MECHANICAL

ENGINEERING

THE MAGAZINE OF ASME
No. 09
137

Technology that moves the world

NETWORKED

THE INTERNET OF EVERYTYHING IS CHANGING THE WAY WE LIVE AND WORK.

PRINTING CARS ON DEMAND

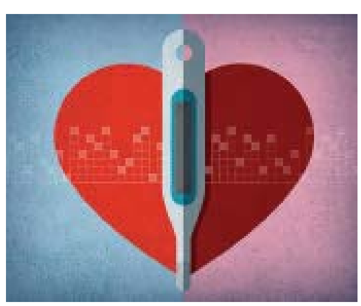
IMAGINE VISITING A MICROFACTORY, choosing a model and options, and then picking up your 3-D printed car the following day. An Arizona-based startup, Local Motors, is aiming to do just that. Everything on Strati—the car built by Local Motors—that could be integrated into a single piece, including the chassis, exterior body, and some interior features, is 3-D printed. Components such as the battery, motor, wiring, and suspension are added conventionally.

For these articles and other content, visit asme.org.

NEXT MONTH ON ASME.ORG

PHANTOM CITY HOSTS INNOVATIVE TECHNOLOGY
A preview of the Center for Innovation, Testing, and Evaluation, which will be a billion-dollar effort to test a range of cutting-edge technologies within a facility that essentially will be a mid-size American city.

Podcast: Next-Generation Tools for Biology and Medicine
Paul S. Weiss, a distinguished professor of chemistry and biochemistry and of materials science and engineering at the University of California, Los Angeles, discusses the advances and challenges that lie ahead in creating, developing, and applying new tools for biology and medicine.



THE HEART ATTACK THERMOMETER

RESEARCHERS AT KOREA'S POHANG University of Science and Technology have created a thermometer that will let patients know whether or not their chest pains are angina or a heart attack.

PODCAST: HOW NANOFLUIDICS CONTROLS CELL MICROENVIRONMENTS

SHUICHI TAKAYAMA OF THE University of Michigan talks about the efforts in his laboratory to develop microfluidic systems to control cell microenvironments.

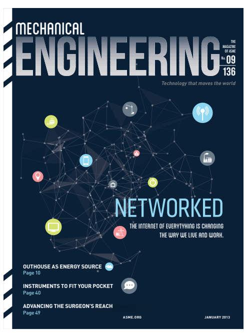
VIDEO: THE FUTURE OF HYDRAULIC FRACTURING: CONTROL SYSTEMS

FROM TEMPERATURE TO COMMUNICATION to data collection, efficient control systems are the key to effective operation of a hydraulic fracturing site.

TABLE OF CONTENTS

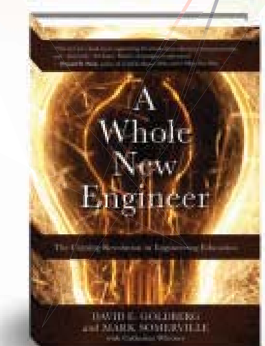
09 137

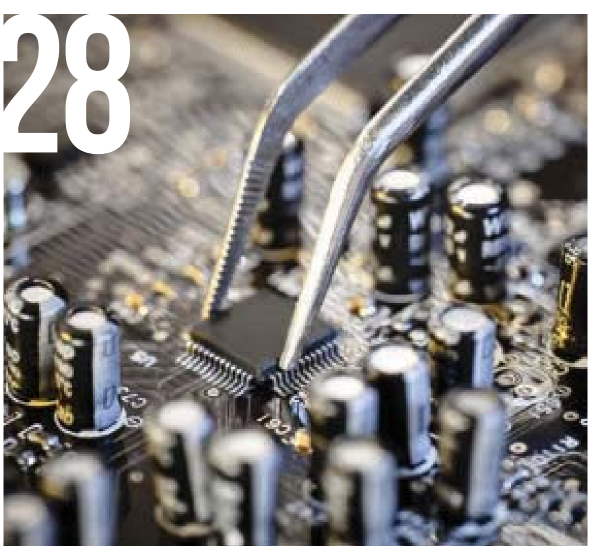
FEATURES



ON THE COVER

ALL TOGETHER NOW
Machines that talk to each other are changing cities and workplaces.





ASME
SETTING THE STANDARD

42 SENSATION

New apps turn smart phones into pocket-size instrumentation.

BY KATHRYN ALEXANDER

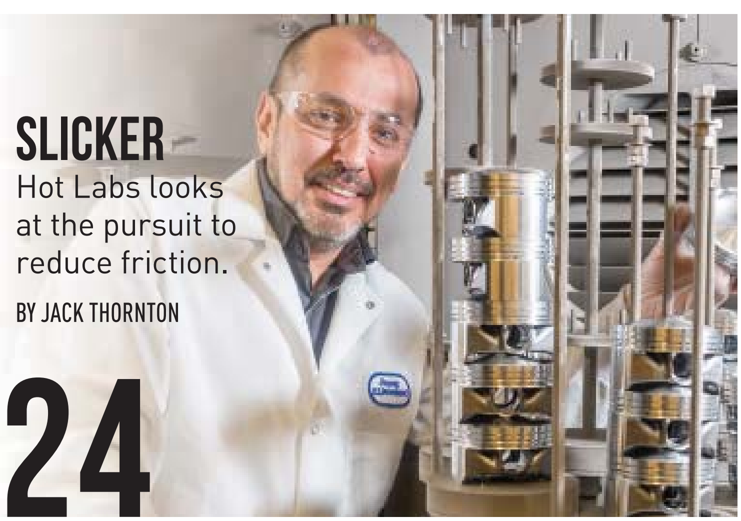
49 DYNAMIC SYSTEMS & CONTROL

Researching critical issues in computer integrated surgical systems.

71 GLOBAL GAS TURBINE NEWS

Highlights from Turbo Expo, 'As the Turbine Turns,' and more.

DEPARTMENTS



24 SLICKER

Hot Labs looks at the pursuit to reduce friction.

BY JACK THORNTON

96 GUAC GUARDS

Drones and dogs cooperate to save Florida's avocados.

BY JAMES PERO

MECHANICAL
ENGINEERING

Contact *Mechanical Engineering*

Mechanical Engineering
memag@asme.org
p. 212.591.7783 f. 212.591.7841
Two Park Avenue, New York, NY 10016

For reprints contact Jill Kaletha
jillk@fosterprinting.com
(866) 879-9144 ext.168

asme.org
on.fb.me/MEMAGAZINE
memagazineblog.org

Published since 1880 by the **American Society of Mechanical Engineers (ASME)**. *Mechanical Engineering* identifies emerging technologies and trends and provides a perspective on the role of engineering and technology advances in the world and on our lives. Opinions expressed in *Mechanical Engineering* do not necessarily reflect the views of ASME.

Give me the place to stand, and I shall move the earth
—Archimedes

ASME offices

Headquarters
p. 212.591.7722 f. 212.591.7674
Two Park Avenue, New York, NY 10016

Customer Sales & Service
e-mail: CustomerCare@asme.org
f. 973-882-5155
ASME, 150 Clove Road, 6th floor, Little Falls, NJ 07424-2139
In U.S., Mexico & Canada toll-free 1-800-THE-ASME (1-800-843-2763)
International 646-616-3100

Washington Center 202.785.3756
1828 L Street, N.W., Suite 810 Washington, DC 20036-5104

Int'l Gas Turbine Institute http://igti.asme.org
Int'l Petroleum Technology Institute asme-ipti.org
p. 281.493.3491 f. 281.493.3493
11757 Katy Freeway, Suite 380; Houston, TX 77079-1733.

Europe Office dogrum@asme.org
p. +32.2.743.1543 f +32.2.743.1550
Avenue De Tervueren, 300, 1150 Brussels, Belgium

Asia Pacific LLC
p. +86.10.5109.6032 f. +86.10.5109.6039
Unit 09A, EF Floor, East Tower of Twin Towers;
No. B12, JianGuo MenWai DaJie; ChaoYang District;
Bejing, 100022 People's Republic of China

India Office NehruR@asme.org
p. +91.124.430.8413 f. +91.124.430.8207
c/o Tecnova India Pvt.Ltd.; 335, Udyog Vihar, Phase IV;
Gurgaon 122 015 (Haryana)

Mechanical Engineering (ISSN 0025-6501) is published monthly by The American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990. Periodicals postage paid at New York, N.Y., and additional mailing offices. POSTMASTER: Send address changes to Mechanical Engineering, c/o The American Society of Mechanical Engineers, 150 Clove Road, 6th Floor, Little Falls, NJ 07424-2139. Return Canadian undeliverable addresses to P.O. BOX 1051, Fort Erie, On, L2A 6C7. PRICES: To members, annually $37 for initial membership subscription, single copy $7; subscription price to nonmembers available upon request.

John G. Falcioni
Editor-in-Chief

IF YOU SQUAWK PEOPLE LISTEN

How can you tell when a chicken isn't happy?

No, this isn't the start of a joke; it's serious business.

A mechanical engineer, Wayne Daley, at the Georgia Institute of Technology is trying to determine when a chicken isn't happy because, it turns out, a chicken with ruffled feathers doesn't eat well and won't fatten up as quickly as a happy and healthy chicken.

Daley and his team have come up with the Sick Chicken Audio Recorder that identifies the clucking and squawking of a chicken that isn't happy because it's sick or because it's too hot in the coop or too cold. Farmers care a great deal about making chickens happy because plump chickens lead to more sales and hefty coffers.

If the chicken is sick and not simply testy about the temperature, the illness will spread quickly to other chickens in the flock. So early detection pays off. Literally.

Of course, chickens aren't the only ones whose conversations are being monitored. The Justice Department recently has been revealing more about the government's use of secret cellphone tracking devices. Controversy over the department's use of these devices heightened when it was discovered that such technology was deployed in airplanes and can scan data from phones of those of us who are not targets of investigations.

The tracking of data, voice and otherwise, is part of the increasingly connected web of everything that everyone does and of what virtually everyone wants.

Soon, you'll be able to turn on your home dishwasher remotely from work; or if you're too tired to get to the supermarket, you'll be able to have your refrigerator automatically reorder from the grocery store the items you're running low on; and you'll also be able to get a notification on your cell phone that the pair of pants that you've had your eye on is on sale at a shop in your neighborhood.

We call this Internet of Things a "smart" new way of doing things.

Technologists are making things smart by attaching sensors and connecting them to the Internet, which will enable this flurry of connectivity and, presumably, lead us to more productive lives.

In this issue we take a deep dive into the smart environments that are burgeoning around us. From the home to buildings and structures, to complex supply and distribution networks that tie the global economy together. The pace of change is rapid, even as adoption may lag.

Industry appears eager to jump in and connect all things to the Internet. But there are reasons for healthy skepticism. Just two months ago, the New York Stock Exchange had a nearly four-hour shutdown in the middle of the day because of a faulty software upgrade that connects buyers and sellers.

Then the Federal Bureau of Investigation told us that millions—21.5 million—of government background investigation records were stolen by hackers who broke into the Office of Personnel Management's network. Days later a computer network malfunction caused a temporary grounding of United Airlines' global fleet. Sometimes, of course, it's not the network's technical malfunction that goes awry and causes pandemonium but the user of the network (see Edward Snowden).

The authors of this month's related feature articles assure us that, as the rate of connectivity grows, our future will be paved with greater productivity, economic growth, and an improved quality of life. I say, let's not count our chickens before they hatch. **ME**

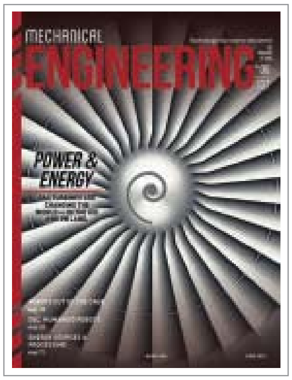
FEEDBACK

Are you eager to embrace the Internet of Things? Email me.

falcionij@asme.org


ENGINEERS START HERE
Access 500,000 in-stock electronics products, custom services, tools and expertise—all in one place. Plus, count on customer service that goes above & beyond to deliver your needs. Complete engineering solutions start at Newark element14.
1 800 463 9275 | newark.com
Newark
element14

LETTERS & COMMENTS



JUNE 2015

Reader Ivan Rice is reminded of a little personal history.

« Readers express concerns over climate science and the environment. Another recalls inspirational science fiction.

SUPPORTING CLIMATE SCIENCE ...

To the Editor: Congratulations on having the courage to publish more letters supporting climate change science. No doubt you will have angry readers, advertisers, and possibly even ASME upper managers.

Science is not magic, but it is the best way to attack problems like climate. Indeed, science has no competition for such issues.

Dudley M. Jones, Life Member, *Princeton, N.J.*

... AND TAKING ISSUE WITH IT

To the Editor: I see in the June edition I am twice cited in the "Letters and Comments" section. Since these comments are rather critical, not to say presumptuous of what one of the writers assumes to be my thought processes, I believe I am justified in claiming the right to respond.

To get a minor quibble out of the way, Galileo's trials and tribulations were anything but a terrible example. In his world, religious dogma was the "scientific consensus" of the day. Such individuals as we might consider "scientists" by modern standards were a frightened minority, thinking their thoughts in private and keeping a very low profile.

In those days disagreement did not culminate in having your paper rejected; it meant burning at the stake. Religion continued to control science, or meddle in it if you prefer, for another century or so. It was impossible for instance, to even attend English universities if you were not a member of the established church and theology was bundled with mathematics, while science you did on your own time. Read Isaac Newton's biography.

Mr. Scott Rappaport asks why I don't believe the data, and accuses me of suspiciously offering an argument based on ignorance. There is nothing suspicious about my simple statement that I have yet to see some convincing evidence for any of the divers theories being bandied around, pro or con. In this respect I freely admit to ignorance on the subject.

Given the amount of time, money, and effort being thrown at this issue I would expect that, by now, we would have some sound basis of factual knowledge available that the mildly interested and technically literate individual could examine objectively and make an informed judgment. I would love to have a look at this body of knowledge, if it existed. So where is it?

Mr. Gordon Rogers gets half way to the solution. Institutions like NOAA are respected sources of data, and there are equally respectable statistical procedures that have been around since 1929 to evaluate trends. The use of Control Charts in QC is hardly rocket science. This seems to be an ideal tool to test the validity or otherwise of all the hypotheses being batted back and forth. Now, all that is necessary to complete my day, is for somebody to direct me to the results of this analysis so I can make my own assessment of the situation.

My contention is that, like me, everybody is ignorant on this issue. The indicator is that after decades of slinging brickbats at each other none of the participants in this melee has come out a clear favorite.

It is not that I do not believe the data. It may be very good data for all I know. I retain a healthy skepticism of "data" which has not been thoroughly and independently reviewed.

It is not a question of belief or non-belief. These are concepts tied to faith, which is what substitutes for knowledge in the absence of evidence.

Douglas L. Marriott, *South Lebanon, Ohio*

The Pratt & Whitney FT50, on the assembly floor in Middletown, Conn., in 1975.

REDISCOVERING THE FT50

To the Editor: I read Lee Langston's articles in *ME* magazine and find them most interesting. His latest article ("Forward Future," June) was of particular interest to me because, when I was with De Laval Deltex in Houston from 1969 to 1974, I made several trips to Finspång, Sweden, regarding power turbines they were furnishing us for GE and Pratt & Whitney jets.

I now know what happened to the one and only P&W 100 MW FT50.

I might suggest that you write another article about the new revolutionizing hot and cold material being used in jets (carbon fibers, printing metal powders, and ceramic matrix composites), new manufacturing techniques (3-D printing, etc.), new cooling methods and thermal barrier coatings, and new thermo and aerodynamic computer programs, all of which have made rapid gains in gas turbine and combined-cycle output and efficiency possible during the past 10 years or so.

You can project what is to come using these new innovations.

Keep up the good work.

Ivan Rice, Spring, Texas

Editor's note: Pratt & Whitney built one FT50 in the 1970s. It was used by a Swedish electric utility and now is being installed at a power plant in Angola.

RIVER CONCERN

To the Editor: If you drive north on Interstate 81 in Pennsylvania and cross the Susquehanna River, there immediately on your right appears to be at least a few tanker trucks and a hose or pipe entering the river.

For the last three years or so, as we have seen pipelines constructed in Pennsylvania and also the short term appearance of drilling rigs there as well. It would appear that something is being sent into the river. I wonder if it is associated with hydraulic fracturing.

Tom Gurdziel, *Oswego, N.Y.*

.

SCI-FI INFLUENCES

To the Editor: I got my B.S.M.E. in 1960, powerfully motivated by reading science fiction from the late '40s to the early '50s. My favorite collection was *Adventures in Time and Space* by Healy and McComas. My favorite novel was *To the Stars* by L. Ron Hubbard, just before he wrote *Dianetics*, which was the starting point for his "religion," now so popular. My favorite writer is, of course, Robert A. Heinlein.

I really wanted to be a spaceman, but was stopped by being colorblind, which was found when I took a Navy physical (several years before Sputnik).

I subscribed to *Astounding Science Fiction* (which published *To the Stars*) for many years, including all the way through my engineering program.

Doug Culy, *Tempe, Ariz.*

Editor's note: In the February cover feature, "How Fiction Puts the Science in Engineering," successful engineers told us how science fiction inspired their career choices.

FEEDBACK Send us your letters and comments via hard copy or e-mail memag@asme.org (subject line "Letters and Comments"). Please include full name, address and phone number. We reserve the right to edit for clarity, style, and length. We regret that unpublished letters cannot be acknowledged or returned.

ENERGY OTHERWISE FLUSHED AWAY

A WATERLESS TOILET CAN PROVIDE THE FEEDSTOCK FOR A BIOGAS DIGESTER.

These days, people are looking to tap just about any natural resource—wind, waves, sunshine—for energy. Now, a British company called Loowatt has developed a product of the same name that pulls energy from the loo, or as we say in the States, the toilet.

According to Chris Holden, the company's head of design, the Loowatt was created for a variety applications, ranging from portable toilets for festivals and outdoor events to regular use in developing countries. The common theme is that it is an off-grid toilet. It cleanly captures solid waste between layers of biodegradable plastic film. The waste is then available to be used as feedstock for an anaerobic digester to produce biogas.

The device, which was invented by the company's CEO, Virginia Gardiner, improves sanitation in areas without conventional plumbing, and if the biogas replaces wood or charcoal, it can improve air quality as well. Fertilizer is another byproduct.

Loowatt has been recognized by a number of organizations including AutoDesk, which bestowed a Clean Tech grant with free use of the company's cloud-based Fusion 360 software. The Bill & Melinda Gates Foundation is providing funds under its Exploration Grant program for a pilot project that will install 100 Loowatt toilets in Madagascar.

An off-grid toilet (right) captures waste between layers of biodegradable film. A Gates Foundation grant is supporting installations in Madagascar (left). *Images: Loowatt*

The company is currently producing trailers for portable toilet applications in the U.K. The trailers can be parked at festivals, construction sites, and elsewhere, and then hauled away when they are no longer needed.

The Loowatt uses plastic film configured into a continuous tube, which is fed down through the toilet into a sealing unit. From there it enters a reservoir, called a cartridge. The sealing unit is about the size of a shoebox.

The system is operated by a hand crank. The mechanism pulls the film downward, applying pressure to the film using a flighted belt (like those used on conveyors), to maintain a seal as the tube and its contents are deposited into the cartridge.

Fresh film is drawn into the toilet, leaving it clean for the next user. A small valve opening allows liquid waste to pass through while locking out odors.

The cartridge can be removed and emptied into a digester, or otherwise disposed of. Refills contain 23 meters of film, or enough for approximately 100 uses. Larger refills are also available for installations at events.

The company, which employs 14 designers and engineers in both England and Madagascar, has patents on the sealing mechanism and the design of the refills.

The product is in the pilot stage, but when it is produced on a commercial scale, with anticipated production in the tens of thousands per month, the target cost will be less than 5 cents per person per day. Holden says the potential market

is 2.5 billion people.

Loowatt uses no electricity or water, making it suited for areas of water scarcity. It can also be useful during emergency recoveries, when sanitation can become critical.

The company's business model includes a variety of scenarios. Products could be sold to entrepreneurs in developing countries, who would make them available to their communities, for free or for a modest charge. With the addition of a digester the owners could sell the gas and fertilizer for income. With a generator, they could sell electricity for charging cell phones and for other uses. Communities could decide to jointly purchase Loowatts, digesters, and generators, and use them as shared resources.

Many cities in the developing world have very poor sewage services. Even in places where sewers exist, sewage is often dumped untreated into remote areas. In these cities, it is envisioned that a service provider would sell refills and pick up the cartridges for disposal. The business could then produce methane gas, electricity, or fertilizer for sale.

In developed countries, Loowatt can provide a drop-in replacement for the portable chemical toilets that are currently used at events and construction sites. The service providers already have relationships with wastewater treatment facilities, which can accept the waste, and in many cases, use it for biogas, or fertilizer, or both. **ME**

R.P. SIEGEL, P.E., is a writer based in Rochester, N.Y.

SOLAR PLANE GROUNDED BY DAMAGED BATTERIES

SOLAR IMPULSE 2, A SOLAR-POWERED AIRPLANE ATTEMPTING A flight around the world, has been delayed in Hawaii, about mid-way in its journey, and probably won't resume flying until the spring of 2016.

The plane finished a five-day non-stop flight from Nagoya, Japan, as planned, but its specialized lithium-ion batteries overheated and were irreparably damaged. The batteries are not off the shelf. They contain, for instance, a new monofluoroethylene carbonate additive to help increase energy density and improve the cycle life of the battery's electrolyte.

The Solar Impulse organization issued a statement explaining that the batteries overheated during the plane's ascent on the first day. The tropical climate, the degree of insulation, and overwork during the climb contributed to the problem.

The aircraft needs to achieve an altitude of more than 8,000 meters at full power during sunlight. It then glides steadily downward for the first part of the night.

Ground crews monitored the batteries and the pilot, Andre Borschberg, was able to complete the Pacific crossing. The plane landed at Hawaii's Kalaeloa airport, not far from Honolulu, early in the morning of July 3 after flying non-stop for 117 hours and 52 minutes over a distance of 7,212 kilometers.

According to Bertrand Piccard, initiator of the Solar Impulse project, by the time the batteries can be replaced, the flying season for the aircraft will have ended. The ultra-light plane needs calm weather to fly safely.

Solar Impulse's engineers will use the interval to study ways to avoid overheating in the future. **ME**

Bertrand Piccard, left, and Andre Borschberg in Hawaii. The five-day non-stop flight from Japan overheated their solar airplane's batteries. *Image: Solar Impulse*

Two vertical axis wind turbines produce enough electricity to power the commercial areas of the Eiffel Tower's first floor.
Photo: Urban Green Energy

EIFFEL TOWER GOES GREEN

One of the world's most recognizable historical landmarks now has a visible symbol to signify a decidedly progressive view of the future. As part of a five-year, $38 million renovation that included a goal of reducing its ecological footprint, the Eiffel Tower has installed wind turbines 400 feet above ground to power the commercial areas of the tower's first floor.

Solar panels, LED lights, high performance heat pumps, and rainwater collection systems are also saving energy, but it's the spinning turbines positioned above the second level to capture wind from any direction and maximize energy production that are making a statement for all to see.

While the result is clearly 21st century, the actual installation of two vertical axis wind turbines set to produce 10,000 kilowatt-hours of electricity per year, enough to power the commercial areas of the tower's first floor, was done the old-fashioned way, using ropes, winches, and pulleys. A highly skilled team of rope workers were harnessed up and hoisted each large component.

This was one of the unique challenges that UGE International faced as the manufacturer of the turbines. "We worked very closely with the general contractor [Bateg, a subsidiary of Vinci Construction France] so that we could adhere to all the laws of the tower," says Jan Gromadzki, UGE's project engineer. That includes no welding, drilling, or using any lifting equipment on the tower.

Gromadzki said the restrictions are both for aesthetic and structural reasons. For example, cranes or other conventional lifting equipment were not allowed because of their weight and also because there is not much room to maneuver within the four puddled iron arched legs that curve inward. So the rope workers climbed their way through the tower's intricate latticework to assemble one turbine component at a time, he says.

The largest parts were the fiberglass blades. Although not heavy, at less than 200 pounds, they are bulky and awkward. Moving the 16-foot blades had to be done carefully because there was not a lot of space to rest them on within the lattice structure and because fiberglass is somewhat fragile.

"That was a bit tricky to make sure they were tied down in a protected way so that they wouldn't get damaged before they were installed, and then just getting them in the air and onto the turbine was definitely the most difficult

continued on p.23 »

$1 STEEL WEDGE REMAKES INDIA'S COOK FIRES

A grate that can be made from cast-off sheet metal drastically reduces particle emissions and saves fuel in wood cooking fires.
Images: Climate Healers

A STEEL WEDGE GRATE PLACED in a traditional Indian cook fire can increase the fuel efficiency and cut soot emissions by more than half, new research has found.

The grate, called the Mewar Angithi, costs about US$1 to make, doesn't require cooks to learn to use anything new or change their cooking habits, and beat two much more expensive high-efficiency cookstoves in real-world comparisons.

Standardized laboratory tests confirmed the device's benefits, according to data that will be published in the next edition of the *Solutions Journal* by Sailesh Rao of Climate Healers in Phoenix, Ariz., who was involved in the development of the grates with a team drawn from the University of Iowa in Iowa City and Maharana Pratap University in Udaipur, Rajasthan, India.

A government-approved cookstove testing center at Maharana Pratap University ran the grate through six rounds of tests. The lab boiled water over

a traditional three-stone cooking fire with and without the grate. The grated fires burned 63 percent less wood and produced 88 percent less soot, the lab reports.

"Our Indian representative, Vasanth Kukillaya, was there," Rao said. "He told me that it took them a whole day to run the tests with and without the Angithi. Further, they repeated the test the next day as well, since they were surprised by the results."

But to Rao, the most meaningful experiments were those done in the kitchens of the women who cook every day over chulhas, traditional cooking fires. The researchers compared cook fires with grates to two brands of high-efficiency improved cookstoves and to cook fires without grates.

Rao and his team looked on as women cooked meals in three homes in the Mewar region of Rajasthan. To even out the differences between the sizes of the meals cooked over each fire and stove, the researchers calculated the weight of wood required to cook one corn roti.

The average weight of wood needed to cook roti over a traditional chulha without the insert was 0.161 kg. The wood needed by one improved cookstove was 0.122 kg, and by the other, 0.126 kg. The grated chulha required 0.066 kg.

Lab tests measured the fires' thermal efficiency, the ratio of thermal energy delivered to the pot versus the amount of thermal energy locked into the wood.

They also calculated the power rating, the rate at which the fire delivers thermal energy to the pot. They found that a grated chulha has an average 24.5 percent efficiency and 1.346 kW power rating, more than double that of the chulha without the grate.

Emissions from grated fires contained 5.97 grams of CO per megajoule of thermal energy delivered to the pot, less than half of the carbon monoxide of grateless fires. Grated fires emitted about one-tenth the total particulate matter.

A cookstove testing expert, Crispin Pemberton-Pigott, a technical consultant to the World Bank for stove programs, told us he was not surprised by the results, although the fuel savings of 63 percent did seem high.

Steel washer manufacturers discard metal sheets punched through with washer-size holes, and the sheets are perfect for creating the grates. Rao and his team found that they could make an insert for about US$1 each using scrap sheets from a manufacturer in Udaipur.

Inserts like this one are not new to cooking. Pemberton-Pigott works to set stove standards in Indonesia and he has seen another grate used there.

"The significant difference between the two devices is that the chulha version has the air entering from the front and the improved keren stove version has the air entering from the back. The rear entrance reduces the amount of charcoal wasted and keeps the flames more to the center, away from the back wall which is a significant source of PM and CO (touching a wall, that is)," Pemberton-Pigott said.

The insert could perform better if it covered a larger area of the floor of the chulha, Pemberton-Pigott said. Another performance enhancement may be to put a hole into the chulha itself to allow the insert to pull outside air through the rear of the stove. He suggests a hole that is 50 mm wide and 20 mm high, aimed directly into the grate.

Also, the grate does not allow for the removal of ash during the burn, which might be a problem, depending on the users' cooking habits. Although Rao said his team intentionally designed the holes in the grate to prevent embers from falling through during the burn.

To improve the stove's efficiency, chulha builders might consider lowering the pot-holder walls.

"If the pot rests are reduced in height to create a control over the amount of air rushing pointlessly through the stove, typically 7-8 mm high is adequate," Pemberton-Pigott said.

ROB GOODIER, ENGINEERINGFORCHANGE.COM


PROTOTYPING • 3D COLOR PRINTING • FDM • INDUSTRIAL DESIGN • LS • URETHANE CASTING •
MODEL MAKING • INJECTION MOLDING • DMLS • RAPID PROTOTYPING •
ONE
PARTNER
FOR EVERY

A FULL SUITE OF TRADITIONAL
& ADDITIVE MANUFACTURING

TECHNOLOGIES

POLYJET · SL · FDM

LS · DMLS · URETHANE CASTING

CNC · TOOLING · INJECTION MOLDING

STRATASYS**DIRECT.COM**

1-888-311-1017

INFO@STRATASYS**DIRECT.COM**

stratasys®

DIRECT MANUFACTURING

NOW YOU SEE'EM —OR NO, YOU DON'T

The quest for **invisibility** leaves a trail in the **U.S. Patent Office.**

There has always been the desire to hide things and, as a number of patents prove, the quest for invisibility is far from over.

Vinegar can be used for invisible writing. There are also numerous patents for invisible ink formulations. An early example includes patent No. 1,423,246 (1922) for a mixture of ferric sulfate and phosphoric acid. A newer example is Hewlett Packard patent No. 6,149,719 (2000) for an invisible ink composition used in printer cartridges.

Camouflage patterns are usually copyrighted (and sometimes the subject of a trademark), not patented. But, there are patents for using camouflage in unique ways. An old example is No. 2,190,691 (1939) where an aircraft is painted in such a way that "the eyes of an observer are drawn to the design covering the wing rather than the actual form of the wing and said observer is confused by the perspective of said designs as to the size of the wing surface and as to the direction in which the wing extends."

Active camouflaging means sensing the surroundings and adjusting the camouflage to look like the surroundings. A good example is Boeing patent No. 7,199,344 (2007). A diffuser screen is illuminated based on signals received from a sensor aimed at the terrain near the screen. In this way, as the sun angle, weather, or other factors change how the terrain looks, the camouflage on the diffuser screen is adjusted accordingly.

And then there is cloaking. In patent No. 5,220, 631 (1993), fiber optic cables and lenses receive light from behind a concealed object and pipe the light to the front of the object. So, if the object is between you and, say a tree, you will see the tree, not the object. In a similar vein, according to patent No. 5,307,162 (1994), a screen is placed in front of the object to be concealed and images from behind the object are displayed on the screen. These two techniques, however, only work when observers are at specific locations with respect to the object to be concealed.

Patent No. 7,206,131 (2007) purports to correct that problem with a "pixel skin" cloak. Also, a fairly new patent by Lockheed, No. 8,495,946 (2013), discloses the use of carbon nanotubes in a camouflage material to display the background in the foreground and thus cloak anything bearing the camouflage material.

Another type of cloaking involves structuring or routing light around an object and letting the light continue on unchanged as if the object wasn't there. Published patent application No. 2008/0024792 by David Smith of Duke University explains that a special metamaterial can provide "a method of concealing an object or volume of space by means of redirecting the electromagnetic field lines around it." Others are also working on different ways of routing light around an object, notably Xaing Zhang – a professor of mechanical engineering at the University of California, Berkeley.

Will a true cloaking device ever be realized? The problem is visible light is made up of so many wavelengths which have to be dealt with simultaneously.

By the way, I found no patent for a drug which can make you invisible. And remember, H.G. Wells's Invisible Man might have been invisible, but he wasn't happy. ME

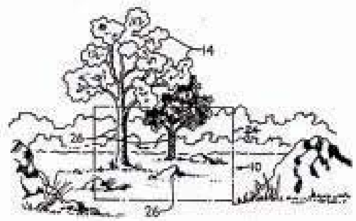


FIG. 1

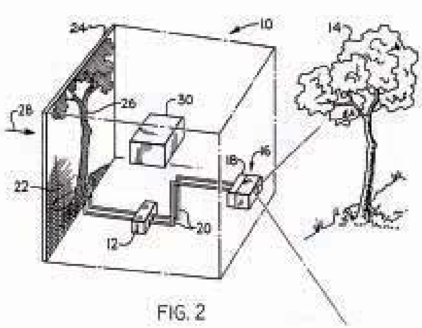
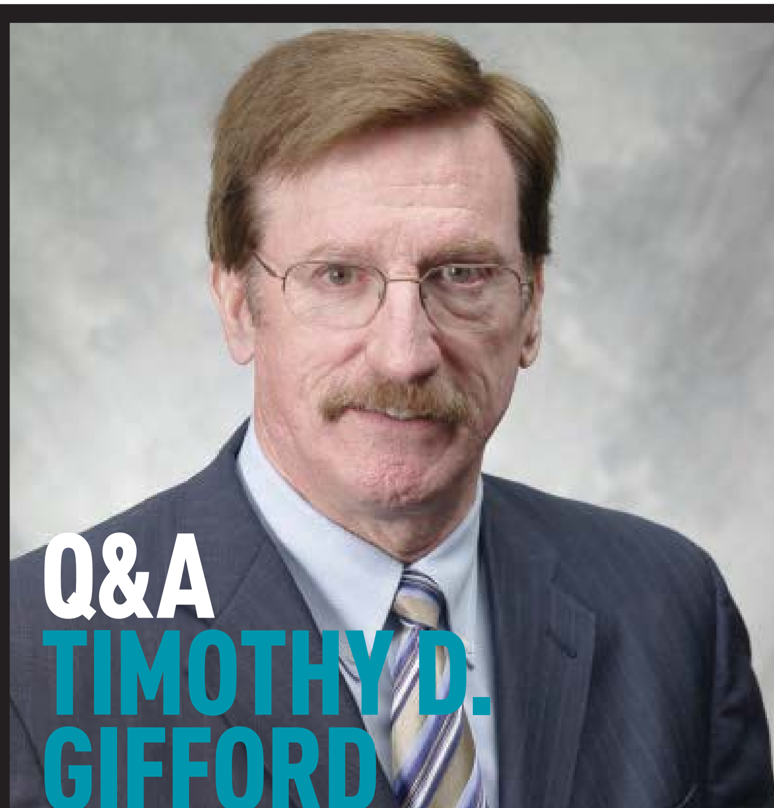


FIG. 2

PRIVACY SCREEN

A cloaking system covered by U.S. Patent 5,307,162 from 1994 uses "optoelectronics and/or photonic components to conceal an object within it."

KIRK TESKA is the author of *Patent Project Management* and *Patent Savvy for Managers*, is an adjunct law professor at Suffolk University Law School, and is the managing partner of Iandiorio Teska & Coleman, LLP, an intellectual property law firm in Waltham, Mass.



Q&A TIMOTHY D. GIFFORD

SKF USA INC.'S SENIOR VICE PRESIDENT and general counsel, Timothy Gifford, learned about counterfeiting eight years ago. A customs official in Alaska asked whether a shipment of SKF bearings from China in packaging stating, "Made in Sweden," raised any questions. It did. Gifford found the boxes, bar codes, and product designations did not match. Since then, he has taken a leading role in the bearing industry's fight against fakes.

ME: How big is the counterfeiting problem?

T.G: It's huge. In 2014 U.S. customs made 23,140 seizures of counterfeit products worth $1.2 billion. I'm sure that's only a fraction of what comes into our country.

Everyone has heard about the recent airbag recall. If the handle of your fake Gucci bag falls off, it won't kill you. But a fake airbag could. So could fake bearings in rotating parts. If a bearing fails catastrophically in a large industrial fan, it could send metal flying.

ME: Is it easy to spot a counterfeit?

T.G: No. I have a suitcase that contains three bearings, and my engineers cannot always tell unless they test them. First, we look at the box and check the bar code, letter spacing, and nomenclature. If we are still not sure, we take precise measurements of the spacing between letters. While counterfeiters are getting better, we have rarely had to do a complete lab analysis.

ME: How do counterfeit bearings enter the market?

T.G: Counterfeits do not really exist in the OEM market, because we ship directly to large manufacturers. But when people need to replace bearings, they turn to the aftermarket, and that's where you find counterfeits.

There are thousands of distributors and some are not authorized. Experienced distributors must know they're not buying real SKF bearings for the price they are paying, but they mark them up and sell them at a 15 or 20 percent discount, and their customers think they are getting a deal.

ME: You've said most counterfeits come from China. What is driving this?

T.G: China is the world's largest bearing market. It has 3,600 bearing manufacturers. They all want to expand, and it is very lucrative to sell counterfeits. If they put on a name like SKF, NSK, or Timken, they don't need any advertising, expensive steel, or R&D. They use our reputation to sell their product.

So Chinese agents will send out an Internet solicitation. If someone places an order, the agent will go to a manufacturer, which copies a design but puts no name on it. Then the bearing goes to someone in an apartment with a laser marking machine. That person adds a logo and boxes it. So if the Chinese authorities conduct a raid, the factory did nothing wrong. Only the person doing the marking goes to jail.

ME: Is China cooperating with you?

T.G: Yes. The World Bearing Association works very closely with Chinese customs officials. I've participated in the destruction of counterfeit bearings with an acetylene torch a year or two ago. I believe China wants to stop counterfeiting now, because they realize that they have intellectual property to protect. We've had tremendous cooperation, but China is a vast country, and the problem is huge and difficult to get a handle on.

ME: How do you deal with counterfeits in the United States?

T.G: We work closely with Customs, the National Cyber-Forensics & Training Alliance, and the Intellectual Property Rights Center to raise awareness of the problem. They have been great.

When we identify firms selling counterfeit parts, we tell them we can do it the easy way or the hard way. They can give us all their counterfeit bearings, the names of everyone they sold them to over the past three years, and pay our legal fees. Or we can sue them and get all the information anyway. It's a federal and state crime to sell counterfeit bearings, and the easy way is better for everyone.

ME: What should engineers know when looking for replacement parts?

T.G: They should buy from authorized distributors. If they suspect a part is counterfeit, they should take pictures of the box and bearings and send it to the manufacturer. SKF even has an app they can use to do it. Most manufacturers have ways to identify counterfeits, though we do not share that information because it would go right back to the counterfeiters. ME

4,000 OIL WELLS TO PHONE HOME

Some 4,000 oil wells are going to connect to the Internet of Things.

BP is working with GE Intelligent Platforms Software to connect all its oil wells in a global monitoring system. GE's data management software will give BP's field engineers real-time information about the operations of equipment at all of BP's wells.

GE uses the term "Industrial Internet" to describe connections of this sort. According to GE, BP can use the data to improve efficiency, avoid failures, and reduce downtime.

The installation will take place in stages, beginning with 650 wells. The other wells will be added over the course of the next several years, the companies said.

Peter Griffiths, BP system optimization strategist, said the project represents a move by BP away from customized solutions in the direction of off-the-shelf technology. One aim is to reduce long-term support costs connected with customized industrial products.

In a feature article on page 30, two GE executives look at the influence of the Industrial Internet on the way people work. ME

AUTOMATION ORDER IN INDIA FOR 2 SUPERCRITICAL UNITS

India's largest energy conglomerate has hired Emerson Process Management to provide automation technologies for two new 800-megawatt supercritical generating units at the Darlipali Super Thermal Power Station in Odisha, India.

The utility, NTPC Ltd., plans to commission Unit 1 in December 2017, and Unit 2 three months later.

According to Amit Paithankar, managing director of Emerson Process Management, India, "Supercritical technologies boost the efficiency of coal-based electricity generation while reducing carbon and other emissions, but the high temperatures and pressures involved make them more challenging to control. Our automation specialists have proven expertise and our Ovation control system is in more than 300 of these complex units worldwide. We welcome this opportunity to apply that experience to these important national assets."

Emerson project teams will engineer, install and commission Ovation systems to monitor and control each unit's supercritical boiler and critical balance-of-plant processes and equipment. Emerson will also provide its Rosemount Analytical online steam water analysis system and continuous emissions monitoring system, and additional instrumentation.

Emerson previously worked with NTPC Ltd. to automate units at the Sipat, Simhadri, and Tanda power stations and is currently carrying out projects at several other sites.

Bharat Heavy Electricals Ltd. is supplying steam generators and electrostatic precipitators for the new units, which are in the village of Darlipali in the Sundergarh District of Odisha. ME

CUSTOMS REFORM ON NEW SILK ROAD

China is conducting a customs clearance reform, to speed up and simplify clearances for importers and exporters.

In July, the reform was extended to ten customs houses in nine provinces along the Silk Road Economic Belt, according to a report by Xinhua, the state-owned news agency.

A notice issued by the General Administration of Customs ordered that the reform be applied to all exported and imported goods from any customs house along the route. Clearance reform enables enterprises to freely choose where they declare their goods, and the checks conducted by one customs house will be recognized by the others.

The reform not only simplifies customs clearance procedures, but also reduces logistics costs for importers and exporters. Online and hotline services are also provided for information inquiry and consultation.

China is developing the Silk Road Economic Belt as an economical trade route connecting Xian in central China with ports and markets in western Asia and Europe.

The original Silk Road was a series of interconnected trade routes that eventually stretched from Beijing to Constantinople and Rome.

Customs reform has been proceeding largely a few places at a time.

Customs authorities in June, for instance, said they would expedite clearance for goods in the Shanghai free trade zone.

In April, the General Administration of Customs said four customs houses in Fujian Province, Guangxi Zhuang Autonomous Region, and Hainan Province would be included in the reform.

Several other regions also have been brought into the reform program.

Customs reform began in 2014 in three regions—Beijing-Tianjin-Hebei, the Yangtze River Economic Belt, and Guangdong Province. **ME**

A square cross-section gives greater contact area for a prehensile tail.
Image: Michael Porter, Clemson University

SQUARE TAILS GRIP BETTER

RESEARCHERS DISCOVER advantages in the seahorse tail that could be applied to robots.

Seahorses don't gallop through the oceans. They are, in fact, the slowest swimming fish in the world. Instead, seahorses spend their days holding onto sea grasses and other objects with long, plated tails, waiting for tasty crustaceans to float by.

Those tails are made of 36 segments, each squarish in cross-section, which is odd for the animal world. "Almost all animal tails have circular or oval cross-sections—but not the seahorse's," said Michael Porter, an assistant professor of mechanical engineering at Clemson University in South Carolina. "We wondered why."

Porter and colleagues at the University of California, San Diego, Oregon State University in Corvallis, and Ghent University in Belgium believe they have found the answer. They have demonstrated that not only do square tails grasp better than round ones, but the square plates make the seahorse tail stiffer, stronger, and more resistant to strain.

To better study how the seahorse tail works, Porter and his team designed and built two artificial exoskeletal tails—one made up of four, overlapping L-shaped plates like a seahorse tail, and a similar one made with quarter-circles instead of right angles. The plates were 3-D printed and held together with springs and elastic bands.

When the engineers ran the two model tails through their paces, the limits of the round one became quickly apparent. The round tail twisted easily, but it required some effort to straighten it out. By contrast, although the square tail didn't twist as much, it more readily returned to its original shape.

What's more, while both square and round tails could bend with the same radius of curvature, the square tail provided more points of contact. The square tail may provide the seahorse a better grip on underwater objects. (Many animals—like monkeys—have prehensile tails with round cross-sections, but they are covered in flesh or fur, which deform to grip objects.)

The square tail also performs as armor. Under crushing pressure—as if a predator was taking a bite—plates of the round tail splayed outward at the sides, while L-shaped plates simply slid next to one another. In lab tests, the square cross-section 3-D printed tail supported a compressive load three times greater than the round one.

The insights into the seahorse's tail may be applicable to robots. Researchers are looking at building robots from soft, deformable parts, but squishy machines are prone to damage. Covering moving parts in armor designed to deform and protect could enable robotic tendrils to snake along and grab objects, or to work their way through rubble. Porter also is interested in developing a steerable catheter, but that's an application where using square corners may be unwise, no matter how strong or flexible they are. **ME**

continued from page 12 »

EIFFEL TOWER GOES GREEN

aspect of the whole process," Gromadzki says. "I was there as the engineer from the manufacturer to show how to put the turbine together, to answer any questions, and make sure everything was done correctly. It was very cool to watch and very efficient."

He says the installation team, which is experienced working on the tower, had never installed wind turbines before.

According to UGE, installing a wind turbine is easy and quick, but it becomes a little daunting to someone without experience with them. "Some people take extra precautions just because it's a wind turbine, but it could just as easily be a conventional HVAC system and can be done by any contractor that has experience working on a lift," Gromadzki says.

While UGE has much experience installing or supervising installations on tall buildings, this structure wasn't a conventional building. And while the turbine installation was simple and the turbines themselves were UGE's standard product, the support structure was another story. "Typically, we install these on buildings that have a concrete foundation," Gromadzki says. "Here we couldn't use a concrete foundation so the contractor built a steel foundation that had to absorb any vibration from the turbines, withstand any resonant frequencies and make sure everything worked well together."

The turbines were installed just above the renowned Le Jules Verne restaurant, where there was deep concern about noise. But the turbines performed as they should, almost silently.

The only customization was painting the turbines the same color as the tower. When they are not spinning, they are hardly visible.

While the turbines, installed in February 2015, will provide only a very small percentage of the total electricity needed each year (10,000 kWh out of 6.7 GWh used), they do contribute and serve to stimulate thinking about renewable energy. The tower itself consumes as much energy as a town of 3,000 people, mostly due to the elevators that take visitors up and down some 15 hours each day, 365 days a year.

According to Gromadzki, "It's a great start and allows people to think about energy and renewable energy more than they have in the past." ME

NANCY S. GIGES, ASME.ORG

Conceptual rendering of hyperbranched polymer molecules being added to engine lubricants to improve viscosity.
Image: Pacific Northwest N.L.

SLICK RESEARCH

TRIBOLOGY, THE SCIENCE OF LUBRICANTS, WEAR, AND FRICTION, is expected to play a key role in reaching the goal of 54.5 mpg corporate average fuel economy by 2025. Pacific Northwest National Laboratory, for instance, has a project looking at oil additives. Meanwhile, Argonne National Lab has investigators working on technologies to apply and control diamond coatings for engine parts.

Researchers at the Department of Energy's Pacific Northwest National Laboratory may be close to solving a long-standing riddle in engine lubricants. That riddle is the tradeoff between lubricity, the ability to reduce friction, and viscosity, which is resistance to shear, particularly problematic at elevated temperatures.

According to Kevin Stork, fuels and lubricants technology manager in the Vehicle Technologies Office, part of the DOE's Office of Energy Efficiency and Renewable Energy: "The trend in engine oils is towards lower viscosity, which enables better fuel economy. However, if the oil gets too thin, surfaces can experience excessive wear. High-temperature thinning of oils effectively imposes a worst-case limiting condition on the degree to which viscosity can be reduced."

Lelia Cosimbescu, project manager and a senior research scientist at the Pacific Northwest Lab, is looking for answers. "In order to offset oil thinning at high temperatures, polymeric additives which expand in size with increasing temperatures have to be used," Cosimbescu said. "These are known as viscosity modifiers or viscosity index improvers."

She and a co-investigator, Tim Bays, are exploring hyperbranched polymers (so called because the molecules are tree-shaped) as lubricant additives.

"We have made good progress with additives but do not yet have all the data we need to make statements about fuel efficiency," Cosimbescu said. "We now have to produce half a kilogram of each of one or two desired candidates for engine testing."

The goal is a gain of more than 2 percent in fuel economy, so the Energy Department is funding the work as part the CAFE 2015 push to 54.5 mpg.

BETTER MILEAGE AND BETTER WEAR

THE LAB Pacific Northwest National Laboratory, Richland, Wash.; Lelia Cosimbescu, principal investigator, and Timothy Bays, co-investigator.

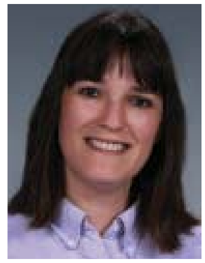
OBJECTIVE Overcoming tradeoffs in engine lubricants between lubricity and viscosity.

DEVELOPMENT Multi-branched methacrylate-based polymers are a promising route for a breakthrough; engine testing begins late 2015.

The researchers' focus is conventional fossil engine oils and not synthetics.

"Our best-performing materials show a sufficiently high viscosity index along with much better friction properties than our benchmarks," Cosimbescu added. "In my world, that's a breakthrough. They would probably work in an engine but we're not that far along yet."

Testing is to be done in coming months at Oak Ridge National Laboratory and will conform to the standards of ASTM International. At Oak Ridge, test engineer Scott Sluder said a 1.6-liter Ford EcoBoost gasoline engine will probably be used.



Lelia Cosimbescu, project manager and senior research scientist at the Pacific Northwest lab.
Photo courtesy of Pacific Northwest N.L.

"Lubricants research presents a rare opportunity to develop a retrofittable technology that can be very quickly deployed in the existing vehicle fleet," Stork said. **ME**

Osman Levent Eryilmaz, Argonne National Lab materials scientist and coatings expert, working with pistons in a vapor deposition process. *Photo: Argonne National Laboratory*

HARD COATS

THE LAB Argonne National Laboratory, Lemont, Ill.; Ali Erdemir, principal investigator, super-tough coatings, and Osman Levent Eryilmaz, co-investigator.

OBJECTIVE Developing surface coatings that can operate at higher temperatures with lower viscosity oils.

DEVELOPMENT Engine industry acceptance of plasma-based physical vapor deposition and chemical vapor deposition to toughen mating parts on a production basis.

Research at the DOE's Argonne National Lab is looking at practical ways to toughen surfaces in response to hotter engines and thinner oils.

Ali Erdemir, an ASME Fellow and distinguished scientist at Argonne, and Osman Levent Eryilmaz, a materials scientist, are seeing years of coatings work come to fruition. Their successes are being applied by companies that produce components such as piston rings and valve tappets used in hottest areas of automotive engines.

High power density and hotter-running engines are under development to meet a Federal fuel economy goal of 54.5 mpg. Gasoline- and diesel-powered engines with higher operating temperatures theoretically have greater fuel efficiency.

Among many efforts to boost mileage, the viscosity of engine oils is being reduced, Eryilmaz said.

According to Erdemir, hotter environments and less-viscous oil present lubrication challenges. Erdemir and Eryilmaz have developed coating technologies to address those issues.

Some of the technology is being adopted by manufacturers, "although slowly and cautiously," Erdemir said.

Diamond-like carbon coatings, made mostly from carbon and hydrogen, are synthesized in hydrocarbon-rich plasmas by physical vapor and chemical vapor deposition. A little tungsten (or other material) is added to improve resistance to wear, oxidation, and heat. A reaction in the plasma forms a metal carbide, the staple of the most durable cutting tools.

Hardness of the coatings can vary from 5 to more than 50 GPa. The thickest coatings—from 10 to as much as 40 micrometers—are needed on piston ring faces exposed to the engine's highest temperatures.

"These coatings are being applied at Argonne as well as by many makers of engine parts," Eryilmaz said, "and we can show companies how to do this."

According to Ann M. Schlenker, director of the Argonne Center for Transportation Research, "More emphasis has recently been placed on accelerating technologies to market and to develop closer relationships with industry." Before coming to Argonne, Schlenker was an engineering director at Fiat Chrysler Automobiles.

She added, "We can't afford the money and time to have a cliff between what's on the shelf and the capability to meet production needs, customer wants, performance requirements, and technical maturity." **ME**

JACK THORNTON, a contributing writer to *ME*, is based in Santa Fe, N.M.

THE DIESEL ENGINE FOR RAIL TRANSPORTATION

LOOKING BACK

Diesel engines were stealing the glamor from steam when this article was published in September 1935.

BY JOHN DICKSON, WESTINGHOUSE ELECTRIC AND MANUFACTURING CO.

An engineer for the company that was supplying engines for some of the era's advanced trains looked at a key question of diesel design: Two strokes or four?

Public interest has been aroused by the advent of high-speed, light-weight trains and the fact that Diesel engines were installed as the motive power of these units has focused attention on the ultimate possibilities of this particular type of engine in the transportation field.

The idea of applying the Diesel engine to rail transportation is not new. Dr. Diesel had visualized this possibility 41 years ago. In his book, *Rational Theory and Construction of a Heat Motor*, published in 1894, he said:

"We consider the new motor specially applicable on railways to replace ordinary steam locomotives, not only on account its great economy of fuel but because there is no boiler. In fact, the day may possibly come when it may completely change our present system of steam locomotives on existing lines of rails."

If we compare the engine with which Dr. Diesel was working then, using powdered coal as fuel, and the marine and land installations which established the practicality of this type of prime mover, with the comparatively light-weight and high-speed engines being offered today for rail transportation, we may conclude that two avenues of approach have been taken in arriving at present-day design. The Diesel designer has modified his slow heavy engine to permit higher speed and the gasoline-engine constructor has fortified his light-weight high-speed unit to stand the heavier stresses imposed by the adoption of the Diesel cycle.

In the Diesel engine there are four functions that must be performed to insure combustion of the fuel: (1) The cylinder must be charged with air; (2) this air must be compressed to a temperature to cause ignition of the injected fuel; followed by (3) a period to give adequate combustion during which power is developed; and (4) scavenging or exhausting of the burned gases must take place before the cycle is repeated.

The problem is, Can these operations be adequately performed without detriment to the engine in one up and down stroke of the piston as in the two-stroke cycle, or is it necessary to be so conservative as to take four strokes of the piston as in the case of the four-cycle engine? ... [T]he power of the two-cycle engine is greater than that of a four-cycle engine of the same dimensions in the ratio of 140 to 80, an excess of 75 per cent. ME

BUILT LIKE AIRCRAFT

In the same month that John Dickson's article appeared, a second article looked at the Comet, a train powered by two 400 hp Westinghouse diesel engines. According to Karl Arnstein, an engineer with Goodyear-Zeppelin Corp., which built the Comet, a high-speed three-car train set, for the New York, New Haven, and Hartford Railroad, the cars were designed so the skin of the roof, side walls, and bottom would bear loads. This monocoque construction was adopted from aircraft design. The train entered service in June 1935.

HEARING ON DOE INNOVATION HUBS

The House Science Subcommittee on Energy has held a hearing titled "Department of Energy Oversight: Energy Innovation Hubs." The purpose of the hearing was to review the Department of Energy's four Energy Innovation Hubs and evaluate their impact on programs in the Office of Science and the DOE's applied energy programs.

The DOE Energy Innovation Hubs, established in 2010, are integrated research centers that combine basic and applied research with engineering to accelerate scientific discovery and technology development in key energy fields. The hubs currently explore new ways of tapping solar energy, improving nuclear technologies, novel energy storage, and critical materials.

The witnesses were the directors of each of the four Hubs. They highlighted achievements that their Hubs have made and spoke to their experiences working with the private sector.

Harry Atwater, director of the Joint Center for Artificial Photosynthesis, said, "There is currently no existing solar fuels industry sector, which is due in part to the basic science challenges that need to be addressed before a solar fuels industry can develop. In fact, this is why a Hub-scale effort is critically needed—to accelerate progress more rapidly in this area—than would be possible via other Department of Energy programs."

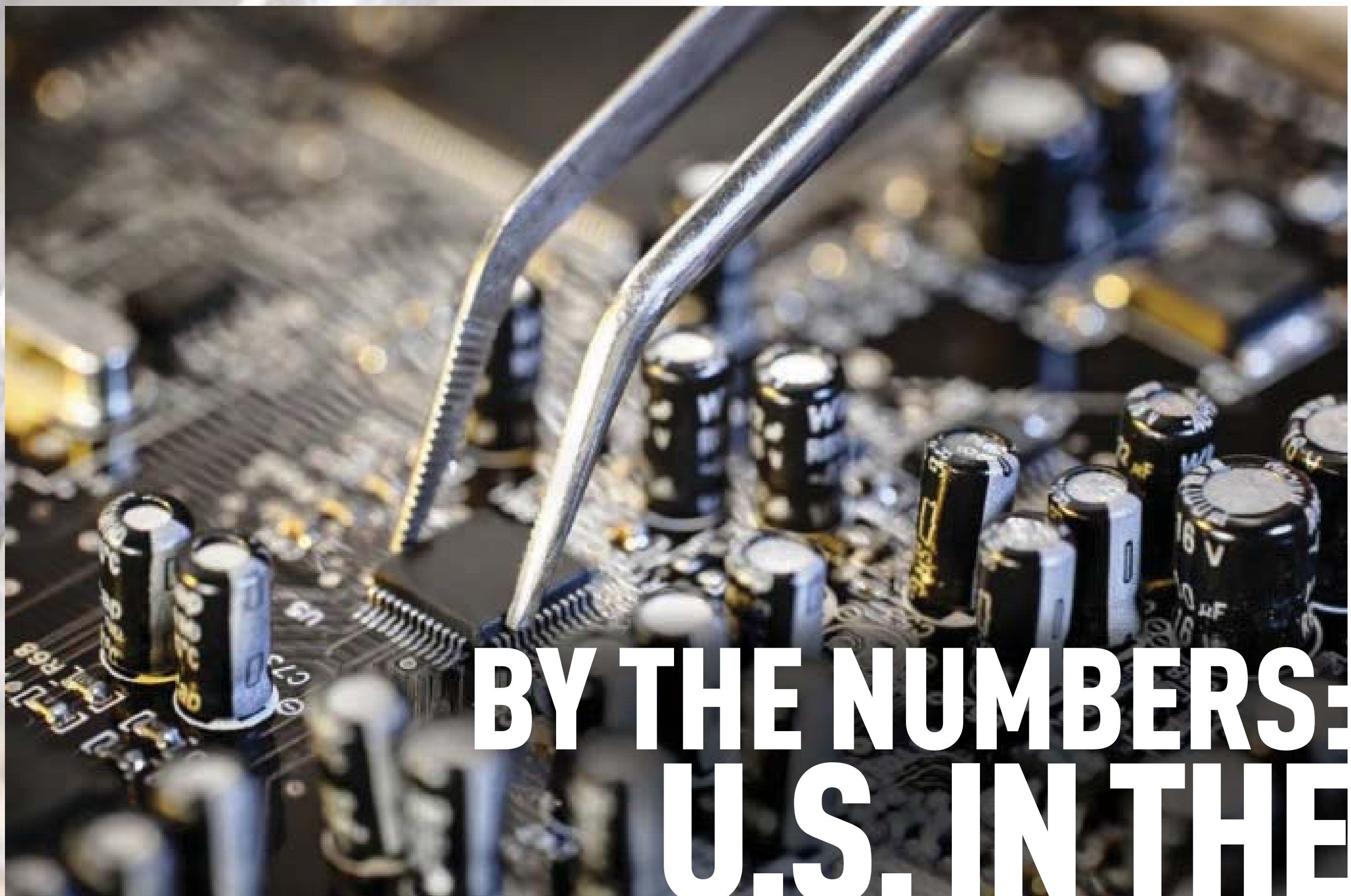
Opening statements and prepared remarks from the hearing are available at tinyurl.com/qgmnd2r. ME

$3 MILLION FOR PLANT COOLING RESEARCH

The Electric Power Research Institute has won a $3 million award from the Advanced Research Projects Agency-Energy's Advanced Research in Dry-Cooling program. The program, known as ARID, is designed to develop a novel dry cooling technology for thermoelectric power plants. The aim is to significantly reduce fan power consumption and steam condensation temperatures required by current technologies and produce a cost-effective option for reducing water use at thermoelectric plants.

EPRI is teaming with Drexel University, University of Memphis, Evapco, WorleyParsons, Maulbetsch Consulting, and utility advisors to develop and demonstrate a 50 kW indirect dry-cooling system that would use advanced phase change materials to improve heat transfer. Developers want the design to be compact, optimized for various geographic and weather conditions, and capable of installation in established power plants.

The EPRI project is one of 14 totaling $30 million to support development of transformative new power plant cooling technologies that can economically reject waste heat with minimal water evaporation. ME



BY THE NUMBERS: U.S. IN THE MANUFACTURING LANDSCAPE

The National Academy of Engineering has looked at manufacturing in the past, but its latest report, *Making Value for America: Embracing the Future of Manufacturing, Technology, and Work*, takes a different view. It accepts that the United States is part of a vast global value chain that stretches from design and engineering to manufacturing and marketing, and that the U.S. can succeed within that global marketplace.

The manufacturing value chain reaches deep into the economy. In addition to factory workers, it also includes designers and engineers, some of whom make products abroad, and software integrators who add intelligence to machines. Together, they account for 25 percent of U.S. employment, 40 percent of GDP, and 80 percent of R&D spending.

They make value by creating goods, services, and business processes. Apple's iPod, for example, combined intuitive design with simple music downloads. Apple bought components from global partners and assembled them in China.

The report finds three factors driving value creation. The first is globalization. China recently surpassed the United States in manufacturing volume. While the U.S. still leads in high-tech manufacturing (aerospace, pharmaceuticals, communications, computers, semiconductors, and advanced instrumentation), China is closing fast. The rest of the world is also catching up in services as well.

Many factors pull manufacturers overseas. Some nations offer low-cost raw materials, energy, and labor. Others offer large markets, which is why Toyota designs and makes minivans and large pickups in America. Many countries have specialized infrastructure, from factories and supply chains to skilled workers and academic partnerships. That is why China dominates consumer electronics, and North America and Europe, biopharmaceuticals.

The second factor is digital technologies. A General Motors plant that employed 5,000 workers to make 120,000 cars in 1965 now has 1,500 employees, and the cars are more complex and higher quality. This explains why, as U.S. factory jobs fell to 12 million in 2014, from 17 million in 2000, value added rose 33 percent, to nearly $2 trillion.

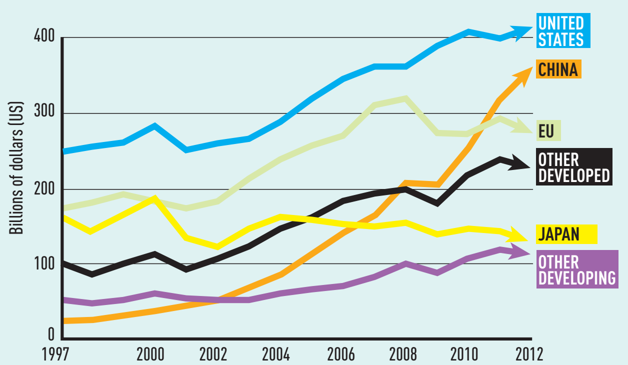
A new generation of flexible robots is making automation more accessible to smaller manufacturers. Meanwhile, engineers, designers, marketers, and others use digital files to collaborate and test designs before building them.

Yet technology cannot succeed by itself. Businesses are redesigning their processes, and that change constitutes a third force driving the global economy. For example, automation did not live up to expectations at GM until the company reengineered its processes to design parts that were easier for robots and people to assemble.

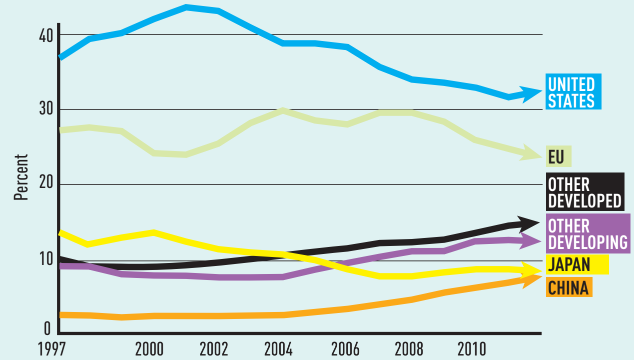
Today, lean production enables companies to boost productivity by eliminating inventories and sending highly trained workers to resolve bottlenecks that prevent parts from arriving on time and in perfect condition. By using lean principles, General Electric was able to reduce appliance assembly time on its new line to 2 hours, from 9-10 hours in the past. Still, many U.S. manufacturers have not adopted lean practices.

Another change is in the education of the U.S. workforce. Between 1960 and 2010, the number of factory workers without a high school diploma fell to fewer than 2 million, from 10 million. At the same time, manufacturing jobs requiring college degrees rose by 2 million.

OUTPUT OF HIGH-TECH MANUFACTURING INDUSTRIES



MANUFACTURING VALUE CHAIN IN TRANSITION



Jobs that require handling and attaching parts or other repetitive tasks are disappearing. Instead, production workers in all but the largest plants must be flexible enough to shift fluidly from task to task.

The United States should have the flexibility to thrive in this environment, the report said, because of its universities, its diverse and increasingly educated workforce, and its entrepreneurial flair.

The U.S. also faces key challenges. Its best schools are increasingly unaffordable. Technology, especially engineering, fails to recruit women and many minorities. More foreign students are returning home after studying in the U.S. Also, entrepreneurs increasingly find themselves shut out from the low-cost capital needed to finance production in the United States.

Recommendations in *Making Value for America* include adoption of best practices, teaching and supporting entrepreneurship, strengthening local innovation clusters, ensuring that startups with longer lead times have access to capital, upgrading infrastructure, and supporting manufacturing value chains.**ME**

ALAN S. BROWN


F30

THE INDUSTRIAL INTERNET AND THE FUTURE OF WORK

As the lines between the digital and the physical continue to blur, we are entering a world where the machines we work with are not just intelligent, but brilliant.

BY MARCO ANNUNZIATA AND STEPHAN BILLER

THE INDUSTRIAL INTERNET AND THE FUTURE OF WORK

A powerful, deep, and far-reaching transformation is under way in industry. It is fundamentally changing the way we design and manufacture products, and what these products can do. It is making the complex supply and distribution networks that tie the global economy together faster, more flexible, and more resilient.

This transformation is what we call the Future of Work. Of the major forces converging to shape this transformation, the one of most interest to mechanical engineers is the Industrial Internet.

The lines between the physical and digital worlds are becoming increasingly blurred. The integration of cloud-based analytics ("Big Data") with industrial machinery ("Big Iron") is creating huge opportunities for productivity gains. In a 2012 white paper for GE, one of us (Annunziata, together with Peter C. Evans) wrote that the rapid decline in the costs of both electronic sensors and storing and processing data now allows us to harvest massive amounts of information from industrial machinery. Using advanced analytics, we can then draw insights that can increase efficiency.

Machines like gas turbines, jet engines, locomotives, and medical devices are becoming predictive, reactive, and social, making them better able to communicate seamlessly with each other and with us. The information they generate becomes intelligent, reaching us automatically and instantaneously when we need it and allowing us to fix things before they break. This eliminates downtime, improves the productivity of individual machines—as jet engines consume less fuel and wind turbines produce cheaper power—and raises the efficiency of entire systems, reducing delays in hospitals and in air traffic.

The Future of Work will substantially accelerate productivity and economic growth. In that 2012 white paper, for instance, the major economic benefits that can accrue from the Industrial Internet alone were estimated for specific sectors. A 1 percent gain in efficiency through deployment of the Industrial Internet would yield $90 billion savings in the oil and gas sector, $66 billion in the power sector, and $30 billion in aviation.

Some economists, notably Robert Gordon of Northwestern University, argue that modern innovations have nowhere near the transformative power and potential economic impact of the Industrial Revolution. But we believe the Future of Work will be as transformational as the Industrial Revolution, and possibly more so. This will bring major improvements to the quality of our lives.

The seeds of this transformation were sown some time ago and have taken time to germinate. But we are now entering the stage where the changes we describe are set to accelerate decisively. To use an expression coined by Ray Kurzweil of Google, we are entering the second half of the chessboard—the phase where changes become all of a sudden a lot more visible, where science fiction more quickly turns into reality.

Even so, this transformation will not happen by itself. We will have to invest in the new technologies and adapt organizations and managerial practices. We will need a robust cyber security approach to protect sensitive information and intellectual property, and to safeguard critical infrastructure from cyber-attacks. The education system will have to evolve to ensure that students are equipped with the right skills for this fast-changing economy. Continuous education and retraining will be needed to cushion the impact of transitional disruptions in the labor market.

It will require time and investment, but this wave of technological innovation will fundamentally transform the way we live.

MACHINES THAT HEAR AND FEEL

The Industrial Internet is creating huge opportunities for productivity gains. Industrial machines are being equipped with a growing number of electronic sensors, which allow them to see, hear, and feel a lot more than ever before—all while generating enormous amounts of data. Sophisticated analytics then sift through this data, providing insights that allow us to operate machines—and thus fleets of airplanes and locomotives, and entire systems like power grids or hospitals—in entirely new, more efficient ways.

We are now entering a world where the machines we work with are not just intelligent, but brilliant.

Electronic sensors have been around for some time, so why are these sensors only now creating such gains in productivity? First, their cost is rapidly declining, making it cheaper and easier to deploy them. And thanks to advances of cloud computing, the cost of storing and processing data from these sensors is also dropping quickly, enabling the use of sensors to scale up at an accelerating pace.

And while many industrial assets have been endowed with sensors and software for some time, software has traditionally been physically embedded in hardware in a way that the hardware needs to change every time the software is upgraded. We are beginning to deploy technologies like embedded virtualization, multi-core processor technology, and advanced cloud-based communications throughout the industrial world. This new software-defined machine infrastructure will allow machine functionality to be virtualized in software, decoupling machine software from hardware and allowing us to automatically and remotely monitor, manage, and upgrade industrial assets.

This allows us to shift to preventive, condition-based maintenance. We'll be able to fix machines before they break rather than service them on a fixed schedule, and it will take us towards zero unplanned downtime: no more power outages, no more flight delays, and no more factory shutdowns.

How will this impact industry? Here's one example: Ten percent of flight delays and cancellations are currently caused by unscheduled maintenance events, costing the global airline industry an estimated $8 billion—not to mention the impact on all of us in terms of inconvenience, stress, and missed meetings as we sit helplessly in an airport terminal. To address this problem, GE has developed a self-learning predictive maintenance system that can be installed on any aircraft to predict problems a human operator might miss. While in flight, the aircraft will talk to technicians on the ground; by the time it lands, they will already know if anything needs to be serviced. For U.S. airlines alone, this system could prevent over 60,000 delays and cancellations a year, helping over 7 million passengers get to their destinations on time.

The health care industry also has huge gains at stake with the Industrial Internet; just a one percent reduction in existing inefficiencies could yield more than $60 billion in savings globally. Nurses today spend an average of 21 minutes per shift searching for equipment, which means less time spent caring for patients. Industrial Internet technologies can enable hospitals to electronically monitor and connect patients, staff, and medical equipment, reducing bed turnaround times by nearly one hour each.

When you need surgery, one hour matters; it means more patients can be treated and more lives can be saved.

Similar advances are taking place in energy, including renewables like wind. Remote monitoring and diagnostics, which allow wind turbines to communicate with each other and adjust the pitch of their blades in a coordinated way as the wind changes, have helped reduce the electricity generation cost in wind farms to less than 5 cents per kWh. Ten years ago, the equivalent cost was over 30 cents—six times as much.

WHILE IN FLIGHT, THE AIRCRAFT WILL TALK TO TECHNICIANS ON THE GROUND; BY THE TIME IT LANDS, THEY WILL ALREADY KNOW IF ANYTHING NEEDS TO BE SERVICED.

FASTER AND SMARTER OUTCOMES

Industrial Internet tools and applications also help people collaborate in a faster and smarter way—making jobs not just more efficient but more rewarding. For instance, secure and reliable cloud-based platforms today allow teams of physicians and caregivers to quickly confer on patient cases, simultaneously access images and reports, and collaborate on diagnosis and treatment plans. By better leveraging each other's reports and expertise, health care professionals can deliver better health outcomes.

Systems like this are made possible by integrated digital software platforms that support a combination of information collection and storage, new analytic capabilities, and new modes of collaboration. These platforms can provide a standard way to run industrial scale analytics, and connect machines, data, and people. They can be deployed on machines, on-premises or in the cloud, and support technologies for distributed computing and big data analytics, asset data management, machine-to-machine communication and mobility—all in a secure environment that protects industrial data and safeguards access to machines, networks and systems.

It isn't only the Industrial Internet that is transforming the nature of work. Advanced manufacturing is digitally linking together design, product engineering, manufacturing, supply chain, distribution, and remanufacturing (or servicing) into one cohesive, intelligent system—what we call the Brilliant Factory. New production techniques like additive manufacturing, or 3-D printing, allow us to create completely new parts and products with new properties.

What's more, technological progress and economic growth are contributing to a seismic shift in the role that human beings play in the production process. Technological progress, notably in high-performance computing, robotics, and artificial intelligence, is extending the range of tasks that machines can perform better than humans can. This may have painful short-term costs as some jobs are displaced and some skills made obsolete. But it dramatically augments the power and economic value of the areas where humans excel: creativity, entrepreneurship, and interpersonal abilities.

And the linking together of the collective intelligence of human beings across the globe, integrated by digital communication networks, will create a human version of high-performance computing—the global brain. Open-source platforms and crowd-sourcing are two of the most effective ways to unleash the creativity and entrepreneurship potential of the global brain. Industry is increasingly relying on both in a trend that will deliver greater flexibility and greater rewards to both employers and employees—and redefine relationships between the two.

TECHNOLOGICAL PROGRESS AND ECONOMIC GROWTH ARE CONTRIBUTING TO A SEISMIC SHIFT IN THE ROLE THAT HUMAN BEINGS PLAY IN THE PRODUCTION PROCESS.

SHAPING THE FUTURE

The Future of Work is being shaped by a profound transformation, driven by the meshing of the digital and the physical worlds, the emergence of new design and production techniques, and a seismic shift in the role that human beings play in the production process. Most of these changes have been under way for some time, but they are now gaining speed and scale in a way that will rapidly change the face of industry as we know it.

The Industrial Internet is leveraging the power of Big Data to create a new generation of brilliant machines that are predictive, reactive and able to communicate seamlessly with each other and with us. Advanced manufacturing techniques like 3-D printing are not only yielding new products, but allowing a faster feedback loop between design, prototyping, production, and customer experience. They are triggering a data-driven reorganization of the supply and distribution networks that tie the individual factory into its ecosystem of customers, distributors, and suppliers.

All this will result in the ability for the entire production process to adjust in real time, automatically, to unexpected circumstances, guaranteeing zero unplanned downtime at the production system level. These changes in turn will allow a faster move towards distributed manufacturing, including through greater reliance on micro-factories.

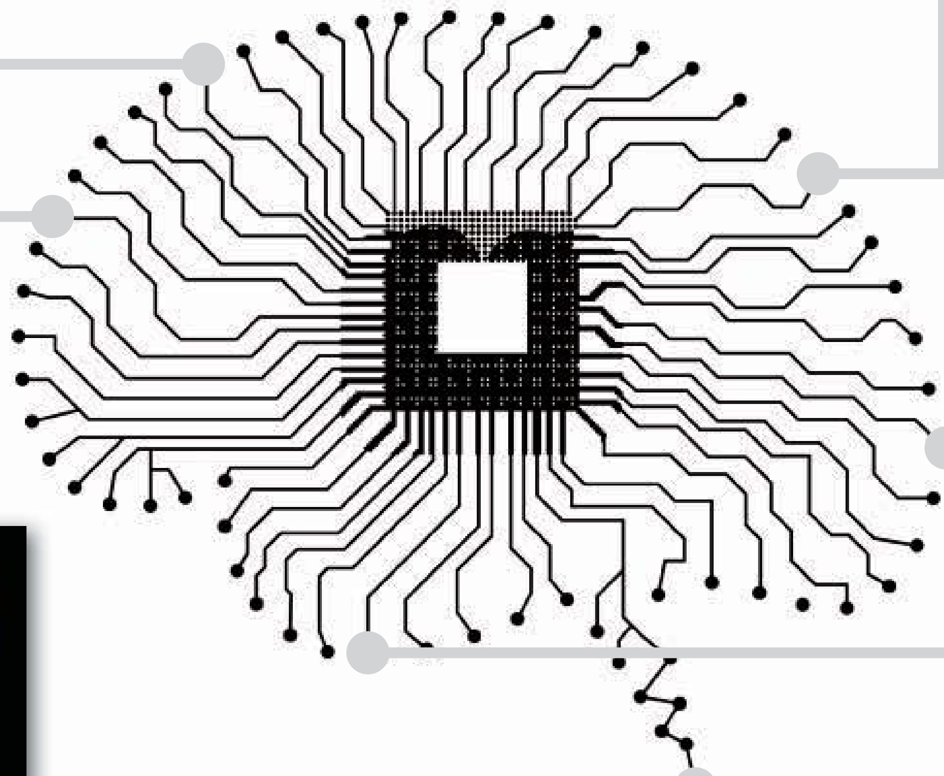
Technological progress will push a growing share of the workforce toward creativity and entrepreneurship, where humans have a clear comparative advantage over machines. The global brain—the collective intelligence of human beings across the globe integrated by digital communication networks—will grow bigger and more powerful as tens of millions more people gain access to education and to the Internet, becoming able to both tap the global stock of knowledge and contribute to it.

This transformation will take time to unleash its full potential. It will require us to invest in new technologies and adapt organizations and managerial practices. We will need a robust cyber security approach to protect sensitive information and intellectual property and safeguard critical infrastructure from cyber-attacks. The education system will have to evolve to ensure that students are equipped with the right skills for this fast-changing economy. Continuous education and retraining can cushion the impact of inevitable transitional disruptions in the labor market.

The Future of Work will require time and investment, but it will reboot productivity growth and economic activity. And it will reshuffle the competitive landscape for companies and countries alike, and it will fundamentally change—for the better—the way we work and the way we live. **ME**

MARCO ANNUNZIATA is chief economist at General Electric. **STEPHAN BILLER** is the company's chief manufacturing scientist.

THE CONNECTED LIFE



THE INTERNET OF EVERYTHING
COMING TO A BUILDING NEAR YOU

BY AHMED K. NOOR

Shower units can sense your arrival, turn on, and adjust the water temperature.

Bathroom scales, such as Withings WS-50 Smart Body Analyzer, communicate with weight management apps, which can use weight and nutrition information to help control calorie intake.

ONE MORNING NOT FAR IN THE FUTURE, it is nearing time for a sleeper to start the day. Sensors in bedcovers and pajamas monitor sleep patterns. The window system adjusts to let more sunlight enter the room.

At the right moment, a wristband vibrates to wake the sleeper up.

The person steps out of bed and heads to the bathroom where a scale not only reads body weight, but also automatically sends the data to a server in the cloud, where it is available through a smartphone app. The system records personal weight, body fat, food intake, water consumption, and overall activity level.

The person heads to the shower where water is already running at the preferred temperature. At the same time, a message triggers the coffeemaker to start.

While the coffeemaker is grinding fresh beans for the morning cup of joe, the smart phone is transmitting the person's preferred cabin temperature and daily schedule to the smart car, preparing it for the trip to the office.

At breakfast the person uses a calorie counter app on a mobile phone. Scanning the barcode on the oatmeal package records information about calories and nutrition.

In the office, the tasks of the day include a type of data analysis that the person has never done before. The cognitive software assistant offers a step-by-step tutorial for the process, along with names of co-workers who have experience with this analysis.

At the end of the work day, as the person steps out of the office, an embedded beacon sensor sends a notice that a smart phablet has been left on the desk.

As the person heads home, the mobile device reports a 30 percent off sale at a favorite clothing store in the mall. At the store, a scan of the barcode on a suit communicates with the digital inventory system, which confirms that the right size is available in stock.

At the end of the day, from the bed, the press of a single button on the smart wrist watch sends commands that turn off the lights, set the home security system, and adjust the thermostat to a comfortable sleeping temperature.

Welcome to life in the smart city.

Although most of the technology to make this scenario happen is commercially available today, it is interconnectivity and the intelligence of the devices that will make the difference in the future. Embedded sensors will be multipurpose and ever-smaller. Devices will have a higher level of intelligence through deep learning—the system of algorithms that let machines learn from experience and observation.

This interconnectivity—the Internet of Things (or perhaps of Everything)—is expected to have a profound influence on all aspects of life, ranging from transportation and utilities to health care and public services. In a time of increasing urbanization, it is expected to be everywhere in the cities of tomorrow.

Systems informed by sensors, systems that talk to each other, systems that cooperate are envisioned as the means to enhance the day-to-day lives of the citizens. They can also improve innovation, productivity, and economic opportunities by increasing efficiency, lowering costs, and engaging more directly with city dwellers.

Buildings—commercial and residential—are the laboratories leading the trend to smart cities. Almost half the connected

Wi-Fi sensors can alert your coffee maker when you get up and start brewing your favorite blend.

things in use this year are building systems, and that proportion is likely to grow. Gartner Inc., the information technology research and consulting firm, estimates that by 2020, buildings will account for more than 80 percent of the applications of connectivity.

At the most fundamental level, smart buildings leverage technology and integrate it with processes to deliver useful services to improve the lives of occupants and make them more productive, at the lowest cost and environmental impact.

Smart systems will improve the efficiency of heat, light, sanitation, security, safety, and a host of services. The savings of energy alone could be significant.

IEEE estimates, for instance, that buildings consume roughly 40 percent of the total energy used in the United States and 70 percent of its electricity. Deploying efficiency-enhancing technologies in buildings represents one of the clearest near-term opportunities for large-scale avoidance of greenhouse gas emissions and reduction in U.S. demand for fossil fuels.

Systems such as elevators, HVAC, lighting, and alarms already constantly report data across building networks. There is potential to make greater use of that information to monitor overall building performance, identify trends in building use, and improve customer satisfaction.

For example, an intelligent building could use data from the building security system to turn off lighting and minimize heating or air conditioning when the building is empty.

Connectivity opens a world of possibilities for improving occupant experience, reducing energy costs, and managing building equipment—three areas that can increase returns on real estate assets.

Companies, large and small, are working on solutions for smart commercial and residential buildings. Examples include large companies like IBM, Siemens, Cisco, Intel,

THE FOURTH INDUSTRIAL REVOLUTION: BRINGING BRAINS TO THE SMART FACTORY

The term Internet of Things (IoT) was first coined by Kevin Ashton in 1999 in the context of supply chain management. Physical objects are made "smart" by equipping them with sensors and connecting them to the Internet—a development leading to the gradual replacement of conventional computers and major changes in most aspects of everyday life. Interactions of various systems and devices can already be seen.

The introduction of the connected car is an example of how connection of the vehicle to the Internet enables real-time communication for increased safety and convenience, such as traffic warnings, navigational systems in combination with vehicle logs, and emergency calls in the event of an accident.

The IoT will also have an effect on the way things are produced, and could trigger another industrial revolution. The first revolution followed the introduction of the steam engine; the second was assembly line mass production, and the third was establishing automation via electronic controllers. It is now time for the fourth industrial revolution, or Industry 4.0, a term coined by the German government. In the United States it is often called the "Industrial Internet."

The fourth industrial revolution paves the way for the smart factory, which will consist of networked machines and components under the guidance of intelligent and highly flexible software. Numerous embedded systems will cooperate as if the factory were one integrated machine. Embedded systems link to digital networks permitting independent data processing, improved use of assets, end-to-end automated decision making, mass customization, as well as product and service innovation.

Smart factories act as intelligent networks in which assembly lines have the potential to communicate not just with one another or within a company, but with systems elsewhere and perhaps with the very products being produced. Industrial production machinery will no longer simply process the product. Instead, the product will communicate with the machinery to tell it exactly what to do.

Smart factories rely on the integration of robotics, 3-D design software, and information and communications technologies that will digitize processes to boost efficiency and productivity.

Sensors, software, machine-to-machine learning, and other technologies are used to gather and analyze data from physical objects or other large data streams—and then use the findings to manage operations.

The result will be higher degree of automation, better communication, and precise coordination within factories, in addition to ensuring flexibility in the maintenance, control, and monitoring processes.

The ProGlove combines RFID, motion tracking, and other features. It can scan products, record activities, or alert a worker when a step is incorrectly performed in a workflow sequence.

and Microsoft, and small ones like TeleSense.

IBM is working with a number of universities, including Carnegie Mellon, to develop cloud-based analytics systems for reducing energy and facility costs in buildings.

The first commercial high-rise smart building in North America is RBC Waterpark Place in Toronto, Canada. Cisco Systems moved its Canada headquarters to that building in May 2015. Cisco will occupy three floors, and the ground floor will hold the company's Internet of Everything innovation center, which will open in September this year.

The building is designed around Internet connectivity. Building services, from lighting and climate control to security and elevators, are monitored and managed through a core network of fiber cabling. For example, lights run off the IP network and not off traditional electric cables, saving considerable amounts of energy. Cables can last for nearly 25 years without replacement, and allow optimal light level output when turned on.

Users can adjust the light level based on their preferences from the control panel, and eventually, even off their own tablet or smartphone. They are able to view their energy consumption and other metrics in real time.

Motion sensors will prevent unoccupied rooms from wasting power on lighting. The net results of Cisco's smart building technology are energy savings and a centralized infrastructure that increases flexibility for tenants using it.

Adolene Inc., a secure IoT platform company in the San Francisco Bay area, is one of the new small companies applying IoT for real-time asset monitoring. The company's TeleSense system focuses on solving three problems in commercial buildings.

First, TeleSense remotely senses temperature, humidity, and air quality thus enabling building managers to make decisions that can improve the occupant experience.

Smart lights by Qualcomm can monitor street traffic and alert engineers if a light malfunctions. It also has acoustic technology that can identify gun shots.

Second, TeleSense monitors energy consumption. It employs advanced machine learning techniques that enable the system to learn the usage behavior of the building and to develop a model that can be used to predict demand and optimize system performance. Usage is optimized through intelligently scheduling the use of HVAC and lighting systems based on occupancy, weather changes, zone temperature variations, dynamic pricing data, and other parameters.

Third, TeleSense monitors vibration, temperature, and acoustics to predict the failure of building equipment, thus migrating from preventive to predictive maintenance.

Technologies for smart connected buildings also include visible light communication, smart glass, and solar panel windows.

Visible light communication, known as light fidelity or Li-Fi, is a wireless optical networking technology that uses light-emitting diodes for high-speed data transmission. It is an alternative to avoid overloaded Wi-Fi networks, replace radio frequency

WaterPark Place in Toronto, where Cisco Systems occupies three floors and hosts an Internet of Things center, has numerous interconnected systems designed to conserve energy and water.

wave connections in certain areas, or provide connectivity in places where electromagnetic wave exposure can be dangerous, such as hospitals, research laboratories, or aircraft. This technology was pioneered by the German physicist Harald Haas, who is now at the University of Edinburgh.

Li-Fi is faster than Wi-Fi; its data cannot be intercepted without a clear line of sight, and it does not interfere with sensitive electronics.

Smart glass aids climate control. Also known as E-glass, it carries a low-voltage current and can adjust the tint of windows automatically. Shading and clearing windows can save as much as 30 percent on the cost of heating, ventilation, and air conditioning.

Smart glass also reduces maintenance costs because there is no need for blinds or shutters. The U.S. Energy Secretary has recommended the use of smart glass in zero-energy buildings, in which the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy created on the site.

Photovoltaic windows are in an early phase. Some current versions can transmit more than 70 percent of visible light, similar to tinted glass windows already in use. The power conversion for the initial designs is low but is expected to exceed 12 percent; typical rooftop solar panels have an efficiency of 15 percent.

One research team calculated that even with 5 percent efficiency the windows could generate over 25 percent of the energy needs of a building. Besides energy generation, the windows can block infrared radiation to reduce thermal loads and energy costs.

Technologies to be commercialized in the future include a new type of fabric created by researchers at the Fraunhofer Institute in Munich. The fabric can detect and precisely locate intrusions in a building and set off an alarm.

Made from a lattice of conductive threads connected to a microcontroller, this smart textile is considerably cheaper than conventional security systems.

In future smart buildings, people will no longer need to switch lights on when they enter a room, or turn off the oven after they bake a cake. These tasks will be done automatically.

Smart connected cities will be the places where sensors of every sort, powerful microcontrollers, and pocket-size supercomputers will be able to measure what people use at any time, with little or no waste. The economy can move away from consuming power and natural resources based on estimates to consumption that is well defined and measurable.

Roads, bridges, traffic signals, electrical grids, homes, and appliances will be connected and will share data to cooperate. In this world, traffic jams, overloads, perhaps even catastrophic structural failures could become things of the past.

Pedestrian detection technology will monitor the volume of people crossing the street and automatically adjust the traffic signal timing.

Vehicles will be networked wirelessly and will be able to broadcast their position and other key data to nearby vehicles. Automobiles can build detailed pictures of what's unfolding around them, revealing trouble that even the most careful driver, or the best sensor system, would miss.

Future smart health care will offer wearable devices for personalized care. The devices will monitor vital signs and give physicians real-time access to a host of patient health indicators.

CONNECTED DEVICES AT CES

A collection bin can tell the pickup crew that it is full.

At the International Consumer Electronic Show last January, exhibitors showed several ideas taking advantage of the Internet of Things.

Qualcomm showed a smart streetlight that not only lights the street, but also tracks activity and possible crimes. The lights can inform engineers when they've stopped working. A unit incorporates sensitive microphones that can recognize the sound of gunshots. Because the lights are connected, the approximate location of the shot can be pinpointed and authorities alerted immediately.

The company also had connected, communicating trashcans. Qualcomm partnered with smart-trash company BigBelly to fit a garbage bin with sensors that can let pickup crews know it is full. A large solar panel on the top powers an internal compactor to make the most out of the space. Even the door can be remotely locked when it gets full, or potentially in the event of a security alert. There are considerable time, effort, and money-saving opportunities to be had by optimizing routes and collecting historical data on usage.

Coca-Cola has developed machines that provide an interactive display, allowing consumers to customize drinks. The machines collect information so Coca-Cola can analyze customers' tastes.

Netatmo, the connected products manufacturer, introduced a home-monitoring camera with face-recognition technology. The tubular camera system offers users a 130-degree field of view. The system can recognize the faces of family members, and will send notifications to an iOS or Android smartphone when someone unrecognizable enters the home. The camera can also live-feed whatever's going on in the house.

Philips showed light bulbs that can be adjusted in color and intensity by smartphone.

LG demonstrated a smart watch that can detect when a person is sleeping restlessly. It can activate soothing music from an audio system, adjust the air conditioner, or pump scented mist from a humidifier.

Connections between things and people, supported by networked processes, will enable everyone to turn vast amounts of heterogeneous data into practical information that can be used to do things that weren't possible before, or to do familiar tasks better.

Cognitive work and service assistants with deep learning and reasoning capabilities will support various human activities.

We can more quickly discover patterns and trends; we can predict and prepare for anything from bus or assembly line breakdowns to natural disasters and quick surges in product demand.

This unprecedented communication can inspire creative thinking and collaborations among businesses and organizations. It can usher in a new era of cognitive knowledge discovery and application (beyond artificial intelligence), intelligent decision making, and service provisioning.

The new era can improve the quality of life and safety of citizens, bring a profound transformation to industry, spur new wave of innovations, and open entirely new dimensions for business processes. **ME**

AHMED K. NOOR is Eminent Scholar Emeritus, and Professor Emeritus of Modeling, Simulation, and Visualization Engineering at Old Dominion University in Virginia.

TO LEARN MORE

More information on smart cities and the Internet of Things, is available at http://www.aee.odu.edu/smartcities/, and http://www.aee.odu.edu/internetofthings/.

The two websites, created as companions to this *Mechanical Engineering* magazine feature, contain links to online material relating to both subjects.

Instruments

Sensors and apps are turning smartphones into engineering measurement tools.

By Kathryn Alexander

THE LATEST PROTOTYPE OF THE FAN LOOKED good. The air flow met the specification. There was just one problem—an annoying whine.

What was causing it? The first step would be to use a frequency analyzer to pinpoint the frequency of the whine. However, we did not have a frequency analyzer, or the budget or time to get one.

My phone buzzed with an incoming text message, interrupting our work. It turned out to be a welcome interruption, because it drew my attention to my smartphone, and I remembered the frequency analyzer app that I had recently downloaded to try out.

I started up the fan again, and took frequency spectrum measurements with the app. There it was—a peak that corresponded to the whine. Just to be

in Your Pocket

sure, I used another app, a frequency generator, to generate a tone at the peak frequency. The generated tone sounded just like the whine.

So the next step was to see if the whine was being generated by the blade passing frequency—the frequency at which the fan blades pass the closest point on the housing. A quick calculation using the number of blades on the fan and the motor rpm showed that the fan blade passing frequency matched the whine frequency. Mystery solved.

We could now consider changing the number of fan blades to shift the whine frequency into a range that cannot be heard as well by the human ear. That would quiet the whine to an acceptable level.

Increasingly, engineers are reaching for their smartphones to test products and equipment. The latest generation of smartphones feature sensor suites and apps that have turned the smartphone into a pocket-size laboratory of engineering instruments.

Smartphones and apps have matured far beyond the consumer market to become real engineering tools. The first generation of engineering apps focused on providing handbook information, CAD and drawing capability, and calculators for engineering formulas or unit conversion.

Now there are apps that can replace tachometers, hygrometers, seismographs, frequency analyzers, and other instruments to make serious engineering measurements immediately available, often at no cost and with no accessories. These apps have been enabled by the rapidly developing sensor suites available on smartphones.

Although smartphones had been around for several years, Apple Inc.'s introduction of the iPhone in 2007 began the era of smartphones with sensors. The first iPhone had a proximity sensor and an accelerometer. In the following years, smartphone manufacturers added sensors including magnetometers, digital compasses, gyroscopes, and barometers.

The Frequency Sound Generator by José Morais was used to confirm the frequency of a troubling whine in a fan.

In 2013 Samsung Electronics Co. Ltd., added temperature and humidity sensors and pulled ahead of the market with the largest sensor suite. In 2014, Samsung maintained dominance in smartphone sensor suites with the Galaxy Note 4 phone, which has heart rate, oximeter, and UV sensors.

Samsung offers "a wide variety of sensors on our devices to allow users to capture accurate information with minimal to no human interaction," the company said. "Sensors provide a great way to continuously provide critical data to allow smarter decision making across multiple industries."

Many apps are available free to the user. The developers monetize their offerings by putting ads in the apps or by offering purchases to upgrade to a "pro" version of the app with more functionality. The free versions generally offer plenty of engineering functionality, such as calibration and data export, with minimally intrusive ads.

The Android app SpecScope Spectrum Analyzer by Nfx Development of Manchester, U.K., was used to measure the fan whine. The Frequency Sound Generator app by José Morais, a developer in Lisbon, Portugal, was used confirm the whine frequency by generating a peak-frequency tone to compare to the whine.

Russ Alexander, president of The Design Factory, uses an Android app, a spectrum analyzer by Nfx Development.

Zephyrus Wind Meter for Android from Gaia Consulting of Verona, Italy, uses the sound of air passing over the smartphone microphone to measure air speed up to 20 meters per second. It displays a wind speed versus time chart along with average and maximum values. Although originally designed for meteorological applications, it can successfully be used as an anemometer to measure velocity of air output by small fans.

A rudimentary night vision app can be used as an alternative to a flashlight in dim rooms. The Android app Night Vision Camera by Fingersoft Ltd. in Kempele, Finland, uses the smartphone's camera (so no infrared sensing), but it boosts visibility in low light by shifting images to the green color spectrum, to which the human eye is more sensitive.

Although most apps are published by individuals and small companies, some are now published by major tool supply companies. For example, the Ridgid Digital Bubble Level for both iPhone and Android comes from the Ridgid Tools Division of Emerson, in Elyria, Ohio. It can be used to level equipment conventionally with the smartphone placed on a surface, or remotely through use of the camera.

Humidity sensors are relatively new to smartphones. Only Samsung's Galaxy S4 and Note 3 phones have them at this time.

The Physics Toolbox by Vieyra Software of Washington, D.C., uses these humidity sensors in its hygrometer app, which is available as a standalone for iPhone or Android. It is also available as part of the larger Physics Toolbox Sensor Suite, which includes the hygrometer as well as a g-force meter, linear accelerometer, gyroscope, barometer, proximeter, thermometer, magnetometer, light meter, sound meter, tone generator, orientation meter, and a stroboscope.

According to Chrystian Vieyra of Vieyra Software, "The Physics Toolbox apps have been used by a doctor who studies head trauma, a test pilot from the military who was looking for cheaper ways to measure g-forces, researchers in the naval aircraft industry, researchers in directional drilling that use the magnetometer app to test for rogue magnetic fields in their equipment, and dancers who want to quantify their abilities using accelerometers. The apps have also been used in industry to diagnose problems associated with vibration in mechanical systems, and by an electrical company that uses vibration to determine tension in cables."

Helen Lucke, a researcher at Covance Laboratories Ltd. in Harrogate, U.K., has used The Physics Toolbox accelerometer app to help train patients in the correct technique for handling a metered dose inhaler.

An MDI has a canister containing the drug and a propellant, and must be shaken by a patient to suspend the drug for delivery. The frequency and intensity of the shaking varies with personal technique and can influence the drug delivery.

To investigate the effects of various shaking methods, users in a study were asked to hold and shake an inhaler, then to hold and shake a smartphone in the same manner. The accelerometer in

The Ridgid Digital Bubble Level works by placing the phone on the equipment to be leveled. It also can function remotely by using the smartphone camera.

the smartphone and the accelerometer app in The Physics Toolbox provided a trace that characterized each approach to shaking the MDI. When compared to the drug delivery data for each shaking method, the preferred shaking mode became clear.

This resulted in a very detailed recommendation for shaking MDIs for best drug delivery: "Keeping your elbow still and holding the canister so the mouthpiece is pointing away from you, shake the canister in an arc for 5 seconds at 1 cycle per second (i.e. using a windscreen wiper-like motion)."

Concerns about air pollution are driving some of the newest available sensors for smartphones. Robert Bosch GmbH of Stuttgart, Germany, is a major sensor supplier to smartphone manufacturers. The company offers a sensor suite that combines a gas sensor with pressure, temperature, and humidity sensors, and provides volatile organic compound detection in the parts per million range. VOCs are outgassed from paint, adhesives, pesticides, furniture, and building supplies, and these pollutants tend to build up indoors leading to air quality concerns.

CO_2 concentration is another measurement of air quality. Asahi Kasei Microdevices Corp. of Tokyo, Japan, manufactures infrared photo-diodes that can be used to detect CO_2 spectroscopically.

Already there are a range of add-on devices to extend the functionality of smartphones with many different types of sensors. These range from low cost, maker-style options to more expensive professional grade devices.

The American Physical Society of College Park, Md., offers SpectraSnapp, an iPhone app that works with a simple accessory to turn the phone into a spectroscope for the identification of light emitting materials. For those with access to a simple maker-space or home workbench, directions are available at itunes.apple.com for making a simple spectroscope that fits over the smartphone camera.

For phones without humidity and temperature sensors, a German company, TFA Dostmann GmbH & Co., offers the Smarthy thermo-hygrometer which plugs into the headphone port on Apple and Android mobile devices. At about $45, it is in the middle price range of smartphone peripherals. It is available in the U.S. through Amazon.com from Dostmann's distributor, LaCrosse Technology of La Crosse, Wis.

Beyond rudimentary night vision apps that shift the color spectrum, FLIR Systems Inc. in Wilsonville, Ore., offers true thermal imaging as an add-on to either iPhone or Android. Seek Thermal Inc. of Santa Barbara, Calif., also offers true thermal imaging accessories for both iPhone and Android. In the $200 - $300 price range, these are among the more expensive peripherals available.

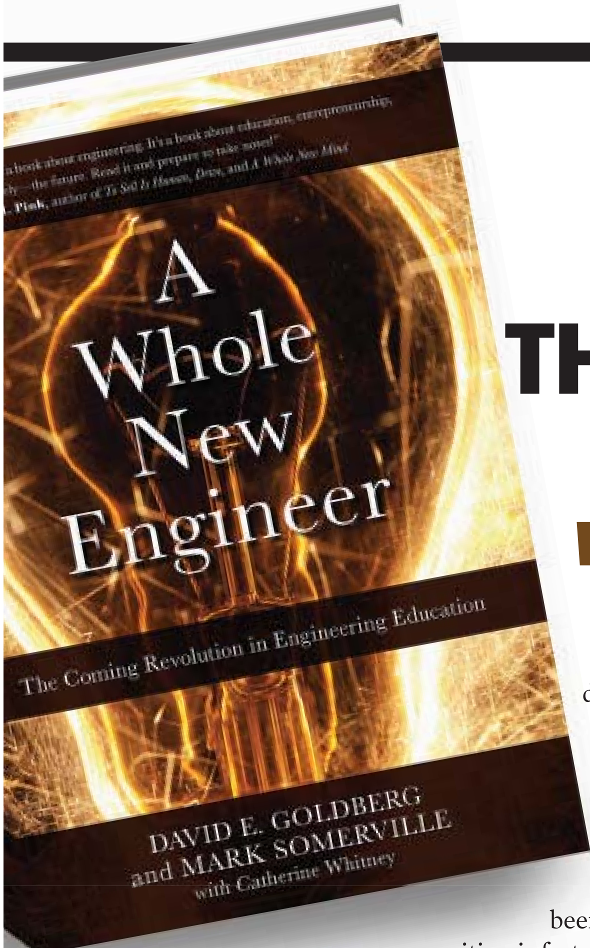
In 2013, the Kickstarter-funded company, Sensorcon of Buffalo, N.Y., launched the Sensordrone with 11 sensors that communicate with a smartphone via Bluetooth. According to Sensorcon, the device measures "carbon monoxide levels, hydrogen sulfide levels, ambient temperature, humidity and pressure, non-contact infrared temperature, oxidizing and reducing gases, and more." Now the company is working on a new product, Sensordrone Core, which can be tailored with a smaller sensor suite to application-specific needs.

Even well-established companies are working on integrating their conventional instruments with smartphones. Fluke Corp. of Everett, Wash., offers Fluke Connect to connect its conventional instruments with smartphones to identify, diagnose, and share data.

The next time you consider upgrading to a new smartphone, consider the sensor suite, and the apps and accessories that are available for your phone of choice. Smartphones, apps, and add-on devices are evolving rapidly, and a smart choice could make your next engineering project go mobile. **ME**

The Smarthy thermo-hygrometer plugs into the headphone port on Apple and Android mobile devices.

KATHRYN ALEXANDER, P.E., is vice president of The Design Factory Inc. in Shrewsbury, Mass.



TO MOOC, OR NOT TO MOOC, THAT IS THE QUESTION

By Mohamed Gad-el-Hak

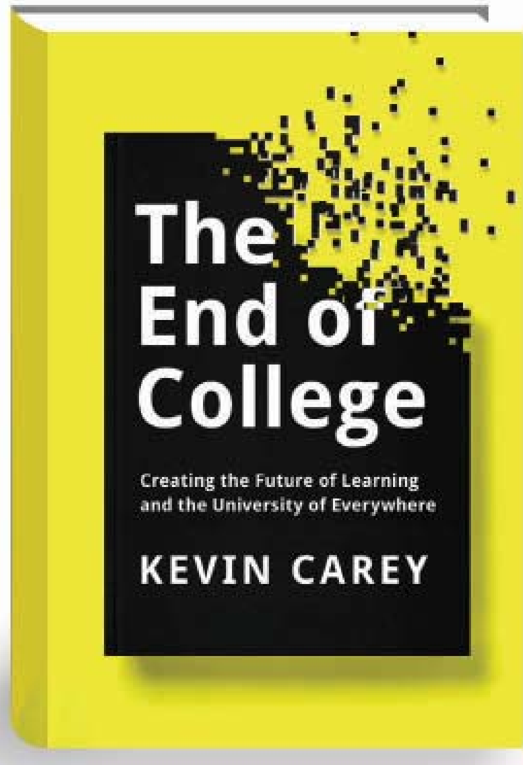
"WE ARE AT A CROSSROADS!" A TIRED PHRASE HABITUALLY uttered by politicians. In the 1998 dark comedy bearing his surname, the fictitious Senator Jay Billington Bulworth was repeating that phrase ad infinitum; eventually he became suicidally disillusioned.

Of late, academics have been waving the crossroads flag. Tuition is fast rising; administrators' compensation and numbers are swelling; academe is a business; for-profit institutions of higher education are mushrooming; the end of college as we know it; online courses will one day reign supreme; engineering students need hands-on training from the get-go. When are we going to reach the freeway?

Two books I recently came across brought those road metaphors racing. The first, *A Whole New Engineer*, by David E. Goldberg and Mark Somerville (ThreeJoy Press: Douglas, MI; 264 pp; 2014), describes the change in engineering education that is taking place at the newly minted Olin College of Engineering and the more established University of Illinois at Urbana-Champaign. By emphasizing entrepreneurship, innovation, creativity, and foremost, hands-on training early in the undergraduate experience, the authors predict a revolution in engineering education, not confined to the two pioneering institutions but rather spreading nationwide, perhaps even worldwide.

In the second book, *The End of College* (Riverhead Books: New York; 277 pp; 2015), Kevin Carey prognosticates the future of learning and the university of everywhere based upon emerging massive open online courses (MOOCs). Rising tuition prices and a flagging global economy, combined with advances in information technology, are leading to a rapidly changing scene from traditional lecture-hall teaching to online education. In a *New York Times* op-ed, the business journalist Joe Nocera describes *The End of College* thus: "[The book] is both a stinging indictment of the university business model and a prediction about how technology is likely to change it. [Carey's] vision is at once apocalyptic and idealistic. He calls

Lecture hall at Baruch College, CUNY



it 'The University of Everywhere'."

While different, the two books ride on a homologous theme: the revolutionary future of undergraduate education. Ironically, however, hands-on engineering is rather difficult to teach online. Carey's book is written in an engaging, journalistic style, while that of Goldberg and Somerville is more scholarly. Both vigorously argue their respective viewpoints. The two books are, for the most part, well researched, argued, and written. Both have been featured in *The New York Times* and similar high-end publications.

Carey is a professional writer, while Goldberg and Somerville are not. It shows. Goldberg self-published *A Whole New Engineer*, and I found the first syntax error in the preface's third line, and others followed. One presumes that copyediting is also a relic. The reading gets enervating after a couple of dozen pages. On the other hand, I couldn't put Carey's book away.

A Whole New Engineer has nine chapters introduction, epilogue, and endnotes, but no index. In a nutshell, here are the seven communiqués commanded by Goldberg and Somerville: (i) Stop taking the crisis in engineering education for granted; (ii) Stop basing the education system on an operating system of fear; (iii) Stop boring our students into dull obedience; (iv) Stop educating engineers as technical brains on a stick; (v) Stop assuming that the central actor in education is the professor; (vi) Stop throwing Ph.D.s into classrooms as experts; (vii) Stop assuming that educational transformation can be performed by a system designed in the 11th century, a system designed to maintain the status quo. Paul Krupin, publicist for the drill sergeants, issued a press release that starts with: "Can we interest you in a feature story, an interview with [the authors], or perhaps a review of the incredible new remarkable book titled *A Whole New Engineer*?" Good grief! Enough said.

The End of College has 12 chapters, endnotes, and index. Carey writes about his experience attending a very successful MOOC, Introduction to Biology—The Secret of Life, offered at MIT by Professor Eric S. Lander, a first-rate scholar and an exquisite teacher.

This is like taking down a sparrow with a machine gun. If one categorizes Carl Sagan's *Cosmos* as a MOOC, then that must be the greatest thing since sliced bread. But the archetypal MOOC class is not offered by either Lander or Sagan. Several of my colleagues and I have taught online classes, and the experience was not particularly enthralling for students or teachers.

Carey occasionally is a bit loose with his facts. For example, he writes that Lander led the Human Genome Project, which in fact was led by Frances S. Collins. Lander was the first author in the 2001 *Nature* paper that presented a draft of the human genome. Carey propagates the error in more than one place. Nevertheless, the book for the most part is meticulously researched and presented.

I happen to have views that somewhat differ from those advocated in the two books. On the issue of pre-calculus, hands-on engineering, I am all right with that as long as the students are made aware of the engineering science to follow. Ant and pyramid engineering were the norm prior to the dawn of modern science, but the space shuttle was designed with a thorough understanding of the laws of nature. Engineering schools should be graduating engineering scientists, not engineering technologists. There is nothing to prevent the former from becoming entrepreneurs, innovators, and idea creators.

I would be happy with an occasional online class offered by the likes of Eric Lander and Carl Sagan. But the structured, lecture-based courses, with frequent assessment, are still needed in order for undergraduates to learn how to learn. MOOCs are not much different from the information available on the Internet. Some are more factual than others. Information and knowledge are, of course, two different animals. In a 2012 *New York Times* op-ed, University of Virginia professor Mark Edmundson, likened a memorable non-virtual course to a jazz composition: "There is a basic melody that you work with—as defined by the syllabus—but there is also a considerable measure of improvisation against the disciplining background."

There are scores of other books and articles that treat the themes discussed in the two books. The jury is still divided as to which side of the road to take. Yogi Berra said, "When you come to a fork in the road, take it." May the best man, woman, or issue take the "right" side of the fork. **ME**

MOHAMED GAD-EL-HAK is the Inez Caudill Eminent Professor of mechanical and nuclear engineering at Virginia Commonwealth University in Richmond. Contact him at gadelhak@vcu.edu.

Join us for this free webinar

MECHANICAL ENGINEERING
WEBINAR SERIES

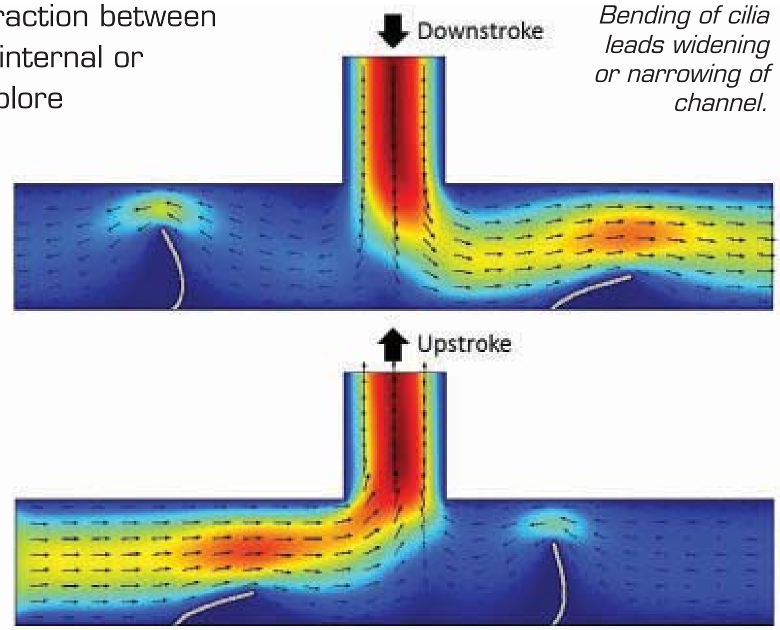
Fluid-Structure Interaction

Date: September 17th 2:00pm EDT

Register today at: http://goo.gl/G63o38

Velocity contours and vector plot for downstroke and upstroke pump motion. Bending of cilia leads widening or narrowing of channel.

Fluid-Structure Interaction (FSI) is the interaction between a moving or deformable structure and an internal or surrounding fluid flow. This webinar will explore characteristic FSI examples, show how to set up FSI problems in COMSOL Multiphysics® with suitable analysis settings, and work through a live demonstration. The demo example involves a new micropump design based on flow rectification by tilted passive cilia. The program cites COMSOL for proof-of-concept and to test a wide range of operating and flow parameters. The webinar concludes with a Q&A session.



Sponsored by:

COMSOL

SPEAKERS:

NAGI ELABBASI
Managing Engineer, PhD
VERYST ENGINEERING

JENNIFER SEGUI
Sr. Technical Marketing Engineer
COMSOL

MODERATOR:

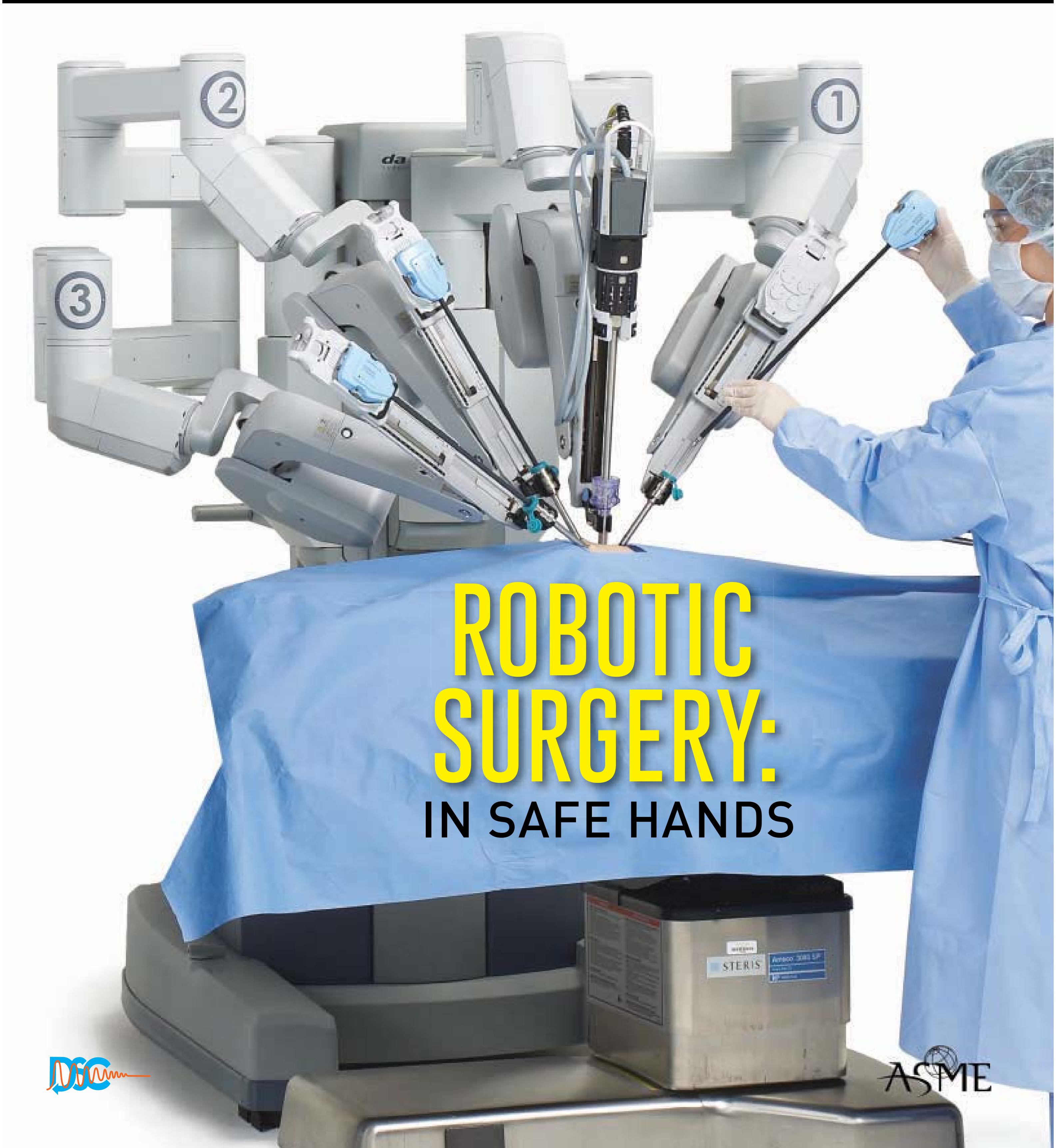
JOHN FALCIONI
Editor-in-Chief
MECHANICAL ENGINEERING

Register today at: http://goo.gl/G63o38

A forum for emerging systems and control technologies.

DYNAMIC SYSTEMS & CONTROL

SEPTEMBER 2015 VOL. 3 NO. 3



ROBOTIC SURGERY:
IN SAFE HANDS

ASME

Robotic Surgery: In Safe Hands

The practice of surgery has been integral to human civilization, with ancient texts from Mesopotamia, Egypt, Greece, India and China highlighting various surgical procedures and tools. The Sushruta Samhita, from India, discusses surgical techniques from simple incisions and probing, to deeply invasive hernia surgery & caesarian sections. The Code of Hammurabi, dating back to 1754 BC, contains specific legislation regulating surgeons and medical compensation. Since then, the surgical experience for both patients and providers has been greatly enhanced by advances in technology (imaging, instruments), techniques (minimally-invasive) and chemistry (antibiotics, anaesthetics).

Arguably, the greatest advances ensued from infusion of "scientific rigor" into the "art of surgery" – by way of systematic record-keeping, characterization, analyses – and further accelerated by the automation/computer-integration in 21st century surgical systems. Various FDA-approved robotic surgical systems significantly enhance and extend the reach of surgeons (and even surgical teams). Arguably the two most critical surgical enablers are *enhancement of perception* and reliable *execution of the intent* via capable tools. Novel modalities (magnified Stereo-Views, Magnetic Resonance Imaging, Computed Tomography scans etc.) have dramatically extended the surgeon's visual perception. Mediating interfaces between surgeon and patient scale and remove tremors while enabling intuitive access to highly inaccessible surgical fields. Other efforts seek to address the loss of tactile sensing, limited field of view, network delays for teleoperation and enhancing training, skill acquisition and assessment.

This special issue presents a snapshot of the five articles discussing *cutting-edge* (bleeding-edge?) research addressing critical issues in Computer Integrated Surgical systems. The first article in this magazine by Nabil Simaan, Russell H. Taylor and Howie Choset highlights efforts with developing natural orifice trans-luminal endoscopic surgery (NOTES) systems by first developing *highly flexible manipulators* and in *enhancing the situational awareness via sensor-fusion*. The second article by Krovi/Corso/Hager groups at SUNY Buffalo/University of Michigan/Johns Hopkins University address the need for *quantitative skill assessment* and development of *data-driven computational-skill models* together with automation tools. The third article by Gregory Fischer exploits the excellent soft tissue imaging contrast within Magnetic Resonance Imaging (MRI) for *closing the loop in image guided surgery*. In the fourth article, Ma and Rosen demonstrate development of *autonomous peg transfer task* (part of the Fundamentals of Laparoscopic Surgery) involving pick-move-drop operations on RAVEN II surgical robot. The last article by Kazanzides and colleagues at Johns Hopkins University showcase *open-source, modular and interoperable software* architectures to match the advances in open-source research platforms (RAVEN II, DVRK: da Vinci Research Kit), laying the foundations of a plug-n-play ecosystem for surgical-robotics research.

We hope that you enjoy the articles in this feature section – I'm grateful to Nabil Simaan in helping identify the authors and to Suren Kumar for the logistics help.

In lieu of news items, this issue features a letter from Del Tesar, with inspiring comments on his vision of the future of mechanical technologies. If you have any ideas for future issues of this magazine, please contact the Editor, Peter Meckl **(meckl@purdue.edu)**.

Venkat Krovi, PhD
Guest Editor, *DSC Magazine*

SUBMIT ARTICLE IDEAS TO:

PETER H. MECKL, PURDUE UNIVERSITY, meckl@purdue.edu (765) 494-5686

SUBMIT DSCD NEWS ITEMS TO:

RIFAT SIPAHI, NORTHEASTERN UNIVERSITY, rifat@coe.neu.edu

Future issues of *Dynamic Systems & Control Magazine* will include the following themes:

December 2015
Powertrain Control

March 2016
Biomimetic Systems

UPCOMING CONFERENCES

THE 2015 DYNAMIC SYSTEMS AND CONTROL CONFERENCE
Columbus, OH Oct. 28-30, 2015
http://www.asmeconferences.org/DSCC2015/

THE 2016 AMERICAN CONTROL CONFERENCE
Boston, MA July 6-8, 2016
Draft manuscripts are due on Sept. 27, 2015
http://acc2016.a2c2.org/

SUMMARY OF THE NEXT WAVE OF TECHNOLOGY

D. Tesar, UTexas, Austin, Tesar@mail.utexas.edu

A new urgency is being recognized at the national level because of under-investment in the mechanical tech base in the U.S. This weakness limits the strength of other tech base sectors (computers, communications, medical, transportation, military, etc.). The urgent need is to create a balance of all supporting technologies required in electro-mechanical systems (trains, orthotics, aircraft, robot surgery, vehicles, etc.), especially those of high economic magnitude. This argument is presented in a paper entitled **Next Wave of Technology** by D. Tesar just submitted for publication to urge serious consideration of this under-investment by our federal agencies. The desired tech base is described in terms of ten major topics which will be summarized here to indicate its relevance to meeting the needs of mankind, to its potential to reinforce our national security, and to augment our consumer product competitive position.

1. OVERALL VISION: The goal is to open up the architecture of electro-mechanical systems, use standardized interfaces to permit plug-and-play of highly-certified components (especially intelligent actuators as computer chips are to electrical systems) produced in minimum sets for each application domain and provided by a competitive supply chain to continuously improve the performance/cost ratio of these components. The concept of long-duration design/evaluation/production of one-off systems would be a thing of the past enabling more rapid infusion of technology, repair on demand, and frequently the elimination of single-point failures and the prediction of performance failure without false alarms.

2. MACHINE SYSTEM INTELLIGENCE: All future machine systems will increasingly be highly nonlinear, reconfigurable to meet changing needs, and architecturally a mixture of serial/parallel control structures. This means that the influence of any one control input (an actuator) faces an ever-changeable physical plant. This complexity can now be addressed by using very low-cost/distributed sensors providing operational data (in a milli-sec., or less) to a criteria-based decision structure (set by humans) with a full evaluation of the system in 5 to 10 milli-sec. (effectively linearizing the system) because of superior computational resources available today. Given decision inputs as a result, the command/response must be managed by ever-improving actuators to adequately respond in the 5 to 10 milli-sec. time frame.

3. COMPUTATIONAL INTELLIGENCE: A computational revolution for decision making is now feasible because of our accelerating computer technology. This revolution will be based on the geometry of the decision process. If it is serial, as for a centralized company (top-down decisions), the criteria are set by leaders at the top of a decision pyramid. Flow control from the bottom is virtually impossible. By contrast, parallel structures (holding companies, universities, multiple government agencies) can accept and facilitate flow control from the bottom in layers with nominal control from the top. Then, decision criteria in the serial case are fewer and change less often. Those criteria in the parallel case are more numerous and change more frequently. The power of predictive analytics would set/rank these criteria based on archived operational data. Of course, mixed/parallel systems do exist and their sensed/archived data would be managed in both the serial and the parallel flow with selected criteria set at each level or intersection of the decision geometry.

4. SYSTEM LEVEL SENSORS: Fortunately, sensors for all components and systems are becoming very low cost (some averaging $1 in quantity). Body sensors will soon enable effective orthotics to assist the disabled. Freight trains will embed sensors to locate hot bearings, cracked wheels, unbalanced loads, etc. Vehicles will embed torque sensors to monitor wheel traction, etc. All this information on component and system performance goes in milli-seconds to inform the decision structure to compare actual and desired performance (against operator-set criteria). Further, the real performance data can then be archived to continuously update the criteria (say, efficiency, response time, lack of precision, temperature, etc.) using predictive analytics. In the past, control techniques were structured to make decisions based on the minimum of sensed data. This approach is no longer germane in today's computational world.

5. MARRIAGE OF MAN AND MACHINE: To meet human needs, we must integrate a parametric representation of the human with that of the responsive system. Each system will be represented by hundreds of performance maps (and envelopes) at two or more physical layers. Each intelligent actuator may require 40 maps to adequately represent its nonlinear nature. Given 10 actuators, that would represent 400 maps, which then, must be built into a reconfigurable decision structure at the system level (because the system may be reconfigured to meet the ever-changing needs of the human). Doing so structures the full decision process and enables highly refined data on the map surface to be retrieved and combined in terms of human-set criteria. Of course, performance maps also apply to the human. Hence, all human and system maps/envelopes become part of the decision process with far less uncertainty and far less response time (clearly, this is useful for operator training, as well). Note that autonomy only augments this process, removing from the human the burden of repetitive low-level decisions (as long realized in the case of a fighter pilot).

6. HUMAN OPERATOR VISUALIZATION: Given truly complex and critical decisions where human life is at stake (surgery, battlefield operations, orthotics, etc.), it becomes essential to provide visual guidance to the human operator so that decisions can be made more rapidly and more accurately. Most visual representations will be to difference an actual system performance envelope relative to an embedded criteria-based envelope (prioritized by the human). This difference must highlight desired sweet spots (say, for efficiency) or operation where danger is involved, etc. A useful difference map must contrast good and bad on the same map so that critical decisions can be made quickly, probably moving away from danger in favor of a good performance region). This command would be tracked visually on one or more supportive decision envelopes.

7. COMMAND/RESPONSE: The idea that all decisions can be predetermined exists far in the past. Today, our low-cost sensors can completely document how all parts of the system are functioning. This data can then inform all parts of the decision structure (autonomy, human, envelope-based criteria, etc.), and then instruct each actuator to respond to its coordinated command, all in 5 to 10 milli-sec, or less. For example, a car moving at 70 mph will cover the distance of 2 feet in 10 milli-sec., which may not be sufficiently quick to respond to special road surface conditions (i.e., loss of traction). The same may be true of surgery, response to battlefield threats, precision response to force disturbances in manufacturing, etc. The 10 milli-sec. decision window enables the linearization of highly complex, coupled, nonlinear systems, enabling strictly algebraic/geometric decisions without the use of cumbersome continua mathematics, which are easily incapacitated by any form of coupling, or nonlinearity in the system. It also means that pseudo inverses which are computational approximations no longer need to be relied on to make timely and accurate decisions.

8. OPEN ARCHITECTURE IN EMS: Computer technology became open in the 1980 decade where standardized and highly-certified computer chips enabled the construction, almost on demand, of unique and popular computer "boards". This, then, created a demand for higher performance at lower cost for all chips utilized in each board's domain of application. Eventually, the whole design process was inverted in favor of a minimum set of computer chips of ever-higher performance-to-cost for each application domain; i.e., the board designer had to design based on the chips readily available in the supply chain or specify a unique, but more expensive, chip for a special function. The Next Wave of Technology is built on this concept of a minimum set of classes of intelligent actuators (from 2 to 4 orders of magnitude better than the SoA) to operate electro-mechanical systems (EMS). The goal is to concentrate on five classes of actuator technology to create an equivalent of Moore's law for actuators. Special cases in each class will meet unique needs (torque density, stiffness, backdrivability, efficiency, shock resistance, etc.), as is now done for computer chips. Each class/case will become available in the supply chain certified to meet acceptable performance standards (i.e., certified in-depth). Each actuator will utilize standard interfaces to permit rapid integration in a targeted domain of application. Then, the system designer becomes an architect assembling the system on demand to respond to the widest possible set of downstream conditions by reconfiguration commands from the operator or from the embedded decision structure (say, the equivalent of autonomy).

9. ENHANCED AVAILABILITY: Durability is one ingredient of availability. Reliability is one measure of durability. Standards for effectiveness and a fixed schedule for component replacements are another means to manage unexpected failure and long down times. Here, this managed failure avoidance will be expanded to enhance the technical basis for almost complete availability, almost no false alarms, and reduced cost by eliminating extended outages. Each system will be composed of components with birth-certificate performance maps. Each component will use predictive analytics to update their actual maps and difference the updated maps against the functionally required maps to estimate remaining useful life (i.e., a modernized form of condition-based maintenance). Based on this predicted RUL, spares can be brought in for replacement before failure in a timely and cost-effective manner. Using this archived data, this degradation history can now be quantified to assist the component designer to improve the design (documented in terms of performance maps), move towards lower cost, and be more responsive to the customer (as part of the supply chain process). Given that the open architecture EMS will continue to become more complex (do more in multiple configurations), this expanded view of availability will become the norm and a necessity.

10. ACTUATOR INTELLIGENCE: Item 5 highlights the absolute importance of intelligent decision making within all future actuators (as it is now for all market-driven computer chips). Given a decision time span of 10 milli-seconds at the system level, it must be 1 milli-sec., or less, for the actuator because these systems are highly coupled in most systems (frequently in a force fight). Unfortunately, all actuators are highly nonlinear making their command/response approach largely untractable by that embodied in the concept of automatic control (usually good for simple linear systems of a few DOF). To make each actuator responsive to command, at least ten sensors (voltage, current, temperature, velocity, acceleration, torque, etc.) must generate data to accurately represent the actuator's real condition (in much less than a milli-sec.). This data, then, locates each performance measure on its respective embedded maps. Each such data point then enables algebraic decisions to be made as to how to respond to commands in the next time frame (say, 1 milli-sec.). These algebraic decisions are based on operator-set performance criteria to meet the system's operational demands in this allotted time span. This includes torque, acceleration, stiffness, backdriving, etc. It also includes condition-based maintenance and fault avoidance. Actuator operational software will be dedicated to each actuator class and evolve over time depending on the application domain. There may eventually be a concentration on forward (what is commanded) and inverse (depending on what actually occurred) decisions.

RECOMMENDED ACTIONS: The weakness in the mechanicals will require a national reawakening especially among the U.S. federal funding agencies. The following may build a wave of development based on a strong tech base community of interest.

1. Convene an industrial council of interested R&D vice presidents of our high-valued industries to advise multiple federal agencies on balancing all technologies, with emphasis on rebuilding the mechanical tech base.

2. Have the DOE revisit the critical role of the mechanicals in the energy sector (oil & gas, efficient vehicles, manufacturing, power plants, etc.).

3. Have DARPA commit to a revolution in intelligent and highly-certified actuators with emphasis on military systems, as it did for the computer chip in the 1970s.

4. Have NSF engineering restructure its program plans to rebalance their portfolio to create a proportional investment in the mechanicals to meet tech base requirements of our major economic product producers taking advice from the recommended industrial council so that young faculty would be able to seek balanced funding to support graduate students better oriented to real industrial needs. ■

INTELLIGENT SURGICAL ROBOTS WITH SITUATIONAL AWARENESS:

FROM GOOD TO GREAT SURGEONS

BY NABIL SIMAAN
ASSOCIATE PROFESSOR
ARMA LABORATORY
DEPARTMENT OF MECHANICAL ENGINEERING
VANDERBILT UNIVERSITY

RUSELL H. TAYLOR
PROFESSOR
LABORATORY FOR
COMPUTATIONAL SENSING + ROBOTICS
DEPARTMENT OF COMPUTER SCIENCE
JOHNS HOPKINS UNIVERSITY

HOWIE CHOSET
PROFESSOR
BIOROBOTICS LABORATORY
ROBOTICS INSTITUTE
CARNEGIE MELLON UNIVERSITY

During the past thirty years, surgeons gradually converted open surgical procedures to minimally invasive laparoscopy and then to robot-assisted multi-port minimally invasive surgery (MIS). This conversion from open to MIS surgical technique has been driven by the aim of decreasing patient trauma, wound site infection, risk of incisional hernia, and post-operative recovery time and scarring.

Surgeons use multiple incisions (typically three to six incisions) to access the anatomy during multi-port MIS. By using insufflation of the surgical site (e.g. the abdomen) the operational field is enlarged to facilitate visualization and operation of multiple tools. Typically, three tools are used (right and left arms for manipulation/ablation and a third arm for visualization). Other access ports may be used for organ retraction and auxiliary tasks of suction or delivery of tools such as blood vessel clips. For instance, the da-Vinci Si system **(Figure 1)** uses a quadruple-armed tele-manipulator allowing the operation of additional tools and collaboration among two surgeons. The dexterous tools of the da-Vinci slave robot are matched via a telemanipulation interface to the mechanical architecture of the wrists of the master user interface. A high level telemanipulation computer relays commands from the master user interface to the slave arms thus allowing motion replication of surgeon's hand movements with tremor filtering and motion scaling.

Robotic systems such as in **Figure 1** have successfully

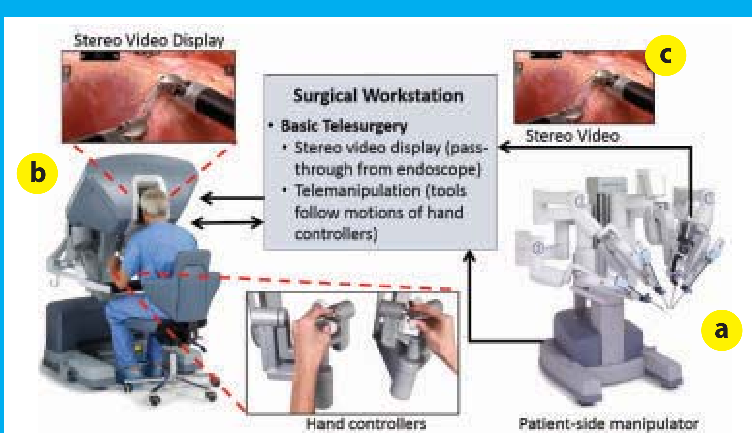


FIGURE 1 The da-Vinci Si system: (a) the patient side manipulator, (b) the surgeon master interface, (c) the correspondence between dexterous tool wrists and the master interface.

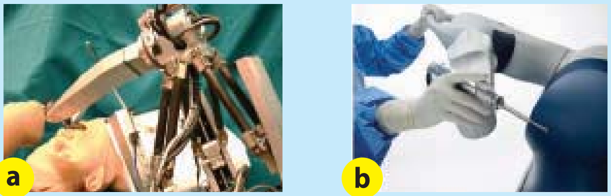


FIGURE 2 Examples of cooperative robots: (a) The JHU REMS robot for head & Neck microsurgery [4], (b) the Mako Rio® for orthopedic surgery.

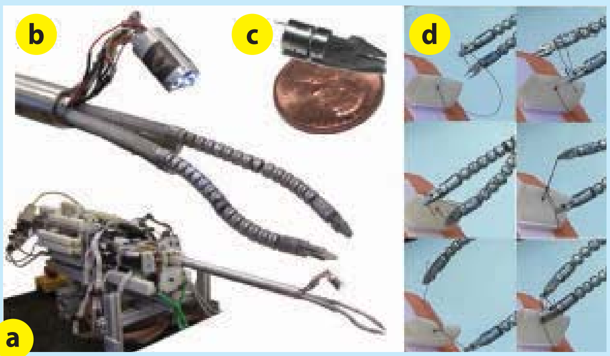


FIGURE 3 (a) The IREP single port access system, (b) the stereo- vision head with two seven degrees of freedom arms, (c) the distal wrist and gripper, (d) example of tying a double-throw knot.

enabled many surgical procedures using the multi-port MIS approach. However, with the aim of further reducing trauma to the patient, the last decade has seen significant growth in works investigating MIS in confined spaces, single port access (SPA) and natural orifice trans-luminal endoscopic surgery (NOTES). These new surgical paradigms present surgeons with unprecedented challenges that require a new approach to robotic assistance. This paper discusses these challenges and puts forth the concepts of *intelligent surgical robots* and *complementary situational awareness* (CSA) as means for achieving new surgical systems with unprecedented capabilities in terms of safety, ease of operation, and exact execution of pre-operative surgical plans. Within the context of this paper, intelligent surgical robots are robots capable of sensing and regulating their interaction with the environment in order to assist the surgeon in achieving safe surgical intervention and to facilitate CSA. Situational awareness is defined in accordance with [1] by the three stages of *sensory acquisition*, *sensory comprehension*, and *projection* (projecting the interpretation of sensed data to decide on a future action). A robotic system with CSA assists the user not only in manipulation, but also in forming the situational awareness regarding the task at hand by using perception resources beyond the capabilities of the user.

In the following sections, we show that the emerging surgical paradigms such as NOTES require new robot designs and human-robot interaction framework that go beyond the use of robots and computer assistance to allow manipulation augmentation. We will show that, while the two approaches of haptics and sensory immersion through virtual reality help surgeons overcome the sensory acquisition step, they do not help surgeons with obtaining full situational awareness. We will put forth the concept of CSA as a natural progression beyond these two approaches thereby allowing robots to help surgeons in interpreting the surgical scene and in projecting the perceived intraoperative sensory data to allow exact safe operation and the execution of pre-operative surgical plans.

FROM MANUAL TO ROBOT AND COMPUTER-ASSISTED MIS

The early drivers for robot surgical assistance stemmed from the desire to improve patient outcomes by achieving two goals: 1) offering patients the benefits while sparing surgeons the difficulties of laparoscopic MIS, 2) improving the accuracy of surgical execution of pre-operative surgical plans to ensure optimal outcomes. These two goals have driven most of the medical robotics research in the past three decades and resulted in several robotic systems reviewed in [2] and more recently in [3].

The concept of robotics for *manipulation augmentation* was introduced to overcome the challenges of manual laparoscopy. This radical move decreased the learning curve of surgeons who no longer had to contend with the reverse manipulation mapping typical of manual laparoscopy. Compared to laparoscopy robots provided increased dexterity, allowed the manipulation of multiple arms, improved precision and steadiness and lowered the physiological performance requirements of surgeons.

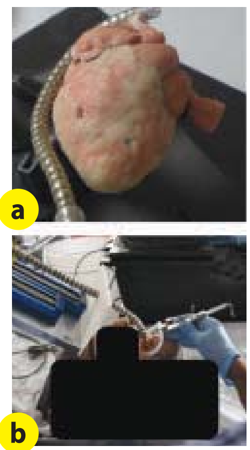


FIGURE 4 The HARP robot: (a) steering around a heart, (b) performing trans-oral access into the airways.

To improve surgical plan execution accuracy, computer assisted surgery was introduced in order to provide *perception augmentation* through intraoperative imaging and guidance. By using image registration a pre-operative surgical plan is matched to the intraoperative surgical reality. While image registration proved feasible for rigid anatomy (e.g. Orthopedics), it has been elusive in general surgery due to organ flexibility, deformation and gravitational shift and/or swelling.

The advantages of telemanipulation robot assistance came at the cost of removing the surgical tool from the surgeon's hand, thus, resulting in limited sensory perception and situational awareness. Surgeons cannot feel the tool interaction with the anatomy and current commercial systems still do not provide force feedback. Surgeons are also challenged with interpreting and relating the surgical scene with pre-operative imaging.

Haptic feedback, augmented reality and assistive manipulation have been proposed to alleviate the loss of sensory presence and situational awareness. Haptic feedback aims at restoring sensory presence through force feedback or by sensory substitution (e.g. substituting force with sound feedback). Augmented reality partially restores situational awareness via image overlay allowing the surgeon to superimpose an intraoperative image or visual cues to anatomical structures on the image display of the telemanipulation master console.

Assistive manipulation uses control laws to help surgeons achieve critical surgical tasks. These control laws include active constraints and virtual fixtures. Active constraints enforce safety barriers preventing the surgical tool from venturing into sensitive anatomy. Virtual fixtures generalize this concept to facilitate tracing of a target geometry such as an ablation path or an anatomical surface (for an up-to-date review see [5]). Assistive manipulation can be applied during cooperative manipulation or telemanipulation. During cooperative manipulation, the robot and surgeon hold the tool and admittance control allows the surgeon to move the tool while benefiting from tremor filtering and enforcement of assistive manipulation laws. Examples of coopera-

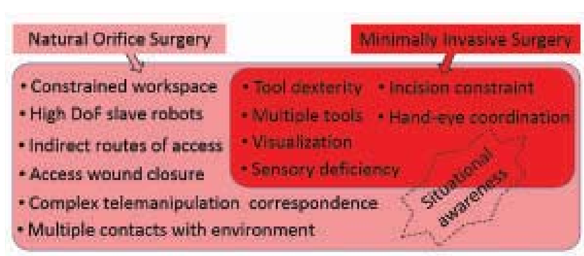


FIGURE 5 The challenges of MIS and NOTES.

tive manipulation robots are the REMS robot and the Mako Rio® shown in **Figure 2.**

By and large, the frameworks of assistive manipulation, augmented reality, and haptics have historically evolved with multiport MIS in mind as an application domain. Intraoperative information seamlessly gathered by the surgeon's hand (e.g. stiffness/constraint cues) during open surgery is not used. Also, existing frameworks for assistive manipulation typically assume single and known contact between the end effector and the environment. The newly emerging surgical paradigms violate these assumptions and therefore require a new approach.

NEW SURGICAL PARADIGMS AND CHALLENGES

Multi-port MIS requires several small incisions that generally heal well, but can also be associated with pain, scarring and potential wound infection and/or hematoma. To ameliorate surgical outcomes, SPA and NOTES have been proposed to reduce or eliminate the number of surgical access incisions. During an SPA procedure a single access port is placed in the abdomen to provide surgical access to the necessary tools. **Figure 3** shows an example of the insertable robot effectors platform (IREP) [6] developed to operate on the abdomen through a single ø15 mm port. During NOTES procedures natural orifices are used to access internal anatomy. Examples of NOTES access routes include transurethral, trans-nasal, trans-oral, trans-esophgeal, trans-gastric, trans-anal, and trans-vaginal surgeries. **Figure 4** shows an example of the highly articulated robotic platform (HARP) designed to provide deep access into the anatomy and recently used for trans-oral surgery [7]. Much of the understanding we gained regarding the limitations of traditional manipulation paradigms has been through experience in using these two systems.

Figure 5 illustrates the encumbered difficulty of NOTES/SPA compared to multi-port MIS. In addition to the challenges of MIS, NOTES adds the complexity of operating in constrained workspace and traversing anatomical passageways. Unlike multi-port MIS where contact with the anatomy occurs only at the dexterous wrists on rigid shaft tools, in NOTES contact occurs along the length of the robot as it is inserted in anatomical passageways, **Figure 6-(a)**. Also, in procedures such as trans-gastric abdominal surgery there is the significant challenge of obtaining wound closure within the gastric wall after completing the procedure. And compared to MIS where generally there is a correspondence between the motion range and shape of the wristed surgical tools and the surgeon's hand (e.g. **Figure 1**), in NOTES the robots must have many degrees of freedom and arms and this correspondence become significantly more complex to learn. Finally, while situational awareness is limited in MIS, the limitation is exacerbated in NOTES due to the further limited perception of robot shape and its interaction with the anatomy. **Figure 6-(b)** illustrates the risks of operating in confined space subject to the limited perception of the endoscope: collisions between the robot and the anatomy can occur outside the perception range of the surgeon.

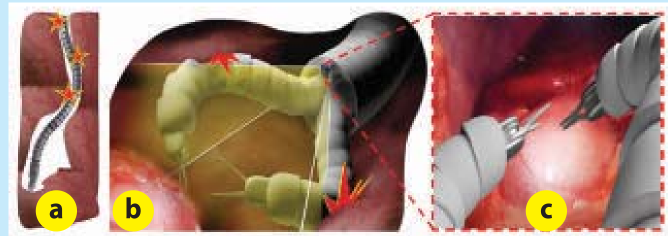


FIGURE 6 Example of perception limitations affecting situational awareness of the user: (a) invisible multiple contacts, (b) contacts outside field of view, (c) the field of view visible to the surgeon.

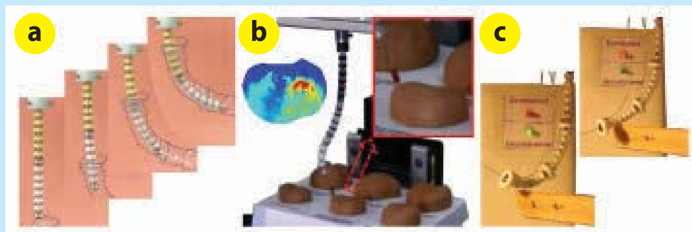


FIGURE 7 Continuum robots with intrinsic sensing capabilities demonstrating (a) active compliance to facilitate insertion [12], (b) palpation [13], (c) contact detection and localization [11].

DESIGN, CONTROL AND SENSING FOR ENABLING CSA

When designing systems for NOTES/SPA, the prerequisites of safe deployment into the anatomical passageways, distal dexterity and collaborative multi-arm workspace must be satisfied. Depending on the mechanical embodiment of the robot, there are four ways of achieving deep access into the anatomy. The first approach tasks the surgeon with steering the front end of the robot using camera visualization and uses the robot controller to execute a follow-the-leader task. Such design requires a very large number of actuators to control the shape of the robot and can lead to slow deployment. The second approach implements passive compliance with a steerable end tip. Once the robot reaches the site the robot structure can be actively locked. The Transport® endoscopic access system by USGI Medical Inc. is an example of such an approach. The third approach is by steering the robot tip while allowing the back end of the robot to alternate motions of locking and relaxation of the robot backbone in order to match the anatomical passageway during insertion. The HARP robot in **Figure 4** uses this approach. Finally, the fourth approach requires the robot to use its sensing capabilities to actively comply with the constraint forces of the anatomy while tasking the surgeon with advancing the robot. **Figure 7-(a)** shows an example of this approach; which has also been reported in [8] to facilitate rapid trans-nasal access into the upper airway.

The second design prerequisite is distal dexterity

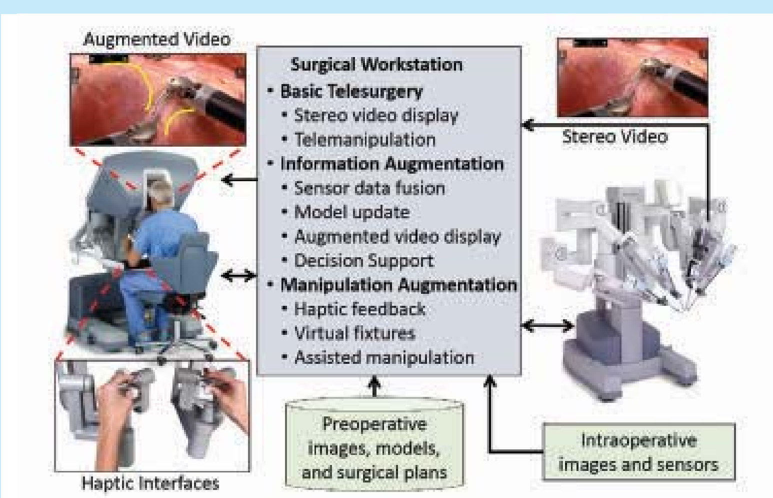


FIGURE 8 From basic telemanipulation to advanced computer-aided surgery via manipulation and information augmentation.

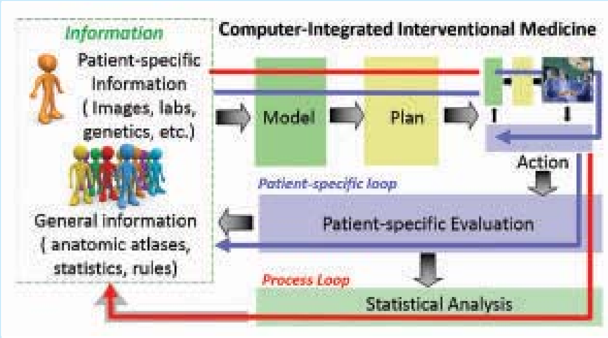


FIGURE 9 **Computer-Integrated Interventional Medicine will exploit technology and information for modeling, planning, surgical execution, and evaluation to help physicians to treat each patient in an optimal manner (blue loops). Further, information about each intervention can be saved, compared to outcomes, and used to improve treatment processes for future patients (red loop).**

with a dual-arm dexterous workspace. To effectively achieve dual-arm tasks, the robot arms must be able to oppose each other as human arms can. This challenging task is called triangulation of tools. This calls for designs enabling multiple dexterous arms to operate with almost parallel shafts. For instance the IREP, shown in **Figure 3**, has been designed with the ability to control the distance between its two snake-like arms in order to facilitate dexterous dual-arm operations such as knot tying. Other example of NOTES systems have been reviewed in [3].

Even if the design prerequisites of NOTES are satisfied, the success and safe use of these systems hinges on implementing advanced sensory and control capabilities to overcome the challenges in **Figure 5**. As initially proposed in [9], smart surgical tools can facilitate manipulation augmentation. In our work, we propose that intelligent surgical slaves are a critical component for enabling CSA. For example, intelligent robots with sensing capabilities can act as both surgical intervention and diagnostic tools much in the same way the surgeon's hand manipulates anatomy and helps in identifying stiff nodules invisible to the naked eye. These robots can act as *perception augmentation* tools by deploying sensory modalities that extend the human perception (e.g. ultrasound, optical coherence tomography, or confocal microscopy). As an example, the continuum robot shown in **Figure 7-(b)** is able to estimate forces and moments acting on its tip and it has been shown in [10] to enable palpation and building a stiffness map of a model prostate. To discern invisible contacts (as in **Figure 6**) [11] proposed kinematics-based models for detecting and localizing the contact. **Figure 7-(c)** shows a continuum robot demonstrating contact detection.

Finally, one of the key benefits of intelligent surgical slaves is their ability to offload cognitively burdensome tasks. To achieve this, the low level controllers of these robots must support force and motion regulation. For example, hybrid force/motion control can be used to facilitate controlled ablation along a path while maintaining a fixed contact force between the ablation probe and the anatomy. Our team is also working on other advanced capabilities of these robots including exploration of an unknown flexible environment with the aim of localizing and mapping the environment shape and stiffness and using this information for registration to a pre-operative model.

TOWARDS COMPLIMENTARY SITUATIONAL AWARENESS

Figure 8 shows our envisioned tele-robotic system with advanced features of computer-aided surgery, taking advantage of the fact that telesurgery systems essentially place a computer between the surgeon and the patient. In addition to basic telesurgery capabilities such as high quality stereo video, distal dexterity, motion scaling, and tremor filtering, these *Complementary Situational Awareness* (CSA) systems have the capability to combine sensing, imaging, and model information to provide the surgeon with significantly enhanced information and decision support, using augmented reality visualization, haptic feedback, and other means. These systems can also assist the surgeon in manipulating tissue through the use of virtual fixtures and other assistive methods. Further, haptic, imaging, and other intraoperative sensing during the procedure can update and refine the computers of the patient and surgical situation.

In the future, we expect that CSA systems will increasingly be embedded within a larger framework of Computer-Integrated Interventional Medicine **(Figure 9)**, in which patient-specific information such as images, lab results, and genomics are combined with general knowledge to model and diagnose the patients' condition and to develop an optimized treatment plan. All of this information will be available to a CSA system to help the physician carry out the treatment plan and assess the results. This closed-loop process (blue loops) will occur over multiple time scales, from an entire patient treatment cycle down to every second in the operating room or interventional suite. Further the CSA system will function as a flight data recorder enabling the creation of a much more complete record of what happened in the operating room. All this information can then be related to observed outcomes and statistical methods can be used to improve treatment processes for future patients (red loop). ■

ACKNOWLEDGEMENTS

Research reported in this paper has been supported in part by the National Robotics Initiative through NSF grants IIS-1327566, IIS-1426655 and IIS-1327657 and by university funds.

REFERENCES

1 Endsley, M. R., 1995. "Toward a Theory of Situation Awareness in Dynamic Systems". *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 37(1), pp. 32–64.

2 Taylor, R., and Stoianovici, D., 2003. "Medical robotics in computer-integrated surgery". *IEEE Transactions on Robotics and Automation*, 19(5), Oct, pp. 765–781.

3 Vitiello, V., Lee, S.-L., Cundy, T., and Yang, G.-Z., 2013. "Emerging robotic platforms for minimally inva- sive surgery". *IEEE Reviews in Biomedical Engineering*, 6, pp. 111–126.

4 Olds, K., Chalasani, P., Pacheco-Lopez, P., Iordachita, I., Akst, L., and Taylor, R., 2014. "Preliminary evaluation of a new microsurgical robotic system for head and neck surgery". In IEEE/RSJ International Conference on Intelli- gent Robots and Systems, pp. 1276–1281.

5 Bowyer, S., Davies, B., and Rodriguez y Baena, F., 2014. "Active constraints/virtual fixtures: A survey". *IEEE Transactions on Robotics*, 30(1), Feb, pp. 138–157.

6 Ding, J., Goldman, R. E., Xu, K., Allen, P. K., Fowler, D. L., and Simaan, N., 2013. "Design and Coordination Kinematics of an Insertable Robotic Effectors Platform for Single-Port Access Surgery." IEEE/ASME transactions on mechatronics, 18(5), Oct., pp. 1612–1624.

7 "Rivera-Serrano, C. M., Johnson, P., Zubiate, B., Kuenzler, R., Choset, H., Zenati, M., Tully, S., and Duvvuri, U." *The Laryngoscope*.

8 Groom, K., Wang, L., Simaan, N., and Netterville, J., 2015. "Robot-assisted transnasal laryngoplasty in cadaveric mod- els: Quantifying forces and identifying challenges". The Laryngoscope, 125(5), pp. 1166–1168.

9 Dario, P., Hannaford, B., and Menciassi, A., 2003. "Smart surgical tools and augmenting devices". *IEEE Transactions on Robotics and Automation*, 19(5), Oct, pp. 782–792.

10 Xu, K., and Simaan, N., 2010. "Intrinsic Wrench Estima- tion and Its Performance Index for Multisegment Contin- uum Robots". *IEEE Transactions on Robotics*, 26(3), June, pp. 555–561.

11 Bajo, A., and Simaan, N., 2012. "Kinematics-based detec- tion and localization of contacts along multisegment con- tinuum robots". *IEEE Transactions on Robotics*, 28(2), April, pp. 291–302.

12 Goldman, R. E., Bajo, A., and Simaan, N., 2014. "Compliant motion control for multisegment continuum robots with actuation force sensing". *IEEE Transactions on Robotics*, 30(4), pp. 890–902.

13 Xu, K., and Simaan, N., 2008. "An Investigation of the Intrinsic Force Sensing Capabilities of Continuum Robots". *IEEE Transactions on Robotics*, 24(3), June, pp. 576–587.

SURGICAL PERFORMANCE ASSESSMENT

BY SUREN KUMAR
MECHANICAL AND AEROSPACE ENGINEERING
STATE UNIVERSITY OF NEW YORK AT BUFFALO

NARGES AHMIDI
DEPARTMENT OF COMPUTER SCIENCE
JOHNS HOPKINS UNIVERSITY

GREG HAGER
DEPARTMENT OF COMPUTER SCIENCE
JOHNS HOPKINS UNIVERSITY

PANKAJ SINGHAL MD
ROBOTIC SURGERY
KALEIDA HEALTH

JASON CORSO
ELECTRICAL ENGG & COMPUTER SCIENCE
UNIVERSITY OF MICHIGAN

VENKAT KROVI
MECHANICAL AND AEROSPACE ENGINEERING
STATE UNIVERSITY OF NEW YORK AT BUFFALO

Skilled performance of manipulation tasks, especially in conjunction with innovative tools "to extend the reach of humans" has been instrumental to human progress. Numerous learning traditions have evolved over millennia to help characterize human sensorimotor skill for performing complex manipulation tasks while simultaneously developing the modeling techniques to capture skill acquisition and retention. For example, the careful assessment, nurturing and refinement of sensorimotor task performance has proven equally pertinent to the skilled operation of machinery as well as mellifluous musical performance. Yet, there are major gaps in our understanding of the human-operator interactions with tools in complex environments.

FIGURE 2 Evolution of surgery starting from open surgery to current minimally invasive teleoperated surgical systems.

In this article, we focus specifically on human skill understanding in the context of surgical assessment and training which has enormous and immediate application potential to enhance healthcare delivery. Surgical procedural performance involves interplay of a highly dynamic system of inter-coupled perceptual, sensory, and cognitive components. Traditional surgeries produced limited quantifiable data and, as a consequence, the skill acquisition and assessment was reliant on the philosophy of 'See one, Do one, Teach one'.

Computer-Integrated Surgery (CIS) systems are a quintessential part of modern surgical workflow owing to developments in miniaturization, sensors and computation. The tremendous proliferation of such devices ensues from their enhanced benefits: (i) reduced recovery time for patients; (ii) augmentation of sensorimotor and cognitive capabilities of operating surgeon; and (iii) potential cost-savings for healthcare-systems. However, these devices constitute additional 'intervening' layers between the operating surgeon and the patient resulting in loss of physical feedback pathways and potentially compromising the performance. Very similar research and development issues arose during the emergence of teleoperator- and haptic-systems [1] leading up to the development of insightful R&D roadmaps. There is significant value in building upon these roadmaps to characterize the extent of the attenuation and to study the role of design and control in enhancing overall system-level performance.

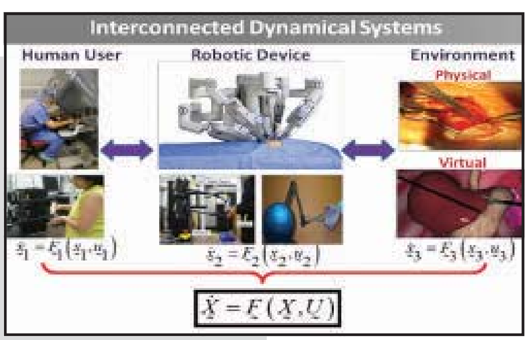


FIGURE 1 Interrelationships between structural sources and empirical spatiotemporal measurements.

It must be noted that the overall surgical task performance is dependent on bi-directional interaction between the neuromuscular system and its dynamic environment (human-machine interface + task dynamics) as shown in **Figure 1**. Given the vast spatio-temporal data from CIS systems, there is tremendous interest in generating atomic level indicators of skill acquisition. Researchers have pursued both 'constituent-element-based compositional modeling' as well as 'data-driven system-dynamics identification' perspectives, both of which we will discuss later.

The rest of the article is organized as follows. We begin with a basic historical perspective on surgical skill assessment both from clinical and research points of view. The *Skill Metrics* section outlines the important properties of a skill metric which in independent of the type of surgery, device, interface and surgical environments. As newer robotic devices are being introduced in Operating Room (OR), more surgical tasks are being automated; the interface between patient and surgeon is continuously evolving. Hence, an abstract treatment of skill is essential to develop quantitative metrics which can be applied to a variety of surgical tasks, devices and environment. The *Quantititative Performance Assessment* section describes recent research that uses a variety of sensor data such as video and kinematics, and their combinations. And last, we outline some of the open research issues with the current skill evaluation techniques.

HISTORICAL PERSPECTIVE

In 1904, Dr. William Halsted created the first residency program in United States, applying the 'See one, Do one, Teach one'[2] paradigm in which novitiate clinicians learn to perform procedures by observing experienced surgeons. The challenges to creation of successful surgical training regimen arise both from the complexity of cognitive- and sensorimotor skill-sets to be trained as well as the mission critical setting (literally life-and-death). Medical education relied on subjective or at best semi-quantitative metrics like Likert-scale proctored by experts, in order to assess the graduation requirements or skill of a surgeon. In select disciplines, such as general surgery and obstetrics, an Objective Structured Assessment of Technical Skills (OSATS) has been developed as an assessment tool – surgical task performance is rated by anonymous experts using task-specific checklists and a global-rating scale of performance with demonstrated inter-rater reliability and validity.

The requirement of an experienced surgeon during training and evaluation (in this apprenticeship- based model) places enormous constraints on the number of operation/trials by a trainee. Over the years, training of skills such as suturing, that are common across multiple procedures, has slowly led to transitioning from an apprenticeship-based to criterion-based models. Over the past decade, the ACGME (Accreditation Council for Graduate Medical Education) has espoused development of a cost-efficient proficiency-based advancement to bypass the limitations in the current apprenticeship-based system. Numerous objective methods for assessing technical skills are being considered for use in many surgical training programs today. OSATS as well as Objective Structured Clinical Examination (OSCE) emphasize the quantitative assessment processes without relying on expert evaluators using appropriate hardware (measurement device) such as Imperial College Surgical Assessment Device (ICSAD) and Advanced Dundee Endoscopic Psychomotor Trainer (ADEPT). But in the vast majority of other sub-specialties, such as pediatric nephrology, ACGME merely requires logging of performed procedures.

The next phase of research in surgical skill evaluation was enabled by the use of simulation methodologies and quantitative skills-assessment tools using the data collected during simulation. Such surgical simulators are relatively cheaper for hospital to operate and maintain and enabled novice surgeons to practice and sharpen specific skills. Computer-assisted surgical simulators (virtual-, physical- or augmented-reality) provide significant opportunities to sharpen the skills via developing different what-if scenarios and repeated/systematic training. Such systems exploit the quantitative recording and user-feedback capabilities of computer-based instrumentation (video and sensors). These simulators give various aggregate measures such as time to completion, path length etc. to rate surgical skill. An imperfect and incomplete understanding of the underlying relationships, coupled with insufficient computational support has led to an assessment regimen focused on easy-to-measure, quantitative but simplistic spatially- and temporally-aggregated measures. However, the use of such aggregated metrics (without repeatability, stability and potentially validity) to steer entire training regimen may lead to undesirable and unforeseen consequences.

The growth of computer integration in minimally-invasive-surgery (MIS) especially in the form of Robotic minimally invasive surgery (rMIS) now offers a unique set of opportunities to comprehensively address this situation. Arguably, the growth in MIS (and especially rMIS) has allowed a sheltering of the erstwhile fundamental challenge of "Nothing can come between a surgeon and his/her scalpel". A range of physical variables can now be transparently monitored via instrumented tool-usage in both simulated and real-life scenarios.

While the collection of quantitative raw physical measurements is growing (in this era of Big Data), the oversimplification inherent in using aggregated measures often results in loss of desirable user-specific discriminative characteristics. Key challenges to assessment and accreditation of surgeons in such a scenario include (1) creating appropriate clinically relevant scenarios and settings and (2) developing uniform, repeatable, stable, verifiable performance metrics; at manageable financial levels for ever increasing cohorts of trainees.

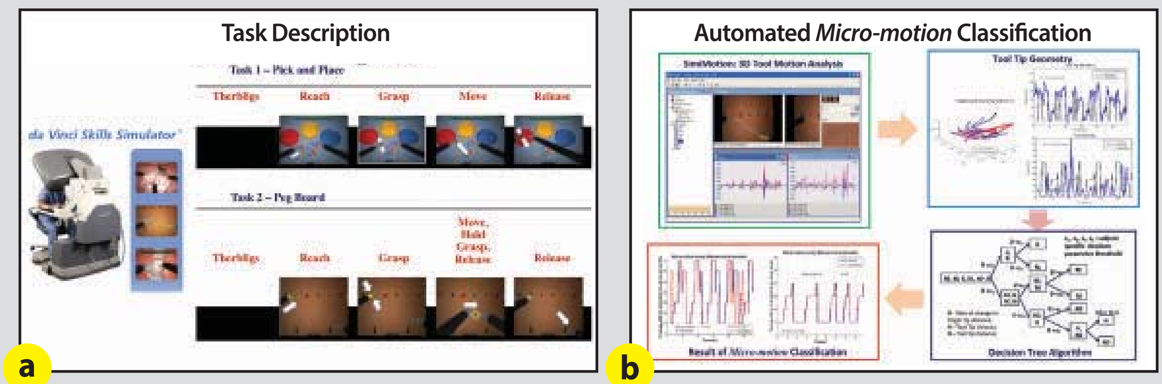


FIGURE 3 (a) Stereo-vision feeds acquired from daVinci Skills simulator; (b) The 3-stage process of extraction of the continuous motion trajectories from stereo; projection via a decision-tree; to facilitate easy comparison of ensuing Finite-State-Machine (FSM) signatures.

SKILL METRICS: DESIRED FEATURES AND CHALLENGES

Skill acquisition is fundamental to human experience enabling us to learn from the experience of people who have already mastered a task. Our education curriculum inherently involves various forms of testing skill acquisition in order to locate and correct various skill specific deficiencies. Entire traditions such as playing instruments, singing rely on the pedagogical approach of having an expert with "trained-ear" to find mistakes. Specific to surgical training, a variety of cognitive and sensorimotor skills must be learned in order to perform a variety of surgical interventions.

Critical impediments to unified skill representation and estimation arise due to the variety of: (i) surgical procedures, (ii) surgical devices; and (iii) anatomical complexity. **Figure 2** depicts the evolution of surgery: from open-to minimally-invasive (MIS) and further to robotic minimally-invasive-surgery (rMIS) which has redefined the surgeon-patient relationship in terms of available sensory feedback.

Given this dynamic relationship, it becomes imperative to consider abstracted/generalized treatment of skill assessment. Over the ages, several guidelines on the design of skill metrics have emerged (with clear implications to surgical education and accreditation)

- **Repeatability and stability (under controlled environments):** The skill metric should converge to a predictable set (law of large numbers) under repeated execution of the same task within an environment.
- **Gradated Feedback Mechanism:** Fundamentally skill evaluation needs to pinpoint the areas of improvement. Hence, in addition to a binary answer (Yes/No), the metrics need to provide a gradated scale. This enables the skill metric to be useful not just an accreditation mechanism but also improve specific skill deficiencies of trainees.
- **Real-time:** Feedback to a trainee/intermediary needs to be provided in (as close to) real-time conditions to enable course corrections.
- **Surgical Outcomes:** The skill levels either binary, discrete or continuous afford a comparison between the skill levels. However, another key characteristic is the need for correlation of skill-levels to actual surgical outcomes.

The aforementioned properties of skill metrics are quite broad, eventually there are some tasks that must be designed to evaluate the skill indicators of a trainee. As food for thought, we note that often analogies are made to liken surgical-task performance to another complex learned cognitive and sensorimotor behavior: automotive-driving.

As in surgery, driving capability can be assessed at a variety of spatial/temporal/hierarchical scales. For example: are we trying to assess a driver's ability to stay in middle of road (local short space-time scale task)? (ii) Or is the ability to get from City A to B under all types of road, traffic and weather (global spatial- and temporal-scale task)? Or are we trying to assess the ability to reject distraction e.g. cell-phones (cognitive vs spatiotemporal) during task performance? Despite these multi-scale issues, various road-transportation authorities have instituted a driving-test to assess performance. Often the test involves 'controlled performance of experiments' e.g. parallel parking test, three-point-turn test, which are scored by a driving examiner. While the manual assessment process is slowly making room for computerized diagnostic- and assessment-programs, this process is by no means complete. However, it may provide a useful roadmap of challenges and considerations for research and development of computer-aided/computer-enhanced surgical assessment.

QUANTITITATIVE PERFORMANCE ASSESSMENT

Many of the quantitative skill metrics currently available use acquired physical-measurement data from real surgeries as well as simulators. We will further elaborate on the type of data used to generate these metrics.

Aggregated Metrics

Contemporary surgical simulators use spatially- and temporally-aggregated measures such as MScore used in Intuitive Surgical's Skills Simulator . The MScore provides a binary (Yes/No) qualification answer and a continuous score to evaluate a trainee on various elementary tasks such as camera targeting, peg board manipulation tasks. Mscore and other similar scores integrate a variety of acquired sensory-data such as tool-drop, master-manipulator range, instrument collisions etc. Yet the MScore's ability – as a normalized weighted combination of multiple physical measurements (time-to-task-completion (TTC)), distance traveled) – to adequately capture subtle task-performance variations to form the discriminative basis between individuals and/or classes remains unclear. Other limitations including uncharacterized reliability, stability and repeatability of the employed metrics, hinder progress towards the final stages of validity.

Micro-Motion Studies

Robotic Minimally Invasive Surgery, and the engendered computer-integration, offers unique opportunities for quantitative computer-based surgical-performance evaluation. In our work[4], we examine an alternate method of manipulative skill evaluation using micro-motion studies, having deep roots in performance evaluation in manufacturing industries . The well-established micro-motion studies' methodology, originated in twentieth century, emphasizes on: (1) a top-down segmentation of a primary task into basic motion elements ('Therbligs'); (2) recording of elements and key subtask performance in process-charts; and (3) obtaining metrics of performance for skill evaluation. Any of the performance metrics of macro-motions—from motion economy, tool motion measurements to handed-symmetry—can now be extended over the micro-motion temporal segments.

Apart from considering representative manipulation exercises from da Vinci surgical (SKILLS) simulator, real surgical videos were also analyzed with a list of predefined 'Therbligs' in order to validate the clinical relevance of this method. This affords relatively controlled and standardized test-scenarios for surgeons with varied experience-levels. The resulting performance metrics over each sub-procedure enabled intra- and inter-user comparative studies.

Language Of Surgery

Colleagues in the Computational Interaction and Robotics Lab (CIRL) [3,5] have studied skill assessment[6] and gesture detection in both training and live patient surgical motions focusing on minimally invasive surgeries (such as robotic hysterectomy, functional endoscopic sinus surgeries (FESS), and septoplasty). Their idea is based on the fact that humans performing dexterous tasks follow a sequence of identifiable recurring motions (motifs) with some variability. To extract the surgical motifs, they designed a new technique that first translates the raw motion data into a domain that highlights the similarities and suppresses many factors of variability and then build a dictionary of important motifs (weighted statically based on their appearance in a particular surgery). The transformation function can be applied to streaming data, does not require manual processing, and is invariant to rigid transformation, cropping, and sampling frequency.

They also designed a similarity function that can measure the similarity between two motion trajectories by comparing them against a dictionary of motifs. They report accuracies about 80 to 90% for different surgical tasks. Besides learning surgical skill by demonstration of expert trajectories, they built a robotic planning system to generate an optimal expert trajectory based on a cost function and anatomical constraints for FESS. They showed that the optimal trajectory is more similar to the ones demonstrated by experts than novices, an indication that experts are probably optimizing their motions against the constraints of the environment.

Video Based Semantic Understanding

The skill evaluation metrics as discussed in the previous sub-sections need a variety of sensory data that limits the application to very specific robotic devices. The lure of using monocular/stereo data for assessment and training is due to the wide-spread availability and quintessential requirement of such modality for tele-operation. Such systems fundamentally rely solely on the surgeon-in-the-loop to ensure safe operation amidst a host of real-world uncertainties and complexities, e.g. the finite life and slack in the cables of the passive-robotic surgical instruments lead to tool-positioning inaccuracies, requiring surgeons to compensate for this error.

However, rich information content in video stream can also be used to automatedly assess surgeries. Specifically, in Kumar et.al [7] they leverage real-time video-based understanding for improved situational awareness and context-based decision support in robotic surgeries. Efforts at video understanding of real and virtual surgeries is pursued with a 2-fold objective: (i) Better understanding of skill of operator and (ii) Have a cascaded framework which can be useful from multiple perspectives – surgical guidance, safety, tracking and skill assessment. Though this preliminary study is restrictive (considers only two tools and two attributes), it can be easily extended to multiple tools and attributes.

OPEN CHALLENGES

Ultimately any automated skill assessment algorithm needs to rate and classify surgeon for which the algorithms need ground truth data. Jun et. al [4] classified surgeons into 3 different categories of expert, novices and intermediate which were pre-classified based on their experience. However this approach did not give any continuous scores. Ahmidi et al [6] used scores generated from human experts such as OSATS which were then classified as expert, novices or intermediates based on the resulting score. However both these works did not provide any sort of continuous/discrete measure of skill.

To our knowledge, published validity studies to benchmark against clinician-skill levels do not exist – although many ipso-facto studies are underway. Nonetheless, many surgical residency programs/hospital administrations are proposing to use such measures on training simulators to help pre-qualify trainees prior to actual wet-lab usage. As the Intuitive Surgical White-Paper notes "universally-accepted and validated" metrics are key to deployment of a staged and calibrated robotic-surgery training curriculum.

The field is replete with numerous open-problems that remain to be tackled. A series of workshops [ICRA2013 https://sites.google.com/site/ieeerassurgrobstandards/], [IROS2014 https://sites.google.com/site/ieeerasmedicalrobotics/] organized by the authors have sought to highlight the critical gaps in both fundamental research and technology development efforts especially as pertains to benchmarking performance of human users; training and accreditation; safety and risk-assessment. A few of them are listed below in no particular order:

- Benchmarked data with standardized metrics for better algorithm development: Surgical robotics hardware is prohibitively expensive to acquire, operate and maintain. To enable better algorithm development, the community needs to ensure open-source standardized information acquisition across various devices.
- Relating metrics to surgical outcomes and using these metrics for certification: Human anatomy shows wide variations and any skill metric should be related to surgical outcomes. The consensus in the community suggests "universally-accepted and validated" metrics are key to deployment of a staged and calibrated robotic-surgery training curriculum.
- Specific feedback such as "Your motion is not efficient while suturing" instead of "Sorry, you need to practice that motion again": Thin slices skill assessment is necessary to have person and operation specific skill assessment and feedback. This would allow one to focus on a particular area of concern such as manipulation, coordination etc.
- Presenting feedback to surgeon to improve safety based on skill: Can we provide real-time guidelines during occlusions or instructions to help doctor get his tools in view?

DISCUSSION

Success in understanding manifestation of human skill within the context of surgical tele-operated systems will have implications for a much broader arena of sensorimotor skill assessment and training, in particular ones assisted by robotic systems. Improved understanding of human manipulatory skills would be critical to designing a broad range of interactive robotic-manipulation systems, from telesurgical systems to various teleoperated vehicles and more generally to human user control of complex machinery.

From a broader scientific perspective, it will give us insights into organization of neuro-musculoskeletal interactions within the brain, including applications involving improvements of sensorimotor performance. The ability to couple quantitative, validated and stable metrics for surgical performance would lead to improvements in assessment and subsequently, training methods. Cognitive assessment can now be extended to also include sensorimotor assessment, with capacity to monitor and track skill across time. They would help usher in the next generation of virtual procedural simulators with significant impact on patient safety by providing a ready means to learn, maintain and improve surgical procedural skills. Specifically for the teleoperated surgical systems, skill understanding will also provide a quantitative method for surgical education assessment. ■

ACKNOWLEDGEMENTS

This work was partially supported by the National Science Foundation (NSF) Awards IIS-1319084, CNS-1314484 and the UB Bruce-Holm Catalyst Fund.

REFERENCES

1 B. Siciliano, O. Khatib, SpringerLink (Online service), Springer handbook of robotics, Springer, Berlin, 2008, pp. lx, 1611 p.

2 S.V. Kotsis, K.C. Chung, Application of the "see one, do one, teach one" concept in surgical training, Plastic and reconstructive surgery, 131 (2013) 1194-1201.

3 H.C. Lin, I. Shafran, D. Yuh, G.D. Hager, Towards automatic skill evaluation: Detection and segmentation of robot-assisted surgical motions, Computer Aided Surgery, 11 (2006) 220-230.

4 S.-K. Jun, M. Sathia Narayanan, P. Singhal, S. Garimella, and V. Krovi, "Evaluation of robotic minimally invasive surgical skills using motion studies," Journal of Robotic Surgery, vol. 7, pp. 241-249, 2013/09/01 2013.

5 Y. Gao, S.S. Vedula, C.E. Reiley, N. Ahmidi, B. Varadarajan, H.C. Lin, L. Tao, L. Zappella, B. Béjar, D.D. Yuh, JHU-ISI Gesture and Skill Assessment Working Set (JIGSAWS): A Surgical Activity Dataset for Human Motion Modeling, DOI.

6 N. Ahmidi, Y. Gao, B. Béjar, S.S. Vedula, S. Khudanpur, R. Vidal, G.D. Hager, String motif-based description of tool motion for detecting skill and gestures in robotic surgery, Medical Image Computing and Computer-Assisted Intervention–MICCAI 2013, Springer2013, pp. 26-33.

7 S. Kumar, M.S. Narayanan, P. Singhal, J.J. Corso, V. Krovi, Product of tracking experts for visual tracking of surgical tools, Automation Science and Engineering (CASE), 2013 IEEE International Conference on, IEEE, 2013, pp. 480-485.

8 S. Kumar, M. S. Narayanan, P. Singhal, J. J. Corso, and V. Krovi, "Surgical Tool Attributes from Monocular Video," in 2014 IEEE International Conference on Robotics and Automation (ICRA), 2014.

by Gregory S. Fischer, PhD
Worcester Polytechnic Institute

ENABLING CLOSED-LOOP SURGERY IN MRI

In the field of automation and control, we often interact with rigid, known objects in a well-defined environment. This is especially true in most manufacturing settings where a continuous stream of consistent products passes down an assembly line with fixtures to hold them in a given pose or vision systems to identify part location. This scenario lends itself well to robotics and automation for reliably performing the required task. However, now think about your body... For starters, everyone is different, so the location and shapes of organs and other structures vary from person to person. Now add on top of that the fact that most internal structures are very compliant. Further, these soft structures do not maintain a consistent shape and can deform due to a patient's orientation, interactions with surgical instruments, or swelling causing a change in volume of an organ as it is being operated on. For example in a surgery where the goal is to remove a cancerous tumor, success of the procedure hinges on how precisely a surgeon identifies the tumor boundaries and ensures removal in its entirety while preventing unnecessary collateral damage. To ensure successful removal of cancerous tissue, often excess tissue is removed (aka increased resection margins) which may improve the odds of eliminating the cancer, but possibly at the additional cost of further complications and invasiveness of the procedure. Ideally one would like to track the structures in real-time and use this information to guide the procedure – this is what we refer to as Image-Guided Surgery (IGS). Further improving on this, we can incorporate electro-mechanical assistant devices to ensure that the surgical plan is performed as intended through Robot-Assisted Surgery (RAS).

IMAGE-GUIDED SURGICAL INTERVENTIONS

The fields of IGS and RAS in their present form have existed for approximately three decades, but the concept of stereotaxis in surgical guidance dates back over a century, with the Horsely-Clark stereotactic mechanical alignment frame to align needles for neurological interventions in 1908. The field of IGS has grown significantly in recent years, with such systems becoming more widely accepted by medical professionals because they enable more information available at the surgical site while performing a procedure. A typical procedure requires a clinician to review preoperative medical images, formulate a plan, mentally register the plan to the patient, and then perform the intervention - often without any imaging updates. Typical IGS systems integrate: imaging, spatial tracking, registration, and visualization. However, often the 3D patient information is a previously acquired preoperative CT or MRI registered to the patient during the procedure and the information used to guide the procedure is essentially "stale" by the time it is being used. There is a tremendous need for integrating interactive, real-time, intra-operative imaging into the surgical navigation environment.

Although direct visualization or endoscopic cameras let us see inside the body, they only provide surface information and not inside of structures. Therefore, various medical imaging modalities and methods of presenting information in a timely manner, in an appropriate location, and assisting with interventions have been active areas of research. X-ray fluoroscopy provides inexpensive, convenient imaging but is typically limited to imaging bony structures or vasculature with the introduction of a contrast agent. Computed Tomography (CT) uses x-rays to generate high-resolution, cross-sectional images of the body. However, both of these approaches have poor soft tissue contrast and subject the patient and physician to ionizing radiation if used intraopereatively. Ultrasound is a very convenient and portable imaging system readily available in an operating room (OR), however it often has poor image quality and suffers from artifacts such as shadowing of tissue beyond a rigid structure or a needle that is being inserted under image guidance, for example.

Magnetic resonance imaging (MRI) is an excellent medical imaging modality for detecting and characterizing diseases due to its outstanding soft tissue contrast that allows for accurate delineation of pathologic and surrounding normal structures. Thus, MRI has an unmatched potential for guiding, monitoring and controlling therapy. In needle biopsies, the high sensitivity of MRI in detecting lesions allows excellent visualization of the pathology, and the high tissue contrast helps to avoid critical structures in the puncture route. Advances in magnet design and magnetic resonance (MR) system technology coupled with fast pulse sequences have contributed to the increasing interest in interventional MRI (iMRI).

INCORPORATING ROBOTIC ASSISTANTS

Computer Integrated Surgery (CIS) requires integration of information and action. The IGS systems provide information to the surgeon in a timely manner as the procedure is being performed. The next level of integration is to couple robotic action with that information to physically assist with the procedure. The field of medical robotics was born in the late 1980's and has seen tremendous growth over the years [Taylor 2003]. Often these systems fall into one of two categories, of which there is some cross-over: tele-operated minimally invasive surgical instruments and image-guided semi-autonomous robotic systems. The former acts much like a remote-controlled robotic manipulator, while the latter uses medical images to guide an intervention – often a needle-based percutaneous procedure.

CLOSING THE LOOP WITH MRI

Magnetic resonance imaging is an ideal interventional guidance modality: it can provide real-time high-resolution 3D images or 2D images at arbitrary orientations, and is able to monitor therapeutic agents, surgical tools, tissue biomechanical properties, and physiological function. With continuously improving MRI image quality and acquisition speed, it is now possible to perform interventions under real-time MR image guidance. However, MR brings unique challenges to the implementation of interventional guidance systems, and the benefits can not be readily harnessed for interventional procedures due to difficulties associated with the use of high-field (>=1.5T) MRI and conventional mechatronics approaches.

WHY IS IT SO HARD?

The ability to create and deploy a device capable of operating within the scanner bore is still frustrated by the high strength magnetic fields, and extreme sensitivity to electromagnetic interference (EMI). MRI poses formidable engineering challenges with limited access to the patient and a strong magnetic field that prevents the use of many conventional materials and electronics as shown in **Figure 1**. For example, the primary actuator in just about all traditional robotic systems is the DC motor – by its design such a device is just about the worst possible type of device to use in an MRI scanner. An MRI machine contains a strong magnetic field aligned with the scanner's axis (a typical 3 Tesla scanner is about 500 times the earth's magnetic field strength) and time-varying magnetic gradients used for localization. A motor typically comprises a steel can (ferromagnetic posing a projectile risk as well as inducing imaging distortion), permanent magnets (distorting the magnetic field as well as a safety risk), and coils of wires (which can induce eddy current that distort imaging as well as induce heating). Further, an MRI scanner incorporates a highly sensitive antenna that is used to pick up the resonant radio frequency signals of the excited Hydrogen atoms in the body – any electronics in the vicinity of the scanner that emit electrical noise may be picked up by the scanner's receiver and significantly degrade the quality of the images obtained.

With all of the benefits of MRI-guided interventions, there is a clear advantage to using MRI. But, due to these challenges the use of robotic assistants in a scalable, clinically viable fashion has really just started to take off. There are a number of technical aspects and concerns to consider when putting an interventional magnet into operation. The most pertinent ones are: configuration and field strength of the magnet (which necessitates a compromise between access to the patient and signal-to-noise), safety and compatibility of the devices and instruments that will be used in or near the magnetic field, spatial accuracy of imaging for localization and targeting, optimal use of the imaging hardware and software (the dynamic range of gradients, limitation and availability of pulse sequences, radiofrequency coils) and level of integration with guidance methods for accomplishing the procedure.

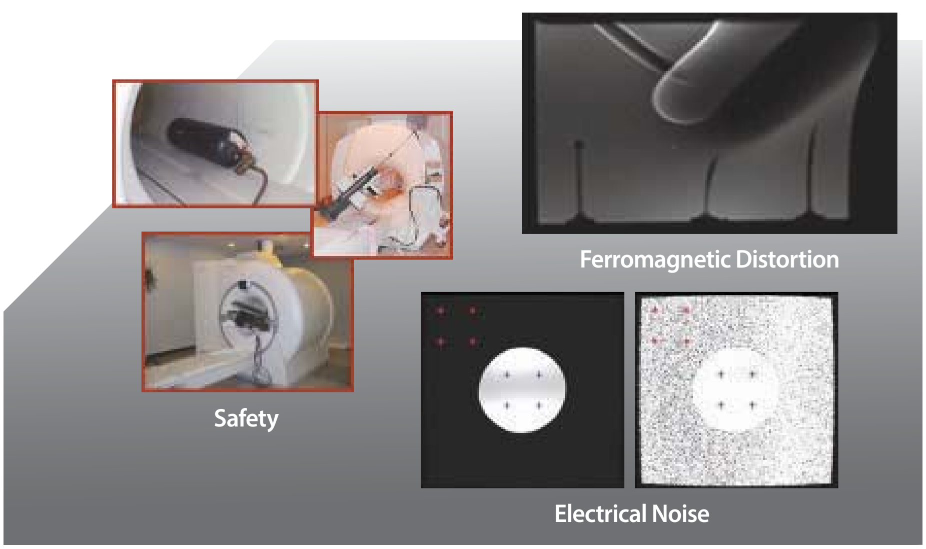


FIGURE 1 Examples of some of the difficulties encountered with robotics introduced into the MRI environment including safety issue due to projectiles, distortion of the magnetic fields, and introducing electrical noise that degrades image quality.

MRI-COMPATIBLE SURGICAL ROBOTS

Robotic assistance has been investigated for guiding instrument placement in MRI, beginning with neurosurgery and later percutaneous interventions with some examples shown in **Figure 2**. One of the first MRI-compatible robotic devices dates back to 1995 by Masamune et al. for stereotactic neurosurgery [Masamune 1995]. DiMaio et al. reported on the use of a robot suspended from a specialized open interventional MRI scanner for MR-guided prostate interventions [DiMaio 2007]. Krieger et al. developed a remotely actuated manipulator for access to prostate tissue under MR guidance in a closed bore diagnostic scanner [Krieger 2005]. Innomotion developed and commercialized a pneumatic robot aimed at performing percutaneous interventions inside the bore of a high field scanner [Melzer 2008]. Fischer et al. also attempted to develop a pneumatically actuated robotic assistant aimed at prostate biopsy and brachytherapy inside the bore of the scanner, with the goal of minimizing interference with the scanner [Fischer 2008]. Attempts at improving the accuracy of served pneumatic devices were attempted in [Wang 2010] and [Yang 2011]. Stoianovici et al. further attempted to improve upon the accuracy problems of pneumatic actuation by developing a robotic assistant for MR image-guided percutaneous prostate interventions based upon novel pneumatic stepping motors [Stoianovici 2007]. Although most systems to date are focused on image-guided percutaneous interventions within the bore of the scanner, Sutherland et al. have developed a dexterous robot for performing neurosurgery beside the bore of the scanner [Sutherland 2008].

ENABLING TECHNOLOGIES FOR MRI-GUIDED INTERVENTIONAL SYSTEMS

In order for a system to compatible with the MRI environment, it should: be safe in the MRI environment, preserve the image quality, and be able to operate unaffected by the scanner's electric and magnetic fields. The latest 2013 American Society for Testing and Materials (ASTM) made a detailed classification for the MRI-compatibility of devices environment [ASTM 2013]. The generally accepted classifications are: *MRI-Safe*: An item that poses no known hazards resulting from exposure to any MRI environment; *MRI-Conditional*: An item with demonstrated safety in the MRI environment within defined conditions; and *MRI-Unsafe*: An item which poses unacceptable risks to the patient, medical staff, or other persons within the MRI environment. Ferromagnetic materials must be avoided entirely because they cause image artifacts and distortion due to field inhomogeneities, and they pose a dangerous projectile risk. Non-ferromagnetic metals such as aluminum, brass, titanium, high-strength plastic, and composite materials are typically permissible with appropriate design considerations. However, the use of any conductive materials in the vicinity of the scanner's isocenter must be limited because of the potential for induced eddy currents to locally deform the magnetic field homogeneity. Electrical systems must be properly shielded and filtered, designed to limit noise emission. Care must also be taken to avoid resonance and heating.

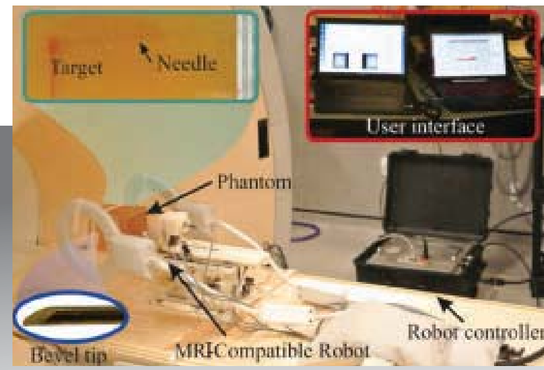


FIGURE 2 Samples of various MRI-compatible robotic approaches: Clockwise from left: A dexterous neurosurgical robot [Sutherland 2008], A percutaneous needle insertion robot [Stoianovici 2007],and an autonomous image-guided needle steering system [Patel 2015].

Actuation Technologies: As previously noted, traditional DC motors are contra-indicated for use in MRI. Although in some circumstances they may be able to be shielded and kept a distance away from the scanner, they are non-ideal and not able to be used within the confines of an MRI scanner's bore. Therefore, the most common approaches taken to actuating a robot designed to be compatible with the MRI environment are: pneumatics (either servo-controlled or more recently with air powered stepper motors), hydraulics (often using water or saline), cable-driven (with remote actuation units), and ceramic piezoelectric actuators (resonant ultrasonic motors and non-resonant low frequency variants). However, it should be kept in mind that often even with these inherently compatible technologies, often commercially available solutions are not practical. For example, most pneumatic cylinders still use steel enclosures, most fittings contain ferrous components, and drive or control electronics often are not configured to minimize the induced electrical noise. Some recent innovations or advancements in the field include pneumatic stepping motors, high precision servo control of pneumatic cylinders, cable-driven actuators, and piezoelectric actuation.

Sensing Technologies: Closed loop control requires multiple levels of feedback. At the joint level, we need a way to detect the position of each linear or rotary joint. This is often done using potentiometers or encoder. In MRI, these technologies can be used with special design considerations. As long as potentiometer housing are nonferrous, then the trick lies on effectively filtering the electrical signals. Optical encoders have proven to be successful for position sensing inside the scanner bore during imaging when coupled with differential line drivers (to eliminate false counts and increase signal robustness), filtering appropriate electrical lines, and thoroughly shielding cables to minimize EMI. Fiberoptic sensing has also been investigated, with available devices available now for absolute and incremental position sensing without direct electrical connections.

Haptics and Teleoperation: Although robotics provides a way to operate within the bore of an MRI scanner, a side effect is the loss of tactile feedback for the clinician. This is valuable information in many cases, and thus we strive to return haptic feedback for teleoperated approaches. Haptic feedback requires estimating or measuring the integration forces of the instrument (e.g. a needle in an image-guided biopsy or therapy delivery case), and therefore it is necessary to incorporate force sensing. An example is described by Su et al., that describes a robotic device for teleoperated needle insertion, where the slave robot detects needle insertion forces and the teleoperation master reflects those forces back to the user [Su 2013]. Similar to potentiometers, traditional strain gauge based load cells may be able to be used if filtered, shielded, and of non-ferrous construction. However, fiberoptic sensors enable high accuracy sensing without imposing such constraints. There are a multitude of approaches that have been investigated for one degree of freedom (DOF) and multi-DOF force/torque sensing. Intensity based approaches measure differences in light intensity returning off a reflective object in the sensor; the problem with many of these approaches is the lack of robustness to various environmental factors (such as flexing of the fiber cables or ambient light). An alternative approach is essentially a fiber optic strain gauge. One technique, known as Fabry-Perot Interferometry (FPI), is based on measuring a change in interference patterns of light passing through a small cavity at the end of an optical fiber. Another technique is the Fiber Bragg Grating (FBG) approach which results in a wavelength shift of light based on the amount of strain in the fiber. Each approach has its strengths and weaknesses with regard to complexity, cost, size, and accuracy.

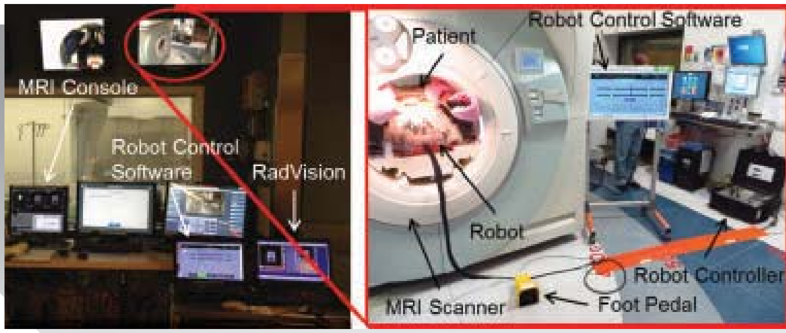


FIGURE 3 An example of a clinical configuration for MR image-guided prostate cancer biopsy using the robot described in [Eslami 2015].

Localization and registration: Not only does the robot need to have proprioceptive feedback, but typically it is required to also have external localization of the robot. Often fiducials are placed on the robot and used to determine the 6-DOF pose of the robot with respect to the MR imaging system, thus enabling targeting of features identified in the MRI images and calculating the corresponding inverse kinematics to move the robot. Various localization approaches have been implemented, including identifying discrete points on the robot as well as localization based on cross-sectional images of various unique patterns. These fiducials are often passive tubes or spheres filled with MR contrast agent, but improvements in imaging may be made with passive self-resonant tracking coils or active tracking coils that directly interface with the MRI scanner. These tracking coils may be integrated into the robot base, its end effector, or in some cases a needle, cannula, or catheter itself.

System Architecture: Various teams have taken different approaches to integrating these technologies into their robotic devices and the corresponding control systems. Often the system design was based upon the requirements of the surgical procedure being addressed. For example, many systems use sensing and actuation technologies that are safe for use in MRI, but are not overly concerned with EMI because the system is designed to iterate between sessions of MR imaging and robotic manipulation rather than manipulation during live imaging. Another design consideration is whether to place the control system (such as the valve controller or motor driver units) inside the scanner room or in the adjacent console room. Putting a controller outside the MRI scanner's room eases some design considerations, but comes with complicating issues. For pneumatics, this requires long air hoses which significantly reduces bandwidth and control performance. For electrical control of piezoelectric motors, this requires running wires into the scanner room which can act as antennas (bringing in unwanted EMI), or require custom patch panels to route signal in and out of the scanner room (which is practical for a permanently installed system, but less so for a portable compact robotic assistant). The use of well-shielded, low-noise control systems that reside in the MRI scanner room and communicate to an external control system via fiber optics allows for ultra-portable devices that require no modifications or special requirements of the MRI suite.

CLINICAL SYSTEMS

MRI is a highly effective soft tissue imaging system, and the ability to utilize this procedure in-vivo coupled with precision computer controlled motion will prove to be an invaluable asset in the future development of minimally invasive surgery. With all of these challenges, there have been some amazing advances of late. Several systems have successfully performed clinical trials such as those described in [Krieger 2005], [DiMaio 2007], [Stoianovici 2007], [Sutherland 2008], and [Eslami 2015]. One such example of an ongoing clinical trial for MR image-guided prostate biopsy is shown in **Figure 3**. New systems on the horizon promise for further integration of real-time imaging with semi-autonomous robotic control of curved needle paths as instruments are delivered to targets in the body such as those described in [Su 2013] and [Patel 2015]. ■

REFERENCES

[ASTM 2013] ASTM, Standard practice for marking medical devices and other items for safety in the magnetic resonance environment, The American Society for Testing and Materials , Vol F2503-13, 2013.

[DiMaio 2007] DiMaio SP, Pieper S, Chinzei K, Hata N, Haker SJ, Kacher DF, , Fichtinger G, Tempany CM, Kikinis R, Robot-assisted needle placement in open MRI: system architecture, integration and validation, Computer Aided Surgery, Vol 12, No 1, pp 15-24, 2007.

[Eslami 2015] Eslami S, Shang W, Li G, Patel N, Fischer GS, Tokuda J, Hata N, Tempany CM, Iordachita I,, In-Bore Prostate Transperineal Interventions with an MRI-guided Parallel Manipulator: System Development and Preliminary Evaluation, Int. J. Med. Robotics and Comput. Assist. Surg., 2015. (in press)

[Fischer 2008] Fischer GS, Iordachita I, Csoma C, Tokuda J, DiMaio SP, Tempany CM, Hata N, Fichtinger G, MRI-Compatible Pneumatic Robot for Transperineal Prostate Needle Placement, IEEE / ASME Transactions on Mechatronics - Focused section on MRI Compatible Mechatronic Systems, Vol 13, No 3, pp 295-305, 2008.

[Krieger 2005] Krieger, A., Susil, R. C., Ménard, C., Coleman, J., Fichtinger, G., Atalar, E., & Whitcomb, L. L. (2005). Design of a novel MRI compatible manipulator for image guided prostate interventions. Biomedical Engineering, IEEE Transactions on, 52(2), 306-313.

[Li 2015] Li G, Su H, Cole GA, Shang W, Harrington K, Camilo A, Pilitsis JG, Fischer GS, Robotic System for MRI-Guided Stereotactic Neurosurgery, IEEE Transactions on Biomedical Engineering , Vol 62, No 4, pp 1077-1088, 2015.

[Masamune 1995] Masamune K, Kobayashi E, Masutani Y, Suzuki M, Dohi T, Iseki H, Takakura K, Development of an MRI-compatible needle insertion manipulator for stereotactic neurosurgery, Computer Aided Surgery, Vol 1 No 4, pp 242-248, 1995.

[Melzer 2008] Melzer A, Gutmann B, Remmele T, Wolf R, Lukoscheck A, Bock M, Bardenheuer H, Fischer H, Innomotion for percutaneous image-guided interventions, IEEE Engineering in Medicine and Biology Magazine, Vol 27, No 3, pp 66-73, 2008.

[Patel 2015] Patel N, van KatwijkT T, Li G, Moreira P, Shang W, Misra S, Fischer GS, Closed-loop Asymmetric-tip Needle Steering Under Continuous Intraoperative MRI Guidance, IEEE EMBC 2015, Aug. 2015. (in press)

[Stoianovici 2007] Stoianovici D, Song D, Petrisor D, Ursu D, Mazilu D, Mutener M, Mutener M, Schar M, Patriciu A, "MRI Stealth" robot for prostate interventions, Minimally Invasive Therapy & Allied Technologies, Vol 16, No 4, pp 241-248, 2007.

[Su 2012] Su, H., Cardona, D. C., Shang, W., Camilo, A., Cole, G., Rucker, D. C., .Webster R. J., Fischer, G. S. (2012, May). A MRI-guided concentric tube continuum robot with piezoelectric actuation: a feasibility study. In Robotics and Automation (ICRA), 2012 IEEE International Conference on (pp. 1939-1945). IEEE.

[Su 2015] Su H, Shang W, Cole GA, Li G, Harrington K, Camilo A, Tokuda J, Tempany CM, Hata N, Fischer GS, Piezoelectrically Actuated Robotic System for MRI-Guided Prostate Percutaneous Therapy, IEEE/ASME Transactions on Mechatronics, 2015. (in press)

[Sutherland 2008] Sutherland GR, Latour I, Greer AD, Integrating an image-guided robot with intraoperative MRI, IEEE Engineering in Medicine and Biology Magazine, Vol 27, No 3, pp 59-65, 2008.

[Taylor 2003] Taylor, R. H., & Stoianovici, D. (2003). Medical robotics in computer-integrated surgery. Robotics and Automation, IEEE Transactions on, 19(5), 765-781.

[Wang 2010] Wang Y, Su H, Harrington K, Fischer GS, Sliding mode Control of Piezoelectric Valve Regulated Pneumatic Actuator for MRI-Compatible Robotic Intervention, ASME Dynamic Systems and Control Conference - DSCC 2010, Cambridge, Massachusetts, September 2010.

[Yang 2011] Yang, B., Tan, U., McMillan, A. B., Gullapalli, R., & Desai, J. P. (2011). Design and control of a 1-DOF MRI-compatible pneumatically actuated robot with long transmission lines. Mechatronics, IEEE/ASME Transactions on, 16(6), 1040-1048.

AUTONOMOUS OPERATION
IN SURGICAL ROBOTICS

BY JACOB ROSEN
PROFESSOR &
BIONIC LAB DIRECTOR

JI MA
STAFF RESEARCH
ASSOCIATE

DEPARTMENT
OF MECHANICAL
AND AEROSPACE
ENGINEERING
UCLA

When a surgical robotic system is introduced to the surgical scene two human-machine interfaces are established and define its primary operation: (1) the surgeon-robot interface (S-R) and (2) the patient-robot interface (R-P). Each has a unique set of requirements that dictates its design capabilities and functions. **Figure 1** maps several commercial systems, research systems and systems during commercialization process that were classified based on these interfaces [1].

The S-R interface is defined by a wide spectrum of control levels provided to the surgeon over the surgical robotic system. Assuming that a certain level of control is required to complete a task, it can be distributed between the human operator and the robotic system at different ratios which in turn defines the level of automation allocated for the task. This level of automation is bounded by two extreme operational modes. The right hand side of the horizontal axis in **Figure 1** describes a mode in which the surgical robotic system is fully autonomous [2-5]. The left hand side of the horizontal axis in **Figure 1** describes a mode of operation in which any movement of the surgical robotic system is in direct response to a real time position/orientation command input provided by the surgeon. The system architecture used to enable this approach is teleoperation, utilizing a master/slave configuration. The master is defined as the surgical console and the slave serves as the surgical robot itself interacting with the patient's tissue through the surgical tools. [6-8].

The robot-patient (R-P) interface determines the level of invasiveness (vertical axis in

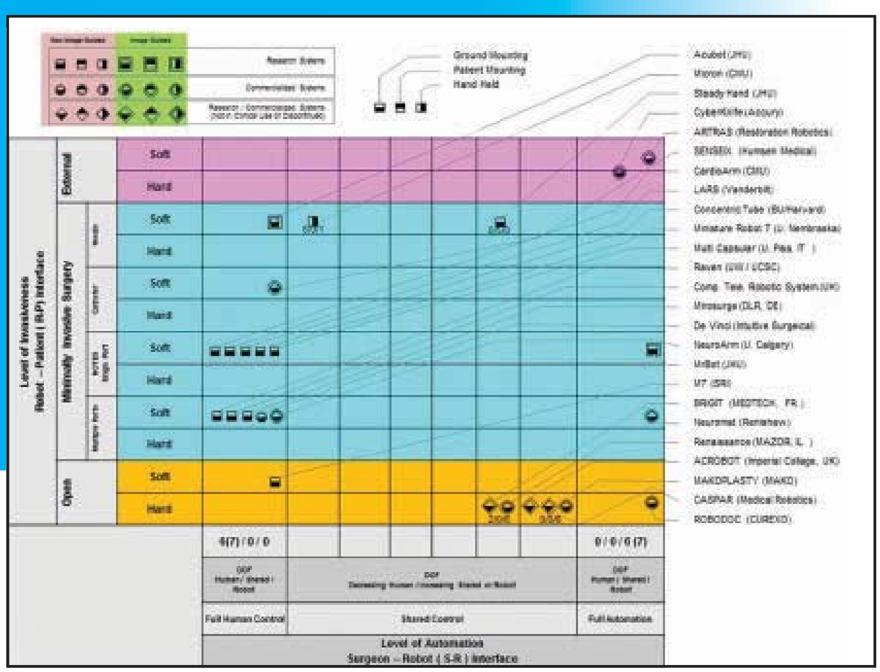
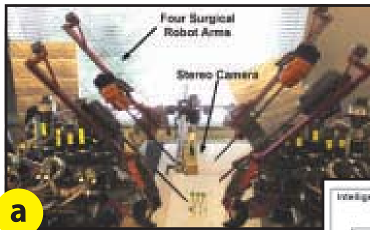


FIGURE 1: Classification of surgical robotic systems based on a Surgeon-Robot (S-R) interface (horizontal axis) defining the level of automation and a Robot-Patient (R-P) interface dictating the level of invasiveness.

Figure 1). The level of invasiveness spectrum spans across a range of surgical approaches including (1) the invasive open-procedure approach, which requires a large incision to expose the targeted anatomy, (2) variations of minimally invasive surgical (MIS) approaches with a gradual reduction of invasiveness, such as multiple tools inserted through ports, natural orifice transluminal endoscopic surgery (NOTES), catheters [9-11] and needles [12,13] and (3) a noninvasive approach in which energy (radiation) is provided by an external source to a localized space to provide a localized therapy [14]. As the level of invasiveness decreases, the level of manipulation also decreases and, as a result, the surgeon has fewer degrees of freedom to mechanically manipulate the tissues. The surgical robotics field as a whole progresses towards the reduction of invasiveness limiting the trauma at the periphery of the surgical site and increase of semi-autonomous operation while positioning the surgeon as a decision maker rather than as an operator.



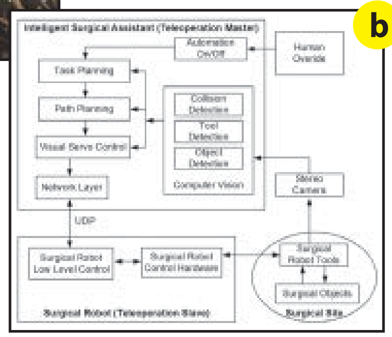


FIGURE 2 System Architecture (a) Raven II surgical robot (b) block diagram of the control system software.

The reported study is focused on developing an algorithm for automation based on stereo computer vision and dynamic registration in a surgical robotic context. The performance of the algorithm was further tested experimentally utilizing the block transfer task which corresponds to tissue manipulation as defined by Fundamentals of Laparoscopic Surgery (FLS) [15]. The surgical task was performed autonomously by a surgical robot (Raven II) and then compared with the performance of a human teleoperating the same surgical robotic system.

METHODS

System Architecture

Raven II (UCLA/UW/Applied Dexterity Inc.) was used as the surgical robotic system for experimentally evaluating the performance of surgical task both in an autonomous mode and in a teleoperation mode [16]. A compact commercial stereo Point Grey Bumblebee2 camera (BB2-03S2C-38) was positioned 0.23m to 0.3m above the surgical site pointing down. This position and orientation allow to encapsulate all the surgical tools into the field of view while eliminating potential collision between the camera and the four surgical robotic arms (**Figure 2a**). The camera has image update rate of 48 FPS at full resolution of 640x480. A custom support for the camera in OpenCV was developed enabling the use of OpenCV as the primary tool for real time image processing. The stereo vision was used for surgical tool detection, surgical tool visual servoing and surgical environment perception.

Given the master/slave architecture of the system a block diagram of the software architecture (**Figure 2b**) depicts the corresponding two components. The slave components software consists of the robot low-level real time servo control software, in a teleoperation mode the surgeon generates the position and orientation command signals using the master. In particular the reference command information sent from master to slave consists of the incremental Cartesian positions, the absolute orientation transformation matrix, and the absolute tool joint angles. However in an autonomous mode the operator is replaced with an intelligent agent generating autonomously the same inputs to the surgical robotic system. The autonomous intelligent software component substituting the operator includes the following modules: (1) computer vision module, (2) task and path planning module, (3) visual servo module, (4) network module and human interface module. A UDP layer is used for the data communication between the two software components. Both manual and automatic switching are included in the software between the teleoperation mode and the autonomous mode.

Task Definition and Decomposition

The FLS are a set of tasks that are used widely and primarily as part of a curriculum for surgeon training in MIS and performance assessment tools. In addition the FLS tasks provide a standard platform for comparing performance of manual operation as well as various teleoperated surgical robot systems. The FLS block transfer is a task that simulates tissue manipulation. It may be also defined as a "pick and place" task in which a set of blocks mounted on pegs are picked with one MIS surgical tool, transferred to the other tools and placed on a new set of pegs one at a time.

The FLS task was further decomposed into subtasks and potential failure modes were identified. The FLS block transfer subtasks are (**Figure 3**): (1) Starting configuration - Three triangle objects are placed in three left pins; (2) Move tool from the initial position to the location of the block; (3) Pick a block from the left pin and place it in the right pin, and then repeat until all three left blocks are transferred to three right pins (4) Move tool back to the initial position. The failure modes are (1) Grasping Failure: failing to grasp the block or dropping the block during the grasping process (2) Transport Failure: dropping the block during the transportation between the pegs (3) Place Failure: Failing to place the block on the peg (4) Collision Failure: Collision or an application of a large force by the tool on the peg board that causes it to move.

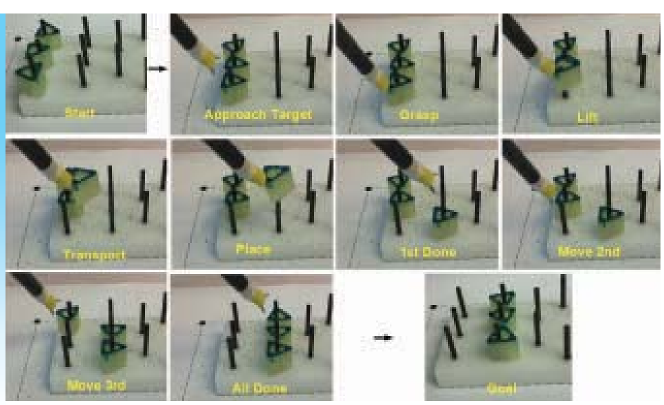


FIGURE 3 FLS peg task of using one tool to transfer three objects.

Computer Vision

Surgical Tool Detection

A high precision but low rate computer vision based method was developed to detect the position / orientation of the surgical tools in the camera frame and enhance the high rate but lower precision forward kinematics approach which is compromised due to the compliance of the cables incorporated into the mechanical system as well as the limited information regarding the exact position and orientations of the robotic arms' bases.

Markers detected by the computer vision were placed on several locations on the shaft of the tools away from the tip in a known location that is not occluded by the potential tool tip tissue interaction. Forward kinematics which is limited to the last two DOF was then used to estimate the tool tip position and orientation. **Figure 4** depicts the Point A and B that were detected in 3D by the computer vision system which led to the

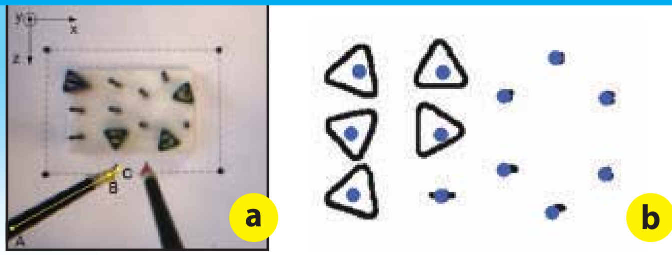


FIGURE 4 Computer Vision Tool and object detection: (a) Locations of markers (Points A, B) on the surgical tool as acquired by the stereo camera for predicting the location of the tool tip (Point C); (b) Top view computer vision detection of the set of pegs tips (dots) and the triangular shaped block.

estimation of point C marking the tool tip.

Object Detection

Each triangular block is placed on a peg with a random rotation angle and with a non-coincided axis with respect to the peg. A dynamic real time algorithm was developed to detect the location and orientations of the blocks and the pegs–necessary information for the path planning. A dynamics real time algorithm is required to deal with potential changes in the environment. In the current experimental setup the environment may change due to collision between the tool and the blocks or the peg board. However in a clinical setting the surgical site is constantly subject to change due to tissue manipulations, dissections, and suturing.

Tool-Environment Collision Detection

Given the lack of force sensor incorporated into the tools substantial tool/environment collision can be detected by a significant translation or deformation of the environment or the tools. In the context of the experimental setup substantial collision is defined by a movement of the pegboard. Such a collision triggered the dynamic registration and facilitated uninterrupted completion of the task autonomously. Furthermore, collision that led to pegboard displacement was also used to quantify as an error for performance evaluation. In a clinical setting fiducial markers or key anatomical structures pointed by laser dots may be used for detecting a significant change on the operational field.

Automation Algorithms

Visual Servo Control of the Surgical Robot

A hybrid Cartesian based visual servo approach was developed to mediate the requirement to update the control loop at a rate of 1 KHz for stable operation and the visual performance rate of maximum 48FPS and visual image processing rate of 25 Hz.

The Raven II robot (slave) is controlled with its low level joint controllers at a 1 KHz rate. The visual servo running at a rate of 25 Hz was incorporated into the automation algorithms controlling the master to provide delta Cartesian position commands (X,Y,Z), which are calculated as the difference between the desired position based on the planned trajectory and the actual position and orientation of the tip as acquired by the stereo camera. The proportional gains of the visual servo controller were selected experimentally to achieve fast and stable response. The visual servo control error at steady state along each axis is within 0.4 mm as measured in 3D camera frame.

Task Planning and State Machine

In order to automate the task, the FLS block transfer subtasks were decomposed into nine states defined in **Table I** and formed a state machine repeating state 1 to 8 three times for transferring the three blocks and terminating the process in state 9. An internal verification mechanism was used to check the completion of each state prior to every switch to the following state. An internal error correction mechanism was incorporated to correct for potential failures within each state and potentially moving to a different state to recover from the potential error. If the failure is not recoverable, such as object is dropped out of camera view, then the state machine will continue to next subtask cycle to transfer the other remaining objects.

Path Planning

Generic path is predefined offline for each state. However the actual 3D path points are dynamically generated to accommodate changes in the operational environment as detected by vision system, such that the path is adjusted in real time. The speed limits were set to 10 mm/s for high precision manipulation and to 30 mm/s for low precision translation.

Experimental Protocol

The block transfer task was completed 20 times (60 block transfers in each mode) in the following modes (1) Autonomous operation (2) Teleoperation by a human subject. Robotic arm kinematics, tool tip trajectory, task completion time, peg board marker motion trajectories and videos from the stereo camera and webcam in teleoperation were all recorded and collected for off line analysis.

RESULTS

Performance Comparison–Summary

Table II summaries the performance difference between the two modes of operation in terms of goal completion success rate, performance measures and safety measure.

Task Goal Achievement

The success rate for block grasping task is 100% in both modes. Although a grasping force sensor is not incorporated into the current design of the tool, the accurate tool tracking and object detection makes the grasping a success in the autonomous mode of operation. During the block transportation the block grasping success rate is again 100% in both modes.

For transporting grasped objects from one location to another location without dropping the blocks, the success rate is 100%. The slight decrease in the success rate of the block placement of 96.7% is accounted for in 4 cases out of 60 in which the blocks didn't fully drop to the base of the peg as a result of small misalignment between the center hole of the block and the peg. The success rate of the human teleoperation mode is as previously 100%.

Subtask Level	Subtask Description
1	Find Object, Obstacles and Destination Locations
2	Fast Move Tool to Object Area
3	Precisely Move Tool Tip to Grasping Location
4	Grasp Object with Tool
5	Precisely Lift Object with Tool
6	Fast Move Tool with Object to Destination Location
7	Precisely Align Object to Peg Pin Upper Location
8	Open Grasper to Let Object Drop on Peg Pin
9	Return to Start Position and Task End

TABLE I Decomposed Subtasks for Autonomous FLS Peg Task.

Categories	Criteria	Autonomous Operation	Human Teleoperation
Goal Completion	Grasping Success (%)	100	100
	Transporting Success (%)	100	100
	Placing Success (%)	96.7	100
Performance Measure	Task Time (s)	25 (± 0)	49 (± 5.7)
	Tool Tip Trajectory Length (mm)	460.45 (± 4.43)	778.04 (± 82.61)
Safety Measure	Peg Board Motion (mm)	6.03 (± 2.75)	78.13 (± 21.18)

TABLE II Data of autonomous operation and human teleoperation.

Task Completion Time

For autonomous operation, the completion time is identical for all the repetitions (25 s). It takes a human operator about two times longer to complete the task (49 ± 5.7) with a standard deviation of about 5% in a teleoperation mode.

Surgical Tool Tip Trajectory

The surgical tool tip trajectory is used to analyze the efficiency of the motion. Given a specific task, a shorter trajectory is also perceived as a more effective trajectory with a lower potential for collisions. The average tool tip trajectory length in the autonomous mode is about 60% shorter than the tool tip trajectory during the human teleoperation mode as depicted in **Figure 5**. As indicated graphically the trajectories of the autonomous mode tend to be straight with smooth transitions between the individual segments. However the trajectories of the tip during the human teleoperation mode are composed of arches which are typically longer than the other mode. The arch like trajectories aim to clear the block from the array of pegs in an attempt to avoid potential collisions which in turn leads to longer trajectories and completion time.

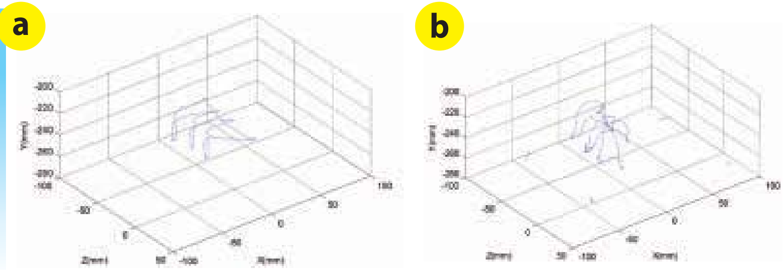


FIGURE 5 **Tool tip trajectory in 3-D space (a) Autonomous Operation The trajectory of four peg board markers has little movement due to dedicated tool-object interaction (b) Human Teleoperation The trajectory of four peg board markers shows large movement due to tool collision.**

Tool-Object Interaction / Environment Collision

The motion of the peg board is a result of force generated as the tool or the object interact with the pegs. The peg board motion is measured to evaluate the tool/environment interaction and defined as the sum of the trajectories of the four markers of the pegboard. Smaller peg board motion means fewer tool environment collisions and a smaller interaction force that may potentially damage the patient's tissue. The pegboard trajectory as a result of collision with the tool during teleoperation mode was more than 12 times longer than the autonomous mode, meaning that during the autonomous operation the collision between the tool and the environment is significantly lower than during the other mode. The trajectories of the markers are depicted in **Figure 5** as well surrounding the trajectory of the tool tip.

CONCLUSION AND FUTURE WORKS

As part of the reported research effort a fully autonomous algorithm was developed for a block transfer of the FLS simulating surgical tissue manipulation in a surgical robotic MIS setting. The algorithm for the autonomous operation is composed of stereo vision based surgical tool detection, surgical tool visual servo control, pegboard environment detection and object detection. The FLS peg transfer task is decomposed into a state machine for task planning and path planning.

The autonomous FLS task is implemented successfully and tested experimentally with the Raven II surgical robot system. The data indicate that the autonomous operational mode has better overall performance and limited tool-environment interaction compared with the human teleoperation mode. In addition the proposed computer vision based automation approach doesn't need the typical precise calibration of the robot arms since the autonomous agent software functions as an intelligent teleoperation master that is independent of the low level robot control system and can potentially be applied to different surgical robot systems.

Since the FLS peg transfer task includes the basic surgical skills and subtasks that are common in other surgical tasks it is likely that the proposed approach can be applied to the rest of the FLS tasks as well as to other surgical procedures' subtasks. One should note that the goal of autonomous mode is not to replace the surgeon but to remove the surgeon from his or her role as an executer of every single motion of the robotic system to the position of a decision maker. A potential expansion of the reported research is the use of trajectories learned from expert surgeon (learn by demonstration) as a substitution for artificially generated trajectories and speed patterns. Furthermore, surgeon's intention may also be extracted from a database [17-19] that may lead to seamless switching between the human operator and the autonomous system [20-21] and in that sense it may allow the autonomous algorithm to cope with more complex surgical environments. ■

ACKNOWLEDGEMENTS

This work is supported by the U.S. National Science Foundation award IIS-1227184: Multilateral Manipulation by Human-Robot.

REFERENCES

1 Jacob Rosen, Surgical Robotics–Chapter 5, In "Medical Devices: Surgical and Imaging-Guided Technologies" edited by Martin Culjat, Rahul Singh, and Hua Lee, John Wiley & Sons 2013 pp. 63-97, ISBN: 978-0-470-54918-6.

2 EH Spence, The ROBODOC clinical trial: a robotic assistant for total hip arthroplasty, Orthopedic nursing (1996) volume: 15 issue: 1 page: 9

3 Bargar, William L. et al, Primary and Revision Total Hip Replacement Using the Robodoc® System, Clinical Orthopaedics & Related Research: September 1998 - Volume 354 - Issue - pp 82-91

4 Shunsaku Nishihara et. al., Clinical accuracy evaluation of femoral canal preparation using the ROBODOC system, Journal of Orthopaedic Science, Volume 9, Number 5, 452-461

5 Arndt P. Schulz et. al., Results of total hip replacement using the Robodoc surgical assistant system: clinical outcome and evaluation of complications for 97 procedures, The International Journal of Medical Robotics and Computer Assisted Surgery, Volume 3, Issue 4, pages 301-306, December 2007

6 Green, P.S.; Hill, J.W.; Jensen, J.F.; Shah, A.; Telepresence surgery, IEEE Engineering in Medicine and Biology Magazine, Vol 14, 3, pp. 324 - 329, May/Jun 1995

7 Madhani, A.J.; Niemeyer, G.; Salisbury, J.K., Jr.; The Black Falcon: a teleoperated surgical instrument for minimally invasive surgery, IEEE/RSJ International Conference on Intelligent Robots and Systems, 1998. Proceedings vol.2, pp. 936 - 944, 13-17 Oct 1998, Victoria, BC , Canada

8 Simon DiMaio, Mike Hanuschik,, and Usha Kreaden, The da Vinci Surgical System, Chapter 7 in Surgical Robotics - Systems, Applications, and Visions, Jacob Rosen, Blake Hannaford, Richard M. Satava (Editors), Springer; 1st Edition, 2011

9 Walid Saliba et. al., Atrial Fibrillation Ablation Using a Robotic Catheter Remote Control System - Atrial Fibrillation Ablation Using a Robotic Catheter Remote Control System, Journal of the American College of Cardiology, Vol. 51, No. 25, 2008

10 Vivek Y. Reddy, et. al. View-Synchronized Robotic Image-Guided Therapy for Atrial Fibrillation Ablation Experimental Validation and Clinical Feasibility, Circulation. 2007; 115: 2705-2714

11 Saliba, Cummings Je, Oh S, et al. Novel robotic catheter remote controlsystem: feasibility and safety of transseptal puncture and endocardial catheter navigation. J Cardiovasc Electrophysiol 2006;17:1102-5.

12 Noah J. Cowan, Ken Goldberg, Gregory S. Chirikjian, Gabor Fichtinger, Ron Alterovitz, Kyle B. Reed, Vinutha Kallem, Wooram Park, Sarthak Misra, Allison M. Okamura, Robotic Needle Steering: Design, Modeling, Planning, and Image Guidance, Chapter 23 in Surgical Robotics - Systems, Applications, and Visions, Jacob Rosen, Blake Hannaford, Richard M. Satava (Editors), Springer; 1st Edition, 2011

13 J. A. Engh, D. Kondziolka, and C. N. Riviere. Percutaneous intracerebral navigation by duty-cycled spinning of flexible bevel-tipped needles. Neurosurgery, 67(4):1117-1123, 2010.

14 W. Kilby et. al., The CyberKnifeÆ Robotic Radiosurgery System in 2010, Technology in Cancer Research & Treatment, Volume 9, Number 5, October 2010

15 E. M. Ritter and D. J. Scott, ìDesign of a proficiency-based skills training curriculum for the fundamentals of laparoscopic surgery, Surgical Innovation, vol. 14, no. 2, pp. 107-112, 2007.

16 Jacob Rosen, Mitchell Lum, Mika Sinanan, and Blake Hannaford, Raven: Developing a Surgical Robot from a Concept to a Transatlantic Teleoperation Experiment, Chapter 8 in Surgical Robotics, Systems, Applications, and Visions, Jacob Rosen, Blake Hannaford, Richard M. Satava (Editors), 1 ed. Springer 2011.

17 J. Rosen, J. Brown, L. Chang, M. Sinanan, and B. Hannaford, ìGeneralized approach for modeling minimally invasive surgery as a stochastic process using a discrete markov model, IEEE Trans. On Biomedical Engineering, vol. 53, no. 3, pp. 399-413, 2006.

18 C. E. Reiley, E. Plaku, and G. D. Hager, ìMotion generation of robotic surgical tasks: Learning from expert demonstrations, in Int. Conf. on Engg. in Medicine and Biology Society (EMBC), 2010, pp. 967-970.

19 J. Van Den Berg, S. Miller, D. Duckworth, H. Hu, A. Wan, X.-Y. Fu, K. Goldberg, and P. Abbeel, ìSuperhuman performance of surgical tasks by robots using iterative learning from human-guided demonstrations, in IEEE Int. Conf. Robotics and Automation (ICRA), 2010, pp. 2074-2081.

20 J. Schulman, J. Ho, A. Lee, H. Bradlow, I. Awwal, and P. Abbeel, "Finding locally optimal, collision-free trajectories with sequential convex optimization, " in Robotics: Science and Systems (RSS), 2013.

21 L. P. Kaelbling and T. Lozano-Perez, "Hierarchical task and motion planning in the now, " in IEEE Int. Conf. Robotics and Automation (ICRA), 2011, pp. 1470-1477.

MODULAR INTEROPERABILITY IN SURGICAL ROBOTICS SOFTWARE

BY PETER KAZANZIDES
RESEARCH PROFESSOR

ANTON DEGUET
ASSOCIATE RESEARCH SCIENTIST

BALAZS VAGVOLGYI
ASSOCIATE RESEARCH SCIENTIST

ZIHAN CHEN
PHD CANDIDATE

RUSSELL H. TAYLOR
PROFESSOR

DEPARTMENT OF
COMPUTER SCIENCE
JOHNS HOPKINS UNIVERSITY

Computers have been used to assist medical diagnosis and treatment for decades; early examples include computer-assisted tomography (CAT or CT) and stereotactic neurosurgery. While computers can only provide information to guide a surgeon, the introduction of robotics enables computers to physically act on the patient, either directly or by providing mechanical assistance to the surgeon. For example, in stereotactic neurosurgery, the location of a suspected tumor is identified in a three dimensional (3D) CT scan of a patient's brain. Initially, passive stereotactic frames were used to position a guide for a biopsy needle based on the 3D coordinates of the suspected tumor. In 1985, a robot was used to position the needle guide [1], representing the first reported clinical use of a robot. In the early 1990s, robots were introduced for invasive surgical procedures, such as transurethral resection of the prostate (TURP) [2] and total hip replacement (THR) surgery [3]; in both of these cases, the robot autonomously performed part of the surgical procedure.

Today, the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA) is the most widely used surgical robot, with 3,266 installations according to the company's 2014 Annual Report. The da Vinci is used for minimally-invasive surgery, especially in urologic and gynecologic applications, but is currently limited to teleoperated control, where the surgeon sits at a master console and controls instruments inserted into the patient's body through small incisions, called ports. Stereo visualization is provided by a stereo endoscope (also robotically controlled) inserted through one of the ports.

Recently, some common research platforms have emerged. The da Vinci Research Kit (dVRK) [4] is a research system based on the mechanical components of the first-generation da Vinci Surgical System. Another common platform is provided by the Raven II surgical robot (Applied Dexterity, Inc., Seattle, WA) [5], which is functionally similar to the da Vinci Patient Side Manipulator (PSM).

The focus of this article is on modular interoperability of the software that is used for these types of systems. This is important for several reasons. First, surgical robots are not just robots, but rather integrated systems that typically incorporate other sources of information. This includes static information, such as preoperative images or models, and real-time information such as mono or stereo computer vision, ultrasound, optical coherence tomography (OCT), fluoroscopy (x-ray), tissue properties, external forces, and user (surgeon) input. There is no single software package that can provide all these capabilities and few, if any, researchers have expertise in all of them. Thus, it is necessary to have modular interfaces to enable interoperability between the different software packages that incorporate the state-of-the-art knowledge and capabilities in each area. Second, even within robotics, there is a need for interoperability between systems. For example, the da Vinci Console (stereo display and master manipulators) could be used to teleoperate other robots, including the Raven II.

SYSTEM AND SOFTWARE ARCHITECTURES

Surgical robots typically adopt the hierarchical multi-rate control architecture that is found in general robotics. This architecture is depicted in **Figure 2** and each layer is further discussed in Section 3. The Hardware and Low-Level Control (LLC) layers are similar to those in general robotics, possibly with additional safety mechanisms. The unique characteristics of surgical robots become more evident at the High Level Control (HLC) and Application layers. The HLC may interface to external sensing, such as force sensing or real-time imaging, to implement closed-loop behaviors based on these sensors. The Application layer implements the surgical workflow and user interface and may include interfaces to other sub-systems, such as a database of patient information and possibly other medical devices.

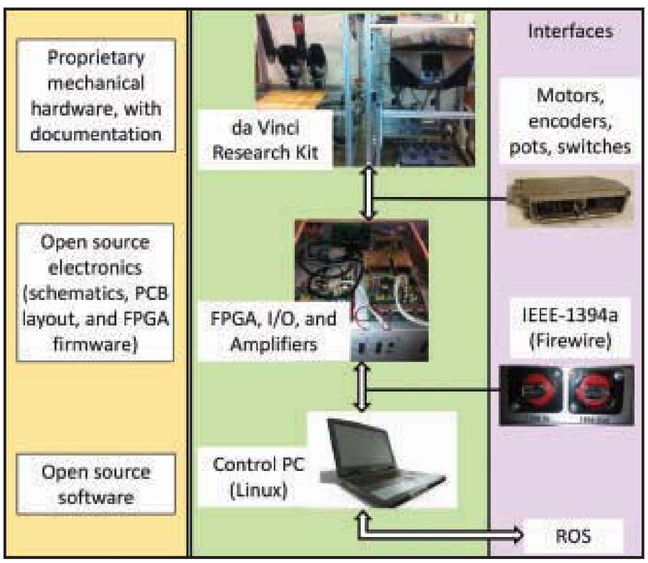


FIGURE 1 Overview of telerobotic research platform: Mechanical hardware provided by da Vinci Surgical System, electronics by open-source IEEE-1394 FPGA board coupled with Quad Linear Amplifier (QLA), and software by open-source cisst/SAW package with ROS interfaces.

From a wider perspective, the surgical robot is often just one component in a larger medical system. **Figure 3** depicts one representative system design that incorporates a telesurgical robot and an ultrasound scanner. In this figure, the Left Master Robot controls Slave Robot 2, which holds an ultrasound (US) probe, and the Right Master Robot controls Slave Robot 1, which holds the surgical instrument (not shown). In a conventional telesurgical setup, the Cartesian position of each Master Robot provides the desired Cartesian position of the corresponding Slave Robot (after transformations from the master to slave coordinate systems). The conventional setup also includes a stereo Camera that provides video images that are displayed on the stereo Diplay Hardware. The new capabilities are due to the addition of the US probe. The system acquires the US images and a Feature Detection module looks for a specified target inside the organ. If the target is found, it is presented as an augmented reality overlay (e.g., a cross-hair marker) in the stereo display and is used to provide haptic guidance to the surgeon via the Right Master Robot. For example, the High-Level Controller can apply a small force on the Right Master Robot to guide the instrument held by Slave Robot 1 to the target. Alternatively, if the target is a critical structure that the surgeon should avoid, the system can impose a safety barrier to prevent accidental damage. In either case, it is necessary for the target to be transformed to the camera and robot coordinate systems. The transformation to camera coordinates is enabled by the Tool Tracking module, which detects the US probe in the stereo images. This module uses the measured position of Slave Robot 2, which is subject to kinematic and non-kinematic errors, but improves the accuracy by directly detecting the tool in the stereo images. Finally, the target position is transformed from camera coordinates to robot coordinates using a known (calibrated) transformation matrix.

One key point in **Figure 3** is that while hierarchical multi-rate control may be suitable for the master and slave robots, there is also a requirement to handle the video and ultrasound images. These image channels have their own timing requirements; for example, the video will typically run at about 30 frames per second, whereas the US is likely to run at a different rate. Furthermore, execution of these channels is distinct from the periodic execution of the robot's low-level and high-level controllers. But, it is also necessary to share data between the channels and the robot controller, as illustrated in **Figure 3**.

The above example motivates the discussion of a software architecture to enable its implementation. In robotics (as in other domains), the original functional programming model gave way to object-oriented programming (OOP), and has more recently transitioned to component-based software engineering (CBSE). In OOP, each module in the system is an object that is an instance of a class. The class methods define the capabilities of that module. For example, the low-level controller (LLC) could contain methods to query the current joint position and to move the robot to a new joint position. The high-level controller would directly invoke the LLC methods; for example, the current Cartesian position is obtained by querying the joint position and then applying forward kinematics. The OOP approach represents a tight coupling, where objects directly invoke methods of other objects. It is more challenging to implement when multiple computations occur in parallel at different rates, as in **Figure 3**, because data transfer between parallel execution threads requires proper use of synchronization primitives such as mutexes and semaphores.

In CBSE, the various modules in **Figure 3** become separate components and interact via message passing. This results in a loose coupling between the components. Essentially, CBSE is similar to the electrical engineering domain, in that software components are the equivalent of integrated circuits, and systems are built by "wiring" software components much like integrated circuits are wired together on circuit boards. Some CBSE implementations require each component to be in a separate process, whereas others enable multiple components to exist in a single, multi-threaded process. The latter is advantageous for hard real-time systems because communication between components can be done more efficiently, especially when the framework provides efficient, thread-safe mechanisms, as in Orocos [6] and *cisst* [7]. In

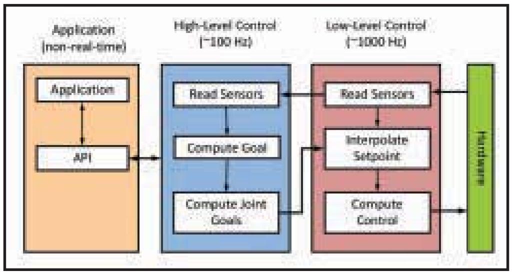


FIGURE 2
Layers of Canonical Robot Control Architecture.

contrast, the Robot Operating System (ROS) [8] requires each component (node) to be a separate process, although there is support for multi-threading via nodelets.

SYSTEM LAYERS AND INTERFACES

The following sections describe the layers shown in **Figures 2** and **3**, focusing on the interfaces to each layer. Although the real-time data channel could be considered part of the high-level control, it is sufficiently distinct from traditional high-level robot control to warrant its own subsection. For interfaces, the Robot Operating System (ROS) [8] provides a common middleware and standardized message types for robots and other devices and has been widely adopted by robotics researchers. The current version of ROS is not designed for real-time processing, however, and thus it is more suitable for the higher-level layers. For the lower-level layers, it is common to use a separate framework, such as OROCOS [6] or cisst [7], often with bridges to ROS. Because ROS is best supported on Ubuntu Linux, it is also common to use other standard protocols, such as OpenIGTLink [9], to interface to software on other platforms.

Physical (Hardware) Layer

The physical layer consists of mechatronics hardware, such as motors, encoders, potentiometers, and associated electronics. Traditionally, the electronics has consisted of input/output (I/O) devices, such as analog-to-digital (A/D) or digital-to-analog (D/A) converters, and power amplifiers to drive the motors. Recently, there has been a trend toward intelligent drive electronics, which combine the functions of the physical and low-level control layers.

Many systems employ custom interfaces to the physical layer, though some standard interfaces have emerged. One common standard is CANOpen (www.can-cia.org), originally developed for the Controller Area Network (CAN) bus, but now available for other physical network layers, including Ethernet. Another option is EtherCAT (www.ethercat.org), which uses a standard Ethernet port on the master device (e.g., PC) and custom hardware on the slave devices. Slave devices can be daisy-chained to form a common bus topology, and all slave nodes can receive data and respond via a single Ethernet frame.

For the dVRK shown in **Figure 1,** the physical layer consists of the mechanical components of the da Vinci and the custom electronics provided by the FPGA and QLA boards. The interface to the physical layer is via IEEE-1394a (FireWire), which is well suited for real-time control due to its high bandwidth, low latency, and support for daisy-chaining, broadcast, and peer-to-peer transfers. This interface was selected to achieve a *centralized computation and distributed I/O* architecture [10], where all control computations are performed on a familiar development environment (Linux PC). The FPGA implements the FireWire link layer so that packet data can be sent to, and received from, the I/O hardware with minimal latency. An Ethernet-to-FireWire bridge has recently been prototyped for the dVRK [11] to take advantage of the wider availability of Ethernet.

Low-Level Control (LLC) Layer

The low-level control layer is often referred to as the servo control layer. Typically, it consists of a simple control algorithm, such as proportional-integral-derivative (PID) control, periodically executing at a high rate (e.g., 1 kHz), to control the individual axes of the robot. The typical low-level control flowchart is to read the robot internal sensor feedback, such as joint encoder positions, compute the error between the desired and measured positions and/or velocities, apply the control law, and then output the desired motor voltage or current. Thus, this layer requires a reliable operating environment, preferably with real-time performance. For this reason, it is often implemented on special-purpose hardware, such as an off-the-shelf (commercial) controller board, or on a PC using a framework that supports real-time processing.

The LLC interface is an obvious candidate for standardization because most robots contain similar low-level controllers. In particular, a standard low-level control inter-

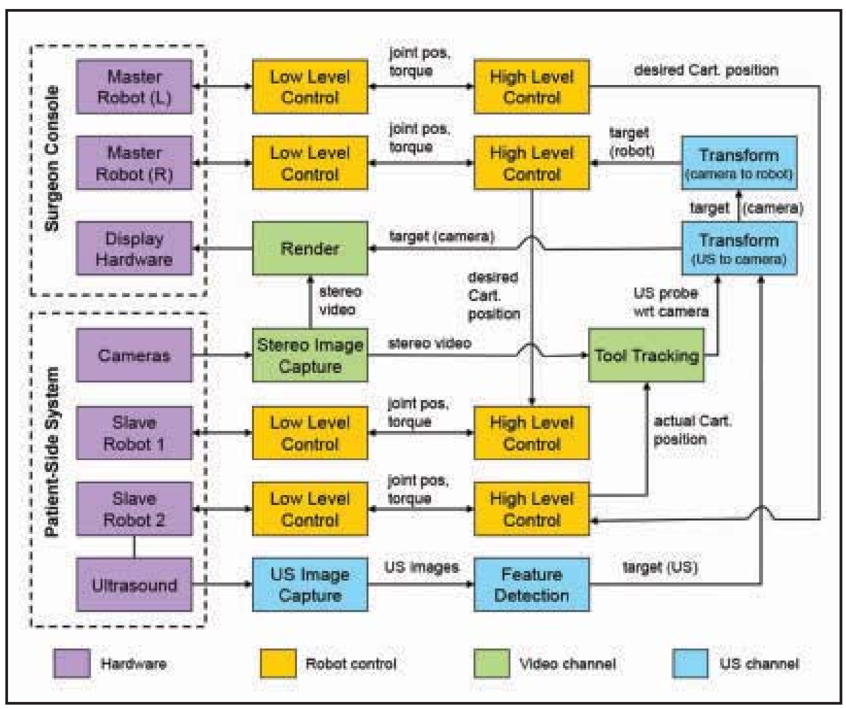


FIGURE 3 **Illustrative system architecture with telesurgical robot (two masters and two slaves), stereo video cameras and display hardware, and ultrasound (US) scanner. US probe is held by Slave Robot 2 and Feature Detection module looks for target. Tool Tracking module estimates position of US probe from stereo camera images, using Slave Robot 2 position to initialize image localization. Result of Tool Tracking is used to transform detected target to camera coordinates, which enables augmented reality overlay within Render module. Target is also transformed to Right Master Robot coordinates (using previously measured transformation) and provides haptic guidance to surgeon to position instrument held by Slave Robot 1 at target.**

face would include commands to enable/disable motor power, home (initialize) the robot, get the current joint positions, and move the joints to a specified position. The other advantage to standardizing at this interface is that it typically forms the bridge between the hard real-time and soft real-time parts of the system. This enables plug-and-play interoperability between systems with very different low-level control and physical layers.

High-Level Control (HLC) Layer

While the LLC provides joint-level control, the HLC provides more sophisticated motion capabilities. One example is Cartesian-level control, where the pose (position and orientation) of the robot end-effector can be measured and controlled in Cartesian coordinates. This requires knowledge of the robot's kinematics. This layer often also integrates feedback from other sensors external to the robot system, such as vision and force, that can be used for visual servoing or force control, respectively. Many surgical robot systems require a human (surgeon) in the loop, and so the high-level control may include assistive control behaviors, such as virtual fixtures.

For the HLC interface, it is straightforward to standardize some basic capabilities, such as Cartesian position control, and to allow system-specific extensions for other capabilities such as sensor-based control modes. This is also the level where ROS interfaces are most common, since the major advantage offered by ROS is the ability to integrate with other high-level software modules.

Data Channel Layer

Data channels are common in surgical robot systems due to the integration with real-time imaging such as video and ultrasound. A data channel consists of a source (e.g., a camera), several filters that process the data, and one or more sinks (e.g., a rendering device). There are two common implementation strategies: (1) a pipeline, where a separate thread or thread pool is used for each filter, and (2) a stream, where a single thread or thread pool is used to sequentially execute each filter. The advantage of the pipeline is that it can provide higher throughput, since processing of new data can begin immediately. The advantage of the stream is that it provides lower latency because there is no need for synchronization primitives between the execution of different filters.

The choice of a pipeline or stream depends on the application requirements and leads to the choice of implementation framework. For human-in-the-loop systems, which are common in surgery, minimizing latency (delay) may be critical, since added delay can affect surgical performance. For this reason, the *cisstStereoVision* (SVL) library (part of the cisst package) supports the stream processing paradigm. In SVL, each filter is a separate component, but the components can exist in a single executable and share memory buffers to reduce overhead. Synchronization primitives are not required because SVL sequentially executes each filter.

If low latency is not required, the pipeline is an attractive option because it enables the use of ROS nodes as filters (ROS provides a large collection of useful image processing components). In ROS, each node is a separate executable, so by default it contains its own thread (or thread pool) and a network of these nodes forms a pipeline.

Application Layer

The application layer primarily consists of the application logic (e.g., surgical workflow) and the user interface. There are many different packages that can be used to implement the application layer. If the application is primarily a graphical user interface, one could adopt a framework such as Qt (www.qt.io). Alternatively, if the application requires the display and manipulation of preoperative and/or intraoperative medical images, the application layer could be implemented in an extensible, open source framework such as 3D Slicer (www.slicer.org). In this case, it would be convenient to use Slicer's built-in OpenIGTLink interfaces. The rviz package provided by ROS is also an attractive option. It is based on the OGRE graphics rendering engine and has plugins to support Qt widgets, images, and other data types. Finally, some researchers choose Matlab/Simulink (The MathWorks, Inc., Natick, MA) as their development platform.

CONCLUSIONS

This article presented an overview of surgical robot systems, with the recognition that these systems are not just robots, but integrated systems that include robots, databases, and real-time sensors such as video and other medical imaging devices. Common research platforms, such as the da Vinci Research Kit (dVRK) and Raven II, have recently become available. This has underscored the need for modular software interoperability, so that researchers can share software modules and more easily integrate other robots and devices. Standardization and interoperability are most applicable at the higher software layers, and can benefit from the availability of widely-adopted middleware such as ROS. Other interface protocols, such as OpenIGTLink, can be useful due to their wide support within the medical imaging and image-guided intervention domains. ■

REFERENCES

1 Kwoh, Y., Hou, J., Jonckheere, E., and Hayati, S., 1988. "A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery". *IEEE Trans. on Biomedical Engineering*, 35(2), Feb, pp. 153–160.

2 Ng, W., Davies, B., Hibberd, R., and Timoney, A., 1993. "Robotic surgery–a first-hand experience in transurethral resection of the prostate". *IEEE Engineering in Medicine and Biology Magazine*, 12(1), Mar, pp. 120–125.

3 Mittelstadt, B., Paul, H., Kazanzides, P., Zuhars, J., Williamson, B., Pettitt, R., Cain, P., Kloth, D., Rose, L., and Musits, B., 1993. "Development of a surgical robot for cementless total hip replacement". *Robotica*, 11, pp. 553–560.

4 Kazanzides, P., Chen, Z., Deguet, A., Fischer, G., Tay.lor, R., and DiMaio, S., 2014. "An Open-Source Research Kit for the da Vinci ® Surgical System". In IEEE Intl. Conf. on Robotics and Automation (ICRA).

5 Hannaford, B., Rosen, J., Friedman, D. W., King, H., Roan, P., Cheng, L., Glozman, D., Ma, J., Kosari, S. N., and White, L., 2013. "Raven-II: an open platform for surgical robotics research". *IEEE Trans. on Biomedical Engineering*, 60(4), pp. 954–959.

6 Bruyninckx, H., Soetens, P., and Koninckx, B., 2003. "The real-time motion control core of the Orocos project". In IEEE Intl. Conf. on Robotics and Automation (ICRA), Vol. 2, pp. 2766–2771.

7 Kapoor, A., Deguet, A., and Kazanzides, P., 2006. "Software components and frameworks for medical robot control". In IEEE Intl. Conf. on Robotics and Automation (ICRA), pp. 3813–3818.

8 Quigley, M., Conley, K., Gerkey, B., Faust, J., Foote, T. B., Leibs, J., Wheeler, R., and Ng, A. Y., 2009. "ROS: an open-source robot operating system". In ICRA Workshop on Open Source Software.

9 Tokuda, J., Fischer, G. S., Papademetris, X., Yaniv, Z., Ibanez, L., Cheng, P., Liu, H., Blevins, J., Arata, J., Golby, A. J., Kapur, T., Pieper, S., Burdette, E. C., Fichtinger, G., Tempany, C. M., and Hata, N., 2009. "OpenIGTLink: an open network protocol for image-guided therapy environment". The International Journal of Medical Robotics and Computer Assisted Surgery, 5(4), pp. 423–434.

10 Kazanzides, P., and Thienphrapa, P., 2008. "Centralized processing and distributed I/O for robot control". In Technologies for Practical Robot Applications (TePRA), pp. 84–88.

11 Qian, L., Chen, Z., and Kazanzides, P., 2015. "An Ethernet to FireWire bridge for real-time control of the da Vinci Research Kit (dVRK)". In IEEE Intl. Conf. on Emerging Technologies and Factory Automation (ETFA).

Global Gas Turbine News

Volume 54, No. 3 • September 2015

In this issue

go.asme.org/IGTI

Email: igti@asme.org

ASME Turbo Expo 2015 Conference Highlights

ASME Turbo Expo 2015 in Montreal, Quebec, Canada maintained its reputation as the world's premier gathering of turbomachinery professionals. Throughout the week, delegates shared practical experiences, knowledge and ideas on the latest gas turbine technology trends and challenges, as well as on related topics in fans and blowers, solar power, and wind and steam turbine technologies. If turbomachinery is part of your professional life, you cannot afford to miss the annual ASME Turbo Expo! To plan for 2016 and to keep informed throughout the year, visit Turbo Expo online at https://www.asme.org/events/turbo-expo.

Grand Opening: Keynote and Awards Ceremony. Approximately 2,000 turbomachinery professionals attended the opening keynote session which featured keynote presentations from prominent industry experts: Walter Di Bartolomeo, Vice President, Engineering, Pratt & Whitney Canada; Chris Lorence, General Manager of Engineering Technologies, GE Aviation; and Richard (Ric) Parker, Director of Research & Technology, Rolls-Royce Group.

...Continued on next page

ASME Turbo Expo 2015 Conference Highlights

Congratulations to the 2015 Turbo Expo Student Advisory Committee Travel Award Winners. Opportunities for Student Travel will be available for the 2016 Seoul event. Check the Turbo Expo Website for more information.

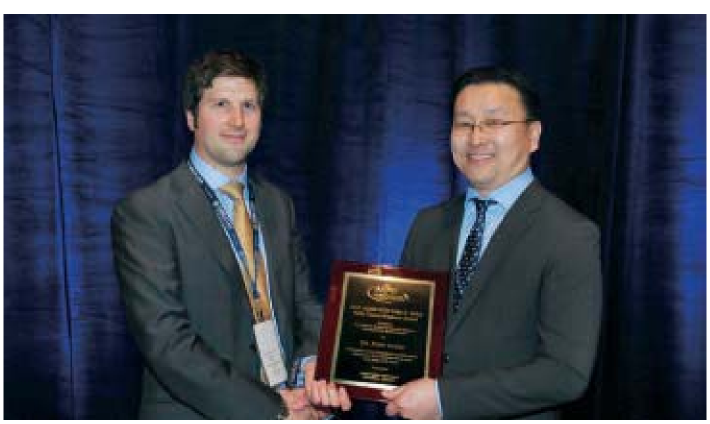
Thank You to the Outgoing IGTI Technical Committee Chairs.

R. Tom Sawyer Award Winner Dr. Lee Langston pictured with ASME President Bob Sims and ASME IGTI Board Chair Seung Jin Song.

Congratulations to the 2015 Turbo Expo Young Engineer Travel Award Winners. Visit the Turbo Expo Web page for student travel opportunities for the 2016 Seoul event.

Dr. Jon Schaeffer, 2015 Industrial Gas Turbine Technology Award Winner, pictured with Geoff Sheard, Conference Chair; Daniel Barpal, Electric Power Committee Vice Chair; and Seung Jin Song, ASME IGTI Chair.

Dr. Dirk Therkorn and Mauro Venturini, 2013 John P. Davis Award winners, pictured with Geoff Sheard, Conference Chair; and Seung Jin Song, ASME IGTI Chair.



Dr. John Coull, 2015 Dilip R. Ballal Early Career Award Winner, pictured with Seung Jin Song, ASME IGTI Chair.

Dr. Harika S. Kahveci and Kevin Kirtley, 2013 ASME Gas Turbine Award Winners, pictured with Bob Sims, ASME President; and Seung Jin Song, ASME IGTI Chair.

ASME Turbo Expo 2015 Conference Highlights

Women in Turbomachinery Networking Dinner
Sponsored by GE and Siemens

Over 100 female turbomachinery professionals attended the popular networking event held at the Ritz Carlton Montreal to hear presentations from Christine Furstoss, GE Global Research Technical Director, Chemical & Materials Technologies, Laura Holland, Siemens Head of Global GT Negotiation Support and from special guest, Dr. Janet Kavandi, Deputy Director of NASA Glenn Research Center.

ASME Turbo Expo 2015 Statistics

This year at Turbo Expo, attendees represented 29 countries worldwide. 1,051 final papers were submitted and 299 conference sessions were held. The exhibit hall included 118 exhibitors.

Thank You to Our Volunteers!

- Turbo Expo 2015 Conference Committee
- Turbo Expo 2015 Local Liaison Committee
- Point Contacts & Vanguard Chairs
- Session Chairs & Vice Chairs
- Reviewers
- Authors
- Speakers

Congratulations to GE for being selected as the People's Choice for Best Large Booth.

Congratulations to Liburdi Turbine Services Inc. for being selected as the People's Choice for Best Small Booth.

Student Mixer

Sponsored by GE

The student mixer was well attended by over 300 young turbomachinery professionals. The students had an opportunity to network with their peers in a relaxed atmosphere with a beautiful view of Montreal!

Turbo Expo 60th Anniversary Museum and Legacy DVD

To celebrate IGTI's distinguished heritage, the IGTI Board provided complimentary DVDs, containing all of the Turbo Expo papers beginning in 1956, to the technical conference registrants of Turbo Expo 2015. The Turbo Expo 60th Anniversary Museum was a great showcase displaying 10 turbine engines provided by Ecole National Aerotechnique, a GE fan blade, and historical Turbo Expo materials.

Thank You, Sponsors

PLATINUM SPONSORS

GE

Pratt & Whitney — A United Technologies Company

Rolls-Royce

SILVER SPONSOR

ANSYS

MERCER

BRONZE SPONSORS

CD-adapco™

NUMECA International

Solar Turbines — A Caterpillar Company

ADDITIONAL SPONSORS

turbo designsuite by Advanced Design Technology

APEX Turbine Testing Technologies

Parker

Diesel & Gas Turbine Worldwide magazine

SIEMENS

TURBOCAM International

TECHNICAL ARTICLE

A Partial History of Water-Cooled Gas Turbines

by William H. Day, President – Longview Energy Associates LLC

Development of water-cooled gas turbines has had a long history starting in 1903, which is summarized in reference 1. The present article focuses on the work done at GE from the 1960s to the early 1980s.

The Beginnings of GE's Work:

During World War II the Schmidt Turbine was an attempt by Germany to use water cooling to enable high temperatures in the turbine section of an aircraft engine, as materials and air cooling technology were not very effective at that time. Cooling the nozzles (stationary airfoils) with water was not a problem, but cooling the buckets (rotating airfoils) proved to be an insurmountable problem because the cooling was closed circuit which created problems getting the liquid in and out of the moving part and distributing it effectively in the presence of a very high centrifugal field, resulting in cracked buckets, so the concept was abandoned.

By the early 1960s there was interest in the gas turbine industry in accommodating low cost and dirty fuels (e.g. coal gas and residual oil like bunker C), but a problem was hot corrosion from the contaminants in the fuels. A possible solution to this problem was water cooling: If you don't have hot airfoil surface temperatures, you won't have hot corrosion.

Dr. Paul H. Kydd, a researcher at GE's Corporate R&D Center in Schenectady, NY thought of a different approach vs. the Schmidt Turbine: Let the water go outside the tip of the bucket, metered so it used about 2/3 of the latent heat of evaporation and expelled the rest. This would keep the bucket surface cool enough to eliminate hot corrosion and keep the pressure low enough to prevent cracking. He demonstrated the concept in a 12 inch diameter rotor using flattened 347 stainless steel tubing for the buckets at atmospheric pressure and 2800° F. This convinced GE's Gas Turbine Division to fund the project of developing a full pressure / full temperature model of the same size. See reference 2 for details.

The Energy Crisis of 1973 and EPRI Program:

With the 1973 Arab Oil Embargo and sharply increasing prices for gas turbine fuel the industrial gas turbine industry went into a sharp decline, as did the entire US power generation business. The Edison Electric Institute enabled the founding of the Electric Power Research Institute, partly because they feared that the federal government would start to dictate R&D in the power generation industry, and they wanted to have some control of that. At that point the electric utilities were mostly regulated monopolies, and EPRI worked with the US regulated utilities to add a charge on consumers' electric bills to fund EPRI. GE won a contract from EPRI to demonstrate the water-cooled turbine concept at full pressure and temperature with realistically shaped airfoils. This was done successfully, at a turbine inlet temperature of 2850° F and 16 atmospheres with metal temperature of less than 1000° F (Reference 3). Test facilities were also built and run to gather data on potential problems such as 1) Long term effects of partial channel water cooling on erosion, corrosion and deposition, 2) Water supply, distribution and collection in the outer casing, 3) Materials testing with contaminated fuels. See reference 3 for details.

The HTTT Program:

The results of the EPRI program were sufficiently encouraging that GE and EPRI decided to advocate a bigger project to the US Department of Energy (then known as the Energy Research and Development Administration or ERDA) to demonstrate the concept in utility size components. The result of that advocacy was the US Department of Energy's High Temperature Technology Turbine (HTTT) Program, which was a major effort to develop advanced turbine cooling technology, including water-cooled turbines. GE was a winner of the 4-way competition for funding on large gas turbines, and the HTTT program was launched in 1977 to carry on the work of the EPRI program, to full scale utility size components.

GE dropped work on water cooling in the early 1980s. The following is speculation by the author, who led the water cooled turbine effort at GE from the late 1960s through 1978 and left GE to join United Technologies in January 1979.

Part of the reason (reference 1) was concern of instabilities in the boiling water. But there were other major forces at work in the gas turbine industry which were arguably more important in GE's decision to drop water cooling:

- By the 1980s the fuel of choice in the gas turbine industry was natural gas, which had become widely available enough for utilities to use it. So coal gas and residual oil were not as important for fuel sources.
- Emissions regulations were becoming stricter, so it was not permissible to simply burn a contaminated fuel; you had to make the fuel clean before it got to the combustor or spend the capital cost of exhaust cleanup. Thus there was less need for a turbine that could burn contaminated fuels.
- Air cooling technology had developed so far, so fast (thanks to military and commercial aircraft engine development) that water cooling was not necessary for industrial GTs to become the most efficient and lowest cost per kW option in electric power generation.

So it seems that water cooling died a natural death as one technology supplanted another.

References

1. S. C. (John) Gulen, "Engineering Building Blocks for an Uberturbine Prototype", Gas Turbine World magazine July – August 2014
2. ASME Paper 75-GT-81, "An Ultra High Temperature Turbine for Maximum Performance and Fuels Flexibility", P.H. Kydd and W. H. Day
3. ASME Paper 78-GT-72, "Development of a Water-Cooled Gas Turbine", M W. Horner, W. H. Day, D. P. Smith and A. Cohn

Correction of polytropic efficiency for ideal gas in Globe GT News May 2015

The only formula shown explicitly in this article indicates the polytropic efficiency calculated for an ideal gas. This formula contains an unremarkable but significant mistake. The corrected formula with its explanations is as follows:
Polytropic efficiency for compressing an ideal gas (formula "IGF"):

p_1, T_1, s_1 = pressure, temperature and specific entropy in state 1 (inlet condition)
p_2, T_2, = pressure and temperature in state 2 (outlet condition)
R: Gas constant
s_3 = specific entropy at p_1 and T_2
η_p: Polytropic efficiency

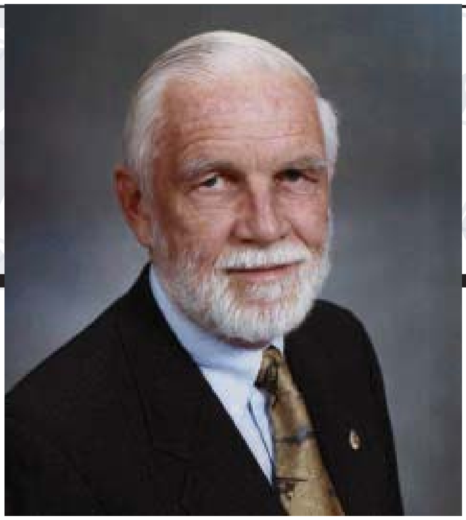
$$\eta_p = \frac{R\ln(p_2 / p_1)}{s_3 - s_1}$$

Additionally the strange definition of s_3 calls for an explanation. This can be given with the very short derivation of this formula based on the incremental definition of the polytropic efficiency described verbally above in the article. Dzung indicated the incremental formula $\eta_p = vdp/dh$. Integrating this analytically by assuming constant η_p and replacing v with the ideal gas equation of state $v = RT/p$ gives:

$\eta_p \int_1^2 dh/T = R\ln(p_2/p_1)$.

The left integral can be replaced either by $\int_1^2 cp(T)/TdT$, which is my preferred version for numeric evaluations, or by the definition of the specific entropy of an ideal gas with the above indicated $(s_3\text{-}s_1)$. This convenient formula for η_p is frequently used in the gas turbine technology in spite of the fact that most textbooks hide it behind many other explanations and do not show the above mentioned short derivation.

AS THE Turbine TURNS



Our Founder - IGTI's R. Tom Sawyer

by Lee S. Langston, *Professor Emeritus, Mechanical Engineering, University of Connecticut*

Anniversaries provide the occasion to look back, and perhaps to better understand what is going on now. This year is the 60th anniversary of International Gas Turbine Institute's Turbo Expo, IGTI's preeminent gas turbine conference. We just had our 60th gathering in Montreal, on June 15-19, 2015.

One way to understand IGTI today, is to know something about its founder, R. Tom Sawyer (1901-1986). "Mr. Gas Turbine," as he was known to many, founded our gas turbine technical institute, and set its course for its first four decades, during which time the gas turbine itself, became one of the world's most useful energy converters. In 1972, IGTI memorialized his work and his name with the establishment of the annual R. Tom Sawyer Award. I had the honor of receiving this year's award in Montreal, to be added to the list of awardees which started with Sawyer and includes Hans von Ohain and Frank Whittle, inventors of the jet engine.

Early Days

Robert Thomas Sawyer was born June 20, 1901 in Schenectady, NY. He got an undergraduate electrical engineering degree at Ohio State University in 1923. Sawyer then joined the General Electric Company, designing and developing early diesel powered locomotives. In 1929, he visited Alfred Büchi, the Swiss inventor of supercharging, and saw his first gas turbine, sans combustor, in the form of a Büchi diesel supercharger [1]. (Remember the first electric power industrial gas turbine was the Neuchatel 4 MW machine, built and tested by Brown Boveri in 1939. [2]).

Sawyer then joined the American Locomotive Company where he was involved with both diesel and gas turbine projects from 1930 to 1956. In 1944 he applied for one of the first gas turbine powered locomotive patents, which was awarded in 1948 [3]. He was the author of ***The Modern Gas Turbine*** [4], a text that was first published in 1945. At the time, it was an authoritative text, giving a well-informed historical account of gas turbines and their applications. (It has a very readable account of initial testing of the 4 MW Brown Boveri gas turbine in 1939 by Professor A. Stodola of ETH.)

Sawyer and ASME

As I reported in an earlier column [5], Sawyer was instrumental in organizing the presentation of the very first ASME gas turbine technical papers. On May 8-10, 1944, ASME's 17th National Oil and Gas Power Conference was held mid-continent (wartime) at the Mayo Hotel in Tulsa, OK. The technical program consisted of four sessions (a total of ten technical papers); three on diesel engine technology and one (two papers) on the newly emerging gas turbine. As ***Mechanical Engineering*** magazine reported: "Demonstrating the technical interest aroused by the gas turbine, first new prime mover in 50 years, a capacity crowd of approximately 250 attended the first technical session which was devoted to that subject." In anticipation of this intense interest in new gas turbine technology, on May 7, 1944, the Executive Committee of the Oil and Gas Power Division voted to form a ten member Gas Turbine Coordinating Committee (GTCC) to provide "...coordination and dissemination of new technical information on the gas turbine through periodic meetings and the presentation of technical papers." This newly formed GTCC with R. Tom Sawyer of the American Locomotive Company as its Chairman, was the start of IGTI.

As the Turbine Turns...

As the number of gas turbine members and papers increased, the ASME Gas Turbine Power Division was formed in 1947, later to be called simply the Gas Turbine Division (GTD). R. Tom Sawyer served as its first chairman. In 1986, GTD grew into the International Gas Turbine Institute.

The IGTI First Annual Gas Turbine Conference and Exhibit was held April 16-18, 1956 at the Hotel Statler in Washington, DC. This very first ASME all gas turbine meeting had 25 exhibitors, six technical sessions, a total of 17 papers and an attendance of about 750. This was the start of IGTI's Turbo Expo, 60 years ago. Sawyer was a key organizer, helping to make the exhibit a successful revenue-producing part of the conference.

R. Tom Sawyer was involved with IGTI to the end of his life in 1986. I first met him at the 1984 TURBO EXPO in Amsterdam when he was 82.

His home was close to New York City in the singularly named New Jersey town of Ho-Ho-Kus (a contraction of a Delaware Indian name, "the red cedar"). Early in our IGTI history, R. Tom went to a jeweler in the City, and had a die made, to cast a miniature multibladed, axial-flow turbine "wheel" lapel pin. Over the years, the resulting gold turbine wheels have been presented to many IGTI volunteers in recognition of their efforts and accomplishments.

In 1964 R. Tom ventured to Broadway, and had ASCAP songwriter Arthur Kent (famous as a composer of hit songs such as "The End of the World") compose IGTI's song, "Onward and Upward with Gas Turbines". Many of you will recognize the song, since we play it at the start and ending of our Turbo Expos. It has recently been updated by a Nashville lyricist.

Author Mark Twain's Tom Sawyer is a famous fictional character, who in one story, pretending alacrity, enticed village boys to whitewash Aunt Polly's fence. Unlike Twain's Tom who gets others to do a task, IGTI's Tom Sawyer was both a motivator and a true achiever, founding and helping to shape our very successful institute. He truly was "Mr. Gas Turbine".

References

1. Hawthorne, W.R., 1994, "Reflections on United Kingdom Aircraft Gas Turbine History", ***ASME Journal of Engineering for Gas Turbines and Power,*** July Vol. 116, pp. 495-510.
2. Langston, L.S., 2010, "Visiting the Museum of the World's First Gas Turbine Powerplant", ***Global Gas Turbine News,*** April, p. 3.
3. Sawyer, R.T., 1948, "Rotary Engine Power Plant", United States Patent Office, No. 2,445,973.
4. Sawyer, R.T., 1945, ***The Modern Gas Turbine,*** Prentice-Hall.
5. Langston, L.S., 2012, "Some IGTI History", ***Global Gas Turbine World,*** February, p. 49.

Get Ready for ASME Turbo Expo 2016 in Seoul, South Korea! June 13 - 17, 2016

Turbo Expo attendees celebrated the launch of ASME 2016 Turbo Expo during the closing ceremony of the 2015 exposition in Montreal, Quebec, Canada. Conference Chair Timothy Lieuwen, Georgia Institute of Technology, spotlighted the 2016 leadership team:

ASME IGTI 2016 Turbo Expo Conference Committee

Executive Conference Chair
Bill Newsom, Mitsubishi Hitachi Power Systems Americas, Inc.

Conference Chair
Tim Lieuwen, Georgia Institute of Technology

Technical Program Chair
John Chew, University of Surrey

Review Chair
Jaroslaw Szwedowicz, Alstom Power

Vice Review Chair
Ray Chupp, REC Consulting, LLC

Vice Review Chair
Zolti Spakovzsky, Massachusetts Institute of Technology

Vice Review Chair
Mark Turner, University of Cincinnati

Local Liaison Chair
Seung Jin Song, Seoul National University

Exhibitor Representative
Dave Pincince, TURBOCAM International

Board Liaison
Geoff Sheard, AGS Consulting LLC

The technical conference has a well-earned reputation for bringing together the best and brightest experts from around the world to share the latest in turbine technology, research, development, and application. The Turbo Expo Leadership Team will collaborate in, once again, fulfilling this must attend event. Furthermore, Turbo Expo will provide over ten networking events where you can connect with peers, colleagues, and industry experts! The ASME IGTI community is excited and ready to establish a strong presence and support in Asia by holding Turbo Expo, for the very first time, in Seoul, South Korea. You will want to be part of this historical moment. Make plans to attend the ASME 2016 Turbo Expo Conference, June 13 – 17, 2016. Visit https://www.asme.org/events/turbo-expo for updated information.

Exposition

ASME Turbo Expo is known for its high-quality exhibition of leading companies in the turbomachinery industry, attracting a key audience from aerospace, power generation and other prime mover-related industries. Exhibiting at Turbo Expo 2016 is your chance to attract new clients, visit with current ones, learn more about the changing needs of the international turbomachinery industry – and ultimately, increase your sales. Exciting brand-enhancing sponsorship packages for the 2016 exposition are now available! Packages are designed around your particular corporate goals and are an extremely effective way for your company to really stand out from the crowd – before, during and after the show. To insure your company's participation in the 2016 exposition, contact ASME IGTI at +1 212-591-8646 or via email at igtiexpo@asme.org.

Call for Papers
ASME Turbo Expo 2016

Abstracts are due by September 14, 2015 and must be submitted online (plain text, 400 word limit) via the Turbo Expo Conference Web site at https://www.asme.org/events/turbo-expo. The 2016 Publication Schedule:

- Abstract Submission – September 14, 2015.
- Draft Paper Due Date – November 23, 2015.
- Paper Reviews Complete – December 28, 2015.
- Author Notification of Paper – Acceptance - January 11, 2016.
- Submission of Final Paper – February 29, 2016.
- Final Paper Approval by Review Chair – April 4, 2016.


TURBO EXPO
SEOUL, SOUTH KOREA | JUNE 13-17, 2016
The Most Important Conference
for Turbomachinery Professionals.
5-day conference sets the world standard for turbine technologies
Over 1200 technical papers – each with a full presentation
Panel sessions featuring industry professionals
Tutorial sessions for those looking to learn about a new topic
Workshops and facility tours create additional educational opportunities
3rd annual student poster session to display ongoing research
3-day exhibition featuring exhibits from the world leaders in turbine technologies
Abundant networking opportunities
turboexpo.org
igtiprogram@asme.org | phone: +1-281-810-5457
ASME
INTERNATIONAL GAS
TURBINE INSTITUTE

The ASME International Gas Turbine Institute presents the fourth annual ASME Gas Turbine India Conference in Hyderabad, India, December 1-3, 2015. The 3-day event attracts the industry's leading professionals and key decision makers, whose innovation and expertise are shaping the future of turbomachinery. Authors and presenters are invited to participate in this event to exchange ideas on research, development and best practices on gas turbines and allied areas. The conference is an excellent opportunity to initiate and expand international co-operation.

ASME IGTI community volunteers who will be responsible for leadership, organization and arrangements at the ASME 2015 Gas Turbine India Conference are Prof. B.V.S.S.S. Prasad, Indian Institute of Technology-Madras Chennai, India (conference chair); Dr. N.K. Singh, BHEL Corporate R&D, Hyderabad, India (technical program chair); and Prof. Joseph Mathew, Indian Institute of Science, Bangalore, India (review chair).

For information on the conference or to register, call ASME (1) 281-810-5457 or visit http://www.asmeconferences.org/GTIndia2015.

ASME STANDARDS & CERTIFICATION
TWO PARK AVE., NEW YORK, NY 10016-5990
212.591.8500 FAX: 212.591.8501
E-MAIL: CS@ASME.ORG

If you are looking for information regarding an ASME code or standard committee, conformity assessment program, training program, staff contact, or schedule of meetings:

PLEASE VISIT OUR WEBSITE: WWW.ASME.ORG/CODES

COMMITTEE LISTING: For a listing of ASME Codes and Standards Development Committees and their charters, visit the Standards and Certification website at http://cstools.asme.org/charters.cfm.

CONFORMITY ASSESSMENT: For a listing and description of ASME Conformity Assessment (accreditation, registration, and certification) programs, visit the Standards and Certification website at http://www.asme.org/kb/standards/certification---accreditation.

TRAINING & DEVELOPMENT: For a listing and description of ASME Training & Development educational opportunities, visit the ASME Education website at http://www.asme.org/kb/courses/asme-training---development.

STAFF CONTACTS: To obtain the ASME staff contact information for a Codes and Standards Development Committee or a Conformity Assessment program, visit the Codes and Standards website at http://cstools.asme.org/staff.

SCHEDULE OF MEETINGS: Meetings of Codes and Standards Development Committees are held periodically to consider the development of new standards and the maintenance of existing standards. To search for scheduled meetings of Codes and Standards Development Committees, by date or by keyword, visit the Standards and Certification website at http://calendar.asme.org/home. cfm?CategoryID=1.

PUBLIC REVIEW DRAFTS
An important element of ASME's accredited standards development procedures is the requirement that all proposed standards actions (new codes and standards, revisions to existing codes and standards, and reaffirmations of existing codes and standards) be made available for public review and comment. The proposed standards actions currently available for public review are announced on ASME's website, located at http://cstools.asme.org/csconnect/PublicReviewpage.cfm.

The website announcements will provide information on the scope of the proposed standards action, the price of a standard when being proposed for reaffirmation or withdrawal, the deadline for submittal of comments, and the ASME staff contact to whom any comments should be provided. Some proposed standards actions may be available directly from the website; hard copies of any proposed standards action (excluding BPV) may be obtained from:

MAYRA SANTIAGO, Secretary A
ASME Standards & Certification
Two Park Ave., M/S 6-2A
New York, NY 10016
e-mail: ansibox@asme.org

ASME maintains approximately 500 codes and standards. A general categorization of the subject matter addressed by ASME codes and standards is as follows:

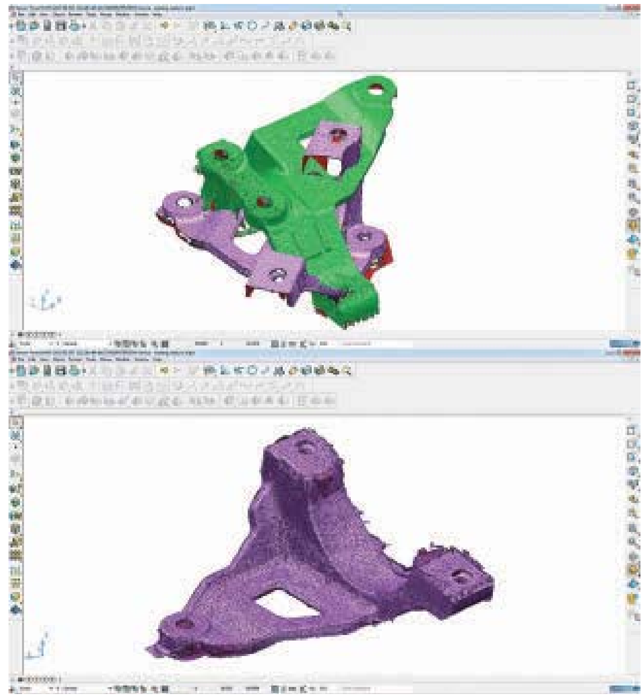
Authorized Inspections
Automotive
Bioprocessing Equipment
Boilers
Certification and Accreditation
Chains
Controls
Conveyors
Cranes and Hoists
Cutting, Hand, and Machine Tools
Dimensions
Drawings, Terminology, and Graphic Symbols
Elevators and Escalators
Energy Assessment
Fasteners
Fitness-For-Service
Gauges/Gaging
Geometric Dimensioning & Tolerancing (GD&T)
High-Pressure Vessels Systems
Keys and Keyseats
Limits & Fits
Materials
Measurement of Fluid Flow in Closed Conduits
Metal Products Sizes
Metric System
Metrology and Calibration of Instruments
Nondestructive Evaluation/ Examination-Nuclear
Operator Qualification and Certification
Performance Test Codes
Piping & Pipelines
Plumbing Materials and Equipment
Post Construction of Pressure Equipment and Piping
Powered Platforms
Pressure Vessels
Pumps
Rail Transportation
Reinforced Thermoset Plastic Corrosion Resistant Equipment
Risk Analysis
Screw Threads
Steel Stacks
Surface Quality
Turbines
Valves, Fittings, Flanges, Gaskets
Verification & Validation
Welding & Brazing

The ASME Standards & Certification section is published as submitted to Mechanical Engineering magazine by ASME's Standards & Certification Department.

REVERSE ENGINEERING

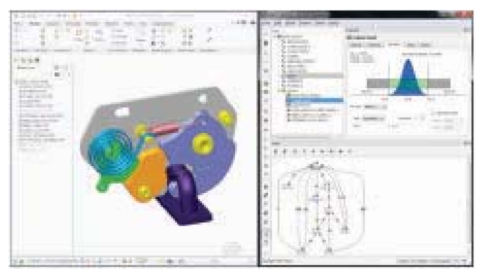
DELCAM LTD., BIRMINGHAM, U.K.

By offering a combination of solid, surface, and direct modeling, together with reverse engineering, PowerSHAPE Pro provides a range of design techniques in a single CAD program. Having all the different technologies in the same package reduces the need to transfer data between different programs and so streamlines product development that requires reverse engineering and CAD functionality. PowerSHAPE Pro connects directly to most scanning hardware to capture and display scan data in real time.



3-D TOLERANCE ANALYSIS

SIGMETRIX, MCKINNEY, TEXAS.



Sigmetrix has announced the availability of its the CETOL 6s v8.4 software for PTC Creo, Creo Elements/Pro, CATIA V5, and SolidWorks CAD systems. CETOL 6s v8.4 includes all of the robust features of the CETOL 6s architecture, enhanced with improved functionality. Cutting-edge technology enables product development teams to reduce time to market and maximize profitability.

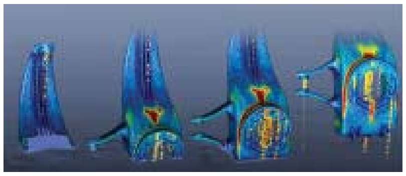
PCB DESIGN

ALTIUM LTD., SAN DIEGO, CALIF.

The Altium Designer 15.1, software for printed circuit board design, introduces several new features for improved productivity, documentation outputs, and high-speed design efficiency. New features include improved support for xSignals, expanded rigid flex support, output documentation options, and design re-use features. The new features add to the foundation set in place with the initial release of Altium Designer 15, which focused on improvements to the high-speed design process.

SIMULATION TOOL

CD-ADAPCO, MELVILLE, N.Y.



STAR-CCM+ v10.02 focuses on multidisciplinary design exploration (MDX) to help accelerate the design decision process. This release allows engineers to drive their simulations through a range of operating scenarios. The approach can be used to gain a complete understanding of the performance of a product across the wide design space. Version 10.02 also offers technology breakthroughs in the field of multiphase modeling by releasing a new interaction model between VOF, fluid film, and Lagrangian models.

PROCESS PLANT SIMULATION

MYNAH TECHNOLOGIES, CHESTERFIELD, MO.

Mimic Simulation Software v3.6 is a next-generation software platform for the process industries, providing fast, easy, flexible, dynamic simulation for plant lifecycle operations. Mimic v3.6 is intended as the next step in an initiative to reduce the cost and time required to develop real-time, accurate dynamic simulations of process plants and includes significant enhancements to Mimic's modeling library. Mimic v3.6 includes the release of the mineral processing object library developed in coordination with Portage Technologies.

CAD/CAM SOFTWARE

MECSOFT CORP., IRVINE, CALIF.

VisualCAD/CAM 2015 is a consolidation and enhancement of various products and solutions that MecSoft has released over the years, resulting in a powerful standalone CAD/CAM solution. This product brings under its umbrella VisualCAD as the CAD front-end and VisualCAM as a plug-in that hosts VisualMILL, VisualTURN, VisualNEST, and VisualART as modules. Each of the modules can be independently licensed and invoked inside of the VisualCAD/CAM environment.

SUBMISSIONS

Submit electronic files of new products and images by e-mail to **memag@asme.org**. Use subject line "New Products." *ME* does not test or endorse the products described here.

PRECISE, LITTLE ROBOT

COMAU, GRUGLIASCO, ITALY.

Comau's new Racer3 six-axis articulated robot combines high speeds (0.36 second for a 1 kg pick-and-place cycle) with +/- 0.02 mm repeatability. Racer3 is designed for smaller firms that want to insert robots into production with minimum fuss. It weighs in at 30 kg, with a 3 kg payload capacity and 630 mm reach. This is compact enough to move and install almost anywhere, including benches, walls, ceilings, and inclines. It has a wide and flexible work area, and can transform itself into a shape that will let it rotate at maximum speed in a crowded environment. Comau is targeting applications in assembly, material handling, machine tending, dispensing, and pick-and-place.

UNIVERSAL ROTARY ACTUATOR

SCHUNK, MORRISVILLE, N.C.

The SRM universal rotary module has internal performance shock absorbers to provide significantly higher moment of inertia capacity, as well as faster swivel times than the current, top-rated Schunk SRU-plus. Features include a large load-mounting surface and a large center bore for feeding through items like cables and hoses. Modular air feed-though and electrical feed-though versions are available. The SRM is available in three sizes ranging from size 16 to 40. Size 16 weighs 0.6 kg. Its torque is rated at 1.5 Nm, and the center hole is 10.5 mm in diameter. Size 40, 5.5 kg, has torque rated at 25 Nm and a 26 mm center hole. All three models have a repeat accuracy of 0.05 percent.

HOLLOW CORE ROTARY UNITS

JVL INDUSTRI ELEKTRONIK A/S, BIRKERØD, DENMARK.

Integrated rotary actuators are available in two table sizes, the HDCT-100 and the HDCT-130, and each with a choice of three motors—the MIS231 integrated stepper or an integrated servo motor, the MAC140 or MAC400. The HDCT-100 has a table diameter of 95 mm (3.74 in.) and a hollow core of 29 mm (1.14 in.). The HDCT-130's table diameter is 120 mm (4.72 in.) and its hollow core is 35 mm (1.38 in.). The HDCT-100 has a nominal output torque of 6.8 Nm (963 oz.-in.), maximum speed of 167 or 200 rpm (depending on the motor), and axial load of 150 N (33.7 lbs.). The HDCT-130 has a nominal output torque of 12 Nm (1,699 oz.-in.), maximum speed of 167 or 200 rpm (motor dependent), and axial load of 200 N (45 lbs.).

HIGH POWER DC MOTOR

MINNESOTA ELECTRIC TECHNOLOGY, MANKATO, MINN.

Many engineers specify brush dc motors because it is easy to control their speed and they have relatively low overall cost. Applications range from salt and sand spreaders and floor cleaning equipment to electric scooters, material shaping and handling equipment, and even baseball pitching machines. The company's new family of high-current, low-voltage dc motors features a new brush design that packs more torque and power into a 3.6-in. frame. The 12 V dc mode develops 500 W and the 24 V dc 750 W (1.0 horsepower) of continuous output at 2,400 rpm.

ASME
SETTING THE STANDARD

Training & Development

Setting the Standard for Workforce Learning Solutions

ASME TRAINING COURSES FOR ENGINEERS AND TECHNICAL PROFESSIONALS — 2015 AUTUMN

SEPTEMBER 2015 – CHICAGO, ILLINOIS, USA

MasterClass Series
Pressure Vessel & Piping Technologies at ASME B31 Code Week

MC110	Application of Piping Flexibility Analysis to ASME B31 Codes	13-14 Sep
MC125	Impact Testing and Toughness Requirements for Pressure Vessels per ASME Section VIII, Divisions 1 & 2 New!	14-15 Sep
MC104	Bases and Application of Heat Exchanger Mechanical Design Rules in Section VIII of the ASME Boiler & Pressure Vessel Code	16-17 Sep

Visit **go.asme.org/MCsept2015**

SEPT. – OCT. 2015 – LAS VEGAS, NEVADA USA

PD391	ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids ASME STANDARDS COURSE	28-29 Sep
PD445	B31 Piping Fabrication and Examination ASME STANDARDS COURSE	28-29 Sep
PD570	Geometric Dimensioning and Tolerancing Fundamentals 1 ASME STANDARDS COURSE	28-29 Sep
PD410	Detail Engineering of Piping Systems New!	28-30 Sep
PD615	BPV Code, Section III, Division 1: Class 1, 2 & 3 Piping Design ASME STANDARDS COURSE	28-30 Sep
PD763	Centrifugal Pumps: Testing, Design and Analysis New!	28-30 Sep
PD184	BPV Code, Section III, Division 1: Rules for Construction of Nuclear Facility Components ASME STANDARDS COURSE TOP SELLER	28 Sep-1 Oct
PD359	Practical Welding Technology	28 Sep-1 Oct
PD448	BPV Code, Section VIII, Division 2: Pressure Vessels ASME STANDARDS COURSE TOP SELLER	28 Sep-1 Oct
PD603	GD&T Combo Course (combines PD570 and PD561) **SAVE UP TO $825!**	28 Sep-1 Oct
PD675	ASME NQA-1 Lead Auditor Training	28 Sep-1 Oct
PD192	BPV Code, Section XI: Inservice Inspection of Nuclear Power Plant Components ASME STANDARDS COURSE	28 Sep-2 Oct
PD432	Turbo Machinery Dynamics: Design and Operation	28 Sep-2 Oct
PD561	Geometric Tolerancing Applications and Tolerance Stacks	30 Sep-1 Oct
PD621	Grade 91 and Other Creep Strength Enhanced Ferritic Steels	30 Sep-1 Oct
PD531	Leadership and Organizational Management	1-2 Oct
PD673	Design and Selection of Heat Exchangers	1-2 Oct
PD692	Communication Essentials for Engineers New!	1-2 Oct

Visit **go.asme.org/lasvegas8**

OCTOBER 2015 – MIAMI, FLORIDA USA

PD100	Introduction to the Maintenance and Inspection of Elevators and Escalators	12-13 Oct
PD475	The Engineering Manager: Engaging Today's Workforce	12-13 Oct
PD567	Design, Analysis and Fabrication of Composite Structure, Energy and Machine Applications	12-13 Oct
PD606	NQA-1 Requirements for Computer Software Used in Nuclear Facilities ASME STANDARDS COURSE	12-13 Oct
PD690	Economics of Pipe Sizing and Pump Selection	12-13 Oct
PD027	Heating, Ventilating & Air-Conditioning Systems: Sizing & Design	12-14 Oct
PD146	Flow Induced Vibration with Applications to Failure Analysis	12-14 Oct
PD467	Project Management for Engineers & Technical Professionals	12-14 Oct
PD633	Overview of Nuclear Codes and Standards for Nuclear Power Plants ASME STANDARDS COURSE	12-14 Oct

CONTINUED, OCTOBER 2015 – MIAMI, FLORIDA USA

PD674	International Business Ethics and Foreign Corrupt Practices Act	12-14 Oct
PD685	The Engineering Manager: Engaging Today's Workforce and Strategic Thinking Combo Course New! (combines PD475 and PD676) **SAVE UP TO $450!**	12-14 Oct
PD720	Layout of Process Piping Systems New!	12-14 Oct
PD620	Core Engineering Management	12-15 Oct
PD657	HVAC Systems and Chiller Performance Combo Course (combines PD027 and PD387) **SAVE UP TO $440!**	12-15 Oct
PD691	Fluid Mechanics, Piping Design, Fluid Transients and Dynamics New!	12-15 Oct
PD602	Elevator and Escalator Combo Course (combines PD100 and PD102) **SAVE UP TO $905!**	12-16 Oct
PD629	Project Management Combo Course (combines 467 and 496) **SAVE UP TO $650!**	12-16 Oct
PD681	International Business Ethics and Foreign Corrupt Practices Act Combo Course (combines PD674 and PD680) **SAVE UP TO $650!**	12-16 Oct
PD686	Layout of Process Piping Systems and Optimization of Plant Layouts Utilizing 3D CAD/CAE Systems Combo Course (combines PD720 and PD721) **SAVE UP TO $650!** New!	12-16 Oct
PD676	Strategic Thinking	14 Oct
PD102	How to Perform Elevator Inspections Using ASME A17.2 and ASME Safety Code A17.1 ASME STANDARDS COURSE	14-16 Oct
PD387	Understanding Chiller Performance, Operation and Economics	15 Oct
PD496	Preparing for the Project Management Professional Certification Exam	15-16 Oct
PD680	Understanding the Foreign Corrupt Practices Act	15-16 Oct
PD721	Optimization of Plant Layouts Utilizing 3D CAD/CAE Systems	15-16 Oct

Visit **go.asme.org/miami3**

OCTOBER 2015 – BARCELONA, SPAIN

PD442	BPV Code, Section VIII, Division 1: Design and Fabrication of Pressure Vessels ASME STANDARDS COURSE TOP SELLER	19-21 Oct
PD635	ASME NQA-1 Quality Assurance Requirements for Nuclear Facility Applications	19-21 Oct
PD645	Code, Section IX: Welding, Brazing and Fusing Qualifications	19-21 Oct
PD720	Layout of Process Piping Systems New!	19-21 Oct
PD767	Pressure Relief Devices: Design, Sizing, Construction, Inspection and Maintenance ASME STANDARDS COURSE New!	19-21 Oct
PD616	API 579 /ASME FFS-1 Fitness-for-Service Evaluation	19-22 Oct
PD643	B31.3 Process Piping Code ASME STANDARDS COURSE	19-22 Oct
PD644	Advanced Design and Construction of Nuclear Facility Components Per BPV Code, Section III ASME STANDARDS COURSE	19-22 Oct
PD443	BPV Code, Section VIII, Division 1 Combo Course ASME STANDARDS COURSE (combines PD441 & PD442) **SAVE UP TO €800!** TOP SELLER	19-23 Oct
PD686	Layout of Process Piping Systems and Optimisation of Plant Layouts Utilising 3D CAD/CAE Systems Combo Course (combines PD720 and P721) **SAVE UP TO €750!** New!	19-23 Oct
PD441	Inspections, Repairs and Alterations of Pressure Equipment ASME STANDARDS COURSE TOP SELLER	22-23 Oct
PD721	Optimisation of Plant Layouts Utilising 3D CAD/CAE Systems New!	22-23 Oct

Visit **go.asme.org/barcelona2**

- LIVE TRAINING
- eLEARNING
- IACET ACCREDITED
- CEUs/PDHs AWARDED

REGISTER NOW: North America +1.800.843.2763 / Europe +32.2.743.1543 / Middle East +971.4428.0315

OCTOBER 2015 – HOUSTON, TEXAS USA

PD539	Bolted Joints and Gasket Behavior	26-27 Oct
PD190	BPV Code, Section IX: Welding, Brazing and Fusing Qualifications ASME STANDARDS COURSE TOP SELLER	26-28 Oct
PD231	Shock and Vibration Analysis	26-28 Oct
PD268	Fracture Mechanics Approach to Life Predictions	26-28 Oct
PD370	B31.8 Gas Transmission & Distribution Piping Systems	26-28 Oct
PD395	API 579-1/ASME FFS-1 Fitness-for-Service	26-28 Oct
PD442	BPV Code, Section VIII, Division 1: Design and Fabrication of Pressure Vessels ASME STANDARDS COURSE TOP SELLER	26-28 Oct
PD619	Risk and Reliability Strategies for Optimizing Performance	26-28 Oct
PD014	ASME B31.3 Process Piping Design ASME STANDARDS COURSE	26-29 Oct
PD644	Advanced Design and Construction of Nuclear Facility Components Per BPV Code, Section III ASME STANDARDS COURSE	26-29 Oct
PD679	Selection of Pumps & Valves for Optimum System Performance	26-29 Oct
PD764	Introduction to Hydraulic Systems NEW!	26-29 Oct
PD443	BPV Code, Section VIII, Division 1 Combo Course ASME STANDARDS COURSE (combines PD441 and PD442) **SAVE UP TO $680!** TOP SELLER	26-30 Oct
PD581	B31.3 Process Piping Design, Materials, Fabrication, Examination and Testing Combo Course (combines PD014 and PD457) **SAVE UP TO $575!** ASME STANDARDS COURSE TOP SELLER	26-30 Oct
PD601	Bolting Combo Course (combines PD539, PD386 and PD577) **SAVE UP TO $1,275!**	26-30 Oct
PD386	Design of Bolted Flange Joints	28 Oct
PD766	Post Weld Heat Treatments in ASME Codes NEW!	28-29 Oct
PD441	Inspections, Repairs and Alterations of Pressure Equipment ASME STANDARDS COURSE TOP SELLER	29-30 Oct
PD575	Comprehensive Negotiating Strategies®: Engineers and Technical Professionals	29-30 Oct
PD577	Bolted Joint Assembly Principles Per PCC-1-2013 ASME STANDARDS COURSE	29-30 Oct
PD457	B31.3 Process Piping Materials Fabrication, Examination and Testing ASME STANDARDS COURSE TOP SELLER	30 Oct

Visit go.asme.org/houston8

NOVEMBER 2015 – DUBAI, UNITED ARAB EMIRATES

PD618	Root Cause Analysis Fundamentals	1-3 Nov
PD715	Principles of Welding and BPV Code, Section IX: Welding and Brazing Qualifications ASME STANDARDS COURSE	1-3 Nov
PD723	B31.4 and B31.8, Liquids and Gas Pipelines NEW!	1-3 Nov
PD726	API 579-1/ASME FFS-1 Fitness-For-Service Evaluation	1-4 Nov
PD642	ASME B31.1 Power Piping Code ASME STANDARDS COURSE	1-4 Nov
PD675	ASME NQA-1 Lead Auditor Training	1-4 Nov
PD725	BPV Code, Section VIII, Division 1: Design and Fabrication with Inspections, Repairs and Alterations of Pressure Vessels ASME STANDARDS COURSE	1-5 Nov

Visit go.asme.org/dubai5

NOVEMBER 2015 – ATLANTA, GEORGIA, USA

MasterClass Series

Pressure Vessel & Piping Technologies at ASME Boiler Code Week

MC104	Bases and Application of Heat Exchanger Mechanical Design Rules in ASME BPV Code Section VIII	1-2 Nov
MC121	Design by Analysis Requirements in ASME Boiler & Pressure Vessel Code Section VIII, Division 2	3-4 Nov
MC111	Piping Vibration Causes and Remedies - a Practical Approach	4-5 Nov
MC113	Techniques and Methods used in API 579-1/ASME FFS-1 for Advanced Fitness-For-Service (FFS) Assessments	5-6 Nov
MC127	Bases and Application of Design Requirements for High Pressure Vessels in ASME BPV Code Section VIII, Division 3 NEW!	5-6 Nov
MC117	Piping Failures - Causes and Prevention	6 Nov

Visit go.asme.org/MCnov2015

The American Society of Mechanical Engineers (ASME)

NOVEMBER 2015 – SAN DIEGO, CALIFORNIA USA

PD107	Elevator Maintenance Evaluation	9-10 Nov
PD382	How to Predict Thermal-Hydraulic Loads on Pressure Vessels and Piping	9-10 Nov
PD077	Failure Prevention, Repair and Life Extension of Piping, Vessels and Tanks ASME STANDARDS COURSE	9-11 Nov
PD146	Flow Induced Vibration with Applications to Failure Analysis	9-11 Nov
PD389	Nondestructive Examination-Applying ASME Code Requirements (BPV Code, Section V) ASME STANDARDS COURSE	9-11 Nov
PD410	Detail Engineering of Piping Systems	9-11 Nov
PD506	Effective Management of Research and Development Teams and Organizations	9-11 Nov
PD513	TRIZ: The Theory of Inventive Problem Solving	9-11 Nov
PD515	Dimensioning and Tolerancing Principles for Gages and Fixtures	9-11 Nov
PD702	Process Safety and Risk Management for Mechanical Engineers NEW!	9-11 Nov
PD359	Practical Welding Technology	9-12 Nov
PD448	BPV Code, Section VIII, Division 2: Pressure Vessels ASME STANDARDS COURSE TOP SELLER	9-12 Nov
PD013	B31.1 Power Piping Code ASME STANDARDS COURSE TOP SELLER	9-13 Nov
PD665	BPV Code, Section I: Power Boilers ASME STANDARDS COURSE	9-13 Nov

Visit go.asme.org/sandiego3

NOVEMBER 2015 – ATLANTA, GEORGIA USA

PD391	ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids ASME STANDARDS COURSE	16-17 Nov
PD449	Mechanical Tolerancing for Six Sigma	16-17 Nov
PD595	Developing a 10-Year Pump Inservice Testing Program	16-17 Nov
PD624	Two-Phase Flow and Heat Transfer	16-17 Nov
PD706	Inline Inspections for Pipelines	16-17 Nov
PD618	Root Cause Analysis Fundamentals	16-18 Nov
PD683	Probabilistic Structural Analysis, Design and Reliability-Risk Assessment	16-18 Nov
PD711	ASME NQA-1 and DOE Quality Assurance Rule 10 CFR 830 ASME STANDARDS COURSE NEW!	16-18 Nov
PD394	Seismic Design and Retrofit of Equipment and Piping	16-19 Nov
PD622	BPV Code: Plant Equipment Requirements ASME STANDARDS COURSE	16-19 Nov
PD632	Design in Codes, Standards and Regulations for Nuclear Power Plant Construction ASME STANDARDS COURSE	16-19 Nov
PD583	Pressure Relief Devices: Design, Sizing, Construction, Inspection and Maintenance ASME STANDARDS COURSE	18-20 Nov
PD596	Developing a 10-Year Valve Inservice Testing Program	18-20 Nov
PD591	Developing Conflict Resolution Best Practices	19-20 Nov

Visit go.asme.org/atlanta6

Free ASME Training & Development Autumn 2015 eCalendar Now Available

Download the FREE Autumn 2015 ASME Training & Development eCalendar listing dates and locations of Live Course offerings in North America and Europe through December 2015, as well as eLearning Courses available worldwide from a PC with Internet access, any time.

Visit:
go.asme.org/autumntraining
or scan with a smart device:

AXIAL PISTON PUMP

HAWE HYDRAULICS, CHARLOTTE, N.C.

The type V40M-028H axial piston pump is suitable for hydraulic fan controls in mobile machines. The pump will displace volumes up to 28 cm^3 per revolution and is designed for maximum operating pressure of 380 bar and peak loads of 400 bar. Optional P1R1 controller features help the pump comply with emission stipulations defined by Tier 4 Final and Euro 6 standards. The P1R1 electronic pressure controller continually adjusts the pump so the fan's cooling output is fine-tuned to the temperature of the machine's engine. It increases pressure in the event of power failure, thus protecting the engine against overheating. The pump, 5.2 in. wide and 7.2 in. long, can be mounted directly to a diesel engine. Several fans can be engaged in standard or reverse operations and run either in sequence or parallel to each other.

WASHER FOR SHAFT COLLAR

AMACOIL/UHING, ASTON, PA.

The Elasto-Ring washer is designed for use with the manufacturer's U-Clip quick-release shaft collars. The washer installs by hand with no tools required and assures easy removal of the U-Clip collar. When a U-Clip is placed on a shaft to hold a reel or core in place, the object being secured can create back pressure against the clip. The pressure may interfere with the quick release mechanism. The Elasto-Ring washer snaps onto the end of the U-Clip collar. When the U-Clip is in place, if back pressure starts to build, it is largely absorbed by the Elasto-Ring which flexes against the U-Clip collar. Elasto-Ring washers are available in the same ten sizes as U-Clip collars for use on shafts with diameters ranging from 8 mm to 35 mm.

SUBMISSIONS

Submit electronic files of new products and images by e-mail to **memag@asme.org**. Use subject line "New Products." *ME* does not test or endorse the products described here.

PURDUE UNIVERSITY

COLLEGE OF ENGINEERING
FACULTY POSITIONS IN PLASMA SCIENCE AND ENGINEERING

AS A PART OF PURDUE University's College of Engineering strategic growth plan that will add as many as 107 faculty over five years, the College of Engineering has recently named four pre-eminent teams in high-priority areas of research (http://www.purdue.edu/newsroom/releases/2014/Q4/purdue-engineering-names-2014-pre-eminent-teams.html). Low-temperature ("cold") plasma has been identified as one of the major thrust areas (https://engineering.purdue.edu/Engr/AboutUs/StrategicGrowthInitiative/Teams). THE COLLEGE OF ENGINEERING THUS invites applications for open-rank (Assistant, Associate, or Full Professor) tenure-track or tenured faculty positions in the general area of low-temperature plasma science and engineering. Successful candidates must hold a Ph.D. degree in engineering, science or a related discipline and demonstrate excellent potential for building an independent research program at the forefront of their field, as well as potential for educating and mentoring students. The successful candidates will conduct original research, advise graduate students, teach undergraduate and graduate level courses, and will perform service at the School, College and University levels. Candidates with experience working with diverse groups of students, faculty, and staff and the ability to contribute to an inclusive climate are particularly encouraged to apply.

THE COLLEGE OF ENGINEERING AT Purdue University has a strong faculty core engaged in low-temperature plasma research as well as significant interdisciplinary efforts across campus, with other academic institutions, and industrial partners. Successful candidates must have expertise and interests in sub-areas of plasma science and engineering that would complement and enhance the existing strengths within the College and are expected to collaborate with other Plasma pre-eminent team members. The appointment will be made in one or more Schools in the College of Engineering.

SUBMIT APPLICATIONS ONLINE AT HTTPS://ENGINEERING.PURDUE.EDU/ENGR/ABOUTUS/EMPLOYMENT/APPLICATIONS, including a curriculum vitae, teaching and research plans, and the contact information for at least three references. In the cover letter and/or research and teaching plans, please indicate which School within the College of Engineering you would prefer to be appointed to. For information/questions regarding applications contact the Office of Academic Affairs, College of Engineering, at coeacademicaffairs@purdue.edu. Review of applications will begin on or before September 30, 2015 and will continue until the positions are filled. A background check will be required for employment in this position.

PURDUE'S MAIN CAMPUS IS LOCATED in West Lafayette Indiana, a welcoming and diverse community with a wide variety of cultural activities, industries, and excellent schools. Purdue and the College of Engineering have a Concierge Program to assist new faculty and their partners regarding dual career needs and facilitate their relocation.

PURDUE UNIVERSITY IS AN EEO/AA employer fully committed to achieving a diverse workforce. All individuals, including minorities, women, individuals with disabilities, LGBTQ, and veterans are encouraged to apply.

PENNSTATE

1855

New Faculty Searches in Mechanical Engineering

Through strong support from the Provost and Dean, The Department of Mechanical and Nuclear Engineering at The Pennsylvania State University is pleased to announce there will be a significant growth of faculty over the next several years. In 2015/16, the Department is seeking excellent applicants to fill six tenure-track positions in ME. The areas of interest include, but are not exclusive to: advanced manufacturing and materials processing, energy systems, computational fluid dynamics, intelligent systems and sensors, autonomous systems, and other emerging areas. Applicants should have demonstrated outstanding scholarly research and teaching interests in mechanical engineering or a related field.

The Department is home to 55 faculty, 280 graduate students, and 1100 undergraduate students. The faculty conduct in excess of $25M per year of funded research across a broad spectrum of traditional and emerging areas. Penn State actively encourages and provides resources for interdisciplinary research collaboration through university-level institutes primarily focused on materials, health, and energy. In addition, many faculty in the Department work collaboratively with scientists and engineers in our Nuclear Engineering Program, the Applied Research Laboratory and the Center for Innovative Metal Processing by Direct Digital Deposition (CIMP-3D, http://www.cimp-3d.org/). The Department offers separate B.S., M.S., and Ph.D. degree programs in both mechanical engineering and nuclear engineering. The Department also offers online graduate degrees in both mechanical and nuclear engineering. Further information on the Department can be found at: http://www.mne.psu.edu/.

Qualifications for these positions include a doctorate in engineering or a related field. The successful candidates will be expected to teach courses at both the undergraduate and graduate levels, to develop an internationally-recognized externally-funded research program, and to contribute to the operation and promotion of the department, college, university, and profession through service.

Nominations and applications will be considered until the positions are filled. Screening of applicants will begin on September 15, 2015. Applicants should submit a statement of professional interests, a curriculum vitae, and the names and addresses of four references. Please submit these three items in one pdf file electronically to job 57752 at https://psu.jobs/job/57752

CAMPUS SECURITY CRIME STATISTICS: For more about safety at Penn State, and to review the Annual Security Report which contains information about crime statistics and other safety and security matters, please go to http://www.police.psu.edu/clery/ , which will also provide you with detail on how to request a hard copy of the Annual Security Report.

Penn State is an equal opportunity, affirmative action employer, and is committed to providing employment opportunities to all qualified applicants without regard to race, color, religion, age, sex, sexual orientation, gender identity, national origin, disability or protected veteran status.

Stanford | ENGINEERING
Mechanical Engineering

Faculty Opening

The Department of Mechanical Engineering at Stanford University (http://me.stanford.edu/) invites applications for a tenure-track faculty appointment at the junior level (Assistant or untenured Associate Professor). Applications will be reviewed across all disciplines of mechanical engineering. As part of recent strategic planning, the department has identified special hiring needs and opportunities in controls, robotics, manufacturing, and biomedical engineering. The winning candidate may excel in experiments, theory and modeling, computations, device fabrication, or any combination of these approaches.

An earned Ph.D., evidence of the ability to pursue a program of research, and a strong commitment to teaching are required. Successful candidates will be expected to teach courses at the undergraduate and graduate levels and to build and lead a team of graduate students in Ph.D. research.

Applications should include a curriculum vitae with a list of publications, a one-page statement each of research vision and teaching interests, and the names and addresses of five references. Please submit your application online at: http://me.stanford.edu/research/open_positions.html

The review of applications will begin on October 1, 2015. However, applications will be accepted until the position is filled.

Stanford University is an equal opportunity employer and is committed to increasing the diversity of its faculty. It welcomes nominations of and applications from women, members of minority groups, protected veterans and individuals with disabilities, as well as from others who would bring additional dimensions to the university's research, teaching and clinical missions.

UNIVERSITY OF CENTRAL FLORIDA
MECHANICAL AND AEROSPACE ENGINEERING

The University of Central Florida (UCF) announces multiple tenure / tenure track faculty positions at all ranks to be filled by the Department of Mechanical and Aerospace Engineering (MAE) in the College of Engineering and Computer Science (CECS). This hiring program is part of a comprehensive growth plan to significantly increase the faculty size. Candidates with backgrounds in any area of mechanical or aerospace engineering or related disciplines will be considered. Exceptionally well-qualified candidates will be considered for Provost Professor designation. For information about the department, please visit our website at www.mae.ucf.edu.

The MAE department offers B.S., M.S. and Ph.D. degree programs. Both BSAE and BSME programs are ABET-accredited. The MAE Department is home to 31 full-time faculty members, several adjuncts, and the Center for Advanced Turbines and Energy Research (CATER). The reputation of the department is continually growing with numerous faculty achievements including NSF CAREER awards, an ONR Young Investigator Award, and fellowships in professional societies.

Located in Orlando, FL, UCF is one of the nation's most dynamic metropolitan research universities, having been recognized as a "very high research activity" institution by the Carnegie Foundation. UCF is ranked consistently in the top 10 in the country in the impact of its patents and on the top list of "Up-and-Coming Schools" by U.S. News & World Report.

Review of applications will begin immediately and continue until the positions are filled. We expect the selected candidates will start in August 2016 or earlier.

UCF is an equal opportunity/affirmative action employer. All qualified applicants are encouraged to apply, including minorities, women, veterans and individuals with disabilities.

For more information on the positions and to apply, please visit http://www.jobswithucf.com/postings/42399.

Michigan Tech

MECHANICAL ENGINEERING-ENGINEERING MECHANICS (ME-EM)

ASSISTANT PROFESSOR POSITIONS

Michigan Technological University, Department of Mechanical Engineering-Engineering Mechanics "ME-EM" invites applications for three tenure-track faculty positions at the Assistant Professor level. Research thrust areas of interest include: advanced manufacturing/additive manufacturing, robotics, powertrain, solar energy, photovoltaic and battery technologies, computational mechanics, high flux heat transfer, microscale heat transfer, phase change heat transfer, wind energy, quality engineering, polymer processes, resilient space systems, small satellite technology, wave energy conversion, and micro/nano manufacturing and assembly.

APPLY: jobs.mtu.edu/postings/3371

For full consideration, application should be received by November 15, 2015; however, applications will be considered until the positions are filled. Only complete application packages are guaranteed full consideration. The ME-EM Department and Michigan Tech encourages minority and female applicants.

Michigan Tech is an AA/EEO educator and employer and aggressively recruits minorities, females, protected veterans and individuals with disabilities in an effort to bring greater diversity to its workers.

LEARN MORE: mtu.edu/mechanical

Mechanical, Automotive and Materials Engineering

University of Windsor

Tenure-Track Assistant Professor in the Aerospace Program

The University of Windsor, Faculty of Engineering, Department of Mechanical, Automotive and Materials Engineering (MAME) invites applications for a tenure-track faculty position at the rank of Assistant Professor in a newly established Aerospace Program commencing as early as **January 1, 2016.** This position is subject to final budgetary approval.

Located at one of Canada's major international intersections, the University of Windsor plays a leading role in the future of the region and the province of Ontario. With approximately 16, 000 students, including 1,700 students in a broad range of masters and doctoral programs, the University of Windsor is Canada's most personal comprehensive university.

MAME (www.uwindsor.ca/mame) being the largest department in the Faculty of Engineering offers a multi-faceted program that tackles real-world problems, interacts with local industry, and provides to students ample opportunities for hands-on experience. The major research areas are in design and optimization of energy conversion systems, light weight and low wear materials, and design of innovative mechanical structures and manufacturing processes.

The successful candidate is expected to teach primarily courses for our new innovative undergraduate program in Aerospace Engineering that spans over the theme of: Aerospace and airplane structures and related systems design.
Concurrently, applicants should have a research expertise and proven track record and/or industrial experience in the area of Unmanned Aerial Vehicles (UAV) design and controls. It is expected that the successful candidate will establish a dynamic externally funded research program that complements and expands our existing Mechanical and Materials Graduate programs, offer graduate courses, supervise graduate students and engage in department and university service activities. Applicants must have a doctoral degree from an aerospace engineering department or significant aerospace engineering expertise and experience, and must have or be eligible for PEng licensure. The selection will be primarily based on the applicants' potential for excellence in teaching and research.

Applications will include:
- a letter of application, including a statement of citizenship/immigration status;
- a current and detailed curriculum vitae;
- a concise statement of teaching and research interest;
- a sample of published research papers; and
- three current letters of reference forwarded directly by the referees to the Department Head.

The short-listed candidates may be invited to provide further information in support of their applications. To ensure full consideration, complete an online application at http://www.uwindsor.ca/facultypositions. Applications will be reviewed on October 31, 2015, but will be accepted until the position is filled.

Questions and Reference Letters to be sent to:
Dr. A. Sobiesiak, Department Head, Faculty of Engineering
Department of Mechanical, Automotive & Materials Engineering
University of Windsor, Ontario, Canada N9B 3P4
Phone: 519-253-3000 Ext. 2596, Email: asobies@uwindsor.ca

University of Windsor is a comprehensive research and teaching institution with more than 16,000 students. The University of Windsor is a welcoming community that is committed to equity and supports diversity in its teaching, learning, and work environments. In pursuit of the University's Employment Equity Plan, members from the designated groups (Women, Aboriginal Peoples, Visible Minorities, Persons with Disabilities, and Members of Sexual Minorities) are encouraged to apply and to self-identify. For accessibility related accommodation, please notify the Employment Coordinator (staff positions) or the Faculty Recruitment Coordinator (faculty-related positions). More general information on the University's accessibility policy can be found on the Office of Human Rights, Equity & Accessibility website. All qualified candidates are encouraged to apply; however, Canadians and permanent residents will be given priority.

Michigan Tech

MECHANICAL ENGINEERING-ENGINEERING MECHANICS (ME-EM)

BIOMECHANICS ASSISTANT PROFESSOR POSITION

Michigan Technological University, Department of Mechanical Engineering-Engineering Mechanics "ME-EM" invites applications for a tenure-track assistant professor faculty position in Biomechanics. Applicants for the position are required to have an earned doctorate in Mechanical Engineering, or a closely related field. The position is offered at the assistant professor level, however other levels may be considered for exceptional candidates. Candidates will be expected to develop externally funded research programs, engage in both undergraduate and graduate teaching, and contribute to professional service.

APPLY: jobs.mtu.edu/postings/3392

For full consideration, application should be received by November 15, 2015; however, applications will be considered until the positions are filled. Only complete application packages are guaranteed full consideration. The ME-EM Department and Michigan Tech encourages minority and female applicants.

Michigan Tech is an AA/EEO educator and employer and aggressively recruits minorities, females, protected veterans and individuals with disabilities in an effort to bring greater diversity to its workers.

LEARN MORE: mtu.edu/mechanical

POSITIONS OPEN

GEORGIA SOUTHERN UNIVERSITY'S DEPARTMENT OF MANUFACTURING ENGINEERING invites applications for **CHAIR** and **PROFESSOR OF THE DEPARTMENT OF MANUFACTURING ENGINEERING.** Reporting to the dean of the college, the chair of the Department of Manufacturing Engineering position requires administrative, some teaching, scholarship, and service responsibilities along with a terminal degree. The full text advertisement, including information about the department, faculty, and the complete position announcement with all qualifications and application instructions, is available at http://academics.georgiasouthern.edu/positions/ or http://ceit.georgiasouthern.edu/facstaff/employment. Screening of applications begins October 5, 2015, and continues until the position is filled. Georgia is an open records state. Georgia Southern is an AA/EO institution. Individuals who need reasonable accommodations under the ADA to participate in the search process should contact the Associate Provost.

Positions Open

Toyota Technological Institute

Toyota Technological Institute has openings for tenured- or tenure-track associate professor positions in the Department of Advanced Science and Technology, Faculty of Engineering. For more information, please visit: http://www.toyota-ti.ac.jp/english/employment/associate.html

POSITION: ASSOCIATE PROFESSOR (TENURED- OR TENURE-TRACK)

Research fields

1. Innovative machining technologies/ Manufacturing Engineering
Innovative machining technologies for the next generation, computer-aided manufacturing engineering, machining processes for advanced materials and manufacturing science, etc.

2. Solid mechanics
Solid mechanics including theory of elasticity and plasticity, structural mechanics, fracture mechanics, dynamics of structures and their applications.

Start date: April 2016 or at the earliest convenience

Documents:
(1) Curriculum vitae
(2) List of research activities
(3) Copies of 5 representative papers
(4) A brief description of the research activities and future plan of your research and education (within 3 pages each)
(5) Names of two references including phone numbers and e-mail addresses
(6) An application form (available on our website)

Deadline: October 31, 2015

Inquiries: Search Committee Chair
Professor Shuji Tanaka
(Phone) +81-52-809-1775
(E-mail) tanaka_mat@toyota-ti.ac.jp

The above documentation should be sent to:
Mr. Takashi Hirato
Toyota Technological Institute
2-12-1, Hisakata, Tempaku-ku
Nagoya, 468-8511 Japan
Please write "Application for (fill in the research field you would like to apply)" in red on the return envelope.

ADVERTISER INDEX

To purchase or receive information from our advertisers, go to **http://me.hotims.com**, visit the advertiser's website, or call a number listed below.

	PAGE	WEBSITE	PHONE
Accu-Mold Inc.	13	accu-mold.com	515-964-5741
ASME Insurance	C3	asmeinsurance.com/pl	800-640-7637
ASME Training & Development	88-89	go.asme.org/training	800-843-2763
ATI Industrial Automation	85	ati-ia.com/mes	919-772-0115
Bluebeam Software, Inc.	5	bluebeam.com/engineer	
Computational Dynamics (CD-Adapco)	23	cd-adapco.com	
COMSOL, Inc.	C4	comsol.com/5.1	
COMSOL, Inc. Conference	19	comsol.com/conference2015	
COMSOL, Inc. Webinar	48	http://goo.gl/G63o38	
Dynatect	9	dynatect.com	800-298-2066
Master Bond, Inc.	86	masterbond.com	201-343-8983
Newark/Element14	7	newark.com	800-463-9275
Omega Engineering, Inc.	27 & 87	omega.com	888-826-6342
Proto Labs, Inc.	C2	go.protolabs.com/ME5GJ	
Smalley Steel Ring, Inc.	90	smalley.com/getcatalog	847-719-5900
Stratasys, Ltd.	16-17	stratasysdirect.com	888-311-1017
Structural Integrity Associates, Inc.	21	structint.com/asme	877-474-7693
Tormach, Inc.	86	tormach.com/mem	
US Tsubaki	15	ustsubaki.com	
Vibration Test Systems	84	vts2000.com	330-562-5729

RECRUITMENT

CONSULTING

CONSULTING

EASTMAN COLLECTION A LANDMARK

The Technology Collection at George Eastman House in Rochester, N.Y.—the world's oldest photography museum—has been designated an ASME Historic Mechanical Engineering Landmark. The collection consists of more than 16,000 artifacts that mark the progression of photographic technology from rudimentary equipment to the digital devices of today.

Key pieces in the museum's massive collection include the full-plate daguerreotype camera, the first camera manufactured in quantity; the hand-held Kodak camera, the first successful camera to use roll film; the Edison Kinetoscope, the first motion picture device to use flexible film; the Brownie camera, which brought photography to the general public; and the Lunar Orbiter Payload camera, which photographed potential landing sites for Apollo missions.

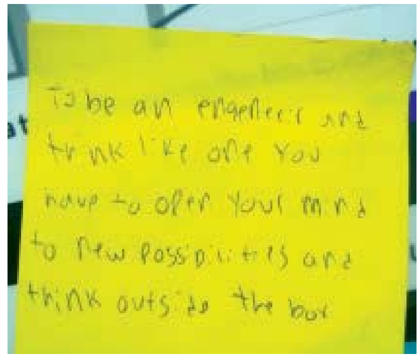
The landmark designation ceremony at the museum's Dryden Theater was hosted by ASME's Rochester Section. The ASME delegation included Past President Madiha El Mehelmy Kotb, who presented a commemorative plaque; Jack Brown, who represented the ASME History and Heritage Committee, and three leaders from the Rochester Section: Joseph Lawson, section chair; Jon Kreigel, History and Heritage chair; and Ronald Saltzman, the section's treasurer. Approximately 110 people—including museum employees and ASME volunteers and staff—attended the event. **ME**

Some of the 16,000 artifacts at ASME's newest landmark, the Technology Collection at George Eastman House, representing the development of photography. *Images: Wil Haywood, ASME*

INSPIRE PROGRAM IN 569 SCHOOLS

A year after it was launched, the ASME Inspire digital STEM education course for U.S. middle and high schools has been adopted in 569 schools—nearly twice the first-year goal set by the program's organizers.

Inspire students post their impressions of the phrase "thinking like an engineer."



The course, which aims to improve math and science literacy among young people and build their interest in engineering, is now being taught by more than 500 teachers across 39 states, with the potential to reach nearly 22,000 students.

Based on a successful pilot program that ASME tested in the Washington, D.C., aerea ASME Inspire is an online, in-class instruction tool for middle and high school students that uses gaming and simulations to teach critical technology and coding skills; spark students' interest in science, technology, engineering, and math; and inform students about careers in those fields.

The ASME Foundation is funding ASME Inspire for its first three years, ensuring that the program is available to schools across the country at no cost to school districts or taxpayers. The Foundation aims to initiate the program in at least 1,000 U.S. schools during that time period.

To mark ASME Inspire's successful first year, events were held in May at six schools where at least 100 students had successfully completed all 16 of the Inspire modules, which address such STEM-related topics as basic computer science and the real-world application of algebra. Events were held at Riverside Middle School in Evans, Ga.; Joseph Cavallaro Middle School in Brooklyn, N.Y.; Roseboro-Salemburg Middle School in Roseboro, N.C.; Sterling High School and Sam Houston High School in Houston, Texas; and Thomas Johnson Middle School in Lanham, Md.

Some of the schools are in geographical areas that ASME and the ASME Foundation are particularly interested in engaging on a deeper level, such as New York and Houston. The list also included schools that had demonstrated a clear passion for the program, as in the case of Roseboro-Salemburg Middle School, where the entire 800-student eighth grade class received certificates.

Noha El-Ghobashy, executive director of the ASME Foundation, was a featured speaker at the event in Brooklyn, where she told the students, "Each and every one of you has the ability to create, the power to recognize a problem and fix it, and the passion to make the world a better place."

Information on Inspire is available from Patti Jo Snyder, ASME's K-12 program manager, at snyderp@asme.org. **ME**

ONLINE VOTING FOR SOCIETY OFFICERS

ASME will introduce an online ballot this fall for the election of Society officers. It will replace the paper ballot that members traditionally received with the September issue of *Mechanical Engineering* magazine.

ASME members will receive an e-mail this September that includes information on how to log into the ballot page and vote for the president and members of the Board of Governors. Members without an e-mail address, and those whose e-mails get bounced back, will be sent a hard copy ballot along with online voting instructions.

Members are advised to check their ASME records to ensure that their e-mail address is up to date or to add an address if one is not on file. They can do so by going to the Membership and Benefits page on asme.org, or by contacting ASME Customer Care at (973) 882-1170 or (800) 843-2763.

Questions about the new voting procedure may also be submitted to RuthAnn Bigley, ASME Governance, by e-mail at bigleyr@asme.org. **ME**

SUPPLEMENT ON CR-MO WELD REPAIRS

ASME has released a supplement to Post Construction Standard on Repair and Testing (PCC-2) on repair welding considerations for chrome moly steel pressure vessels. The supplement provides a high-level overview of deterioration mechanisms and subsequent factors that need to be considered in developing a detailed repair, examination, and testing plan for the successful repair of Cr-Mo pressure vessels.

This Cr-Mo Welding Considerations supplement is applicable to pressure vessels for refinery, petrochemical, power generation, and other similar services.

The supplement discusses types of damage, operating conditions under which to expect damage, the specific degradation phenomena, and which materials are typically susceptible to the damage. It also includes typical considerations for weld repair.

The ASME PCC-2 Repair of Pressure Equipment and Piping with Supplement is available in both print and digital versions on ASME.org, at www.asme.org/products/codes-standards/pcc2-2015-repair-pressure-equipment-piping-(1). **ME**

BUG OFF MY GUACAMOLE

GUACAMOLE HAS BEEN POPULAR for a long time—well before there was even an orchard in Florida: The name has been handed down to us from an Aztec word that means "avocado sauce." In the U.S., football fans go through about 8 million pounds of the stuff each Super Bowl Sunday.

But in Florida, the No. 2 avocado-growing state, a deadly fungus is attacking the avocado trees. The fungus, carried by redbay ambrosia beetles, causes a vascular disease called laurel wilt; more than 90 percent of trees die within six weeks of infection.

The infection has killed about 9,000 trees in the past three years, out of approximately 700,000 trees in the state.

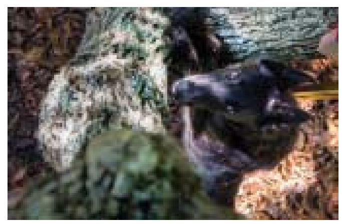
A team at Florida International University, however, has developed a detection program involving drones and dogs to help counter the spread of the fungus.

FIU provost and executive vice president Kenneth G. Furton and biological sciences professor DeEtta Mills, a forensic chemist, came up with the scheme, which uses commercially available multi-rotor helicopters to scan orchards for signs of infection. Suspect trees are then tested by trained dogs.

Ty Rozier, owner of a company called Elevated Horizons LLC, operates the drones. Each drone carries a modified Canon Sure Shot camera with filters that will capture images in the near infrared and other wavelengths. The drones are given flight plans through an iPad and, although they are automated, remain in sight of the pilot.

Multi-rotor power systems can give the drone more than 30 minutes of flight time and lift up to 10 pounds of equipment, Rozier said.

The model that is used was manufactured in 2013 by a company called Infinite Jib in Ontario, Canada. The drones can cover about 5 to 10 acres in about 15 minutes, flying above the trees between 50 and 200 feet in the air to capture data.



Once suspected trees are spotted, dogs are used to sniff out the disease pathogen.

The images recorded during the flights allow for the calculation of a "vegetation index." The object is to spot differences in chlorophyll content and densities that distinguish stressed trees from healthy trees. The data is analyzed, and once the researchers see a tree that appears stressed, they can bring in dogs trained to detect the odor of the disease pathogen.

The team has one Belgian Malinois named Cobra and two Dutch shepherds named Candy and One Betta. If the dogs find that a tree is infected, it will be removed so it does not serve as a reservoir for the pathogen.

Mills said that she and her colleagues came up with this interdisciplinary project from each of their areas of expertise. "As a team of researchers, we have a higher probability of being able to stop the spread of the disease until they can find a solution/fungicide that will stop it," she wrote in an e-mail. "The inspiration came from seeing the avocado trees dying within the growing area and knowing how the loss of this agro-industry would impact the local and national economy."

The fungus can also spread to surrounding trees via the roots, without inoculation by beetles. When a diseased tree is identified and removed, the common practice is to treat neighboring trees, if they appear healthy, with a fungicide that can prevent infection, although it is not a cure.

JAMES PERO

UAVs operated by Elevated Horizons are equipped with modified cameras.
Image: Elevated Horizons

beazley

GREAT NEWS! Thanks to our **NEW** partnership with one of the leading engineering professional liability insurance carriers, Beazley Insurance Company, Inc., you now have access to an expert resource for your firm's professional liability needs. And because of this partnership, if you are an ASME member you are eligible for a 10% premium discount* exclusively through our program.

INTRODUCING THE NEW ASME PROFESSIONAL LIABILITY PROGRAM

ASME
SETTING THE STANDARD
ASME INSURANCE PROGRAM

DESIGNED SPECIFICALLY FOR ASME

The new Professional Liability Program is offered through a proven industry leader in the engineering professional liability marketplace: Beazley is one of the top engineering insurance carriers that understands the unique risks engineers face. That's why the Professional Liability Program includes flexible policy limits and deductible options. It covers firms of all sizes as well as self-employed individuals.

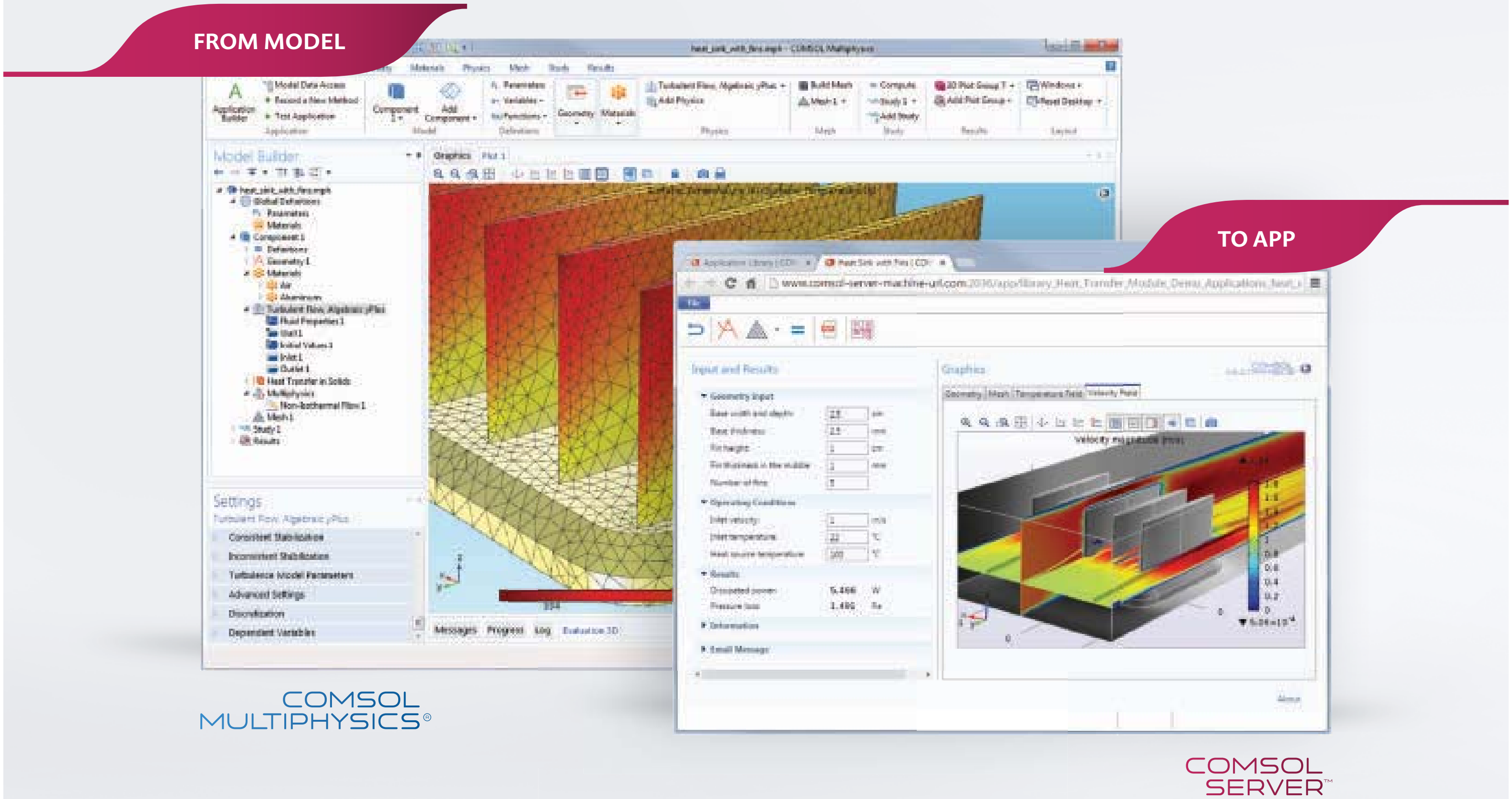
ASME MEMBER EXCLUSIVE COVERAGE BENEFITS:

- 10% premium discount* through our program
- Consent to settle enhancement
- Early resolution deductible credit

Call today at 1.800.640.7637 or visit www.asmeinsurance.com/pl

*Based on state filed minimum premium requirements.

This program is administered by Mercer Consumer, a service of Mercer Health & Benefits Administration LLC.
In CA d/b/a Mercer Health & Benefits Insurance Services LLC • CA Ins. Lic. #0G39709 AR Ins. Lic. #100102691
This plan is underwritten by Beazley Insurance Company, Inc. • CA Ins. Lic. #0G55497 WA Ins. Lic. #1298



Verify and Optimize your Designs with COMSOL Multiphysics®

NOW FEATURING APPLICATION BUILDER & COMSOL SERVER™

The Application Builder provides you with tools to easily design a custom interface for your multiphysics models. Use COMSOL Server™ to distribute your apps to colleagues and customers worldwide.

Visit comsol.com/5.1

Product Suite

› COMSOL Multiphysics®
› COMSOL Server™

ELECTRICAL
› AC/DC Module
› RF Module
› Wave Optics Module
› Ray Optics Module
› MEMS Module
› Plasma Module
› Semiconductor Module

MECHANICAL
› Heat Transfer Module
› Structural Mechanics Module
› Nonlinear Structural Materials Module
› Geomechanics Module
› Fatigue Module
› Multibody Dynamics Module
› Acoustics Module

FLUID
› CFD Module
› Mixer Module
› Microfluidics Module
› Subsurface Flow Module
› Pipe Flow Module
› Molecular Flow Module

CHEMICAL
› Chemical Reaction Engineering Module
› Batteries & Fuel Cells Module
› Electrodeposition Module
› Corrosion Module
› Electrochemistry Module

MULTIPURPOSE
› Optimization Module
› Material Library
› Particle Tracing Module

INTERFACING
› LiveLink™ *for* MATLAB®
› LiveLink™ *for* Excel®
› CAD Import Module
› Design Module
› ECAD Import Module
› LiveLink™ *for* SOLIDWORKS®
› LiveLink™ *for* Inventor®
› LiveLink™ *for* AutoCAD®
› LiveLink™ *for* Revit®
› LiveLink™ *for* PTC® Creo® Parametric™
› LiveLink™ *for* PTC® Pro/ENGINEER®
› LiveLink™ *for* Solid Edge®
› File Import *for* CATIA® V5

COMSOL