MECHANICAL ENGINEERING

Technology that moves the world

THE MAGAZINE OF ASME

No. 03 138

from FIRE to WATER

INSTEAD OF FLARING STRANDED GAS, USE IT TO HARVEST WATER FOR NEW WELLS.

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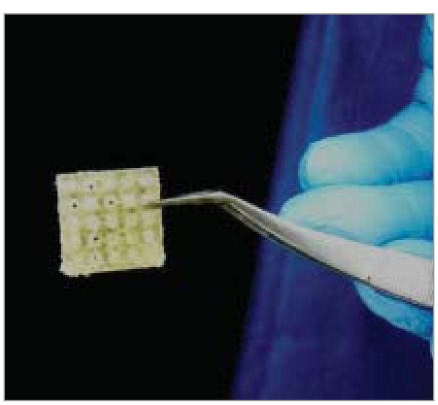
MARCH 2016

MALARIA DIAGNOSIS IN MINUTES

BIOENGINEERS AT TEXAS A&M UNIVERSITY have combined a smartphone's camera with optics to create a polarized light microscope that could be used to detect malaria. The device has the potential to rapidly diagnose malaria by providing microscopic resolution on a cellphone, with the same level of accuracy as benchtop spectroscopy. After the device is attached to the phone, the diagnosis could take just minutes using an app.



3-D PRINTING BONES

THOSE IN NEED OF BONE GRAFTS must occasionally dream of a magical machine that could make exactly what their bodies need with the push of a button. That magical machine may soon be in hospitals everywhere.

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

PALM TREES SWAY WIND TURBINE DESIGN

Wind turbines are getting larger, but new designs are needed to take the technology to greater capacities. The University of Virginia's Eric Loth is looking to the flexibility of the palm tree in designing lightweight segmented rotor blades that can morph with the wind and potentially generate up to 50 MW.

VIDEO: DEVELOPING A BETTER BATTERY

REZA SHAHBAZIAN-YASSAR, an associate professor of mechanical engineering at the University of Illinois at Chicago, has shown that zinc nanowires are effective in providing electrical conductivity, offering great promise in sodium-ion battery development.

NEXT MONTH ON ASME.ORG

VIDEO: The Multidisciplinary Nature of Bioengineering
Dr. Billy Cohn of Baylor St. Luke's Medical Center in Houston discusses the role of engineers in innovating and developing biomedical devices.

VIDEO: America Makes Advances Additive Manufacturing
John Wilczynski of America Makes talks about how academia, government, and industry can collaborate to accelerate the adoption of additive manufacturing.

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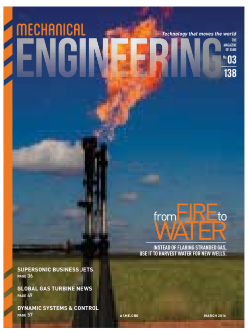

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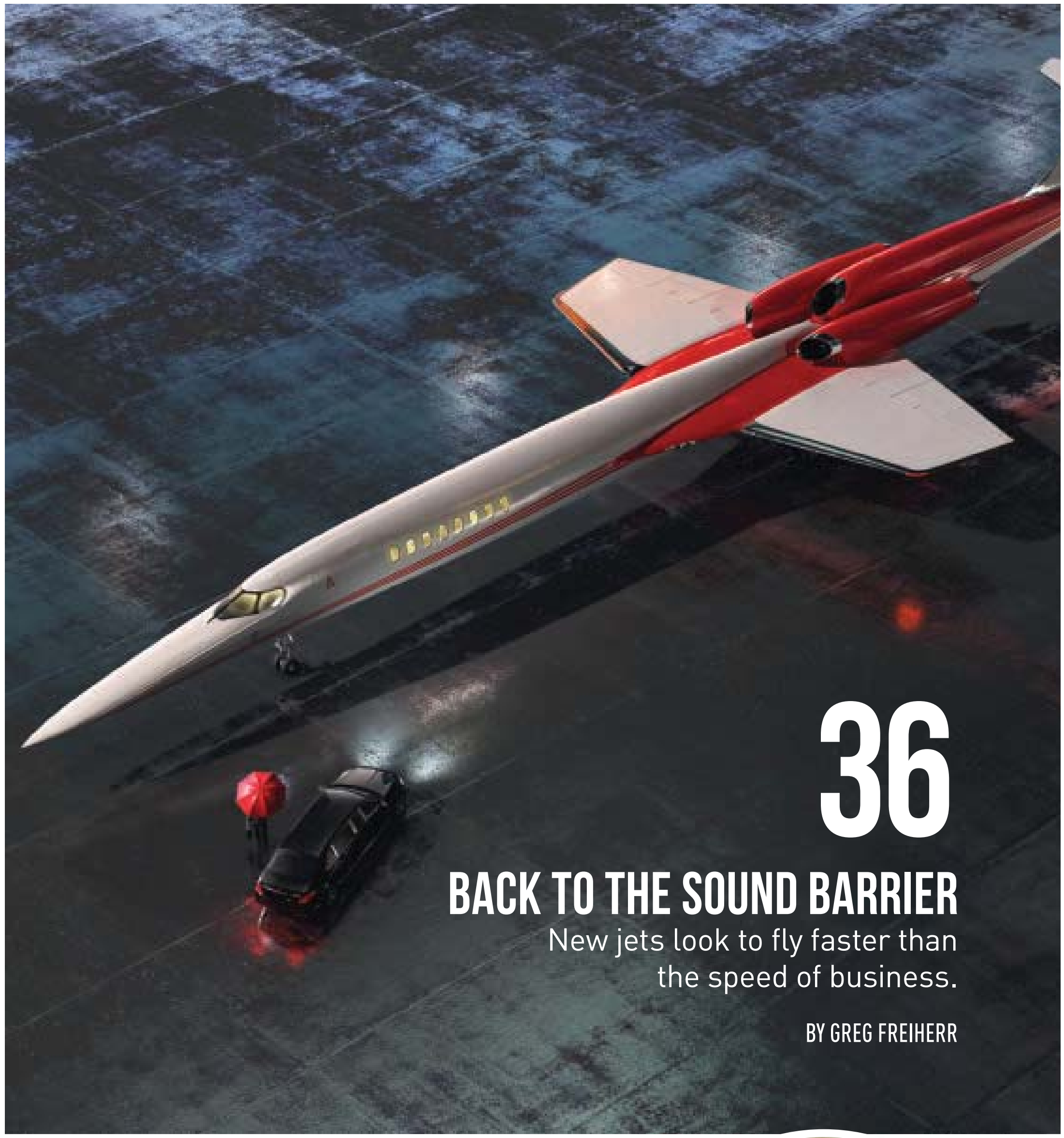

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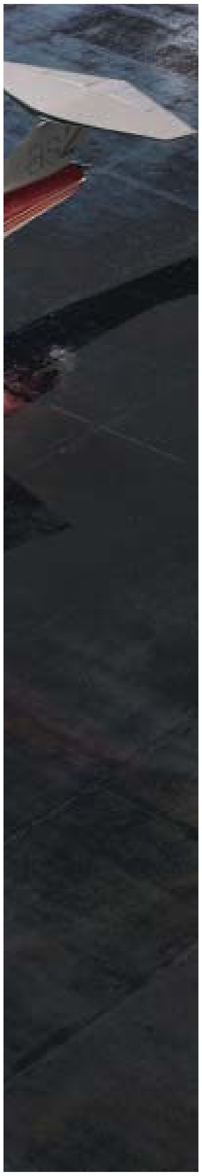

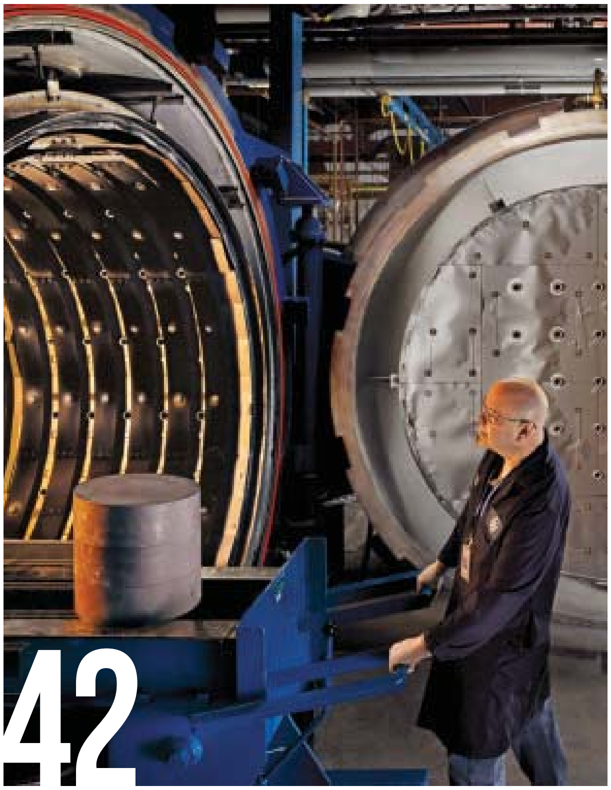

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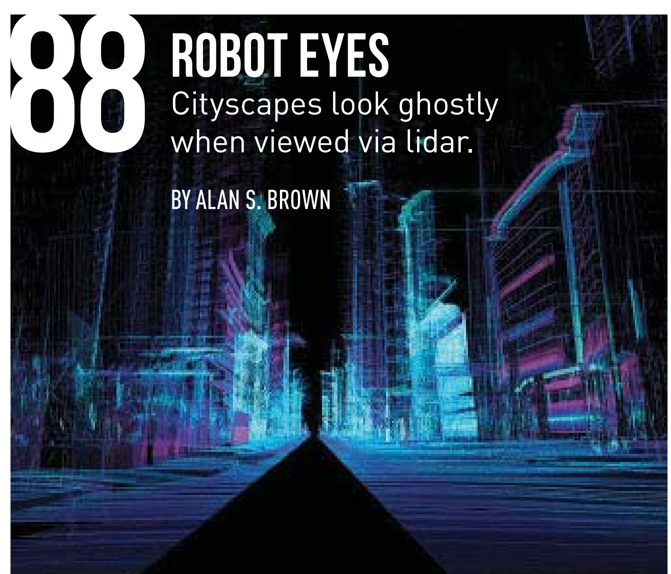

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Give me the place to stand, and I shall move the earth
—Archimedes

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John G. Falcioni
Editor-in-Chief

MASTERING THE FOURTH INDUSTRIAL REVOLUTION

Once again, I didn't make it to Davos this year. But the gusts from the snow-banked Switzerland streets could be felt all the way to where I'm sitting in New York. Davos refers to what the cognoscenti call the World Economic Forum, a yearly gathering of pols and plutocrats—an influential list of celebrities, wealthy financiers, and leaders of countries and multinational corporations. Some of the attendee names are instantly recognizable: Vladimir V. Putin, Bill Gates, and Joseph R. Biden Jr.

I couldn't tell you what happens behind closed doors during the mid-January forum, but there are always a lot of open discussions on an array of not-so-light topics, such as balancing the world's nuclear arsenal, climate change, geopolitics, and the world economy. The conversations provide great fodder for headline writers, as things occasionally go unscripted and often get testy in Davos. This year, the headline we're mostly interested in has to do with "The Fourth Industrial Revolution."

Just when we were beginning to understand the "Internet of Things," poof, along comes this new revolution. (We hardly knew you, IoT.) But in fact, the IoT is part of a suite of new technologies that includes smart machines, artificial intelligence, robotics, 3-D printing, material science, nanotechnology, and energy storage. Those technologies will synthesize with new business models to produce a new industrial revolution—an epoch more disruptive than the first three industrial revolutions.

The First Industrial Revolution mechanized production; the second one used electric power for mass production; and the third one used information technology to automate production. This fourth revolution will blur the lines between the physical, the digital, and biological realms.

As for the overall impact of the fourth revolution, opinions vary. Some at Davos worried publicly over the cooling off of the tech boom, as a recent drop in public and private valuations of technology firms suggests. But the evangelists look at technology innovation and the emerging revolution as means to secure long-term gains in efficiency and productivity and more effective supply chains, as well as bigger profit potentials. That will impact the workforce in different, if yet undetermined, ways. Certainly, it will usher in an even greater need than we have now for a knowledgeable and informed engineering workforce.

In a recent essay, Klaus Schwab, the founder and executive chairman of the World Economic Forum, said, "The Fourth Industrial Revolution has the potential to empower individuals and communities, as it creates new opportunities for economic, social, and personal development. But it also could lead to the marginalization of some groups, exacerbate inequality, create new security risks, and undermine human relationships."

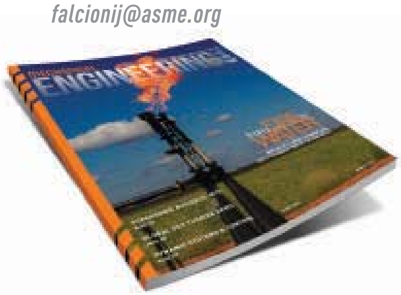
This is a sobering reminder of the heavy weight of responsibility borne on the shoulders of today's engineers and other technologists who have created this upheaval. The obligation doesn't stop with building robust new tools and processes. It also includes engaging and working with public and private sectors to manage the technologies.

To that end, Davos served as an appropriate platform to begin the conversation, at least broadly, about the implications of the Fourth Industrial Revolution on economic, social and political systems. While the ensuing debates, probably in less prominent locations, aren't likely to produce the headlines that Davos does, they are the discussions that will move the world toward a progressive and sustainable future. **ME**

FEEDBACK

How will the Fourth Industrial Revolution reshape how we live? Email me.

falcionij@asme.org



LETTERS & COMMENTS

JANUARY 2016

Reader Zurn detects bias in our coverage of ethanol.

« One reader wonders whether GM got too lean; another stresses the need to keep the U.S. manufacturing base.

POTENTIAL OF ETHANOL

To the Editor: For years, I've noticed that *ME* is negative to ethanol ("Federal Biofuel Mandate Under Fire," Tech Buzz, January 2016). To one who works in ethanol, it is extremely disappointing that a magazine representing ASME, people who strive to benefit the health and welfare of society, can so consistently ignore overwhelming positive findings from government, academia, and health organizations on the benefits of ethanol from corn. *ME* seems completely unaware of the simple fact that fiber and protein in corn, 1/3 the kernel mass, comes through the ethanol process and provides a high-value feed.

Perhaps *ME* is just lazy in its efforts to understand the ethanol industry or maybe it is politics. *ME* seems to simply drink the American Petroleum Institute Kool-Aid regarding ethanol and make it sound like burning gasoline is good for our health. I dare *ME* to write on the mileage and pollution impact if auto engines were designed for a 30 percent ethanol and premium gasoline blend.

Andrew Zurn, P.E., *Benson, Minn.*

LEAN CONCERNS

To the Editor: After reading, with great interest, the article by Gary Cowger ("All-Out Lean," January 2016), I reflected upon my experiences in R&D, design engineering, and production in the nuclear submarine world, and came away with the following thoughts:

Cowger does a good job of relating the all-out lean philosophy and "efficiencies" gained in such metrics as hours gained in value-added work and bottom-line profits. What was missing, however, was any mention of metrics that indicate either effects or changes in product safety and reliability.

I totally agree that an emphasis on vendor scheduling and quality is necessary, but the article does not convince me the example of General Motors was a successful employment of the philosophy. An emphasis on exposing and fixing problems must reach beyond immediate production line activities. In particular, the years cited by Cowger for GM were plagued by product recalls and subsequent litigation for defective parts. Ignition switches and air bags are but two prominent examples.

If safety and reliability are sacrificed for other efficiencies, the product will stand as inferior and unacceptable for the public. Additionally, incentives for honesty and integrity need to be included in the philosophy of "all-out lean," as well as accountability for the opposite behavior.

Art Spero, *Front Royal, Va.*

MAKE IT IN AMERICA

To the Editor: As a retired engineer, I have great appreciation for something in your piece on U.S. manufacturing ("All-Out Lean"). It reminded me of an observation my wise old boss (a gruff old German, who was really a "cream puff" after you got to know him) once made.

Deloitte and the Manufacturing Institute published a survey in 2011 that said, "Seventy-nine percent of Americans believe a strong manufacturing base should be a national priority."

My old boss said, "We cannot survive very long by taking in each other's laundry."

We truly do need to reestablish our position in the world as a manufacturing powerhouse. Otherwise we will end up simply taking in each other's laundry.

Bob Balhiser, *Helena, Mont.*

NET GAIN IN WATER

To the Editor: I really liked the creative approach in "Pulling Water From Thin Air" (Input Output, December 2015).

Fognet, I think, can also help in recovering vast quantities of water from cooling tower exhaust air/drift also. This can bring down drift losses significantly and help save scarce, costly water.

Akshay Harlalka, *Mumbai, India*

ENTROPIC DISMAY

To the Editor: We are dismayed about the imprecise and naïve content regarding the second law of thermodynamics, disorder, entropy, and energy in the December 2015 column ("Entropy and the Environment").

The use of disorder to explain macroscopic thermodynamics principles relating to energy and entropy is inappropriate and misleading. Statements such as "The greater the entropy, the greater the losses, waste, and environmental impact…" and that a wooden log "… contains energy that is neatly organized…" are puzzling.

Many of the environmental applications of thermodynamics in this piece miss the mark. Asserting that "Nuclear energy … creates solid waste that should be easier to contain and manage (than air pollution)" minimizes the challenges in making proper decisions about such alternatives.

Decision-making in the crucial areas of energy and environment is never a simplistic application of a single principle such as the second law, but instead involves engineering, economics, regulatory requirements, and many other considerations. The laws of thermodynamics will always prevail, but this article oversimplifies the issues.

M.J. Moran, ASME Fellow, *Ohio State University*
H.S. Shapiro, ASME Life Member, *Iowa State University*

PROVING MODELS

To the Editor: After reading, "The Cost of Emissions Cheating," (Tech Buzz, January 2016), I looked up and read the referenced article in the *Environmental Research Letters* to learn more. The underlying models (processes) used to generate the damage estimates that are the focus of that article are implied to be generally accepted and beyond question in the base article.

I've spent 30 years applying mechanical engineering principles and practices to the manufacture of automobiles and other durable goods. The basic feedback practices in manufacturing have parallels in most other engineering disciplines: Engineer a process, execute the process, measure the output of the process, and adjust the process based on those measurements.

It seems to me that this is an ideal opportunity for the purveyors of environmental research to evaluate the output of their models and to adjust them based on those measurements. This is what other engineers do as a matter of course across industry around the world.

This particular occurrence represents an anomaly relative to what previous environmental models, and the statutes they drove, predicted. Since the effects of this particular occurrence are predicted by these same environmental models to have concentrated the "damage" in a relatively few isolated geographic areas, proving the models' predictions should be relatively straightforward.

I believe that it would be well worth the environmental researchers' time to use epidemiologically sound methods to measure the actual unexpected early deaths, as well as the increases in hospitalizations, e-room visits, and respiratory diagnosis, over what the statute driving models predicted. This situation would seem to present an ideal opportunity to verify their models or, alternatively, to adjust those models to more closely reflect reality.

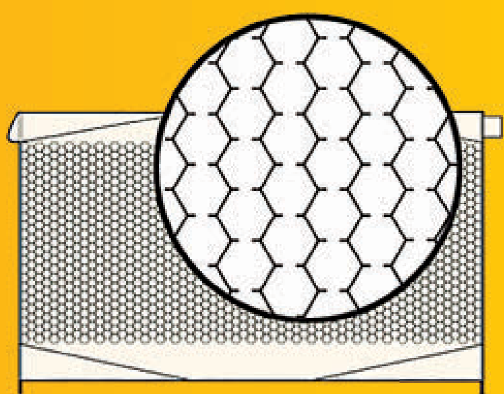
As a resident of a relatively small neighborhood that contains several of these affected vehicles, I would be much more interested in what actually happened than in what the environmentalists' models predict happened, as a result of the increased NO_x and particulates my family has been exposed to.

Robert H. Bonner, *Denver, N.C.*

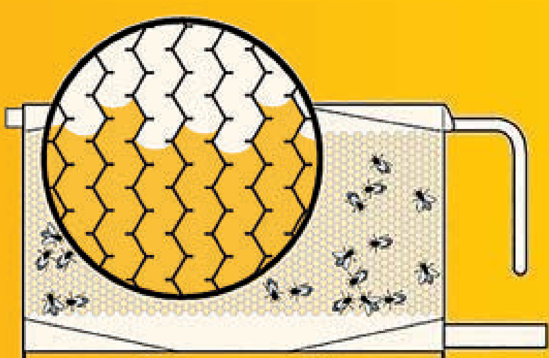
FEEDBACK Send us your letters and comments via hard copy or e-mail memag@asme.org (subject line "Letters and Comments"). Please include full name, address and phone number. We reserve the right to edit for clarity, style, and length. We regret that unpublished letters cannot be acknowledged or returned.

HONEY ON TAP

HOW DOES IT WORK?



The Flow Frame starts with partially formed cells (above). Bees complete the cells by adding wax and then fill them with honey. Once the cells are capped with wax, the honey is ready for harvesting.



To harvest, the beekeeper turns a crank to lift one side of each row of cells. That motion cracks the beeswax and turns the hexagons into a zigzag channel that runs to the bottom of the frame. Honey flows down the channel, into a trough, and out a tap at the bottom.

A NEW BEEHIVE MAKES EXTRACTING HONEY AS EASY AS TURNING A CRANK.

Engineers want to believe that if you build a better mousetrap, the world will beat a path to your door. Thanks to the Internet, the world now brings cash to jumpstart your business.

That's the experience of Stuart and Cedar Anderson, a father-and-son team from rural Australia. Via the crowd-funding site Indiegogo.com, they secured $12.5 million for a new type of beehive, one that enables beekeepers to extract honey through a tap without getting stung or upsetting bees.

Stuart Anderson, a former social worker, started a back-to-the-earth community outside Byron Bay, a town best known for surfing. Cedar, a 35-year-old musician, grew up there without TV or even a normal electrical connection.

Both Andersons were beekeepers and backyard engineers. Stuart acted as the neighborhood's handyman. Cedar pulled apart abandoned cars (they were that far into the hills) and made musical instruments from their horns. About 10 years ago, after his brother was badly stung, Cedar began looking for a better way to extract honey from a hive.

For the past 150 years, beekeepers had kept bees in boxes that held frames where the insects built their honeycombs. To remove honey, beekeepers donned protective suits, sedated the bees with smoke, and pulled out the frames. After cutting wax caps off the honeycombs, they put the frames in a spinner, extracted the honey, and returned the frame to the hive.

Cedar wanted to simplify the process, but was stuck for years trying to figure out how to remove honey from the frame's hexagonal cells. He eventually hit upon the idea of shape-changing cells.

In the Andersons' Flow Hive,

each frame consists of rows of plastic cells with gaps at the top and bottom of each hexagon. Bees complete the hexagon by patching those gaps with wax. They then fill the cells with honey.

When it comes time to harvest, the beekeeper inserts a crank. Turning it lifts one side of each row of hexagons. This cracks the beeswax used to complete the cell and turns the hexagons into a zigzag channel that runs from the top of the frame to the bottom.

Honey flows down the channel, into a trough, and out a tap at the bottom. Reversing the crank realigns the hexagons, allowing the bees to chew out the wax cap and begin depositing honey again.

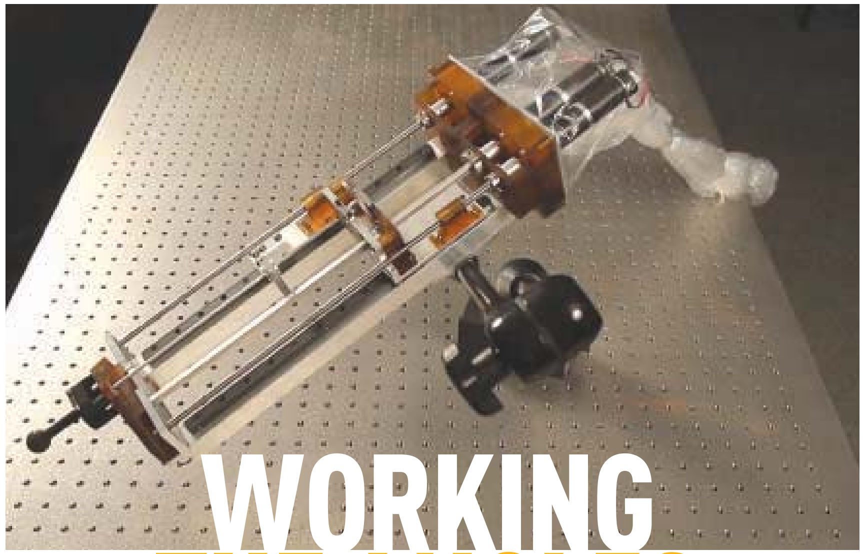
Beekeepers do not open the hive, so they are less likely to get stung. The bees remain undisturbed, and may not even realize that the fruits of their labor are being siphoned away, Cedar said.

Of course, not everyone thought it was so easy. If social media made Flow Hive a success, it also brought a wave of criticism. Some beekeepers complained that its very simplicity might reduce beekeeping to a mechanical process and promote poor practices that create health issues for nearby hives. Others fretted that it would encourage people to exploit bees instead of living with them in harmony.

The Andersons reacted by listening. Their Facebook page encourages their more than 200,000 friends to join local beekeeping clubs and learn more about bee health and safety.

In the meantime, though, the father and son are as busy as bees trying to keep up with demand. **ME**

ALAN S. BROWN



WORKING THE ANGLES

Part of what is so incredible about the body is all the angular twists and turns. While it can be awe-inspiring, it also makes it difficult for surgeons to perform surgery and limit scarring. "You think of the nose, so many parts. You need to be able to work with difficult angles," said Robert Webster, associate professor of mechanical engineering and electrical engineering at Vanderbilt University. "We've been working on trying to make that an easier challenge."

Focusing on needlescopic surgery in his career, with its microscopic incisions, the beginnings of his work go further back than one might guess.

"This work really started in grad school for me," said Webster, who also has secondary appointments at Vanderbilt University's medical school in otolaryngology, neurosurgery, and urologic surgery. "I had been working on actual needles. I was thinking about how we make needles to be used inside of soft tissue. How do we make them steer? Can we get them in open space in sinus cavities? That's where the robot ultimately comes in."

His team created a constant-curvature robot, with tubes in which an operator can telescope or change the axial direction of the robotic arm. By doing that, a tube acts as a tentacle that can elongate and bend.

The material the researchers were using was nitinol, but it had its limits in the way it was used. "We've worked on this for years, but then you realize if you could make those tubes tighter then we could make them better for surgery," he said. "You can only curve it so much until plastic deformation. We overcame this by selectively cutting the tube. We made cuts through the tip almost all the way through and that creates small hinges that help it bend."

Webster says the work could be particularly helpful for sinus surgeries. "When you think about all the nooks and crannies in the nose, that's the first application we're looking at," he says. "But longer term, you could be looking at procedures in the abdomen."

A future challenge, Webster said, will be the interface for the surgeon.

"We have the robot aspect pretty well built right now but we need to work on what we show visually," he said.

But the ultimate goal is to vastly improve what can be a difficult conversation. "You look at what the doctors go through where they have to talk to the patient about cutting a hole in them and maybe not being able to guarantee that there won't be complications," Webster said. "If we can make the conversation a more positive one, that would be an important outcome."

ERIC BUTTERMAN, ASME.ORG

SIX BEST PRACTICES FOR SUSTAINABLE ARCHITECTURE

Earthships, such as this one in Taos, N.Mex., are designed to draw water, heat, and power from their surroundings. *Photo: Earthship Biotecture*

ARCHITECTS AS FAR BACK as Vitruvius in the first century B.C. have tried to condense the best practices of their craft into a handful of points. In his *Ten Books of Architecture*, Vitruvius created some of the first building codes by way of hundreds of pages of detailed text and diagrams.

Since that time, architects from Palladio to Le Corbusier have tried to express design principles, while a few have sought to address the pressing challenges facing architects today.

Michael Reynolds and his team at Earthship Biotecture in Tres Piedras, N.M., have been working towards establishing a best practice for decades, and

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Solar Panel Installation Update
Offset Parapit 6ft. From Edge
Verify Dock Slope

continued from page 12 »

SUSTAINABLE PRACTICES

have ultimately settled upon six points that can guide architectural design towards an ecologically sustainable future.

In October 2015, I attended the Earthship Academy, a one-month, intensive training course on Earthship building methods in Taos, N.M. Half the time was spent on the construction sites of projects surrounding the campus. The other half was spent in the classroom where the six points structured the entire curriculum.

Rather than harnessing Earth and bending it into a built environment, Reynolds's six points seek to encounter the Earth so as to allow the planet to provide its abundance. This includes water from the sky, sunlight that brings life from the water, and the earth itself, which provides massive heat and building material.

Those phenomena are at the core of the six points:

1: Regulate temperature with the Earth and sun.

While many best practices call for substantial insulation and numerous ventilation standards, the fact that the Earth itself can provide consistent temperature regulation is often overlooked. The strategic use of thermal mass—included within the insulation envelope and accompanied with effective venting—can allow a livable space to remain at 72 °F year-round with no mechanical heating or cooling. While systems such as geothermal heat pumps seek to harness this energy through expensive, complicated systems, Earthships simply "dig in."

2: Harvest rainwater.

Rainwater catchment is a common strategy to lower a carbon footprint. Most often, that water is used to flush toilets. With a bit of filtering, however, rainwater can be harvested for all purposes at the scale of a modest-sized home. Using a combination of gravity, a small pump, and sand or ceramic filters, Earthship residents can use this water for washing, cooking, and drinking.

3: Generate power from renewables.

Electrical power (and the communication capabilities that come with it) is often considered a basic need. The current state of technology requires substantial government investment in antiquated centralized distribution systems. The use of local energy sources, such as solar, wind, and hydro, leapfrogs that public sector investment. Moreover, when moving to a decentralized system, the ability to choose either ac or dc power can ensure that the user can employ the most efficient form of electricity.

4: Harvest gray water for growing food.

Many cutting-edge, modern buildings use filtered gray water (water that has been used once for cleaning or cooking) to flush toilets. Such filtering systems remove valuable nutrients that can be put to good use. Planting systems not only filter the water through natural means, they do it while also filtering the air quality of the space and providing food along the way.

5: Treat sewage locally.

For thousands of years humans have been constructing sewers to move human waste underground to a single point. The waste is then either dumped into the sea or passed through enormous processing facilities—then dumped into the sea. At the local level however, black water can be a resource. By treating the sewage locally—within the property lines of a single family plot—the black water can be used to irrigate landscaping or crops, and then harmlessly returned to the environment through transpiration.

6: Build with recycled materials.

The Earthship team has identified garbage—car tires, plastic bottles, and cans—not only as great materials that can be upcycled into the construction process, but as items that are unfortunately indigenous to almost all parts of the world. Using materials that would otherwise go directly to a landfill is both responsible and cost effective when the project is designed and constructed well.

Earthship Biotecture has not only developed the theory behind each of these points through countless experimental constructions, they are also approaching a modular architectural solution that functions within each of these points and can be built anywhere.

The Global Model Earthship, as it has been called, employs all of the Earth's phenomena to bring forth the abundance that the planet provides.

The Global Model creates living space for a family of five (complete with Wi-Fi Internet, hot water, and even surround sound) that is sustainably independent and a re-creation of the true environment of man.

Vitruvius likely would have thoroughly endorsed the six points of Earthship Biotecture. After all, in Book 10 of his Ten Books, he stated "all machinery is derived from nature." ME

CHARLES NEWMAN is the Kenya Country Director for the Kounkuey Design Initiative in Nairobi.

ETHICS REVISITED

The U.S. Environmental Protection Agency alleged in 2015 that, due to a software algorithm called a defeat switch, certain Volkswagen diesel automobiles emit up to 40 times more nitrogen oxides than regulations allow. Volkswagen officials have confirmed this for 11 million vehicles worldwide and are taking steps to rectify the situation.

In a letter to the Volkswagen Group of America, the EPA wrote that the cars' electronics sense the position of the steering wheel, the vehicle speed, the duration of the engine's operation, and the barometric pressure. It went on to say that "the software was designed to track the parameters of the federal test procedure and cause emission control systems to underperform when the software determined that the vehicle was not undergoing the federal test procedure."

Isn't this something engineers would have to devise? And wouldn't it raise a question about professional ethics?

Ethics education materials are replete with examples of engineering failures. The Mars Climate Orbiter disintegrated when SI and non-SI units were jumbled. The first jet airliners, de Havilland Comets, crashed due to metal fatigue, which wasn't understood at the time. But those weren't about ethics, per se: errors in engineering are inevitable, if sometimes inexcusable, and we must learn from mistakes.

Better perspectives come from cases of poorly-designed products combined with flawed management responses or inadequate project controls. The Space Shuttle *Challenger* accident tops this list. Despite knowing the shortcomings of the O-ring joint, engineers and managers, citing previous success, allowed the *Challenger* launch to proceed. The list continues with ignition switches on GM vehicles, airbags supplied by Takata, and Ford's Pinto. All involve organizations tolerating known failure modes rather than addressing the underlying problem.

It is clear in any aftermath that something different should have been done, but management decisions are not always easy. The Pinto was neither worse in overall safety-related performance than similar vehicles, nor much worse for rear-end collision fires. Ford was acquitted in a highly publicized murder trial. (Always debatable is the acceptable level of performance.) Often, the cost of litigating and settling product liability cases is pitted against the cost of correcting a problem. When injuries or deaths are involved, however, financial considerations alone are not enough.

William Weiblen, a retired aerospace engineer, former president of ASME, and current chair of the Society's ethics committee, notes that in many of these cases engineers have warned their organizations. But upper management, often non-engineers, overrode them. "That's the sort of thing that engineers really have to be on the watch for," he said.

Engineers must understand that they are part of the decision-making process, not just advisors and implementers. Convincing positions, based on sound knowledge, must come from engineers at every level of an organization. And objective whistleblowing, as a last resort, is indeed an option.

But the Volkswagen case might be a different animal altogether. In a *New Yorker* article soon after the story broke, James Surowiecki wrote, "...this was not, as in most auto-industry scandals, a case of a defective part but rather a deliberate corporate effort to deceive consumers and regulators... " ("The Environmental Legacy of the Volkswagen Scandal," Sept. 24, 2015).

ENGINEERS MUST UNDERSTAND THAT THEY ARE PART OF THE DECISION-MAKING PROCESS, NOT JUST ADVISORS AND IMPLEMENTERS.

If engineers were involved, which seems all but certain, it would violate engineering codes of ethics. ASME's version states, "Engineers shall hold paramount the safety, health, and welfare of the public in the performance of their professional duties," and also, "Engineers shall consider environmental impact and sustainable development in the performance of their professional duties."

"It hurts all engineers when things like that happen," Weiblen said, referring to any situation in which engineers were complicit, yet stayed quiet. "That is the sort of ethical example that all engineers should learn from," he said. ME

JAMES G. SKAKOON is a retired mechanical design engineer and a frequent contributor.

NICKEL CATALYST MAY MATCH PLATINUM

Engineers have been interested for decades in polymer electrolyte membrane fuel cells because they operate at lower temperatures and pressures than other kinds of fuel cells.

Unfortunately, the most efficient PEM cells rely on platinum catalysts for the electrochemical reactions that produce current.

Now, researchers at the University of Delaware in Newark and the Beijing University of Chemical Technology have developed a catalyst made of nickel nanoparticles supported on nitrogen-doped carbon nanotubes. The new catalyst acts similarly to platinum-group metals in an alkaline electrolyte. This promises a pathway to reducing the cost of PEM fuel cells.

> The elements needed for the new catalyst are more common and much cheaper than $50-a-gram platinum.

The work, reported in *Nature Communications*, involved synthesizing nanoparticles of nickel that were then deposited on the nanotubes. The nanotubes, which were doped with atoms of nitrogen, help promote catalytic reactions as well as physically support the nanoparticles. Indeed, the interaction between the nickel nanoparticles and the nitrogen atoms were found to activate one of the catalytic processes, known as the hydrogen oxidation reaction, needed for a PEM fuel cell.

Because the elements needed for the new catalyst are more common and much cheaper than $50-a-gram platinum or other platinum-group metals, the researchers hope that they could lead to less costly PEM fuel cells—which in turn would lead one day to fuel cell-powered cars that are roughly comparable in price to standard vehicles. ME

HYPERSONIC TESTING FOR 3-D PRINTED PART

A 3-D printed combustor for a hypersonic engine recently completed a test at the NASA Langley Research Center in Hampton, Va.

According to a statement from the contractor for the project, Orbital ATK, the combustor was subjected to a variety of high-temperature, hypersonic flight conditions over the course of 20 days, including long-duration propulsion wind tunnel tests. Analysis confirms the unit met or exceeded all of the test requirements, the company said.

The test at Langley was an important challenge for Orbital ATK's new combustor design, which was produced through an additive manufacturing process known as powder-bed fusion. The company believes an acceptable part could not have been built without additive manufacturing.

"Complex geometries and assemblies that once required multiple components can be simplified to a single, more cost-effective assembly," said the company in a press release. "However, since the components are built one layer at a time, it is now possible to design features and integrated components that could not be easily cast or otherwise machined."

> "This combustor is a great example of a component that was impossible to build just a few years ago."
>
> — Pat Nolan, V.P and G.M. Orbital ATK missile products division.

Part of an engine known as a scramjet, the combustor houses and maintains stable combustion under quickly changing conditions. A goal of the testing was to see if the additively manufactured part could meet mission objectives while operating in such a volatile environment.

The company release quoted Pat Nolan, vice president and general manager of Orbital ATK's missile products division: "Additive manufacturing opens up new possibilities for our designers and engineers. This combustor is a great example of a component that was impossible to build just a few years ago. This successful test will encourage our engineers to continue to explore new designs and use these innovative tools to lower costs and decrease manufacturing time." ME

Q&A JOHN A. SWANSON

NO NAME IS MORE INTIMATELY ASSOCIATED with the widespread use of finite element analysis to predict real-world behavior than John Swanson. In 1970, he pioneered a flexible software program, ANSYS, to apply FEA to a variety of problems. Today, the company he founded is a market leader. Swanson has received the ASME President's Award and the American Association of Engineering Societies' John Fritz Medal for his achievements.

ME: What led you to found ANSYS?

J.S: I was working on the U.S. nuclear rocket program at Westinghouse, and we were analyzing the daylights out of everything. I began to see a systematic pattern to what I was doing. The structures were different, but the underlying math was the same. I thought we could develop flexible software to do those calculations. Westinghouse wanted me to stay in project management, so I started my own company.

ME: How did that work out?

J.S: Once I was out, I consulted for several Westinghouse divisions during the day, and worked on software at night. I used punch cards, and could only do two turnarounds per day. Can you imagine? Now, if there is a problem, you can correct it in seconds.

ME: ANSYS software originally required extensive training. Now, everyone uses it. How did that happen?

J.S: I liken ANSYS to an onion. At the very core is a simultaneous equation generated by finite elements from a mesh that comes from geometry created by a CAD model, and so on. Each outer layer gets closer to the engineer. Today, the software is easier and more intuitive, but you need to know engineering to use it correctly.

ME: Since retiring, you have donated millions of dollars to schools and organizations. What guides your giving?

J.S: Everything I became, someone helped me to get there. I was a National Merit Scholar. Cornell University paid for my fifth year. Westinghouse funded my Ph.D. I've heard that you can't take it with you, so now that my family is taken care of, it is time to give back.

I'm especially interested in giving to engineering students and the systems that support them. That means investing in institutes and programs that facilitate the engineering process. The product, however, is always the students. We're investing so we can build their résumés and knowledge, so they can get a job in an engineering field. My wife and I also support animal welfare organizations.

ME: You support ASME Federal Fellows, who take a year off to work in government. Why?

J.S: I have been active in ASME for a long time. If you are a mechanical engineer, that's part of the culture. I was asked to help raise funds to expand the Fellows program, so engineers can go to Washington and get some exposure to how government processes work. I think we need to make more technical expertise available to government. I hope that the better the information, the better the decisions.

ME: You have helped change the world of engineering for 40 years. How will engineering change the world in the future?

J.S: I'm very clear about that: energy. I'm trying to be agnostic about climate change, but cheap, renewable power certainly can't hurt us. I've installed solar on my house, given lectures, and invested in Green Key Village in Florida, which is building homes that generate as much energy as they use.

Some years ago, I invested in a company that promised to lower the cost of solar cells to $1 per watt, from $3. Since then, costs dropped to 52 cents and put them out of business. But I declare that a victory for renewable energy. Things are happening very quickly now. Communities are building solar sites outside town and sharing energy. We're developing better batteries, and I think their prices are going to drop dramatically in the next two to five years. That will change everything. **ME**

WHY HUMANS AREN'T WALL-CRAWLERS

If engineers perfect temporary adhesives as strong as those on gecko feet, would people wearing sticky shoes be able to scamper up sheer walls?

Researchers believe they have an answer to that question. It all depends on the ratio of surface area to body mass, according to a team of investigators at University of Cambridge in England.

"As animals increase in size, the amount of body surface area per volume decreases—an ant has a lot of surface area and very little volume, and a blue whale is mostly volume with not much surface area," explained David Labonte, a doctoral student in the Department of Zoology's Insect Biomechanics Workgroup.

"This poses a problem for larger climbing species because, when they are bigger and heavier, they need more sticking power to be able to adhere to vertical or inverted surfaces, but they have comparatively less body surface available to cover with sticky footpads," he said.

The researchers compared 225 different species—insects, frogs, lizards, and even a mammal—that use adhesive pads to climb. They found that larger animals needed relatively larger pads to manage the feat. The ratio of adhesive pads to body surface for mites were 200 times smaller than the ratio for geckos, the largest wall climbing animals.

And humans? We would need sticky footpads 80 percent as large as our total front surface area to walk straight up a wall.

Labonte believes his research on size limits will help scientists develop better bio-inspired adhesives, which are now limited to very small areas. ME

The spider cricket can leap 60 times its body length in a single bound. *Photo: Johns Hopkins*

EXPLORING THE MYSTERIES OF MOTION

ROBOTICISTS OFTEN TURN TO the natural world for inspiration, especially when it comes to motion. Functional prototypes such as butterflies and rattlesnakes already exist in nature, so the challenge becomes understanding the intricacies of their motions well enough to advance robotics design. This month we discuss two university labs that seek inspiration in nature to design robots that can walk and jump and robotic limbs that help restore normal motion for amputees.

The latest biolocomotion project at Johns Hopkins University's Flow Physics and Computation Lab involves spider crickets, which can leap a distance that is about 60 times their body length and still land on their feet. For humans, this feat would be equivalent to jumping the length of a football field.

Director Rajat Mittal and his students spent eight months using high-speed videography (400 frames per second) to study spider crickets in motion to discover how they jump so far. The film shows that, during the initial part of a jump, the crickets assume a streamlined posture that reduces drag and helps them to jump farther.

"However, shortly before reaching the apex of their jump, the crickets rapidly transition to a 'stabilization posture,'" Mittal said. "They extend all their limbs outwards and their bodies assume a nearly constant angle from the horizontal of 55 to 60 degrees."

Initial analysis suggests that this body posture is stable enough to prevent angular rotations and allows the crickets to maintain aerodynamic stability. By maintaining this orientation, the crickets land first on their powerful hind limbs, allowing them to "stick" the landing.

One application for this knowledge is the development of small jumping robots that can traverse rugged terrains, search for victims after earthquakes, or carry out other dangerous tasks.

"One of the things I enjoy the most about our research is the chance to discover beauty in the seemingly mundane world around us," said Mittal. "Everybody considers these insects as nothing more than pests, but once we start looking at them closely we find this amazing beauty and grace that evolution has imbued in them." ME

JUMPING GENIUSES

THE LAB Flow Physics and Computation Lab, Johns Hopkins University, Baltimore; Rajat Mittal, director.

OBJECTIVE Deepen our understanding of biological motion and fluid dynamics through computational modeling in order to design improved robots, medical products, and other devices.

DEVELOPMENT Learning how insects can maintain control while leaping long distances.

More than one million Americans have had a leg amputation. Many individuals walking with prostheses fear falling, and no wonder: Human limbs evolved to walk over uneven terrain and recover instantaneously from trips and shoves. Artificial limbs do not come close.

Hartmut Geyer, director of the Legged Systems Group at Carnegie Mellon University, hopes to close the gap between the natural and the artificial by developing robotic limbs that mimic human reflexes and dexterity.

"The modeling suggests that reflex-like control of the knee joint would enable it to recover from trips and other disturbances that might otherwise lead to a stumble or fall," said Steve Collins, associate professor of mechanical engineering and robotics, who works closely with Geyer on wearable robots. "My laboratory is developing a prosthetic knee emulator system to test these strategies with above-knee amputees in laboratory experiments."

This emulator lets researchers test prosthetic legs and control systems. *Photo: Carnegie Mellon*

Based on prior emulators, Collins expects the tethered prosthesis his team develops will be exceptionally responsive and lightweight, allowing for very precise testing. The team will also develop prosthesis and exoskeleton emulators for other joints and incorporate additional degrees of actuation. Their near-term goal is to create a complete lower-limb system.

MORE NATURAL PROSTHETICS

THE LAB Legged Systems Group, Robotics Institute, School of Computer Science, Carnegie Mellon University, Pittsburgh; Hartmut Geyer, director.

OBJECTIVE Improve quality of life for people who need prosthetics by developing advanced robotics to assist, replace, or restore physical capabilities.

DEVELOPMENT Developing control strategies for robotic limbs that mimic human reflexes and dexterity while running and turning.

Geyer hopes his control strategies will lead to the development of advanced prosthetics to help above-knee amputees. Their lack of knee joints prevents them from shifting their weight quickly when they stumble. Robotic systems with control systems that provide very rapid feedback could help them maintain balance and control as they walk, even over bumpy ground.

"Being involved in robotics research to help improve the quality of life for people who depend on technology to assist, replace, or restore their physical capabilities is a truly rewarding experience," said Geyer. "It is also an exciting area of research for mechanical engineers who have a strong interest in multidisciplinary approaches to solving engineering challenges." ME

MARK CRAWFORD is a geologist and independent writer based in Madison, Wis.

"WE WERE FEARING THAT there would be a hard landing in China, but almost everybody here at Davos now feels that it is not going to be a hard landing. We are going to see an evolution, not a hard landing, and a move towards sustainable growth."

Christine Lagarde, managing director of the International Monetary Fund, as quoted by the The Financial Express (India) *on January 23, 2016.*

TOYOTA INVESTS $1 BILLION IN AI, ROBOTICS

TOYOTA WILL INVEST $1 billion over the next five years in artificial intelligence, autonomous vehicles, and robot development through a new research subsidiary, the Toyota Research Institute, the company recently announced.

The move firmly plants Toyota's flag in home robots as well as autonomous vehicles.

"It is entirely possible that robots will become for today's Toyota what the car

Gill Pratt (left), CEO of the Toyota Research Institute, with Toyota Motor Corp. president Akio Toyoda.
Photo: Toyota

industry was when Toyota made looms," said Gill Pratt, TRI's CEO, referring to what was then a textile machinery company's decision to begin making automobiles in 1933.

Toyota has put together an impressive team of researchers. Pratt, for example, led DARPA's high-risk Robotics Challenge, which culminated in June 2015, when three robots successfully removed debris, found and closed a valve on a leaky pipe, and connected a fire hose in a simulated nuclear accident.

Pratt brought two DARPA program managers to Toyota with him, as well as James Kuffner, former head of Google Robotics—Cloud Computing. TRI's advisory board includes iRobot and Rethink Robotics founder Rodney Brooks and Facebook AI director Yann LeCun.

Toyota previously announced that it will devote $50 million over five years to AI and robotics research at Stanford University and Massachusetts Institute of Technology. TRI plans to locate its first two facilities within walking distance of both universities.

Pratt has set an ambitious course for the new enterprise. He argues that today's autonomous systems only handle a limited range of speeds, weather conditions, street complexity, and traffic.

"What has been collectively accomplished has been relatively easy because most driving is easy," Pratt said. "Where we need autonomy to help us is when the driving is difficult. And it's this hard part that we intend to address."

While society might tolerate human error, Pratt said, it expects machines to be always alert and nearly perfect. Pratt's goal is to create cars that are "incapable of causing a crash," and that can transport seniors and people with special needs. He also plans to leverage those advances to create what he calls "products for indoor mobility," though he left open whether that might include exoskeletons, smart wheelchairs, or other types of service robots.

Intriguingly, Pratt hopes to use advances in AI and machine learning to accelerate scientific discovery in materials science.

Some of the projects TRI hopes to fund could have far reaching consequences. With Toyota funding, Stanford will launch a project called "Uncertainty on Uncertainty" to create generalized software to handle unanticipated events an autonomous car has never seen before.

An MIT project, "The Car Can Explain," will enable autonomous cars to explain why they took unexpected actions. That way, passengers can be sure their cars are working in their best interest. **ME**

CELLULAR PLASTICS IN AIRCRAFT

BY CARROL C. SACHS, CONSULTING ENGINEER, NORTH HOLLYWOOD, CALIF.

A consultant in plastics applications 70 years ago explored the use and manufacture of lightweight materials to reinforce aircraft structures.

The design and fabrication requirements of high-performance military airplanes have repeatedly undergone basic changes in the airframe or load-carrying structure. With the advent of the stressed-skin type of structure, the old phenomenon of compression-buckling took on a new significance. As stronger light metals became available, the skin gages were repeatedly reduced until failure by compression-buckling became of first-order importance to the aeronautical engineer. One of the immediate steps which could be taken to alleviate skin-buckling was to provide periodically spaced stiffeners. ...

Where weight is an important factor in performance, as in airplane design, there is obviously a limit to the number of stiffeners which are practical. Another method o f stabilizing the skins of airplanes against compression-buckling is through the adhesive attachment of a supporting core of rigid cellular plastic of low specific gravity. ...

The oldest form of blowing agent is that of using a solid which will yield a gas. Probably the best classical example of this type of blowing is in the baking of biscuits or cakes. Either sodium carbonate or bicarbonate may be used, since both yield carbon-dioxide gas upon decomposition. ...

All of the common thermoplastics may be converted into cellular materials by means of the carbonate blowing agents. Among these may be included cellulose acetate and acetate butyrate, the vinyl esters and ethers, styrene, acrylates and methacrylates, and ethyl cellulose. Vinyl-acetal and vinyl-chloride cellular boards have been produced in England. ...

Cellular boards of the various plastics can be attached adhesively to high-strength skins on either face. It might be pointed out that the entire fuselage of the "Mosquito" bomber consisted of such a sandwich, i.e., a balsa-wood core separating aircraft spruce skins. Among the various adhesives used to bond skins to core, furane resins are outstanding. **ME**

LOOKING BACK

Plastics were in the introductory stage as structural material for aircraft when this article was published in March 1946.

NOVEL COMPOSITIONS

In the same month that Carrol Sachs discussed structural properties of plastics, an inventor working for Devoe and Raynolds Co., Sylvan Owen Greenlee, applied for a patent. Issued in 1950, patent 2,521,911 covered "phenol-aldehyde and epoxide resin compositions." It marked the commercial launch of epoxy, a key ingredient in composite polymer materials currently used in aerospace, automotive, and other demanding applications.

A majority of the Boeing 787 Dreamliner, including the one-piece barrel sections of its fuselage, is made of composite materials. *Photo: Boeing*

USING STRAIN TO READ DNA

Strain gauges measure such physical properties as flexing in a material or changes in pressure. But geneticists may soon use a new type of strain sensor to sequence DNA faster and cheaper than anything they now have in their labs. The approach could make it more economical to sequence the genomes of individuals to match medicines to patients or to link crime-scene evidence to perpetrators.

The spiraling double strands of DNA have a ladder-like structure. The rungs on the ladder consist of bound pairs of compounds: cytosine and guanine or thymine and adenine. Conventional DNA sequencing involves breaking the ladder rungs to form an individual strand, then copying, labeling, and reassembling pieces of DNA to read the genetic information.

For 20 years, researchers have tried pulling DNA strands through porous materials and reading the electrical charges on the molecule as they pass. That works, but the signal has been too weak to read accurately.

A new proposal, based on a simulation created by a team of researchers from the National Institute of Standards and Technology in Gaithersburg, Md., and University of Groningen in the Netherlands, puts an interesting twist on this.

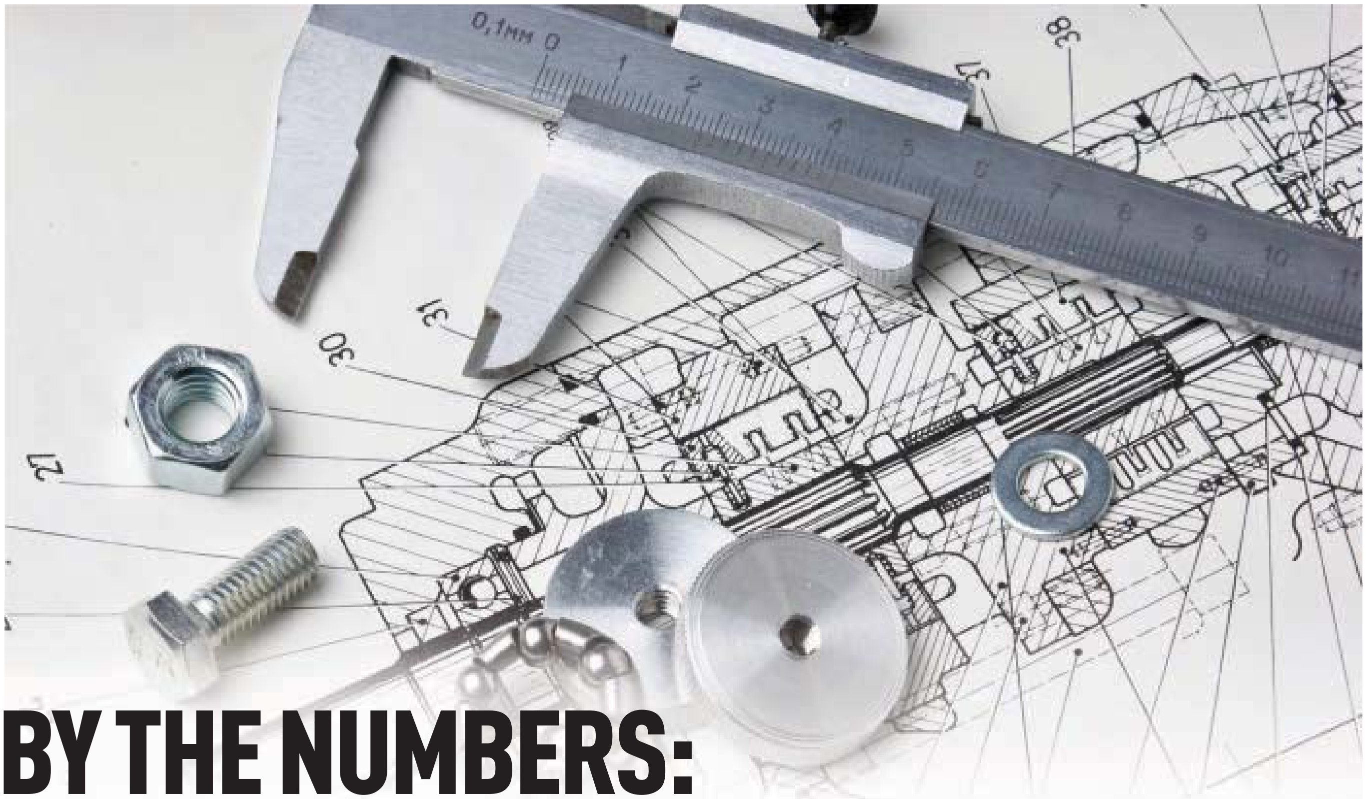
The concept starts with drilling pores in graphene, an atomically thin sheet of carbon that can convert mechanical strain to current. Chemists then would attach several of the same DNA base compounds, such as cytosine, to the pore.

Pulling a single strand of DNA through the pore would cause the strand to stick briefly every time a guanine passed by and bound to the cytosine. That stick-and-break action creates a strain that the graphene turns into electrical current.

According to a simulation by the group led by NIST's Alex Smolyanitsky, that current is large enough to read accurately.

Stacking four graphene sensors, one for each base, on top of each, could enable a device to read an entire strand of DNA. The researchers believe that four independent readings of a single strand could achieve 99.99 percent accuracy.

Other than the step of attaching DNA base compounds to the nanopore, every other component of the proposed sensor has been demonstrated experimentally. ME



BY THE NUMBERS: WHO HIRES THE MEs?

A 10-YEAR PROJECTION FOR MECHANICAL ENGINEERING EMPLOYMENT HAS SOME UPS AND DOWNS, BUT GAINS OUTNUMBER LOSSES.

A forecast from the Department of Labor shows mechanical engineering employment holding its own through 2024—growing a little more than engineering jobs overall and only a bit more slowly than overall job growth in the United States.

The U.S. Bureau of Labor Statistics predicts that mechanical engineering employment in the U.S. will total 290,000 jobs in 2024. That's 5.3 percent more than the 277,500 jobs that the agency counted in 2014.

That compares with a predicted 7 percent increase in all jobs and a 4 percent increase in all engineering jobs.

The most significant growth is predicted in the area of professional, scientific, and technical services as companies continue to contract work. This category of employment had 87,000 jobs in 2014 representing 31.5 percent of the ME profession. The BLS forecasts a 16.8 percent increase to 102,100 jobs in 2024, accounting for 35 percent of jobs.

$83,060

2014 MEDIAN SALARY FOR MECHANICAL ENGINEERS, MORE THAN DOUBLE THE MEDIAN FOR ALL U.S. JOBS.

Within that category, jobs identified specifically as "mechanical engineering services" are expected to grow almost 23 percent to 65,000 in 2024 and to constitute more than 22 percent of total ME employment.

The agency also predicts a 13 percent increase to 288,600 jobs in mining, quarrying, and oil and gas extraction.

Mechanical engineering jobs in other fields are also expected to show double-digit increases, although from smaller bases. The BLS predicts employment in construction, for example, will grow almost 14 percent from 3,700 to 4,200 jobs.

Manufacturing is still expected to be the leading employer of mechanical engineers in 2024, when it may account for 46.2 percent of the profession, but overall the field is expected to show a small decline. Manufacturing companies employed almost half the MEs working in the U.S. in 2014, some 136,800 people. The BLS expects U.S. manufacturers to employ 134,900 mechanical engineers in 2024, 1.4 percent fewer than in 2014.

The median salary for mechanical engineers in 2014 was $83,060, about $5,000 less than the median for all engineers, but more than double the median for all U.S. jobs.

More information, including the full table with a line-by-line breakdown of mechanical engineering jobs, can be found online at http://tinyurl.com/MechEngOutlook. ME

LEADING EMPLOYERS IN 2014

SECTOR	% OF ENGINEERING JOBS
Engineering services	19
Machinery manufacturing	15
Computer and electronic product manufacturing	7
R&D in the physical,engineering, and life sciences	6
Aerospace product and parts manufacturing	6

MECHANICAL ENGINEERING JOBS: NOW AND IN 2024

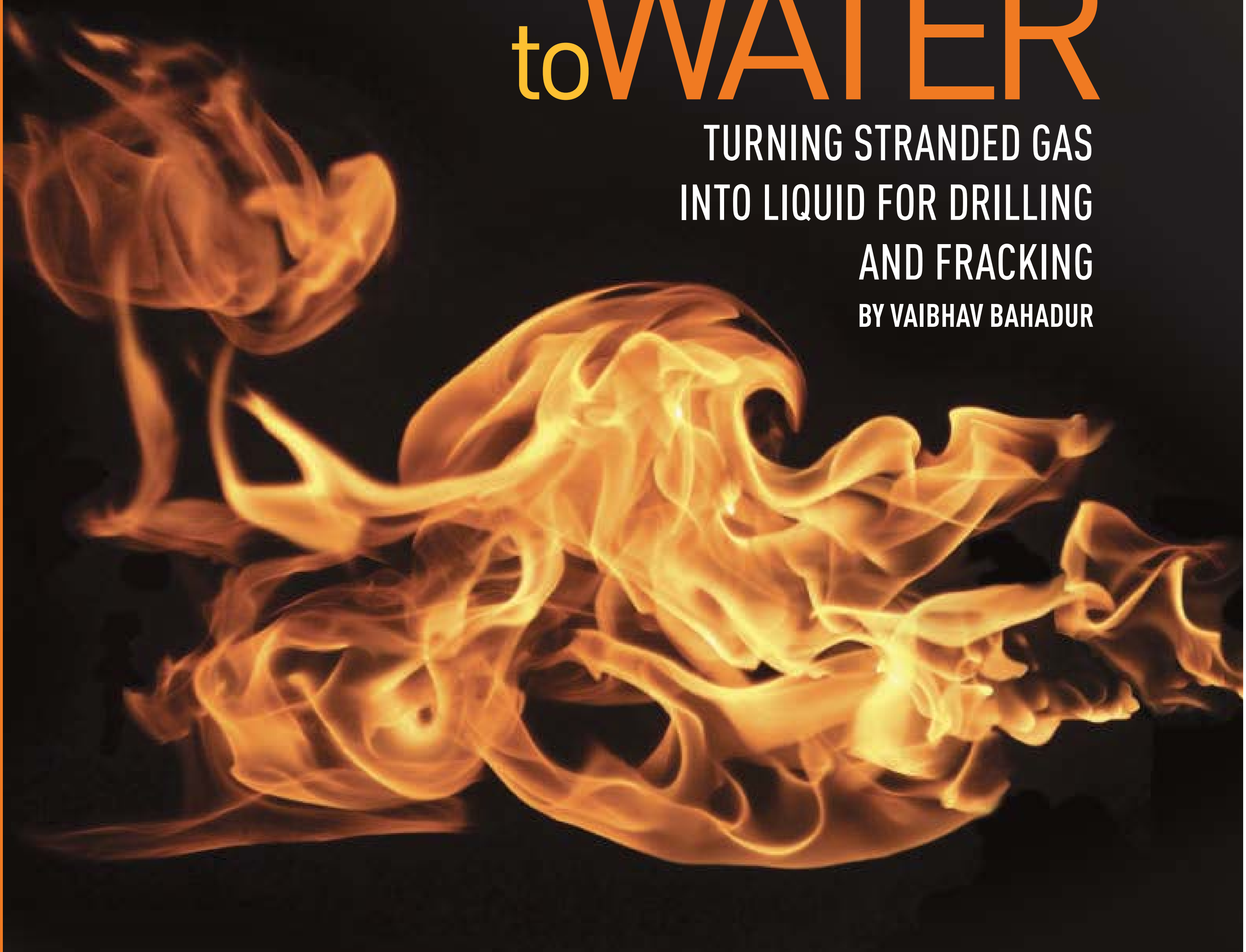
	2014		2024		
TITLE	EMPLOYMENT*	% OF OCCUPATION	EMPLOYMENT*	% OF OCCUPATION	% CHANGE
TOTAL EMPLOYMENT	277.5	100.0	292.1	100.0	5.3
SELF-EMPLOYED WORKERS	*3.4*	*1.2*	*3.5*	*1.2*	*2.5*
WAGE AND SALARY EMPLOYMENT	*274.0*	*98.8*	*288.6*	*98.8*	*5.3*
Mining, quarrying, and oil and gas extraction	2.4	0.9	2.7	0.9	13.2
Utilities	1.5	0.5	1.3	0.5	-9.5
Construction	3.7	1.3	4.2	1.4	13.9
Manufacturing	136.8	49.3	134.9	46.2	-1.4
Wholesale trade	7.8	2.8	8.3	2.8	6.3
Professional, scientific, and technical services	87.4	31.5	102.1	35.0	16.8
Engineering services (subset)	*52.9*	*19.1*	*65.0*	*22.2*	*22.8*
Management of companies and enterprises	7.6	2.7	8.0	2.7	5.0
Administrative and support and waste management and remediation services	7.4	2.7	8.3	2.8	12.6
Educational services; state, local, and private	1.5	0.5	1.6	0.5	5.2
Federal government	12.4	4.5	11.2	3.8	-9.6
State and local government, excluding education and hospitals	1.7	0.6	1.8	0.6	4.5
All other wage and salary employment	3.8	1.5	4.2	1.6	10.5

**Employment (in thousands) Numbers may not total due to rounding.*

from FIRE to WATER

TURNING STRANDED GAS INTO LIQUID FOR DRILLING AND FRACKING

BY VAIBHAV BAHADUR



Even with the recent crash in prices, oil production from unconventional formations, such as shale or tight sandstone, has transformed the industry.

Since 2008, when U.S. crude oil production was 1,830 million barrels (lower than any year since 1947), the country has become the largest petroleum producer in the world, with production in the 12 months through October 2015 at an amazing 3,412 million barrels.

The combination of horizontal drilling and hydraulic fracturing gets the credit for most of that increase.

But the so-called fracking revolution has had a downside, which is not well known to the general public: the increasing cost of water for oilfield operations. According to data from the Interstate Oil and Gas Compact Commission and the Ground Water Protection Council, while the drilling of an average well requires about 250,000 gallons of fresh water, the hydraulic fracturing of a well is much more water-intensive, averaging about 2.5 million gallons water per well.

Much of this hydraulic fracturing activity happens in regions with acute water shortages. Some 48 percent of U.S. wells are located in extreme water stress areas, where more than 80 percent available ground and surface water is already allocated for such uses as agriculture, power generation, and human consumption. Several oil-producing states expect added stress on limited water supplies from future population increase.

The Eagle Ford formation in south Texas is considered ground zero for fracking-related water issues. There are thousands of wells in the Eagle Ford region, and they consume water at a rate about double the national average. Compounding the problem is that 98 percent of the wells there are in areas with at least medium water stress, and 28 percent are in extreme stress areas.

It makes sense that there would be a scramble for water in south Texas, but surprisingly, water is also a bottleneck in the Bakken, despite its location in the wet and cold climate of North Dakota.

There, the challenges are attributed to a lack of access points, limited storage depots, and permitting restrictions. In oil and gas production regions as diverse as the Marcellus in Pennsylvania and the Monterey in California, water issues are a big concern.

Total water costs for a fracked well can reach 15 cents per gallon, which works out to as much as $2 per barrel of oil produced.

These water challenges are starting to significantly affect the bottom lines of oil producers, particularly in the current low-price environment. Treatment and reuse of flowback and produced water is a promising option, but is associated with high water treatment costs. Freshwater supply for fracking has rapidly become a multibillion dollar business with several leading oilfield services companies getting in the game. Freshwater procurement can cost up to 3 cents per gallon in some areas. The real wallet drainer, however, is transportation which can cost as much as 12 cents per gallon. Total water costs can therefore reach as much as 15 cents per gallon, which works out to $6 per barrel of water or as much as $2 per barrel of oil produced.

It isn't just the direct cost to oil producers. Trucks are the workhorse of water transportation and trucking distances can be huge. Trucks bring along the expected problems of traffic, road damage, noise, and accidents, which make for unhappy communities.

While obtaining water is a headache for drillers, they also have at their disposal the means for providing their own water. A technology known as atmospheric water harvesting can wring moisture from humid air at a surprisingly rapid rate. And though the technology has a reputation for being energy-intensive, oil production sites often have on hand fuel that they can't use—and indeed, simply burn (flare) off.

By harnessing natural gas that is now often just flared off, oil producers could eliminate a large fraction of their water needs.

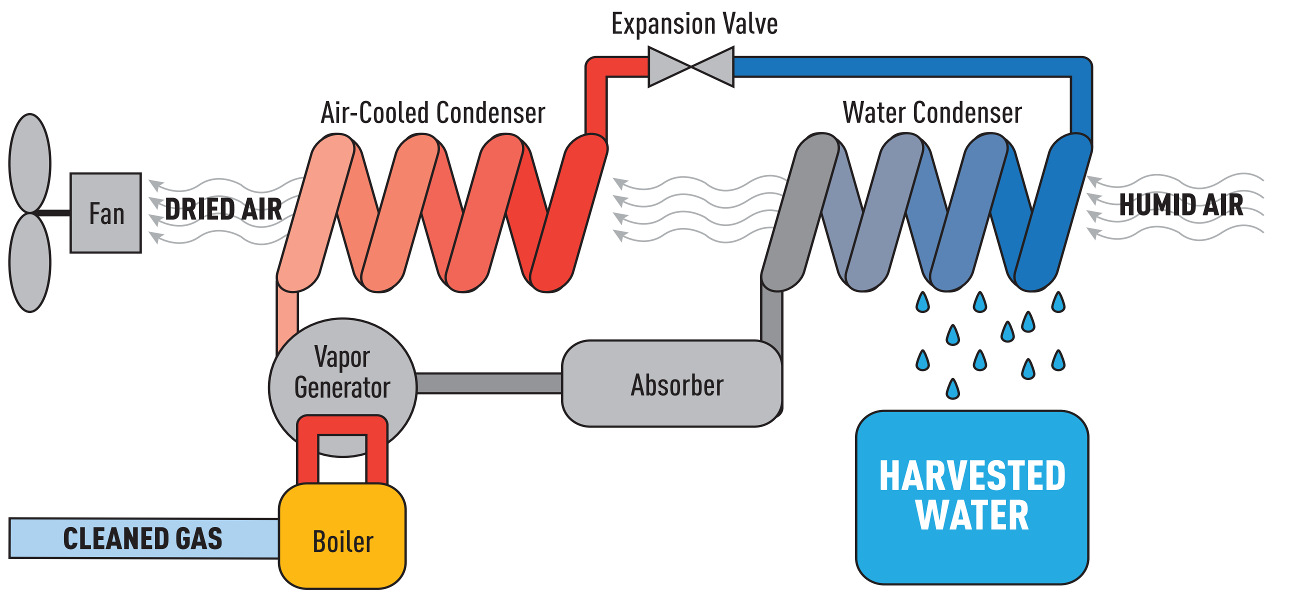
WASTE AND OPPORTUNITY

Flaring is a big problem in its own right. While oil spills and refinery explosions get widespread media coverage, flaring often manages to stay below the media radar, despite having severe negative consequences in terms of pollution and constituting an enormous waste of energy.

The extent of the problem can be seen from satellite images of the Earth's night side: flared gas creates bright gashes in sparsely settled areas from Northern Africa to North Dakota. About 140 billion cubic meters of natural gas was flared worldwide in 2012, which is the latest year for which figures are available. That is 4 percent of global production or 20 percent of gas consumption in the United States. By any yardstick this is an enormous waste of energy, and would be valued at over $50 billion at today's natural gas prices. Flaring also accounts for more than 1 percent of global carbon emissions.

The U.S. has seen a rapid increase in the amount of gas being flared, and now the country is the fifth largest flarer in the world, behind Russia, Nigeria, Iran, and Iraq.

Some 40 percent of the flaring in the U.S. occurs in North Dakota, where it is estimated that a third of the gas produced is flared, since the Bakken is primarily an oil play with gas having a marginal value. Certain Bakken producers flare



Flared gas-powered vapor absorption cycle for atmospheric water harvesting: The water condenser draws moisture from the air; a secondary liquid absorbs the evaporated refrigerant; a gas-powered boiler heats the solution to release the refrigerant as high-pressure vapor. The vapor condenses, expands through a valve, and the cycle repeats.

more than three-quarters of the gas produced. In Texas, the second-place flaring state, development of the Eagle Ford Shale increased flaring by 400 percent from 2009 to 2012. Eagle Ford now accounts for 54 percent of the flaring in Texas despite having only 3 percent of the state's wells.

One reason that both the Bakken and the Eagle Ford fields produce so much wasted gas is the wide employment there of hydraulic fracturing. After fracturing and completing a new oil well, there is an initial burst of natural gas, like the gas that fizzes out when you pop a soda can. Most oil wells in these regions do not have the infrastructure in place to utilize or capture this gas, and flaring remains the only practical solution to dispose it off.

Other factors promote flaring as an option. Texas producers, for instance, do not pay royalties or taxes on flared gas, and there are no restrictions on flaring in North Dakota in the first year, when most of the flaring actually happens. Recent rules in North Dakota require producers to have gas capture plans for new fields, but it is doubtful that regulations alone will reduce flaring, since more than half of flaring in North Dakota is from wells already connected to gas-gathering infrastructure.

Flaring is a big missed opportunity for producers. The biggest reason for producers to sell oil and burn gas is that gas has a much lower value than oil. But there are innovations that utilize flared gas to create value.

WRINGING WATER FROM AIR

Flared gas has been used for onsite electricity generation; however, this requires sufficient onsite demand or access to the grid. Extraction of natural gas liquids (NGLs) from the gas stream is another option that is practiced in some places. Reinjection of gas to the reservoir provides another alternative to flaring, but increases the cost of the project. More recent efforts have studied the use of flared gas to treat the flowback water that follows fracking.

While the emergence of such technologies is encouraging, the solutions involve expensive infrastructure which often reduces the economic advantage of flared gas utilization projects.

Water, on the other hand, is a bottleneck to oil extraction and is increasingly more valuable than electricity or NGLs. And it turns out that there is a means to use flared gas to create water right at the production site.

The solution is called atmospheric water harvesting, or AWH. The idea is to tap the enormous freshwater reservoir in humid air by condensing moisture on chilled surfaces using a refrigeration cycle, similar to what happens in an air conditioner or a dehumidifier. This can be done even in places that receive very little rainfall.

Much like a refrigerator, however, the AWH process is very energy-intensive. Indeed, the cost of energy has been the deal breaker for industrial-scale AWH. Over the last decade, for instance, several electric-powered AWH units have been developed that are capable of harvesting hundreds of gallons of water per day. But the cost of the harvested water is more than 20 cents per gallon, which makes such harvesters impractical for industrial scale operation.

For each well fracked with AWH water, 450 truck roundtrips are eliminated—reducing traffic, pollution, and accidents.

But electricity isn't the only way to power refrigeration cycles. In places where electricity is unreliable or prohibitively expensive, propane or kerosene-powered refrigerators are available. Similarly, a large-scale AWH system can be run using gas (or some other energy source, such as sunlight or wind).

In a natural gas-powered vapor absorption refrigerator, cooling is generated by evaporating a suitable refrigerant in a bundle of tubes called an evaporator. The evaporated refrigerant is then absorbed by a secondary liquid. The refrigerant-saturated solution is then heated in the vapor generator to release the refrigerant as high-pressure vapor. This vapor condenses in the air-cooled condenser, and the cycle continues.

Natural gas from the wellhead that might otherwise be flared off can be fed to a boiler (after treatment in a gas conditioning module). The steam generated in the boiler can then be used to release the refrigerant in the vapor generator of the refrigeration cycle.

Vapor absorption-powered AWH has advantages over other refrigeration options, such as vapor compression and desiccant dehumidification. Calculations indicate that cooling via vapor absorption yields more water than competing technologies, because of the higher cooling capacity generated per unit of gas burnt. An important advantage is that, at the wellhead, the gas is essentially free.

The amount of water that can be expected to be harvested depends on flaring rates and the ambient weather. The average flaring rate per well in the Eagle Ford is 9,600 cubic meters per day; for the Bakken, it is 5,500 cubic meters per day. Employing that gas to run AWH units instead of simply flaring it could yield as much as 30,000 gallons of fresh water per day from a single well in the Eagle Ford. From the Bakken, that figure is 18,000 gallons. Such harvest rates are possible from the gas that gushes out of a newly fracked well. Gas production declines in the weeks and months after a new well comes online. The decline rates vary a lot and are not well reported, which makes it challenging to predict the water production over time. In all, about 2 billion and 4 billion gallons water (about 10 percent and 66 percent of total water consumption) can be harvested annually from all the gas flared in the Eagle Ford and Bakken respectively.

What can that water be used for? While many oilfield operations require water, the two most important ones are drilling and hydraulic fracturing. At more than 50 locations in the Bakken (which flare more than 34,000 cubic meters per day), the water required to drill a new well can be provided onsite using flared gas in just three days. The water required to frack a new well can be met in three weeks. Those numbers suggest that with proper planning, AWH can supply a significant fraction of the water required to develop additional wells at existing sites. All told, 22,000 wells can be drilled or 2,200 wells can be fracked from the water produced annually by using flared gas in North Dakota and Texas.

THE FIRE TO FIGHT FLARING

The benefits of onsite water harvesting go beyond reduced water costs. For each well that is fracked with AWH water, 450 truck roundtrips are eliminated. My research estimates that using harvested water can eliminate 7 million truck roundtrips annually in Texas and North Dakota. There are many other soft benefits in the form of goodwill generated in local rural communities due to reduced traffic, pollution, and accidents.

Despite the strong case for flared gas-based AWH, there are still challenges to be overcome before this technology can be deployed. For instance, in order to make the technology economically viable, the AWH system has to be made compact to the point that it can be mounted on a semi-trailer. Portability is critical, since flaring is a temporary situation and the equipment needs to be relocated where it is needed.

The systems that are the most cumbersome are the water condenser and the air-cooled heat exchanger, both of which are bulky configurations of metal tubes and plates. Researchers are working to increase the performance of the condensers by coating the condenser tubes with water-shedding superhydrophobic materials, which drain the condensed water and can increase the thermal performance by a factor of ten.

Similarly, there are multiple R&D efforts targeted at developing compact, lightweight air-cooled condensers. Notably, the Advanced Research Projects Agency-Energy has a specific program on this effort. The good news is that large-scale refrigeration systems of the required tonnage are already available. Ongoing R&D efforts across the nation will provide solutions that make this technology more viable than it is today.

Looking beyond the United States, AWH can benefit oil producing regions such as the Middle East and portions of Africa which flare large volumes of gas, face perpetual water crises, and have year-round high humidity. The technology can also be positioned as an alternative to desalination in humid places with high flaring rates, but which lack brackish water sources that could be treated.

In an era when natural gas prices have remained stubbornly low, employing this technology in parched countries could be a means to provide a new market for natural gas.

"Keep burning gas, but to create water" sounds like a business-as-usual message to an industry that is traditionally slow to change. It remains to be seen if industry has the fire to fight flaring with water. ME

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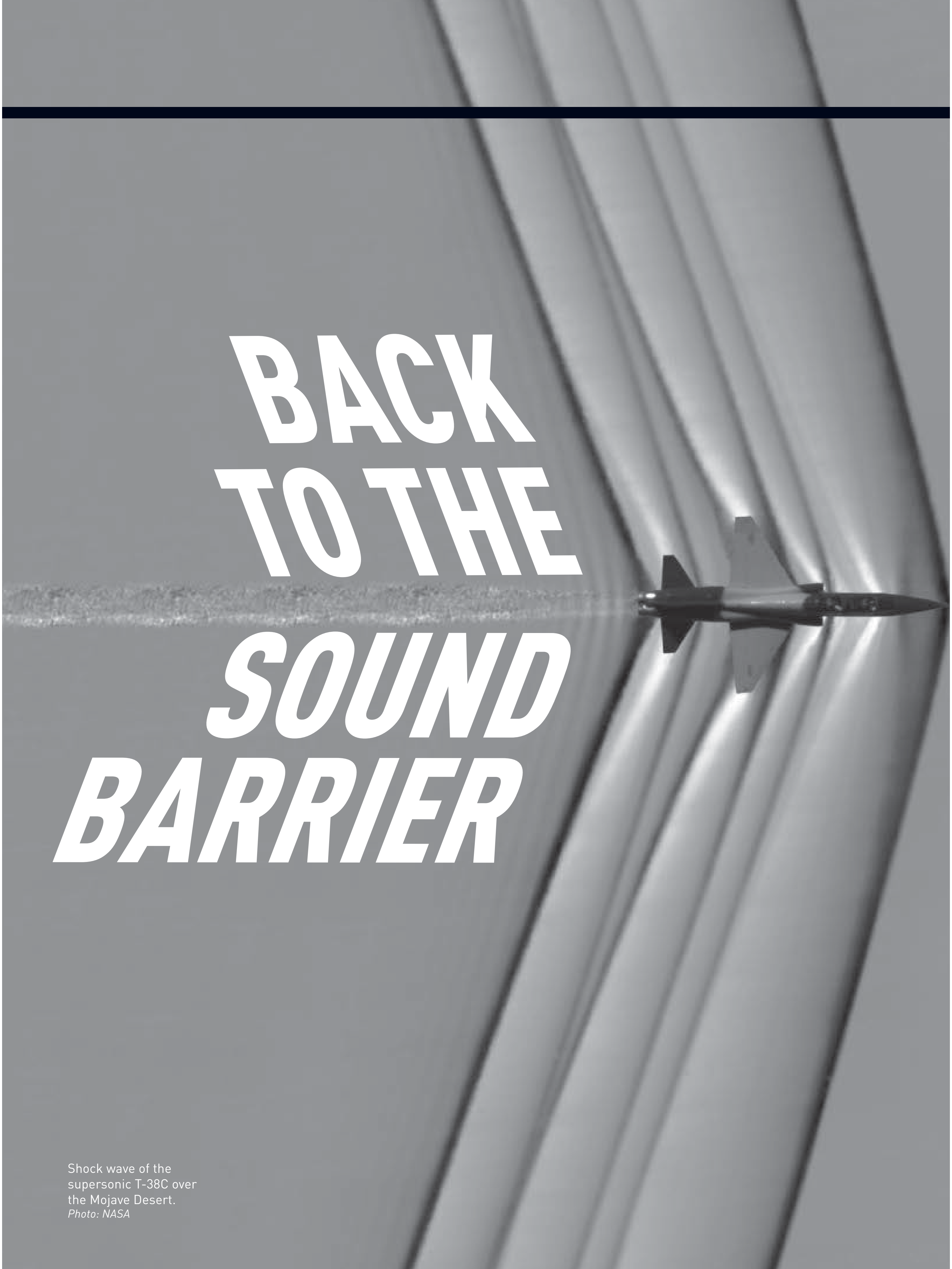
BACK TO THE SOUND BARRIER



Shock wave of the supersonic T-38C over the Mojave Desert.
Photo: NASA

The market for supersonic business jets such as the AS2 is expected to be only about 30 per year. *Illustration: Aerion Corp.*

BUSINESS JETS RACE FOR THE SUPERSONIC PRIZE

BY GREG FREIHERR

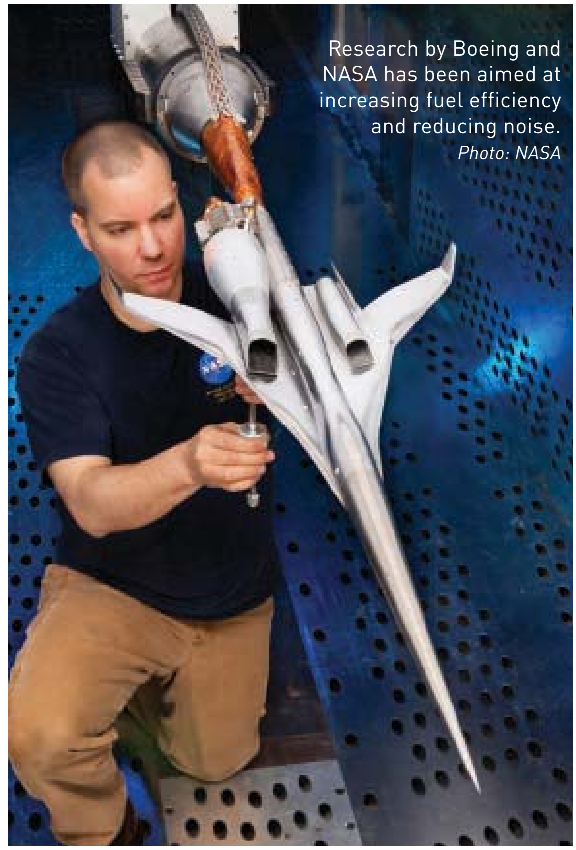
Last September, a delegation of executives from Airbus Defence and Space, the European aerospace consortium, spent four days in the offices of Reno-based Aerion Corp. Though the companies had been partners for more than a year, this was the first time senior engineers and project managers from both companies had met to discuss their joint development, a business jet called the AS2. Executives and managers from the two companies reviewed the engineering on every structure and system on plane.

If all goes as planned, in 2023 business travelers be able to board an AS2 and fly faster than the speed of sound.

"It showed us the great progress we had made in one year of collaborative effort and set a clear path for our next steps," said Aerion's CEO, Doug Nichols, who described the effort as the "only supersonic program to have shifted into the aircraft development program phase."

It will be Aerion's job to build the business jet. Airbus, a premier manufacturer of commercial aircraft, will be a "tier-one supplier of aerostructures," Nichols said. Airbus is already providing Aerion with design tools, as well as advising the company "in a number of engineering and program management areas."

The partnership will bear fruit with the first supersonic flight of its AS2 business jet in 2021, Aerion spokesman Jeff Miller said. He



Research by Boeing and NASA has been aimed at increasing fuel efficiency and reducing noise.
Photo: NASA

said the company expects certification and entry into service in 2023.

The Aerion-Airbus partnership is one of a half dozen or so ventures looking into supersonic transports. Among them is Spike Aerospace, whose slick artist renderings show an 18-passenger business jet that company founder Vik Kachoria promises will one day cruise at Mach 1.6. Spike is targeting 2018 for the first supersonic test flight of a “rudimentary, proof of concept” prototype and 2022 for delivery of its first production model, Kachoria said.

The schedule is “very aggressive, very ambitious,” he said. “But we also recognize that our investors have a time horizon.”

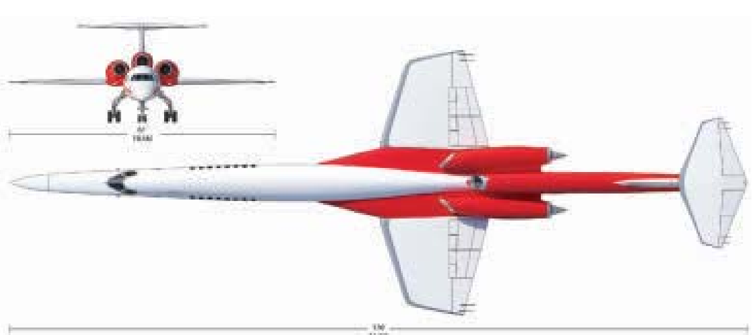
Gulfstream, which makes the G650 Flexjet, a leading business jet, has conducted supersonic research, but has not publicly discussed plans for a supersonic aircraft since the early 1990s. Its former partner, Russian aircraft maker Sukhoi, however, may still be interested, having displayed a model of a supersonic business jet two years ago at a Moscow air show.

Dassault Aviation, the French maker of business jets and military fighters, showed interest in the late 1990s, but has said little since.

Dark horses with a declared interest in developing supersonic business jets are Reaction Engines and Supersonic Aerospace International.

Although Reaction Engines focuses primarily on propulsion, the company claims to have designed two airframes, one capable of Mach 5, another of suborbital flight.

The CEO of Supersonic Aerospace is J. Michael Paulson, who has said that he wants to carry on the vision of his father, Allen Paulson, the one-time



owner and CEO of Gulfstream who, before his death in 2000, worked with Lockheed Martin to design a supersonic business jet.

Two aerospace goliaths with supersonic transport programs, Lockheed Martin and Boeing, are decidedly old school. The N+2 design by Lockheed Martin would seat 80 passengers; the Boeing ICON-II would seat 120.

Their designs have a place in the past but not the future, according to Richard L. Aboulafia, vice president of analysis at the Teal Group, an aerospace and defense consulting company. The chief reason is that their designs would require public subsidies to operate.

"The Concorde-size SST will never ever happen again," he said. "The good old days of taxpayers generously giving billions of dollars to rich people have become passé."

The Concorde, which last carried passengers in October 2003, was first conceived in the 1950s. The French and British governments paid Aérospatiale (whose assets were acquired by Airbus) and the British Aircraft Corp. billions of dollars to develop and build the Concorde, then provided subsidies to Air France and British Airways to operate the planes. The Concorde existed in "a moment in time when technology was funded by the state without any thought to earning money," Aboulafia said.

Current efforts to return civilians to faster than sound travel are all privately funded.

ROOM FOR ONE

Aerion's 12-seat tri-engine AS2, unveiled in spring 2014, is designed to have a range up to 5,000 nautical miles; reach 51,000 feet; and cruise at speeds between Mach 1.2 and Mach 1.6. About the time it is ready to fly commercially, possibly as early as 2023, the market could support annual sales of 30 supersonic business jets, according to Aboulafia. That's enough volume for one provider.

"But it has to be just one player," he said. "If it's two, they are going to lose their shirts."

With fewer passengers, business jets would be far smaller than the Concorde. Along with improvements in design and engineering and the use of lighter materials, they promise improved performance and increased range. This makes for an economically viable supersonic transport with a price in the range of $120 million per plane, according to Aerion.

This stratospheric price—about twice that of a Gulfstream G650—won't be hard to swallow. Aboulafia said interest in top-end business jets "has exploded in the last couple of decades, not only in terms of total demand but in what people will pay."

The market may be willing, but the next generation of SSTs must meet several technical challenges to get off the ground. Supersonic business jets will have to combine a powerful engine with a fuel-efficient design; demonstrate low emissions, especially at high altitudes where the ozone layer is vulnerable; and abide by tough airport noise standards.

An even bigger concern, say many in the aerospace industry, is what they believe led to the downfall of the Concorde: a ban on civilian supersonic travel over land and territorial waters. This ban, enacted in the mid-1970s by the Federal Aviation Administration and stretched around the globe by international regulators, limited demand for the Concorde to airlines with ocean routes.

Aerion, on the other hand, contends that fuel efficiency is more important than reducing sonic

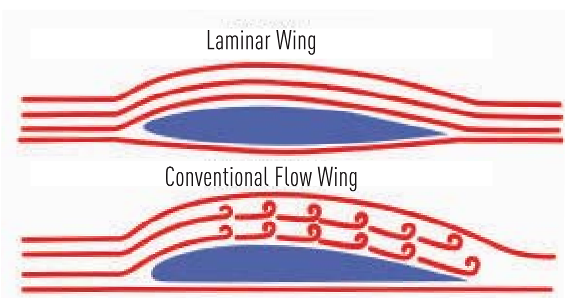
The AS2 business jet: Aerion and Airbus hope to have it in the air by 2021,

NASA and Lockheed Martin have been exploring a variety of options for quieting sonic booms. This artist's conception of the N+2 concept shows a vehicle shaped to reduce sonic shockwaves and reduce drag. *Image: NASA/Lockheed Martin*

booms. Aerion's market surveys have documented demand for a "not everywhere" supersonic business jet that would fly efficiently at subsonic speeds over land and supersonically over oceans.

To achieve those efficiencies, Aerion relies on what it calls natural laminar flow, said Richard Tracy, the company's chief technology officer. It protects the boundary layer, the thin sheet of air that flows over the skin of the airframe. Increasing speed can disrupt this layer and increase drag.

Natural laminar flow, which smooths the boundary layer, requires an unconventional wing design. A cross-section of a conventional wing looks like the top half of an elongated teardrop, with a flat bottom and a curved top that tapers toward the rear. Aerion's natural laminar flow wing looks like a complete teardrop, with tapering curves on both top and bottom.



This design breaks from 100 years of aviation history. It is what has put Aerion on the map.

"As our investor Bob Bass likes to say, laminar flow and the tools for designing and optimizing the aircraft design to achieve it is really our secret sauce," Tracy said.

The impact of natural laminar flow is immediately visible in the AS2's design. In conventional subsonic aircraft, wingspan roughly equals fuselage length. Aerion's SST design calls for a long, thin fuselage with stubby thin wings. In fact, it resembles the Starfighter 104, a 1950s high-performance combat aircraft.

"The Starfighter actually can generate laminar flow and NASA did some tests back in the late 1950s with Neil Armstrong flying the plane," Tracy said. "We were pleased to find that it [laminar flow] happened before, but we found those reports after we had settled on our wing shape."

Unlike the AS2's stubby wings, the delta wings that characterize competitors' designs are "swept" to minimize drag at supersonic speeds. Natural laminar flow, leveraged in the AS2 design, reduces drag at supersonic speeds, as well as at subsonic, thereby improving fuel efficiency and range, Tracy said. The jet will also be able to cruise efficiently just below the speed of sound, at Mach 0.95 to 0.96.

And that just might be necessary.

BUSTING THE BOOMS

In its Strategic Implementation Plan, released in 2015, NASA states that "the viability of commercial supersonic service depends on permissible supersonic flight over land."

The wording of the Federal Aviation Administration's ban on supersonic flight actually gives SST boosters hope. FAA prohibits jets from exceeding the speed of sound *except* when such operations will *not* cause a "measurable sonic boom overpressure to reach the surface." NASA has been working with corporate partners to tame sonic booms for decades, refining low-boom technologies as it hatches plans to research how much boom is too much for the American public.

To further its studies, NASA photographed the formation of shockwaves at the nose, wings, and fuselage. These shockwaves appear as the aircraft nears Mach 1 and are fully developed as the aircraft reaches Mach 1.2, according to Peter Coen, project manager for the NASA commercial supersonic technology project.

"To reduce the boom you want the shockwaves to be as equal in strength as possible and spaced fairly evenly along the length of the airplane," Coen said.

In one of the more interesting tests, performed in 2006 and 2007 in collaboration with Gulfstream, NASA gauged the effect of a telescoping device called the "Quiet Spike." Like the nose of a supersonic Pinocchio, it extended and retracted. In a NASA wind tunnel test, changes in length and diameter produced a more even set of shockwaves that could reduce sonic booming. Researchers also flight-tested the device on a NASA F-15B for stability.

Since then, NASA has discovered other ways to reduce sonic booms. "We have been able to achieve similar types of shockwave control by shaping the fore body of the airplane," Coen said. "Our new designs have a series of subtle 'steps' in area growth that produce small shocks that do not coalesce."

Low-boom innovations might keep the noise to about 70 decibels, according to Coen, about a third quieter than Concorde-created booms. Such sonic "thuds" might not be much of a problem in cities, he said, but they could be a problem in rural America, especially in the quiet of national parks. NASA hopes to have a better handle on what the American public will accept after exposing people on the ground to sonic booms and then surveying them about their opinions. Controlled boom tests could take place in the next few years.

"There are always going to be people who find any noise unacceptable," Coen said. "It will be up to the regulators to decide where to draw the line."

Meanwhile, Aerion is building an aircraft that can operate efficiently within today's regulatory framework.

"That is the most sensible starting point for introducing a new generation of supersonic aircraft," Miller said. "Without clear regulatory definition, manufacturers lack sufficient guidance for designing a low-boom supersonic jet."

Also on the noise front, supersonic business jets will have to meet restrictions applying to take-off and landing. Aerion claims it will achieve airport noise levels as quiet as the quietest business jets today, adhering to what are known as Stage 4 noise standards.

The AS2 will also be able to land on standard runways at just 120 knots.

To get off the ground, a supersonic business jet needs a high-performance engine. Unfortunately, that engine does not exist. Reaction Engines says it has a design, but not a working model. Several years ago, Aerion had settled on a design built around two Pratt & Whitney JT8D engines, off-the-shelf models that propelled Boeing 727 and MD-80 jetliners. But the JT8D has since been phased out of production. Jet engines built for combat aircraft are too inefficient for supersonic business jets. But commercial jet engines—with the proper modifications—might do the trick. Aerion is counting on it.

MARKETS PAVE THE WAY

The success of the next generation of SSTs will ultimately come down to economics. Demand for business jets in the United States is strong, but less so in other parts of the world. During the first half of 2015, global shipments of business jets fell 4.1 percent compared with the same period one year earlier, according to the General Aviation Manufacturers Association. Business has suffered the effects of the Great Recession. The 722 business jets that shipped in 2014 were little more than half the 1317 that shipped in 2008.

Prospective buyers of supersonic business jets will include corporations and ultra-high net worth individuals, according to Aboulafia. Others may be the providers of fractional ownerships and premium charter services.

"Perhaps the most intriguing would be heads of state or military buyers," he said. "The world is filled with crises and trouble. The faster you can get a rapid reaction team there, the better."

While demand will play a big role in the success of supersonic business jets, so will keeping a lid on operational costs. Maintenance and training issues will have to be addressed. The greatest technical challenge to commercial supersonic flight, however, is the sonic boom, industry experts agree.

If the boom can be tamed, the ban on supersonic flights over the U.S. and other countries might be lifted.

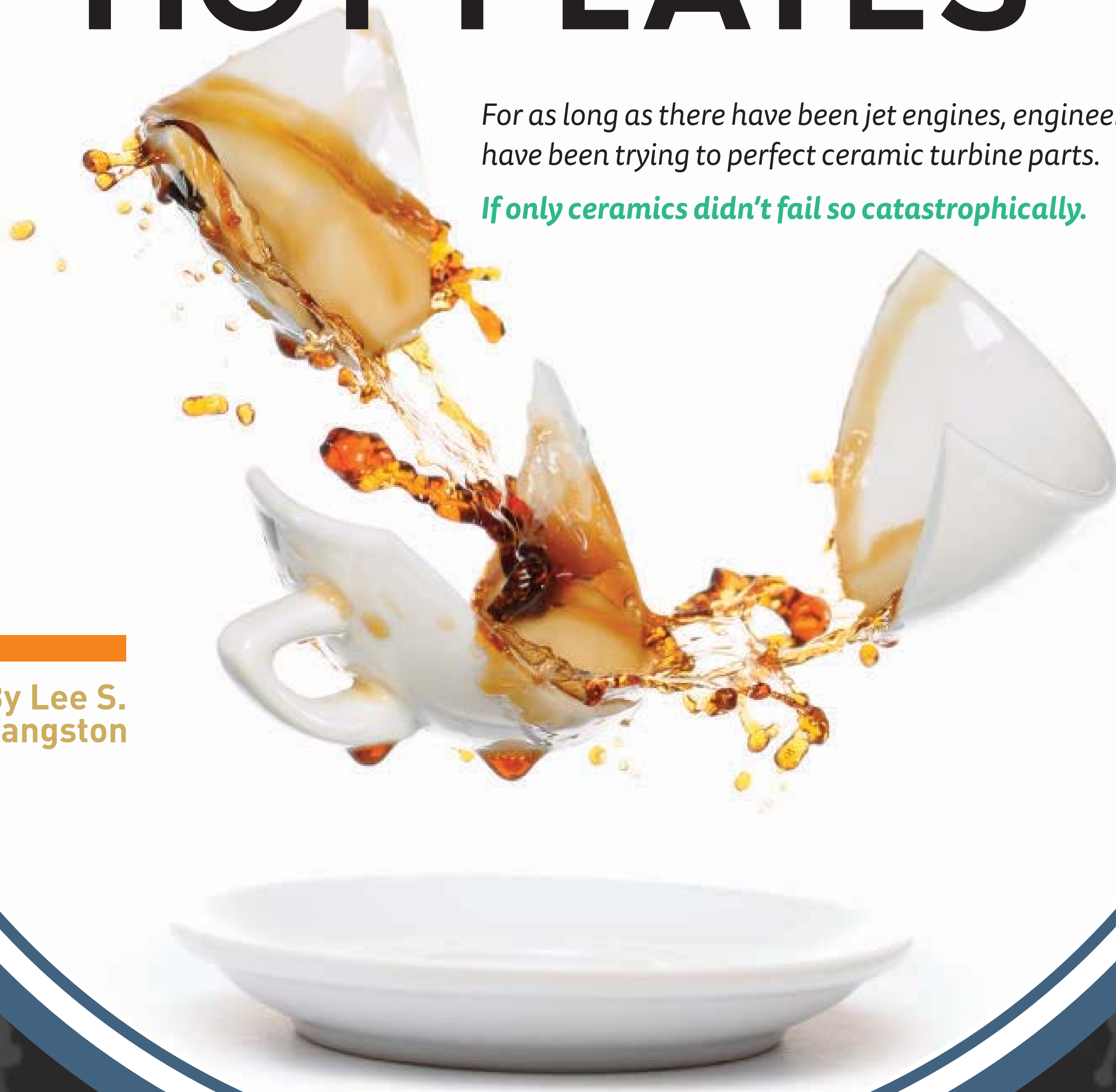
And business jetsetters will be free to set speed records as never before. **ME**

GREG FREIHERR is a writer based in Fond Du Lac, Wis.

HOT PLATES

For as long as there have been jet engines, engineers have been trying to perfect ceramic turbine parts.

If only ceramics didn't fail so catastrophically.



By Lee S. Langston

Ceramic Power

This GE jet engine uses lightweight, heat-resistant ceramic matrix composite materials throughout its hot section.

Photo: GE Aviation

Animal, vegetable, or mineral?

Those are the classic choices from the 20 questions game. But materials science presents a wider array of options for making advanced products. Carbon-based materials—in the form of fibers, nanotubes, or sheets of graphene—are full of promise. Aerogels, in which the liquid component of a conventional gel is replaced by a gas, are remarkably lightweight for a solid and have extremely low thermal conductivity.

But as David Richerson of the University of Utah has pointed out, most solid materials that aren't metal, plastic, or derived from plants or animals, are ceramics. Traditional ceramics such as pottery, tile, bricks, stone, and glass that date from antiquity. Today, sporting goods stores sell ceramic knives, and bullet-proof vests have ceramic plate armor. High-temperature superconductors are made from complicated ceramics, and ceramic materials are used in aerospace applications for heat shielding.

The makers of gas turbines have—from the beginning—looked at ceramics and wondered how to make use of them. Ceramic materials have many favorable characteristics. Compared to metals now used in gas turbines, they often can have superior corrosion resistance and hardness, lower density, and higher temperature capability. It seems obvious that gas turbines ought to be made with ceramic parts.

I remember a story told to me by Dick Goldstein, a past president of ASME, about his late colleague at the University of Minnesota, Ernst Eckert. Eckert was a famous heat transfer expert and was also a colleague of jet engine pioneer Ernst Schmidt at the German Aviation Research Institute in Braunschweig in the late 1930s and early 1940s. Eckert was working on gas turbine designs, and while carefully doing calculations and design of metal air-cooled turbine blades, a coworker (possibly Schmidt) remarked to him that his design was probably done in vain. Ceramics soon would be taking over, negating the need for the air cooling of the blades.

That confident prediction did not come to pass.

The main drawback for ceramics, which over the first 75 years of gas turbine technology had never been sufficiently overcome, is comparatively low toughness, and the resultant possibility to fracture in a catastrophic brittle mode.

Toughness is a measure of load or stress needed to drive a crack through a material. A china dinner plate is not easy to break in half, but if it has a slight crack, fragmentation is easy, compared to say, an identical ductile metal plate. Ceramics subjected to compressive stresses, where crack defects are made smaller, are very strong. But when ceramics are subject to tensile or bending stresses (such as in rotating turbine blades), any crack defects are pulled apart and can cause sudden failure.

So it is news indeed that commercial jet engines with ceramic components in their hot section are coming to market. After more than a billion dollars in research and development, General Electric has recently opened a $125 million plant in Asheville, N.C., and is planning a $200 million factory in Huntsville, Ala., to mass produce gas turbine components out of an advanced material called ceramic matrix composites.

First Attempts

Ceramic turbine blades and vanes developed in the years around 1940 for possible use in German jet engines.

Credit: Thomas Sattelmayer, Technical University of Munich

These components will operate at a temperature that would soften or melt the superalloys currently used in jet engines.

If these ceramic parts perform as promised, both operationally and economically, it could radically alter the jet engine industry. But with the price for failure so catastrophic, that isn't a prediction that can be made with confidence.

The promise of ceramics is that by taking advantage of their lower weight and superior high temperature properties, one could replace the complex air-cooled metal components with simpler ceramic components more tolerant of high temperatures.

Turbine inlet gas temperatures can reach 3,600 °F (1,982 °C) in advanced military jet engines and 2,700 °F (1,482 °C) in stationary gas turbines. Those all require air-cooled hardware, since superalloy metals soften and melt in the 2,200-2,500 °F (1,204-1,371 °C) range. By contrast, a ceramic formed by silicon carbide decomposes at 4,950 °F (2,730 °C), well above current turbine gas path temperatures. Thus, a replacement SiC part would save weight and reduce the need for cooling air, which would increase gas turbine efficiency and reduce fuel consumption.

But it wasn't simply ceramics' material properties that enamored the gas turbine pioneers; it is also a function of place and time. After the first jet-powered flight, near the Baltic city of Rostock, Germany, on August 27, 1939, work commenced on six jet engine programs at the German companies of Heinkel, Junkers, BMW, and Daimler Benz. That put the Germans years ahead of other countries in the establishment of jet engine technology and production.

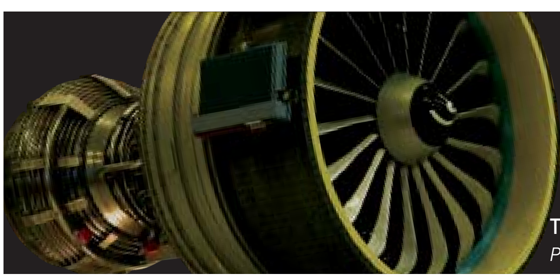
It was somewhat natural that ceramics would be seriously considered for German jet engine hot section components. German ceramic technology at such companies as Siemens Neuhaus and Degussa was well advanced, going back to 1709 when Europe's first successful porcelain, or bone china, was developed at Meissen in Saxony. Also, with the Second World War just beginning, Germany had an increasingly difficult time importing raw material of strategic value, including high temperature alloy metal such as nickel. German scientists looked to the possible use of ceramics for engine hardware.

Before the Nazi regime took power in Germany, Ernst Schmidt was a leading thermodynamics researcher and academic; the dimensionless number formed by the ratio of momentum and mass diffusivities is named after Schmidt. With the war on, Schmidt led a program at the top-secret German Aviation Research Institute—which in German is compounded into *Luftfahrtforschungsanstalt* and abbreviated LFA—to adapt ceramics to jet engine construction.

Schmidt quickly abandoned any effort to use ceramic rotor blades because of their brittleness in tension and problems associated with their attachment. He also considered, briefly, the construction of a turbine in which the casing rotated and the rotor was stationary, much like the WWI French Gnome rotary piston engine. In that way the rotating airfoils would be put under secure compression instead of tenuous tension.

The ceramic gas turbine work at LFA did lead to turbine stator development, with Degussa and Siemens Neuhaus furnishing alumina stators. Those, however, proved to be relatively sensitive to heat shock.

Thus, despite the pioneering German work on gas turbine ceramics, there is no evidence that ceramics were used in the gas paths of any of the approximately 7,000 production jet engines built by Germany by the end of WWII. Turbine airfoils were made of metal alloys, and air-cooled when necessary.



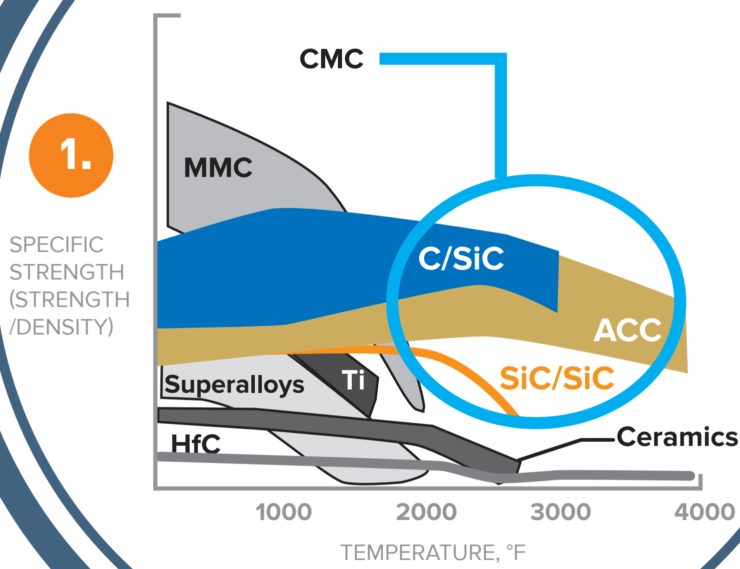
*A ceramic formed by silicon carbide decomposes at **4,950 °F**, well above current turbine gas path temperatures.*

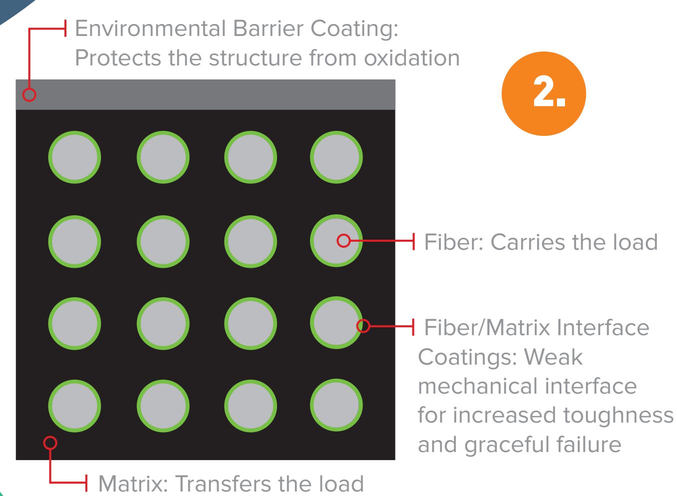
The LEAP engine.
Photo: GE Aviation

The challenges involved in developing ceramic rotating parts for a gas turbine have persisted in the decades since. As David Richerson pointed out in a 2004 paper, ceramics introduce a wide spectrum of challenges in the high temperature ranges found within gas turbines. For instance, how do you go about designing and fabricating components using these brittle materials in such high stress and possibly high impact applications? There's virtually no margin for error: a cracked rotating ceramic turbine blade can suddenly fail, taking out other blades and causing total engine failure.

Also, under high temperature and high pressure gas path conditions, some advanced ceramics can oxidize and react to water vapor, causing strength degradation.

Of course, high melting point ceramics have always served as cores and molds for investment casting of advanced superalloy turbine blades and vanes which can have very intricate geometries. And current engines in production use ceramic thermal barrier coatings, called TBCs, which raise the high-temperature capacity of a metal part by hundreds of degrees





ADVANCED CERAMICS

1. Material specific strength as a function of temperature: ACC-*advanced carbon/carbon*. CMC-*ceramic matrix composite*. C/SiC-*carbon/silicon carbon*. HfC-*hafnium carbon*. MMC-*metallic matrix composite*. SiC/SiC-*silicon carbon/silicon carbon*. Ti-*titanium*.

2. Schematic of a CMC with fibers embedded in a matrix.

Images: David Glass, NASA Langley

and increase its life. Critical component loading is carried by the coated metallic part itself, so that the brittle coating isn't subjected to high stresses.

One difficulty engineers have had in developing ceramic components is the inability to put promising designs in production gas turbines for a true "beta" test. For example, the very extensive and far-reaching high-temperature automotive ceramic gas turbine program run by the Ford Motor Co. centered around an experimental automotive single-shaft high-temperature ceramic gas turbine.

The Ford ceramic gas turbine program began in 1967 with the promise of low exhaust emissions, an advantage the continuous combustion of a gas turbine had over the intermittent combustion of the piston engine. Designated as Model 820, the turbine comprised an all-ceramic rotor with a radial compressor and an axial flow turbine part of the all-ceramic hot flow gas path. The ceramic rotor was the biggest challenge, and it was successfully tested, proving that a low-cost one-piece low inertia ceramic rotor for production would be possible.

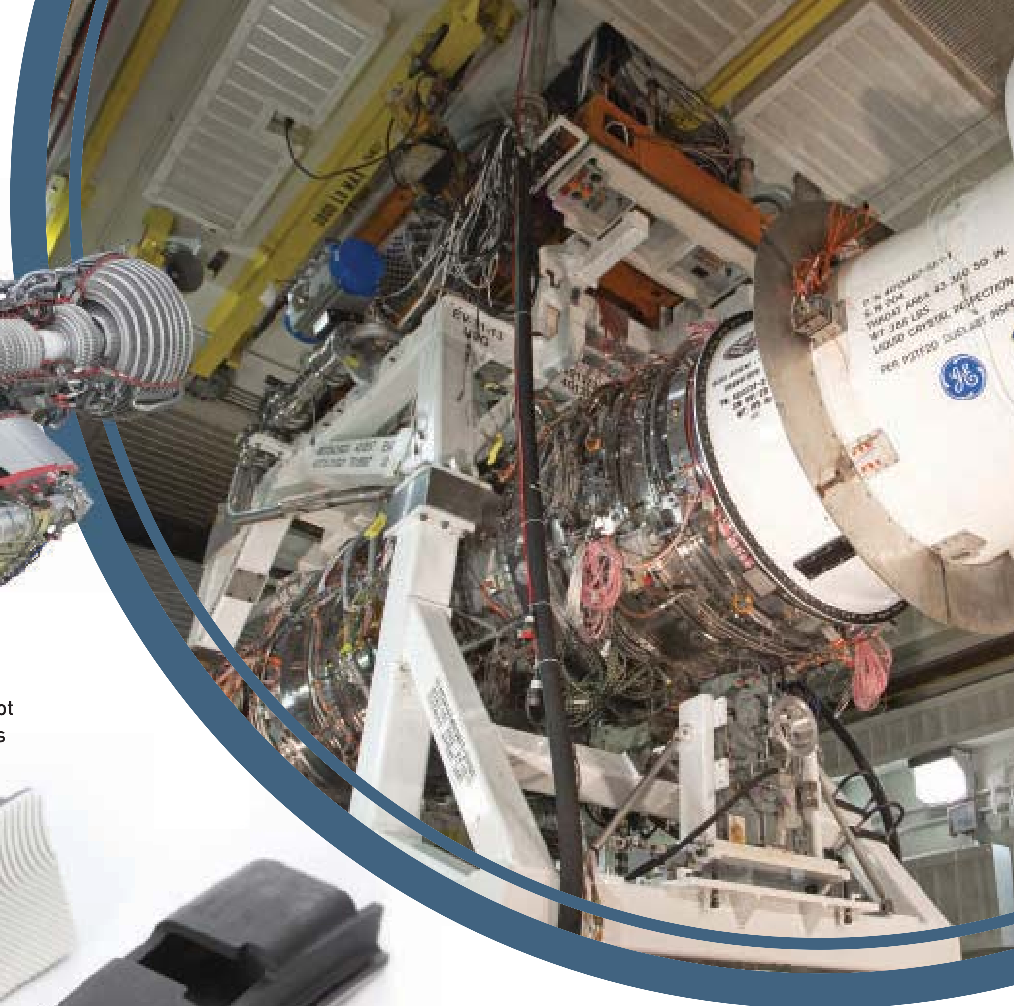
But the Model 820 Program never made it to the production test phase. While the program progressed over the years, reciprocating engines were developed with direct fuel injection and computer-aided electronic controls. Those new engines successfully met emission standards, and since the company had a high capital investment in building reciprocating engines, it didn't make financial sense to make an equally large investment to continue developing and then manufacture gas turbines.

The turbine program was folded around 1990.

While researchers and developers have explored the use of ceramics in gas turbine high-temperature gas path applications, none have gone into a major production engine. But General Electric is now changing this, by using gas-path parts made from ceramic matrix composites in the company's new LEAP production engines.

CFM International, jointly owned by GE Aviation and SNECMA of France, is developing the LEAP—short for Leading Edge Aviation Propulsion—high-bypass turbofan engine as a successor to the very successful CFM56, the top-selling commercial jet engine in the world. (Some 28,000 of these 19,000-to-27,000-pound thrust engines have been delivered since 1994.) In development since 2008, the LEAP is scheduled to enter into service this year and already has more than 8,000 orders.

The ceramic matrix composites used in the LEAP's hot section have one-third the



GREAT LEAP FORWARD

1. Cutaway illustration of the LEAP engine. **2.** GE is also developing an engine for military aircraft that will make use of CMC parts in its hot section. **3.** GE's first use of CMC parts will be as the shroud in the the first-stage high-pressure turbine in the LEAP engine. **4.** A worker at a facility in Delaware places CMC material into an oven to melt silicone into a matrix.

Images: GE Aviation

density of conventionally used nickel-cobalt superalloys. CMCs have more heat resistance and require less cooling air. Such properties promise to enhance engine durability, fuel economy, and performance. GE's first use of CMCs is as the shroud of the first-stage high-pressure turbine, which, as the inner structure of the engine casing, provides the closest stationary surface to the rotating first stage turbine blade tips.

The CMCs in use there are a composite consisting of fine intertwined ceramic silicon carbon fiber, embedded in and reinforcing a continuous silicon carbon-carbon ceramic matrix. The SiC fibers are continuous, reaching more than 5 cm in length while being just a fraction of a human hair in diameter, and relatively free of oxygen (which can degrade high-temperature properties). The resulting intertwined fiber reinforcers are covered with a multi-layer coating based on boron nitride.

The shroud itself also has an environmental barrier coating to protect the CMC from chemical reactions with turbine gases.

To get around the potential for sudden and catastrophic failure of the ceramic part, the fiber-reinforced CMCs have a unique failure mechanism, dubbed a "graceful failure" mode. As the SiC-C matrix cracks develop under imposed thermal or mechanical stresses, the load is transferred to the reinforcing SiC fibers. Their multi-layer boron nitride coating then permits the fibers to slide in the matrix, allowing load transfer and energy absorption. Instead of one micro-crack quickly becoming a point of failure, multiple micro-cracks can build up prior to actual fracture, resulting in increased toughness that imitates the ductile behavior of a metal. This mitigating crack tolerance that resists the classic brittle failure of a pure ceramic, should also yield gas turbine parts that are not highly sensitive to manufacturing flaws.

GE plans to expand its application of ceramic matrix composites use in its 100,000 pound thrust GE9X engine, now under development for Boeing's 777X airframe and scheduled to enter service in 2020. It will feature CMC combustion liners, high-pressure turbine stators, and first stage shrouds. Early last year, GE ran tests on a turbine rotor with CMC blades—the ultimate structural test of this new material.

One factor the company must work on is cost. Currently, CMCs are very expensive, hundreds to thousands of dollars per kilogram. GE is counting on cost reduction by process scale-up, automation and improved machining.

But overall, GE's use of CMC gas path parts looks very promising. CMC's graceful failure mechanism will allow the use of this promising composite ceramic, with its light weight and high-temperature characteristics. The company estimates an advantage of at least 180-360 Fahrenheit degrees (100-200 Celsius degrees) in comparison to metals currently in use. That means that CMC parts could operate at about 2,400 °F (1,315 °C), well above the softening and melting point of superalloys. Competitor Pratt & Whitney estimates a CMC operating temperature at 2,700 °F.

This brief account describing the management of tensile cracking does not do justice to the research, analysis, and testing GE and others have done to develop CMCs for gas turbines.

Trying to manufacture a ceramic material structure that can imitate what nature provides in a ductile metal is an enormous challenge.

It should be noted, however, that success does not always favor the pioneer. In the late 1960s, for instance, Rolls-Royce attempted to first use a composite ducted fan on its then new RB211 engines, for the Lockheed L-1011 airframe. The fan, using Hyfill, a carbon fiber composite, failed final testing. This setback ultimately led to the bankruptcy of the company in 1971.

The jet engine industry has since developed successful composite fans, but the inaugurating company got off to a rocky start.

Coming after seven decades of development, it may seem that the day for ceramic gas turbine components has finally arrived. Who will reap the rewards of that breakthrough remains to be seen. **ME**

LEE S. LANGSTON is an ASME Fellow and professor emeritus of the mechanical engineering department at the University of Connecticut in Storrs.

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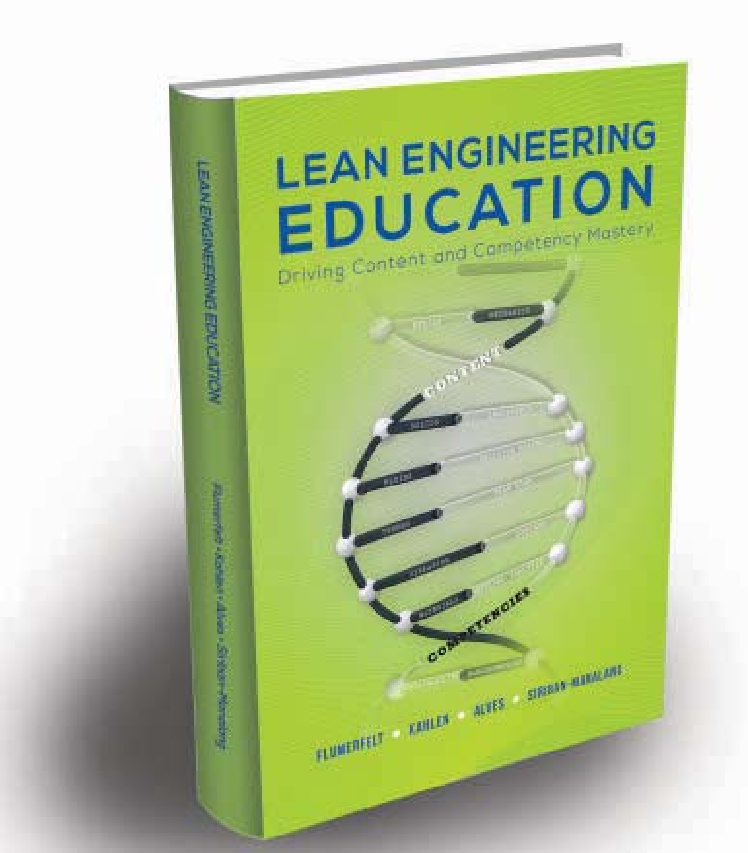


FEATURED

LEAN ENGINEERING EDUCATION: DRIVING CONTENT AND COMPETENCY MASTERY

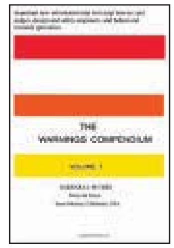
BY SHANNON FLUMERFELT, FRANZ-JOSEF KAHLEN, ANABELA ALVES, AND ANNA BELLA SIRIBAN-MANALANG

ASME Press Books, Two Park Avenue, New York, NY 10016-5990. 2015.

The authors of Lean Engineering Education admit that no one can predict the future, but they argue that we can plan for it. Right now, they say, studies are finding that engineering graduates are lacking key skills they need in engineering practice. The implication is that gaps in skills can only increase as the profession evolves. One possible change that could require new skills is that engineers will address not only traditional issues in the design, assembly, and use of new products, but also how the product or system will be dismantled or recycled after its useful life. Employers, the authors say, are asking for better collaboration between schools and the workplace to prepare engineering graduates.

The title adopts a term often applied to the Toyota production system. The authors cite parallels between an education system of the future and Toyota's lean culture, which they say is based on two principles, continuous improvement and respect for people.

144 PAGES. $59; ASME MEMBERS, $47. ISBN: 978-0-7918-6050-2.

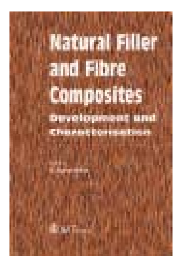


THE WARNINGS COMPENDIUM

Barbara J. Peters
CreateSpace, a brand of On-Demand Publishing LLC, a subsidiary of Amazon.com Inc. 2015.

Warnings come in all forms and definitions. This compendium, planned as the first of two volumes, is a methodical examination specifically of warnings about physical hazards. Warnings rely on someone not only to perceive them, but also to understand and then to act on them appropriately. According to the author, an attorney with Peters & Peters in Santa Monica, Calif., "warnings are considered the least effective means of risk reduction," largely because a warning does nothing to remove a hazard. They are to be used as a last resort. Peters discusses a safety hierarchy, warning fatigue, defining hazards, and other points. She also discusses design, wording, placement, and other critical features of warnings. Being a compendium, the text explores many areas beyond signage, labels, and lights, including warnings we receive from smell, taste, and touch.

710 PAGES. $60. ISBN: 978-1-5191-1135-7.



NATURAL FILLER AND FIBRE COMPOSITES: DEVELOPMENT AND CHARACTERISATION

S. Syngellakis, Editor
WIT Press, Ashurst Lodge, Ashurst, Southampton, SO40 7AA, U.K. 2015.

The articles in this collection explore the design of engineered materials that use various natural components as reinforcement or matrix. The natural constituents of the materials are attracting the interest of researchers and engineers, who see environmental advantages in using them. The articles address composition, structure, manufacture, and properties of the materials to encourage greater use in engineering practice. The book discusses advanced manufacturing processes involving cellulose nanofibers, nanocrystals, and micro-fibrillated cellulose. Innovative processes include techniques for combining jute fibers and rice straw with a biodegradable matrix. Also included are results of experiments conducted on various fibers and composites to measure their performance under tension and flexure, their fracture behavior, impact resistance, and thermal conductivity.

236 PAGES. $198. ISBN: 978-1-78466-147-2.

Global Gas Turbine News

Volume 55, No. 1 • March 2016

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ASME Turbo Expo 2016 Keynote

Along with being a first in Asia, Turbo Expo - held this year in Seoul, South Korea - will have another first in changing the format of the keynote from a lecture session to a panel session. Moderators will field questions from the audience and have the panelists answer. We have some exceptional high profile industry experts lined up to be the moderators and panelists. Bringing their expertise and experience, they will make this a worthwhile part of the conference. Do not miss your chance to join over 2,000 turbine colleagues from around the world who will take part in this! It will be held on **Monday**, June 13, with an awards ceremony followed by a luncheon, included with your registration.

The Keynote theme is **Energy and Propulsion in the Information Age**. The keynote session will explore those innovations and how they are impacting rotating machinery in the power generation, aircraft, and oil and gas industries, including manufacturing and fleet monitoring and maintenance.

Two plenary sessions will follow the same format on the following days. A session on **Tuesday** morning, June 14, will cover **Asset Optimization and Monitoring in the Information Age**. Significant growth in sensor technology, models, and data analytics is revolutionizing our capabilities to optimize the performance and proactively manage and monitor the health of gas turbines. Many OEM's, utilities, and operators now have large, networked monitoring centers for optimizing the health of specific engines or fleets of engines. Moreover, new challenges and questions around data ownership, privacy, and cybersecurity are emerging, which could severely constrain these prospects. This plenary session will explore these opportunities and threats and discuss future outlooks for asset monitoring.

...Continued on page 51

ASME IGTI Student Scholarship Program

Introduction and Purpose

ASME International Gas Turbine Institute has a long and proud history of providing scholarships to students who show promise in the turbomachinery field. The aim is to attract young talent to the profession and reward their commitment, favoring their upcoming enrollment and active participation. ASME IGTI has supplied more than $1 million dollars to fund these scholarships over the years. In the 2016-2017 school year up to 20 scholarships at $2,000 each will be awarded. The scholarship is to be used for tuition, books, and other university expenses. The check will be made out to the university on the student's behalf. The student application deadline is June 15, 2016. Scholarship winners will be notified by the end of October 2016. Scholarships will be dispersed in November.

Eligibility of the Applicants

The nominee must be pursuing an academic degree (bachelor's, master's, Ph.D., or equivalent degrees) in an engineering discipline related to turbomachinery. Students must be currently registered at an accredited university (either U.S. or international). The university must have a gas turbine or turbomachinery program of some type, which can mean simply that a gas turbine or power course with a significant gas turbine or turbomachinery content is offered.

Application Requirements

The application package must contain:

a) A succinct motivational letter (maximum 1 page) illustrating reasons that should lead to a positive decision by the selection committee

b) The application form listing data concerning the eligibility of the applicant, duly signed

c) A nomination form and recommendation letter by the applicant's academic supervisor, or by an industry professional involved in his/her studies. Student should follow up with nominator to confirm the packet has been sent to ASME.

d) Any other document the applicant wishes to attach in order to support the application. (Proof of awards and honors, memberships in honorary or professional societies showing offices held, extra-curricular activities, etc.)

The selection committee rewards brevity: valuable accomplishments are self-explanatory. Fill out the application form (https://community.asme.org/international_gas_turbine_institute_igti/m/mediagallery/8510/download.aspx) and send in one pdf to ASME at igtiawards@asme.org.

ASME 2015 ORC Conference

The third edition of the ASME ORC Conference (http://www.asme-orc2015.be) was held in Brussels, Belgium, on October 12 – 14, 2015, continuing the success of the previous editions. The scientists, industry practitioners, professionals, and government officials working in organic Rankine cycle technology who attended networked during the welcome reception, the Belgian beer tasting event, and the conference dinner, where they listened to a string quartet concert in the world-class theater hall of the Hotel De La Plaza.

Conference Statistics

- 343 attendees from 34 countries
- 130 oral presentations
- 53 poster presentations
- 140 final papers available for download on the conference website http://www.asme-orc2015.be/online/proceedings.htm

Keynote Speakers

David Gilles, Enertime SAS, spoke about his experience gained and lessons learned in creating and establishing a company that designs and builds MW-size ORC power plants for the international market.

Piero Colonna, Delft University of Technology, (chair of ASME IGTI) spoke about Mini-ORC turbogenerators. He explained that, as mini systems, they will be designed for standardized large series production. The first envisaged application is waste heat recovery from longhaul truck engines. The small capacity offers challenges and opportunities. The small and fast turbine is one such challenge. Options for this turbine and concerned research were addressed. Several new applications based on these miniature power plants were described, like distributed concentrated solar cogeneration, and ideas for the path forward were proposed.

Sylvain Quoilin, University of Liege, provided an overview of the state of the art and main research trends in ORC power systems. He highlighted and described a few relevant topics originating from the previous ORC conferences and from the scientific literature.

The ASME ORC 2017 Conference will be held in Milano, Italy!

ASME 2015 Gas Turbine India Conference

In its fourth year, the ASME 2015 Gas Turbine India Conference succeeded in bringing together the gas turbine professionals from academia, industry, and government including engineering students in India to the Hyderabad International Convention Center. Hyderabad is home to design and development centers of several multinational businesses engaged in gas turbine and allied technologies. This conference, held December 2-3, 2015, provided a unique opportunity for sharing knowledge, experience, and challenges among colleagues in the field of turbomachinery. The two keynote presentations were well attended: "Unsteady Flows in Turbomachines" by Om Sharma, senior research fellow at United Technologies Research Center (UTRC) and "Integration: The Key to Success in Defence Programmes" by Conrad Banks, chief engineer for the aerospace division of Rolls-Royce. One of the panel sessions covered the immediate demand for aircraft engines, due to the huge backlog of orders by airlines, and the future needs with new technologies in development. We would like to thank our platinum sponsors, GE and Rolls-Royce, our silver sponsors, ANSYS and Bharat Forge Limited, and our bronze sponsors, Hindustan Aeronautics Limited (HAL) and Quest, for supporting this conference. We also recognize the Gas Turbine India Conference Committee for the wholehearted and selfless volunteer hours that they collectively dedicated toward the successful technical program of the conference.

Keynote speaker: Om Sharma, senior research fellow, United Technologies Research Center

Continued from page 1

Gas Turbine Manufacturing in the Energy Age will be covered on **Wednesday** morning, June 15. The next industrial revolution in manufacturing is being forged at the intersection of physical and digital worlds. Next generation turbines will be engineered from cradle to grave in a virtual design space, enabling the design, manufacturing, and utilization of turbines to be optimized at an overall system level. This plenary session will explore that new industrial manufacturing renaissance and what's coming next.

Pre-Conference Workshops

Pre-conference workshops will be held at the COEX Center on **Sunday**, June 12, 2016, from 8:00 a.m to 5:00 p.m. Seize this opportunity to earn 7 Professional Development Hours (PDH's) and receive a certificate of completion. Consider attending one of the workshops and take advantage of the low registration fee. Registration is available online. For detailed information about the workshops visit: https://www.asme.org/events/turbo-expo/program/workshops.

- **Physics-Based Internal Air Systems Modeling**
- **Technology and Applications of Gas Turbine Coatings**
- **Uncertainty Quantification and Turbomachinery**
- **Introduction to Gas Turbine Performance Modeling with GSP**
- **Gas Turbine Aerothermodynamics and Performance Calculations**

TECHNICAL ARTICLE

Engine Architecture for High Efficiency at Small Core Size

Wesley K. Lord and Gabriel L. Suciu, Pratt & Whitney

Advanced fuel-efficient commercial aircraft for entry into service in 2035 may have quite different configurations than current transports, requiring new architectures for their jet engines. One such airframe design, shown in Fig. 1, features close-coupled, rear-mounted turbofan jet engines, with the fuselage sculpted to sweep fuselage boundary layers into engine inlets for reduced fuel consumption.

NASA has defined environmental goals for future subsonic transport aircraft as a function of the technology generations beyond today's capability. The goals for long-term technology at three generations beyond today, N+3, include reduction in aircraft fuel consumption of 60% relative to a B737-800. To meet this goal for a 2035 entry into service, a new rear-mounted engine architecture is described here (and in more detail in [1]), the result of conceptual design studies conducted by an MIT, Aurora Flight Sciences, and Pratt & Whitney team, and based on the original engine configuration developed by Pratt & Whitney [2].

Design Space

The vehicle was designed for a mission that is representative of a B737-size aircraft. It has a twin-aisle "double-bubble" fuselage with two flush-mounted boundary-layer ingesting engines located at the upper aft fuselage (Fig 1). As a result of the unique D8 aircraft configuration, as well as envisioned advances in aerodynamics, airframe materials, and propulsion, the estimated takeoff thrust size of the engines is 13,000 lbf (58 kN), half that of the current engine on a B737-800.

Aircraft engine overall efficiency can be considered to be the product of thermal and propulsive efficiency. To meet the aggressive N+3 performance goal, significant increases in both thermal and propulsive efficiency, compared to current engines, are required. Thermal efficiency is associated with the process of burning fuel to produce usable power. High thermal efficiency requires high overall pressure ratio (OPR), high component efficiencies, high turbine inlet temperature, and minimal turbine cooling air. Propulsive efficiency is associated with the process of converting the power output of the core engine to propulsive power. High propulsive efficiency in a subsonic transport aircraft requires low thrust per unit mass flow, implying very high bypass ratio with a large fan at relatively low fan pressure ratio (FPR). Fuselage boundary layer ingestion also provides a propulsive efficiency benefit in the concept engine. The target engine cycle for the N+3 engine had 50 OPR at cruise, FPR in the range 1.3 to 1.4, and BPR of 20 or higher.

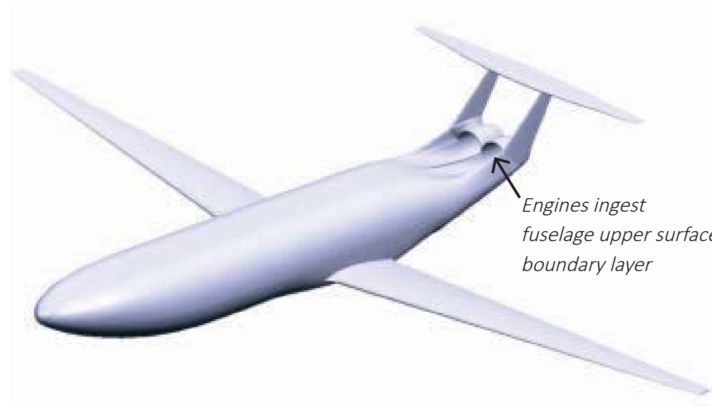

Figure 1 – MIT D8 Double Bubble aircraft with fuselage boundary layer ingestion *Image credit: MIT*

Challenges

The N+3 engine design space of high OPR, low FPR, and small thrust size drives the engine design to a small core size, defined as the compressor exit flow corrected for exit pressure and temperature (lbm/s or kg/s). In these units the core size of our N+3 engine is about 1.5 lbm/s, a factor of 5 smaller than that of current engines for B737/A320 aircraft.

There is a direct correspondence between corrected flow size and the physical scale of the flowpath at the back end of the compressor. Existing engines in service show a change in architecture at a core size of about 3.5 lbm/s, from all-axial compressors to compressors that have a centrifugal rear stage. At this condition the blade height of the last airfoil in an all-axial machine is about 0.5 inches (1.3 cm). As the blade height goes below 0.5 inches, the efficiency of an all-axial compressor decreases rapidly due to increased sensitivity to tip clearance and airfoil manufacturing tolerances. Current engines with CS < 3.5 and centrifugal rear stage, however, are limited to OPR less than 25 due to thermal-mechanical stresses in the impeller. A major challenge is thus how to (i) achieve 50 OPR and (ii) maintain high efficiency levels at 1.5 core size.

Another major challenge is associated with the D8 engine installation, with its two closely spaced engines located within the pi (π) tail. The FAA "1-in-20 rule" [3] concerns engine installation design guidelines to prevent loss of aircraft in the unlikely event of an uncontained turbomachinery rotor failure; a turbine disk burst in one engine should not cause shutdown of the other engine or damage the tail surfaces to the extent that there is loss of flight control.

Alternative Engine Architecture

The proposed unconventional engine architecture addresses both of these challenges. The concept engine has a high-OPR two-spool gas generator that is aerodynamically coupled to the power turbine/propulsor in a reverse offset arrangement, as illustrated schematically on the right side of Fig 2.

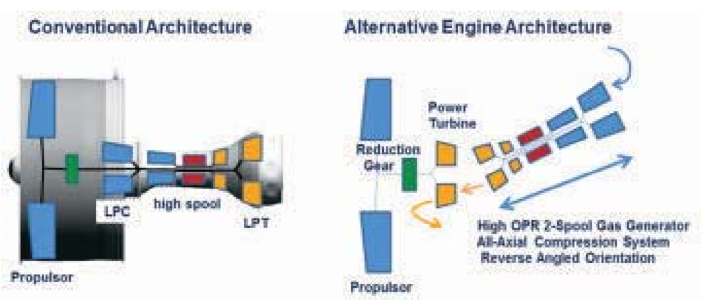

Figure 2 – Conventional and alternative engine architecture for high-OPR, small core size

Conventional architecture for high BPR engines has the low pressure turbine that drives the fan located at the back of the engine, so the drive shaft must pass through the core. In the alternative architecture, the gas generator is not mechanically coupled to the propulsor, and the drive shaft connecting the power turbine to the fan does not pass through the core. This allows the core engine flowpath to be pulled inward to a smaller radius, enabling a larger blade height for a given flow area. Elimination of the power turbine drive shaft constraint allows us to push the design space boundary for an all-axial compressor to smaller core size at the target OPR and to operate within a feasible axial compressor rim speed mechanical design space. The alternative engine architecture also allows the cores to be oriented at an angle that keeps the adjacent engine, and the critical aircraft flight control surfaces, out of the burst zone, providing an effective means to address the 1-in-20 rule (Fig 3).

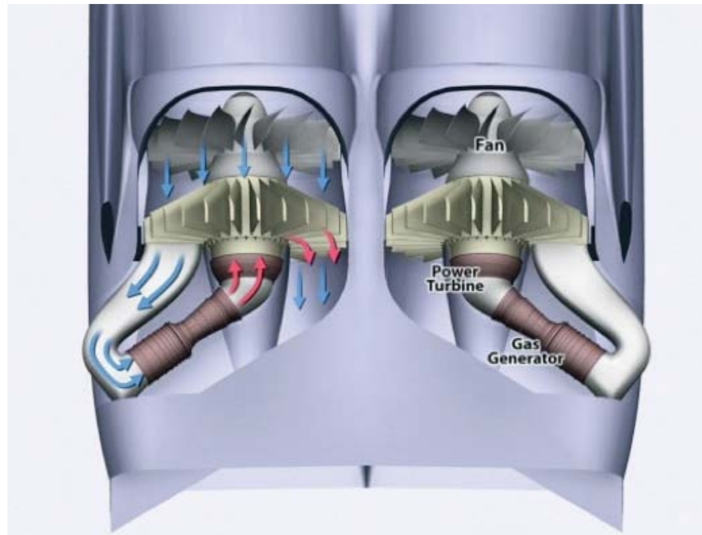

Figure 3 – Concept engine installation on the MIT D8 aircraft to meet the 1-in-20 rule

In summary, the alternative engine architecture potentially enables a high-OPR all-axial compression system at small core size, while maintaining high compressor and turbine efficiencies. The concept engine also makes use of the reverse angled core to address the FAA 1-in-20 rule. It is noted that the reverse angled core engine concept architecture is only feasible at ultra-high BPR such that the core engine can be packaged within ducting positioned crosswise to the fan exit flow. Future studies would consider 3-D design of the high turning ducts and compressor design technology for reduced exit Mach number to further increase exit annulus height and reduce sensitivity to tip clearances.

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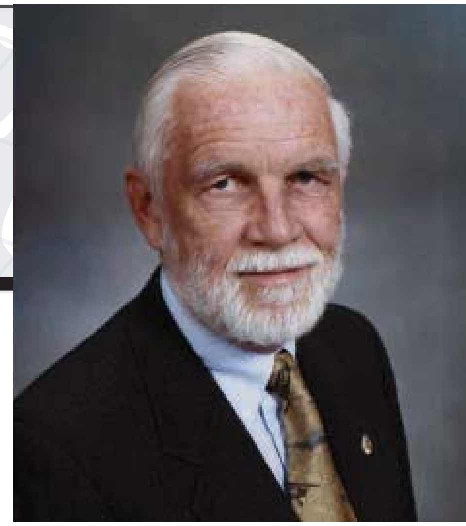
As the Turbine Turns



PALS - An Auspicious New Gas Turbine Seal

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

You may recall the words of Lewis Carroll's *Alice in Wonderland* walrus: "The time has come, to talk of many things: Of shoes - and ships - and sealing wax -." In a metaphorical sense, the design and operation of gas turbines depend on lots of "sealing wax." Seals abound in both aviation and non-aviation gas turbines.

At our TURBO EXPO '14 in Düsseldorf, there was an interesting paper [1] given on a new gas turbine shaft seal, called the pressure activated leaf seal and appropriately acronymed as PALS. Clay Grondahl, its inventor and coauthor of the paper, alerted me to its unique features and advantages. The PALS assembly is shown in Fig. 1, but before we explain its operation, let us briefly review gas turbine seals in general.

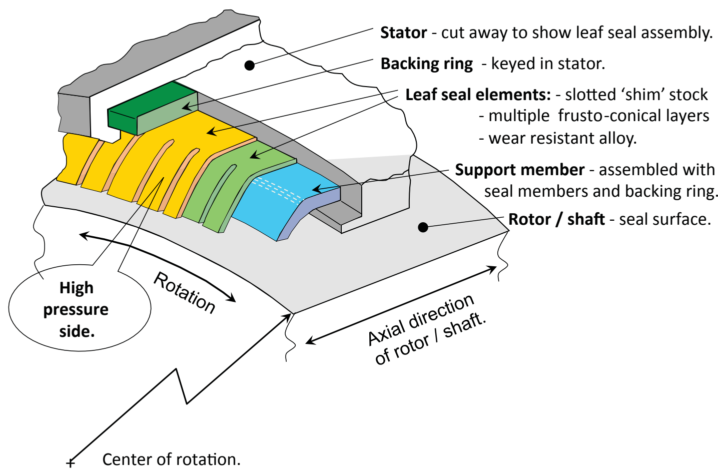


Figure 1. PALS - Pressure Activated Leaf Seal Assembly [1].

The Seal Story

The extensive review of current seal technology by Chupp, et al.[2], shows that most gas turbine seals don't seal - at least not completely - but reduce undesirable flows. Seal locations are primarily in engine mainshaft areas and in gas path locations. Seals are used to prevent oil leakage from engine bearings, to reduce tip leakage in rotor blading, and in general to reduce air leakage between high and low pressure components, both rotating and stationary.

How important are seals? By and large, an engine can't have sustained successful operation without seals. In addition, consider a simple economic example. Take the case of a large electric power gas turbine, whose annual fuel cost might be on the order of $100 million. A seal improvement in one location might increase engine efficiency by 0.1%, which is seemingly not large. However, that would result in a fuel savings of about $100,000 annually, and about $1 million for a fleet of 10 such machines.

Labyrinth Annular Gas Seals

Let us focus on the intended application of PALS, as an air-to-air gas turbine rotor seal between stationary and rotating parts. This application is critical for both power generation and aviation gas turbines performance, where the goal is to minimize leakage between high and low pressure turbine sections (and the intermediate section, in the case of a three-spool engine).

Consider the labyrinth seal shown in Fig. 2A (taken from[3]), fixed on a turbine case, separating high and low pressure regions, and suspended to provide a seal clearance to a large diameter rotor seal surface. Labyrinth seals, named for the maze-like structure in Greek mythology where the Cretan Minotaur dwelled, are widely used in turbomachinery, going back to steam turbine inventor Charles Parsons' machines in the early 1900s. There are many newer, more advanced seals (e.g. brush seals) which are treated in [2], but labyrinth seals are still used extensively in turbomachinery.

The annular labyrinth seal in Fig. 2A has teeth (like a course comb) that form successive cavities. As leakage air flow passes from high pressure under each tooth, it expands in an irreversible process into the next cavity, so that a series of thermodynamic throttling processes occur, dropping its pressure, as it approaches the low pressure region. A tighter clearance gap makes the sealing throttling process more effective.

As the Turbine Turns...

However, during actual engine operation the clearance gap can vary, as shown by the sketch in Fig. 2B. The rotor seal surface diameter increases in response to shaft speed and rising gas path temperatures. On startup and shutdown, the clearance gap can close down due to the changing engine conditions. Also, the center of rotation of the rotor seal surface may shift as shaft bearing lubrication varies or shaft vibrations occur. Asymmetric thermal growth of support structures and sudden load changes can lead to circumferential clearance gap variation. Inspection of used seals reveals that these effects result in tooth rub which wears away the teeth or deforms them. In some cases an abradable coating on the rotor surface is worn away. In all cases the clearance gap is irreversibly enlarged, leading to more leakage and reduced efficiency.

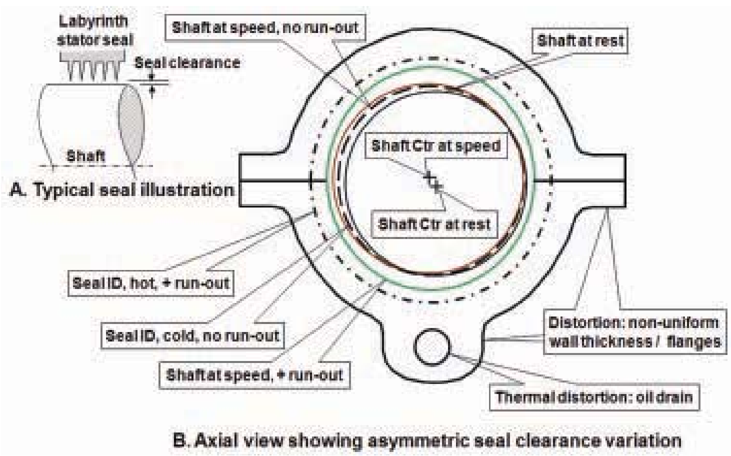


Figure 2. Shaft seal clearance design considerations [3].

PALS to the Rescue

PALS, shown in Fig. 1, is designed to use changing pressure drop forces across the seal to eliminate rub. The seal elements stay clear of the rotor seal surface during startup and shutdown transients, and subsequently close to a small, non-contacting, steady state running clearance.

The seal elements, or leaf seals, are formed from the two layers of circumferentially slotted, wear-resistant alloy shim stock, as shown in Fig. 1. The two slotted layers are imbricative, i.e. arranged a bit like overlapping shingles on a roof, such that each slot is covered by an upper or a lower leaf.

During startup or shutdown, when the axial pressure difference across PALS is small, the leaves are in a relaxed open position, providing a generous clearance gap for possible rotor seal surface eccentricities. At operating speeds, the resulting axial pressure difference causes the leaf element to elastically deflect and close, reaching the design clearance when they contact the support member shown in Fig. 1.

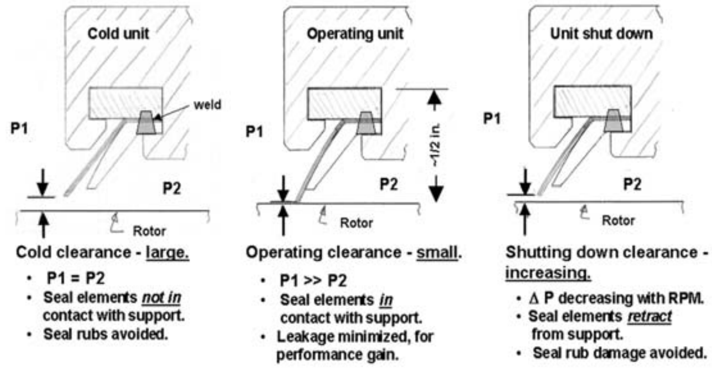


Figure 3. PALS operational characteristics [4].

PALS Future

Fig. 3 [4] gives a good overall picture of a PALS operation cycle. As reported in [1], test results show that the PALS concept provides for a potentially viable, robust, low leakage seal for gas turbine applications.

You may ask just how reliable is a leaf seal? As you read this, consider the multiple leaf seals in your own heart. Your aortic valve has three such leaflets, that open and close 50-70 times a minute - hopefully, for many years. Their operation is governed by the same fluid dynamic forces as those in PALS.

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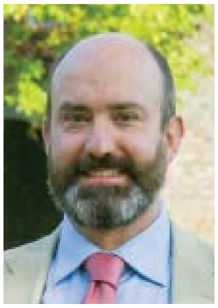
A VIEW FROM THE CHAIR

By Piero Colonna, Chair, ASME IGTI Board



Before sharing some news about our community, I take this opportunity to briefly introduce myself, the new chair of the IGTI board, as I am a new face to almost all members. I am the Professor of Propulsion and Power at the Delft University of Technology in the Netherlands. I come from Milano, Italy, where I initially studied Aerospace Engineering, and then went on to Stanford University. I moved to Delft in 2002, and since then enjoyed the very international academic environment and the charming city center with its canals. I lecture Thermodynamics to undergrad students, and Modeling of Energy Conversion Systems to masters students. My research interests cover organic Rankine and supercritical CO_2 power cycles and turbomachinery fluid dynamics. For this reason I ended up studying also quite fundamental aspects of what is now called non-ideal compressible fluid dynamics (NICFD).

I became a member of ASME in 2000, joined the Advanced Energy Systems Division, and later found my home at IGTI. Following the growing interest in ORC power systems, I chaired the organization of the first international seminar in 2011 at my university. More than 250 people participated, from companies, academia, and governments. I talked to Dillip Ballal, and he introduced me to the IGTI board. The result was that we organized the second edition of the conference as ASME ORC 2013 in Rotterdam and there formed the IGTI ORC Power Systems committee. This time we were 350 from all over the world, a very lively and dynamic sub-community with its own website, scholarships, workgroups, and inspiring enthusiasm.

Much to my surprise in 2014 I was asked to become a member of the IGTI board, and I humbly accepted this honor with the same fervor that propelled me throughout the ORC adventure. The more IGTI people I met, the more my sense of belonging grew, as I recognized that I shared the same values, passion for our technologies, idea of global and diverse community, sense of commitment toward society, and drive for high technical and scientific standards. The experience with the board has been amazing and I cannot thank enough the former chair Seung Jin Song (SJ for us) and the other board members, Hany Moustapha, Vinod Philip, Geoff Sheard, Al Volponi, James Free, and James Maughan (acting treasurer) for all that I have learned from them. I was even more bewildered and deeply honored when I was asked to succeed SJ in December, and…here I am.

Now on to news!

The excellent work of the Turbo Expo Conference Committee chaired by Tim Lieuwen, of hundreds of volunteers, and of our staff is paving the way to an exciting first Turbo Expo in Asia. A novelty will be that we will enjoy plenary sessions not only on Monday, June 13, but also on Tuesday and Wednesday. On Monday a panel formed by Eric Gebhardt (chief platforms & operations officer, Current - Powered by GE), Thomas W. Prete (vice president, engineering, Pratt & Whitney), and Daniela Gentile (CEO, Ansaldo Sviluppo Energia) will discuss "Energy and Propulsion in the Information Age." Moderators will be Tim Lieuwen (professor, Georgia Institute of Technology) and William A. Newsom, Jr. (executive vice president of sales & marketing, Mitsubishi Hitachi Power Systems Americas, Inc.) The plenary of Tuesday is titled "Asset Optimization and Monitoring in the Information Age" and the panelists are Maria Sferruzza (turbomachinery contractual and maintenance services GM, GE Italy) and Dr. Eisaku Ito (general manager, Mitsubishi Heavy Industries R&D). Moderators will be James R. Maughan (technical director, aero-thermal and mechanical systems, GE Global Research) and James M. Free (director, NASA John H. Glenn Research Center). On Wednesday Vinod Philip (chief technology officer, Siemens Power and Gas) and Akimasa Muyama (executive vice president & head of turbine products, Mitsubishi Hitachi Power Systems) will discuss "Gas Turbine Manufacturing in the Energy Age." Moderators will be Richard A. Dennis (advanced turbines technology manager, U.S. Department of Energy National Energy Technology Laboratory) and Karen A. Thole (department head of mechanical and nuclear engineering, professor of mechanical engineering, Pennsylvania State University).

More recently, the board has agreed to participate in a Task Force promoted by the Technical Events & Content (TEC) council, whose objective is to provide recommendations for the way forward for IGTI within TEC. This task force had its first teleconference on January 6, 2016, and is committed to completing its recommendations by the start of this month. As requested by the committee chairs, representatives of sponsor companies, and past IGTI board members, I will keep our community posted on our progress.

A forum for emerging systems and control technologies.

DYNAMIC SYSTEMS & CONTROL

MARCH 2016 VOL. 4 NO. 1

BIO-INSPIRED SYSTEMS

FROM ARTIFICIAL SKIN TO BIOLOGICAL INTELLIGENCE

ASME

SUBMIT ARTICLE IDEAS TO:

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SUBMIT DSCD NEWS ITEMS TO:

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

June 2016
Control Education

September 2016
Health Care Systems

Bio-Inspired Robotic Systems

Animals have shown the ability to survive and even thrive in harsh marine, ground, and air domains. Millions of years of evolution have provided elegant examples of sensing, actuation, and control that can be investigated in order to advance the operation of today's robotic platforms. Inspired by these examples, recent research has made substantial strides toward emulating the traits that have enabled the success of animals in nature. This issue of the *Dynamic Systems and Control* magazine presents a broad overview of recent progress and ongoing challenges in the field of bio-inspired and biomimetic sensing, actuation, modeling, and control for robotic systems.

In the first article, Feitian Zhang and colleagues discuss flow-relative control of a robotic fish prototype using distributed flow sensing inspired by the lateral line system of cartilaginous and bony fish. By assimilating measurements from a distributed array of local flow velocity and pressure difference sensors that function as the superficial and canal neuromasts of fish, the authors are able to estimate properties of the surrounding flow environment and use the ensuing estimate to control a flexible robotic prototype to a desired flow-relative swimming angle or speed. In the second article, Joseph Ayers draws biological inspiration from the animal nervous system toward the design of autonomous underwater robots whose control closely follows the neuronal circuit behavior of the lobster and lamprey. By mimicking the command neuron, coordinating neuron, central pattern generator (CCCPG) architecture that has evolved in nature, the article shows how two types of autonomous vehicles, the RoboLobster and RoboLamprey, perform sophisticated biomimetic motion including walking patterns and undulatory swimming. The third article by Yonas Tadesse and colleagues discusses recent advances in bio-inspired actuation, namely, the twisted and coiled polymer (TCP) muscle that aims to mimic the operation of biological muscle tissue. Using TCP muscle actuators and 3D printing techniques, the article presents the design and analysis of a musculoskeletal ball and socket joint that may serve as a building block component for future humanoid robots. In the final article, Carmel Majidi focuses on recent advances and ongoing challenges in soft electronics and sensors for bio-inspired robots. The article discusses how the merging of mechanics of materials with sensing and controls has resulted in elastomeric, soft-matter sensors that may function similarly to traditional solid state sensing technologies but more closely match the mechanical compliance of biological tissue.

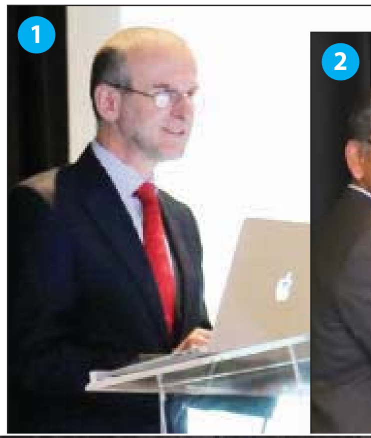
We greatly appreciate the authors whose hard work and dedication to their fields have contributed the content for this issue of the *Dynamic Systems and Control* magazine.

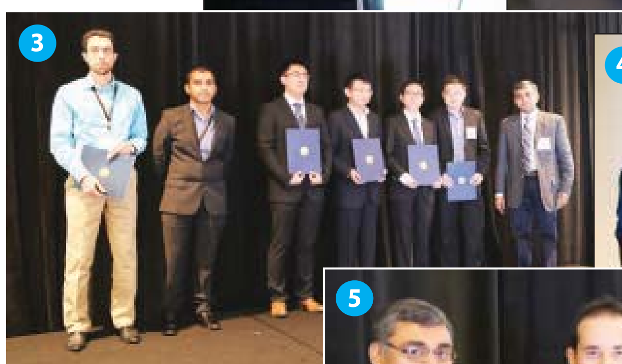
If you have any ideas for future issues of this magazine, please contact the Editor, Peter Meckl **(meckl@purdue.edu)**.

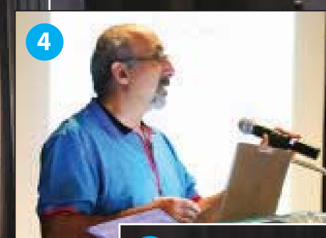
Levi DeVries, Ph.D., Assistant Professor
Kiriakos Kiriakidis, Ph.D., Professor of Estimation and Control
Department of Weapons and Systems Engineering
United States Naval Academy
Guest Editors, DSC Magazine

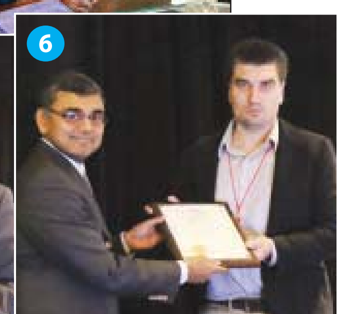
ASME 2015 DYNAMIC SYSTEMS AND CONTROL CONFERENCE AWARD RECIPIENTS

The ASME 2015 Dynamic Systems and Control Conference was held October 28-30 in Columbus, Ohio. Led by **Giorgio Rizzoni** as General Chair and **Rama Yedavalli** as Program Chair, there were 15 invited sessions, 30 contributed sessions, along with several workshops and special sessions. Given the location, the conference themes included manufacturing and automotive industries, along with explorations at the intersection of biology, ecology, and the life sciences as well as information technology in mechanical and aerospace engineering.









Satish Narayanan (Chair, DSCD Honors & Awards Committee) announced several awards to members of the DSCD community. Join us in congratulating the following award recipients:

Figure 1 – The Rufus Oldenburger Medal was given to **Manfred Morari** from ETH Zurich's Automatic Control Laboratory for his pioneering theoretical contributions to process control, hybrid system analysis, and model predictive control and for his practical applications to biomedical engineering, chemical process control, and automotive systems.

Figure 2 – The Nyquist Lecture, given by **Miroslav Krstic** of the University of California – San Diego, was titled, "Extremum Seeking and Its Applications."

Figure 3 – The Best Student Paper Award was given to **Molong Duan** (second from the far right), Keval Ramani, and Chinedum Okwudire from the Univ. of Michigan for "Tracking Control of Non-Minimum Phase Systems Using Filtered Basis Functions: A Nurbs-Based Approach."

The additional finalists, pictured from left to right with student names indicated in bold face, were:

Ramin Bighamian and Andrew Reisner from the Univ. of Maryland for "A Control-Oriented Model of Blood Volume Response to Hemorrhage and Fluid Resuscitation."

Prasad Divekar, Qingyuan Tan, Xiang Chen, and Ming Zheng from the Univ. of Windsor for "Diesel Engine Fuel Injection Control Using a Model-Guided Extremum-Seeking Method."

Chaozhe He, Wubing Qin, Necmiye Ozay, and Gabor Orosz from the Univ. of Michigan for "Hybrid System Based Analytical Approach for Optimal Gear Shifting Schedule Design."

Daniel Meyer, Wenlong Zhang, and Masayoshi Tomizuka for "Sliding Mode Control for Heart Rate Regulation of Electric Bicycle Riders." Daniel Meyer is from the Technische Universität München. His award was received by Wenlong Zhang.

Jiechao Liu, Paramsothy Jayakumar, Jeffrey Stein, and Tulga Ersal from the Univ. of Michigan for "An MPC Algorithm with Combined Speed and Steering Control for Obstacle Avoidance in Autonomous Ground Vehicles."

Figure 4 – The Yasundo Takahashi Education Award was given to **Jacob Apkarian** from Quanser in recognition of outstanding contributions in classroom teaching, courses and workshops, course development, lab development, textbook publishing, and software publishing.

Figure 5 – The Outstanding Young Investigator Award was given to **Rifat Sipahi** from Northeastern University for his outstanding research contributions in fields of interest to the DSCD.

Figure 6 – The Rudolf E. Kalman Best Paper Award was given to **Davide Spinello** (pictured) and Daniel Stilwell on "Distributed Full-State Observer with Limited Communication and Application to Cooperative Target Localization." This paper appeared in the *ASME Journal on Dynamic Systems, Measurement and Control* in 2014. ■

Edited by Denise McKahn, Smith College
Thanks to Marcello Canova, Ohio State Univ.

ROBOTIC FISH:

FLOW-RELATIVE CONTROL BEHAVIORS USING DISTRIBUTED FLOW SENSING

BY FEITIAN ZHANG,* FRANCIS D. LAGOR,* HONG LEI,† XIAOBO TAN,† DEREK A. PALEY*

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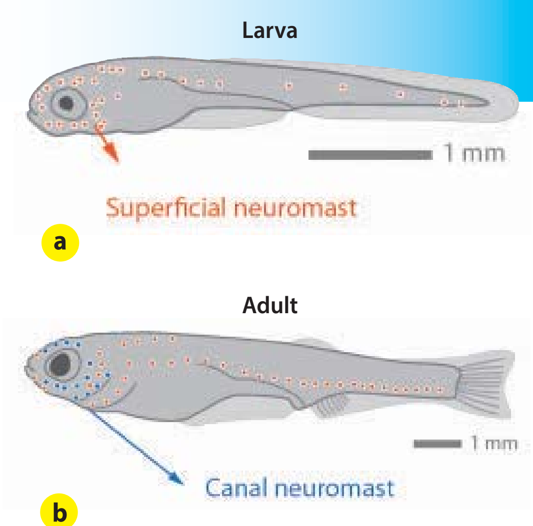
Over millions of years of evolution, fish have developed a flow-sensing system to detect the surrounding fluid motion, which consists of hundreds of receptor organs distributed on – and under – the skin [1]. Flow sensing serves an important role in swimming behaviors such as rheotaxis (orientation into or against the flow direction), station holding, predation, and schooling.

Advanced underwater vehicles that are biologically inspired attract scientific attention because of their potential for energy efficiency and maneuverability [2,3,4,5]. A flow-sensing capability enables robotic fish to navigate in unknown, murky, and cluttered environments. To demonstrate bio-inspired flow sensing and control using distributed pressure and velocity sensors, a rigid airfoil-shaped robotic fish [6,7] and a flexible, self-propelled robotic fish [8] have been developed at the University of Maryland. The robots are capable of rheotaxis, station holding, and speed control using a recursive Bayesian algorithm to assimilate measurements of the flow. A closed-loop control strategy that comprises feedback and feedforward designs has been validated in experiments.



THE LATERAL-LINE SYSTEM

The lateral line is the fish's sensory system for flow movement and vibration **(Figure 1)**. It consists of two types of sensing organs: canal neuromasts, which approximate the pressure gradient, and superficial neuromasts, which measure local flow speed [1]. A variety of artificial lateral-line systems [9,10] have been proposed for detecting flow movement, with the majority inspired by canal neuromasts due to the advantages in availability and performance of pressure sensors as compared to velocity sensors. There exists some research on flow estimation by underwater robots using artificial lateral-line systems [11,12], mostly based on empirical flow models generated from training data and/or applied to a towed rigid-body underwater robot. However, we have found very little prior work in the area of flow sensing for a flexible, self-propelled underwater robot using an analytical flow model and no prior work

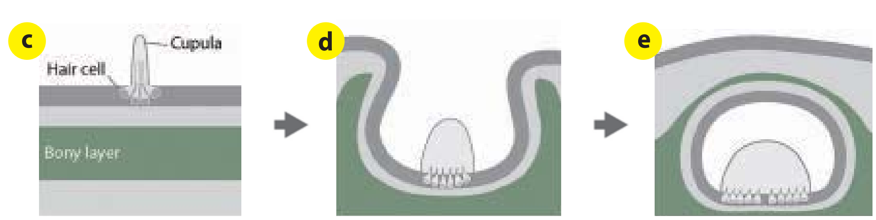


FIGURE 1 The lateral-line sensing organ in zebrafish; (a) Superficial neuromasts in larval fish; (b) canal neuromasts in adult fish; (c) structure of a superficial neuromast; (d) development of a canal neuromast; (e) structure of a canal neuromaast.

ZEBRAFISH DRAWINGS COURTESY OF MATTHEW MCHENRY, UNIVERSITY OF CALIFORNIA, IRVINE for this type of robot executing closed-loop behaviors based on an estimated flow field.

ROBOTIC-FISH DESIGN

The Collective Dynamics and Control Laboratory at the University of Maryland has constructed two robotic fish to study bio-inspired flow sensing and control of underwater vehicles. **Figure 2** shows a rigid, airfoil-shaped robotic fish made from composite polymer using a 3D printer. Mikro-Tip Catheter pressure sensors SPR-524 from Millar Instruments and ionic polymer metal composite (IPMC) sensors fabricated at Michigan State University [7,13] are embedded to measure local water pressure and velocity, respectively. The shape of the robot is a Joukowski airfoil, which is the output image of a conformal mapping of a circle [14] and is conducive to modeling the fluid analytically. This robotic fish measures 9.9 cm long, 2.2 cm wide, and 6 cm tall. A stepper motor with high-precision position control regulates its orientation and cross-stream position in a flow channel (185 L, Loligo).

The second robot is a flexible, self-propelled robotic fish **(Figure 3)** fabricated using a soft material, Ecoflex silicone rubber from Smooth-On with Shore 00-30 hardness. A mold was designed in Solidworks with the Joukowski airfoil shape and manufactured using a high-precision 3D printer; the mold holds the mixed compound of the soft material until cured. Embedded in the robot during the molding process are MEMS-based pressure sensors from Servoflo (MS5401-BM), which output analog voltage in proportion to the local pressure. The flexible robotic fish measures 20 cm long, 3.6 cm wide, and 12 cm tall. A shaft from MakerBeam was inserted at the one-quarter-point of the chord behind the leading edge to serve as the actuation-axis pivot. When rotated, the fish robot body deforms in a continuous way with the largest displacement at the trailing edge, mimicking fish swimming motion.

FLOW-SENSING ALGORITHM

Fish sense pressure differences (resp. local flow velocities) using canal (resp. superficial) neuromasts. Robotic flow sensing relies on mathematical modeling that relates pressure and velocity measurements to flow states such as the angle of attack and flow speed. Our research leverages two flow models: a quasi-steady potential-flow model [14] and an unsteady vortex-shedding model [15,16]. The quasi-steady model describes the flow past a cambered Joukowski airfoil using the relative flow speed, the angle of attack, and the camber ratio of the fish robot, which reflects the degree of the body bending. The velocity vector field is calculated from a complex potential function that depends on the three flow parameters. The vortex-shedding model captures the unsteady effect of fish flapping by introducing a point vortex into the flow field at each time step. However, the resulting increase in the system dimension leads to an unaffordable computational burden for real-time application. Thus, the quasi-steady flow model is used in the estimation algorithm and the vortex-shedding model is used only in simulation.

From the Bernoulli equation, the pressure difference between two sensors is a nonlinear function of the local flow speed at the locations of those two sensors. The nonlinearity in the measurement function led us to adopt a Bayesian filter [17] to assimilate sensor measurements for flow sensing. A Bayesian filter is a general probabilistic approach for estimating an unknown probability density function (pdf) from incoming measurements. It permits a nonlinear measurement function and non-Gaussian measurement noise. The flow-sensing measurements obtained from the robotic fish are the pressure differences between each pressure sensor pair and the local flow velocity at each IPMC sensor (when available). The estimation states may include the relative flow speed, the angle of attack, and the camber ratio, which is zero in the case of the rigid robot. The Bayesian filter recursively updates the pdf of

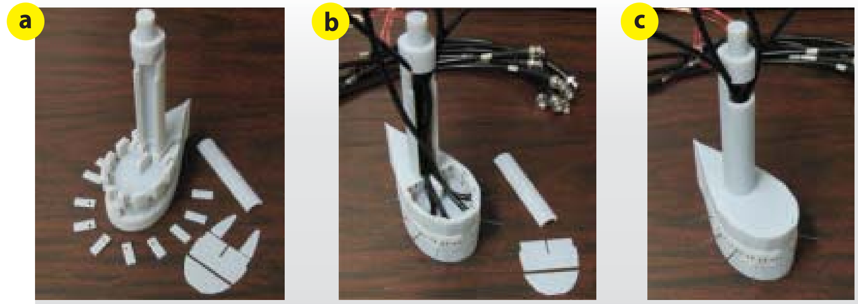


FIGURE 2 Rigid robotic-fish design with eight IPMC sensors and four pressure sensors [7]. (a) Modular 3D-printed parts; (b) sensor configuration; and (c) full assembly of robotic fish with artificial lateral line.

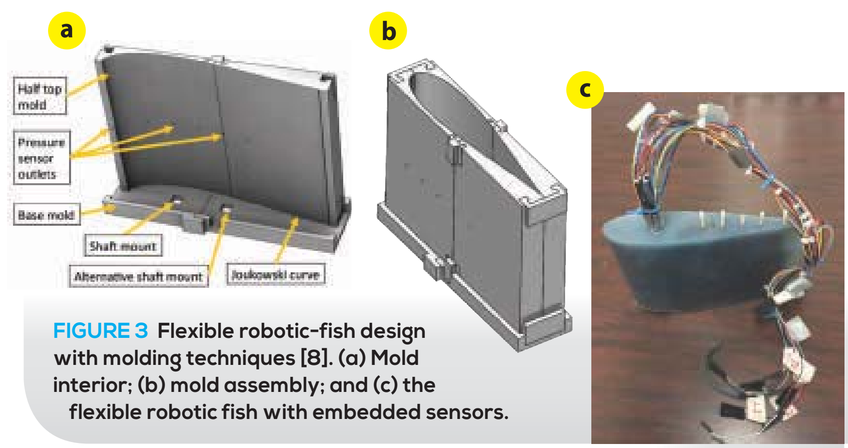


FIGURE 3 Flexible robotic-fish design with molding techniques [8]. (a) Mold interior; (b) mold assembly; and (c) the flexible robotic fish with embedded sensors.

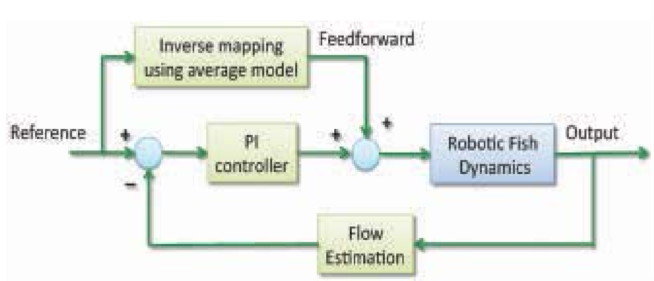


FIGURE 4 Block diagram of the closed-loop control system, combining feedforward and feedback control.

the estimated states that describe the flow field in order to provide real-time flow parameter estimates to the controller.

FLOW-RELATIVE CONTROL

A closed-loop control strategy that comprises feedforward and feedback designs achieves flow-relative behavior in the flexible robotic fish. **Figure 4** illustrates the control design in block-diagram form. The objective is to drive various states of the robotic fish to track desired reference signals by regulating the flapping amplitude and frequency. The feedforward controller is the inverse mapping of the dynamic model [18] of the robotic fish averaged over a single flapping period. The feedback controller includes proportional and integral terms based on information from the flow estimate. The feedforward term accelerates the convergence of the tracking control, and the feedback term improves the tracking performance by reducing the steady-state error.

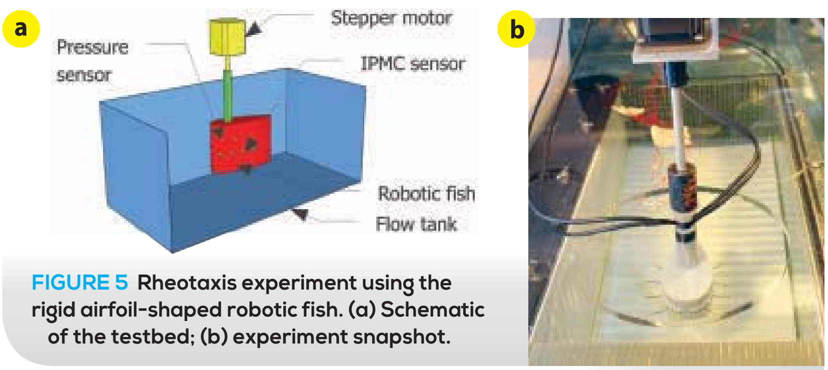


FIGURE 5 Rheotaxis experiment using the rigid airfoil-shaped robotic fish. (a) Schematic of the testbed; (b) experiment snapshot.

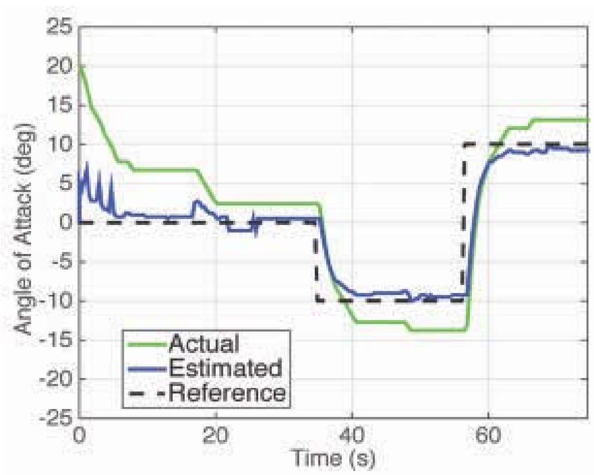


FIGURE 6 Trajectories of actual (solid green), estimated (solid blue), and reference (dashed black) angle of attack in rheotaxis experiment [7].

RHEOTAXIS CONTROL

Rheotaxis is a form of taxis observed in fish in which they generally orient into (or against) an oncoming current. The rheotaxis behavior requires sensing the flow direction. The rigid airfoil-shaped robotic fish **(Figure 2)** experimentally demonstrated rheotaxis behavior using a 185 L Loligo flow tank that generates approximately laminar flow **(Figure 5)**. A real-time, recursive Bayesian filter assimilated the pressure and IPMC sensor data in order to estimate the flow speed and angle of attack. A servomotor used these estimated quantities to regulate the orientation of the robotic fish by tracking the desired angle of attack, e.g., zero degrees, which is the upstream direction. **Figure 6** illustrates the trajectories of the actual and estimated angle of attack plotted versus time for a 75-second experiment under step inputs of the desired angle of attack. As the Bayesian filter estimation converges to the actual value, the servomotor steers the robotic fish to the desired orientation with a steady-state tracking error of less than 5 degrees.

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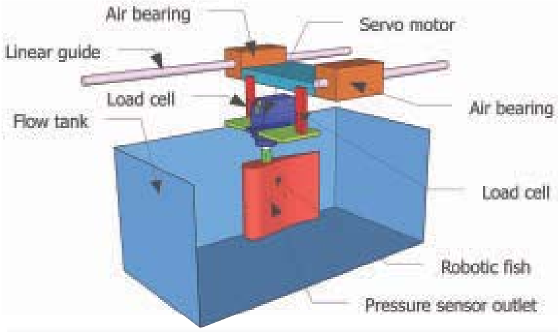
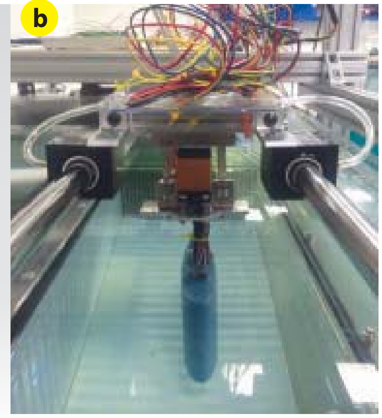


FIGURE 7 Schematic of the speed-control experimental testbed.

FIGURE 8 Speed-control experimental testbed. (a) Side view; and (b) front view.



SWIMMING-SPEED CONTROL

Closed-loop control of the flow-relative swimming speed plays an important role in fish predation and schooling behavior. We used the flexible, self-propelled robotic fish **(Figure 3)** to implement the speed-control behavior based on distributed flow estimation. A one-dimensional swimming testbed **(Figures 7** and **8)** includes air bearings to support the linear motion of the robotic fish in the along-stream direction. A servomotor driven in a periodic sinusoidal waveform controls the flapping motion, where the flapping amplitude and frequency are the control variables. The pressure measurement data is acquired using National Instruments DAQ 6225. The data is transmitted via USB to a laptop that runs the Bayesian filter for data assimilation and the closed-loop control, coded in Matlab 2013b. The control commands for the angle of attack are sent via serial communication to an Arduino UNO that drives the servo. The robotic fish demonstrated satisfactory control performance at a forward speed between 10 and 25 cm/s when actuated at a flapping frequency of 0.75 Hz. The steady-state speed tracking error was less than 5% and the convergence time less than two flapping periods **(Figure 9)**.

CONCLUSION AND ONGOING WORK

Bio-inspired flow sensing and flow-relative control using distributed sensor measurements were described and demonstrated with two underwater robots. Prototypes of the robotic fish were designed for experiments to include a rigid airfoil-shaped robot and a flexible, self-propelled robot. Flow past a Joukowski foil was modeled using quasi-steady potential flow theory and unsteady vortex-shedding techniques. The closed-loop control of the flexible robot comprised feedforward and feedback controls. Rheotaxis and speed-control experiments demonstrated the effectiveness of the flow sensing and control algorithms. In ongoing work, we are investigating a novel actuation approach using an internal reaction-wheel for flexible fish propulsion. ■

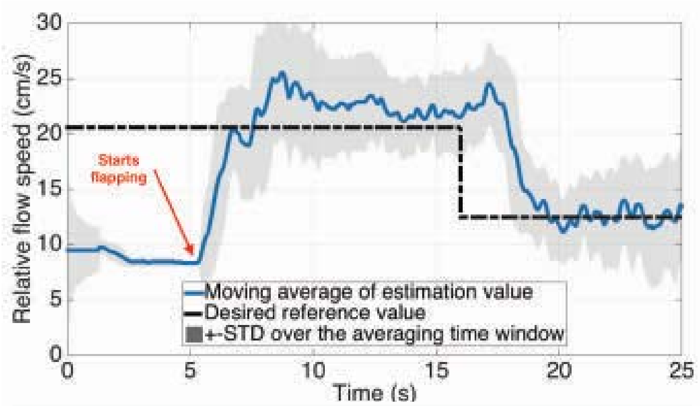


FIGURE 9 The moving average of flow-relative speed calculated using a time window equal to a single flapping period [8].

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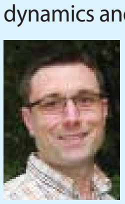

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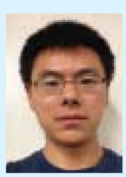

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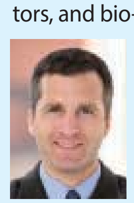

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UNDERWATER VEHICLES BASED ON BIOLOGICAL INTELLIGENCE

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Recent advances in biomimetics have made it feasible to integrate underwater robots that capture the performance advantages of their animal models [1, 2]. Animals that live in underwater environments are typically only slightly negatively buoyant so hydrodynamic forces are much stronger than gravitational forces [3]. Although most have visual systems, their ability to use vision is often hampered by low light and/or turbidity. As a result these animals have developed behavioral sets mediated by a limited sensor suite and differ profoundly from terrestrial or aerial animal models [4].

We have selected two predatory animals as models for our underwater robots **(Figure 1)**. Lobsters are high-end generalist predators that occupy a broad variety of ecological niches ranging from estuaries to beyond the continental shelf [5]. They are among the most maneuverable of arthropods and are able to walk in any direction and change their direction on a step-by-step basis while maintaining hydrodynamic stability.

The sea lamprey is equally at home in both still and flowing water. It is able to pursue fish and then attach itself with its oral sucker both to feed and to migrate. [6]. Most importantly, due to the presence of re-identifiable neurons, both the lobster and lamprey have become canonical neurobiological models and the basis of much of their behavior is understood at the level of neuronal circuits [5, 7, 8]

NEURONAL ARCHITECTURE

At the level of innate behavior, these animals have evolved a self-organized command neuron, coordinating neuron, central pattern generator (CCCPG) architecture that is conserved among all animal groups [9, 10]. This architecture is illustrated in Figure 2 and is based on several categories of network elements [11]. The most fundamental are central pattern generators [12], which are central networks that generate rhythmic behavior in the absence of timing information from the brain and sensory feedback. The central pattern generators are coordinated by intersegmental coordinating neurons that cause a governed CPG to perturb its timing relative to a governing CPG to establish an intersegmental gait [13]. The highest elements in this hierarchy are command neurons that turn on CPGs through parametric modulation and control their average frequency [14, 15]. These central networks are modulated by self-generated proprioceptive sensory feedback and external exteroceptive sensory feedback (due to gravity or flow) to adapt to contingencies of the environment.

Our initial explorations of biomimetic robot controllers were based on finite state machines that implemented the rules of the CPGs for lobster walking and lamprey swimming [16, 17]. Although these systems generated excel-

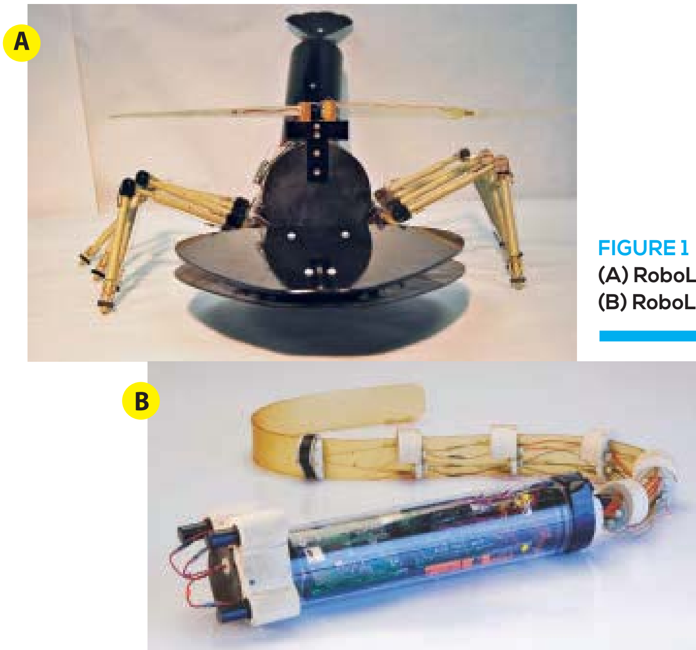

FIGURE 1 (A) RoboLobster. (B) RoboLamprey.

LAMPREY: BRIAN TUCKER BRESNAHAN PHOTOGRAPHY, ROBOLOBSTER: JAN WITTING PHOTOGRAHY

lent replicas of the behavior of the model organisms, they did not capture the adaptability of the animals to external perturbation. We explored the use of electronic neurons [18, 19], which are analog computers that solve the dynamical equations describing living neuronal activity. Electronic neurons generate highly adaptive motor programs **(Figure 6)**, but are physically too large to fit in the biomimetic robots. Although these systems can be implemented in subthreshold analog VLSI circuits, it is difficult to tune the parameters for the equations that determine dynamics [20].

DISCRETE TIME MAP NEURON AND SYNAPSE MODEL

We have settled on a phenomenological model of neurons and synapses [21, 22] based on a two dimensional map **(Figure 3)**. As this map represents the dynamics of the membrane potential trajectory, it profoundly reduces the dimensionality of the model, allowing real-time computation on small processors. The equations **(Figure 3A-B)** define a fast (x) and slow variable (y) that constrain a two-dimensional map of the membrane voltage in cycle n+1 as a function of the membrane voltage in cycle n **(Figure 3C)**. The function is nonlinear over different ranges of x_n corresponding to sub-threshold, threshold, and spiking activity **(Figure 3B)**. The nonlinear function **(Figure 3A-B)** is solved in a discrete-time loop and generates a new neuron voltage xn+1 when passed the present voltage x_n, the previous voltage x_{n-1}, and a synaptic current input. These maps define the voltage trajectory as a function of time and define a broad variety of neuronal types **(Figure 4)**. Two control parameters, alpha (α: **Figure 3B**) and sigma (σ: **Figure 3A**), determine whether the neuron is silent, spiking, or bursting and its average frequency **(Figure 4)**. The synaptic current (β) is calculated using the following variables: relaxation rate, synaptic strength, postsynaptic voltage, and reversal potential. The topology of the network is specified in the synapse structures that point to pre- and post-synaptic neurons. This architecture allows us to implement a broad range of neuronal integrative mechanisms.

The primary advantage of this model is that it is based on difference equations rather than differential equations so that large networks can execute in real-time on small processors [22, 23]. In fact, the neuron and synapse model will execute in real-time on the Lego Mindstorms™ brick [24]. In the Lego implementation, the neurons and synapses are instantiated as LabView instruments. In the biomimetic robots, neurons and synapses are represented as structures and the equations for each element are updated asynchronously at discrete times in a run-time loop.

CENTRAL PATTERN GENERATORS

To build electronic nervous systems we start with central pattern generators based on the biological networks [25-27]. The lobster CPG **(Figure 5A)** consists of a 4-component endogenous pacemaker-based neuronal oscillator that generates a 3-phase oscillation (early swing, late swing, and stance). The elevator synergy functions as the neuronal oscillator that determines the frequency of stepping and alternates with the depressor. Two elements of this neuronal oscillator (swing and stance) activate both bifunctional synergies of the basilar joint (protraction and retraction). Walking commands uncouple the inappropriate synergy to generate the forward and backward walking motor programs **(Figure 6)**.

In the lamprey CPG **(Figure 5B)**, there are three pools of about 50 functionally-similar neurons in each hemisegment. CC (contralateral caudal) neurons inhibit the contralateral CC, LIN (lateral interneuron) and EIN (excitatory interneuron) neuronal pools. Here the oscillation is generated primarily by reciprocal inhibition between the hemisegments of

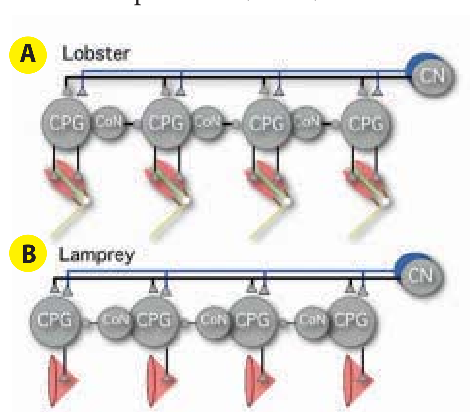

FIGURE 2 CCCPG Architecture. Abbreviations: CN: Command Neuron; CPG: Central Pattern Generator; CoN: Coordinating Neuron

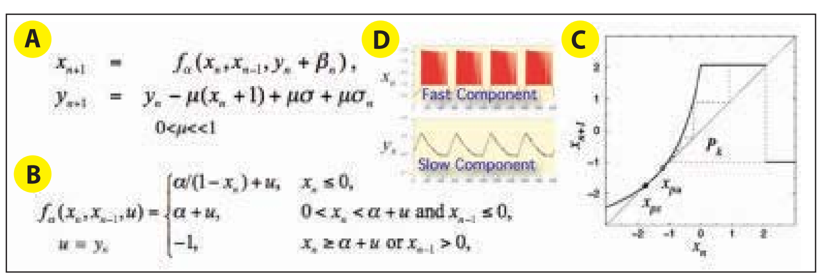

FIGURE 3 Discrete time map-based neuronal model. A. Fast and slow variables defined. B. The nonlinear function over different ranges of x_n. C. The map of x_{n+1} vs x_n. D. Time series representation of x_n and y_n.

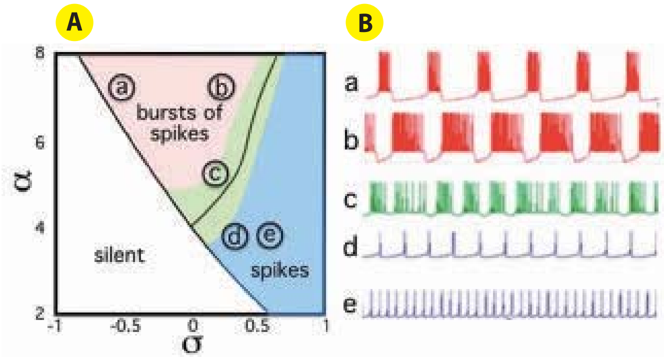

FIGURE 4 Parameter Space for the Neuronal Model A. State space of alpha (α) vs sigma (σ). Red area generates bursts of spikes (traces a, b), Blue area generates isotonic spikes (traces d, e). Green area generates chaotic activity (trace c). B. Corresponding waveforms. Each trace represents the waveform corresponding to the α/σ value pairs in A.

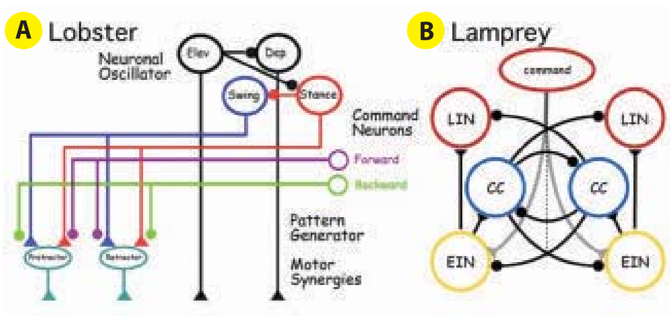

FIGURE 5 Central pattern generator networks. A. Lobster walking CPG. Abbreviations - Elev: elevator; Dep: depressor; Swing: swing phase interneuron; Stance: stance phase interneuron B. Lamprey swimming CPG. Abbreviations - LIN: lateral interneuron; CC: contralateral caudal interneurons; EIN: excitatory interneurons. Closed circles represent inhibitory synapses while triangles represent excitatory synapses.

opposite sides of the lamprey body, although the EIN neurons have endogenous pacemaker properties [25].

To complete the electronic nervous system, coordinating neurons **(Figure 2)** are used to connect the pacemakers of adjacent segments and are tuned to achieve the appropriate gait. Finally the descending commands are connected to the CPGs to bring them into operation **(Figure 2)**. In the lobster walking system there are four commands for forward, backward, lateral leading, and lateral trailing [28]. These can be activated in combinations to achieve diagonal walking. Separate commands operate on the antigravity depressor synergy to control height, pitch, and roll [29]. In RoboLamprey there are commands for slow and fast forward swimming, backward swimming, and amplitude modulation.

ARTIFICIAL MUSCLE

The electronic nervous system activates artificial muscle formed from shape memory alloys to control the behavior of the vehicles. The shape memory alloy Nitinol is used to form heart stents **(Figure 7A)**. When formed into wires it can be used as artificial muscle. Contractions are mediated by heating the wire ohmically, which causes it to convert from a deformed martensite state to a more compact austenite state **(Figure 7B)**. When cooled by the surrounding seawater, it becomes deformable and can be stretched by the action of the antagonist muscle by about 5% over its austenite length to the deformed martensite state.

To achieve excitation/contraction coupling, we use a comparator to generate a square wave from the motor neuron action potential **(Figure 7C)**. The square wave in turn gates a power transistor to apply current from a battery through the Nitinol muscle. The current heats the wire to proportionally convert it from the martensite to the austenite state. Thus we use heat in the same way that living muscle uses Ca^{++} to mediate excitation/contraction coupling [30]. By varying the frequency of motor neuron action potentials, we can achieve pulse width duty cycle control of both contraction velocity and the amplitude of contractions. In RoboLamprey, the actuators form a chevron between segmental "vertebrae" to mediate lateral undula-

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tions **(Figure 7D)**. In RoboLobster, pairs of actuators activate the different joints of the leg [19].

EXTEROCEPTIVE REFLEXES

Environmental feedback is sensed by analog sensors and converted to a labeled line code in sensory neurons [31]. To mediate a sense of direction, we use an analog compass **(Figure 8A)**. Here the actual heading is compared with the desired heading to generate a heading deviation statistic **(Figure 8C)**. The heading deviation magnitude is used to modulate a heading deviation (HD) neuron such that it discharges maximally when the heading deviation is 180° and is silent when it is 0°. The HD neuron excites three sensory interneurons that are connected by lateral inhibitory connections with increasing thresholds so that each of the three responds to different ranges of heading deviation.

These sensory interneurons activate command neurons to mediate fusion of exteroceptive reflexes, where several command neurons are activated in parallel and their effects are combined at the CPGs **(Figure 9)**. Primary command neurons project from the "brain" to each of the segmental CPGs and their synaptic and modulatory effects summate there. Analogous commands exist for decapods such as the lobster [32], but are complicated by the capability for lateral walking in addition to forward and backward walking. Layered exteroceptive reflexes therefore control heading and mediate adaptations to optical and

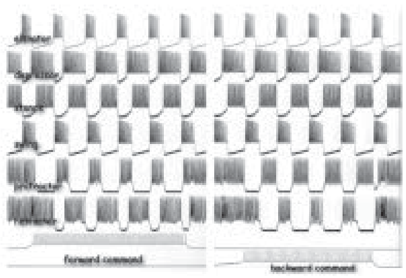

FIGURE 6 Walking Motor Programs. The top four traces are from the interneurons in the neuronal oscillator of Fig. 5A. The fifth and sixth traces are from the bifunctional protractor and retractor motor neurons. The bottom two traces are from the forward (left) and backward (right) command neurons. This simulation was performed with Hindmarsh-Rose neurons [18].

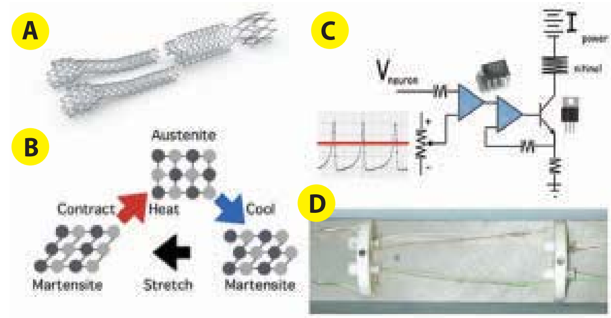

FIGURE 7 Shape memory alloy muscles. A. A heart stent. B. Conversion between austenite and martensite states with heating, cooling, and stress. C. Excitation/Contraction coupling circuit. A comparator forms a pulse from electronic neuron action potentials that gates the power transistor applying current to the Nitinol actuator to heat the wire. D. Chevron muscle configuration to generate lateral undulations.

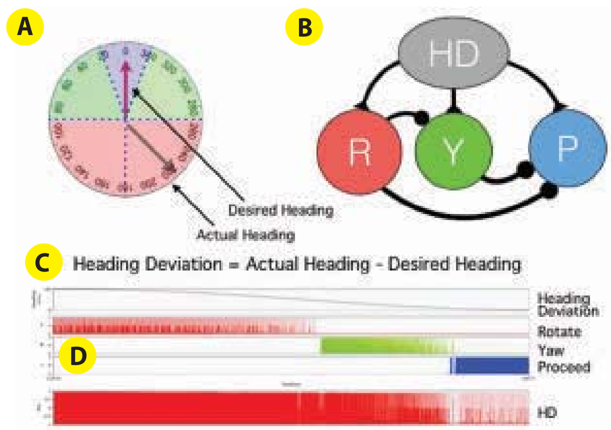

FIGURE 8 Heading deviation neurons. A. Compass indicating desired and actual headings B. Lateral inhibition-based range fractionating network. C. Heading deviation computation. D. Operation of Range Fractionation Network. Heading deviation computed from C is used to proportionally activate the HD neuron.

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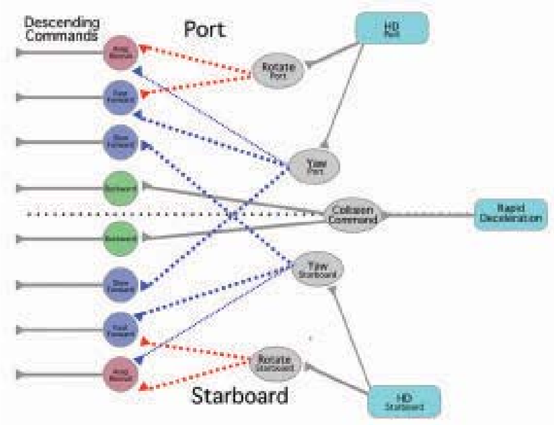
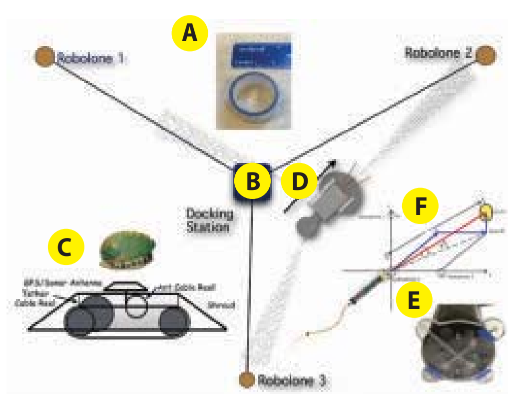


FIGURE 9 **Exteroceptive reflex architecture in the RoboLamprey brain. The objects on the left represent descending commands (see Fig. 2), for backward swimming, slow and fast forward swimming and amplitude modulation. These command neurons descend to activate segmental CPGs on the port and starboard sides. The dashed lines represent projections from Rotate and Yaw sensory interneurons that are activated by heading deviation neurons (HD) as in Fig. 8. An accelerometer modulates a collision interneuron (Rapid Deceleration) that excites backward swimming commands to mediate obstacle avoidance reflexes.**

FIGURE 10 **Localization and communications sonars. A. A 40kHz Q piezoelectric transducer is used for communications and localization. B. An array of Robolones are cabled to a docking station that has a wireless link to shore. C. Tracked Robolones deploy a cable and an acoustic transducer to form a long-baseline sonar array. D. During operations, the walking and swimming vehicles are deployed on a search vector consisting of a heading and a distance. At the end of the vector, the vehicle pings, is localized by the docking station and given a subsequent search vector. E. Short-baseline sonar array on the vehicle. F. Filters and a localization algorithm compute the deviation of a sonar beacon in azimuth and inclination to allow homing and docking.**



hydrodynamic flow, collisions, and gravity in parallel.

REACTIVE AUTONOMY

We plan to control the systems by supervised reactive autonomy. Consider a human taking a dog on a walk. The human is the supervisor and the dog is reactively autonomous. If the human throws a stick in a lake, the dog autonomously fetches it and returns. This is the natural way to control robots in the field and allows a single operator to control multiple robots.

Nature provides excellent lessons of how to mediate supervised reactive autonomy. The waggle dance of bees provides a canonical example [33]. Here guide bees communicate a heading relative to the sun and a distance to the food source. We have implemented a visual odometer in the honeybee platform and this will operate in an analogous fashion in the walking and swimming robots [34]. Search vectors composed of a heading and a distance monitored by a compass and visual odometry can organize the autonomous behavior of the vehicles and these supervisory commands can be transmitted to the vehicle via sonar by a human operator or random search algorithm.

COMMUNICATIONS AND LOCALIZATION

We are integrating a long baseline array for communications and localization of the robots [35]. Basic communications are provided by a piezoelectric acoustic transducer (**Figure 10A**) [36]. Supervisory commands will be transmitted as message packets of four tones delivered at discrete intervals (i.e., 50, 100, 150, etc.). The four tones will define three intervals that specify a target, method, and data. When a vehicle receives and successfully decodes a message it will send an acknowledgement.

Figure 10B illustrates how a long baseline sonar array will be configured in the field. Three tracked robots based on the Abalone (Robolone, **Figure 10C**) will host a cabled float antenna with GPS and sonar transducers. A central base station will integrate batteries, an inductive charging station and a wireless sonobuoy link to shore. The Robolone will form a tri-radiate array, elevate the GPS to the surface to establish an absolute position, then submerge to the optimal depth for sonar communications and these will be transmitted through cables to the base station (**Figure 10B**). At the end of search vectors, coded tones transmitted by the vehicles will be detected by the Robolone and relative arrival times will be used to compute the position of the vehicle relative to the docking station (**Figure 10D**). When the vehicle needs to home to dock, it can use a short baseline sonar array (**Figure 10E**) to compute the deviation of the sonar target from the hull in azimuth and inclination (**Figure 10F**) to mediate heading deviation reflexes that will allow the vehicle to home on a sonar beacon on the docking station. A key goal of this system will be to achieve energy autonomy and persistence in underwater habitats.

A fundamental premise of this system is that the intrinsic control of the system is based on neuronal synaptic networks. This biological intelligence can mediate supervised reactive autonomy through neuronal integrative processes in networks [37]. The only algorithms will be in the localization and communication systems. These will communicate goals to the vehicle's electronic nervous system, such as the desired heading and synaptic strengths proportional to the desired distance. Exteroceptive reflex networks will use these goals to govern the achievement of the desired path. The networks of biological intelligence represent a viable alternative to the algorithms of artificial intelligence in the achievement of robotic autonomy. ■

ABOUT THE AUTHOR

Joseph Ayers is a neurobiologist who specializes in the neuroethology of motor systems in vertebrates and lower vertebrates and the application of this knowledge to the development of electronic nervous systems to control advanced robots. He received his PhD from the University of California, Santa Cruz and was a post-doc at CNRS, Marseille and UCSD. He is a professor of marine and environmental sciences and biology at Northeastern University and conducts his research at the Marine Science Center in Nahant, Mass., where he was director from 1991-2001.

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MUSCULOSKELETAL SYSTEM FOR BIO-INSPIRED ROBOTIC SYSTEMS

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A musculoskeletal system is the fundamental structure that allows complex mobility of biological systems. Several research attempts have been made in the past to mimic this structure using synthetic materials for use in robotic systems. The challenge to develop such systems is multifaceted, including design, manufacturing, system integration, control methods and energy usage. The most important element of a musculoskeletal system is artificial muscles or actuators used in this system. Even though many types of actuators are proposed in the literature, most of them do not match the performance of natural muscles in all metrics such as force generation, strain output, frequency, power density, ease of control, and repeatability. This article briefly describes the recently introduced *twisted and coiled polymer* (TCP) muscles and a novel design of musculoskeletal system based on ball and socket joint, as well as their application in a 3-D printed humanoid robot. The musculoskeletal system can serve as a building block for bio-inspired systems that can be cascaded in various fashions to create complex robots.

SYNTHESIS OF TCP MUSCLES AND STRUCTURES FOR ROBOTS

Twisted and coiled polymer muscles are soft polymer muscles formed by inserting twists in a polymer precursor

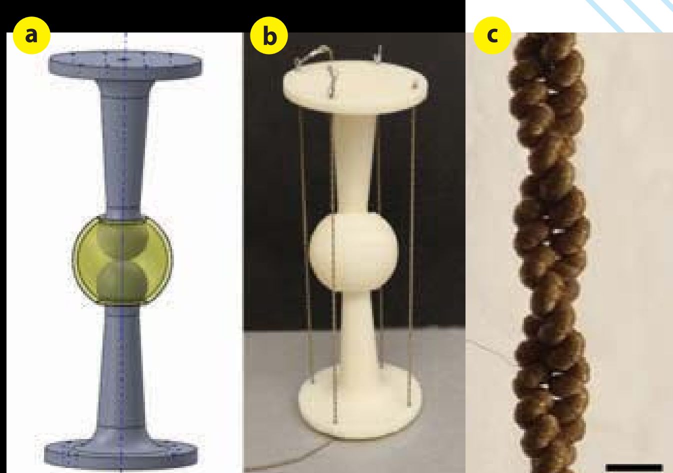

FIGURE 1
Ball and socket joint (a) CAD model, (b) 3-D printed prototype, and (c) twisted and coiled polymer muscle. The bar scale is 1 mm long.

fiber such as polyethylene fishing line or nylon sewing thread (silver-coated nylon precursor) using a simple rotatory motor or coiling the fiber around a mandrel while it is pre-tensioned by a weight, followed by thermal treatment [1]. When heated electrothermally (resistive heating, by applying electrical power across the ends), the silver-coated TCP muscles contract, generating force/stress. The material is suitable to develop soft robots, assistive devices, prosthetics or orthotics, and humanoid robots. TCP muscles wrapped with carbon nanotubes (CNT) can be actuated electrothermally. It was shown that the muscles could sustain millions of cycles before failure [1]. Wrapping with CNT is not necessary, but it helps in heating the polymer due to the high

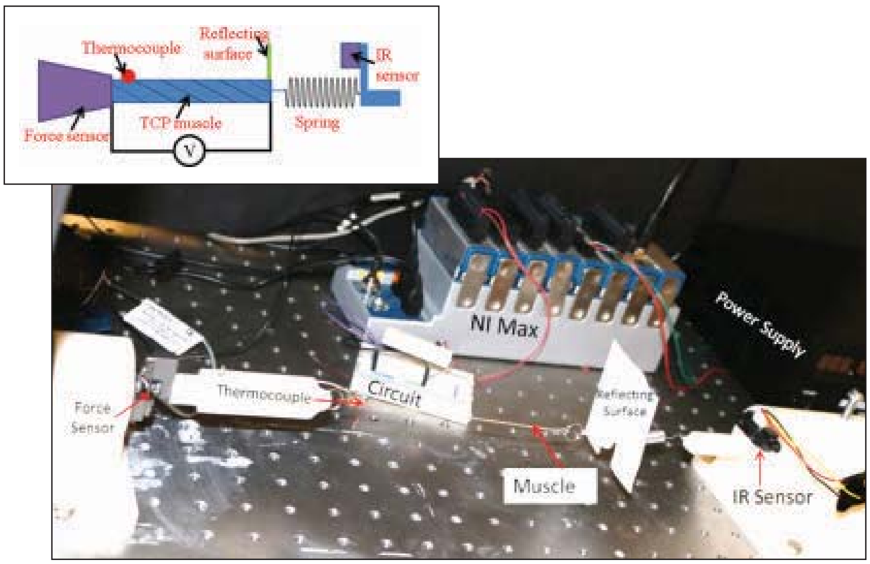

FIGURE 2 **Experimental setup used to test the time domain response of the 1-ply TCP muscle. The inset is the schematic diagram.**

conductivity of CNT. Silver-coated TCP material (without CNT) was used to develop a novel musculoskeletal system (shown in **Figure 1**). The muscles are arranged to actuate a ball and socket joint in two axes. Another two diagonal muscles can be integrated for the third rotation. Extremely twisted coiled polymer muscles could provide large strain (20-49%), large stress (1-35 MPa) and high mechanical work (up to 5.3 kW/kg) [1]. Therefore, it is worth investigating this material further for application in robotics.

The resistance of the TCP muscles changes during actuation, which can be detected by a microcontroller for sensing applications [1, 2]. Therefore, the muscles have self-sensing capabilities and do not require external sensors. Since the muscles are inexpensive as compared with other actuators, they can be used for multiple purposes. The fundamental material properties are dependent on the synthesis technique (coiling speed, weight used, heat treatment, fiber alignment, annealing time, and precursor materials). There are currently few studies about the relationships between these parameters and performance. Therefore, experiments and theoretical modeling are required to establish the synthesis-performance relationships of TCP at various scales and domains (macro and micro).

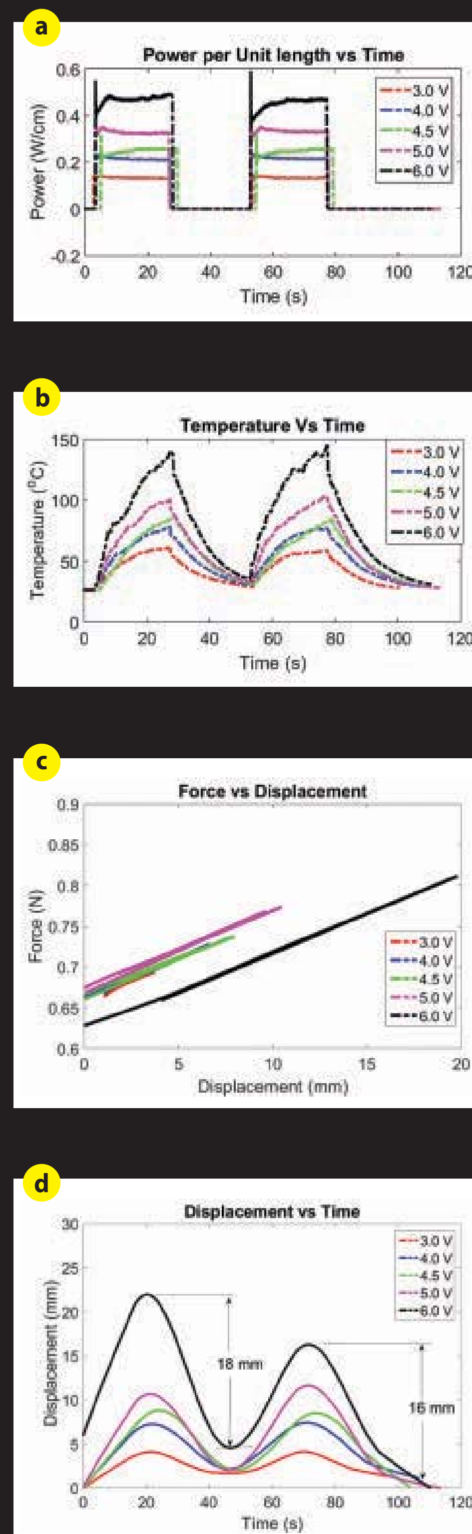

FIGURE 3 **Time domain experimental results of 1-ply TCP muscle: (a) power, (b) temperature rise, (c) force, and (d) displacement.**

SOFT ACTUATORS FOR BIOMIMETIC ROBOTS

Actuators are the building blocks of many robots, and a fundamental understanding of their operation and construction is required to create novel bio-inspired robots. Several soft biomimetic robots are presented in the literature, including hydrogen fuel-powered robotic jellyfish made out of MWCNT/SMA/Pt [3], and 3-D printed elastomeric tentacle structures integrated with shape memory alloy actuators [4]. The MWCNT/SMA/Pt is a composite muscle consisting of platinum catalyst-coated multi-wall carbon nanotube (MWCNT) sheets, wrapped on the surface of nickel–titanium (NiTi) shape memory alloy (SMA). SMAs are useful for soft robots. However, they are expensive (e.g., BMX150 costs $115/5m, equivalent to $3000/kg) compared with the TCP material ($5/kg for the precursor fiber) presented in this article. Other actuators such as dielectric elastomers, conducting polymer, fluidic, hydraulic, hydrogel, and carbon nanotube actuators are in general the subjects of continued research to improve their performance.

TCP MUSCLES—ELECTRICALLY ACTIVATED

Recently, some research groups have presented experimental results of TCP muscles (referred to as coiled nylon in most papers) on various aspects such as variable stiffness structure [5], torsional actuation [6], and actuation using hot air [7]. We recently demonstrated [8] a contraction of 22% for a coiled monofilament fiber when heated/cooled by 25°C and 95°C water while lifting a 200 g weight for actuation of a robotic finger. However, actuation using resistive heating of the silver-coated muscle is easier for robotic applications.

We have conducted experiments on single ply (1-ply) muscle using resistive heating to actuate the muscle and obtain time domain experimental measurements using LabVIEW. We used a K-type thermocouple, an Omega LCL-010 load cell, and a Sharpe IR displacement sensor for the measurement of temperature, force, and displacement, respectively. Current and voltage were measured by NI modules and electrical power was provided to the muscle using computer controlled BK Precision (1687 B) power supply as shown in **Figure 2**.

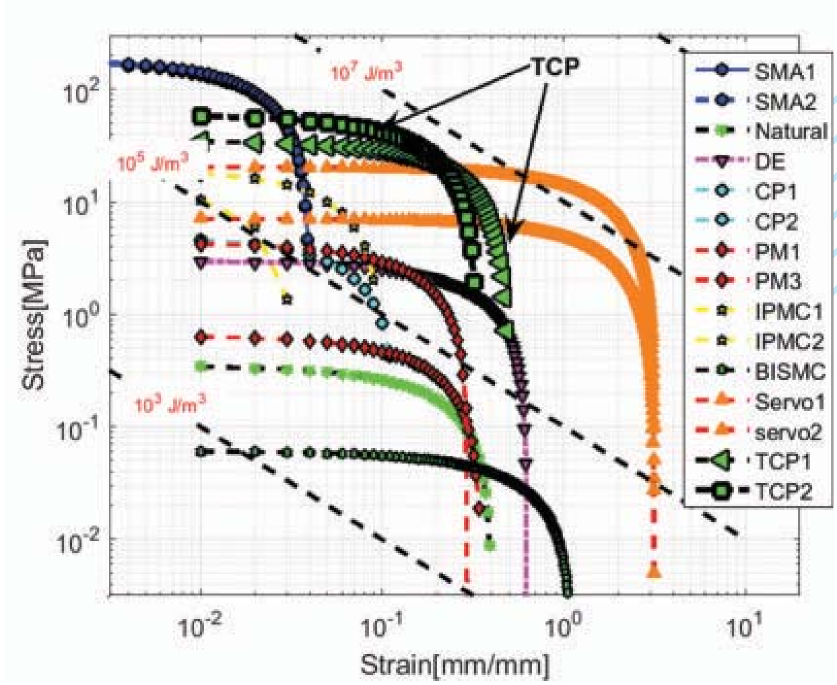

FIGURE4 Actuator technologies comparison , blocking stress-strain and energy density [1],[12]. CP = Conducting polymer; SMA = Shape memory alloy; DE = Dielectric elastomer; PM = Pneumatic muscle; BISMC = Bioinspired composite; BMF = Biometal fiber SMA; IPMC= Ionic metal composite; Servo = Small RC servo HS81; Natural = Skeletal muscles; TCP = Twisted and coiled polymer muscle.

We used five different values of power as shown in **Figure 3a** and performed experiments for two cycles. The corresponding temperature distribution is provided in **Figure 3b,** where the rise in temperature ranges from 60°C to 150°C. The Force-Displacement diagram is illustrated in **Figure 3c**, where the force has an almost linear relationship with the displacement, and has almost zero hysteresis. In **Figure 3c**, all the forces begin from ~0.65 N due pre-straining of the muscle. Pre-strain is an important factor in performance and life of the muscle. The actuation of the 1-ply muscle reaches up to ΔL=18 mm displacement, which corresponds to 20% strain as shown in **Figure 3d**. Actuation strain is defined as $\varepsilon = (\Delta L/L)$ 100%, where ΔL is the displacement from initial position and L is the length of the actuator or the muscle before actuation (L= 90 mm).

Several researchers have reported results on TCP muscles, including a strain of 50% at 80 MPa using a fiber diameter of 0.5 mm [7], and 29% actuation at 4.1 MPa stress with regard to the coil cross-sectional area (26.8 MPa when normalized with the fiber diameter) using precursor fiber diameters of 188 µm and 296 µm [9]. Another report showed 10% actuation at 1 N force using a precursor fiber diameter of 720 µm [10]. In our experiments on 1-ply muscle, a 0.8 N force has been observed at maximum of 18 mm displacement (20% actuation strain), as can be seen in **Figure 3c**. The muscle for this test was prepared from a silver-coated precursor diameter of 180 µm and twisted and coiled under a 120 g load, resulting in a coiled diameter of 920 µm and length of 90 mm. Performance of the muscle is very much dependent on the way the muscle is synthesized, including the annealing process. For instance, 33% to 11.6% hysteresis were reported in [7]. But we have observed much less hysteresis loss, as can be observed from **Figure 3c**.

FIGURE 5a 3-D printed ball and socket joint: left (no actuator), right actuated by 4 TCP muscles.

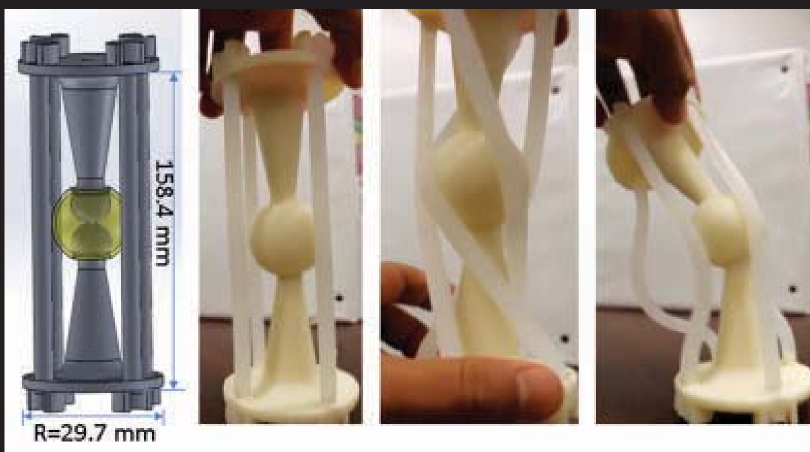

FIGURE 5b 3-D printed ball and socket joint with silicone elastomer support. CAD design and prototype twisted manually.

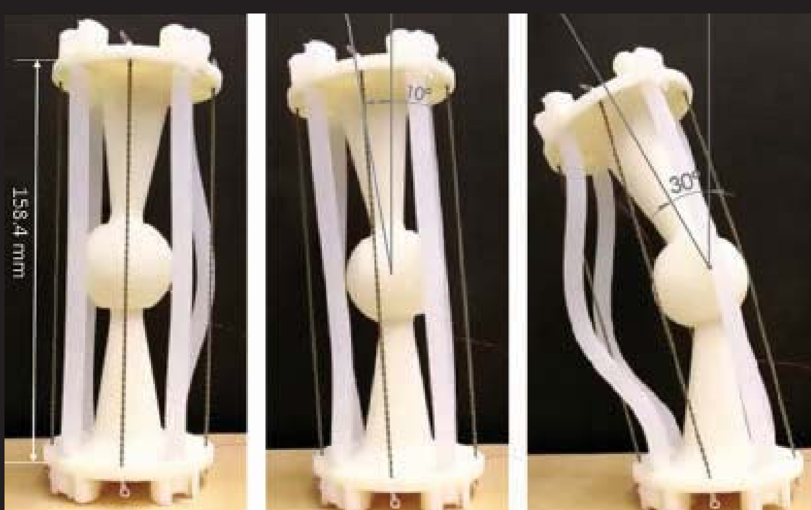

FIGURE 5c Front view of ball and socket joint with silicone elastomer support and actuators (one muscle actuated).

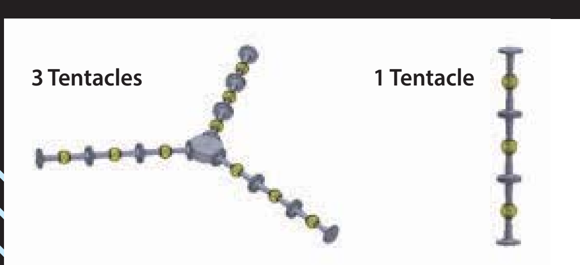

FIGURE 5d CAD models of other bio-inspired robots made by cascading a musculoskeletal system building block.

WHY TCP?

The key parameters for comparison of artificial muscles are the free strain and blocking stress [11, 12]. **Figure 4** depicts some of the performance indices of suitable actuators for soft robots and humanoid robots in terms of stress-strain and energy per volume. In the plot, cylindrical SMA actuators showed the highest stress, greater than 100 MPa and energy density between 10^5-10^7 J/m^3 (diagonal lines). In general, SMA actuators were the best actuators for low frequency applications in the last decades. However, this position is challenged by recent development in artificial muscle, specifically twisted and coiled polymer muscle, which is extremely inexpensive, compared to SMA and overcomes the limitations of SMA [1], [8], [12], [13]. As can be seen in **Figure 4**, the TCP muscle exhibits superb performance in stress-strain and energy density (diagonal line) graphs.

NOVEL MUSCULOSKELETAL SYSTEM CHARACTERIZATION

The musculoskeletal system shown earlier in **Figure 1** was tested to generate multidimensional actuation. The design and prototype are illustrated in **Figure 5a**. Based on this design, we developed prototypes shown in **Figure 5b**. **Figure 5b** shows the prototype (ball and socket joint with cylindrical soft silicone support, Ecoflex® 00-30 hardness), which has the ability to twist in any angle. In another prototype, as shown in **Figure 5c**, the TCP muscles are integrated in parallel with the cylindrical silicone supports. The current prototype can reach a maximum bending angle of 30°. The muscles were produced following a similar fabrication procedure as reported in [1]. Here 120 g was used as the dead weight during twist insertion. Then the coiled muscles were folded in the middle to make 2-ply muscles. The muscles after annealing and appropriate training can achieve around 6.5%~14% actuation under a power of 0.14~0.21 W/cm (note that this actuator is different from the one shown in **Figure 3**, 1-ply muscle). In order to actuate in two axes, 4 TCP muscles were crimped on both ends and then anchored in parallel to the bottom and top plates of the joints.

The TCP muscles were placed in agonist/antagonist pairs so that the joint rotation can be controlled by adjusting the power input to the muscles. The bio-inspired ball and socket joint can be cascaded to create complex robots as shown in CAD design in **Figure 5d**, e.g., 1 or 3 tentacle robots. Such robots could be used in underwater or terrestrial environments.

HUMANOIDS

In the areas of humanoids, robots have been developed in universities and research institutes. The actuators used in these robots are not inexpensive, not based on smart actuators, and not biomimetic. Some of the advanced humanoids include ASIMO, Robonaut, and HRP-4C. Therefore, more work is needed to make humanoids smarter and more affordable. Smart materials are responsive to external stimuli such as stress, temperature, electric field, magnetic field, humidity, and pH. They can be used as actuators (artificial muscles), sensors, and energy harvesting systems. We have made several efforts in creating humanoids using various smart actuation technologies: piezo-

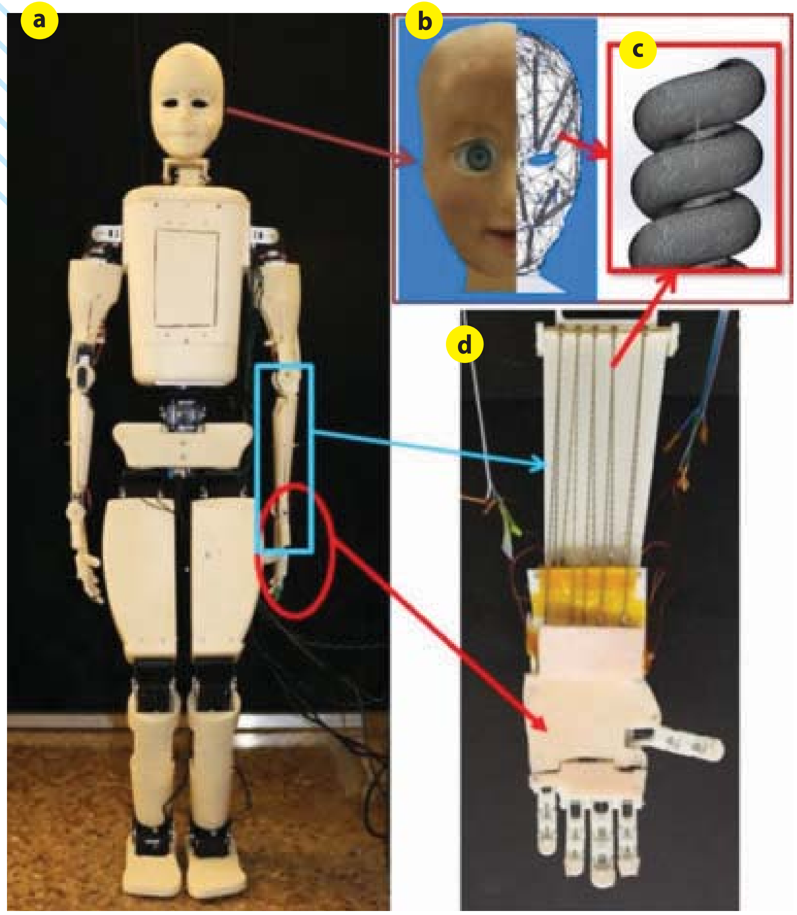

FIGURE 6 (a) Our 3-D printed humanoid robot HBS-1, (b) conceptual design of TCP muscle for the face, (c) inset of the muscle, and (d) robotic hand actuated by TCP muscles for the hands and servomotors for other joints.

ABOUT THE AUTHORS

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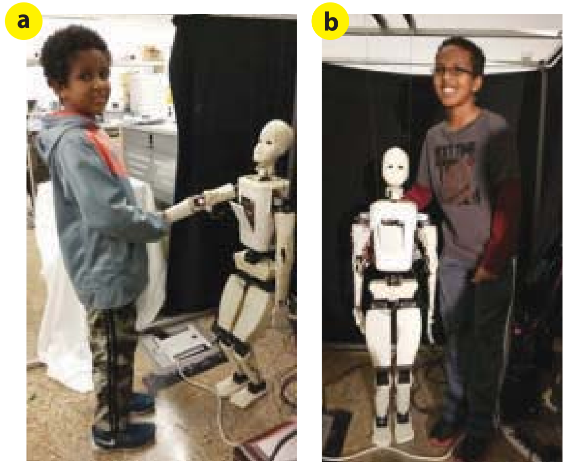

FIGURE 7 (a) and (b) Kids interacting with our humanoid robot HBS-1.

electric motor, conducting polymer, and shape memory alloy actuators. The latest humanoid is actuated by TCP muscles and uses additive manufacturing technology. Key scientific challenges (synthesis, characterization and modeling) and performance of smart materials were described in our previous works [8, 12, 14]. **Figure 6a** is our humanoid robot, HBS-1, that has been developed using TCP muscles and other actuators. The TCP muscles are used for actuation of fingers **(Figure 6d)** of the robots [15] and the muscles can also be applied for facial muscles as shown in **Figure 6b** and **6c**. Other actuation technologies have been investigated in the literature. However, not all of the requirements of cost, performance, complexity, and usability have been met.

HUMANOID ROBOT APPLICATIONS AND OUTLOOK

Humanoid robots can assist human beings in numerous ways, from military applications and firefighting to entertainment, socially assistive devices, medical studies, and childhood education. Soft actuators are showing excellent results for the development of these humanoids for cognitive studies or for training medical professionals. In addition, facially expressive robots are demonstrating encouraging results as therapeutic tools for children with Autism Spectrum Disorder (ASD). Various studies suggest that the design space of humanoid robots needs to be advanced in order to achieve conclusive results. Young children would like to interact with a humanoid robot as long as it is under their size. As shown in **Figure 7a** and **7b**, two brothers (10 and 12 years old) enjoyed interacting with our humanoid HBS-1. They want the robot to have high capability just like Spiderman.

Some of the challenges in humanoid design are the degrees of freedom and the synergetic combination of hardware and software to perform a particular task. The other challenge is affordability of the platform. Most humanoids are very expensive. Since the TCP-based actuators are inexpensive and musculoskeletal systems inspired by biological systems are optimum for performance, they will address these problems. The bio-inspired ball and socket joint shown earlier in **Figure 1** can be cascaded to create complex robots, for example, for the shoulder joint of a humanoid. ■

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ARTIFICIAL SKIN

SOFT ELECTRONICS & SENSORS FOR BIO-INSPIRED ROBOTS AND WEARABLE COMPUTING

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In order to match the versatility and robust mechanical properties of their natural counterparts, bio-inspired robots must be soft and elastically deformable [1]. This not only requires new classes of "artificial muscle" actuators but also artificial nervous tissue and skin to support stretchable electronic connectivity, sensing, and automation. In recent years, a broad range of materials, composites, and so-called "deterministic" micropatterned architectures have been introduced to support soft and stretchable electronic functionality [2]. These include conductive textiles, wavy circuits, graphene and nanotube films, filled elastomer composites **(Figure 1)**, and liquid metal microfluidics **(Figure 2)**. A common feature of these materials and architectures is their intrinsic mechanical compliance, stretchability, and low mass density. Such properties are especially important in wearable systems for personal computing and human motor assistance. By matching the mechanical properties of skin and nervous tissue, these materials can be mounted to the body or embedded in clothing without causing discomfort or injury. However, replacing rigid (and semi-rigid, i.e. flexible but inextensible) electronics with stretchable materials introduces new

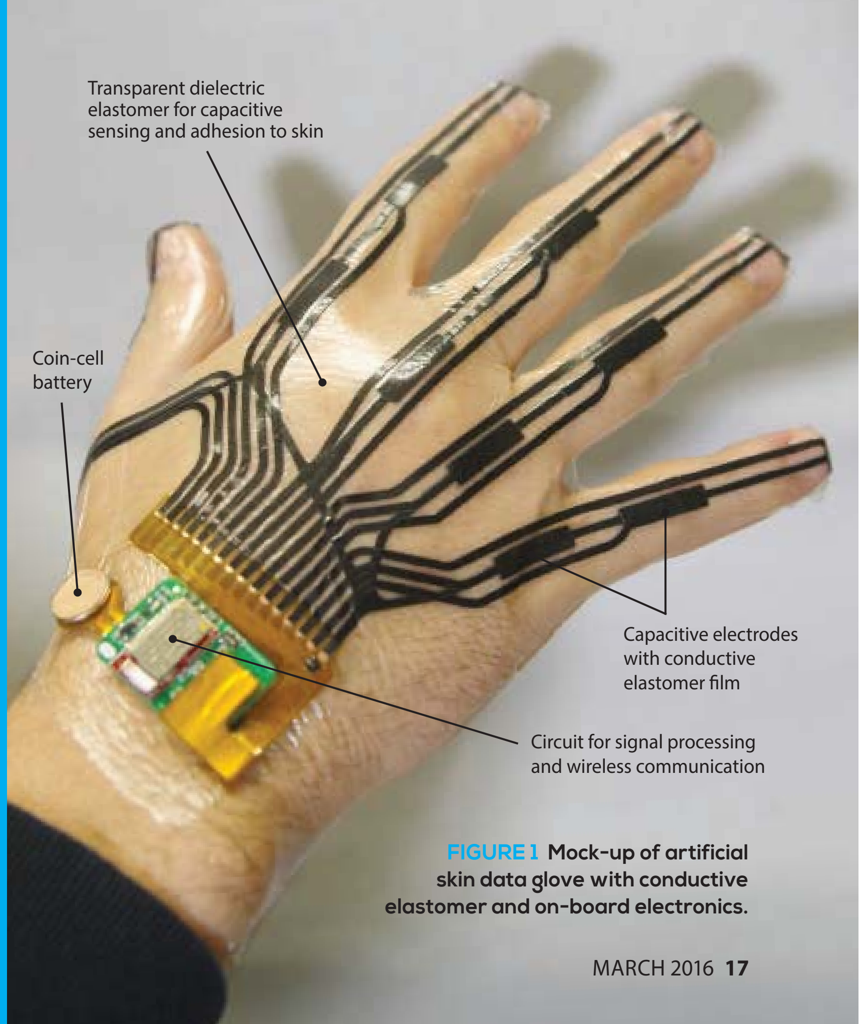

FIGURE 1 Mock-up of artificial skin data glove with conductive elastomer and on-board electronics.

challenges in dynamic state estimation and feedback control. As they deform, soft circuit and sensing elements can exhibit dramatic changes in electrical conductivity, capacitance, or inductance. This electro-elasto coupling has important implications in circuit design and sensing functionality. Addressing these effects in soft bio-inspired systems represents a new and exciting opportunity to merge the mechanics of materials with sensing and controls.

Sensorized electronic skins are an essential element in wearable computing and co-robotic systems that engage in physical interaction with humans. These include strain and bend sensors for joint proprioception and gesture monitoring, pressure sensors for monitoring surface tractions, and tactile sensors for detecting light touch and data entry. A variety of sensing architectures and materials are currently being explored in the Soft Machines Lab (SML) at Carnegie Mellon University. This work incorporates conventional microelectronic and flex circuit technologies and also builds on principles and practices in the emerging fields of *soft robotics* and *soft-matter engineering*.

FIGURE 2 Tactile sensor with laser-patterned traces of eutectic gallium-indium (EGaIn) liquid metal (LM) embedded in silicone elastomer.

ARTIFICIAL SKIN FOR SOFT ROBOTS

Like their counterparts in nature, soft bio-inspired robots are primarily composed of lightweight elastic materials that can easily deform and adapt their shape to contacting surfaces [1, 3]. This compliance and mechanical versatility allows soft robots to grasp delicate objects and navigate through tightly confined spaces with limited sensing and closed-loop control. Quadrupeds, undulators, and snake-like robots represent a particularly exciting class of soft bio-inspired systems that could have a revolutionary impact on unmanned, autonomous field exploration, particularly in unmapped or unstructured environments.

Examples of soft robot quadrupeds are presented in **Figure 3**. The quadruped limbs contain artificial muscles that are typically powered with pneumatics/inflation [4,5] or shape memory alloy. Ionic-polymer metal composites (IPMCs), dielectric elastomer actuators (DEAs), combustion, motor-driven cables, and series elastic actuators represent other common sources of actuation in bio-inspired robotics [6-8]. The latter two are particularly popular for humanoid robots that engage in physical human interaction during assistive co-robotic tasks.

Just as soft robots depend on artificial muscles for actuation, they also require artificial skin and nervous tissue for sensing, wiring, and signal processing. As with technologies for wearable computing, these sensors and circuits must be soft, lightweight, and stretchable so that they don't interfere with the mechanics of the host. Therefore it helps to turn to recent advancements in wearables in order to identify materials and sensing architectures for soft and elastic functionality.

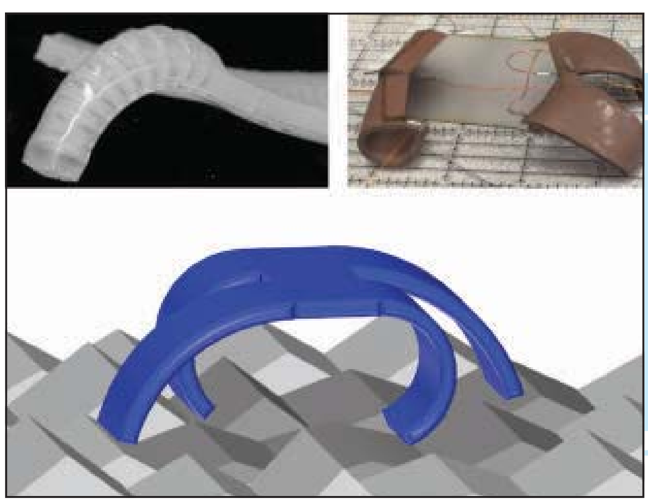

FIGURE 3 Soft quadruped robots with artificial muscle limbs powered by (above left) pneumatics [4,5] or (above right) shape memory alloy.

SENSORS FOR NEXT-GENERATION WEARABLES

Wearable computing is a rapidly growing sub-domain in the electronics industry and has the potential to transform how we work, play, get information, and interact with others. There are already thousands of wearable electronic devices on the market, with millions of users and projections for hundreds of millions more within the next 5-10 years [9]. Although most existing wearables are constructed from conventional solid-state microelectronics, there is increasing interest in incorporating novel materials and architectures. One

FIGURE 4 Materials and architectures for wearable computing (clockwise from top left): iSkin with conductive silicone elastomer [10]; wireless dataglove with adhesive electronic skin; wavy copper traces for stretchable functionality [11]; UIUC Electronic Tattoo [12].

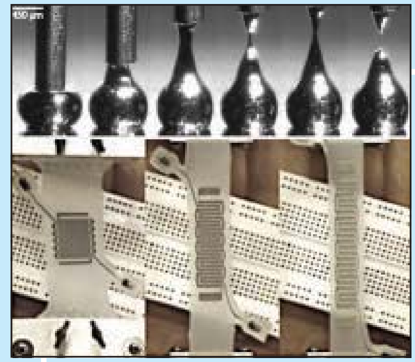

FIGURE 5 (top) Eutectic gallium-indium (EGaIn) alloy is a "moldable" liquid that forms a nanometer-thin oxide skin in air [15]. (bottom) A fluidic channel of EGaIn embedded in silicone deforms with the surrounding elastomer [17].

popular approach is to use elastomeric composites in which rubber is embedded with percolating networks or films of micro/nano-scale conductive filler. Early efforts have focused on structured carbon black (see top insets in **Figure 4** [10]) and metal powders, while more recent attention has shifted to co-polymer blends, silver flakes, carbon nanotubes, and graphene [2]. Another emerging technique is to interface solid state sensors with wavy circuits and other so-called "deterministic architectures" that achieve stretchable functionality through pre-buckling, wrinkling, helicity, or serpentine shapes (e.g. bottom insets in **Figure 4** [11,12]).

In recent years, there has also been increasing interest in using soft microfluidics. This includes soft silicone elastomers that are embedded with microfluidic channels of ionic solution [13]. Stretching the elastomer or applying pressure to the surface alters the geometry of the channels and changes its electrical resistance. By monitoring this change in resistance, the elastic deformation can be inferred. An alternative is to replace the ionic fluid with liquid-phase metal alloy. As far back as the late 1940s, liquid metal (LM) electronics have been used for stretchable wiring and stretch sensing – most notably the mercury-based strain gauge developed by Reginald Whitney for biomechanical measurements [14]. In 2007, researchers at Harvard University discovered an approach to LM-based soft microfluidic electronics involving a safe alternative to mercury [15]. This is accomplished with eutectic gallium-indium (EGaIn; see inset of **Figure 2**). EGaIn is an alloy composed of 75% Ga and 25% In (by wt) that is liquid at room temperature, has high electrical conductivity ($\sigma \sim 3\times10^6$ S/m), low toxicity, and negligible vapor pressure. As shown at the top of **Figure 5**, the liquid oxidizes in air and forms a nanometer-thin oxide skin

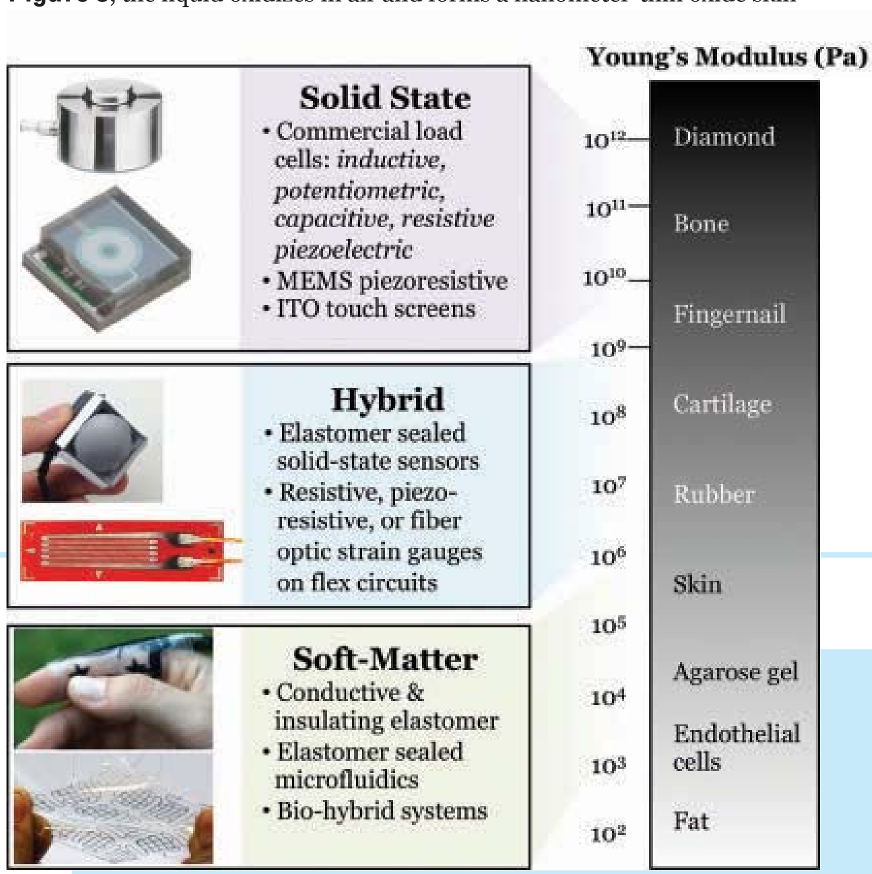

FIGURE 6 Pressure and strain sensing technologies for robotic grippers. Soft robotic applications require "soft-matter" and "hybrid" technologies that match the mechanical compliance (e.g. Young's Modulus) of soft biological tissue.

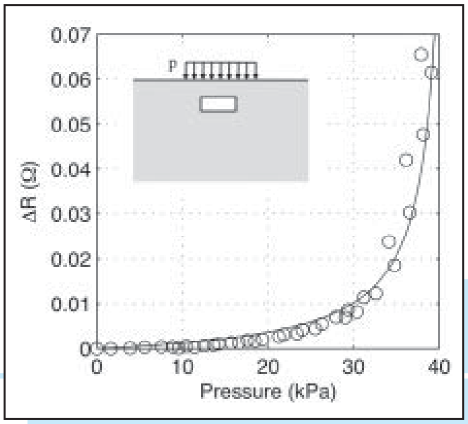

FIGURE 7 **Change in electrical resistance (ΔR) of an EGaIn channel in response to surface pressure (p) applied to the surrounding silicone [18].**

that allows the droplet to hold its shape and be molded. Such oxidation and moldability allows EGaIn to be patterned with a variety of techniques based on soft lithography, additive manufacturing, and laser rapid prototyping [16]. It also enables wetting to soft silicones and urethanes so that the liquid channels can conform to stretch and other deformations (bottom **Figure 5**, [17]).

Lastly, there are opportunities to integrate conventional sensing technologies with soft materials and deterministic architectures. Referring to **Figure 6**, these *hybrid* technologies combine the sensing mechanisms (resistive, capacitive, inductive, optical) of solid-state devices with the soft, flexible, and stretchable functionality of elastomeric and thin-film technologies. Such integration is especially important for precision sensing and measurement of vitals for personal healthcare monitoring. For example, a pulse oximetry or glucose monitoring chip mounted to a wavy or soft microfluidic circuit can be embedded into a bandage or clothing and placed virtually anywhere on the skin. Current technical challenges include electrical interfacing between solid-state chips and soft-matter circuits and antennae as well as power for RF transmission.

Figure 6 also shows the difference in Young's modulus for different sensing technologies and how they compare with materials in nature. Young's modulus scales with the force required to elastically deform a material and is only defined for small (<1%) strains. In the case of soft and biological materials, there are other essential metrics for capturing elastic and rheological properties, including strain limit, shear modulus, and dynamic (shear) viscosity. Moreover, mechanical compliance and deformability represent just a few of the many properties that a sensor must exhibit for applications in soft robotics and wearable computing. Attention must also be given to the influence of materials selection and sensor architecture on dynamic range, sensitivity, bandwidth and allowable sampling rate, signal-to-noise ratio, and hysteresis.

Because of the large spectrum of materials, layups, geometries, and sensing mechanisms, there is an almost endless number of possible design combinations. In order to navigate this vast design space, it helps

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to have reliable theoretical models or computer-aided tools that accurately predict sensor performance under anticipated loading conditions. This includes multi-physics models that combine 3D elasticity, electrodynamics, and effective medium theory to predict the change in the electrical properties of a soft-matter circuit embedded in an elastically deforming medium. **Figure 7** shows an example of one theoretical model for predicting the change in electrical resistance of an EGaIn channel as surface pressure is applied to the surrounding silicone. This strong agreement is achieved without data fitting and utilizes a combination of Ohm's law along with classical solutions in linear elasticity [18]. Models like this have the potential to dramatically reduce the number of design iterations required to select appropriate materials and geometries for soft microfluidic sensing.

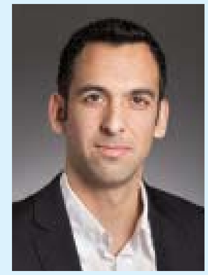
FIGURE 8 Middle-school workshop on materials for wearable computing with hands-on interactive.

OPPORTUNITIES FOR STEM OUTREACH

Because of its close connection to personal electronics and fashion, artificial skin technologies represent a good opportunity for STEM outreach at the middle and high school levels. Wearable technology is a promising path to STEM education since it is relevant to the daily experiences of teens and pre-teens, regardless of their social, cultural, and economic background. Through hands-on projects that combine e-textiles and fashion accessories with rapid prototyping and open-source electronics hardware, youth can readily connect STEM topics with arts, crafts, and personal expression [19]. Middle school students are an especially appropriate target, since they have adequate intellectual preparation for hardware prototyping but are still at the earliest stages of developing their academic interests.

Members of SML have participated in several outreach events on the theme of materials for wearable sensing. This includes an interactive in which students can produce their own wearable touchpad and use it to move a cursor or play Tetris. Instead of custom laboratory-prepared materials, we provide the students with commercially available conductive fabrics and elastomers that they can cut out and bond to a soft insulating adhesive (e.g. 3M VHB tape). An example is shown in **Figure 8**, taken from a recent workshop hosted by the Gelfand Center for Service Learning and Outreach at CMU. ■

ABOUT THE AUTHOR



Carmel Majidi was born in Wilmington, Delaware in 1980. He received his B.S. degree from Cornell University and M.S. and Ph.D. degrees from UC Berkeley. At Berkeley, he worked with Profs. Ronald Fearing and Bob Full to examine natural gecko adhesion and develop a gecko-inspired shear-activated adhesive. After completing his Ph.D. in 2007, Carmel was a postdoctoral fellow in the Princeton Institute for the Science and Technology of Materials (PRISM) and worked with Profs. Mikko Haataja and David Srolovitz (currently at UPenn) to examine the physics and morphological stability of piezoelectric nanostructures. Later, he did a fellowship at the School of Engineering and Applied Sciences at Harvard University where he worked with Profs. Robert Wood and George Whitesides to explore new paradigms in soft robotics and soft-matter electronics. In Fall 2011, Carmel joined CMU as an Assistant Professor, where he leads the Soft Machines Lab. He is a recent recipient of Young Investigator awards from DARPA, ONR, AFOSR, and NASA all for work related to soft-matter robotics and engineering.

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2016 American Control Conference

BOSTON, MA, JULY 6-8, 2016

Led by General Chair **Danny Abramovitch** (Agilent Labs) and Program Chair **George Chiu** (Purdue Univ.), the 2016 American Control Conference (ACC) will be held in Boston, Massachusetts, July 6-8, 2016.

The ACC is the annual conference of the American Automatic Control Council (AACC), the U.S. national member organization of the International Federation for Automatic Control (IFAC), and is co- sponsored by several other professional societies, including ASME, IEEE, IFAC, SIAM among others.

Recognized internationally as a premier scientific and engineering conference, the ACC is dedicated to the advancement of control theory and practice, as well as control systems education. The 2016 ACC will bring together an international community of experts in these domains, within a high caliber technical program comprising regular and invited sessions, tutorial sessions, and special sessions along with workshops and exhibits.

Among many exciting programs, the 2016 ACC program will also feature a special **Applications Friday event on July 8**, including a plenary lecture, applications tutorial sessions, exhibits, undergraduate poster session, special lunchtime sessions as well as a public lecture. To promote participation from students and local engineers, researchers, and scientists, a special one-day registration option will also be available.

Details can be found on the conference web site at
http://acc2016.a2c2.org/

Edited by Kam K. Leang (ACC 2016 Publicity Chair) and Rifat Sipahi

Photo courtesy of the Greater Boston Convention & Visitors Bureau

2016 ASME Dynamic Systems and Control Conference

Minneapolis, MN, October 12-14, 2016

THE NINTH ASME DYNAMIC SYSTEMS AND CONTROL CONFERENCE (DSCC) will be held in Minneapolis, Minnesota, October 12-14, 2016.

KIM STELSON (University of Minnesota) and **JIONG TANG** (University of Connecticut) will serve as General Chair and Program Chair, respectively.

The DSC Conference, organized and led by the members of the **ASME DSC Division**, provides a focused and intimate setting for dissemination and discussion of the state of the art in the broad area of dynamic systems and control from theory to industrial applications and innovations in education.

In addition to regular sessions, the conference program will also include **contributed sessions, invited sessions, tutorial sessions, special sessions, workshops, and exhibits.**

The 2016 DSCC will be preceded by the **FLUID POWER INNOVATION AND RESEARCH CONFERENCE (FPIRC)** at the same location, October 10-12, 2016, which offers an expanded research program and more networking opportunities.

Edited by Kim Stelson and Rifat Sipahi

For details on the conference schedule, please visit ASME Conferences at https://www.asme.org/events/dscc

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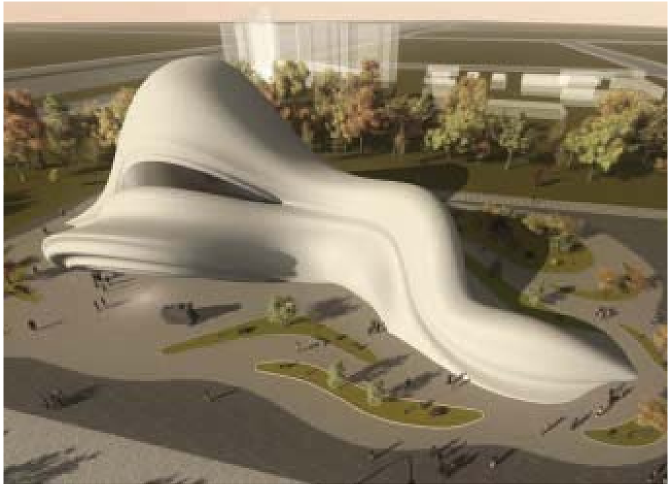
COMPONENT MODELING

SIEMENS PLM SOFTWARE, PLANO, TEX.

Parasolid is a 3-D solid modeling component application that is the foundation of Siemens PLM's NX and Solid Edge products. It is also offered to third-party developers. Version 28.0, recently released, features a number of productivity-related enhancements. For instance, users can now identify and delete blends in locally non-manifold bodies, which eliminates a series of separate operations. Also, an improved swept tool operation enables a tool body to be swept along a path that is offset from the path provided. That allows the user follow existing geometry rather than requiring the creation of a specific path.



IMMERSIVE VISUALIZATION

ABVENT, PARIS

Abvent S.A. has announced the release of Twinmotion 2016, an application for Windows that enables architects and designers to instantly create digital models of their 3-D projects, adding lifelike effects in real time. Compatible with most 3-D modeling software, Twinmotion is designed to have an intuitive user interface. The application is capable of creating high-quality images and animations very quickly, and according to the developer, the new release has been graphically optimized to make it 25 percent faster in final rendering. The new release can also import terrain from Google Earth and features an expanded library of objects, including vegetation and vehicles.

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SHEET METAL FABRICATION

VERO SOFTWARE, CHELTENHAM, U.K.

The latest release of the Radan suite of sheet metal applications improves CAD/CAM, Radbend, Radm-ax, and Radtube functions and provides a closer link between those individual modules. The new release now supports nine more machine tools than earlier versions. Radan 2016 also allows users to specify areas of the parts and nest to automatically tool, including individual variations of the parameters, such as the settings for a complicated aperture. The software also sports a new simulation engine, capable of more accurately showing detailed machine movements; earlier editions of the application restricted simulation to the CNC program.

MOBILE ACCESS

BENTLEY SYSTEMS, LONDON.

OpenRoads Navigator is a new mobile application that provides civil and transportation engineers quick access to civil design information in the field. Users can view and analyze a wide variety of project information, including 3-D models and terrain, and can navigate that data via a touch-based interface. The app enables virtual walk-throughs of a project design using GPS coordinates. Designers also can publish engineered models directly to the cloud for quick and easy access within OpenRoads Navigator while they are in the field.

CAE SUITE

BETA CAE SYSTEMS, THESSALONIKI, GREECE

The ANSA/Enilysis /μETA v16x suite provides a complete solution in the CAE field, according to the company, and the new version improves the interaction between the different programs. In ANSA, for instance, connection handling has been expanded in bolt and adhesive representations, which can now be automatically converted to connection entities. And the visualization of material orientation is now improved by continuous lines that define the orientation. The v16x version of the μETA post-processor builds upon the tools available in previous releases and now supports an increased array of new interfaces, including Enilysis, the in-house solver of BETA CAE Systems.

ENGINEERING SIMULATIONS

ALTAIR, TROY, MICH.

SimLab 14.0, the recent release of the process-oriented, feature-based finite element modeling application, introduces a new graphic user interface based on the HyperWorks framework. The user interface is now similar on both the Windows and Linux operating systems, which enables users to work seamlessly between the two platforms. The goal is to improve the ability to understand the interface while enabling the user to quickly and accurately set up simulations for engineering problems for the most complex assemblies. Additionally, SimLab 14.0 comes with Japanese language support, a new ribbon interface based on self-explanatory icons, and a custom toolbar to create user-defined workflows.

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Maseeh College of Engineering and Computer Science
PORTLAND STATE UNIVERSITY

The Mechanical and Materials Engineering Department at Portland State University seeks a highly qualified candidate to fill a tenure track position at the level of **Assistant Professor** with research and teaching interests in the area of **Advanced Manufacturing.**

Applicants must have a Ph.D. in a relevant science or engineering discipline. Specific areas of interest include, but are not limited to, automation, mechatronics, robotics, control systems, manufacturing of advanced materials production, and sensors and MEMS for manufacturing applications. Applicants with interests in related areas such as additive manufacturing, 3D manufacturing, and sustainable manufacturing are also encouraged to apply.

The successful candidate will be responsible for: Teaching courses at the undergraduate and graduate levels; Mentoring graduate students toward completion of their degrees; Developing significant independent research programs that are funded from federal government, state government, or other public agencies and industry; Serving on departmental and university committees; Collaborating with local and national manufacturing industry members to support graduate degree programs and research, and to enhance economic development in Oregon.

The starting annual salary rate for this position will be dependent upon qualifications and experience with an excellent benefits package including 95% premium paid healthcare; a generous retirement and vacation package; and reduced tuition rates for employee, spouse or dependent at any of the Oregon Public Universities.

For additional information, and to apply, please visit: https://jobs.hrc.pdx.edu/postings/search. To learn more about Portland State University's Mechanical and Materials Engineering Department, consult: http://www.pdx.edu/mme/.

POSITIONS OPEN

Institute of Marine Engineering and Thermal Science in the College of Marine Engineering at Dalian Maritime University, China, invites applications for faculty positions at the **Assistant Professor/Lecturer or Associate Professor** level starting September of 2016. We are particularly interested but not limited to in the areas of marine engineering, thermal science, manufacturing, design, fluid control, and material. Candidates should have a **B.S. degree in Engineering and a Ph.D. degree in Mechanical Engineering**, or closely related field with a strong evidence of research in the interested area. Candidates must demonstrate an ability to teach undergraduate and graduate courses. The successful candidate will be expected to establish an externally sponsored research program, and to develop and teach courses at the undergraduate and graduate levels in both core engineering and specialized areas. Required documentation includes a cover letter, curriculum vitae, list of three professional references, and a statement of research interests. Interested candidates email all required documents to Ms. Bohan Tian at Tianbohan@dlmu.edu.cn or bohantian@163.com. Review of applications will begin on March 1, 2016 and the positions will remain open until filled.

SYRACUSE UNIVERSITY
Department of Mechanical and Aerospace Engineering
Chair

Syracuse University invites applications and nominations for the position of Chair of the Department of Mechanical and Aerospace Engineering. The Chair will be a respected scholar and a dynamic leader who will join the Department at an exciting time. In the last six years, the Department has achieved significant growth in enrollments in its undergraduate and graduate programs, and it has hired 10 outstanding faculty members. Now, the Department has exceptional opportunities to elevate its research profile and educational mission via a recent commitment from New York State to revitalize the five-county Central New York region, which is envisioned to include strategic investments relating to research, development and manufacturing of "precision sensing technologies and data analytics" with an initial focus on the testing, innovation, and manufacturing of unmanned aerial systems. The University seeks a visionary and strategic individual who will enable the Department to maximize these potentially transformational opportunities.

Mechanical and Aerospace Engineering is one of four departments within the College of Engineering and Computer Science at Syracuse University. The Department offers two ABET-accredited B.S. programs (aerospace engineering, mechanical engineering), three M.S. programs (mechanical and aerospace engineering, energy systems engineering, engineering management) and one Ph.D. program (mechanical and aerospace engineering). The programs currently enroll approximately 500 undergraduate students and 260 graduate students. The Department faculty recently has grown to include 24 faculty members, including 19 tenured or tenure-track faculty members. The Department enjoys a vibrant and rapidly growing research environment with a funding portfolio that includes awards from major federal and state agencies, companies, and foundations. In the last three years, sponsored expenditures have been in the range from $2.9 to $3.5 million annually; the department envisions achieving increases funded research in the near term through support for development of junior faculty and strategic initiatives.

Syracuse University's College of Engineering and Computer Science is undergoing significant renewal under the leadership of Dean Teresa Dahlberg, with outstanding opportunities for growth and reinvention across all departments. Departments in the College are mutually supportive and the Department Chair will be in a position to foster synergies between departments and between colleges at the University level. In addition, Department Chair benefits from many substantive collaboration opportunities with the Syracuse Center of Excellence in Environmental and Energy Systems, the Center for Advanced Systems Engineering, Syracuse Biomaterials Institute, and many other centers and institutes at the University.

Applicants must have earned a doctoral degree in either mechanical or aerospace engineering or a closely related discipline. The applicant must have a distinguished record of accomplishments in education and research and qualify for the rank of Full Professor. The applicant is expected to teach undergraduate and/or graduate level courses in their field of expertise, supervise graduate level research, develop and grow a strong, externally funded research program and elevate the national profile of the Department. For a more detailed job description visit: **http://eng-cs.syr.edu/careers/**.

Interested applicants should submit a detailed curriculum vitae, statements of research and teaching interest, and at least five professional references. Applicants must complete an online Faculty Application and attach, electronically, a cover letter, curriculum vitae, and the names of the five references at **www.sujobopps.com**. (job number **072331**).

Review of applications will start on March 15, 2016 and continue until the position is filled. For additional information, please contact the Chair of the Search Committee, Professor Roger Schmidt, via email at **rrschmid@syr.edu**.

Syracuse University is an Affirmative Action/Equal Opportunity University.

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA
Mechanical Engineering
Faculty of Applied Science

Seaspan Chairs in Naval Architecture and Marine Engineering

The Naval Architecture and Marine Engineering (NAME) program at The University of British Columbia (Vancouver campus) seeks two outstanding individuals for tenure-track or tenured positions at the Assistant, Associate, or Full Professor level, who will occupy two Seaspan Chairs. The Seaspan Chairs are part of the $33 billion National Shipbuilding Procurement Strategy of the Government of Canada. The Chairs will hold an appointment in one or more of the following Departments: Mechanical Engineering, Materials Engineering, and Civil Engineering. The starting date of the appointments will be September 2016, or as soon as possible thereafter.

The two new faculty members will complement our existing strength in NAME (http://name.engineering.ubc.ca). We welcome applications from individuals who have expertise in any area relevant to NAME, and particularly encourage specialists in any of the following disciplines to apply: ship production engineering, ship design for sustainability, ship materials, and structural engineering.

Candidates should be able to develop a major R&D program, enhance further existing facilities, and lead a group of graduate students, technicians, and faculty members. Owing to the need for close cooperation with industry and government, a track record of successful industry experience would be a key asset. Applicants must either have demonstrated, or show potential for, excellence in teaching and service. They will hold a Ph.D. degree or equivalent in Naval Architecture and/or Marine Engineering, Civil Engineering, Materials Engineering, Mechanical Engineering, or a closely related field, and will be expected to register as a Professional Engineer in British Columbia. Successful candidates will be required to apply for Natural Sciences and Engineering Research Council (NSERC) grants in partnership with Seaspan.

Further information on the employment environment in the Faculty of Applied Science is available at www.apsc.ubc.ca/prospective-faculty.

Applicants to faculty positions in UBC Applied Science are asked to complete the following equity survey https://survey.ubc.ca/s/Seaspan-Chairs/. The survey information will not be used to determine eligibility for employment, but will be collated to provide data that can assist us in understanding the diversity of our applicant pool and identifying potential barriers to the employment of designated equity group members. Your participation in the survey is voluntary and anonymous. You may self-identify in one or more of the designated equity groups. You may also decline to identify in any or all of the questions by choosing "not disclosed".

The University of British Columbia hires on the basis of merit and is committed to employment equity. All qualified persons are encouraged to apply. We especially welcome applications from members of visible minority groups, women, Aboriginal persons, persons with disabilities, persons of minority sexual orientations and gender identities, and others with the skills and knowledge to engage productively with diverse communities. Canadians and permanent residents of Canada will be given priority.

Applicants should submit a curriculum vitae, a statement (1-2 pages) of technical and teaching interests and accomplishments, and names and addresses (fax/e-mail included) of four referees. Applications should be submitted online at http://www.hr.ubc.ca/careers-postings/faculty.php.

The closing date for applications is April 1, 2016, or until the positions are filled. Please do not forward applications by e-mail.

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RUSSELL WINS WASH. STATE AWARD

ASME Fellow **Armistead (Ted) G. Russell**, an engineering researcher and professor at the Georgia Institute of Technology, recently was honored with the Washington State University Alumni Association Alumni Achievement Award for his work in air quality science related to health, public policy and sustainable development. Russell received his bachelor's degree in mechanical engineering from WSU in 1979; the award is the highest honor bestowed by the school's Alumni Association. In addition to his position at Georgia Tech's civil and environmental engineering department, Russell is also co-director of the Southeastern Center for Air Pollution Epidemiology and director of the Air Resources Engineering Center. Russell's work modeling air pollution particulates, nitrogen oxides and ozone, and the impacts of alternative fuel use on the atmosphere has had significant societal impact, and his analyses of air contaminants and health is a foundation for a modeling system recently adopted by the U.S. Environmental Protection Agency.

ASSANIS TO LEAD DELAWARE

ASME Fellow **Dennis Assanis** (left), provost and senior vice president for academic affairs at Stony Brook University in New York, has been elected president of the University of Delaware, after a unanimous vote by the university's board of trustees. At Stony Brook, Assanis launched a number of initiatives strengthening research activities and global engagement. Since 2011 he has also served as vice president for Brookhaven National Laboratory Affairs. Before joining Stony Brook, Assanis was a member of the University of Michigan faculty for 17 years. The recipient of ASME's Pi Tau Sigma Gold Medal in 1990 and the Internal Combustion Engine Award in 2008, Assanis has served ASME in a number of capacities over the years, including member of the Mechanical Engineering Department Heads Committee and associate editor for the *Journal of Turbomachinery* and the *Journal of Engineering for Gas Turbines and Power*. **ME**

MODELING AND SIMULATION FOCUS OF V&V EVENT

Engineers and scientists who use computational modeling and simulation will discuss methods and share ideas at the fifth ASME Verification and Validation (V&V) Symposium in Las Vegas, Nev.

The event will address the theme, "Connecting the Computational Modeling and Simulation Community," and will run May 18 to 20 at the Westin Las Vegas Hotel.

The V&V symposium provides stakeholders who use computational modeling and simulation with a venue for showcasing and exchanging methods and solutions in verification, validation, and uncertainty quantification.

Attendees will have the opportunity to interact with V&V specialists from leading international organizations, including Los Alamos National Laboratory, ANSYS, Westinghouse Electric Co., Dassault Systèmes, Bechtel National Inc., Sandia National Laboratories, Southwest Research Institute, the U.S. Air Force Research Laboratory, the Medical Device Innovation Consortium, and VEXTEC Corp.

Keynote presenters scheduled to speak include Luis G. Crespo, senior research engineer for the Dynamic Systems and Controls Branch of NASA Langley Research Center; Mark D. Benedict, computational materials scientist and program manager in the U.S. Air Force Research Laboratory's Manufacturing Technology Division; Chris Rumsey, senior research scientist at NASA Langley Research Center; and Sankaran (Maha) Mahadevan, the John R. Murray Sr. Professor of Engineering and co-director of the Laboratory for System Integrity and Reliability at Vanderbilt University.

Scheduled keynote speakers for the ASME Verification and Validation Symposium include (clockwise from top left) Chris Rumsey; Sankaran (Maha) Mahadevan; Mark D. Benedict; and Luis G. Crespo.

Immediately prior to the start of the V&V symposium, three two-day ASME Training and Development seminars will be offered: "Probabilistic and Uncertainty Quantification Methods for Model Verification and Validation," led by David Riha and Ben Thacker of Southwest Research Institute; "Verification and Validation on Scientific Computing," led by William Oberkampf, an engineering consultant, and Chris Roy of Virginia Tech; and "Beyond V&V: Simulated-Based Decision Making," led by Charles Farrar and François Hemez of Los Alamos Dynamics LLC.

Five ASME standards development meetings to discuss V&V practices for solid mechanics, fluid dynamics, nuclear power, medical devices, and advanced manufacturing will also be offered on May 17.

For more information on the V&V symposium, or to register, visit www.asme.org/events/vandv. **ME**

ASME TO HOST ADVANCED MANUFACTURING SUMMIT

The Advanced Manufacturing Innovation Summit, a special one-day forum to focus on research and workforce development partnership opportunities offered though the National Network for Manufacturing Innovation Institutes, will be held March 17 at the Westin Tampa Harbour Island in Tampa Bay, Fla.

ASME will present the summit, which will be co-located with the Mechanical Engineering Education Leadership Summit and the ASME Industry Advisory Board meeting.

The event will focus on both present and near-term workforce development partnership opportunities among industry, government, and academic entities that are being fostered by the innovation institutes, including the American Institute for Manufacturing Integrated Photonics, America Makes, the Digital Manufacturing and Design Innovation Institute, the Institute for Advanced Composites Manufacturing Innovation, Lightweight Innovations for Tomorrow, the Flexible Hybrid Electronics Manufacturing Institute, and PowerAmerica.

Topics expected to be covered include discussions of institute missions, technologies, memberships, and operations.

A special showcase will highlight specific examples of actual ongoing projects and current proposals, and a networking reception will be held to encourage further one-on-one communication between institute leaders and summit participants.

Registration for the Advanced Manufacturing Innovation Summit is $95 for ASME members, $145 for nonmembers. For more information on the Summit, contact Raj Manchanda, director, Emerging Technologies, at (212) 591-7789, e-mail manchandar@asme.org. ME

CLEAN ENERGY JOURNAL LAUNCHED

Batteries, fuel cells, and other energy conversion and storage technologies are the focus of a new journal launched by ASME in February.

The *Journal of Electrochemical Energy Conversion and Storage* replaces another publication, the *ASME Journal of Fuel Cell Science and Technology*. The focus of the new journal reflects the latest scientific thinking on energy conversion and storage technology. The bi-monthly publication will report on the range of disciplines that impact the research and development of electrochemical energy conversion and storage systems, from fundamental electrochemistry and materials, to engineering design, analysis, and manufacturing.

Areas under investigation include batteries, fuel cells, electrolyzers, distributed energy, alternative fuels, carbon capture, and solar energy.

With the leadership of a new and expanded editorial board, this new journal will target a fast review time while continuing to improve publication quality.

Papers for the *Journal of Electrochemical Energy Conversion and Storage* are invited from researchers, industry, and government agencies.

For more information, please go to: https://journaltool.asme.org/Content/JournalDescriptions.cfm?journalId=30&Journal=JEECS. ME

PIPELINE TRAINING WEEK SCHEDULED FOR APRIL

ASME Training and Development will offer a special Pipeline Technology and Standards Training Week event April 11 to 14 at the Grand Hyatt Denver. Discounted registration rates are available for ASME members as well as attendees who register for more than one course.

The training event is comprised of courses that focus current technologies, codes and regulations, and key issues relevant to today's market. The courses will be conducted by industry experts and code authorities, who will discuss proven techniques and best practices for pipeline design, construction, and integrity management.

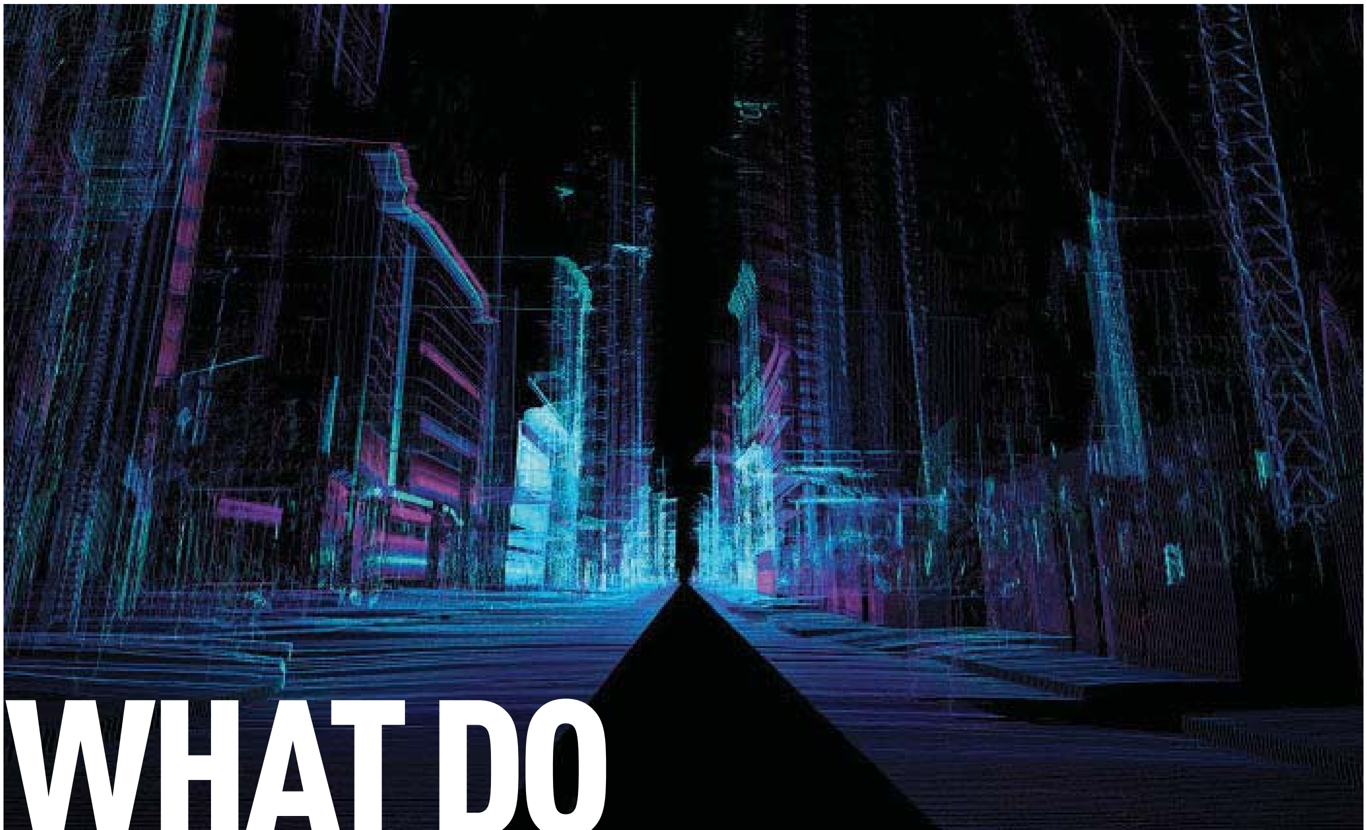
One highlight of the training event will be the plenary session, "Pipeline Safety: Implications of Proposed Rule Making (Recent NPRMs)." This special workshop, to be led by the training event's co-chairs, Thomas Bubenik and Keith Leewis, will discuss recently proposed rules for liquid transmission pipelines and future gas transmission pipelines. The session will provide attendees with a review of the recent NPRMs and an open discussion of those new U.S. pipeline regulations and their implications.

Five training courses will make their debut in Denver: "Pipeline Stress Corrosion Cracking Management," "Integrity Management of Natural Gas Pipelines Using ASME B31.8S Standard," "Integrity and Repair of Process Piping and Tanks," "Pipeline Defect Assessment," and "Pipeline Integrity Issues, Mitigation, Prevention & Repair Using ASME B31.8S Standard."

ASME members can save up to $200 on the price of course registration. Attendees who sign up for multiple courses will save an additional 15 percent on registration.

To learn more about Pipeline Technology and Standards Training Week, or to register, visit http://go.asme.org/pipelinetraining.

For more information on the training event's technical program, contact Jennifer Delda at deldaj@asme.org. ME



WHAT DO ROBOTS SEE

A New York City streetscape (above) looks ghostly to the scanning laser of an autonomous car. Below, an immersive 3-D rainforest created by ScanLAB with artist Daniel Steegmann at the New Museum in New York City.

What does a city look like to an autonomous car?

To William Trossell, 30-year-old co-founder of London-based ScanLAB Projects, the question is more than idle curiosity.

"This is going to be the way we navigate and explore cities in the future," Trossell said, referring to scans taken by autonomous cars. Those machines will continuously record and map; Trossell and his partner, Matthew Shaw, want to make that data visible.

Such data could have many possible uses. It would provide a map of the as-built city with millimeter accuracy. It might eliminate the need for surveyors when architects and engineers plan changes.

Besides, Trossell and Shaw find inherent errors in the scans beautiful.

Inherent errors? Trossell and Shaw work with lidar, a laser system that maps its environment by taking millions of measurements per second. These form "point clouds" that define objects, which can then be imported into 3-D CAD.

That's the theory, and it works well under ideal circumstances. Cities, however, are not ideal. They are bursting with reflective glass surfaces, moving vehicles, rain, and fog. This causes light to scatter, causing aberrations and mirages. Even a single bicycle will cast shadows on the data an autonomous car expects to see.

Trossell and Shaw see those shadows as beautiful. Their works reproduce scenes that, like dreams, are both familiar and surpassingly strange at the same time.

"We were really blown away by the ability of scanners to record space digitally. We wanted to produce it as a new form of media, an evolution of the camera into the way we and machines will be seeing in the future," Trossell said. ME

ALAN S. BROWN