SMART foundry 2020

B. Ravi

Manufacturing processes can be broadly classified as additive, subtractive, and formative (see Fig. 1). Additive manufacturing technology, also called *three-dimensional (3-D) printing* (usually in plastics) or *rapid prototyping* (in plastics as well as metals), is less than 30 years old. It is best suited for fabricating small parts directly from their 3-D computer-aided design (CAD) models, using layer-by-layer addition of the material extruded from a nozzle (as in fused deposition modeling) or sintered using a laser beam (as in selective laser sintering). There is negligible set up time; no part-specific programming or tooling is required; hence the first part can be produced within hours. But the next part also takes the same amount of time. As a result, this process is not suitable for mass production and is mainly limited to producing prototypes (for testing) and parts required in small numbers (for repair and maintenance). The step-like surface created by layers limits the surface finish.

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Subtractive manufacturing, also referred to as *machining* or *material removal process* (by lathe turning, boring, milling, grinding, and polishing, among others), is relatively older—the first horse-powered boring machine for making canons was developed approximtely 300 years ago. These machines are widely used for producing a variety of metal parts with high dimensional accuracy and surface finish. Most of these machines are now computer numerically controlled (CNC) and can be programmed for the automatic production of parts in large numbers but involve significant wastage of raw material stock.

Formative manufacturing processes involve some tooling (die or mold) against which the part material is forced in either a liquid state (as in metal casting and plastic injection molding) or in a solid state (forging, sheet metal forming, powder metallurgy) to obtain the desired shape, thereby minimizing material wastage compared to machining. The earliest bronze figurines and coins made by casting are dated nearly 3,000 years. Parts with high geometric complexity, including internal features, can be produced in large numbers at very little cost. The development of the required tooling however, requires deep technical knowledge and several shop-floor trials, to produce the first good sample part with the required quality.

Metal casting

Among formative processes, metal casting is the most versatile. It is used to produce a wide range of parts required for transport (automobile, aerospace, railways, shipping), industrial machinery (for cement, chemical, food processing, petroleum, steel, and other plants),

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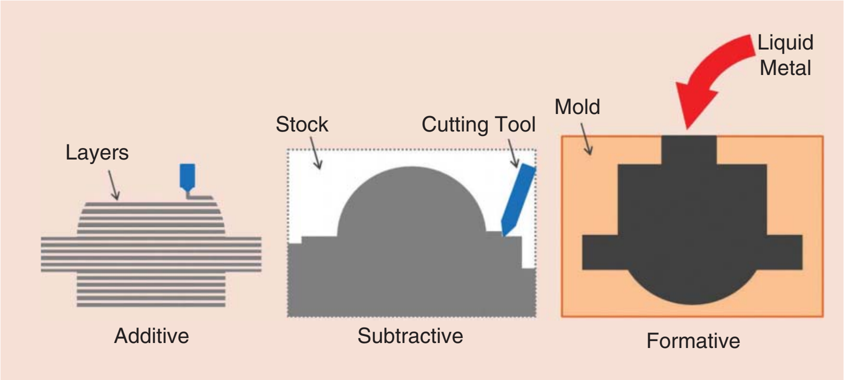

FIG1 A broad classification of manufacturing processes.

energy (electrical motors and generators, thermal, wind, ocean, solar, nuclear), construction, farming, mining, household appliances, utilities (water pipes, pumps, valves, treatment equipment), medical implants (bone plates, hip and knee joints) and other sectors (see Fig. 2). These involve a range of metals and alloys (aluminium, copper, zinc, titanium, iron, and steel) that are melted and poured into molds. It is not surprising that metal casting is often referred to as the "mother" industry that feeds most other manufacturing sectors.

Three countries—China, the United States, and India—together produce nearly 70% of the world production of metal cast parts, which stands at over 100 million tons/year. The Indian foundry industry employs over one million people, either directly or indirectly. Most of these units are small and medium enterprises that are in a tight position with casting buyers on one side demanding zero defect parts and material suppliers on the other side continuously raising the input costs.

Metal casting is also an energy intensive process (up to 50% of the energy consumed by a foundry is used for melting metal) and negatively impacts the environment (air, water, and soil pollution)—one reason foundries in Europe and other Western countries are shutting down. Owing to decreasing profitability, most foundries find it difficult even to maintain a clean workplace, let alone to invest in advanced technologies. Gradually, they become dirty, difficult, and dangerous and are shunned by the younger generation.

At present, India has nearly 350 million people younger than 15 years old, who will be seeking jobs within the next decade. The manufacturing sector, which currently employs about 12% of the total population, is seen as the engine of growth—to create employment opportunities as well as contribute to economic development. The government of India is rolling out several schemes to push the contribution of this sector from the present 15% to 25% of gross domestic product. The flagship program "Make in India" exhorts multinational companies to set up their manufacturing units in the country, following the success stories rolling out from China. While this may address the employment issue to some extent, the side effects of environmental pollution cannot be ignored.

Given the importance of metal casting in the economic development of a nation, there is a need to set up new foundries and augment the capacity of existing foundries, but the resultant negative impact on environment is not acceptable. Therefore, alternative paradigms need to be explored, which will accelerate manufacturing and create entrepreneurship opportunities but in an environmentally sustainable manner.

Smart manufacturing

The fourth industrial revolution, also referred to as "Industrie 4.0" in Germany, "Distributed Manufacturing" in the United Kingdom, "Smart Manufacturing" in the United States, and the "Internet of Manufacturing Things" in China, is changing the way products will be manufactured in the near future. By embedding sensors in process equipment, and making them "talk" to each other, it is possible to take factory automation to a new level. By streaming sensor data to the Cloud (servers connected to the Internet), and performing big data analytics, it

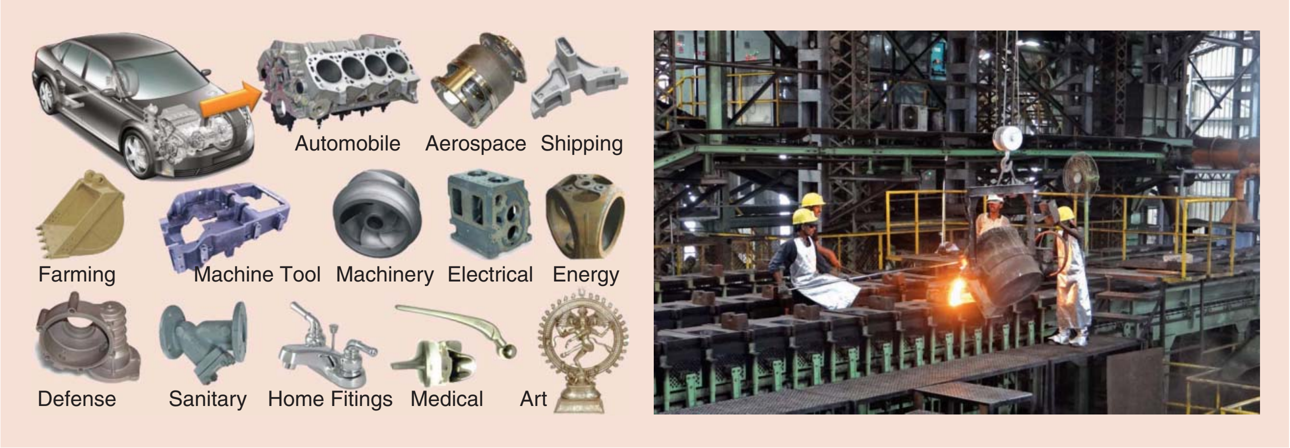

FIG2 Metal cast parts are made by pouring liquid metal into molds.

is now possible to remotely visualize, analyze, optimize, and control the manufacturing process.

The "factory of the future" as a concept has been around for several decades, but the technologies for fully enabling it at a low cost (for wide penetration) have evolved only recently. The promise of increasing the utilization efficiency of manufacturing resources (especially materials and energy), coupled with reducing the emission of hazardous substances (into ground, water, and air) has provided additional momentum to the wave of smart manufacturing sweeping across the world. Furthermore, smart technologies allow distributed manufacturing, leading to smaller-scale remote production closer to end-users, enabling wider employment opportunities as well as better understanding and fulfilment of user needs.

There are five key technology drivers for smart manufacturing: virtual engineering, Cloud computing, smart sensors, the Internet of Things (IoT), and big data analytics. *Virtual engineering* refers to computer-aided design (CAD), analysis, simulation, testing, and optimization of product design, tooling, and the manufacturing process. Cloud computing (essentially a network of computers with preinstalled software that can be accessed as service over the Internet) enables distribution of above tasks by teams working in different locations, who share common databases. Smart sensors embedded in process equipment collect data such as temperature, pressure, vibration, and noise; other sensors (such as cameras and radio frequency identification) track the movement of materials and in-process parts through the factory.

The *IoT* refers to the network of software, databases, sensors, and other objects, enabling the exchange of data and the integration of virtual and physical worlds. Big data (by definition, data sets that cannot be handled by traditional methods) streamed by a number of sensors and stored in the Cloud, can be analyzed by specially developed software programs to detect patterns that can be used to predict and prevent potential problems in manufacturing processes.

All five technology drivers for smart manufacturing have one thing in common—they are part of the broad set of information technologies, where India has made rapid progress in spite of its many challenges, including extreme poverty and ethnic diversity. The country has crossed one billion registered mobile phone users. Its information technology (IT) and IT-enabled services industries employ over 10 million people (mostly young) and generate revenues worth US$150 billion. Is it possible to leverage this resource to drive smart manufacturing, especially in metal casting?

SMART foundry

The challenge was taken up by ten technical institutes (public as well as private) and research institutes in India, who joined hands to "reinvent" the metal casting process for education and entrepreneurship, by leveraging the relevant enabling technologies. The acronym SMART stands for sustainable metalcasting by advanced research and technology. Its goal is to develop a compact SMART foundry that can be used for rapid manufacture of small parts required in tiny order quantities, which is not economical for conventional foundries. A large number of such parts are required for prototyping purposes and maintaining old but valuable machinery.

The entire facility can be set up in a small room (25 m^2), which is ideal for training students, who, in turn, can set up micromanufacturing units with very little investment. They can also use it for making metal busts of people, household appliances, hobby work, and other innovative applications. The new process aims to change the perception of metal casting from "dirty, difficult, and dangerous" to "sustainable, smart, and safe."

The architecture of the overall system is shown in Fig. 3. It will have the following key technology elements.

- Intelligent design: Part models are created using 3-D CAD or 3-D scanning and converted into pattern models by providing draft or taper (for their easy removal from mold), fillets (for smooth flow of metal), and allowance for shrinkage (during solid-state cooling of metal), as well as machining. Then gating channels (through which liquid metal poured from a ladle will flow into part cavity), and feeders (to compensate for volumetric shrinkage during phase change) are modeled to obtain the 3-D model of full casting. This is verified by the simulation of molding filling and casting solidification to achieve the desired quality at maximum possible yield.

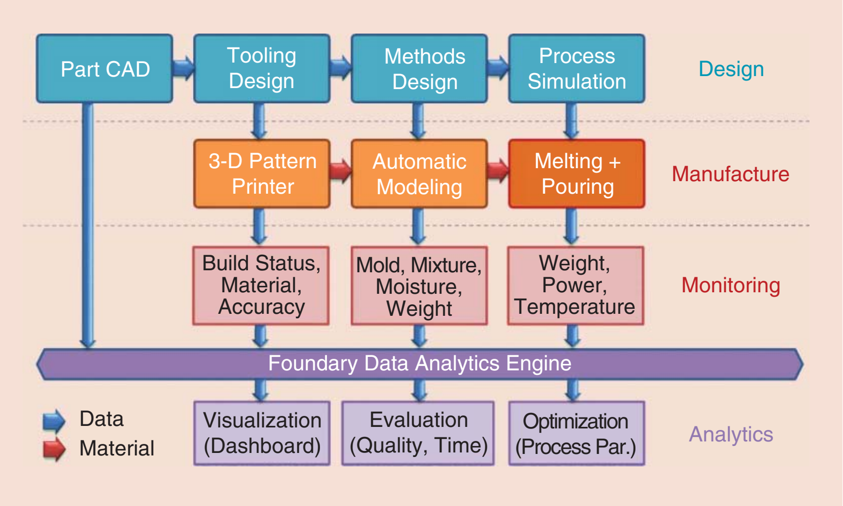

FIG3 The building blocks of a SMART foundry system.

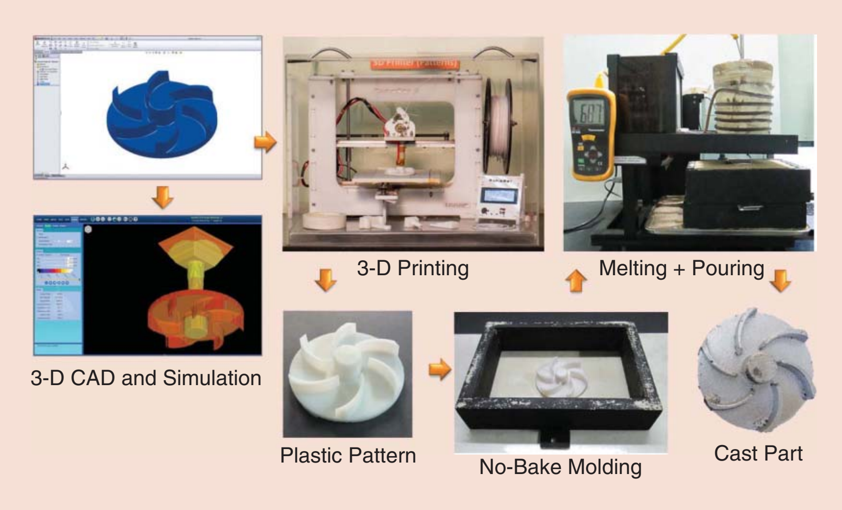

FIG4 A prototype system to demonstrate the process.

- Automated manufacture: The 3-D model of casting (part + feeders + gating) is sliced into layers to generate the machine code for additive manufacture. This is downloaded to a 3-D printer, where a plastic pattern corresponding to the full casting is fabricated. This pattern is used to create a mold by packing sand mixed with chemical binder around the pattern and removing the pattern after the hardening of the sand. The mold block is inserted in a specially designed induction furnace, where metal is melted and released into the mold. After cooling, the mold is broken to obtain the metal cast part. The same pattern can be used to make several molds and castings.
- Process data analytics: Sensors embedded in casting equipment will continuously measure temperature, pressure, weight, vibration, and other parameters. These will be streamed to the Cloud to visualize, analyze, and optimize mobile phones/tablets.

A proof-of-concept of the system has been developed by the team to demonstrate the feasibility of manufacturing a small metal part starting from its 3-D CAD model—the first part within a day, and subsequent parts within an hour each. The manufacturing lifecycle of an aluminium impellor is shown in Fig. 4. Its cost is an order of magnitude less than that fabricated by a metal 3-D printer.

Conclusion

There is a need to accelerate manufacturing in developing countries like India to provide employment for millions of young people and contribute to economic development, but it needs to be achieved with minimal adverse impact on the environment. Smart manufacturing allows for the wider distribution of related activities, creating employment opportunities closer to the end users based on their need, and reducing wastage of production resources as well as logistics. The enabling technologies, which are all broadly related to information technology, can be used to reinvent the manufacturing processes, especially metal casting, to make it more sustainable. The SMART foundry system being developed by a collaborative team of researchers across India, is expected to get young people interested in manufacturing, who can set up small-scale businesses, becoming job creators instead of job seekers.

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Read more about it

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Smart Manufacturing

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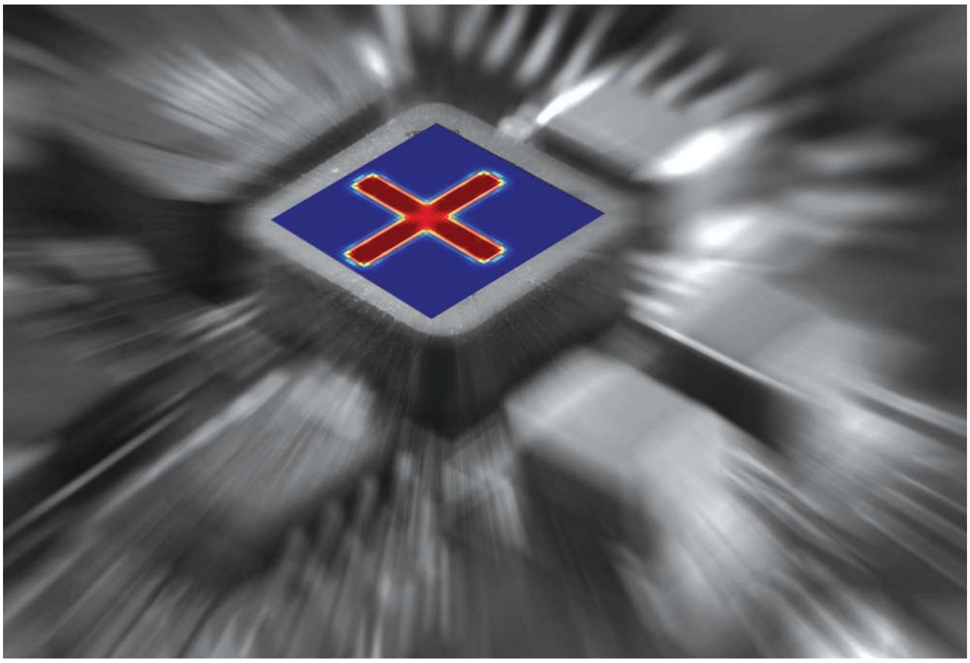
Exposure optimization in scanning laser lithography

Andrew J. Fleming, Adrian G. Wills, and Ben S. Routley



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In 1959, the integrated circuit (IC) was invented simultaneously by Jack Kilby of Texas Instruments and Robert Noyce of Shockley Semiconductor [Kilby, 2000]. This development has been considered one of mankind's most significant innovations.

The most popular and economical process for IC fabrication is the complementary metal–oxide semiconductor (CMOS) process [Baker, 2010]. Like other processes, the CMOS process involves a series of implantation, deposition, and etching steps to build the structure additively. Each implantation or etching step is preceded by a photolithography step, where a resist layer is added and then selectively removed from the wafer. After the deposition or etching process is complete, the remaining resist is removed in preparation for the next process step.

An example of a simple CMOS process is the 1um XC10 process, illustrated in Fig. 1, which is offered by XFab AG, Germany. This process requires at least ten masking steps but up to 23 masking steps if features like high-voltage transistors, optical windows, or sensors are required.

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By 2017, the half-pitch of a transistor will have reduced to 32 nm. This requires an extreme-UV (EUV) light source and a sophisticated optical system to satisfy the required numerical aperture. The foremost problem with this development is the cost and complexity of the EUV light source and mask infrastructure. At present, a mask-set costs upwards of US$1 million and is predicted to increase tenfold as dimensions shrink and complexity increases. The cost of infrastructure is also predicted to dramatically increase, for example, the cost of a suitably powerful EUV light source is in the tens of millions of U.S. dollars, which is an order-of-magnitude more expensive than the excimer lasers used previously.

There are two major consequences of the increasing development and processing costs of ICs. First, the best performance technology will only be available to the highest volume applications, such as computer memory and cell phone processors. Second, future innovations in device technology will be dampened by the prohibitive manufacturing costs.

The infrastructure and processing cost of microelectromechanical systems (MEMS) is also of major concern. In particular, prototyping services are time consuming and expensive, since a single MEMS device still requires a complete set of

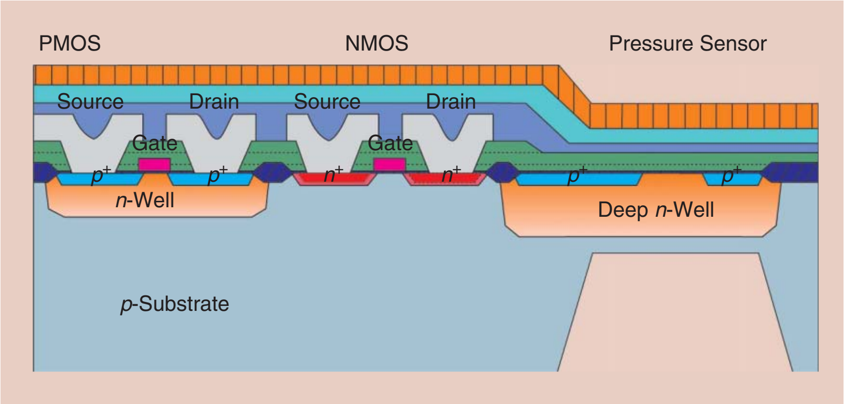

FIG1 A cross section of a CMOS inverter and a pressure sensor manufactured on the XFab XC10 process. (Figure reproduced with permission from XFAB, 2008.)

masks. If the requirement for masks and the optical delivery system could be eliminated, the cost of MEMS prototyping would be dramatically reduced. A decrease in development costs would be a major stimulant to MEMS innovation.

To bypass the physical limitations and cost of mask production, a number of maskless lithography processes have been developed.

The rise of maskless lithography

To bypass the physical limitations and cost of mask production, a number of maskless lithography processes have been developed [Lin, 2007]. The most promising technique for future IC processes is electron beam lithography (EBL) [Altissimo, 2010]. This process involves the selective modification of a resist layer by electron bombardment in vacuum. Like a scanning electron microscope, the beam is scanned over the surface, which eliminates the need for a mask.

The foremost difficulty associated with EBL is the slow process speed. However, this may be improved by using many parallel beams. Further difficulties include placement inaccuracy due to drift, substrate heating, charging, and proximity effects [Menon et al., 2005]. Ion beam lithography (IBL) is a similar technique but suffers from even slower speed and worse drift. EBL and IBL cannot be used to prototype a standard mask-based process, since the resist chemistry is different. The infrastructure cost is also significant.

In addition to EBL and IBL, maskless optical lithography is also developing. In its simplest form, a laser beam is focused to a spot size of approximately 500 nm and scanned over the surface. A faster method for maskless optical lithography is zone plate array lithography. In this technique, a controllable grating array creates a dot-matrix-like image on the photoresist. By scanning the wafer while changing the image, a larger complex image can be realized. To date, feature sizes of 150 nm have been demonstrated with zone plate lithography. However, the feature size is limited by the wavelength of the light source, which must be continuous-wave. Future improvements will be possible with the availability of shorter wavelength continuous-wave lasers. Other problems with zone plate lithography include limited image contrast and "stitching errors" at the boundary of each image [Menon et al., 2005].

An alternative to the controllable grating array discussed previously is the use of a micromirror array. The micromirror array effectively replaces the mask in a standard optical system. However, an extremely high demagnification factor of greater than 200 times is required to transfer the micron-sized features of the mirror to the nanometer-sized features of the target. Unfortunately, since refractive optics are required, this technique cannot be extended to wavelengths below 157 nm. Further problems include the number of required pixels (10 million) and the need to correct for the response of each individual pixel.

Rather than focusing light through an objective lens, it can also be directed through a sharpened optical fiber or probe as shown in Fig. 2. Below one wavelength from the fiber tip, the emitted light forms an evanescent field with highly localized intensity. If the fiber tip is positioned within a few nanometers from the surface, the near-field intensity can be used to expose the resist with nanometer precision.

Since the light delivery does not require any optics or free-space transmission, the resolution is not diffraction limited like other optical lithography techniques. Probe-based exposure also avoids some of the disadvantages associated with EBL. For example, there is no charging, proximity effects, or scattered electrons; and most importantly, probe-based exposure is compatible with standard photoresist chemistries.

A number of challenges exist with probe-based and scanning laser photolithography. First, the throughput is extremely low compared to mask-based methods. However, advances in nanopositioning systems have

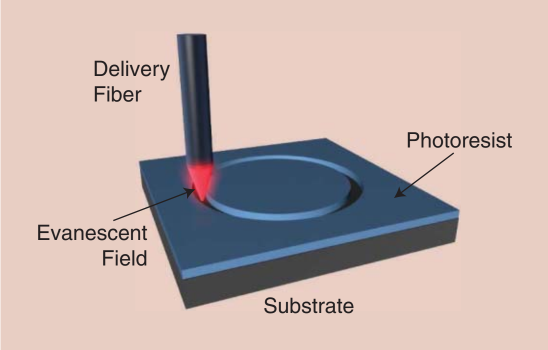

FIG2 A circular pattern exposed using a scanning fiber.

allowed scan rates to exceed 1,000 Hz, which can allow thousands to millions of features to be written per second [Fleming and Leang, 2014]. The probes have also been optimized to maximize throughput and resolution in lithographic applications [Routley et al., 2015].

Another major difficulty is the problem of finding a suitable exposure pattern that optimizes the fidelity of developed features. In other words, where, when, and how long the laser should be activated while the substrate is being scanned. This is a challenging problem that involves modeling and optimizing the nonlinear optical and chemical behavior of the exposure and development process. In the next section, this modeling process is introduced. A nonlinear programming approach is then employed to find an exposure pattern that minimizes the difference between the desired and developed feature geometry [Fleming et al., 2016].

Exposure modeling

Once the desired feature size becomes similar to the wavelength of the illumination source, diffraction and interference play a major role in the developed feature geometry. In standard lithographic techniques, these problems have been tackled by resolution enhancement techniques (RETs) that aim to minimize the differences between the desired and exposed pattern. Methods for prewarping the mask, known as *optical proximity correction*, can be categorized into rule- and optimization-based methods. The rule-based methods improve proximity effects based on rules derived from simulations, experiments, or a combination of the two. Optimization-based techniques use a forward model that maps input light intensity to a developed feature. An optimization technique then modifies the input pattern to improve the developed resolution.

At present, these methods require significant computing power and don't guarantee convergence to the optimal solution. In maskless lithography, the exposure problem can be thought of as an attempt to create sharp images by scanning a blurry spot of light over the photoresist. It turns out that the properties of the photoresist actually make this feasible.

Beam modeling

The first step is to develop a model of the exposure process that is compatible with optimization methods. In scanning laser lithography, the beam profile represents the optical power as a function of distance from the center. In our experiments, the beam profile is represented by a two-dimensional Gaussian function:

$$B(x,y)=\frac{2P}{\pi w_0^2}e^{-\frac{2(x^2+y^2)}{w_0^2}}, \qquad (1)$$

where x and y indicate the transverse axes of the beam at focal point w_0, and P is the total power in the beam. An example of this function is plotted in Fig. 3.

Photoresist modeling

The photoresist model quantitatively characterizes the chemical reactions of the photoresist based on the dosage energy received. The simplest model is a threshold function that indicates 100% conversion when the dosage is above a threshold. A more realistic model of the exposure is a smooth function that relates the energy to the fraction of converted photoresist. A sigmoid function is employed for this purpose:

$$\widehat{Z}(x,y)=(D(x,y))=\frac{1}{1+e^{-\gamma(D(x,y)-T)}}, \qquad (2)$$

where $\widehat{Z}(x,y)$ is the fraction of converted photoresist, T is the threshold energy, and the parameter γ dictates the steepness of the sigmoid. When this parameter is large, the function resembles a binary exposure model.

Process model

A simplified model of the exposure process is illustrated in Fig. 4. Physically, the exposure profile $E(x)$ represents the time interval where the laser shutter is open, which is proportional to the resulting dosage since the beam power is constant. Another possibility is to

Scanning laser and probe-based exposure offers an attractive alternative to standard lithographic methods for prototyping and low-volume production.

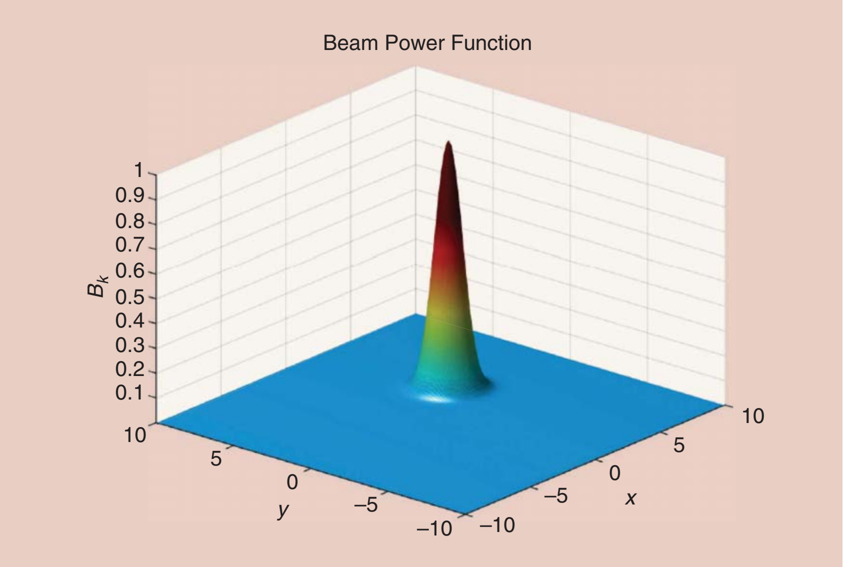

FIG3 The normalized beam power function, where the center is located at $x = 3$ and $y = 2$.

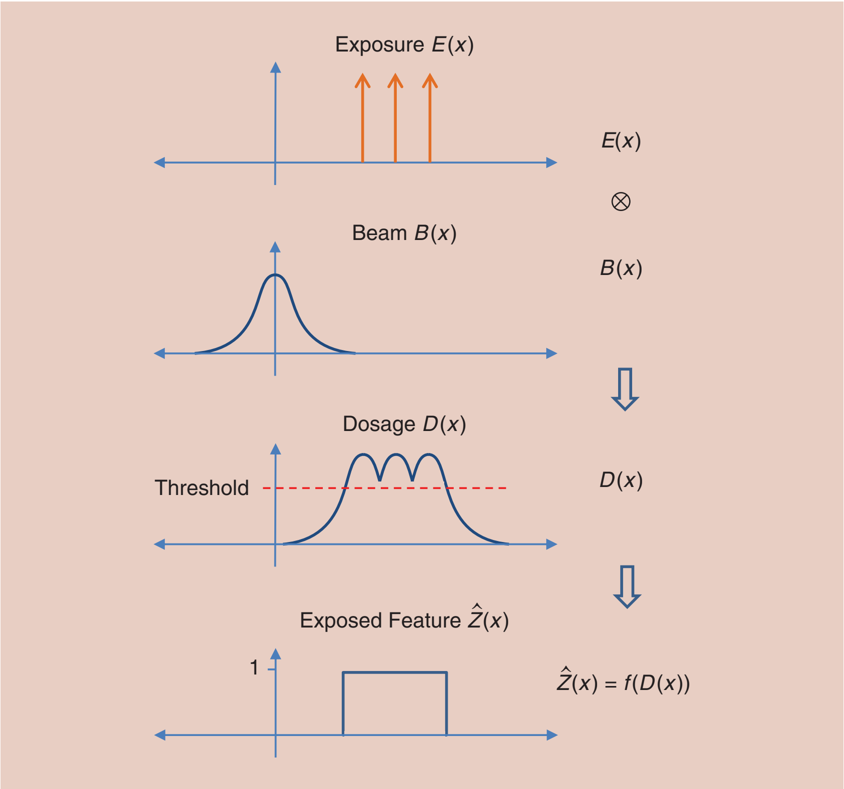

FIG4 A simplified one-dimensional model of scan-based photolithography. In this example, the exposure pattern $E(x)$ is three discrete exposures of equal energy. The resulting dosage $D(x)$ is the sum of each exposure point convolved with the beam profile $B(x)$. Finally, the photoresist function $f(\sigma)$ maps the cumulative dosage $D(x)$ to the exposed feature $\widehat{Z}(x)$.

Simple devices can already be exposed in less than a second and current research aims to create millions of features in a similar time frame.

directly modulate the laser power from 0 to 100%.

The light intensity (in W/m^2) is a Guassian function described in (1). To calculate the dosage $D(x)$ (in J/m^2) at a single point, the intensity is multiplied by the exposure time, that is $D(x)=t_{on}B(x)$. Where multiple exposures (t_i) are involved at arbitary locations (x_i), the total dosage is

$$D(x)=\sum_{i=1}^{N} t_i B(x-x_i). \quad (3)$$

Equation (3) is observed to be a convolution operation that can be generalized to discrete or continuous exposures in one or more dimensions. That is, in general

$$D(x,y)=E(x,y)\otimes B(x,y), \quad (4)$$

where $\otimes$ is the convolution operator. When the exposure function is discrete, the dosage can be expressed as

$$D(x,y)=\sum_{i=1}^{N_x}\sum_{j=1}^{N_y} E_{i,j}B(x-x_i\, y-y_j). \quad (5)$$

Once the dosage is known, the fraction of converted photoresist (0 to 1) can be computed by applying the photoresist function to the dosage. That is, the exposed feature $\widehat{Z}(x,y)$ is

$$\widehat{Z}(x,y)=f(D(x,y)), \quad (6)$$

where $f(D(x,y))$, is defined in (2).

Optimization

The aim of the optimization is to compute an exposure pattern that minimizes the difference between the desired and predicted features. The target shape Z is defined over a finite grid with $N\times N$ locations, such that $Z_{i,j}$ is the desired value (typically either 1 or 0) at row i and column j of the image matrix. This grid corresponds to points in the transverse x, y-axes, where $x(k)=k\Delta_x$ and $y(k)=k\Delta_y$ with Δ_x and Δ_y defining the x and y axis resolutions.

With the process model described previously, it is possible to define a measure of distance between the desired image matrix Z and the predicted one. This distance becomes part of a cost function that can be minimized to determine the optimal exposure pattern. At the same time, it is important that the exposure pattern does not produce high dosage levels, which is achieved by simultaneously minimizing the feature errors and applied energy. The exposure profile must also be constrained to positive values since negative values aren't physically realizable.

The above problem is a nonlinear and, importantly, nonconvex programming problem. In the absence of the thresholding function the problem reduces to a quadratic program (QP) with simple positivity bound constraints. However, the sigmoid thresholding function, while smooth, is neither convex nor concave and renders the problem more difficult to solve.

Nevertheless, this optimization problem can be solved by employing a barrier function approach where the inequality constraints are replaced with a weighted logarithmic barrier function [Fiacco and McCormick, 1968]. This method also requires the computation of a gradient vector that can be obtained efficiently using a Hessian approximation. An in-depth description of the optimization process can be found in [Fleming et al., 2016].

Example exposure

In this example, the optimal exposure profile will be obtained for the feature plotted in Fig. 5. The target exposure is 0.9, which implies a 90% conversion of the photoresist. The optimization assumes a beam width of 500 nm with unity power. The photoresist development threshold is 1 with a steepness of $\gamma = 5$.

The initial condition for the exposure function was obtained by exposing at every point where the feature is desired, which is shown on the top left of Fig. 6. This initial condition results in a gross over-exposure, which is evident in the dosage and feature geometry plotted in the top row of Fig. 6. After 20 iterations (middle row), the exposure function and feature geometry are observed to show significant improvement. After 80 iterations, the algorithm converges to an optimal solution with excellent correlation between the desired and predicted exposures. Since the beam-width is

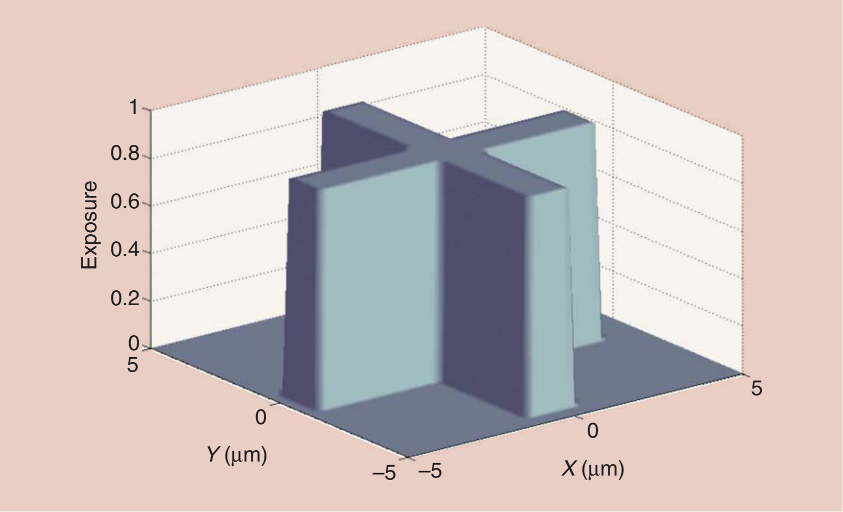

FIG5 The desired feature Z(x, y) used in the simulation has a target exposure of 0.9, which implies a 90% conversion of the photoresist. The exposure area is $10 \times 10\ \mu m$ with a resolution of 200 nm.

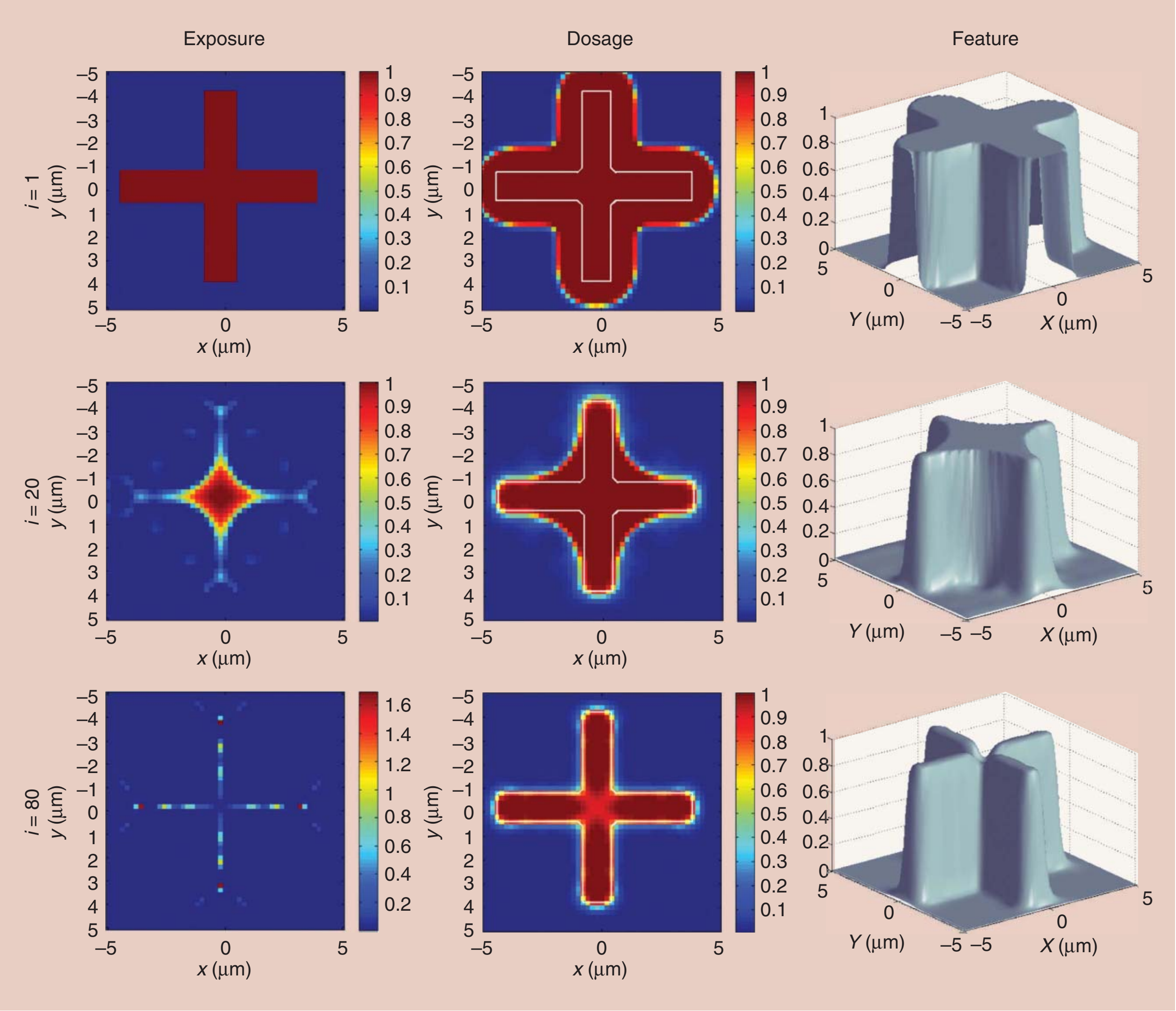

FIG6 The optimization results with the initial conditions ($i = 1$), a midway point ($i = 20$), and the optimal result ($i = 80$). The exposure function, resulting dosage, and feature geometry are plotted in the left, middle, and right columns. The optimized feature is observed to closely match the desired feature plotted in Fig. 5.

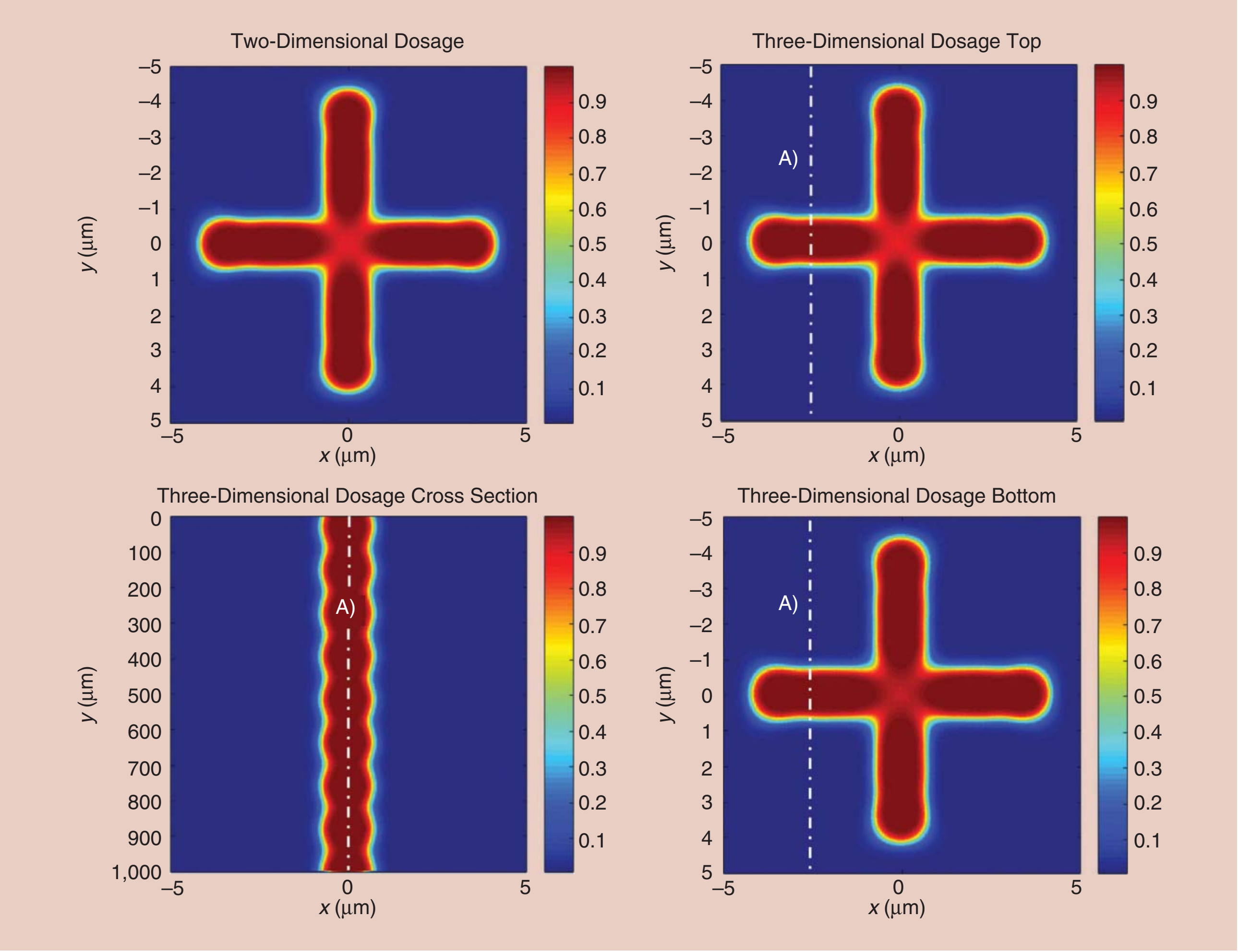

FIG7 The optical modeling results for the simplified two-dimensional model and slices taken from the three-dimensional model at the top layer, bottom layer, and a cross section taken through A). The cross section reveals the presence of an interference pattern formed in the cavity between the top and bottom surfaces of the photoresist.

similar in dimension to the feature resolution, the optimal exposure reduces to a line-scan along the major axes of the feature. Interestingly, the additional exposure points near the external corners of the feature are similar to the "hammerhead" points that are empirically added to masks to improve corner fidelity.

Optical simulations

To validate the proposed optimization process, three-dimensional optical simulations were preformed. The model was created within the COMSOL multiphysics framework, which solves Maxwell's equations in the frequency domain over a nonuniform mesh. To drastically reduce computation time, the photoresist was assumed to have fixed optical properties, ignoring photo-bleaching. The photo-bleached state's optical proprieties were used to produce the worst case optical scattering [Routley et al., 2015]. This assumption allowed for the point spread function (PSF) or beam profile to be modeled in two dimensions. The PSF was then revolved and convolved with the exposure function. Producing a three-dimensional representation of the dosage.

The photoresist under consideration is AZ-701 from Microchemicals GmbH, which provided the optical properties. A 1-μm-thick photo-resist layer was used with a glass substrate. The wavelength of the light source was set to 405 nm and the profile was a Gaussian beam with a width of 500 nm. The results shown in Fig. 7 indicate that there is little beam divergence. With the top layer dosage and the bottom layer dosage having almost identical features. This low divergence is due to the large beam width when compared to the wavelength. The cross section indicates that there is optical

Scanning laser and probe-based exposure offers an attractive alternative to standard lithographic methods for prototyping and low-volume production.

FIG8 A three-dimensional representation of the resulting feature after the photoresist is developed. The vertical walls are slightly corrugated by an interference pattern created through the thickness of the film.

interference occurring in the photo-resist, due to reflections off the glass substrate.

These interference patterns can also be seen if Fig. 8, which represents the resulting feature after the photoresist is developed. It was produced by thresholding the three-dimensional dosage data at 0.9. In Figs. 7 and 8, the corners appear somewhat rounder than those found in Fig. 6; however, this is primarily due to the higher resolution used for the optical modeling.

Conclusion

Scanning laser and probe-based exposure offers an attractive alternative to standard lithographic methods for prototyping and low-volume production. As the speed of nanopositioning systems increases, these methods will become increasingly competitive. Simple devices can already be exposed in less than a second and current research aims to create millions of features in a similar time frame.

This article focuses on the problem of finding an exposure pattern which optimizes the geometrical fidelity of the developed features. The solution is based on a nonlinear programming approach that can be solved with a gradientbased method. By changing the beam profile function, this method is applicable to all forms of serial lithography including e-beam, probe-based, and scanning laser.

Current research includes adapting the algorithm to handle images with a massive number of features and/or ultra-high resolution. It is also necessary to consider uncertainty in the optical and photoresist models, for example, variations in film thickness and photoresist constants, among others. Although technical challenges still exist, the development of this technology will dramatically improve access to a low-cost, ultrahigh resolution lithographic process. We hope that this will stimulate the development of new fabrication processes and myriad new technologies and devices that rely on them.

Although technical challenges still exist, the development of this technology will dramatically improve access to a low-cost, ultra-high resolution lithographic process.

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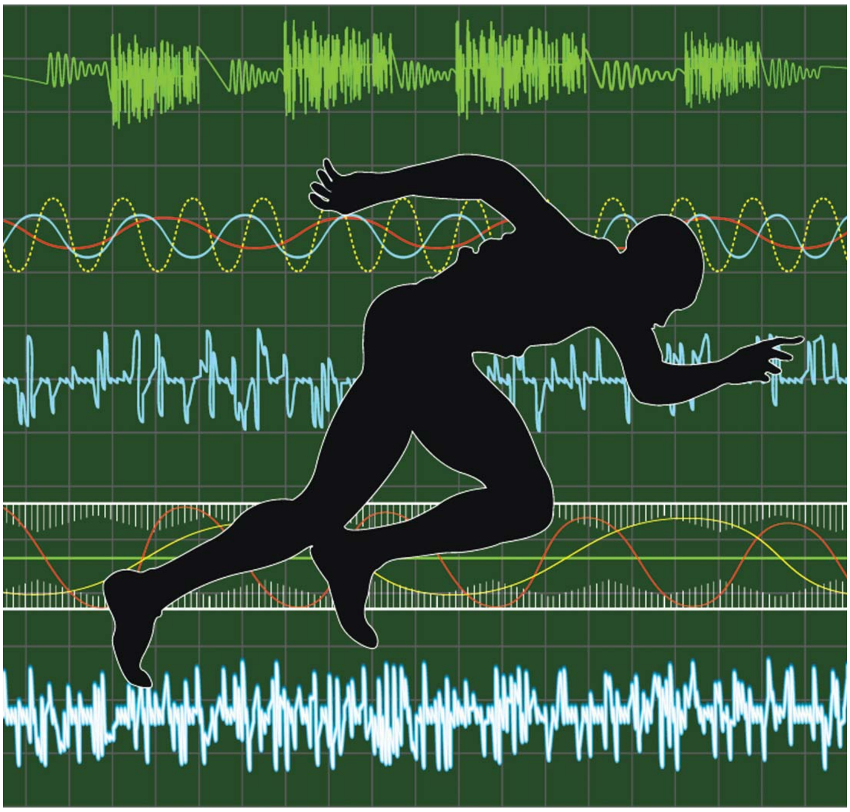
Wireless sensor devices in sports performance

By Róisín Howard



Accelerometers, gyroscopes, and inertial measurement units (IMUs) play an important part in human movement analysis. In recent years, there has been a significant emphasis on physical activity and health monitoring, and the use of accelerometers for physical activity monitoring has become popular. Electromyography (EMG) is a popular technique in the analysis of muscle activations in sports biomechanics. Widespread use was limited due to devices originally being bulky and expensive. Recent developments have incorporated wireless functionality in these devices.

These latest advances enabled the gathering of muscle data in sports, which initially proved too cumbersome. For instance, in track and field athletics, it is much simpler to gather muscle data using wireless EMG. Tests can be done to gather information on muscle fatigue, performance, rehabilitation, and injury prevention. The analysis of specific muscles can be extremely useful in the area of injury prevention; by identifying when the muscles are most active during a movement, it can be seen why in certain sports certain muscles are prone to injuries.

An example of EMG signals of the calf muscle during the standing calf raises exercise is shown in Fig. 1. Simple processing techniques, such as full wave rectification along with a root-mean square or a low-pass filter, are used by researchers to identify periods of muscle activity.

EMG sensors are not keeping up with IMU devices, which have become smaller and more readily available to the consumer. There are many wired and telemetric EMG devices available for use in various applications of sport. However, for more complex movements, the data collection process is not as easily done with these devices: data loggers and wires causing encumbrances. A treadmill is commonly used for such devices, restricting the speed and movement of the athlete.

Becoming unencumbered

There is a need for wireless devices that can be used in quick movements like sprinting. These devices need to perform to the same specifications, in both acquisition and analysis, but be small, have fewer encumbrances, and, most importantly, be wireless. The athlete can then optimally sprint in

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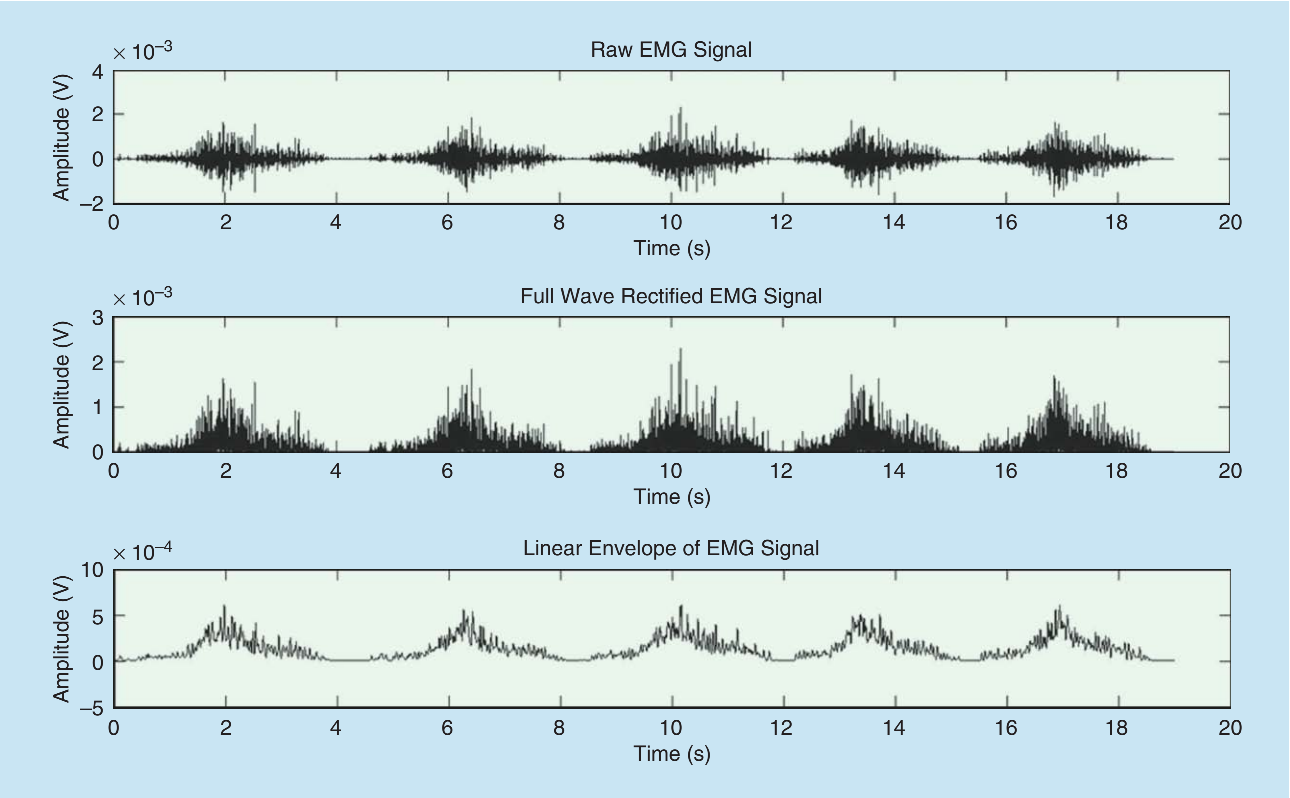

FIG1 EMG signals of the calf muscle during standing calf raises.

an ecologically valid environment giving both reliable and accurate results. Figure 2 shows a participant preparing to sprint, and EMG sensors with built-in accelerometer sensors are attached to the lower limbs, along with full body markers for three-dimensional (3-D) motion analysis. This participant is free from wires and can sprint without any encumbrances, allowing researchers to analyze the sprint action in terms of muscle activations, kinematics (joint angles), and accelerations.

Accelerometers are very commonly used in gait studies and to quantify physical activity. It is possible to calculate different kinematic data from accelerometer data, such as joint angles during particular phases of a movement or whole body and segment accelerations. During movement, the orientations accelerometer changes, and it no longer matches the global access. Thus, in vertical jump analysis, the vertical axis of accelerometer is no longer measuring the vertical component of the movement. The use of gyroscopes or magnetometers is used to understand the rotation of the device or its orientation in space. The functionality of these sensors can be used to re-orientate the signal to the global coordinate system. Figure 3 provides an example of a 3-D shape being rotated around the *x* axis.

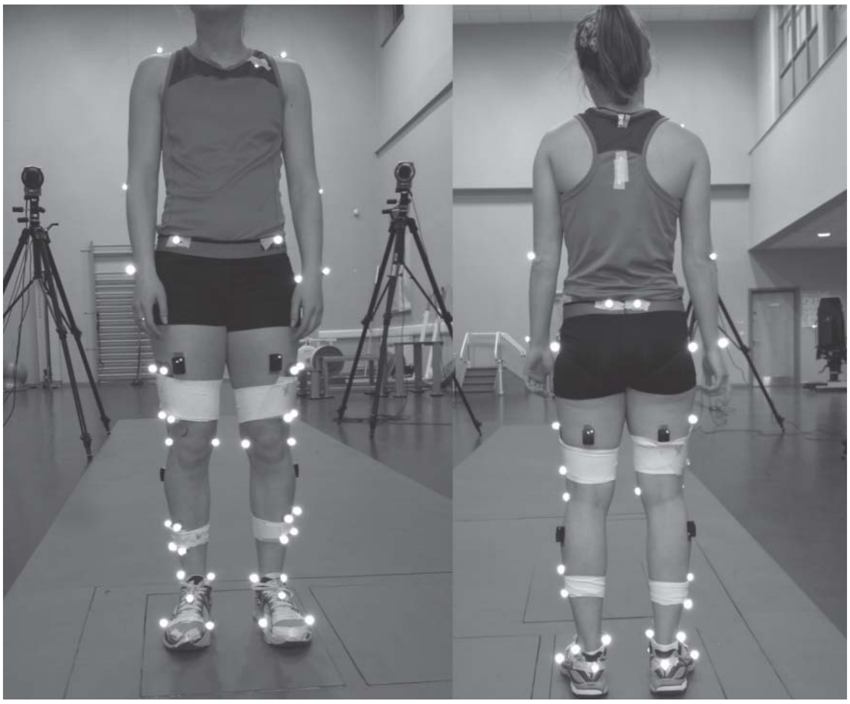

FIG2 A participant in a sprint study with EMG electrodes attached to the lower limbs and full body markers for 3-D motion analysis.

The usability for the ease of movement of the participant wearing the device is important, which highlights the need for wireless functionality. To achieve accurate results, the need for non-encumbrance and an environment that is ecologically valid for participants is necessary. Many sensor devices currently available are of a single-channel nature. Technology is ever-growing and expanding, and it is necessary to make use of this technology; the use of wireless multisensor devices for examining sports biomechanics is very significant. To achieve accurate results about the position, kinematics, and external forces (via acceleration) of the segment of the human body being studied, data must be captured in one single device. The combination of sensors in one device is essential to achieve the results necessary in examining muscle activity, forces, directionality and acceleration.

Room for improvement

Sport performance is a very popular measurement in sports biomechanics. It is important to continually look for ways to improve an athlete's performance. This can be achieved in many different ways, from injury prevention to improving movement patterns or rehabilitation. Knowing exactly what the different parts of the body are doing in terms of muscle activations and joint movements can be extremely beneficial.

The use of a wireless multichannel sensor can allow data to be collected during training or at sporting events when the athlete is performing as he/she does in his/her natural environment rather than trying to recreate movements in the restriction of a laboratory. This is why the need for a small, lightweight, multichannel wireless device that is easy to use and gives accurate and reliable results is what practitioners are seeking.

Companies looking to produce sensor devices for use in sporting applications need to work alongside practitioners to understand what works and what needs to be produced: What is the practitioner looking to measure with this device, and what data do they expect to see? Further work needs to be done in the area of a multichannel sensor device.

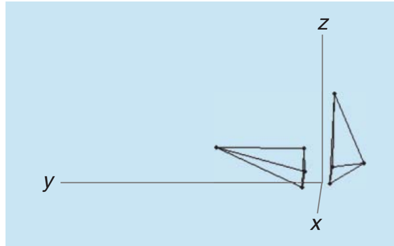

FIG3 The rotation of a 3-D shape around the *x* axis.

By having all of the necessary sensors on one single device, multiple measures can be recorded during one testing session. Data gathering will be simplified for both the practitioner and the athlete being monitored. One single multichannel sensor will eliminate synchronization issues and reduce set up time. All data could be streamed to one software package that contains all the necessary post-processing tools for each sensor in the device. A critical component of the software package is the post-processing and the usability of both the acquisition and analysis for the practitioner. If the software is difficult to use and navigate through, it will not be used in the field.

Conclusion

The need for multichannel sensor devices is clear. The aspects of human movement being analyzed require many different metrics to show improvement in performance, injury prevention methods, or rehabilitation. By having data from the various sensors available, a more complete picture of human movement can be formed. If all this information was available on a single device with user-friendly software, the research into sports performance, injury prevention, and rehabilitation can facilitate a deeper understanding of movement patterns.

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Róisín Howard (roisin.howard@ul.ie) is a research student who is finishing her final year of a Ph.D. degree program. She graduated from the University of Limerick in 2012 with a degree in computer engineering. With a keen interest in sports, particularly track and field athletics, she is working on the improvement of signal processing and sensor devices with a view to sports performance and injury prevention.

Homebuilt: A glove-operated robot

By Gaurav Gautam

Since childhood, I have been interested in working on projects. I used to repair gadgets and tackle small projects, and for engineering, I had opportunities to complete big projects. In my second year of engineering school, I attended a workshop where I learned the basics of robotics and how to work with a microcontroller. At the end of the workshop, there was a robot competition where my team secured second place, and that moment was very encouraging. The top three teams were offered a chance to compete in the final round of competition held at the Indian Institute of Technology, Guwahati, India.

Before the final competition, I joined a summer training program on robotics and embedded systems and worked on a variety of mini projects where I gained a lot of knowledge. I was optimistic for my trip to Guwahati. After participating in the competition, we were unable to achieve any of the top prizes. The reasons for our team's performance were the failure of a sensor and a byzantine program. The robot program was based on analog values that change according to supply voltage and temperature. They changed at the wrong moment, and we lost. I was heartbroken, and then my mentor motivated me by proposing work on another project.

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He told me that robotics kits were available at our college (Dronacharya College of Engineering), and I began working on them. There was not a robotics club at that point, so I became the first member of the robotics club at my college. By reading the manual of the kits, I completed small projects that were provided in a manual.

There were limitations with working on kits, and I wanted to take the projects to a higher level. So I started working on image processing. I wanted to control my robot by using my hand via image processing.

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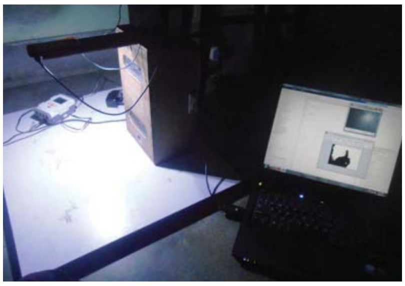

FIG1 The setup for image processing program testing.

FIG4 The chassis base channel.

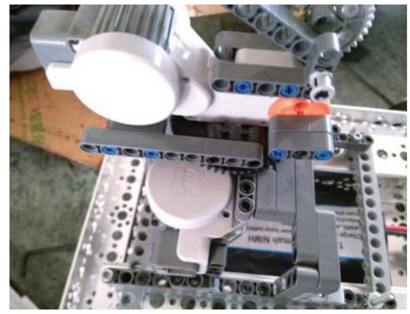

FIG6 The servo motors and gear assembly.

FIG2 The LCD, accelerometer, flex sensor, and microcontroller.

FIG5 The dc motors.

FIG7 An NXT brick.

Figure 1 shows the setup for program testing in my room. The outcome was not successful with a simple camera. High-quality and expensive depth cameras are required. A simple camera was not successful in image processing for different lighting exposures.

I looked to build a stable robot that could work in different environmental conditions and light exposures. As a result, I switched the controlling part to hardware. I decided to sense the movement of a hand. Now, taking inputs from different sensors was required.

I began working on different parts of the project. First, I collected all the components, shields, and kits required (Figs. 2 and 3).

LEGO kits were useful in creating the arm. Three servo motors (Fig. 6) were used to make it, two to control vertical and horizontal movement and a third to handle the claw movement. These servo motors had the capability to operate at different powers, and the gear mechanism made movement of these motors slow and controllable. The arm of the robot had two degrees of freedom (DOF), which allowed it to pick nearby objects.

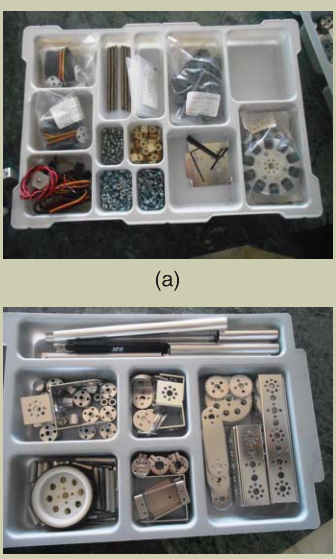

FIG3 (a) and (b) The kits that were used in the project.

Since the robot was the "hero" of the project, a strong chassis was needed to hold the microcontroller and the arm.

The robot and arm

I began with the robot. Since the robot was the "hero" of the project, a strong chassis was needed to hold the microcontroller and the arm. A metallic body was totally suitable for the base (Fig. 4). Next, motors for movement of chassis, which must handle all of the weight, was constructed. A 12-V dc motor (Fig. 5) with gear assembly was the right choice, with heavy motors, a heavy battery, and a motor driver also required. A ten-cell battery pack (3,000 milliamp hours, nickel-metal-hydride) had the power to drive the chassis.

An NXT brick (Fig. 7) was used for the robot's intelligent mind. An NXT brick has a 32-b ARM7TDMI-core Atmel AT91SAM7S256 microcontroller with 256 kB of flash memory and 64 kB of RAM, plus an 8-b Atmel AVR ATmega48 microcontroller and bluetooth support. Three servo motors can be connected to the NXT brick. It also had a liquid crystal display (LCD) for the graphical user interface and a 9-V rechargeable battery.

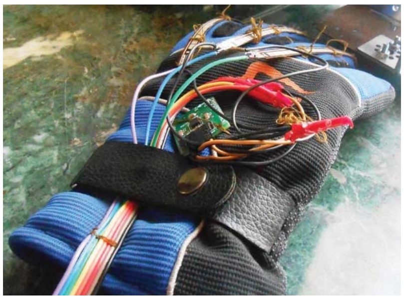

FIG8 The accelerometer.

FIG9 The flex sensor.

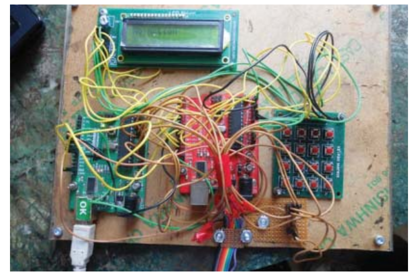

FIG10 The LCD, keypad, and microcontroller assembly.

There were only three servo motor output ports available on the NXT brick, which were already used by the three servo motors of the arm. To connect the two dc motors of the chassis, another motor driver was used, which was connected to the sensor input port of the NXT brick. This sensor input port was then programmed as an output port. This controller receives data by an I2C interface.

Building the glove

In day-to-day life, human hands are the most used part of the body. A human hand has 27 DOF. My goal was to sense these movements of the hand and process them for the control of the robot. To detect movement of the hand, I first took a glove and placed an accelerometer on it (Fig. 8). An accelerometer is a device that measures proper acceleration and provides three analog outputs x, y, and z. These outputs were given to 10-b analog-to-digital converter (ADC) pins of the microcontroller, which provides values ranging between 0–1,023 in the program. With the help of an algorithm, these values are processed to get the final five outputs.

Then it was time to work on the flex sensor (Fig. 9) to handle bending movements. When this sensor is bent, its resistance changes. We can measure that change in resistance by measuring current. The higher the bend, the higher the resistance change. In this project, I used three flex sensors.

All of the outputs were connected to the microcontroller. Interestingly, I wanted to protect my project from unwanted users, so I added a password program. I took a microcontroller and connected an LCD and keypad to it. Then I uploaded a password protection code. This microcontroller generates a signal after getting the right password, which allows the glove to operate the robot.

An Arduino UNO board was used, which has an ATmega328P microcontroller (Fig. 10). It has six 10-b ADC input pins. All of the analog ADC pins were filled up by accelerometer and flex sensors. Not enough pins were left on the microcontroller to connect the LCD and the keypad, so another microcontroller was used for the password protection aspect.

The program is the soul for any machine, and the programmer decides how intelligent that soul will be.

Time to program

The program is the soul of any machine, and the programmer decides how intelligent that soul will be. I had to program in three different integrated development environments, namely MATLAB, Arduino, and Mindstorm. It was really hard to connect these microcontrollers at a single place, but MATLAB made it all possible. Some trouble came during connection, like when the NXT firmware did not support MATLAB, so I updated it.

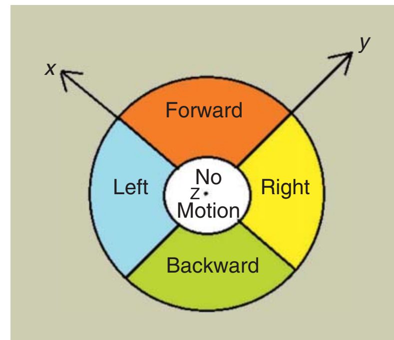

FIG11 The accelerometer controls.

First, the Arduino microcontroller reads the sensor values and decodes the operation that should be performed and sends it to MATLAB. Then, from MATLAB, commands are sent to the NXT brick, such as which motor to run, how much power, and in which direction.

Gaining control

To start controling the robot, I wore the glove on my right hand and switched on all the power switches on the robot. The MATLAB program was started, and the password was entered on the

FIG12 The LCD, keypad, and microcontroller connected to the accelerometer.

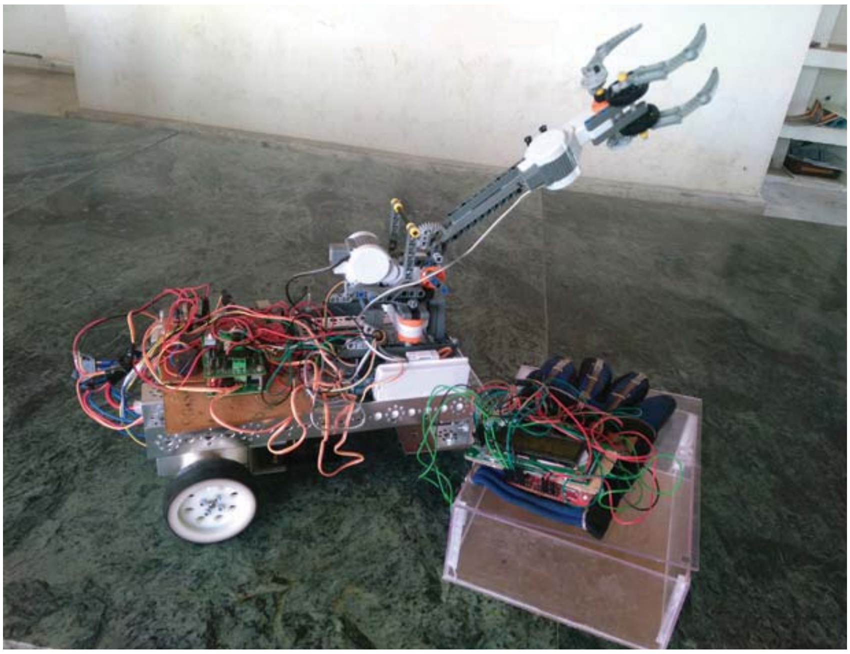

FIG13 The completed project.

keypad. Once the correct password was entered, the microcontroller started sending data to the robot. First, I put my hand parallel to the horizontal plane, and this was the default position for no motion. To move the robot forward, I bent my ring finger and tilted glove toward the front ($+x, -y$ axis; see Fig. 11) by providing wrist flexation. For moving the robot right or left, I tilted the glove toward the right ($+x, -y$ axis) or left ($-x, +y$ axis), respectively. The accelerometer was calibrated to sense tilt. Similarly, the forefinger controls the robotic arm's left, right, upward, and downward movements. The middle finger controls the opening and closing of the claw.

Wired to wireless

The glove was attached to a microcontroller by wire (Fig. 12), and as a result, the user cannot move around freely. It was time to turn the connection of the glove from wired to wireless. Bluetooth was the best option available. I found out how to connect the microcontroller with the computer via Bluetooth. I had connected the microcontroller with MATLAB, and, as a result, all of the data was directly sent to MATLAB via Bluetooth. The password protection part was removed from microcontroller, causing it to use less hardware. The small size of the microcontroller made it possible to place all components on the glove.

Every drop of knowledge that I have collected since my childhood made it possible to complete this project.

NXT to Arduino

The arm of the robot was working fine, but the dc motors of the chassis were experiencing some delay in their operation. This was basically due to the loop taking more time to complete. The motor driver was not supporting the program well.

I wanted to take this project to different competitions, and there was a possibility that it would get rejected due to the use of the NXT brick, so it was time to change to another microcontroller. I was familiar with the Arduino UNO board (ATmega328P), so I decided to use this microcontroller. A totally new program was made for the robot, and a Bluetooth HC-05 module was used for wireless operation. Setting up the connection between Arduino and MATLAB was a very challenging task. To connect them, I had to make my own original basic code using fscanf() and fwrite() commands. All of the basic learning and training, including the use of MATLAB, was beneficial to me.

Conclusion

Every drop of knowledge that I have collected since my childhood made it possible to complete this project. One project can be accomplished by putting a few mini-projects together. In my case, they were the glove, the robot, and the password protector. Further, it may seem like a good idea to increase the complexity of a project, but it's best to make it as simple as possible. Upgrading a project from time to time is important to realize improvements. Each time I took the robot (Fig. 13) to a competition, it won. A brief working video of the project is available at **https://youtu.be/CQwnxTfQR2I**.

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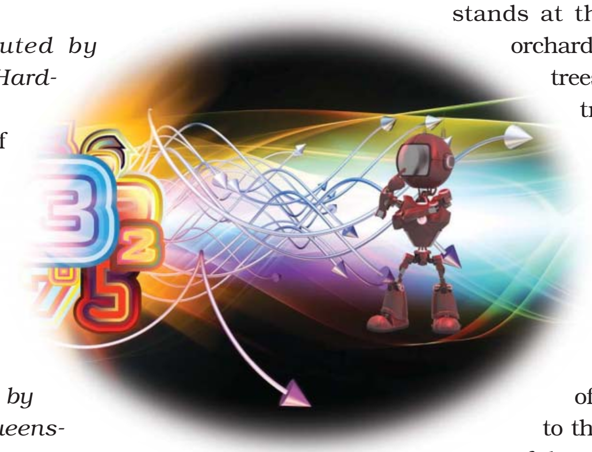
GAMESMAN PROBLEMS

Problem #1: It's All Natural

[This problem was contributed by Diego Bouche, a student at Harding University.]

Using the pattern of squares of natural numbers $1^2 = 1$, $2^2 = 4$, $3^2 = 9$, ... and knowing that $555^2 = 308{,}025$, find, without a calculator, the value of 556^2.



NUMBERS—© CAN STOCK PHOTO/AGSANDREW, ANDROID—© CAN STOCK PHOTO/KIRSTYPARGETER

Problem #2: Going Ballistic

[This problem was contributed by Ian Clarkson of Brisbane, Queensland, Australia.]

I launch a rocket from somewhere on or near the equator, and after the rocket has used up all its fuel, it is above the International Date Line at a height of 100 km, traveling east at 5,000 km/h^{-1}. Where will it be, roughly, in 15 min?

Problem #3: High-Altitude Stories

[This problem was contributed by Ian Clarkson of Brisbane, Queensland, Australia.]

a) My friend told me: "Last night, very late, when it was quiet, I heard a satellite. I raced outside to have a look at it. It was traveling from north to south." What's wrong with this story?

b) My friend told me: "Last night I saw a satellite and noted its direction of travel. A few nights later, I saw it again and it was traveling in the opposite direction." Is this possible?

c) My friend told me: "Last night I saw a satellite moving quite quickly and noted its direction of travel. Two hours later on the same night I saw it again, and it was traveling in the opposite direction." Is this possible?

Problem #4: Pólya's Orchard

Consider an orchard in which the trees are planted at the coordinates (i, j), where i and j are both integers. Suppose the tree at the origin is missing. The orchardist stands at the origin and looks out at the orchard. From his position, some of the trees are obscured. For instance, the tree at (2, 0) is obscured by the tree at (1, 0) and the tree at (3, 3) is obscured by the tree at (1, 1). He decides to walk through his orchard in a straight line from the origin. To set his course, he decides to walk to the left of the closest tree he can see at (1, 0) and to the right of the next closest tree he can see to the left of it at (1, 1) and to the left of the next closest tree he can see to the right of that at (2, 1), and so on. On what bearing does he set off?

Problem #5: Norden's "New Invention"

Since John Norden published *England: An Intended Guyde, for English Travailers* in 1625, it has been common on road maps to include a triangular table of distances between points of interest—major cities, for instance. (These tables appeared even before 1625, since Norden's self-proclaimed "new invention" had been featured in German publications over 50 years earlier.)

What if some of them were wrong? Is there a simple way to tell? Suppose we record the *square* of the Euclidean ("as the crow flies") distance between point i and point j in the ith row and jth column of a matrix.

a) Is there something about this matrix that could be used to detect errors? *Hint:* it's something about the rank.

b) Supposing there's a single error, is there a way to discover between which pair of points the error has been made? *Hint:* my solution uses the singular value decomposition.

P

If you have a problem for the Gamesman, submit it along with the solution to potentials@ieee.org. If we publish your problem, you'll receive a free IEEE t-shirt, so please include your size. Thanks. Solutions are on page 5.

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