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THE MAGAZINE OF ASME

No. 06
136

THE RIGHT STUFF

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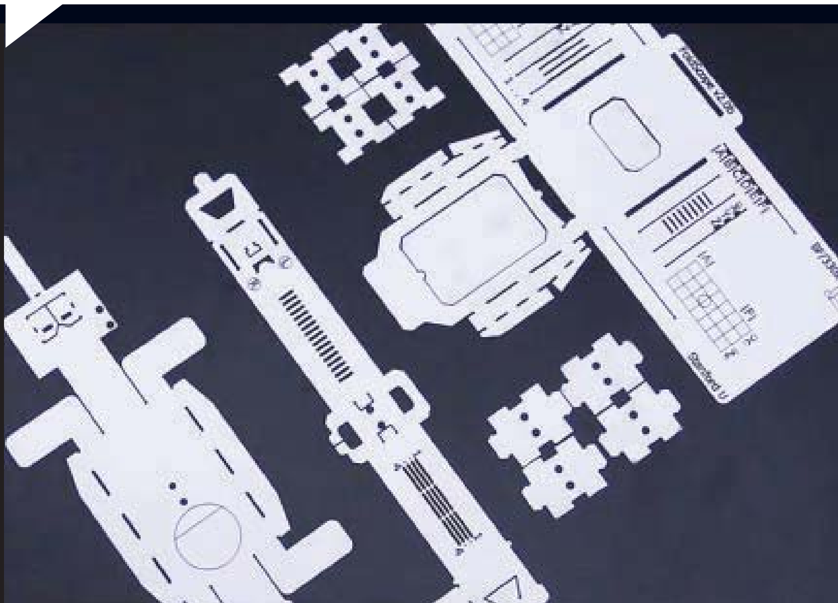

FOLDING MICROSCOPES FROM FRUGAL SCIENCE

STANFORD UNIVERSITY RESEARCHERS have developed Foldscope, a folding microscope built using principles of origami, as an inexpensive tool to help health-care providers in developing areas. Now, they are trying to put the microscope in the hands of elementary school children around the globe.

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

INVISIBLE TO THE EARS

Researchers at Duke University are turning fiction into reality by creating a cone of silence with a pyramidical sound cloak made of metamaterials.

VIDEO: 3-D PRINTING IGNITES STEM EDUCATION

A new initiative at SUNY New Paltz is leveraging 3-D printing to ignite **STEM** education and stimulate creative thinking.

SUPERSONIC: THE FUTURE OF FLYING Boston-based engineering firm Spike Aerospace is aiming to bring supersonic travel back by developing a business jet, which might cut international travel time by half.

SPIKE AEROSPACE

NEXT MONTH ON ASME.ORG

SEEING THE BIG PICTURE

A DIY digital camera designed at Columbia University's Computer Vision Laboratory is aimed at teaching kids exactly what goes into making a camera click.

PODCAST: BREAKING BARRIERS IN 3-D PRINTING

Dr. Darrell Wallace, deputy director of Advanced Manufacturing Enterprise at America Makes—the National Additive Manufacturing Innovation Institute, discusses the barriers and challenges of 3-D printing.

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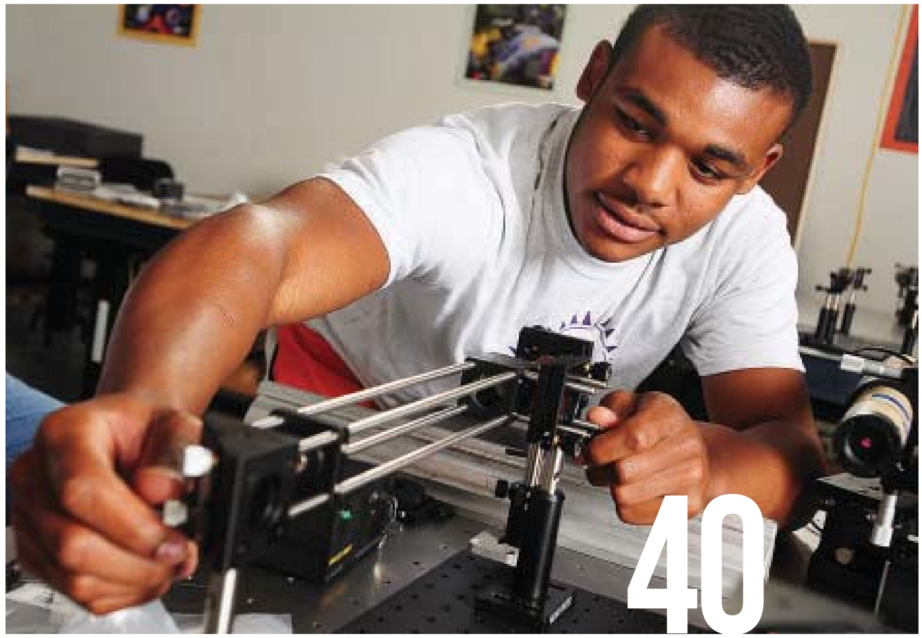

ON THE COVER

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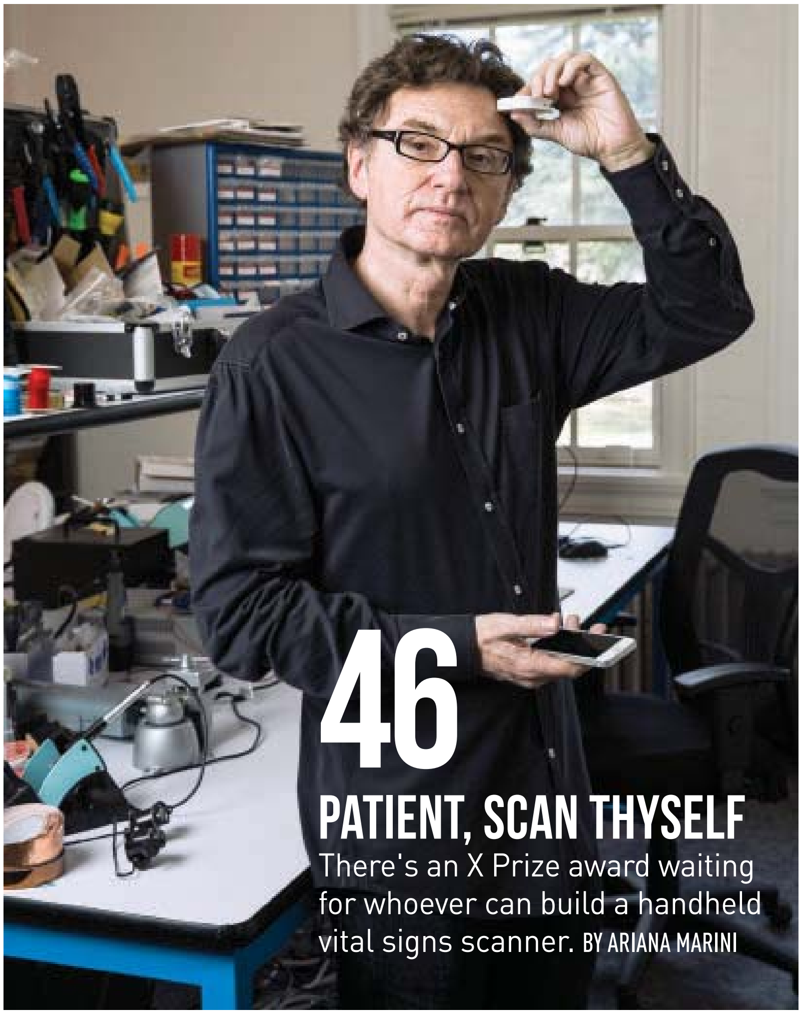

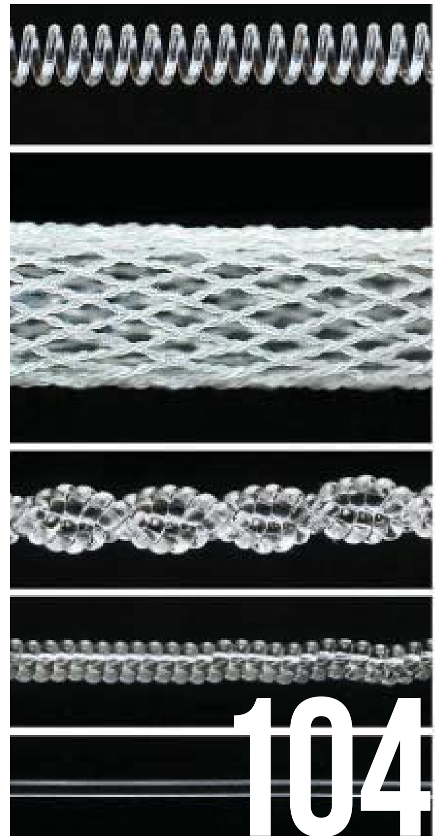

INSIDE

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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

A EULOGY FOR AMERICAN MANUFACTURING?

I've been to towns across the country where they still mourn the demise of local manufacturers that closed years before. It wasn't an easy thing to see, but it was even harder if you lived there.

Manufacturing in the United States used to dominate the world and these industrial towns served as the backbone. These were the places were icons were born, companies like Ford and Boeing, Maytag, Levi Strauss, and Kodak. They became synonymous with American ingenuity.

These towns and cities, especially in the Northeast and Midwest, flourished. Jobs grew, the middle class grew, the economy grew, and manufacturers were making money—a lot of money.

Then these towns collapsed. The region, formerly known as the manufacturing belt, became the rust belt. The reasons why this occurred are complex and well documented. Some manufacturers and factories moved to areas in the United States where it was cheaper to do business, namely the South. Increased automation had an impact too. Then globalization and internationalization happened, along with the decline of the U.S. steel and coal industries. Each of these factors chipped away at manufacturing's underpinnings. As manufacturers began closing their doors, it wasn't long before local economies failed.

But as Mark Twain protested in 1897, after his obituary was mistakenly published in a New York newspaper, that "The report of my death was an exaggeration," so too was the death knell of manufacturing in the United States presumptuous.

In "The Right Stuff," this month's cover story, U.S. manufacturing czar Michael Molnar says he is optimistic. Molnar heads the Advanced Manufacturing Office for the National Institute of Standards and Technology, and is also director of the Interagency Advanced Manufacturing National Program Office. "The United States has added more than 600,000 new manufacturing jobs since early 2010, the first sustained rise in 15 years," he says. And this is just one of the trends Molnar talks about that give him reason to believe things are looking up for U.S. manufacturing. "Industry's 'golden age' has not come and gone," he adds.

Some of the cities that were struck hard by the decline in manufacturing aren't sitting on their hands waiting for Molnar's prediction to come true. They're being proactive.

One such city is Rochester, N.Y., home to former photo giant, Kodak. About 25 years ago Kodak employed 60,000 workers from the Rochester area, but by 2014 the number had dropped to 5,000. As associate editor Alan S. Brown reports, Rochester could have been another dying rust belt city. "Instead, led by smaller firms, the city's optical industry [along with Kodak] reinvented itself and preserved the superb technical training program that was the lifeblood of the industry," he says.

"Seeing the Light," isn't just a feel-good story; it's a story with a moral. Rochester legislators, in partnership with local industry, used the same sort of manufacturing ingenuity that was being lost to inspire themselves and create an enviable turnaround. Every town that suffered from the downtick in manufacturing can't expect to have its own Kodak moment, but Rochester's climb back should give every presumably dying town pause.

Sometimes, the obituary you read in the newspapers isn't entirely accurate. **ME**

FEEDBACK

Is the U.S. experiencing a manufacturing renaissance? Email me.
falcionij@asme.org

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LETTERS & COMMENTS

MARCH 2014

Reader Rothkopf says mechanical engineering is the foundation for other fields.

One reader explains the value of an ME degree. Others defend climate science and object to political letters.

ADVANTAGES OF ME

To the Editor: I am not sure if Ron Corradin wanted to stir up emotions in his letter ("Working at a Disadvantage," March) concerning the value of mechanical engineers, but wow, his comment that "nothing in mechanical engineering has come close to the advances electrical engineers have made" is false.

Mechanical engineering has always been a foundation for several other fields. An ME degree does not pigeon-hole you into a career. Many ME college students take biomedical, electrical controls, materials, and optics classes, which lead to huge medical advances and laser technology. The human genome project could not have succeeded without MEs, and I would suggest that that project is much more important than any advances in telecommunication.

All the advances in cutting-edge robotics and MEMS, again, would not have succeeded without MEs.

If he is talking about salaries, mechanical engineering has kept pace with other professions. In the same issue, the salary charts showed ME well ahead of software or electrical engineering.

Mr. Corradin does bring up a good point though: How do you maintain this profession if most engineers move on after five years?

Where did they go? They became managers, moved into related fields, or felt that engineering was not how it was described in college once they hit the workplace.

We need to educate students on two things. First, an ME degree is a great foundation for many different engineering fields including non-traditional engineering positions. Engineering teaches you how to think, calculate, and deduce a solution.

Second, what you learn in college is not always how industry works; budgets, timelines, and politics play huge (and sometimes contradictory) roles. If we can provide industry-realistic education to students, they will go into the workplace better prepared and hopefully become less disenchanted with engineering as their careers progress.

I am an ME, but I moved into manufacturing, management, then operations, then quality and now regulatory consulting. This does not diminish all the knowledge I gained as an ME graduate. On the contrary, I could not have succeeded without my ME degree.

David Rothkopf, *Ashland, Mass.*

CONCLUSIONS AND CREDENTIALS

To the Editor: We non-expert mechanical engineers can debate whether or not there was a pause in warming, or how accurate the climate models are. Here is one solid fact on climate change: over 4,000 papers were written between 1991 and 2011, explicitly taking a position on whether climate change is happening and whether human activity is a significant cause. These papers were written and reviewed by the people who are the experts, and who have spent their lives studying this. Ninety-seven percent of those papers agree: Climate change is happening and we are a significant cause. The science is, in fact, settled.

Recent letter writers (Letters, April) with no expertise in the subject prefer to come to their own conclusion, in conflict with this overwhelming majority of experts. In 1884, ASME created the first boiler testing code, based on a consensus of experts. I imagine some people thought the code was just written by steel makers so they could sell more steel. And I imagine that when the Code became law in Massachusetts, some people thought it was incorrect because politicians advocating it had no expertise, and it was "needless government interference." They may have come to their own conclusions about boiler safety, in conflict with the overwhelming majority of experts, with results that are not something to be emulated.

I hope the ASME continues to support the likely, if not iron-clad, conclusions of the vast majority of climate scientists. If there is only a 10 percent chance that the worst-case predictions are true, then current efforts to undo the damage are very cheap insurance.

Steve Cohen, *South Windsor, Conn.*

INAPPROPRIATE CONTENT

To the Editor: Two recent letters (April) are clearly tainted by political and religious sentiments and have no place in a technical magazine. I hope that in the future similar letters are not published as they are devoid of any relevant engineering content.

J.G. Simmonds, *ASME Fellow, Charlottesville, Va.*

FEEDBACK

Send us your letters and comments via hard copy or e-mail **memag@asme.org** *(use 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.

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WORLD'S LARGEST FLOATING GAS WORKS

The world's largest floating structure is going to work northwest of Australia. It will be a sea-borne factory for liquefying natural gas. The vessel's owner, Royal Dutch Shell plc, expects to meet strong demand for LNG in Asia.

ANALYSTS PUT THE COST OF THIS FLOATING liquefied natural gas project at $13 billion, but Shell has remained mum on the cost.

Shell says the vessel, called *Prelude*, is an important development for the LNG industry because it will reduce both the project costs and the environmental footprint of LNG development. Because the LNG plant is on site, there is no need for pipelines or compression platforms to get the gas to shore. Operations require no harbor dredging, no jetty construction, and no onshore infrastructure.

Shell says the technology is a key to unlocking stranded gas fields that are too far from shore or too small for conventional processing. *Prelude* will be moored about 200 kilometers from the nearest dry land.

Construction began in 2009. *Prelude* is 488 meters long and 74 wide. Fully loaded, the vessel will weigh around 600,000 metric tons, roughly six times as much as the largest aircraft carrier. Shell notes that about 260,000 tons of that weight is steel.

The hull was launched late in 2013 at the Samsung Heavy Industries shipyard on Geoje Island, South Korea. Finishing the work—fitting out *Prelude*'s enormous hull as a floating LNG factory and storage facility—is to take until late 2016. Shell's technical partner is Paris-based Technip, which has formed a consortium with Samsung to build *Prelude*.

Full offshore production is expected in 2017. Shell says "full" means about 110,000 barrels of oil equivalent per day,

QUICK FACTS:

WHAT IT IS:
Floating liquefied natural gas plant.

DIMENSIONS:
488 meters long and 74 wide.

PRODUCTION CAPACITY:
110,000 BOE per day.

OWNER:
Royal Dutch Shell.

A rendering of Prelude, *which will carry an LNG plant to operate at a well site.*

LNG PROCESSING EQUIPMENT SUCH AS CRYOGENIC HEAT EXCHANGERS WERE ADAPTED FOR USE OFFSHORE.

totaling at least 5.3 million tons of liquids in a year—3.6 million tons a year of LNG plus 1.3 million of condensates and another 400,000 of liquefied petroleum gas.These liquids will be taken away aboard LNG transports ships.

The vessel is to be moored for 25 years at the Shell's Prelude and Concerto gas fields. Ocean depth there is a relatively shallow, 250 meters. *Prelude*'s hull was designed to last 50 years, Shell says. Sometime after 2040, *Prelude* will be towed to a drydock, refurbished, and then towed to another undersea gas field. Since it does not travel under its own power, *Prelude* is not a ship.

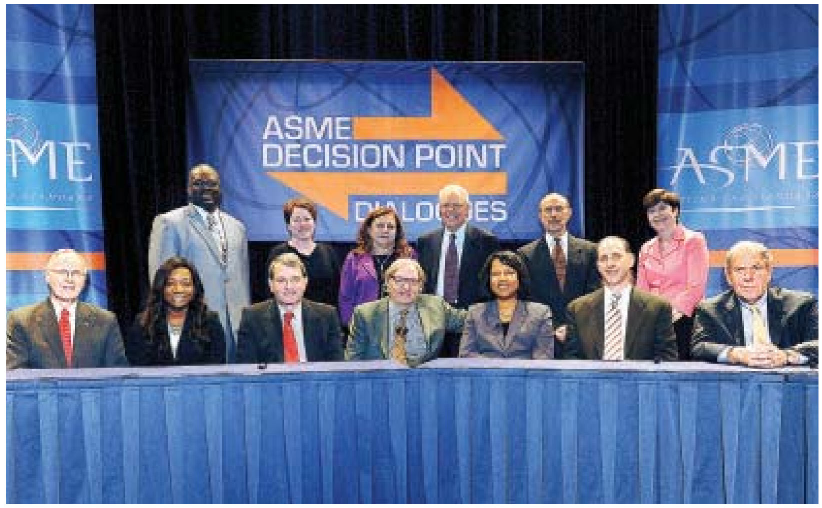
Putting a complex factory afloat presented engineers with many challenges such as LNG tanks that can handle sloshing, close coupling between the seafloor wells and LNG processing, and the turret mooring system which allows the vessel to swing with winds and currents. In addition, LNG processing equipment such as cryogenic heat exchangers were adapted for use offshore.

Prelude was designed and engineered to withstand a Category 5 cyclone—sustained wind speeds over 254 km per hour.

For storage and transportation, LNG is chilled to -162 °C and shrunk in volume by a factor of 600. To help with the chilling, 50 million liters of cold ocean water will be drawn aboard every hour, Shell said.

Shell predicts that natural gas demand will increase worldwide by 60 percent from 2010 to 2030 with strong growth for LNG. **ME**

JACK THORNTON is a contributing writer to *Mechanical Engineering*. He lives in Santa Fe, N.M.



Moderator John Hockenberry, seated center, and the panelists of the dialogue "What Really Matters in STEM." The program will be broadcast on the web. Photo: Bill Petros.

WHAT REALLY MATTERS IN STEM

The rollout of the 2014 ASME Decision Point Dialogues—Critical Thinking, Critical Choices: What Really Matters in STEM, begins this month online at asme.org/dialogues.

The program engages 12 thought leaders in a unique Socratic dialogue tracing a hypothetical case story tugging at the heart of the issues confronting the future of STEM education. The program, moderated by John Hockenberry, host of public radio's *The Takeaway* program, was videotaped at the U.S. News STEM Solutions Conference in April.

The panelists are Mark Conner, public school teacher and director of The Engineering Academy at Hoover High School in Hoover, Ala.; James Douglas, former governor of Vermont; Tamara Hudgins, executive director of Girlstart; Madiha Kotb, president of ASME; Arthur Levine, president of the Woodrow Wilson Foundation; Michelle Lezama, executive director of The National GEM Consortium; Regis Matzie, retired chief technology officer at Westinghouse; Ioannis Miaoulis, president and director of the Boston Museum of Science; Irene Neequaye, graduate student at The George Washington University; Hal Salzman, sociologist and professor of public policy at Rutgers University; Kenneth Williams, public school teacher in Prince George's County, Maryland, and a STEM teacher for Project Lead the Way; and Pat Wingers, journalist at Hechinger Institute on Education and the Media and a former *Newsweek* reporter.

The program will be broadcast over five consecutive Tuesdays beginning on June 10 at 2 pm Eastern Time, and ending on July 8. Each segment will be approximately 15 minutes and it will be followed by a live online chat with a STEM expert from technology, education, or innovation taking questions.

A related webinar will be held June 3 at 2 p.m. Eastern Time.

All programing will be presented on asme.org/dialogues. Visit the website for program details. ■

Stay connected to the ongoing STEM dialogue with subject matter experts and access exclusive content by visiting **go.asme.org/STEMdialogues.**

SMALL MODULAR NUCLEAR REACTORS

Interest in small modular nuclear reactors as a solution for low-carbon power for future generations continues to grow as several U.S. companies move forward with design plans, spurred by the U.S. Department of Energy.

NuScale Power has designed self-contained units that operate independently in a multi-module setup managed from a single control room. Image: NuScale Power.

The reactors, about one-third the size of current nuclear power plants, would be made in factories and transported to the locations where they would be installed instead of being built in place.

The trend in nuclear plant construction until fairly recently was to go large because of the economy of scale, says Paul Genoa, senior director for policy development at the National Energy Institute, but that is changing. The smaller size will mean lower capital costs for each project, faster construction, and more flexibility in where and for what purpose the small reactors can be used. Another benefit is that the modular reactors, just as large reactors, are a low-carbon source of electricity, having greenhouse gas emissions comparable to renewables over their lifetime.

The Energy Department's Office of Nuclear Energy has placed high priority on the development and commercialization of small modular reactors as part of its push for clean, affordable nuclear power options. To support licensing and development by private industry, the Nuclear Energy Office has a fund of more than $400 million. The modular reactors, generally rated at 300 megawatts electric or less compared to a typical nuclear power plant of 1,000 or more megawatts, would help energy providers meet Environmental Protection Agency rules under consideration that place limitations on carbon emissions. One of the proposed rules, published in January of this year, would limit carbon emissions from new power plants to an extent that would make it difficult for new coal-fired power plants to be built in the U.S. although modern natural gas plants do

continued on p.14 »

WASHINGTON

LAST YEAR'S MODEL: RECORD EFFICIENCY

ALTHOUGH ENERGY PUNDITS ARE TOUTING RISING domestic petroleum production, the other side of the oil equation is improving, too. According to preliminary data from the U.S. Environmental Protection Agency, model year 2013 vehicles had an adjusted average fuel economy of 24 miles per gallon, an all-time record.

When the EPA first compiled fuel economy data in 1975, average efficiency was only 13 miles per gallon. From the late 1980s, when fleet fuel economy reached 22 miles per gallon, there was a gradual worsening of efficiency. Improvements in automobile technology were swamped by increases in vehicle weight and horsepower as consumers gravitated toward so-called light trucks. Since 2004, however, fuel economy has rebounded.

According to the preliminary EPA data, Mazda was the manufacturer with the highest adjusted fuel economy, 27.5 miles per gallon, followed by Honda and Toyota. Although Chrysler-Fiat had the worst fuel economy, 21.6 mpg, that figure was still an 11 percent increase over its 2011 fleet efficiency. By 2025, fleet fuel economy is scheduled to increase to more than 54 miles per gallon.

MANUFACTURING

CUSTOM PARTS MAKER ACQUIRES ADDITIVE SERVICE

A MINNESOTA MANUFACTURER SPECIALIZING IN custom parts for prototyping or short run production has entered the business of additive manufacturing through an acquisition.

The manufacturer, Proto Labs Inc., based in Maple Plain, Minn., has acquired FineLine Prototyping Inc. of Raleigh, N.C. FineLine offers stereolithography, selective laser sintering, and direct metal laser sintering services.

Proto Labs said FineLine will continue to operate from Raleigh and will "retain the services of all key employees, including FineLine principals Rob Connelly and Craig Goff."

FineLine's revenues in 2013 were about $9.7 million in 2013. Proto Labs has agreed to a total consideration of $38 million for FineLine.

Proto Labs also has completed its renovation of a new plant in Plymouth, Minn. The site will employ 175 people, a number that is expected to grow to 300 employees by May 2017. Proto Labs said the new plant expands the company's U.S. manufacturing capacity to support up to 425 CNC machines and 180 injection-molding presses. ■

Namita Banka, CEO of Banka BioLoo, in front of an installed row of the company's biotoilets.
Photos: Bioloo

BIOTOILETS FOR

India's sanitation problem needs a radical, low-cost solution. Half the people in the country of 1.2 billion lack regular access to toilets. Sewer infrastructure and centralized treatment are costly and point-of-source collectors like pit latrines require regular maintenance and emptying.

That's why Namita Banka founded the biotoilet company Banka BioLoo, which her husband, Sanjay Banka, leads. The Banka biotoilets incorporate military technology and extremophile bacteria to treat waste right at the toilet. The only byproducts are clean water, carbon dioxide, and methane. Collecting the methane can yield combustible biogas for cooking or energy production, Sanjay Banka said.

"From the outside, a bio-toilet is similar to a normal toilet. The difference is primarily in terms of waste treatment," he said.

The biotoilets have a multi-chambered tank that holds a

continued from page 12 »

SMALL MODULAR NUCLEAR REACTORS

meet minimum standards.

If all goes according to plan, the first such reactors could be up and running in the first half of the next decade. In December, the Energy Department announced it was providing funding to Oregon-based NuScale Power to support a new project to design, certify, and help commercialize small reactors.

This was the second small modular reactor project awarded funding. The first funding went earlier last year to Babcock & Wilcox for a program that could result in installing small modular reactors in Oak Ridge, Tenn., by 2022. That project also involves Bechtel Corp. and the Tennessee Valley Authority.

NuScale's timeframe is for Nuclear Regulatory Commission design certification and commercial operation around 2025 in an as-yet-unselected site in a western state. The company's partners in its project include Energy Northwest, Fluor Corp., and Rolls-Royce.

Advocates of small modular reactors say the more compact size permits greater flexibility in use. They can be shipped to developing nations which don't have the infrastructure or funds to support gigawatt-scale power plants and lack the capability to construct their own nuclear plants. The small units can be used in remote locations and added incrementally at the same sites over time as more power is required, both in the U.S. and overseas. In the U.S., municipal utilities and cooperatives, which cannot afford a huge outlay of capital at once, can diversify their portfolios of power sources, including replacing aging fossil fuel sources, by adding these smaller units incrementally. It may also be possible to re-power an existing plant by replacing old fossil units with small reactors.

"We're trying to build these small reactors to fit in those situations, not just for large industrial utilities," Genoa says. "It's very exciting."

Genoa acknowledges that there are some engineering challenges, especially related to the regulatory process.

In a report by the consulting firm Ernst & Young, Mike McGough, chief commercial officer for NuScale, said, "With a design certification application running to nearly 10,000 pages, and 39 months for the Nuclear Regulatory Commission to review a new design, regulatory uncertainty can be a key challenge."

Genoa notes that in the "old days," the way testing was done is that all kinds of startup testing would be conducted once the plant was built. "You would run it and measure everything," he says.

In modern licensing, "we test in the field as the plant gets assembled," Genoa says. The question now is "how do you do it when all the reactor components are already fabricated and come out all in one piece. That's a new engineering challenge. How do you test things before they are assembled? How do you know after it's shipped that it wasn't damaged in the shipment? We are trying to sort out those things," he adds. ME

NANCY S. GIGES / ASME.ORG

MORE ON SMRs This month, the Nuclear Energy Division is publishing a special supplement focusing on small modular reactors. The supplement begins on page 57.

A HEALTHIER INDIA

culture of bacteria to treat the waste. These bacteria are weather-resistant cryophiles with ancestors that hail from cold places like the Himalayas and Antarctica. They've been adapted to work in a wide range of temperatures to eliminate waste within the oxygen-free bio-digester tank, Sanjay Banka said.

The process that breaks down waste also destroys the microbes that cause disease and produces useful byproducts. The water that results is safe for gardening and the biogas can be burned for heating, cooking, and even electricity production, he added.

"The system meets all regulatory and environmental compliances and enhances the socio-environmental fabric of India," Sanjay Banka said.

And the BioLoos are easy to set up, he added. And they're located in many places.

Travelers on Indian trains, for instance, may have looked down into an onboard toilet and noticed the tracks visible below. Many trains still employ a system of moving open defecation, but BioLoos are helping change that. Bio-digester tanks fitted under the car treat waste hygienically, Sanjay Banka said.

The BioLoos might require a little user training, however. Too much flushing or use in a single sitting can overload the tanks. ME

ENGINEERINGFORCHANGE.ORG

Viewed from above, the bio-tanks before installation. The red cushion is added for the bio-digester culture to nurture and grow.

INVENTION MACHINE

Patents for tools that would lead to patent-worthy ideas.

I want a cure for cancer, a transporter, and an end to aging. Maybe I could have all these things if I had an invention machine. Could a computer program solve the world's problems? Some people think so and have patented ways to invent.

An early example is No. 5,153,830, issued to Fisher at al. in 1992, for a computer program called "Idea Fisher" (get it?), which supposedly helps you create by "reminding the user of thoughts, feelings, experiences, facts, and images stored so deeply in memory that they normally cannot be retrieved at will. When the user comes up with his own associations, the invention allows these associations to be stored along with those already in the system."

Patent No. 5,581,663 provides a good overview of TRIZ—a theory by Russian Genrich Altshuller popular in invention circles concerning inventive problem solving. The patent also notes several unsuccessful attempts to computerize TRIZ. Instead, the more modest goal of this patent is a computer-based method of identifying and structuring a problem so it is then easier to solve.

Another problem analysis program, offered by Invention Machine Corp. of Boston, is disclosed in patent No. 7,536,368 for a tool which "automatically reformulates a problem statement into a natural language or Boolean query that is automatically submitted via a knowledge search tool to a database, and responses to this query from the database are automatically provided."

Patent No. 6,101,490 is more ambitious—a true computer program problem solver. The example problem given in the patent? A beaver strips bark off a tree and you want to save the tree. The computer's solution? Transplant bark to the damaged location on the tree.

As best as I can ascertain, patent No. 7,685,118 is for an invention machine based on ontology. Maybe one day it can solve the problem of explaining ontology.

Patent application No. 2002/0111817 is for the Invention on Demand method which identifies "white spaces" where patented inventions are needed.

Published application No. 2011/0202420 is for a brokered invention method. You have a problem which needs solving and you set a price for a solution. Your broker then seeks out people with potential solutions. Solutions submitted are rated and the winner then gets paid.

This sounds a little like InnoCentive Inc. (www.innocentive.com)—a Boston-based open innovation facilitator. A patent application describing InnoCentive's bounty-based invention method is No. 2010/0293040.

So, we don't yet have a fully realized invention machine. Why can't some of the inferior invention machines generate slightly better versions of themselves which then generate slightly better versions and so on? Maybe I should patent that idea. ME

KIRK TESKA is an adjunct law professor at Suffolk University Law School, and the managing partner of Iandiorio Teska & Coleman, an intellectual property law firm in Waltham, Mass.

WHAT IS TRIZ?

Genrich Altshuller, left, with a follower, Isak Bukhman, at a 1983 TRIZ workshop in Yaroslavl,Russia.

The Altshuller Institute for TRIZ Studies (aitriz.org) defines TRIZ as "a systematic process that develops critical thinking skills and promotes creativity and innovation." It was originated by Genrich (or Genrikh) Altshuller, a Russian engineer who searched patents and identified patterns of problem-solving. The result is an algorithmic approach to analyzing and solving problems. TRIZ is an acronym for the Russian name of the process, which means "Theory of Inventive Problem Solving." TRIZ emerged in the 1940s and then was driven underground by the Soviets as "heretical." It re-emerged after the fall of the U.S.S.R.

This prototype of a new type of biomolecular tweezers could aid in the study of the biochemical activity of cells. Image courtesy of Lizhi Cao.

A GENTLE SQUEEZE

Cellular biologists often look at the chemistry of cells. But a new tool may enable them to better understand how cells react to (very slight) pressure.

PEOPLE REACT DIFFERENTLY UNDER STRESS—SOME, SAY, ARE MORE willing to confess when put on the rack than when sitting in a comfy chair. Cells are much the same.

Red blood cells, for instance, normally deform as they circulate through the body, their normal Cheerio-like shape stretching into something more like a bullet when it passes through a capillary. Some diseases, such as malaria, affect red blood cells so that they lose the ability to change shape. And that keeps the cells from doing their job of carrying oxygen to other cells in the body.

Researchers have long studied how cells behave under pressure through such direct means as sucking them through a narrow pipette while watching through a microscope. Last decade, scientists discovered that by attaching tiny beads to their membranes, you could use laser light to stretch individual cells. That gave researchers more control, but they were still limited to stretching one cell at a time.

FLEXIBILITY WILL ENABLE THE SAME DEVICE TO WORK ON BIOLOGICAL SAMPLES AS LARGE AS CELLS OR AS SMALL AS PROTEINS.

Biomechanical engineers at Georgia Institute of Technology in Atlanta have developed a new device to stretch cells they think can be turned into an array. That would enable researchers to stretch thousands of cells at a time.

Instead of laser light, the Georgia Tech tweezers apply magnetic and electrical forces to the biological sample being studied. One end of the sample is attached to a minuscule polystyrene bead containing magnetic nanoparticles while the other is attached to a magnetic pad. The magnetic force draws the bead toward itself while electric current running through the pad acts on the bead, pushing it away. Researchers can balance the electric and magnetic forces to create as much stretching or squeezing as needed.

That flexibility will enable the same device to work on biological samples as large as cells or as small as individual proteins.

The research team, Thomas Barker, Lizhi Cao, and Wilber Lam, are working with a prototype that can work on 225 samples at a time. The goal is an instrument built via photolithographic techniques that can apply varying forces to thousands of biological samples simultaneously. The developments were published in a February issue of the journal, *Technology*. ■

NATURAL GAS

Westport Innovations and Tata Motors are partnering to develop natural gas engines for commercial vehicles in India.

The companies have jointly introduced a spark-ignited engine using technology developed by Westport. They have also worked together to develop a dual-fuel natural gas diesel engine. So far, prototypes of the engines have been shown publicly, at India's Auto Expo in New Delhi in February.

Westport, based in Vancouver, British Columbia, specializes in designing technology for natural gas engines. Tata is India's largest automobile company.

The spark-ignited engine is a turbocharged 3.8-liter model that uses the Westport WP580 engine management system. The engine is designed for light-duty vehicles and medium-duty vehicles.

The companies say that, later this year, the Westport WP580 system will be applied to Tata's 5.7-liter engine for medium-duty applications.

The WP580 contains proprietary control electronics and spark plugs adapted for natural gas. According to Westport, the engine management system is designed to meet Euro VI emission standards.

Tata refers to the engine as the 3.8 SGI, for "sequential gas injection." Electronic controls rely on about a dozen inputs from sensors in the engine.

Westport and Tata have also developed a "gas enhanced methane diesel" engine, identified by the trademark GEMDi, in a new Tata 5-liter engine intended for medium-duty trucks and buses. The companies are billing it as a practical solution for regions, like India, where the natural gas infrastructure is developing. They say the engine will meet Euro IV and V emissions standards.

Tata says the GEMDi engine produces about 180 hp and torque of 650 newton-meters. Performance is similar when the engine is burning natural gas or diesel fuel.

Westport will supply Tata with proprietary natural gas components that will be integrated directly into the engine.

According to Westport, a dual-fuel engine typically uses conventional diesel engine hardware, with some modification for natural gas. In dual-fuel mode, natural gas is taken into the combustion chamber with air and compressed. Diesel fuel is injected near the end of compression stroke to ignite the mixture of natural gas and air.

The engine can run on diesel fuel alone if that becomes necessary. Westport says that, according to its analysis, a dual-fuel vehicle can operate at a fuel substitution ratio of about 60 percent. That is the fraction of total fuel energy contributed by natural gas. The remaining 40 percent

ENGINES FOR INDIA

would come from diesel fuel. Higher fuel substitution ratios are possible through improved engine design and control.

A recent report by TechSci Research, a management consulting firm with offices in the U.K., Canada, and India, predicts that India's natural gas market will increase at a compound annual growth rate of 26 percent for the next five years. The report, *India Natural Gas Market Forecast & Opportunities, 2019*, sees demand and supply rising together as Indian energy companies increase production and the country imports more liquefied natural gas.

TechSci Research estimates that natural gas represents 10 percent of India's energy consumption. It says that share will grow because of rising concern over greenhouse gas emissions and the low price of natural gas.

The government is promoting natural gas production in India with a new pricing policy for companies producing domestically. The government is also encouraging production from unconventional resources such as coal bed methane and shale gas.

The report says India's pipeline network is rapidly expanding, with new lines to be commissioned during the next five years. ME

Tata offers a spark-ignition natural gas engine that uses Westport's WP580 engine management system.

Q&A ALEX PENTLAND

ALEX PENTLAND, OFTEN CALLED THE GRANDFATHER OF Google Glass, and cited by *Forbes* in 2012 as one of the seven most powerful data scientists in the world, wears so many hats it boggles the mind. Pentland directs both the Human Dynamics Laboratory and the Media Lab Entrepreneurship program at the Massachusetts Institute of Technology. The lab pioneered the idea of society enabled by Big Data and has developed reality mining, which uses mobile phone data to extract patterns to predict human behavior. He also is a driving mind behind organizational engineering, biometrics, and wearable computing.

ME: How has your work and educational background along with your interests led to your present roles?

A.P: I've always been interested in human-machine systems, ranging from cars with assisted driving to distributed organizations to governments and society generally. I was also lucky enough to get a solid mathematical, signal processing, and machine learning background early on. As an undergraduate at the University of Michigan I was put in charge of a NASA project building systems for space satellite remote sensing of the environment. My first job was counting Canadian beavers from space!

ME: What's been your most challenging project to date?

A.P: The current problem of how our society promotes greater sharing of ideas and information while at the same time protecting personal privacy and security. This is the focus of the discussion group I co-led at Davos for the World Economic Forum in 2011 and it constitutes much of my research here at MIT and research elsewhere in the world. Our current best solution is to give individuals greater control over information that is about them through the mechanism of personal data stores (PDS). Our openPDS solution is what MIT and the European Institute of Technology are currently experimenting with to address the thorny sharing versus privacy problem.

ME: Do you wear Google Glass?

A.P: I'm often called the grandfather of Google Glass so I sort of have to, don't I? To not wear Glass would be letting down both the wearables community and my former students.

ME: Can you talk about a few projects at the Human Dynamics Lab you're involved with? What, for instance, is reality mining? What is the idea of a society enabled by Big Data?

A.P: We have entered an age where our current systems—power, transportation, governance, health—are all failing because they're built on static designs of the 1800s. At the same time we suddenly have digital data about almost everything; breadcrumbs thrown off by cell phones, credit cards, car transponders, and such. We use reality mining to analyze that data and build dynamic, predictive systems that are far more efficient and robust than current systems. Such dynamic systems can address the grand challenges facing our society. But to achieve that promise we must also solve the problems of privacy and government surveillance.

ME: Of what in your life are you most proud, workwise?

A.P: I have always been able to rise above the ongoing research dialog and ask, "Why are we focusing on particular questions?" and then offer more fundamental and productive questions for the community to pursue. This has let me change the direction of several research communities: imaging, wearable computing, transportation, technology for development, multimedia, health sensing, and social networks, among others.

ME: When you were a kid what did you want to be when you grew up?

A.P: Hari Seldon, a fictional character who built mathematical models of society's evolution. In Isaac Asimov's *Foundation* trilogy, Hari was able to guide the human race to salvation by use of small, exactly timed nudges.

ME: Anything else you want to add?

A.P: My new book, *Social Physics* (Penguin Press), came out in February 2014, and I think it is the nearest thing yet to a mathematical, practical theory of human society. Anyone with a technical bent who is interested in human-machine systems, privacy, or building better organizations will probably really enjoy it. **ME**

U.S. ENERGY USE ROSE IN 2013

Americans used more renewable, fossil, and nuclear energy in 2013, according to the most recent report by Lawrence Livermore National Laboratory. The laboratory estimates that Americans used a total of 97.4 quadrillion Btu in 2013, versus 95.1 quadrillion in 2012.

Wind energy's contribution increased 18 percent, from 1.36 quadrillion BTUs, or quads, in 2012 to 1.6 quads in 2013 (3,400 Btu is equivalent to about 1 kilowatt-hour). New wind farms continue to come on line with bigger, more efficient turbines. Most new wind turbines can generate 2 to 2.5 megawatts of power.

1.6
quads

Natural gas prices rose slightly in 2013, reversing some of the recent shift from coal to gas in the electricity production sector. Even so, "the power industry is building a lot of natural gas plants," said A.J. Simon, group leader for Energy at Lawrence Livermore National Laboratory. "Gas plants are cheaper than coal plants. Natural gas is going to be a winner into the foreseeable future." Overall natural gas use increased by 0.6 quad.

26.6
quads

Nuclear energy grew to 8.27 quads in 2013, up from 8.03 quads in 2012. Petroleum use rose to 35.1 quads in 2013 from 34.7 quads the previous year.

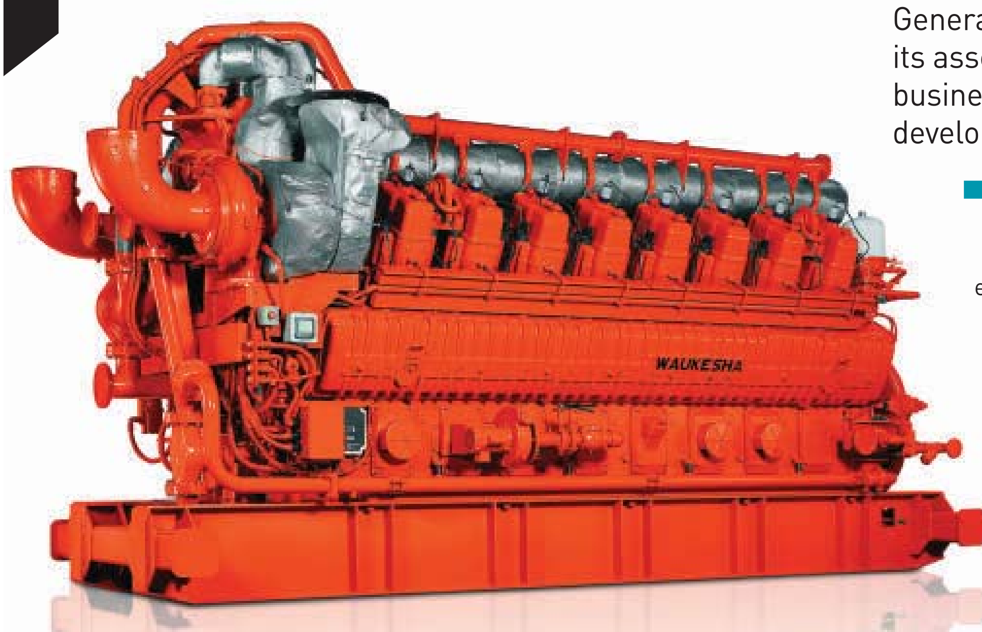
The largest consumption sectors in 2013 were electricity, at 38.2 quads, followed by transportation, with 27 quads. The industrial sector was a close third at 24.7 quads.

The laboratory also has released a companion chart illustrating the nation's energy-related carbon dioxide emissions. Americans' carbon dioxide emissions increased to about 5,390 million metric tons, compared with about 5,290 MMt in 2012. It was the first annual increase since 2010. ■

8.27
quads

The laboratory presents the information in flowcharts. Data for 2013 and previous years is available online at https://flowcharts.llnl.gov/energy.html#2013.

DISTRIBUTED POWER SYSTEMS FOR



The Waukesha 12V275GL+ gas engine is one of several technologies marketed by GE's new distributed power business.

General Electric has reassigned some of its assets to form a new distributed power business with an initial emphasis on developing markets in southeastern Asia.

The new business combines three GE product lines—aeroderivative gas turbines, Jenbacher gas engines, and Waukesha gas engines. According to GE, the company plans to invest $1.4 billion over four years in the new unit "to help meet the world's growing demand for on-site power systems that are easier to finance, faster to install, and more efficient and reliable for customers."

Lorraine Bolsinger, CEO of the distributed power business, said, "With more than 1.3 billion people lacking access to reliable power today, our distributed power business is ideally positioned to serve communities in both developing and industrialized countries where demand grows for distributed power solutions to

SOUTHEAST ASIA

improve local energy security and comply with more stringent environmental regulations."

A GE white paper, "The Rise of Distributed Power," estimated that in 2012 distributed power systems accounted for 142 gigawatts, or almost 40 percent, of new electrical generating capacity. The report defined distributed power as systems generating about 100 MW or less.

Also noted was that businesses and communities are installing the systems in remote areas, with poor or non-existent electric grids, to improve access to electricity.

GE introduced the new business at a press conference in Jakarta, Indonesia. A story in *The Jakarta Post* quoted GE's vice chairman, John G. Rice, who said Indonesia was "the perfect place" to develop distributed power technology because about a quarter of the country's 240 million people have no access to electricity. National, and even large regional, connections are complicated because the country is spread over several thousand islands.

The company has signed a number of agreements in recent months for distributed power systems in southeastern Asia. The deals are not only for electricity generation, but also for gas compression.

It has two supply and service agreements, for instance, with a distributed power project developer, Navigat Energy Pte. Ltd. of Singapore, for 100 Jenbacher gas engines that will generate a total of 330 MW at sites in Indonesia and Thailand.

Two memoranda of understanding with a developer, Clean Power Indonesia, and the state-owned electricity company, PLN, concern GE's new integrated biomass gasification power system. The plan is to build synthetic gas plants using local bamboo and wood sources as feedstocks.

GE will supply four Waukesha 12V275GL+ gas engines and two VGF48GL units to upgrade a gas compression station operated by Pertamina, the Indonesian state-owned gas and oil corporation.

An agreement with a Malaysian biotechnology company, Green & Smart Sdn. Bhd., aims to establish a waste-to-power system using Green & Smart's patented technology in anaerobic digestors and GE's Jenbacher gas engines.

Besides bringing electricity to places where it is rare or unavailable, GE is also promoting the unit's products as providing a cleaner alternative to many established distributed generation systems.

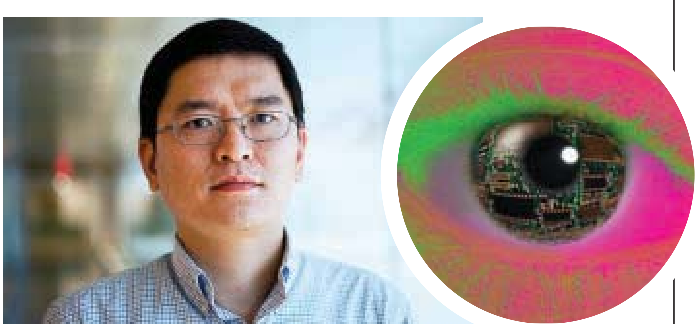
A GE press release quoted Handry Satriago, the company's CEO for Indonesia: "With our distributed power business, GE has numerous technologies that can hasten the substitution of natural gas for diesel throughout the more than 17,000 islands of the Indonesian archipelago. Making the move to natural gas and biogas will go beyond helping Indonesia improve its fiscal sustainability and energy security to reducing greenhouse gas emissions." ME

 BY JEAN THILMANY

INFRARED INSIGHTS

An RAF pilot wears night-vision equipment. A newly developed sensor might significantly lighten the bulky equipment, which is prone to overheating.

LIGHT NIGHT VISION



THE LAB The Zhong Group, University of Michigan, department of electrical engineering and computer science; Ann Arbor, Mich.; Zhaohui Zhong, principal investigator.

OBJECTIVE Night vision without the bulk via carbon-based nanomaterials.

DEVELOPMENT An infrared sensor on one-atom-thick graphene.

Researcher Zhaohui Zhong's lab is developing a new super-thin infrared sensor that could be the basis for night-vision contact lenses, as simulated above right, for use in military and science applications.

Two university laboratories are working with infrared technology to dispel darkness and distance. One lab is looking to create a lightweight alterative to night-vision goggles and the other has created an algorithm to search infrared images for hidden nuclear weapons.

Night-vision goggles are heavy. And they run hot so they need a built-in cooling mechanism, which makes them even heavier. Contact lenses would be a lot lighter to carry and to wear.

Researchers at the Zhong Group have created a super-thin infrared sensor. According to Zhaohui Zhong, who leads the group, the sensor could add lightweight night vision to contact lenses, Google Glass, or smartphones so users could see in the dark. The lightweight technology will find military and science use, he added.

The group's sensor prototype is smaller than a pinky nail and can be scaled down even smaller, he said.

The sensor is made of graphene, a carbon structure a single atom thick. Not only is it considered the world's strongest material, but it can sense the entire infrared spectrum as well as visible and ultraviolet light. Graphite is composed of stacked layers of graphene, Zhong said.

To create the sensor, his team engineered a new way to boost the sensitivity of graphene in order to generate an electric signal from infrared light.

Infrared light is electromagnetic radiation with longer wavelengths than those of visible light. Researchers have had trouble getting graphene to absorb enough light to produce an electrical signal, Zhong said.

The researchers sandwiched an insulating barrier between two layers of graphene and added an electrical current to the bottom layer. When infrared light hit the top layer, it dislodged electrons as it normally would. But the electric current amplified the pattern of electron movement and could be used to reconstruct the infrared image, Zhong said.

"We envision that people will be able to adopt this same mechanism in other material and device platforms," Zhong said.

NO HIDING PLACE OUT THERE

THE LAB Brigham Young University, Gustavious Williams, civil and environmental engineering professor, and Candace Berrett, assistant professor of statistics; Provo, Utah.

OBJECTIVE Long-distance nuclear weapons detection.

DEVELOPMENT A way to search images for nuclear materials.

Gustavious Williams, left, and Candace Berrett, right, created an infrared analysis method that could spot from a distance sites where nuclear weapons are being made. Photo credit: BYU.

Infrared technology has the potential to spot from afar whether a site is being used to make nuclear weapons.

Hyper-spectral infrared cameras capture light in hundreds of narrow bands. Since different materials reflect or absorb different bands of light, scientists can characterize the materials by analyzing the picture.

Unfortunately, other signals bouncing back to the camera from such factors as temperature and weather conditions can muddle the analysis by adding noise to the material's light signature, said BYU civil and environmental engineering professor Gustavious Williams.

Williams joined forces with assistant professor of statistics Candace Berrett to develop a way to analyze infrared images. They developed a muddle-free model to detect and describe materials in each pixel of an infrared photograph.

Their method separates the incoming signals to provide the material's unique signature. According to Williams, other methods deal with the noise by matching the combined signals in a database to search for material type.

"What we wanted to know is, if you didn't know anything about the material in an image and if we had a number of pictures over time, could we let the algorithms figure out what the different materials are and separate them out?" Williams said.

The information returned from the model is akin to measuring the material with a spectrometer in a lab, he said. The model can also group together pixels that are related to each other to map out the various materials in an image.

As the technique develops, Williams added, the method could be used for other purposes, such as to detect gas leaks—along with the exact gas being leaked and its concentration—in an area recently hit by an earthquake. **ME**

HOUSE UNIT EXPLORES PRIZES AND INNOVATION

The House Science, Space, and Technology Subcommittee on Research and Technology held a hearing to examine the role of incentive prizes in spurring technical innovation.

The hearing, named "Prizes to Spur Innovation and Technology Breakthroughs," considered prizes funded by the private sector and federal science agencies. H.R. 4186, the Frontiers in Innovation, Research, Science, and Technology Act, or FIRST Act, was introduced earlier this year, and encourages more public-private partnerships for science and technology prize competitions.

"WHY FIND THE NEEDLE IN THE HAYSTACK WHEN THAT NEEDLE CAN FIND YOU? HOSTING A PRIZE DOES JUST THAT."

In his opening statement, Committee Chair Lamar Smith (R-TX) observed, "A top priority of the Science Committee is to encourage such innovation and technological advancements. To maintain our competitive advantage, we must continue to support fundamental research and development that encourages the creation and design of next generation technologies. ... The FIRST Act improves federal science prize authority. It allows federal science agencies to better partner with the private sector to maximize the value of every taxpayer dollar invested in research and development."

One witness, Christopher Frangione, vice president of prize development for X Prize, summed up the challenge: "At X Prize we say, 'Why find the needle in the haystack when that needle can find you?' Hosting a prize does just that."

According to Frangione, "Prizes are powerful for many reasons, the most important of which include leveraging your investment, democratizing innovation, and reducing risk."

Another witness was Donnie Wilson, CEO of Elastec/American Marine, which won $1 million from the Wendy Schmidt Oil Cleanup X Challenge for developing an efficient means to retrieve oil from the surface of water. The challenge was a response to the *Deepwater Horizon* accident in the Gulf of Mexico.

Elastec/American Marine's grooved disc skimmer technology was awarded $1 million by the X Prize Foundation in 2011. Photo: Elastec

Pursuing the prize, the company developed a system that could take up 4,670 gallons a minute at almost a 90 percent efficiency ratio of oil to water.

According to Wilson, "In just six months the X Prize Foundation had become the catalyst to advance the efficiencies of oil spill recovery more than in the previous twenty years."

The statements of the hearing witnesses and an archived webcast of the hearing are available at http://science.house.gov/hearing/subcommittee-research-and-technology-hearing-prizes-spur-innovation-and-technology. ■

MEDICAL DIAGNOSIS IN THE PALM OF YOUR HAND?
The Qualcomm Tricorder X Prize brings Star Trek to the near future.
PAGE 46.

LOOKING BACK

ABOUT THE VAULT

Gas turbines, now essential to transportation and power generation, had yet to develop a commercial market when this article was published in June 1944.

GAS TURBINES: PRESENT STATUS & FUTURE PROSPECTS

BY S.A. TUCKER, ASSOCIATE EDITOR OF *POWER*.

Seventy years ago, as the Second World War drew to a close, gas turbines were a new technology, largely untried in civilian applications.

Mentioned among immediate applications for gas-turbine units are (1) locomotive drive, (2) ship propulsion, (3) blast furnace air supply, and (4) experimental power units.

For the immediate future, the question that must be answered is: Who will first be ready to invest money in what may be regarded at best as an experimental unit? The railroads, maritime operators, the steel industry, and power people all have a stake in further development of gas turbines. Of these, the Maritime Commission has taken the initiative by ordering a main propulsion unit of around 2,000 hp from the Elliott Company for a CI-MA-V1 coastwise cargo ship. It is probable that one of the railroads can be persuaded to try an experimental locomotive as soon as war pressure lets up on turbine shops.

From the long-run viewpoint, it would be most desirable for all concerned if the first machine were to be a power unit for the best of engineering and operation could be assured unhampered by the extraneous problems inevitably associated with transportation and shipping. However, such a trial would require at least two years, and manufacturers are hardly in a mood to sit idly by while some one of their competitors acquires so great a lead.

As soon as the European phase of the war can be seen to take an obvious turn for the better, perhaps by the end of this year, manufacturers will want to build gas-turbine units and the several industries named will want to buy them despite the "growing pains" that normally accompany new application and new apparatus. Indications are that railroad, ship, and power trials will proceed more or less simultaneously. **ME**

THE BIGGEST DAY

S.A. Tucker was looking for the war in Europe to take a turn for the better by the end of 1944. On June 6, 160,000 Allied troops landed in Normandy, and the war in the European theater ended 11 months later. The D-Day assault by air, sea, and land was the largest amphibious invasion in world history.

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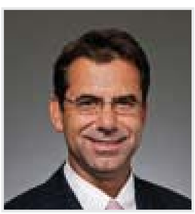
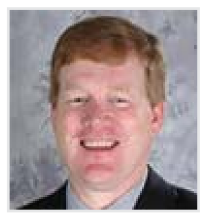


Dr. Helmuth Ludwig
KEYNOTE SPEAKER
CEO
Siemens Industry Sector, USA



Thomas Lange
KEYNOTE SPEAKER
Director, Modeling & Simulation, Global Capacity Organization, Corporate R&D
The Procter & Gamble Company

Brett Chouinard
COO
Altair, Inc.

Martin Berardi
President, Medical Devices Group
Corporate Vice President
Moog Inc.

Bre Pettis
Co-founder and CEO
MakerBot

Dr. Rodney Brooks
Founder, Chairman and CTO
Rethink Robotics

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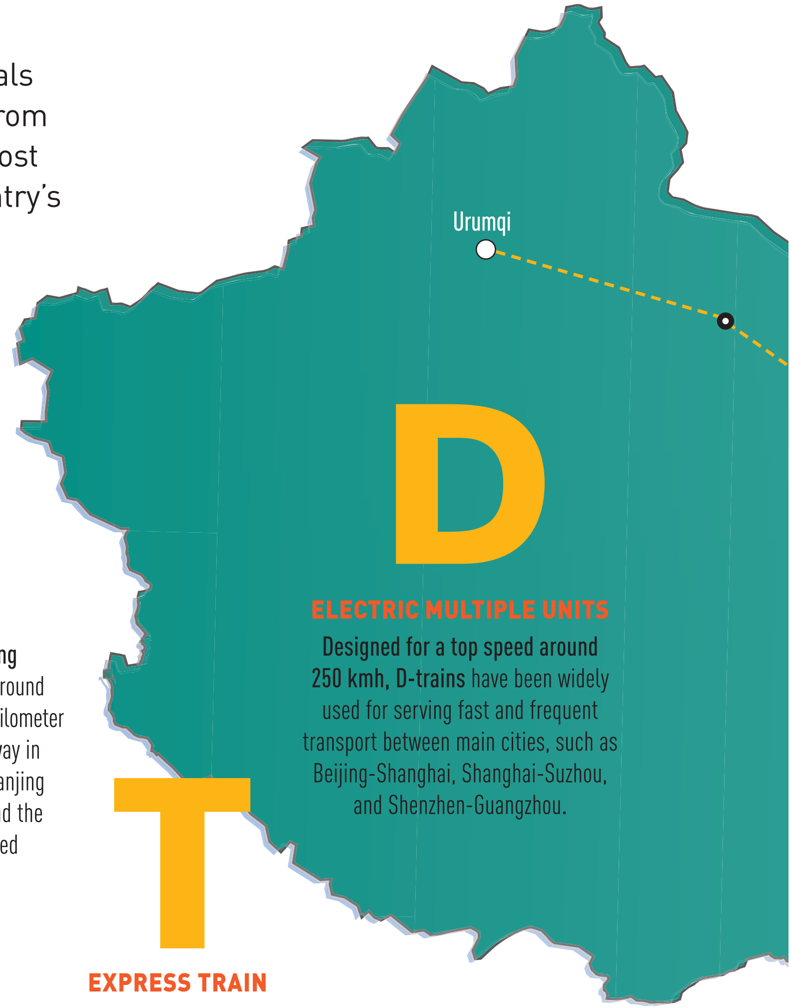
BY THE NUMBERS: WHERE HALF OF

China wants to have almost all its provincial capitals within an eight-hour train ride from Beijing, and from each other. The government a plans to spend almost $100 billion this year alone on expanding the country's high-speed rail network.



G

HIGH-SPEED ELECTRIC MULTIPLE-UNIT TRAIN

This is the fastest running for long distance in China, with a top speed around 350 kmh. A G-train can finish the 1,068-kilometer Wuhan-Guangzhou High-Speed Railway in three hours, the 301-km Shanghai-Nanjing High-Speed Railway in 73 minutes and the 458-km Zhengzhou-Xian High-Speed Railway in two hours.

D

ELECTRIC MULTIPLE UNITS

Designed for a top speed around 250 kmh, D-trains have been widely used for serving fast and frequent transport between main cities, such as Beijing-Shanghai, Shanghai-Suzhou, and Shenzhen-Guangzhou.

T

EXPRESS TRAIN

The T-train has limited stops on its routes, mainly in major cities. The highest speed is 140 kmh. Almost every T-series is equipped with the options of a soft sleeper, soft seat, hard sleeper, or hard seat.

Source: TravelChinaGuide.com

The high-speed rail system in China extended more than 11,000 kilometers at the end of last year, and the country is still building. According to Xinhua, the government-owned news agency, China has about half of the world's total of high-speed track.

In a separate report, Xinhua said China plans to add another 6,600 kilometers of rail this year, but the report did not say how much of that would be for high-speed service.

People's Daily reported in January that 2,285 km of high-speed rail was added in 2013 and that the goal is to extend the system to 18,000 km by 2020.

The system will connect most regional capitals and the national capital, as well as other major cities. Construction plans for high-speed rail links with the Tibet autonomous region and Sichuan province in Southwest China haven't been decided.

High-speed rail lines carry about 2 million passengers a day. They have cut into the ridership of conventional trains and domestic airlines. On one route, conventional train ridership fell from 150,000 to 45,000 a week. After the introduction of high-speed train service between Wuhan and Guangzhou, for instance, daily flights between the cities were reduced to 9, down from 13.

There are different types of trains in China, and the fastest are the G-trains, used on long-distance runs, which can reach 350 kilometers an hour. A slower high-speed service, the D-train, tops out around 250 kmh.

According to a travel-service website, TravelChinaGuide.com, "A G-train comprises two VIP sightseeing-areas, a business cabin, first-class passenger cabins, second-class passenger cabins, and a dining cabin."

The high-speed system is operated by China Railway Corp., which was formed in March 2013 after a shakeup of the old Ministry of Railroads. Some of the ministry's activities were transferred to the Ministry of Transport. The balance, including construction and operation of the high-speed service, was assigned to the corporation.

The China Railway Corp. had a total indebtedness of $510 billion in the third quarter last year. Its debt-to-asset ratio was 63 percent. **ME**

HARRY HUTCHINSON

THE HIGH-SPEED RAIL LINES ARE

COMPARING THE RIDE:
BEIJING TO SHANGHAI
about 1,300 km

TRAIN	NUMBER OF STOPS	TRAVEL TIME	SECOND CLASS FARE
T109	10	14h., 48m.	$**83***
D313	3	11h., 41m.	$**52**
G153	10	5h., 45m.	$**93**

**Fare is for a soft sleeper, one step down from the luxury soft sleeper.* *Source: TravelChinaGuide.com*

NEED MORE INFORMATION? These are some of the sources used for this article.

"China's high-speed-rail network and the development of second-tier cities," journalistsresource.org, Harvard Kennedy School, Shorenstein Center on Media, Politics, and Public Policy, 2014.

"China's Bullet Trains Facilitate Market Integration and Mitigate the Cost of Megacity Growth," Siqi Zheng and Matthew E. Kahn, *Proceedings of the National Academy of Sciences*, March 18, 2013.

Train travel information, including the map, accommodations, schedules, and fares are taken from TravelChinaGuide.com.

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THE RIGHT STUFF

There is a case for believing that factories in the United States are making a comeback.

By Michael F. Molnar

This past February the federal government announced the two newest members of the nascent National Network for Manufacturing Innovation. While each industry-led institute has a unique charter, all share a common mission: to use applied research to scale up new factory-ready industrial processes and materials.

Engineering is a team sport and a contact sport, and NNMI embodies this. It creates a new space for industry and academia to meet and collaborate on precompetitive industrial challenges. Industry-led consortia compete for one-time federal investments. The winners must, at the very least, match this seed capital and provide enough value to become self-sustaining within five years.

The 60 initial members of the Lightweight and Modern Materials Manufacturing Innovation Institute, based near Detroit, matched the federal investment of $70 million. The 73 founders of the Digital Manufacturing and Design Innovation Institute, headquartered in Chicago, quadrupled their $70 million federal investment. If the growth of the year-old pilot institute on additive manufacturing, which now has more than 100 members, is any guide, the number of participants and their commitment will grow steadily.

Clearly, some businesses believe the future is bright for American manufacturing, and they are willing to back that up with their own resources.

Despite dire warnings a few years ago, U.S. manufacturing is not only alive but growing. U.S. output of manufactured goods is growing, exports are rising, and more and more firms are planning to expand or open factories in the United States.

In fact, many experts are optimistic about manufacturing's future. They see strong evidence that the United States is ready for a manufacturing renaissance—one that strengthens our ability to innovate, gives rise to new industries, and creates high-quality jobs. This is important not only to manufacturers and engineers, but to the United States economy as a whole.

LONG-TERM TRENDS

Most engineers have already heard the bad news. Between the start of 2001 and 2010, more than 64,000 factories closed their doors and one-third of all factory workers—5.7 million men and women—lost their jobs.

Some economists argue that U.S. factories have grown more productive, and that it takes fewer factories and workers to make the same amount of products. Yet many industries, including plastics, printing, wood and paper products, experienced declining output. As these plants closed, the ecosystem that nurtured them—small and medium-size firms with specialized skills—withered as well. With a weaker supply base, the remaining factories found it harder to compete effectively.

Meanwhile, many technologies invented in America migrated to overseas manufacturers. When it comes to promising new products, America is the world's idea factory. Americans pioneered everything from integrated circuits and computer networks to flat panel displays, electric cars, and photovoltaic cells. Yet the United States no longer mass produces many of these products.

So if the news is so bad, why am I optimistic?

After more than 10 years of bleak news about manufacturing, we are seeing signs of a turnaround. The United States has added more than 600,000 new manufacturing jobs since early 2010, the first sustained rise in 15 years.

Starting in mid-2012, the number of U.S. factories has grown for four straight quarters. While the numbers are not large, they represent the longest sustained increase in manufacturing facilities since 2000.

Manufacturing's share of the overall economy is also growing. According to a recent working paper by the International Monetary Fund, the current recovery

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marks the first time in 35 years that manufacturing not only bounced back but actually exceeded its percentage of the total U.S. economy before a recession.

Exports have been growing as well. In 2012, U.S. exports rose five times faster than those of other advanced economies and three times faster than emerging Asian nations, according to Bridgewater Associates, a large hedge fund. In 2013, when world trade slowed and exports from other advanced economies fell, U.S. exports continued to rise.

Additionally, U.S. trade deficits in advanced technology products are beginning to decline.

These trends, by themselves, do not define a manufacturing renaissance. But a close look at three critical trends—cost, risk, and energy—shows American manufacturing could prove competitive for decades to come.

The United States retains a leadership position in productivity that continues to ratchet down unit production costs. As a result, Bridgewater Associates has found that the United States manufacturing unit costs are lower than in Germany and other peer countries. Moreover, after adjusting for productivity, Bridgewater found U.S. unit costs are also lower than costs in such developing nations as Mexico and Brazil.

There is still a large gap in wages between the United States and Asian nations, but this gap is narrowing. Wages are rising throughout Asia. According to the International Labor Organization, they doubled between 2000 and 2010. Given higher U.S. productivity, many industries are likely to find the difference in total unit cost is shrinking, even before taking shipping and inventory costs into account, as Boston Consulting Group noted.

Long supply chains, where products may spend months in transit, often carry hidden risks, as well as time, management, and environmental costs.

By their very nature, extended supply chains increase risk. The 2011 earthquake off the Pacific coast of Tōhoku and ensuing tsunami caused catastrophic destruction and loss of life in Japan. Less broadly known was the global manufacturing impact, as plants worldwide slowed or stopped when critical parts were not available. Many companies were surprised to learn their supply base was dependent on materials sourced solely from Japan.

Long supply chains may have several months of goods in the pipeline. This keeps companies from rapidly adding popular new features or correcting defects. Supply chains extended by time and distance make it difficult to correct quality problems not caught at the factory.

Companies increasingly factor in travel and management needed to keep far-flung supply chains moving smoothly and to ensure the protection of intellectual property. They must also deal with unexpected business risks, especially in societies without strong rule of law. It is not surprising, then, that a 2012 study by Harvard Business School professors Michael Porter and Jan Rivkin found that 56 percent of offshoring companies experienced unexpected increases in total landed costs.

In fact, more than half the manufacturing executives who brought new production back to the United States listed supply chain shortening as a top reason, according to Morgan Stanley. The Wall Street firm also found that 70 percent of executives surveyed planned to expand U.S. capacity within the next five years. Also, Boston Consulting found that nearly half of companies with more than $10 billion in sales were actively considering moving production from China to the United States.

Manufacturing is an energy-intensive sector, and over the past two decades, U.S. manufacturers have increasingly become leaders in industrial energy efficiency. Moreover, the United States is enjoying an unprecedented surge in energy production due to technological innovations in shale gas and oil extraction. U.S. natural gas prices are now less than half those of Europe and one-third those of Japan and South Korea.

Natural gas and oil are direct inputs in many manufacturing sectors, including aluminum, chemicals, glass, iron and steel, paper, foundry products, fabricated metals, plastic and rubber products, and especially chemicals, where hydrocarbons provide both energy and feedstock materials.

In May 2012, the American Chemistry Council estimated that lower gas prices would generate 200,000 jobs in these eight industries, plus nearly 1 million jobs among industry suppliers and elsewhere in the economy. It projected that these industries would invest $72 billion in new capacity that would generate another 1.1 million jobs in construction and capital equipment production. These forecasts illustrate how access to low-cost energy could ripple through the economy and affect a broad range of industries while improving U.S. competitiveness.

Closing the cost gap, shortening supply chains, and taking advantage of lower energy costs are long-term trends that are likely to improve America's manufacturing outlook for years to come. But to create a true renaissance, one that grows new industries and adds millions of new jobs, we need to do more.

MANUFACTURING MATTERS

To fuel a true rebirth in innovation and economic growth requires investment in advanced manufacturing capabilities.

Let's start with innovation. Most engineers instinctively understand that a $1 billion computer chip factory is more valuable economically than a $1 billion warehouse complex. Why? Because even though manufacturers make up just 12 percent of the U.S. economy, they fund 70 percent of all private sector R&D, generate 70 percent of U.S. patents awarded to U.S. entities, and employ 60 percent of all R&D professionals.

Research, development, and design are intimately connected with product development and production—and proximity is essential. New ideas and insights for future improvements emerge as engineers and scientists struggle to resolve production problems, reduce costs, and improve performance. This type of iterative innovation enables manufacturers to build sustainable competitive advantages.

Bell Labs famously housed dreamers and doers under a single roof for this reason, and today Boeing has moved engineers to the production floor and Intel locates semiconductor plants near design facilities. As the U.S. National Research Council in its ongoing Making Value in America study and MIT's *Production in the Innovation Economy* report assert, manufacturing, design, and innovation are not independent pillars of business success, but are intimately linked.

A UC Berkeley economist found that the average manufacturing job supports 1.6 jobs outside of manufacturing. In advanced manufacturing, each job generates nearly five other jobs.

Moving production offshore isolates designers and engineers from their best opportunities for learning. If manufacturing moves offshore, eventually engineering—and America's ability to profit from its innovations—will follow.

Manufacturing also creates good jobs. Over the last decade, new hires in manufacturing earned an average of 38 percent more than new hires in non-manufacturing industries. And over a career, a manufacturing worker earns 17 percent more in wages and benefits than his or her counterpart in other sectors, according to U.S. Commerce Department data.

Yet this tells only part of the story. Today's factories are no longer the vertically integrated enterprises they were 50 years ago. They buy not only raw materials and components, but also specialized services once done by manufacturing employees. A plant, for example, might hire firms to clean heat exchangers, manage logistics, retrofit plumbing and wiring, maintain machinery, test materials or welds, model stress in molds, and even design its products. In Michigan, the fastest growing technical jobs are for automotive-related software and application developers. Most of these jobs are not classified as "manufacturing."

No wonder Enrico Moretti, a University of California, Berkeley, economist, found that the average manufacturing job supports 1.6 jobs outside of manufacturing. In advanced manufacturing, each job generates nearly five other jobs.

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Manufacturing plays a critical role in both innovation and jobs, and there is nothing inevitable about its decline.

Some economists, for example, argue that the rapid decline in U.S. manufacturing jobs is due to rising factory productivity. Yet U.S. manufacturing employment remained fairly stable—about 17.5 million workers—between 1965 and 2000 before declining by one-third between 2001 and 2010.

Productivity was rising throughout that entire 35-year period. And both Yale economist William Nordhaus and the Brookings Institution found that U.S. industries that boosted productivity the fastest were those most likely to increase employment.

In Germany and other developed countries, manufacturing's share of the economy declined, but key industries remained competitive against offshore competition. The reason, many assert, is simple: those nations treat manufacturing as an important part of their national economic infrastructure.

GLOBAL APPROACHES

Many governments offer direct support to manufacturers. China, for example, offers tax incentives, low-cost factory space, and export subsidies. Singapore entices top tech startups with direct investment, free or low-cost space, and subsidies for new science and engineering hires.

Germany partners with local manufacturers to train students from high school through graduate school. It supports more than 60 Fraunhofer Institutes, which provide high-quality, short-term R&D that small- and medium-size enterprises could not otherwise afford. It also hires graduate students and postdocs, usually for three to six years, before they find industry jobs.

Fraunhofer's relentless pursuit of applied research produces factory-specific solutions and a highly skilled R&D workforce. It strengthens the entire manufacturing ecosystem so manufacturers can compete on value rather than price. It is an important reason why more than 1,100 small- and medium-size German firms rank first or second in European or global markets for their products.

In the United States, innovation policies associated with manufacturing have a mixed reputation because they are sometimes associated with picking winners and losers.

Yet there is one area where innovation policy has had an undeniably positive impact: basic research. Long-term funding for basic science has created an outstanding culture of innovation and wealth creation in the United States.

> We hope to kick off at least four more institutes this year. Each one will develop a platform technology that has the potential to change other industries.

Today, the United States leads the world—often by large margins—in nearly every metric used to measure research success. These include research funding, research paper citations, royalties and fees, and U.S. patents granted in biotechnology/pharmaceuticals, medical equipment, automation and control, and other technology areas, to name a few cited by the National Science Foundation.

While private industry dominates the "development" side of R&D, NSF finds that government-funded universities conduct most basic research. Federal support underwrote the basic science behind many of the vibrant industries pioneered in the United States. These include integrated circuits, computers, LEDs, flat screen displays, optical communications, nanotechnology, and biotechnology.

Yet many of these industries have moved abroad, to nations that invest in incentives and infrastructure to support them. Even startups in emerging technologies are being pulled overseas by aggressive government incentives, according to Elizabeth Reynolds of Massachusetts Institute of Technology, who discussed the subject in the November 2013 issue of this magazine. Reynolds and several colleagues studied the fortunes of 150 startups that had licensed technology developed at MIT.

The flow of manufacturing offshore is not inevitable. Thirty years ago, the United States faced the precipitous decline of its semiconductor industry in the face of better funded Japanese competitors. In 1987, the federal government and 14 U.S. semiconductor manufacturers founded SEMATECH to regain lost competitiveness by addressing common manufacturing problems. The Department of Defense invested a total of $848 million, which was matched by industry. By 1996, SEMATECH had become self-sustaining and had begun to expand—and its now robust members had returned nearly $35 billion in tax revenue to the federal government. Today, SEMATECH is widely credited with retaining American leadership in semiconductors and attracts members from around the world.

SEMATECH was one of the models we looked at when creating the National Network for Manufacturing Innovation. We also looked at best practices from Germany, Japan, Canada, and other developed nations that compete on know-how rather than cost. We found much to build on, while leveraging such unique American strengths as our world-renowned research universities, industry-leading manufacturers, and entrepreneurial culture.

Like SEMATECH, NNMI institutes do not pick winners or losers. The institutes are viable only when private companies are willing to commit significant matching funds of their own. Each institute will have its own specific focus, and must line up broad-based industry funds to become self-supporting within five to seven years.

Like the Fraunhofer Institutes, NNMIs will develop factory-ready technologies for their target industries' entire manufacturing ecosystems. They will also serve as "teaching factories," training R&D professionals to transform research into sustainable competitive advantage and establishing a workforce familiar with these new technologies.

The NNMI program seeks to transform an unquestioned American strength—pioneering R&D—into new growth industries.

Our first four institutes focus on digital manufacturing and design, lightweight materials, power electronics, and additive manufacturing. We hope to kick off at least four more institutes this year, including the Advanced Composites Manufacturing Institute. Each one will develop a platform technology that has the potential to change other industries. They could help the United States take the lead in products as varied as ultra-efficient automobiles, high-efficiency appliance motors, customized production, and personalized yet affordable prosthetics.

The United States invests more money in research than any other nation. It is time to receive full value from this investment by making what we invent.

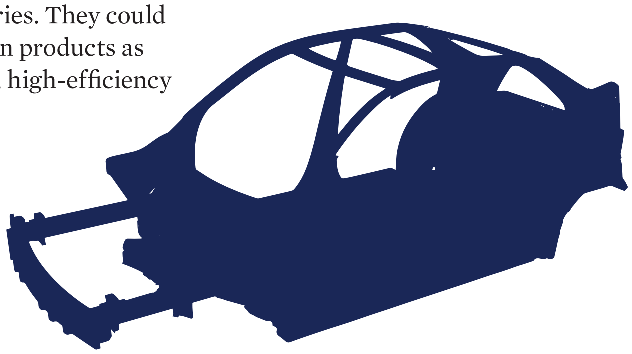
The National Network for Manufacturing Innovation has already drawn bipartisan support in Congress. It is only one of several proposals to improve the competitive position of U.S. manufacturing. The Obama administration has proposed reforming the tax code to reduce tax rates and eliminate incentives to build factories abroad. There is strong bipartisan support for improving and certifying technical and vocational training in community colleges, as well as certifying the training of returning veterans and upgrading our national infrastructure.

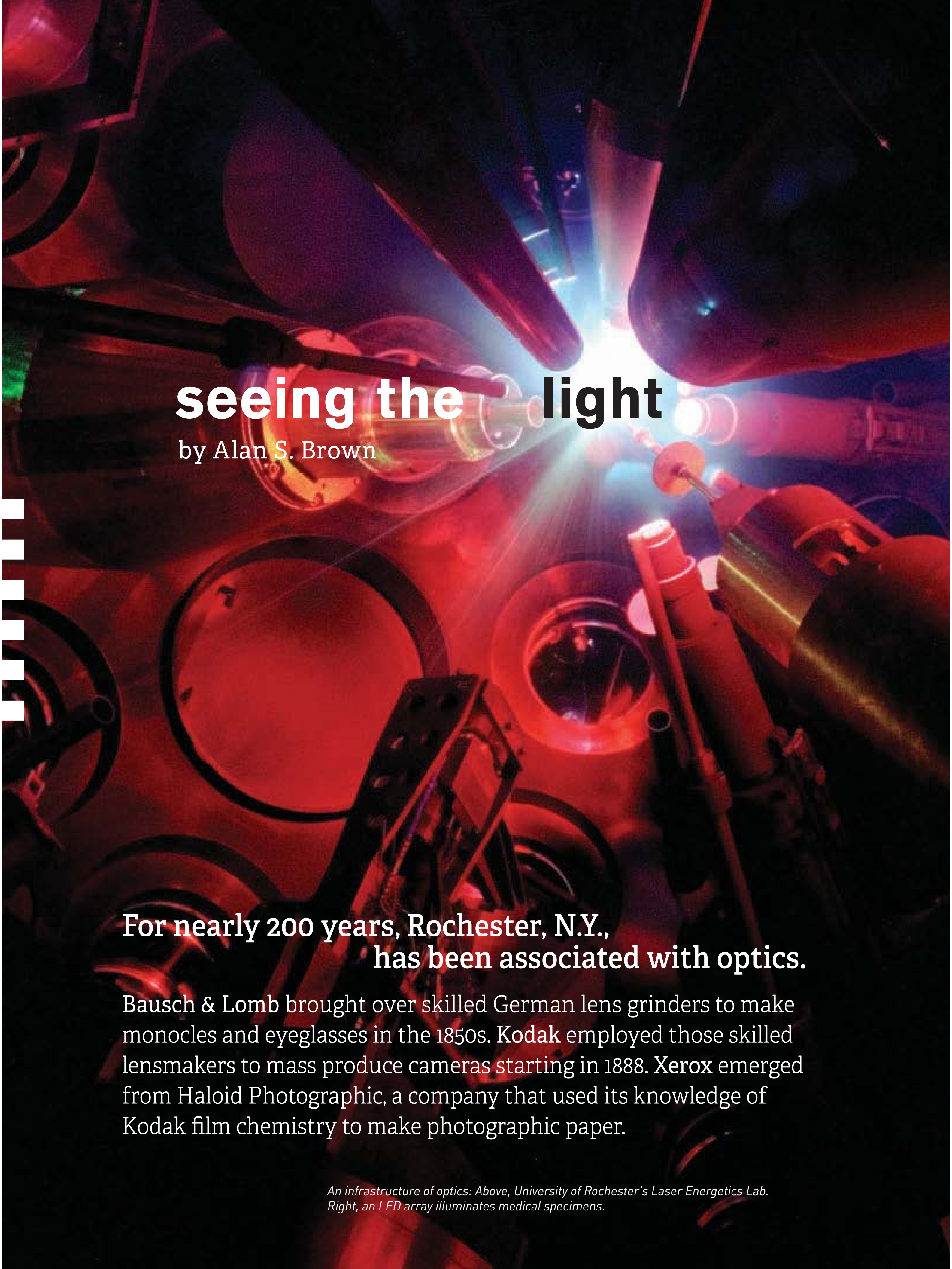
U.S. manufacturing is poised for a turnaround. The wage gap with foreign competitors has narrowed, U.S. companies have a greater appreciation of the hidden costs of long supply chains, and energy prices have been falling.

There is growing awareness in the importance of manufacturing as a means to expand employment and create wealth—but also to stimulate new rounds of innovation. This special role in the U.S. innovation ecosystem is why a manufacturing renaissance benefits all sectors.

This is why we must invest for the long-term in U.S. manufacturing. Industry's "golden age" has not come and gone. We have the knowledge and the path to ensure that the best of American manufacturing is yet to come. **ME**

MICHAEL F. MOLNAR, P.E. and ASME Fellow, is director of the Advanced Manufacturing Office for the National Institute of Standards and Technology, director of the Interagency Advanced Manufacturing National Program Office, and president of SME.





seeing the light

by Alan S. Brown

For nearly 200 years, Rochester, N.Y., has been associated with optics.

Bausch & Lomb brought over skilled German lens grinders to make monocles and eyeglasses in the 1850s. **Kodak** employed those skilled lensmakers to mass produce cameras starting in 1888. **Xerox** emerged from Haloid Photographic, a company that used its knowledge of Kodak film chemistry to make photographic paper.

An infrastructure of optics: Above, University of Rochester's Laser Energetics Lab. Right, an LED array illuminates medical specimens.

How pluck, luck, and perseverance helped Rochester's optics industry get its groove back.

By 1995, it was clear those companies were faltering. Bausch & Lomb had exited most lens businesses in the 1980s. Xerox had lost its stranglehold on the domestic market for copiers in the 1970s and was diversifying out of Rochester.

Kodak, which employed 60,000 people around Rochester in 1980, was already downsizing as it struggled with foreign competition and poor business decisions. By 2014, it would employ fewer than 5,000 people in the Rochester area.

Rochester could have been another dying Rustbelt city. Instead, led by smaller firms, the city's optical industry reinvented itself and preserved the superb technical training program that was the lifeblood of the industry.

It took persistence, preparation, a bit of luck, and a new way of seeing themselves. It began when Chris Cotton walked into Tom Battley's office in 1995 and asked, "What do you know about clusters?"

Cotton, an optics designer, had recently started his own company. Battley was still settling into his job as director of economic development for Monroe County, which includes Rochester.

At that point, the concept of clusters was only a few years old, but Battley had been reading up. Clusters happen when an industry congregates in a region, like computer technology in Silicon Valley and finance on Wall Street. Ecosystems of suppliers, schools, and specialized services sprout to serve it. As people and ideas circulate, they spawn new opportunities and businesses that make the cluster even more competitive.

Cotton wanted to create a group that would take advantage of Rochester's optics and photonics cluster. That included the big firms like Kodak, but also the smaller firms that Battley was just getting to know. Battley had learned about them when he visited Rochester Photonics on his first field trip as director of economic development.

"I came from a manufacturing background and had always worked with engineers, but I had no idea what these guys were doing," Battley said. "They were making polymer surfaces engineered at the micron level, and I couldn't even understand why people would need something like that."

The company's owner, Michael Morris, told Battley that Rochester had many firms like his that specialized in one piece of the manufacturing process. Battley found more than 50, making products as diverse as night vision goggles and lenses for manufacturing semiconductors. Many were hiring and expanding.

The city also had strong optics programs at its schools. Morris, for example, had been a researcher at University of Rochester's Institute of Optics, the nation's first optics program. Rochester Institute of Technology offered top Ph.D. programs in imaging and color science. The city hosted two federally funded laboratories, one for lasers and the other for optics manufacturing. Monroe Community College had a program to train optical technicians.

It was the very definition of a cluster, but the companies that drove it were beginning to fall apart.

BEER AND CHICKEN WINGS CROWD

"The day before Kodak announced they were laying off thousands more people, they would send over their government relations director to tell us," Battley said. "The next day, it would be on the front page. The newspaper reporters would bang on the door of the county executive and mayor and want to know about our shrinking economy."

On the front pages, Rochester looked like another withering northern industrial city. Yet Battley knew Rochester was growing jobs faster than Kodak could lay off workers.

Cotton wanted his business to grow too. "I read a book about word-of-mouth marketing, and one of the things it said was to join an organization and take an active role to get your name out," he recalled. "I looked around and there wasn't one."

But Cotton did find an informal optics group that met irregularly for chicken wings and beer. It attracted many of Rochester's small business owners to trade information and exchange gossip.

"I jumped on it," Cotton said.

The group began meeting monthly. It attracted new members. One was Jim Sydor, who joined his father's small firm after graduating from Monroe Community College's optical technician program. Kodak made up three-quarters of Sydor Optics' business. Like the others, Sydor needed to reinvent the family business.

So when Bob Breault, a successful optical engineering entrepreneur from Tucson, Ariz., came to town, several beer-and-wings guys went to hear him speak. Breault talked about clusters, and how he positioned Tucson's optical industry as Optics Valley, the center of the nation's optics industry.

Cotton, who was there, had never thought of Rochester's optical industry that way before. Yet Rochester had a larger and more established optical industry than Tucson. Cotton asked Battley to help him put it on the map. Two weeks after the visit, the Rochester Regional Photonics Cluster was born.

"We realized we had to do what they did in Arizona," Battley said. "We had to promote our cluster.

"We wanted people to know that if a Rochester company recruited you, you could move here and there would be sufficient opportunity if it did not work out. This was not the land that Kodak forgot."

This was not the

Researchers rely on precision optical components from Rochester. Above, windows from Sydor Optics are used in Sandia National Laboratories' Z-Beamlet, a powerful x-ray laser. Below, Rochester's Laser Energetics Laboratory.

SHOWS OF FORCE

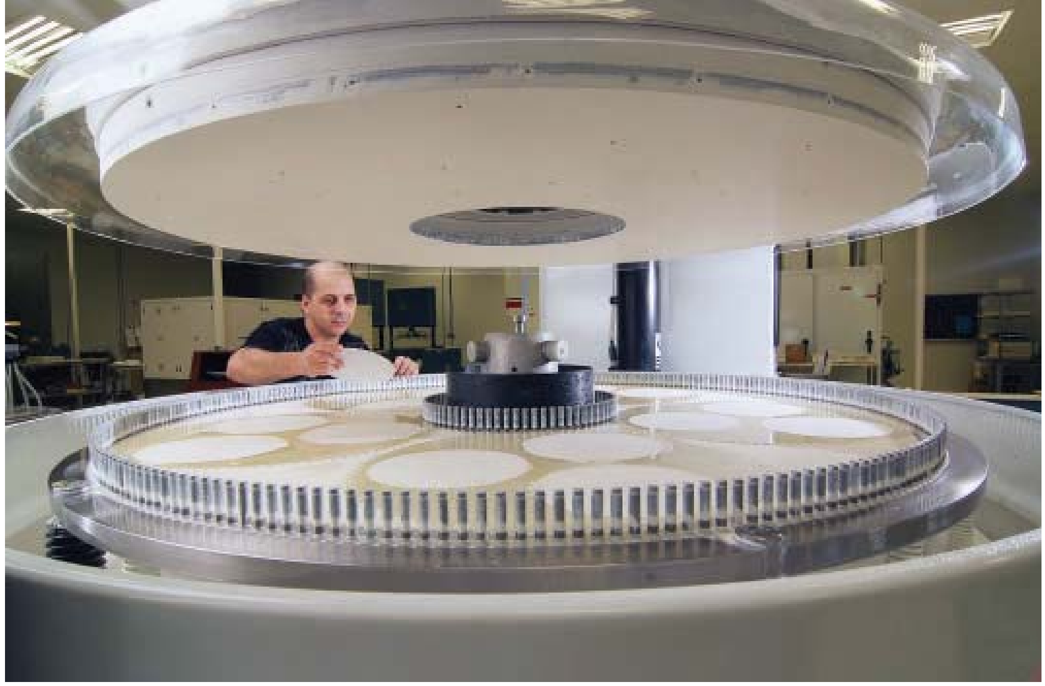
The Rochester Regional Photonics Cluster sought ways to promote itself. Instead of going to trade shows individually, they rented an aisle as a group.

"Now everyone knows they can come here to design their device, make the optics and electronics, and assemble it in a precision housing. It's one-stop shopping," Sydor said.

To raise its profile, the group approached an international optical society, SPIE, to launch a biennial conference on optics fabrication in Rochester. The conference, OptiFab, opened in 2003 and drew 1,700 people, 500 more than expected. The cluster also convinced the Optical Society, which was founded in Rochester 1916, to hold some of its annual meetings, including its 100th anniversary, in the city. The cluster also drew several small but prestigious NASA and Naval Air meetings.

It was not all smooth sailing. The year after OptiFab opened, the University of

When digital cameras upended Rochester's iconic company, Kodak, small optics companies like Sydor Optics, right, had to adapt to survive.



land that Kodak forgot.

Rochester optics firms needed to raise their profile. At left, Rick Plympton, Tom Battley, and Chris Cotton lobbied Congress about the importance of optics, photonics, and imaging. Local firms created a "Rochester aisle" (right) to boost their cluster's visibility at optics conventions.

Rochester's Center for Optics Manufacturing, one of the city's two key laboratories, closed. Meanwhile, Kodak's business was crumbling as digital cameras ate away its film business.

Many smaller optics firms had already diversified and survived Kodak's fall. But they were just waking up to the fact that they relied on Kodak to train their technical workforce.

Optical technicians are the men and women who build prototypes, and set up and run the manufacturing systems. Kodak had partnered with Monroe Community College to teach its employees these skills. Kodak funded MCC's labs and its 30 to 40 tuition-paying students every year paid the salaries of the program's three full-time professors.

"That program was important," Cotton said. "For every engineer, you need two or three technicians. There is no other place technicians can go to get that type of training." Cotton and others recruited MCC students or hired them away from Kodak.

Without Kodak to fill those seats, the program had withered to just three students by the time Dianna Phillips joined the college as dean of technical education in 2005.

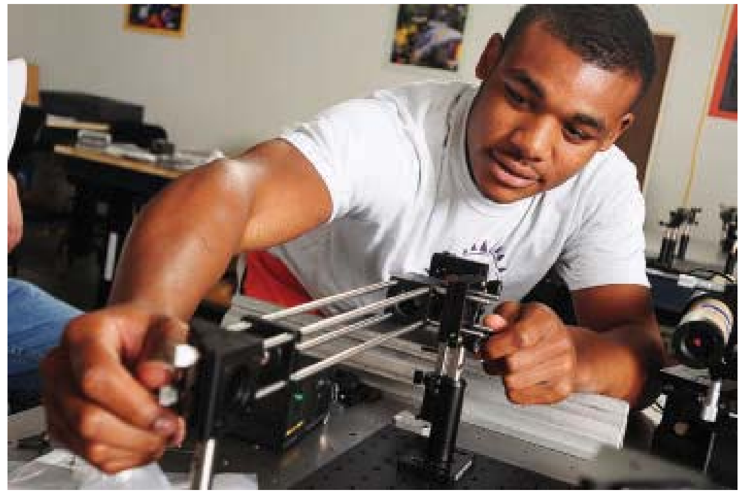
"The technology we had was obsolete, and some of the faculty had been there a long time and didn't want to update the curriculum," she recalled. She had to decide whether or not to pull the plug on the program.

Then she began talking with Battley, Cotton, Sydor, and others. They made it clear how much they needed the community college graduates and offered to help. Industry leaders helped Phillips update the curriculum. They spent hours interviewing new adjunct faculty candidates.

One was Josh Cobb, who learned about the adjunct position while substituting in a baseball game. Cobb came to Kodak from IBM in 1996, and was working at Corning Advanced Optics. He had designed precision optical instruments for more than 20 years, and had taught classes at IBM.

"I said I would like find out about the position, but when I called, I was told they couldn't discuss it until I filled out an application," Cobb recalled.

Local firms teamed with Monroe Community College to hold events, right, that introduced high school students to optics. Below, local businessman Tony Marino helps move equipment into East High School's new Optics Fabrication Lab.



"I didn't hear anything for a few weeks, and they called and asked me to come in.

"I was ambushed. It was a full-blown interview, with five or six people—I knew all of them—across the table from me. Three days later, I received a letter welcoming me to the faculty and telling me that I started in two weeks."

With no time to prepare, Cobb offered to teach a lab instead.

The school still had only a handful of students, but it was upgrading on the fly. Phillips wanted access to modern equipment, but had no money. So she asked photonics cluster members for help. One company let the college hold a class in its factory.

"We hired their engineers as adjunct faculty and got a world-class optical machining course. That's how closely they worked with us," Phillips said.

Student numbers began to rise, but not fast enough to offset costs. Phillips found herself reselling the program to the new college presidents and provosts as administrations changed.

"Industry needed our graduates," Phillips said. "They could get good jobs, and we were doing what community colleges were supposed to do. But the better story was to show how local industry leaders were in it with us."

She remembers taking a new president to eight different optics companies in one day, introducing presidents and CEOs, and also MCC graduates. Each stop showed the local commitment to the program. She also brought around science and technology faculty, so they could learn about opportunities for optical technicians.

The cluster tried to generate interest. It sent press releases about expansions and new companies to local newspapers, and gave talks about opportunities in optics. Members opened their shops for tours. They held events for high school students at the community college campus.

To really fill seats, MCC needed a pipeline from local high schools. All it took was a teacher upset about the time it took for one of his students to get eyeglasses.

THE NEXT GENERATION

Paul Conrow was teaching physical sciences at Rochester's East High School. A few days into the new term, he rearranged his class. Cedric, a tall, awkward student, moved from the front to the back of the classroom. His behavior plummeted.

Conrow quickly diagnosed the problem. Cedric saw nothing from the back of the room and was easily distracted. Conrow called Cedric's mother and the school nurse, yet it took until mid-February for Cedric to get glasses.

"Rochester is one of the poorest school districts in the nation," Conrow said. "It's not like the mom didn't care. She worked and didn't qualify for free glasses, and like the parents of many urban students, she didn't have the time or money to make glasses priority."

While Conrow was glad that Cedric got his glasses, he was upset it took so long. "So I did what any hot-blooded American male would do," he said. "I made a PowerPoint."

The presentation outlined a plan for a school workshop that would teach students to make eyeglasses for other students. Conrow's best friend at the school, a biology teacher who spent three years as a Navy optician, would teach the course.

Conrow presented the idea to the district superintendent, who had been principal in the only school in America with a student eyeglass program. He introduced Conrow to teachers at a sister high school where members of the cluster were helping to plan a precision optics program. There, he met Battley.

"Tom took me on tours of these precision optics factories," Conrow recalled. "I saw that 80 percent of the people were skilled technicians. I thought, 'We could train high school kids to do this level of work.' "

He put that thought on the back burner while he put together a $30,000 proposal for a school optician shop. Meanwhile, the state ordered Rochester to close East's sister school. That school had already lined up a $150,000 federal technology grant that East High inherited. Conrow learned about it

Monroe Community College students receiving expert instruction in the optics lab.

when the principal invited him into his office.

"He said, 'We need a budget by tomorrow at 5 p.m. Otherwise, we'll have to order laptops and smartboards. Can you spend it?' " Conrow said.

Conrow immediately got on the phone with Battley, Cobb, and others he had met. The next morning, he went to a diner with Jim VanKouwenberg, a training coordinator at OptiMax Systems, a specialist in complex lenses. Together, they pored over catalogs and put together an optics lab.

They had only weeks to spend the grant money. Fortunately, Tony Marino, president of another optics manufacturer, Advanced Glass Industries, also dealt in used equipment. He fulfilled the shopping list by the June 30 deadline.

"For every dollar we spent, Tony gave us five dollars of machinery," Conrow said.

That happened in spring 2010. On the last Friday in January, Conrow received an email from the state. East High School had won a $466,666 grant for its optics initiative. The state had forgotten to notify him in August and, naturally, everything was due immediately.

By then, Conrow knew where to turn for help. And today, East High School has a world-class lab capable of making industry-grade optics. The vision care class is also up and running.

"We have to aim very high, so that we can train kids with the exact skills that employers want and need," Conrow said.

Conrow is now recruiting 10th graders and showing them Rochester's optics industry. Instead of the dirty, noisy factories they expect, he takes them to clean workplaces with polished white floors. Some come back and sign up for optics classes. They may take jobs when they graduate or enter MCC's optics program. When they get there, the students will already have college credits from their high school courses.

The photonics cluster is reaching out to other high schools to create similar programs. As the pipeline builds and word of the MCC's program grows, the school is receiving job postings from optics companies in other states.

For several years, Conrow joked that his high school workshop was better than MCC's labs. That will change. The community college recently landed a $500,000 grant for new equipment from the Corning Foundation, whose parent, Corning, makes optical glass and has close ties with the cluster. Sydor matched it with a $250,000 grant of his own.

At University of Rochester and Rochester Institute of Technology, optics programs continue to turn out talented scientists and engineers who quickly find jobs.

Meanwhile, the Rochester Regional Photonics Cluster has morphed into New York Photonics, with additional clusters in Buffalo, central New York, Albany, and Long Island. It now represents hundreds of optics and photonics companies throughout the state.

Of course, it is never clear sailing. While Rochester survived the great recession, its manufacturers suffered. This included Bausch & Lomb. Valeant Pharmaceuticals bought it last year, moved its headquarters to New Jersey, and downsized its operations.

Paul Ballentine, who analyzes technology opportunities as deputy director of University of Rochester's Center for Emerging and Innovative Sciences, sees plenty of upside. Light-based systems are continuing to grow, but Rochester's optics community will have to reinvent itself to thrive.

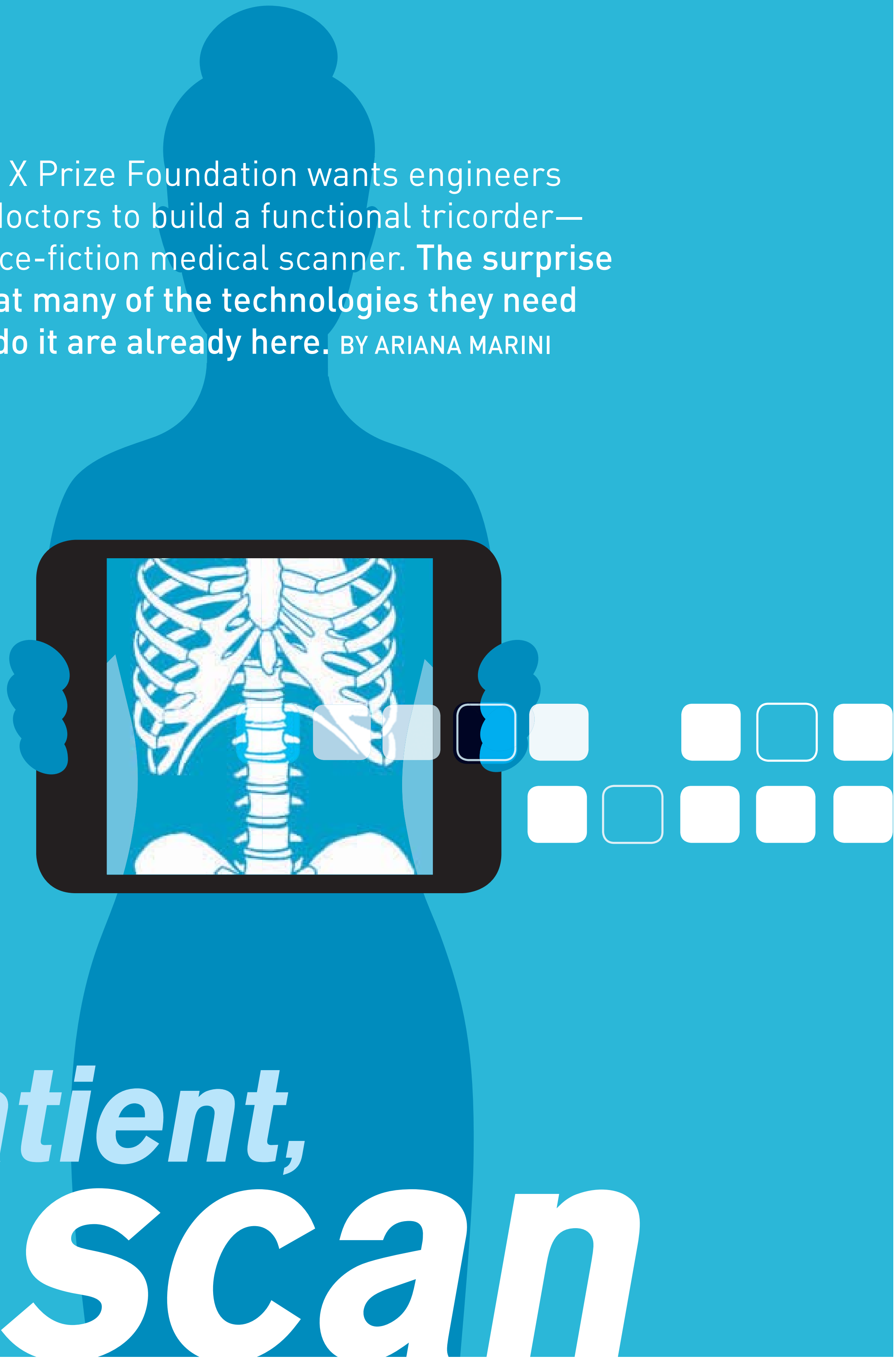
"They have got to recruit more companies that do integrated photonics, combining display and electronics, to Rochester," Ballentine said. "We've got the highest concentration of optic companies in the country. It's a good base to build on."

And, he might have added, one that knows how to adapt to change. **ME**

ALAN S. BROWN is an associate editor of *Mechanical Engineering*.

patient, scan

The X Prize Foundation wants engineers and doctors to build a functional tricorder—a science-fiction medical scanner. **The surprise is that many of the technologies they need to do it are already here.** BY ARIANA MARINI



necessity is the mother of invention.

That was true on a weekly television series back in the 1960s, when the writers of *Star Trek* needed to enable a character to quickly diagnose a medical problem. So they invented a device that could scan a patient in seconds.

The original Star Trek *tricorder has inspired generations of biomedical engineers to develop handheld diagnostic devices.*

The props department built a box with a strap, repurposed some high-end salt shakers, and the medical tricorder was born.

Star Trek was set centuries in the future, but researchers are busily at work building a fully functional tricorder today. They are spurred by $10 million being offered up by the X Prize Foundation and the Qualcomm Foundation, which have teamed up to launch a worldwide competition to develop a portable, wireless device that is able to accurately diagnose 21 specific health conditions.

In addition, all devices must be easy enough to use without extensive training, and must weigh five pounds or less.

thyself

A disposable nose clip developed by Xhale measures pulse, oxygen saturation, and other cardiorespiratory vital signs. The company also makes a monitor (right) that looks for chemical markers on the breath.

Turning science fiction into practical technology on a deadline—judges select a winner next fall—may sound like a tall order. But the promise of a multimillion-dollar prize has moved teams to accomplish some outlandish goals, from launching a privately built reusable spaceship to creating a production-capable ultra-high-fuel-economy car.

And people at the X Prize Foundation believe the capacity to perform some *Star Trek*-style medical diagnostics may take nothing more than some modified sensors and a clever smartphone app. To claim the prize, however, teams will have to combine multiple technologies and miniaturize them into a device that can fit in the palm of a hand.

“There really is no product out there today that can handle a multiplicity of health conditions,” said Mark Winter, senior director of the Qualcomm Tricorder X Prize. While an increasing number of health apps are available for smartphones, “for the most part, the mobile health industry has focused to a large degree on fitness products,” Winter said.

Winter believes the teams actively competing for the $10 million prize can do better. The competition attracted roughly 300 teams, which were narrowed down to 30 contenders in November 2013. X Prize will select the final 10 teams in August.

“I think that it’s important to emphasize that our role at X Prize is to really try to create a threshold change, a movement, where the impossible or what’s seemingly impossible becomes possible,” Winter said. “We view this competition as sort of a version 1.0 demonstration to the world that, in fact, the technology, the talent, and the ability exist to actually create the device and to show that it can actually be effective and work.”

According to the terms of the contest, the winning tricorder will be able to read such vital signs as blood pressure, heart rate, body temperature, respiratory rate, and oxygen saturation. The list of ailments that the device will diagnose runs from such common diseases as anemia, urinary tract infection, and strep throat to serious health conditions such as Type 2 diabetes, atrial fibrillation, stroke, and tuberculosis.

It is expected that such a variety of problems will be a challenge for one compact device to detect. For instance, teams must implement several types of sensors; some may require contact with body fluids while others could be completely noninvasive. The device may also need to include sensors to examine the environment around the patient, sniffing for biochemicals released into the air.

While no single device currently does all that, many technologies that could power a tricorder have already been developed, and more are on the way.

Take, for example, the Proteus Digital Health ingestible sensor, which signals when a patient has taken his or her medication. This may not sound like a *Star Trek*-worthy advance, but the company’s chief medical officer, George Savage, argues that half of all patients fail to take medication or take it incorrectly. This is especially true if they take many pills, have memory issues, or do not like the side effects.

The ingestible sensor could alert caregivers about compliance issues, and the technology is elegant. The sensor itself consists of a 1-millimeter-square chip that contains a tiny, short-range radio transmitter and two battery terminals. When the chip is ingested, stomach acid acts as an electrolyte to create a circuit between the terminals and power the battery.

“Those three things, the anode, cathode, and the wet environment of your stomach, create a power source, which can then power up that novel integrated circuit and start to communicate a pulsed electrical signal which has been carried through your body’s tissues,” said David O’Reilly, chief product officer at Proteus. “What’s important is there’s no traditional pow-

Performing some Star Trek-style medical diagnostics may take nothing more than a clever smartphone app.

To claim the prize, however, teams will have to combine multiple technologies and miniaturize them into a device that can fit in the palm of a hand.

er source and there's no traditional antenna because it's using your body as a wire."

Each chip sends a unique signal that identifies the medication to a second device, a disposable patch worn by the patient. The patch receives the unique signals coming from each ingested sensor. The patch also has accelerometers and sensors to monitor heart rate, respiration, and physical activity.

"That second device then communicates the information on the medicine you swallowed, all of your therapy, and how your body is responding," O'Reilly said. The patch does this through a Bluetooth radio connection to a mobile phone or computer. Caregivers and patients can access the data on a secure application.

"I think about this as sort of the democratization of health care technology," O'Reilly said. "The more initiatives there are like Tricorder X Prize and what Proteus is doing and like what tons of the other people are starting to work on, the more we're going to really personalize therapy and allow consumers to take control of their own health care."

Xhale, a company based in Gainesville, Fla., also monitors compliance, but instead of relying on chips, it looks for chemical markers. It offers an alcohol-based food marker that drug companies incorporate into their medicines. Once the patient ingests the pill, the body absorbs the marker (or its metabolites) into the bloodstream. After taking the medication, patients blow into Xhale's SMART device, which identifies the markers on their breath. ("SMART" stands for "Self-Monitoring and Reporting Therapeutics.")

According to the company's CEO, Richard Allen, the method will tell if a patient has taken the right dose of the right medication at the right time. The SMART system can use several sensing technologies, including miniature gas chromatographs and surface acoustic wave sensors. The latter, the same type of MEMS used in first responder gas sensors, coat micrometer-size cantilevers with chemicals that bind only to a specific marker. As markers attach to the coating, they change the weight of the cantilever and alter its vibration. This signals that the medication has been taken.

Xhale has also developed a small, disposable sensor that attaches to the side of the nose. It measures pulse, oxygen saturation, respiratory rate, airway obstruction, and other cardiorespiratory information. The sensor could be teamed with ingestible markers to give physicians a clearer picture of how medication affects patients. In fact, the company claims the sensor is reliable and unobtrusive enough to replace many existing hospital monitoring systems.

A patch developed by Proteus captures data—such as heart rate, level of physical activity, and whether medication has been taken—from ingested and built-in sensors and sends the information via Bluetooth signals to a smart phone or tablet.

Delmedica's X-Halo compares breath temperature with core body temperature to predict when a patient is in danger of having an asthma attack.

Other companies are also using breath as a means to monitor health. Singapore-based Delmedica Investments offers the X-Halo thermometer, which monitors exhaled breath to predict asthma attacks. By comparing breath temperature with core body temperature, the device can predict when a patient is nearing an asthma attack. This would help patients, particularly children and their caregivers, know when to take medication or even get to a hospital before a severe attack occurred.

The X-Halo is simple enough for children to use. A user inhales through the nose and exhales into a mouthpiece, timing each action to a blinking LED. The mouthpiece directs the breath into a vacuum-isolated measurement block, where it warms a metal core until its temperature stabilizes. That usually takes a few minutes.

If the temperature is significantly higher than the body core, the device warns of an impending attack. The device stores up to 122,400 measurements, which doctors can scan for trends and to identify issues.

According to Jas Gill, the company's managing director, X-Halo can also help detect chronic obstructive pulmonary disease and respiratory tract infections, such as bird flu, SARS, MERS, pneumonia, influenza, and tuberculosis.

"The X-Halo can pick up the signal from these viral and bacterial infections before the patient has any physical symptoms, allowing him a small window of up to 48 hours in which to consult his or her physician," Gill said.

Meanwhile, a Cornell University associate professor of mechanical engineering, David Erickson, has led a team that developed a device that works with a smartphone application to detect cholesterol by analyzing color changes in a test strip. Users add blood, sweat, or saliva to the test strip. The liquid goes through a series of separation steps and chemical reactions. Users then insert the strip into the device, which looks a bit like a credit card reader. It illuminates the test strip evenly, takes a picture, calibrates the hue and saturation of the colors, and displays the results on the phone.

Pulsewave MAX from Biosign embeds sensors in an arm cuff and finger clip to measure five vital signs simultaneously and send that data to a cloud-based computer.

Right now, the device measures total cholesterol. Erickson is working on ways to break that data into low-density and high-density lipoproteins ("bad" and "good" cholesterol) and triglycerides. The lab developed a similar system to test for gum infections and measure electrolyte levels in sweat.

Apps can use smartphone cameras to look at other vital signs. Instant Heart Rate by Azumio, for example, analyzes fingertip color changes to count your pulse, the same technique used by medical pulse oximeters. AF Detect, an app developed by University College London and HealthSTATS, a Singapore-based company, uses similar technology to detect irregular heartbeats.

But specially built devices can do more. Scanadu, a California start-up that raised $1.6 million in capital on the crowd-funding website Indiegogo, has developed a small, white, circular device it calls the Scout that contains thermal, optical, and electrode sensors.

When users press the Scout to their foreheads, it begins to monitor such vital signs as heart rate, heartbeat regularity, blood pressure, blood oxygenation, breathing rate, and temperature—all within seconds. Scout sends the data via Bluetooth to a smartphone app, where users can track and analyze the information and, if they wish, share it with a physician.

According to Walter De Brouwer, the company's CEO and founder, "Scanadu Scout has the potential to completely disrupt the clinical pathway by bringing the place of care back into the home and into the hands of the consumers. It's a game changer for consumer medicine."

Scanadu is building on its existing technology in its entry for the Tricorder X Prize. Other companies are using the same strategy.

"The technologies imagined by the Tricorder X-Prize are either available now or on the cusp of availability," said Robert Kaul, CEO of Biosign, a Canadian company that builds medical devices. Biosign was developing a sensor platform when the competition was launched.

"We've been working on the Pulsewave MAX for over two years," Kaul said. "When the Tricorder

X-Prize was announced we saw immediately that our technology qualified for the contest."

Pulsewave MAX, an advance over the company's Pulsewave heartbeat and pulse measuring system, is bulky compared with other X Prize contenders; its sensors are embedded in an arm cuff and finger clip and were designed for immobile hospital patients. Still, it had a working system that transmitted five vital signs to a cloud computing system. Biosign's project team in the Qualcomm X Prize competition, Cloud DX, partnered with others to develop a system that could analyze blood, saliva, and urine.

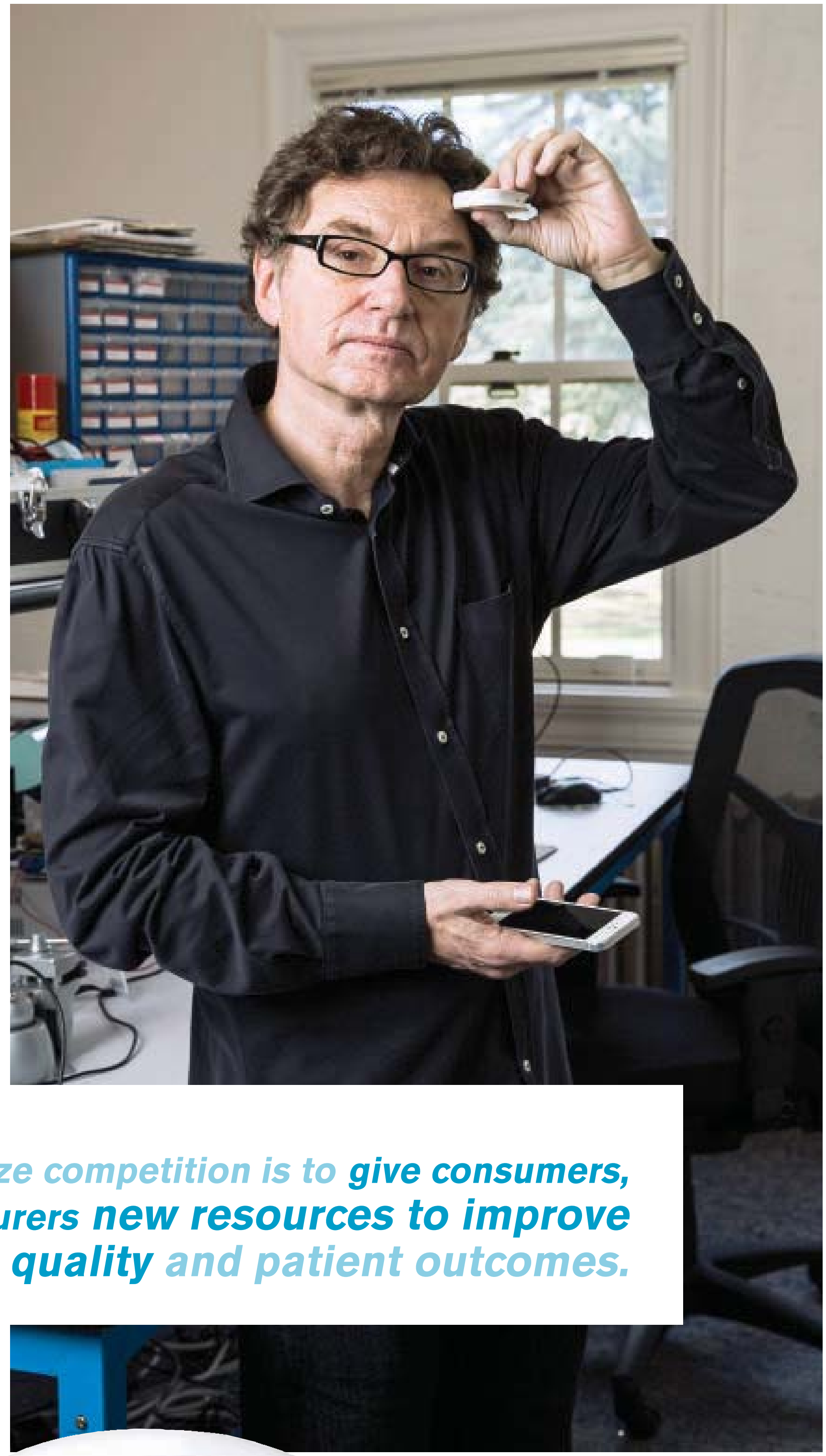
Technology exists to do many of the tasks set out for a potential tricorder. Integrating them into single device is no easy challenge.

As Delmedica's Jas Gill put it: "We are charting an undefined path. No one has ever done this before, so there are no rules to follow."

According to Gill, "We have an expert team of engineers, biologists, scientists, designers, and doctors, but we are still experimenting, and learning as we go. In order to meet consumer, medical, and FDA standards, we have to make sure the device is accurate, seamless, and actionable. This is no simple feat."

The X Prize's Mark Winter said he thinks the main goal of the competition is to give consumers, care providers, and insurers new resources to improve health care quality and patient outcomes. In addition to driving down costs, putting tricorders in the hands of non-professionals could help individuals seek treatment before a malady becomes an emergency.

Winter said he hopes that engineers will recognize "the tremendous changes going on that they can participate in as engineers in bringing completely new types of health technologies to people that really were, in the past, solely in the domain of clinical laboratories." **ME**



The main goal of the X Prize competition is to give consumers, health care providers, and insurers new resources to improve health care quality and patient outcomes.

Walter De Brouwer (above), CEO of Scanadu, demonstrates how his company's Scout device can be pressed against the forehead to measure blood pressure, heart rate, and temperature within seconds.

ARIANA MARINI is a student at Emerson College in Boston. She interned at *Mechanical Engineering* in 2013.

SEPT. - OCT. 2014 – BARCELONA, SPAIN

PD146	Flow-Induced Vibration with Applications to Failure Analysis	29 Sep-1 Oct
PD389	Nondestructive Examination -- Applying ASME Code Requirements (BPV Code, Section V) ASME CODE COURSE	29 Sep-1 Oct
PD442	BPV Code, Section VIII, Division 1: Design and Fabrication of Pressure Vessels ASME CODE COURSE TOP SELLER	29 Sep-1 Oct
PD635	ASME NQA-1 Quality Assurance Requirements for Nuclear Facility Applications	29 Sep-1 Oct
PD645	BPV Code: Section IX Welding, Brazing and Fusing Qualifications	29 Sep-1 Oct
PD616	API 579 /ASME FFS-1 Fitness-for-Service Evaluation	29 Sep-2 Oct
PD643	ASME B31.3 Process Piping Code ASME CODE COURSE	29 Sep-2 Oct
PD644	Advanced Design and Construction of Nuclear Facility Components Per BPV Code, Section III ASME CODE COURSE	29 Sep-2 Oct
PD672	BPV Code, Section XI, Division 1: Inservice Inspection 10-Year Program Updates for Nuclear Power Plant Components ASME CODE COURSE	29 Sep-2 Oct
PD675	ASME NQA-1 Lead Auditor Training	29 Sep-2 Oct
PD716	BPV Code, Section 1: Power Boilers NEW! ASME CODE COURSE	29 Sep-2 Oct
PD443	BPV Code, Section VIII, Division 1 Combo Course ASME CODE COURSE SAVE UP TO €800! TOP SELLER	29 Sep-3 Oct
PD684	BPV Code Section III, Division 1: Rules for Construction of Nuclear Facility Components ASME CODE COURSE	29 Sep-3 Oct
PD441	Inspections, Repairs and Alterations of Pressure Equipment ASME CODE COURSE	2-3 Oct

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OCTOBER 2014 – ATLANTA, GEORGIA USA

PD107	Elevator Maintenance Evaluation	6-7 Oct
PD391	ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids ASME CODE COURSE	6-7 Oct
PD394	Seismic Design and Retrofit of Equipment and Piping	6-7 Oct
PD539	Bolted Joints and Gasket Behavior	6-7 Oct
PD077	Failure Prevention, Repair and Life Extension of Piping, Vessels and Tanks ASME CODE COURSE	6-8 Oct
PD370	B31.8 Gas Transmission and Distribution Piping Systems ASME CODE COURSE	6-8 Oct
PD506	Research and Development Management	6-8 Oct
PD513	TRIZ: The Theory of Inventive Problem Solving	6-8 Oct
PD571	The Taguchi Design of Experiments for Robust Product and Process Designs	6-8 Oct
PD597	Risk-Informed Inservice Testing	6-8 Oct
PD618	Root Cause Analysis Fundamentals	6-8 Oct
PD683	Probabilistic Structural Analysis, Design and Reliability-Risk Assessment	6-8 Oct

CONTINUED, OCTOBER 2014 – ATLANTA, GEORGIA USA

PD632	Design in Codes, Standards and Regulations for Nuclear Power Plant Construction ASME CODE COURSE	6-9 Oct
PD675	ASME NQA-1 Lead Auditor Training ASME CODE COURSE	6-9 Oct
PD432	Turbo Machinery Dynamics: Design and Operation	6-10 Oct
PD601	Bolting Combo Course SAVE UP TO $1,260!	6-10 Oct
PD386	Design of Bolted Flange Joints	8 Oct
PD449	Mechanical Tolerancing for Six Sigma	8-9 Oct
PD698	Predictive Maintenance Technologies NEW!	8-10 Oct
PD575	Comprehensive Negotiating Strategies®: Engineers and Technical Professionals	9-10 Oct
PD577	Bolted Joint Assembly Principles Per PCC-1-2013 ASME CODE COURSE	9-10 Oct
PD591	Developing Conflict Resolution Best Practices	9-10 Oct
PD706	Inline Inspections for Pipelines	9-10 Oct

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OCTOBER 2014 – HOUSTON, TEXAS USA

PD115	The Gas Turbine: Principles and Applications	20-21 Oct
PD313	Fundamentals of Fastening Systems	20-21 Oct
PD624	Two-Phase Flow and Heat Transfer	20-21 Oct
PD146	Flow Induced Vibration with Applications to Failure Analysis	20-22 Oct
PD231	Shock and Vibration Analysis	20-22 Oct
PD395	API 579-1/ASME FFS-1 Fitness-for-Service	20-22 Oct
PD410	Detail Engineering of Piping Systems	20-22 Oct
PD442	BPV Code, Section VIII, Division 1: Design and Fabrication of Pressure Vessels ASME CODE COURSE TOP SELLER	20-22 Oct
PD523	Quality Assurance (QA) Considerations for New Nuclear Facility Construction ASME CODE COURSE	20-22 Oct
PD619	Risk and Reliability Strategies for Optimizing Performance	20-22 Oct
PD633	Overview of Codes and Standards for Nuclear Power Plant Construction ASME CODE COURSE	20-22 Oct
PD702	Process Safety and Risk Management for Mechanical Engineers NEW!	20-22 Oct
PD014	B31.3 Process Piping Design ASME CODE COURSE	20-23 Oct
PD672	BPV Code, Section XI, Division 1: Inservice Inspection 10-Year Program Updates for Nuclear Power Plant Components ASME CODE COURSE	20-23 Oct
PD679	Fundamentals of Pumps and Valves and Their Selection for Optimum System Performance NEW!	20-23 Oct
PD443	BPV Code, Section VIII, Division 1 Combo Course SAVE UP TO $645! ASME CODE COURSE TOP SELLER	20-24 Oct
PD581	B31.3 Process Piping Design, Materials, Fabrication, Examination and Testing Combo Course ASME CODE COURSE SAVE UP TO $575!	20-24 Oct

CONTINUED, OCTOBER 2014 – HOUSTON, TEXAS USA

PD665	BPV Code, Section I: Power Boilers **ASME CODE COURSE**	20-24 Oct
PD699	Reliability Excellence Fundamentals **NEW!**	22-24 Oct
PD441	Inspections, Repairs and Alterations of Pressure Equipment **ASME CODE COURSE**	23-24 Oct
PD567	Design, Analysis and Fabrication of Composite Structure, Energy and Machine Applications	23-24 Oct
PD634	Comparison of Global Quality Assurance and Management System Standards Used for Nuclear Applications **ASME CODE COURSE**	23-24 Oct
PD457	B31.3 Process Piping Materials Fabrication, Examination and Testing **ASME CODE COURSE**	24 Oct

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NOV. 2014 – SAN DIEGO, CALIFORNIA USA

PD100	Introduction to Elevators and Escalators	3-4 Nov
PD382	How to Predict Thermal-Hydraulic Loads on Pressure Vessels and Piping	3-4 Nov
PD445	B31 Piping Fabrication and Examination **ASME CODE COURSE**	3-4 Nov
PD531	Leadership and Organizational Management	3-4 Nov
PD539	Bolted Joints and Gasket Behavior	3-4 Nov
PD673	Design and Selection of Heat Exchangers	3-4 Nov
PD077	Failure Prevention, Repair and Life Extension of Piping, Vessels and Tanks **ASME CODE COURSE**	3-5 Nov
PD190	BPV Code, Section IX: Welding, Brazing and Fusing Qualifications **ASME CODE COURSE**	3-5 Nov
PD349	Design & Applications of Centrifugal Pumps	3-5 Nov
PD389	Nondestructive Examination -- Applying ASME Code Requirements (BPV Code, Section V) **ASME CODE COURSE**	3-5 Nov
PD513	TRIZ: The Theory of Inventive Problem Solving	3-5 Nov
PD674	International Business Ethics and Foreign Corrupt Practices Act	3-5 Nov
PD359	Practical Welding Technology	3-6 Nov
PD448	BPV Code, Section VIII, Division 2: Pressure Vessels **ASME CODE COURSE** **TOP SELLER**	3-6 Nov
PD601	Bolting Combo Course **SAVE UP TO $1,260!**	3-7 Nov
PD665	BPV Code, Section I: Power Boilers **ASME CODE COURSE**	3-7 Nov
PD681	International Business Ethics and Foreign Corrupt Practices Act Combo Course **SAVE UP TO $635!**	3-7 Nov
PD386	Design of Bolted Flange Joints	5 Nov
PD449	Mechanical Tolerancing for Six Sigma	5-6 Nov
PD690	Economics of Pipe Sizing and Pump Selection **NEW!**	5-6 Nov
PD102	How to Perform Elevator Inspections Using ASME A17.2	5-7 Nov
PD621	Grade 91 and Other Creep Strength Enhanced Ferritic Steels	5-7 Nov
PD700	Risk-Based Asset Management **NEW!**	5-7 Nov

CONTINUED, NOV. 2014 – SAN DIEGO, CALIFORNIA USA

PD575	Comprehensive Negotiating Strategies®: Engineers and Technical Professionals	6-7 Nov
PD577	Bolted Joint Assembly Principles Per PCC-1-2013 **ASME CODE COURSE**	6-7 Nov
PD680	Understanding the Foreign Corrupt Practices Act	6-7 Nov
PD692	Communication Essentials for Engineers	6-7 Nov

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NOVEMBER 2014 – AMSTERDAM, NETHERLANDS

PD634	Comparison of Global Quality Assurance and Management System Standards Used for Nuclear Applications **ASME CODE COURSE**	3-4 Nov
PD714	BPV Code, Section VIII, Division 2: Pressure Vessels **ASME CODE COURSE**	3-5 Nov
PD616	API 579 /ASME FFS-1 Fitness-for-Service Evaluation	3-6 Nov
PD622	BPV Code: Plant Equipment Requirements **ASME CODE COURSE**	3-6 Nov
PD632	Design in Codes, Standards and Regulations for Nuclear Power Plant Construction **ASME CODE COURSE**	3-6 Nov
PD642	ASME B31.1 Power Piping Code	3-6 Nov
PD643	ASME B31.3 Process Piping Code **ASME CODE COURSE**	3-6 Nov
PD644	Advanced Design and Construction of Nuclear Facility Components Per BPV Code, Section III **ASME CODE COURSE**	3-6 Nov
PD686	Layout of Process Piping Systems and Managing 3D CAD/CAE Systems	3-7 Nov
PD577	Bolted Joint Assembly Principles Per PCC-1-2013 **ASME CODE COURSE**	6-7 Nov

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NOV. 2014 – MIAMI, FLORIDA USA

PD387	Understanding Chiller Performance, Operation and Economics	10 Nov
PD475	The New Engineering Manager: Moving from Technical Professional to Manager	10-11 Nov
PD561	Geometric Dimensioning and Tolerancing Advanced Applications with Stacks and Analysis **TOP SELLER**	10-11 Nov
PD583	Pressure Relief Devices: Design, Sizing, Construction, Inspection and Maintenance **ASME CODE COURSE**	10-11 Nov
PD606	NQA-1 Requirements for Computer Software Used in Nuclear Facilities **ASME CODE COURSE**	10-11 Nov
PD467	Project Management for Engineers and Technical Professionals	10-12 Nov
PD515	Dimensioning and Tolerancing Principles for Gages and Fixtures	10-12 Nov
PD685	The New Engineering Manager: Moving from Technical Professional to Manager and Strategic Thinking Combo Course **SAVE UP TO $465!**	10-12 Nov
PD010	ASME A17.1 Safety Code for Elevators and Escalators **ASME CODE COURSE**	10-13 Nov

CONTINUED, NOV. 2014 – MIAMI, FLORIDA USA

PD603	Geometric Dimensioning & Tolerancing Combo Course **SAVE UP TO $380!**	10-13 Nov
PD620	Core Engineering Management	10-13 Nov
PD622	BPV Code: Plant Equipment Requirements **ASME CODE COURSE**	10-13 Nov
PD657	HVAC Systems and Chiller Performance Combo Course **SAVE UP TO $475!**	10-13 Nov
PD691	Fluid Mechanics, Piping Design, Fluid Transients and Dynamics **NEW!**	10-13 Nov
PD602	Elevator and Escalator Combo Course **SAVE UP TO $635!**	10-14 Nov
PD629	Project Management Combo Course **SAVE UP TO $635!**	10-14 Nov
PD686	Layout of Process Piping Systems and Managing 3D CAD/CAE Systems	10-14 Nov
PD027	Heating, Ventilating and Air-Conditioning Systems: Sizing and Design	11-13 Nov
PD676	Strategic Thinking	12 Nov
PD570	Geometric Dimensioning & Tolerancing Fundamentals 1 **ASME CODE COURSE**	12-13 Nov
PD268	Fracture Mechanics Approach to Life Predictions	12-14 Nov
PD496	Preparing for the Project Management Professional Certification Exam	13-14 Nov

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DEC. 2014 – PRAGUE, CZECH REPUBLIC

PD442	BPV Code, Section VIII, Division 1: Design and Fabrication of Pressure Vessels **ASME CODE COURSE** **TOP SELLER**	8-10 Dec
PD615	BPV Code, Section III, Division 1: Class 1, 2 & 3 Piping Design **ASME CODE COURSE**	8-10 Dec
PD621	Grade 91 and Other Creep Strength Enhanced Ferritic Steels	8-10 Dec
PD645	BPV Code: Section IX Welding, Brazing and Fusing Qualifications	8-10 Dec
PD643	ASME B31.3 Process Piping Code **ASME CODE COURSE**	8-11 Dec
PD443	BPV Code, Section VIII, Division 1 Combo Course **ASME CODE COURSE** **TOP SELLER**	8-12 Dec
PD684	BPV Code Section III, Division 1: Rules for Construction of Nuclear Facility Components	8-12 Dec
PD441	Inspections, Repairs and Alterations of Pressure Equipment **ASME CODE COURSE**	11-12 Dec

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DEC. 2014 – NEW ORLEANS, LOUISIANA USA

PD595	Developing a 10-Year Pump Inservice Testing Program **ASME CODE COURSE**	8-9 Dec
PD599	BPV Code, Section III, Division 1: Class 1 Piping Design **ASME CODE COURSE**	8-9 Dec
PD624	Two-Phase Flow and Heat Transfer	8-9 Dec
PD231	Shock and Vibration Analysis	8-10 Dec
PD395	API 579-1/ASME FFS-1 Fitness-for-Service	8-10 Dec

CONTINUED, DEC. 2014 – NEW ORLEANS, LOUISIANA

PD410	Detail Engineering of Piping Systems	8-10 Dec
PD442	BPV Code, Section VIII, Division 1: Design and Fabrication of Pressure Vessels **ASME CODE COURSE** **TOP SELLER**	8-10 Dec
PD615	BPV Code, Section III, Division 1: Class 1, 2 & 3 Piping Design Combo Course **ASME CODE COURSE** **SAVE UP TO $470!**	8-10 Dec
PD633	Overview of Codes and Standards for Nuclear Power Plant Construction **ASME CODE COURSE**	8-10 Dec
PD702	Process Safety and Risk Management for Mechanical Engineers **NEW!**	8-10 Dec
PD014	B31.3 Process Piping Design **ASME CODE COURSE**	8-11 Dec
PD184	BPV Code Section III, Division 1: Rules for Construction of Nuclear Facility Components **ASME CODE COURSE**	8-11 Dec
PD359	Practical Welding Technology	8-11 Dec
PD644	Advanced Design and Construction of Nuclear Facility Components Per BPV Code, Section III **ASME CODE COURSE**	8-11 Dec
PD679	Fundamentals of Pumps and Valves and Their Selection for Optimum System Performance **NEW!**	8-11 Dec
PD192	BPV Code, Section XI: Inservice Inspection of Nuclear Power Plant Components **ASME CODE COURSE**	8-12 Dec
PD443	BPV Code, Section VIII Division 1 Combo Course **ASME CODE COURSE** **TOP SELLER** **SAVE UP TO $645!**	8-12 Dec
PD581	B31.3 Process Piping Design, Materials, Fabrication, Examination and Testing Combo Course **ASME CODE COURSE** **SAVE UP TO $575!**	8-12 Dec
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PD634	Comparison of Global Quality Assurance and Management System Standards Used for Nuclear Applications **ASME CODE COURSE**	11-12 Dec
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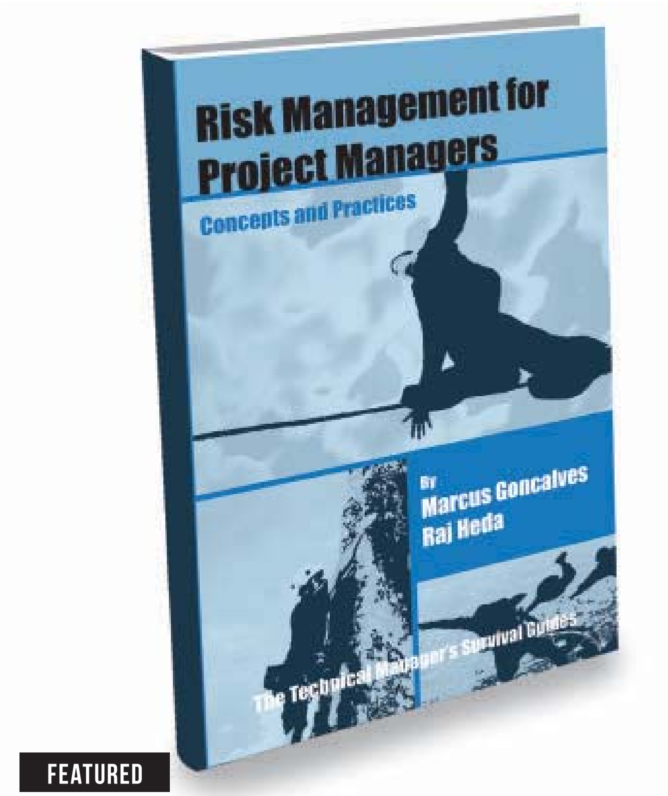


FEATURED

RISK MANAGEMENT FOR PROJECT MANAGERS: CONCEPTS AND PRACTICES

MARCUS GONCALVES AND RAJ HEDA

ASME Press Books, Two Park Avenue, New York, NY 10016-5990. 2014.

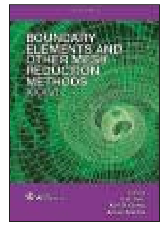
This is the newest volume in The Technical Manager's Survival Guides series. Chapter one covers how the goal of assessing risks is to understand them and to find strategies for managing them. In practical terms, risk management is the process of minimizing, or mitigating, undesirable events. It starts with the identification and evaluation of possible events and extends to the optimization of the resources used to monitor them and minimize their effects.

Chapter two discusses how risk is no longer a measure solely restricted to the financial world, where analysts monitor the risk of a financial investment.

According to the authors, anything that we endeavor in life has a risk factor associated with it. As technology has become an increasingly core aspect of world economies, risk management has come to the fore in recent years. Given the extreme importance of risk, it is inevitable that we must have a formalized theory and approach to the risk management process.

Other chapters include: "Developing a Risk Assessment and Mitigation Strategy," "The Risk Management Process," and "Risk Analysis Tools and Methodologies."

104 PAGES. $42; ASME MEMBERS, $34; ISBN: 978-0-7918-6023-6.



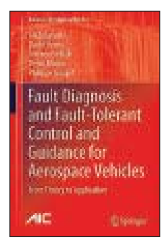
BOUNDARY ELEMENTS AND OTHER MESH REDUCTION METHODS XXXVI

X.W. Gao, A.H.-D. Cheng, and C.A. Brebbia.

WIT Press, USA, 25 Bridge Street, Billerica, MA 01821. 2014.

The Conference on Boundary Elements and Mesh Reduction Methods is an international forum for the latest advances in these techniques and their applications in science and engineering. Launched in 1978 the conference has become the forum for rapid dissemination of developments throughout the international scientific community. Practically all new boundary element ideas have first appeared in the proceedings of these meetings. The vitality of boundary element research is mainly due to its ability to evolve. This evolution has developed a range of mesh-reduction methods. Chinese researchers in particular have made major contributions to mesh reduction, which this conference hopes to highlight. The importance of research carried out in China led to the organization of the 36th Conference, which sets the basis for a closer collaboration between scientists from other countries and their Chinese colleagues.

568 PAGES. $488. ISBN: 978-1-84564-841-1.



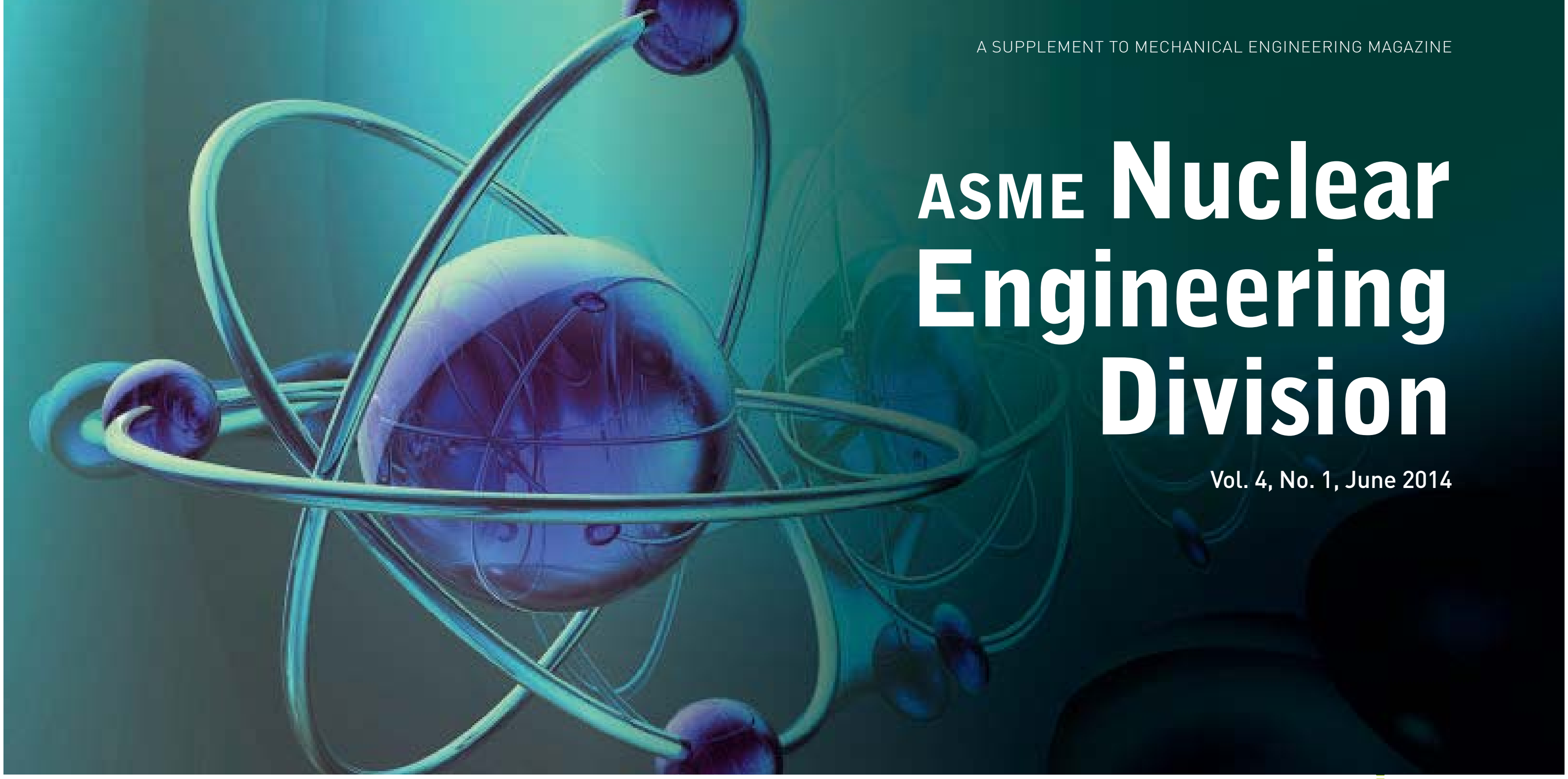
FAULT DIAGNOSIS AND FAULT-TOLERANT CONTROL AND GUIDANCE FOR AEROSPACE VEHICLES: FROM THEORY TO APPLICATION

Ali Zolghadri, David Henry, Jerome Cieslak, Denis Efimov, and Philippe Goupil.

Springer-Verlag GmbH, Tiergartenstrasse 17, 69121. Heidelberg, Germany. 2014.

Fault Diagnosis and Fault-Tolerant Control and Guidance for Aerospace Vehicles seeks to demonstrate the attractive potential of recent developments in control for resolving such issues as improved flight performance, self-protection, and extended life of structures. The text deals with a number of considerations, including tuning, complexity of design, real-time capability, evaluation of worst-case performance, robustness in harsh environments, and extensibility when development or adaptation is required. The authors call on experience gained in research collaboration with academic and industrial partners to validate advanced fault diagnosis and fault-tolerant control techniques with realistic benchmarks or real-world aeronautical and space systems.

240 PAGES. $129. ISBN: 978-1-44715-313-9.



A SUPPLEMENT TO MECHANICAL ENGINEERING MAGAZINE

ASME Nuclear Engineering Division

Vol. 4, No. 1, June 2014

A Message From the Chair of the ASME Nuclear Engineering Division

Jovica R. Riznic

I am writing this message with sincere gratitude to our numerous division volunteers, including paper reviewers, track and session organizers, members of the executive committee and many more who contributed to our Nuclear Engineering Division (NED). It is because of your selflessness and great support that our division remains one of the strongest divisions within the ASME.

With a large NED membership (i.e., almost 8,000 members in the first three selection areas of the ASME divisions) we have a devout responsibility to promote nuclear engineering all over the world. Along with Power, Design, and PVP, the NED is among the largest technical divisions within the ASME and will continue to lead the society in identifying and resolving the technical issues faced by the industry. It is indeed my greatest honor and privilege to be associated with such a dedicated group of professionals.

It is truly exciting time for the NED and for the ASME. ASME NED focuses on the design, analysis, development, testing, operation, and maintenance of nuclear power systems and components, nuclear fusion, heat transport, nuclear fuels technology, plant radwaste

A responsibility to promote nuclear engineering all over the world.

systems, and radioactive high- and low-level waste disposal technologies. The Nuclear Engineering Division strives to meet the challenges of disseminating timely technical information through a number of activities, which include organizing technical conferences, conducting workshops, and supporting ASME technical journals.

➤This is the perfect time to reinforce the learning culture, which is a cornerstone of our industry.

I am very saddened to report you that we lost our friend, colleague, and role model, Dr. Novak Zuber. He was an outstanding researcher, educator, a wonderful friend, and a nice person. In collaboration with the Heat Transfer Division, we were preparing a symposium to celebrate Dr. Zuber's 90th birthday during the IMECE 2013.

Dr. Zuber died before the symposium in his honor could be held. Instead, it became a tribute to his life and legacy. More than 20 distinguished scholars and researchers presented evaluations of the man's contributions to nuclear technology.

In addition to the symposium, the NED sponsored four highly attended sessions on nuclear power plant design and safe operation. Keeping in mind that this was just a second year of the NED's return to the IMECE, it was great success with regards to the number of papers and quality of work presented.

Before the IMECE, we delivered ICONE21 held in Chengdu, China, with a record number of papers (718) presented. Also, in collaboration with the ASME Environmental Engineering Division, the NED had a very well received 15th International Conference on Environmental Remediation and Radioactive Waste Management (ICEM 2013) held in Brussels, Belgium.

The quality and breadth of work being presented at these meetings is remarkable. New work is appearing across the spectrum of the nuclear engineering field, including plant operation and maintenance, fuel and materials, nuclear safety and security, thermal hydraulics, fuel cycle, radioactive waste management, and decommissioning. While much of this relates to the current generation of operating nuclear power plants, there is a healthy contribution in basic research and development in support of new light water and Gen IV reactor systems, and interest in small modular reactor concepts.

Last year we initiated the ASME *Technical Journal on Nuclear Engineering and Radiation Science* (first issue to be published in January 2015) and a new series of concise monographs, *Nuclear Technologies for the 21st Century*. We hope these new publications will be a valuable addition to our industry.

Our future depends on students and young professionals. In addition to providing student travel support, the division has supported the NED Student Program for many years. The ICONE Student Competition has helped young engineers develop their professional careers. It is part of our effort to make the division useful and attractive to all members.

The primary mission of the NED is to establish and maintain quality technical and professional practices in all areas of nuclear engineering. This is the perfect time to reinforce the learning culture, which is a cornerstone of our industry.

Since the incident at the Fukushima Daiichi plant, the industry, regulatory agencies, academia, national laboratories, and technical support organizations have acted quickly to collect and evaluate information for lessons learned to prevent and mitigate such incidents in future. Further, these lessons have been translated into practices and guidelines. The implementation of lessons learned is still work in progress, but the level of commitment demonstrated to identify and address those lessons promptly is something of which we can be proud.

The nuclear industry weathered the storm fairly well; however, we did take a few steps back when construction projects were slowed down or postponed. Today, we can celebrate a number of new plants under construction from the Vogtle and the V.C. Summer plants in North America to plants in the United Arab Emirates, India, and China.

It is time to push the reset button. There are a number of signs that the economy is starting to pick up and the latest global recession may be on the way out.

ICONE22 will go to Prague in July. You can learn more about the event on page 66.

CZECHTOURISM

In July, we will hold our 22nd ICONE in the beautiful city of Prague in the Czech Republic. It is a joint effort of the ASME, JSME, and CNS.

These efforts to keep the ASME nuclear technical community active and vibrant are essential to the future of nuclear power. Consider the impact of ASME, with its 110,000 members. When ASME speaks about nuclear power, the organization's reputation as a premier engineering society, whose codes and standards protect the public, causes people in general and government decision makers in particular to take notice.

Thus, we in the NED have an important responsibility to ensure that this industry continues to deliver benefits to our civilization. With ICONE22 we are setting a new record with number of submitted presentations (1,024 accepted abstracts and 965 draft papers), another sign of the resilience of our professional community.

If you haven't yet planned to attend ICONE22, review your professional schedule and consider a change in plans. In this era of tweeting and networking, some may assume that the new ways of communication have now overcome any face-to-face opportunities. Social media does hold an important place in doing business, but nothing can take the place of speaking first-hand and going eye-to-eye with colleagues and even competitors. If you return from Prague with just one bit of information that may help you figure out a new way to address your technical problem, you are definitely a winner.

As you plan your summer calendar, remember to join others in your nuclear professional community July 7-11 at ICONE22.

We welcome anyone who would like to volunteer their time and talent to division matters. We also encourage your suggestions and comments.

~ Jovica Riznic, PhD., P.Eng., ASME Fellow, is the NED Chair, 2013-2014.

> ➤ Thus, we in the NED have an important responsibility to ensure that this industry continues to deliver benefits to our civilization.

SMALL MODULAR REACTORS

NuScale: A Versatile and Economical Plant

NuScale has developed a new kind of nuclear power plant—a small, scalable version of pressurized water reactor technology, designed with natural safety features. Natural forces of physics—gravity, convection, and conduction—are used for normal operations and safe shutdown. This eliminates many of the large and complex systems (e.g., reactor coolant pumps, motors, valves, large bore reactor coolant system piping) found in today's nuclear power plants and other SMR designs. We have striven to design a plant that is safe, simple, and economical to build and operate.

Each NuScale Power Module consists of a fully integrated reactor vessel, pressurizer, steam generator, and containment vessel, and is accompanied by a companion turbine, which generates an output of more than 45 MWe.

NuScale power plants are scalable. A single facility can have from one to 12 NuScale Power Modules. In a multi-module plant, one unit can be taken out of service without affecting the operation of the others, providing plant owners with a highly reliable power plant capable of meeting customer energy requirements. NuScale's 160 MW thermal output also makes it a perfect fit for process heat and steam applications, such as refining, desalination, and district heating.

➤ NuScale's design incorporates several features that reduce complexity, improve safety, enhance operability, and reduce risks.

NuScale's design incorporates several features that reduce complexity, improve safety, enhance operability, and reduce risks. The design includes:

- The ability to safely shut down and self-cool, indefinitely, with no operator action, no ac or dc power, and no additional water, which we call our *Triple Crown for Nuclear Plant Safety*.
- Seven barriers between the nuclear fuel and the local community and environment, as compared to three for commercial plants currently in construction and operation.
- A complete containment and reactor vessel module that can be shipped in segments, by rail, truck, or barge, for quick installation at the plant site.
- Below grade operating bays for the NuScale Power Modules that are enclosed in an aircraft-impact-resistant seismic Category 1 reactor building.
- Natural circulation, coolant flow residual heat removal, and

NuScale Power Modules can be shipped to remote locations. As many as 12 units can operate with one control room.

emergency core cooling systems powered by natural forces—gravity.

- A common pool that provides seismic dampening and radiation shielding for the NuScale Power Module.

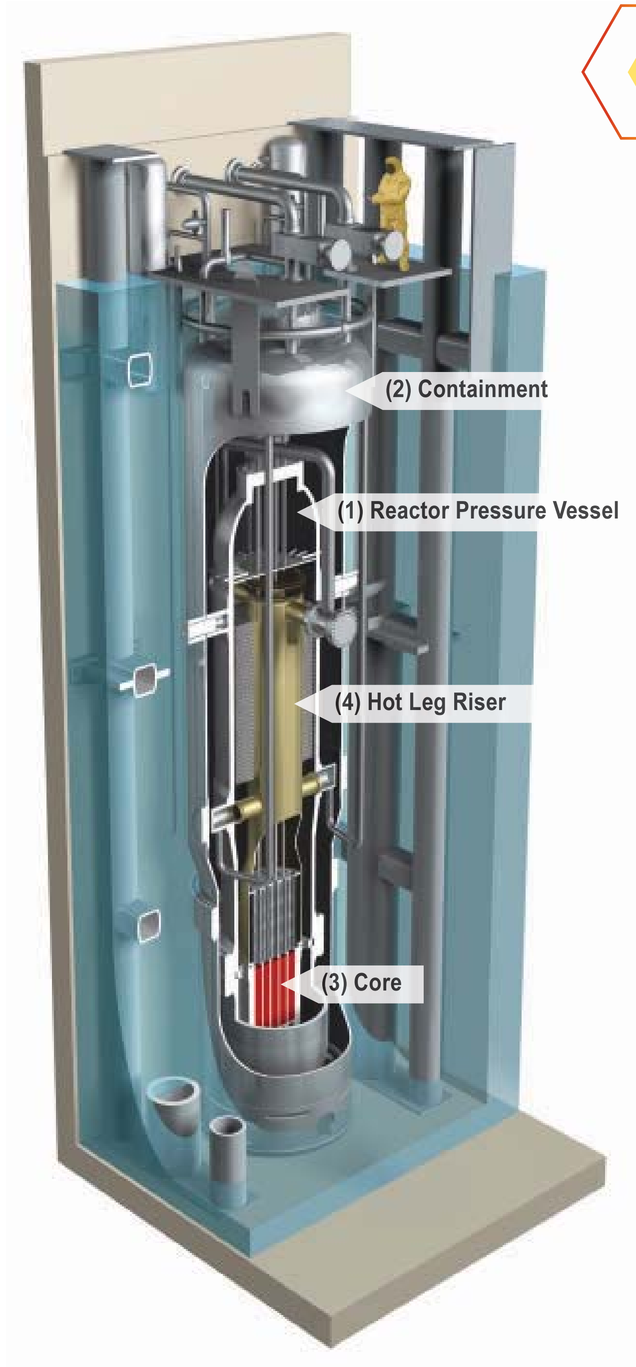
- A 60-year plant life.

- A projected capacity factor of more than 95 percent.

How NuScale's Technology Works

Each NuScale Power Module is self-contained and operates independently of the other modules in a multi-module configuration. However, all modules are managed from a single control room.

The reactor vessel (1) measures 65 feet tall x 9 feet in diameter. It sits within a containment vessel (2) 80 feet tall x 15 feet in diameter. The reactor and containment vessel operate inside a water-filled pool that is built below grade. The reactor operates using the principles of natural circulation—conduction, convection, and gravity; hence, no pumps are needed to circulate water through the reactor. Water is heated as it passes over the core (3). As it heats up, the water rises within the interior of the vessel through a riser tube much like a chimney. Once the heated water reaches the top of the riser (4), it is drawn downward by water that is cooled passing through the steam generators. The cooler water has a higher density. It is pulled by gravity back down to the bottom of the reactor where it is again drawn over the core. Water in the reactor system is kept separate from the water in the steam generator system to prevent contamination. As the hot water in the reactor system passes over the tubes in the steam generator, heat is transferred through the tube walls and the water in the tubes turns to steam. The steam turns turbines which are attached by a single shaft to the electrical generator. After passing through the turbines, the steam loses its energy. It is cooled back into liquid form in the



The NuScale Power Module generates 45 MW of electricity and 160 MW of heat.

condenser then pumped by the feedwater pumps back to the steam generator where it begins the cycle again.

The NuScale design was initially developed in 2000 and has been demonstrated and in testing programs since 2003 in a fully instrumented one-third scale electrically heated test facility in Corvallis, Ore. In addition, NuScale commissioned a full-scale multi-module control-room simulator in May 2012. ●

SMALL MODULAR REACTORS

Westinghouse: Overcoming the Economies-of-Scale Issues

A distinct challenge common to small nuclear reactor designs is that of economies of scale. Traditionally, as the size of the nuclear power station increases, the cost per megawatt decreases. This economy of scale is what has historically driven vendors to incrementally increase the size of traditional nuclear power plants. The reason is that the cost of many supporting systems is not directly proportional to the reactor power and therefore cannot be scaled. This economic impact of scalability suggests that a direct scale-down of a large nuclear reactor design to a smaller plant will not result in an economically advantageous small reactor.

➤ One method for reducing costs is to make the components smaller than if they were scaled proportionally.

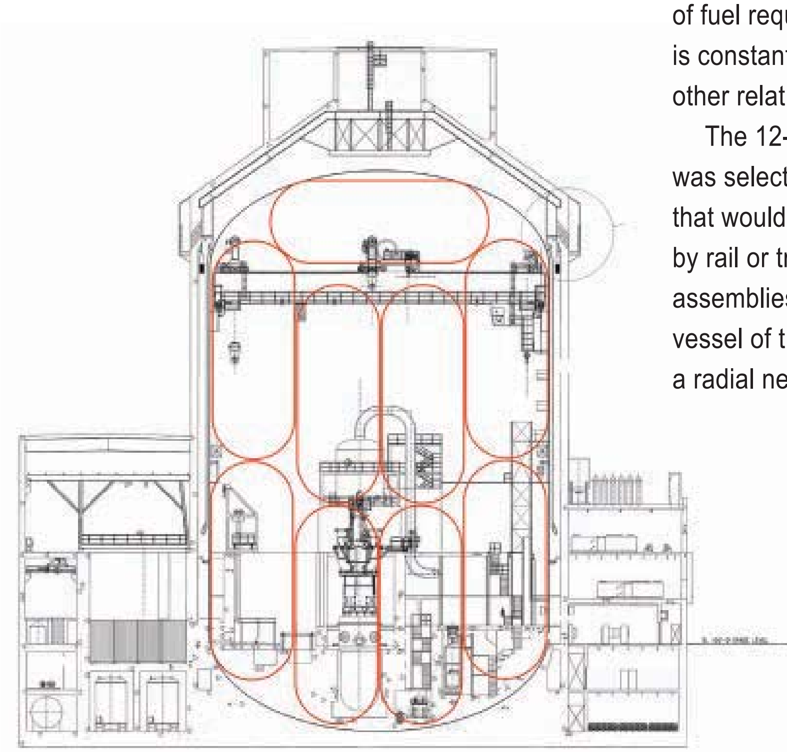
One such example of a support system whose cost is essentially unaffected by plant size is the instrumentation and control (I&C) system. A minimum number of process parameters is required, regardless of the size of the plant, to adequately keep a status of the normally operating plant systems. This results in costs for the I&C system which are independent of the power produced by the plant.

The Westinghouse Small Modular Reactor (SMR) design incorporates innovative approaches to compensate for the non-scalable costs of the plant, like the I&C system. One method for reducing costs is to make the components smaller than if they were scaled proportionally. For instance, the containment vessel has been reduced in size well beyond the one-fifth power reduction ratio of the 225 MWe Westinghouse SMR, as compared to the 1,100 MWe AP1000 plant. For the sake of comparison, 25 Westinghouse SMR containment vessels could fit within the containment vessel of the AP1000 plant. The decreased wall stress associated with a smaller diameter pressure vessel would allow the Westinghouse SMR to accomplish this very significant reduction in size without compromising the safety of the plant.

Coolant flow in the Westinghouse SMR is similar to that in conventional reactors.

The small containment diameter would be accomplished, in part, through the use of an integral reactor vessel. All reactor coolant system (RCS) components would be encapsulated within the reactor pressure vessel (RPV), including the reactor vessel internals, primary riser, pressurizer, steam generator, reactor coolant pumps, downcomer, and the reactor core.

The coolant flow through the Westinghouse SMR primary system is similar to that of conventional nuclear systems. The flow is designed to be heated in the core and then driven, via the eight reactor coolant pumps, upward through the reactor vessel internals. At the top of the internals cavity, it is funneled into the primary riser via a flow transition cone. The flow is designed to rise to the top of the primary riser, where it turns 180 degrees to flow downward through the straight tubes of the steam generator. In these tubes, the heat is then transferred from the primary coolant, through the tubes and into water in the secondary side of the steam generator. The primary flow exits the steam generator and then



proceeds to the reactor coolant pumps. The coolant is subsequently drawn into the pump hydraulics and forced radially out to the downcomer, where it flows to the bottom of the RPV cavity, turns 180 degrees and flows up into the core to complete the flow cycle.

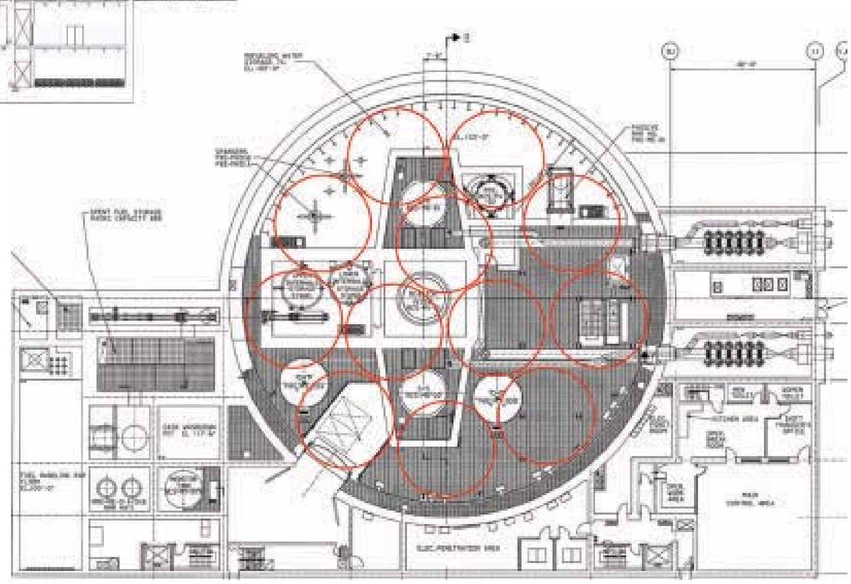
This integral arrangement results in the components being physically close together in a single pressure vessel. In addition to reducing the size of the combined components, the arrangement is designed to eliminate the need for large-bore connecting piping. The result is an SMR that overcomes economies-of-scale challenges, becoming economically competitive with large-capacity new nuclear plants.

The reactor vessel height design is also minimized to accomplish the 25 to 1 size ratio of the Westinghouse SMR to the AP1000 plant containment vessel. In a number of instances, the height of the reactor vessel is related to its diameter; in other words, the smaller the diameter, the greater the height. There is a balance between diameter and height to obtain an optimized system. For example, the amount of fuel required to generate the desired 800 MWt is constant when neglecting neutron leakage and other relatively small effects.

The 12-foot diameter of the reactor vessel was selected, as this is the largest diameter that would result in a reactor vessel shippable by rail or truck. Eighty-nine 17 x 17 robust fuel assemblies are designed to fit in a reactor vessel of this diameter when an allowance for a radial neutron reflector and a downcomer is considered. The fuel assemblies are designed to be reduced to an eight foot active fuel height and still obtain the desired power. This reduction in fuel height is intended to result in a corresponding reduction in reactor vessel height.

The RCS flow rate required to safely cool the 89 fuel assemblies is intended to be proportional

At 225 MWe, the Westinghouse SMR generates about one-fifth the power of the AP1000, but the ratio of size is greater: 25 of the modules can fit inside the AP1000 containment vessel.



to the power generated. Therefore, during power operation, reactor coolant pumps are used to deliver sufficient flow (100,000 gpm) to the core in a compact package. During post-trip conditions, the available height is designed to be sufficient for natural circulation to provide adequate flow for the reduced power associated with decay heat generation.

The reactor vessel height is also reduced through the use of an innovative approach to steam separation. Traditionally, pressurized water reactors (PWRs) have had either U-tube steam generators that include steam separation equipment or additional heat transfer area to heat the steam generator secondary side cooling water to superheated conditions. In the Westinghouse SMR, the steam separation equipment commonly found in U-tube steam generators is designed to be removed from containment and placed in an external steam drum. This steam generator and steam drum are connected with piping for recirculation of the cooling fluid, much like in a U-tube steam generator. This arrangement would allow the heat transfer to occur over a minimal surface area without requiring one of the most expensive structures of a nuclear power plant, the containment vessel, to house large steam separation equipment. Much like the fuel, the diameter of the steam generator is designed to accommodate shipping, so the advantage is seen in the vertical height of the integral pressure vessel.

➤ The eight reactor coolant pumps are designed as off-the-shelf, thus minimizing development and manufacturing costs.

The height of the reactor vessel is further minimized by using a set of nested plates to connect the pressurizer to the primary RCS flow path. The nested plates result in a flow connection that would create a pressure drop, as flow moves through a tortuous path. As a result, the nested plates provide a similar effect

The 12-foot diameter of the Westinghouse small modular reactor makes it suitable for shipment to a plant site by rail or by truck.

to a lengthy surge line in a traditional PWR. The nested pressurizer surge plates also allow for a thermal boundary between the saturated pressurizer and subcooled reactor coolant system that otherwise would not be available in components physically adjacent to each other.

Outside the reactor vessel, but still within the containment vessel, similar approaches in the design have been taken to minimize size. The passive safety system includes four core makeup tanks (CMTs) and two sump injection tanks (SITs). Each of these six tanks is sized to allow its diameter to fit between the reactor vessel and the containment vessel. Within each of the four CMTs is a passive residual heat removal (PRHR) heat exchanger. The combination of the CMT/PRHR would allow for the passive safety-related functions of decay heat removal, shutdown criticality control, and the initial stages of reactor coolant inventory addition to be accomplished using a single component. This arrangement, like that of the reactor vessel, is designed to allow for close physical proximity of portions of the plant that perform different functions.

Additionally, the use of small (less than three-inch diameter) connections to the reactor vessel and secondary PRHR cooling loops that transfer residual core heat outside of containment allow for the mitigation of all design basis events and postulated accidents using a small containment free volume. The secondary PRHR cooling loops transfer the residual heat to one of two ultimate heat sink pools, each of which is designed to have sufficient capacity for removing the residual heat for at least 72 hours. The ultimate heat sink pools are intended to have the ability to feed the outside containment pool, which surrounds the containment vessel during normal operation and allows heat to be removed from the outside surface of the containment.

The lower portion of the containment region between the containment shell and the reactor vessel holds an in-containment pool (ICP). This ICP is divided functionally into two halves that are filled with water and are each in communication with one of the two SITs. Following a loss of coolant accident (LOCA), the ICP is designed to allow the reactor coolant, CMT, and SIT water to quickly increase the head of water available in the containment sump to promote long-term recirculation through the core. This design results in a reactor core that remains covered at all times during a LOCA and prevents any substantial core heat-up. Without the ICP, the required inventory to accomplish long-term recirculation would be much larger and drive the length of the CMTs and SITs and the length of the containment.

The design of the Westinghouse SMR further leverages this smaller size by using off-the-shelf components to the largest extent possible. The eight reactor coolant pumps are designed as off-the-shelf, thus minimizing development and manufacturing costs. This allows the pumps to be fabricated in existing facilities and widens the potential supplier base. An additional advantage of this approach is that the pumps are proven technology with established operating experience, reducing the amount of required testing and technological uncertainty.

Reactor coolant system components are contained within the reactor pressure vessel.

Construction costs are a significant portion of the expense of large nuclear plants. To further address the economies of scale challenge, the Westinghouse SMR has been designed to be rail or truck shippable. These shippable components are fabricated in a factory prior to transport to site for assembly. For instance, the upper and lower portions of the integral reactor vessel each fit on a rail car. Other components, such as the containment vessel, including its passive safety system components, have been specifically segmented to ship by rail and truck.

This design results in a passive safety system that would perform similar functions to those of the AP1000 plant in a package that would allow for easy transport to site. The shippable components are then assembled into large modules before being lifted into place. Elimination of a lengthy site construction period by using modern modular fabrication and assembly techniques is intended to result in significant cost reductions.

Through the use of these innovative approaches to the design of a nuclear power plant, the Westinghouse SMR design compensates for the non-scalable costs of the plant, like the I&C system. As a result, the Westinghouse SMR is designed to overcome the economies-of-scale challenge of small nuclear designs and be economically competitive with large-capacity nuclear plants. ●

Welcome to the 22nd International Conference on Nuclear Engineering in the Beautiful City of Prague

By Asif H. Arastu and Guoqiang Wang

This year the 22nd International Conference on Nuclear Engineering (ICONE22) will be held in Prague, Czech Republic, July 7-11.

We have come a long way since Nov. 4, 1991, when the first ICONE opened at the Shinjuku Keio Plaza Inter-Continental Hotel in Tokyo. The Japan Society of Mechanical Engineering (JSME) and ASME were the sponsors and organizers for that meeting. In 2005, the China Nuclear Society (CNS) became the third major sponsor. Thus began a truly international series of this important annual nuclear engineering event. The second ICONE was in San Francisco in 1993 and then Kyoto (1995), New Orleans (1996), Nice (1997), San Diego (1998), Tokyo (1999 and 2003), Baltimore (2000), Nice (2001), Washington, D.C. (2002 and 2004), Beijing (2005), Miami (2006), Nagoya (2007), Orlando (2008), Brussels (2009), Xi'an (2010), Osaka (2011), Anaheim (2012), and Chengdu (2013). The vice premier of China (one of the honorary chairs) opened the historic ICONE13 meeting when China became a major sponsor. From the ASME side, the Nuclear Engineering Division (NED) Executive Committee members with ASME staff support have been instrumental in organizing, conducting, and developing the ICONE events. Their efforts are greatly appreciated as we approach ICONE22. Historically, it is interesting to note that the use of CDs for conference proceedings distribution was pioneered by NED to cater for increasing ICONE proceedings paper volumes.

During 2012 when the twentieth ICONE meeting was held in Anaheim, the conference organizers paid tribute to the ICONE founders in the form of ICONE Founder Awards. From ASME, these awards were given to Ed Harvego, Scott Penfield, and Howard Chung by Igor Pioro, Joe Miller, and Asif Arastu.

From JSME, the awards were given to the late Dr. Mamoru Akiyama (award taken by Dr. Koji Okamoto on Dr. Akiyama's behalf), Dr. Saburo Toda (award taken by Dr. Yasuo Koizumi on Dr. Toda's behalf), and Dr. Hideki Nariai (award taken by Dr.

ICONE Founder Awards were presented (clockwise from above) to Ed Harvego, Scott Penfield, and Howard Chung by Igor Pioro, Joe Miller, and Asif Arastu.

Yutaka Abe on Dr. Nariai's behalf).

Last year, the ICONE21 conference was held in Chengdu, known as the "Country of Heaven" in China.

This year's conference (ICONE22) will be held July 7 -11 in Prague, Czech Republic. The host organizations are ASME, JSME, and CNS, which are also the main sponsors. Other co-operating societies and organizations include the International Atomic Energy Agency (IAEA), Atomic Energy Society of Japan, Nuclear Power Institute of China, Korea Nuclear Society, European Nuclear Society, Canadian Nuclear Society, Nuclear Society of Slovenia, and International Association for Structural Mechanics in Reactor Technology (IASMiRT). The honorary chairs are Frantisek Pazdera, president of the European Sustainable Nuclear Energy Technological Platform and past deputy minister of the Ministry of Industry and Trade of the Czech Republic; Alexander Bychkov, deputy director general of IAEA; Ganjie Li, vice minister of Environment Protection Department, China; and Toyoshi Fukeda, commissioner of the Nuclear Regulation Authority in Japan.

The general conference chairs are Danny Roderick, president and CEO of Westinghouse Electric Co.; Naoki Chigusa of Kansai Electric Co.; Qin Sun, chairman of China National Nuclear Corp.; and Hamid Ait Abderrahim, deputy director general of SCK.CEN. ASME conference chair is Jovica Riznic.

Conference technical and logistic support is provided by ASME. As one may imagine, planning for a large international conference is a significant undertaking. A pre-conference planning meeting was held in Prague in December 2013 to discuss the conference logistics, and details of sessions, panels, and workshops.

The ICONE22 keynote theme is "*Nuclear Power—Meeting Global Energy Needs.*" It will cover a wide range of topics that span the different types of current and future nuclear power reactor designs. In particular, the meeting will place a specific emphasis on understanding fundamentals of nuclear engineering and technology to ensure safe operation of the current nuclear generation fleet. Additionally, the conference will focus on presenting developments and applications of innovative technologies in design, operation, maintenance,

JSME ICONE Founder Awards were accepted by surrogates on behalf of Mamoru Akiyama, Saburo Toda, and Hideki Nariai.

outage management and inspection. Over 1,000 abstracts have been accepted and over 700 final papers are expected in the following 20 technical tracks:

- Track 1 Plant Operations, Maintenance, Engineering, Modifications, Life Cycle and Balance of Plant.
- Track 2 Nuclear Fuel and Materials.
- Track 3 Plant Systems, Structures and Components.
- Track 4 Radiation Protection and Nuclear Technology Applications.
- Track 5 Next Generation Reactors and Advanced Reactors.
- Track 6 Nuclear Safety and Security.
- Track 7 Codes, Standards, Licensing and Regulatory Issues.

- Track 8 Fuel Cycle, Radioactive Waste Management and Decommissioning.
- Track 9 Thermal Hydraulics.
- Track 10 Computational Fluid Dynamics (CFD) and Coupled Codes.
- Track 11 Reactor Physics and Transport Theory.
- Track 12 Nuclear Education, Public Acceptance and Related Issues.
- Track 13 Instrumentation and Controls (I&C).
- Track 14 Fusion Engineering.
- Track 15 Beyond Design Basis Events.
- Track 16 Innovative Nuclear Power Plant Design and New Technology Application.
- Track 17 Student Paper Competition
- Track 18 Industry Forum: Keynote, Plenary, and Panel Sessions.
- Track 19 Workshops and Professional Development Seminar.
- Track 20 Nuclear Codes & Standards Workshop

After the incident at the Fukushima Daiichi plant, a lot of work has been done by the nuclear industry and other organizations to evaluate and analyze the event in order to protect the plants from such incidents in future. At ICONE, we introduced a track on Beyond Design Basis Events. With 46 abstracts accepted in this track, one can see a healthy interchange of knowledge on this subject. Track 16 is another new track introduced to cater for innovative new nuclear technologies.

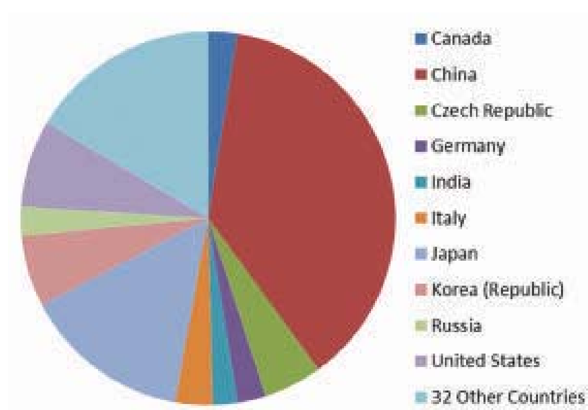
The International nature of the technical tracks is illustrated by the chart on this page showing the share of papers submitted by the top contributing countries.

A large number of panel discussion sessions are planned in Track 18. The panels making presentations will consist of recognized industry leaders and technical experts from government, industry and academia. The panel session topics are: Small Modular Reactors; Nuclear Energy Strategic Plan and Nuclear Power as a Basis of Future Energy Production in the World; Issues related to the Fukushima Daiichi Incident: Regulatory Standards and Restart of NPPs and Nuclear Facilities after the Fukushima Accident; International Co-operation; Education for the Next Generation; Industrial Approaches to Continuous Safety Improvements of NPPs; Safety in Shutting Down (Phasing out) of NPPs; Advanced Reactors and Future Designs: Siting Considerations and Challenges; Robust Fuel Development (Accident Tolerance); Beyond Design Basis; Relative Risk and Emergency Preparedness; Decommissioning and Decontamination; and Increasing Public Acceptance of Nuclear Power.

In addition to the panels, a number of workshops are scheduled in Track 19. These include Computational Fluid Dynamics (CFD); Forthcoming Seismic PRA for US Operating Plants Following Fukushima Event; Microwave NDE of HDPE Butt Fusion and Electro-fusion Joints; Water Hammer Theory and Practice; Hot Isostatic Pressing (HIP) of Nuclear Components; BEPU Methods: Challenges and Applications in Licensing Framework; and Thermal Hydraulic Methods and Experimentation. In addition, there will be a codes and standards comprehensive workshop covered under Track 20. These workshops will be conducted by national and international experts providing in-depth discussions.

A student paper competition is scheduled in Track 17. Students from Europe, North America, and Asia will compete in this program. This track recognizes the need to develop, nurture, and encourage bright young

International Sources of Tech Papers



engineers in the nuclear field. Workforce development is a growing concern as the nuclear renaissance proceeds throughout the world. Thus, knowledge transfer from seasoned practicing professional to future nuclear engineers is necessary for workforce development.

Exhibits by leading companies such as CANDU Energy, AREVA, GE-Hitachi, Mitsubishi, Westinghouse, Toshiba, and many more are expected at ICONE22. The conference provides an excellent opportunity to promote nuclear energy and networking.

Legacies of Prague: The astronomical clock in Old Town Square; the Charles Bridge, Lower Town, and Prague Castle; Frank Gehry's Dancing House.

The Venue—Prague

Prague is one of the most beautiful cities in Europe. Sitting on both banks of the Vltava River, its townscape includes burger houses and palaces punctuated by towers, and individual buildings of distinction. Built between the 11th and 18th centuries, the Old Town, the Lower Town, and the New Town speak of the great architectural and cultural influence enjoyed by this city since the Middle Ages.

Many of the city's magnificent monuments, such as Prague Castle, St. Vitus Cathedral, Charles Bridge, and numerous churches and palaces, were built mostly in the 14th century under the Holy Roman Emperor Charles IV.

Prague represents one of the most prominent world centers of creative life in the field of urbanism and architecture across generations, human mentality, and beliefs. Prague architectural works of the Gothic Period (14th and 15th centuries), of the High Baroque in the first half of the 18th century, and of the rising modernism after the year 1900 influenced the development of Central Europe, perhaps even all European architecture.

Prague belongs to the group of historic cities which have preserved the structure of their development until the present times. As early as the Middle Ages, Prague became one of the leading cultural centers of Christian Europe. The Prague University, founded in 1348, is one of the earliest in Europe. The milieu of the university in the last quarter of the 14th century and the first years of the 15th century contributed among other things to the formation of ideas of the Hussite Movement which represented the first steps of the European Reformation.

As a metropolis of culture, Prague is connected with prominent names in art, science, and politics, such as Charles IV, Petr Parléř, Jan Hus, Johannes Kepler, Wolfgang Amadeus Mozart, Franz Kafka, Antonín Dvořák, Albert Einstein, Edvard Beneš (co-founder of the League of Nations), and Václav Havel.

Further Information...

All registered participants will receive a copy of the ICONE22 Proceedings. Attendees can register via the ICONE22 website: http://www.asmeconferences.org/icone22. This website gives more details about the conference program, workshops, technical tours, and other activities.

~ Asif H. Arastu, P.E. and ASME Fellow, is the Organizing Committee Chair for ICONE22. Guoqiang Wang of Westinghouse Electric Co. is the ICONE22 Technical Program Chair.

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

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

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

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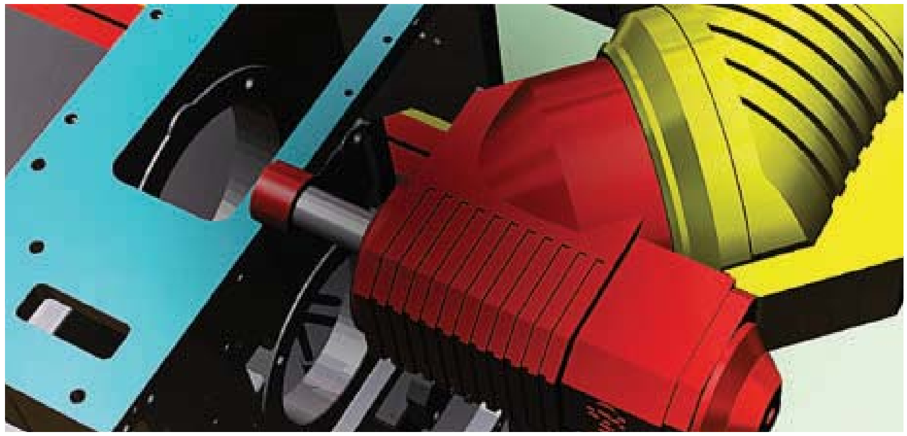
Boilers
Certification and Accreditation
Chains
Controls
Conveyors
Cranes and Hoists
Cutting, Hand, and Machine Tools
Dimensions
Drawings, Terminology, and Graphic Symbols
Elevators and Escalators
Energy Assessment
Fasteners
Fitness-For-Service
Gauges/Gaging
Geometric Dimensioning & Tolerancing (GD&T)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

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

REVIEW MACHINE SIMULATIONS

ROBORIS, PISA, ITALY.

EUREKAMOBILE IS A FREE MOBILE app that complements Eureka Virtual Machining, Roboris's flagship product. Through EurekaMobile, ISO program simulations made by Eureka Virtual Machining can be reviewed and analyzed on any mobile device. In addition to the 3-D simulation of all the machine motions, the application provides an analysis of any messages, warnings, or errors generated during the simulation. In case of collision, the colliding parts are highlighted in 3-D so the issue can be easily identified. The application is available for download from Google Play for Android devices and from Apple Store for Macintosh devices. It will be available soon also for Windows mobile devices.



Machine tool operators can now review ISO program simulations on their smartphones or tablets. Image: Roboris

CFD HEX-CELL MESH

POINTWISE, FORTH WORTH, TEXAS.

The latest release of Pointwise computational fluid dynamics meshing software features an extension of the company's T-Rex hybrid meshing technique. The extension method uses hexagonal cells in the boundary layers instead of prisms, said John Steinbrenner, Pointwise vice president of research and development.

T-Rex (anisotropic tetrahedral extrusion) is an automated, advancing layer technique for generating a CFD mesh with boundary layer and wake resolution. The technique extrudes layers of high-aspect ratio, right-angle-included tetrahedra outward from a surface mesh. A post-processing operation sequentially combines three successive tetrahedra into a stack of prisms.

In the upgraded release, extrusion from a quadrilateral surface mesh begins with a single pyramid, after which the usual tet extrusion begins. The resulting tets are post-processed into stacks of hexes.

TURBOMACHINERY DESIGN

CFTURBO SOFTWARE & ENGINEERING, DRESDEN, GERMANY.

CFturbo 9.2, for turbomachinery design, can be used for conceptual design of radial and mixed-flow centrifugal pumps, fans, blowers, compressors, and turbines, as well as for vaned and unvaned diffusers, return channels, and volutes. Direct interfaces to all major standard CAD and CFD systems are available.

CAM INSIDE CAD

AUTODESK, SAN RAFAEL, CALIF.

Inventor HSM 2015 is an integrated CAM solution for Inventor users. It helps machinists, designers, and engineers turn their designs into manufacturable parts by generating machining toolpaths inside the Inventor design tool. Inventor HSM 2015 includes a full license of Inventor 2015 software. It also includes 2.5-D, 3-D, and 3+2 toolpath options and settings for surface finish, simulation tools to help verify the machining process before running CNC programs, customizable post-processors, and a CNC editor to tailor programs to the CNC machine.

HEAT EXCHANGER SIMULATION

OPTIMIZED THERMAL SYSTEMS, COLLEGE PARK, MD.

CoilDesigner is a customizable software tool for simulating tube-fin, microchannel, flat tube, tube-in-tube, and wire-fin heat exchangers. It includes simulation and data visualization techniques. Advanced features include the capability to carry out parametric analysis and detailed optimization studies. The parametric analysis capability is helpful for developing catalog data. The optimization feature uses a multi-objective genetic optimization algorithm to explore a complete design with multiple variables and constraints but with reduced computation time. A data visualization capability allows for review and analysis of the results.

SCAN TO MODEL

TRIMBLE, COLORADO SPRINGS.

Trimble Scan Explorer Extension is an extension for SketchUp Pro, which allows engineers and others to create models from scanned 3-D data. The extension connects the high-resolution field data from scanners with modeling software. The extension reduces the time required to generate a SketchUp Pro 3-D model from scan data. Tools and one-touch features allow users to extract construction points and lines that are used as a guide to simplify and expedite the modeling process. Automated plane extraction tools further increase modeling efficiency, particularly when modeling building interiors and facades. ME

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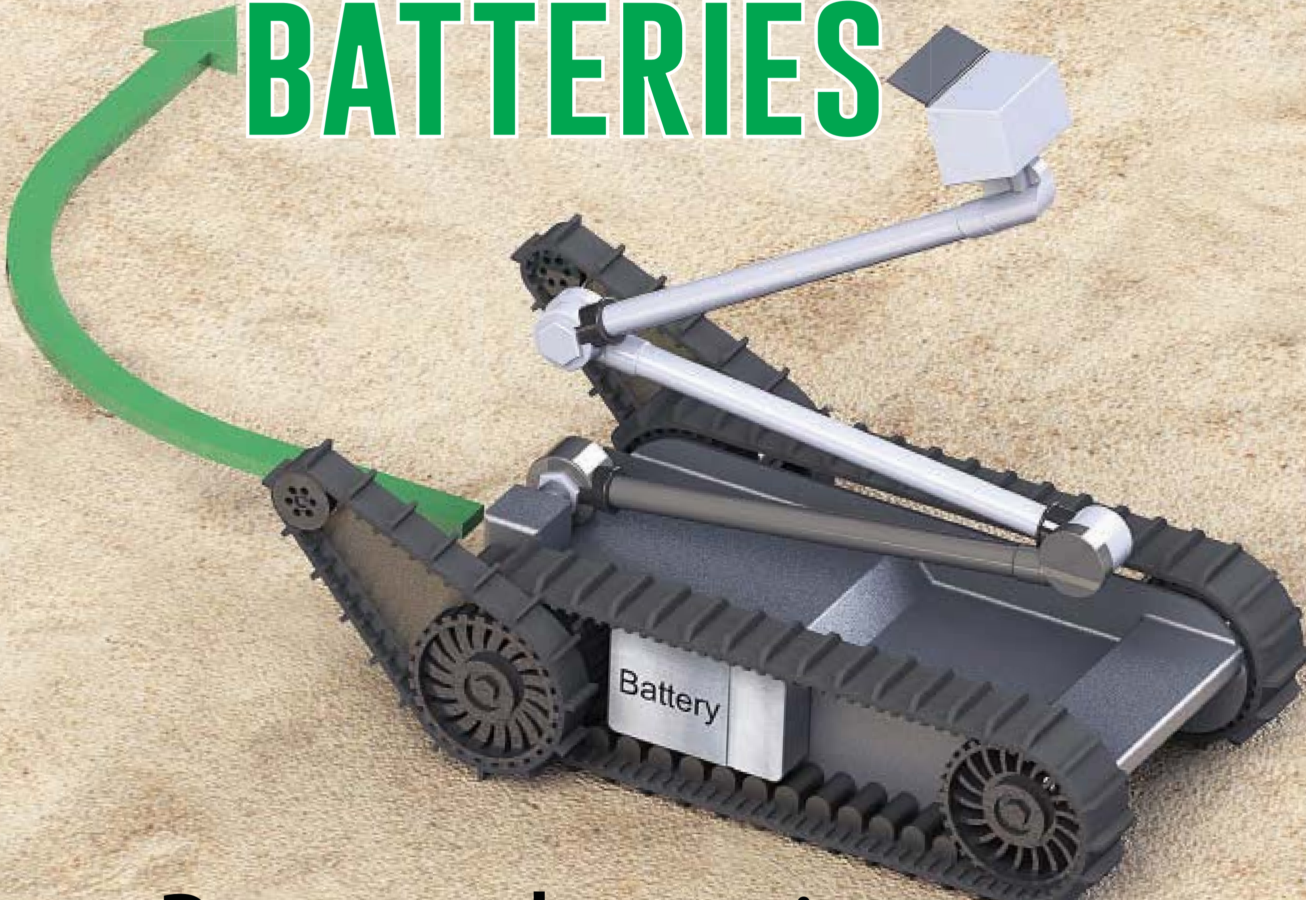
A forum for emerging systems and control technologies.

DYNAMIC SYSTEMS & CONTROL

JUNE 2014 VOL. 2 NO. 2

BETTER BATTERIES



Battery dynamics and control

DSC
ASME

SUBMIT ARTICLE IDEAS TO:
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(734)-936-0407

SUBMIT DSCD NEWS ITEMS TO:
RIFAT SIPAHI, NORTHEASTERN UNIVERSITY, rifat@coe.neu.edu

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

September 2014
Rehabilitation Robotics

December 2014
Advanced Manufacturing

Cover photo: Tulga Ersal

Getting the Most Out of Batteries

From cell phones to computers to electrified vehicles, batteries are everywhere in our daily lives. This issue of ASME *Dynamic Systems and Control (DSC) Magazine* focuses on improving batteries through dynamic modeling, estimation and control.

Tulga Ersal and his collaborators (Youngki Kim, John Broderick, Tianyou Guo, Amir Sadrpour, Anna Stefanopoulou, Jason Siegel, Dawn Tilbury, Ella Atkins, Huei Peng, Judy Jin, and Galip Ulsoy) from University of Michigan focus on battery management in unmanned ground vehicles (UGVs) being extensively used by the US Army. Typical UGVs need to execute various missions using only energy available from an onboard battery, and recharging times can be extensive. The mission can involve various terrain (i.e., road surface types, grades) and environmental conditions (e.g., temperatures), which significantly influence battery performance. Trajectory planning, battery monitoring, road roughness modeling, real-time monitoring and prior knowledge can be utilized in an integrated manner to improve battery management for such missions.

Hosam Fathy with co-authors Donald J. Docimo, Mohammad Ghanaatpishe, Michael J. Rothenberger and Christopher D. Rahn, from the University of Pennsylvania, provide a step-by-step introduction to lithium-ion battery modeling from a control systems perspective. They focus on simple explanations of the underlying physics and chemistry of these batteries and how that science can influence time- and frequency-domain behavior.

Scott Moura and Hector Perez from University of California at Berkeley utilize dynamic modeling and control theory to focus on the problems of state-of-charge (SOC) and state-of-health (SOH) estimation for batteries, as well as the constrained control of batteries. Such algorithms are capable of getting the most out of batteries by extracting increased energy and power capacity and providing faster charge times.

In the next *DSC Magazine*, to appear September 2014 and to be guest edited by Peter Meckl, you can look forward to articles on how control technology is playing a role in rehabilitation robotics. As always, I look forward to receiving your comments and suggestions at **ulsoy@umich.edu**.

A. Galip Ulsoy
Editor, *DSC Magazine*

KEEPING GROUND ROBOTS ON THE MOVE THROUGH BATTERY & MISSION MANAGEMENT

by Tulga Ersal, Youngki Kim, John Broderick, Tianyou Guo, Amir Sadrpour, Anna Stefanopoulou, Jason Siegel, Dawn Tilbury, Ella Atkins, Huei Peng, Jionghua (Judy) Jin, and A. Galip Ulsoy

From cleaning floors, handling warehouse materials, and inspecting sewer pipes, to locating and disarming explosives, ground robots are increasingly helping humans in new ways with dangerous, tedious, or inconvenient tasks[1]. Their utility and impact, currently limited by their on-board batteries, would be enhanced if their energy and power capabilities can be extended. Understanding the dynamic limitations of the batteries with stringent design criteria (e.g., no cooling due to volume and weight considerations), and better management of the battery and the mission, can lead to longer and safer operations.

This article summarizes a recent collaboration at the University of Michigan's Automotive Research Center that considered best use of batteries in ground robots from several perspectives, such as planning the mission and tracking energy during its execution. **Figure 1** illustrates the four main subproblems addressed in this collaboration. Specifically, an area coverage problem is considered using a tracked robot, and the development of an energy efficient coverage plan is first addressed. Track-terrain interaction is then modeled to better predict the power consumption due to locomotion on different types of terrains. An electro-thermal model of the battery is developed and used in a model predictive control framework to ensure that the battery is always operated within its electrical and thermal limits. A current-limiting approach is implemented to prevent the battery from overheating. Finally, a framework is developed that can combine the prior information from simulations or experiments with the online measurements to provide an adaptive and probabilistic estimate of the mission energy requirements. This framework allows the robot to predict the likelihood for a given mission to be completed with what energy remains in the battery. If mission failure is expected, coverage for the remaining area can be replanned with the available energy.

This article discusses these subproblems and the ongoing efforts to address them. A case study is presented to highlight the importance of the interactions among these subproblems.

The key message is that battery and mission management play a multi-faceted role in ground robotics. The most effective use of batteries in ground robots requires an integrated framework that considers all these factors. This is an important and exciting area to which the dynamic systems and control community can contribute.

ENERGY EFFICIENT COVERAGE PLANNING

Area coverage is a common task for a ground robot; applications include floor cleaning, lawn mowing, or sweeping a sensor through a region, searching for explosives or chemicals, or performing surveillance. Unlike traditional motion planning tasks, which involve moving from a start to a target point, the coverage task determines a path along which the robot passes near every point in the region. It is a time and energy intensive task. Previous research in creating algorithms to generate coverage paths typically did not seek to achieve an optimal path with time and energy constraints[2]. Our work extends the previous coverage planners by planning an optimal velocity trajectory along the route using the techniques of optimal control to balance the mission time, the efficiencies of the electrical system, and the area remaining to be covered[3].

The proposed solution to this problem can be summarized in the following three steps. First, a coverage path is planned using any existing algorithm from the literature, treating the path as a series of waypoints. In our study, we used the boustrophedon decomposition method[4]. The area is broken down into polygonal regions and each region is covered by simple back and forth movements. Other methods for path planning are summarized in reference 2 and can also be used for the purposes of this step. In addition to knowing the region, the key parameter for these methods is the search distance from the robot. This value is based on the current sensor in use and defines how far apart the adjacent path segments must be for coverage. Second, a cost function is defined as a linear combination of the track forces, the ratio of remaining area to be covered to the total area, and motor efficiency. Hence, this cost function penalizes *(1)* the energy expended by the robot while completing the mission through the track forces, *(2)* the uncovered areas, and *(3)* the operation of the motor in inefficient regions. Finally, in the third step, an optimal control problem is solved for this cost function to find an optimal velocity profile on the path generated in the first step. In addition to the cost function, the optimal control formulation includes a dynamic model for the robot that uses position, heading, forward velocity, and yaw rate as the states. At each waypoint, the robot must turn towards the next waypoint. A moving turn is used instead of having the robot come to a complete stop at each waypoint and turn in place. This promotes efficiency due to the terramechanics as discussed in the next section, albeit at the cost of missing small patches of area to be covered.

As an example, **Figure 2** shows a simple region with the path generated in Step 1 shown on the x-y plane, where the shaded region represents an obstacle. The optimized velocity profile over the path is shown as the third dimension of the plot. While many sections of the profile look similar, there are differences in the velocity as the robot covers more area. Full analysis of the tradeoffs between time and energy are presented in reference 3. Once the full trajectory has thus been planned, the robot can be driven along this trajectory using a trajectory-tracking controller.

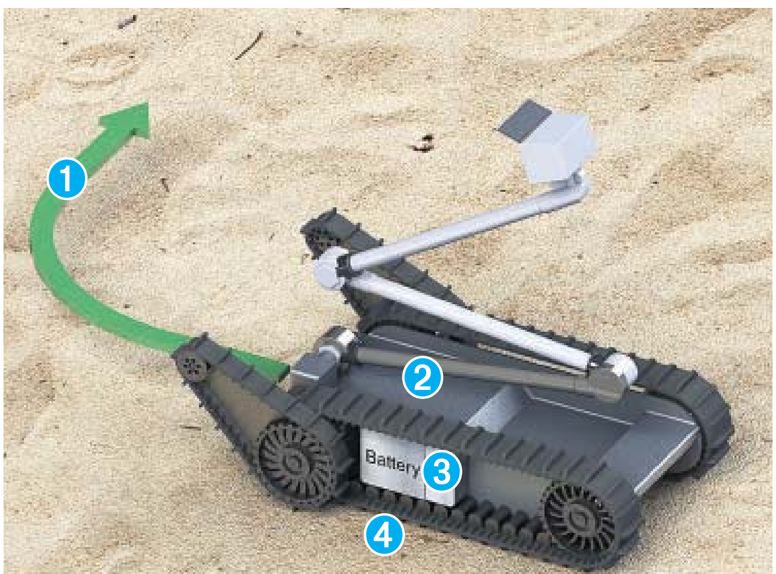

FIGURE 1
Overview of the four major subproblems considered in the collaborative effort

1. **ENERGY EFFICIENT COVERAGE PLANNING** The velocity profile along the path is optimized to minimize energy consumption, avoid inefficient motor operation, and maximize coverage.
2. **ONLINE ENERGY TRACKING** The probability of completing the mission with the remaining energy is tracked combining prior knowledge about the mission with real time data.
3. **BATTERY POWER MANAGEMENT** Using a thermo-electric model, the maximum battery power is controlled to avoid violation of voltage, temperature, and SOC limits.
4. **LOCOMOTION POWER ESTIMATION** Terramechanics models are used to predict the power needed for locomotion on a given terrain type depending on velocity and turning radius.

LOCOMOTION POWER ESTIMATION

Locomotion power (straight-line travel and skid steering) can consume a large percentage of the total power in a tracked ground robot. For example, order-of-magnitude power requirements might be 100W for locomotion, 10W for computation, and 1W for communication. Therefore, a terramechanics model is critical for accurate power and energy analysis.

Compared to straight-line travel, modeling skid steering of tracks is more difficult on soft soils because of the track-soil interaction and the distributed nature of shear stress along the large contact area. Thus, researchers developed several methods to approximate skid steering in steady state operation. Our power modeling of skid steering is based on Wong's theory, in which the turning resistance coefficients vary with both turning radius and forward vehicle velocity[2]. However, our approach includes some simplifications to achieve computational efficiency assuming uniform pressure under the tracks and a small slip ratio. The basic idea of this fast computation method is that the skid steering equations can be separated into the computationally expensive part of accounting for the shear displacement - shear stress distribution on the track and the computationally cheaper part of solving the force and moment balance equations for the vehicle. Our formulation solves the first part separately and stores the solution in look-up tables to be used in the second part. This approach gives results very close to solving the two parts in a coupled manner. Details can be found in reference 6 along with experimental validations.

As an example, **Figure 3** shows the power consumption predictions of the model during skid steering for two different soil types, dry sand and sandy loam. This figure serves two purposes. First, it shows that the typical trend is that the power consumption increases for smaller turning radii and higher velocities. This is the reason why it is beneficial to slow down while negotiating the turns as seen in Fig. 2 and why a moving turn was preferred in the coverage planning task instead of stopping and turning on the spot. Second, Fig. 3 illustrates that the locomotion power requirement can change by as much as 100% due to the soil type. This is why it is critical to have a terramechanics model as part of the robot battery and mission management framework.

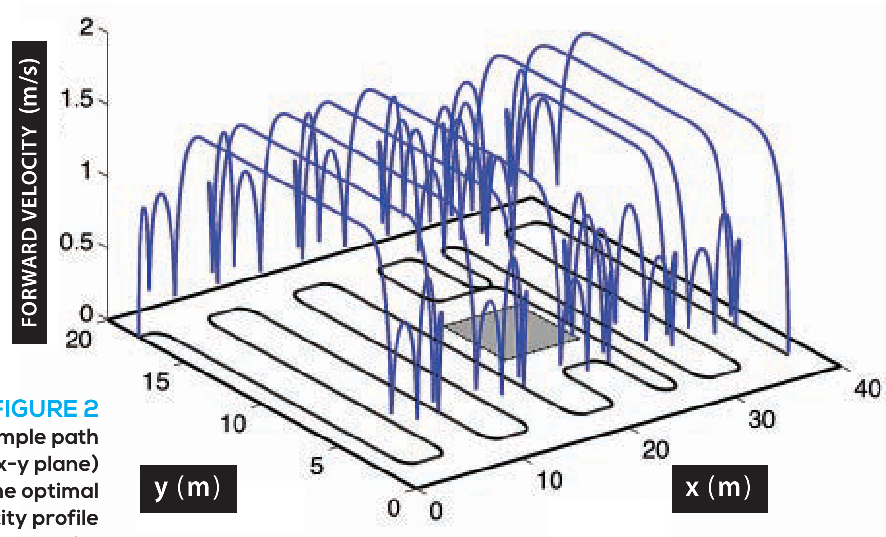

FIGURE 2
Example path (on the x-y plane) with the optimal velocity profile shown as the third dimension.

BATTERY POWER MANAGEMENT

The third major component in this collaborative effort is the development of a new battery power management strategy. In this context, battery power management refers to ensuring that the battery is operated within its voltage and temperature limits.

In this study, a lithium-ion battery is considered as a typical battery type. To avoid aging and capacity loss, and to ensure safe operation, limits on the operating temperature of the battery must be enforced. In general, temperature regulation of battery packs involves using either active thermal management systems or limiting the peak current drawn from the pack[7]. These strategies increase the rate of heat rejection or limit the rate of internal heat generation, respectively. In a mobile robot application, the first strategy is not feasible, since mobile robots rarely have a cooling system due to volume and weight limits. It is critical to control the discharge current of batteries so that operating temperatures do not exceed maximum value. Thermostatic or proportional-integral-derivative (PID) controllers are traditionally used to limit current or power drawn from the battery when temperature exceeds the predefined limits. But calibrating thermostatic thresholds, deadbands, and PID gains and integrating them with the overall power allocation strategies in battery management systems is a challenge. As an alternative, we have developed a model-based method to estimate the maximum power capability of the battery that accounts for not only electrical constraints such as terminal voltage and battery state-of-charge (SOC), but also thermal constraints.

In estimating the maximum power capability, the following factors are considered:

- The thermal and electrical dynamics of a lithium-ion cell are intrinsically coupled. For a constant current, any arbitrary increase in cell temperatures will cause reduced internal losses, and subsequently generate less heat.
- The rate of change of internal resistance with respect to temperature decreases with increasing temperatures.
- Over a reasonably short horizon, the temperature increase can be assumed to be bounded. Similar arguments can be made for the change in the electrical quantity SOC.

The above statements are valid insofar as the temperature of the cell does not exceed the threshold temperature at which thermal runaway is initiated. Since thermal dynamics are much slower than electrical dynamics, considering electrical and thermal constraints independently over a short horizon yields conservative estimates of power capability. Consequently, the thermal and electrical constraint problems are addressed separately in our approach. This is done by developing models capturing the electrical and thermal dynamics, and using them to calculate the maximum constant current over a prediction horizon of 10 seconds that does not lead to any voltage, SOC, or temperature violations. If the demanded current from the battery exceeds this maximum allowable current, the actually delivered current is limited by the maximum amount. The maximum power capability can then be found as the product of the maximum allowable current and the terminal voltage[8].

Figure 4 illustrates the performance of the battery power management algorithm during repeated duty cycles. Note that all constraints are inactive initially. Hence, the battery can meet the power demand up to 4705 s until the voltage constraint is violated first. This is because as the power is drawn from the battery, the battery SOC is reduced. The corresponding decrease in open circuit voltage and voltage drop caused by internal resis-

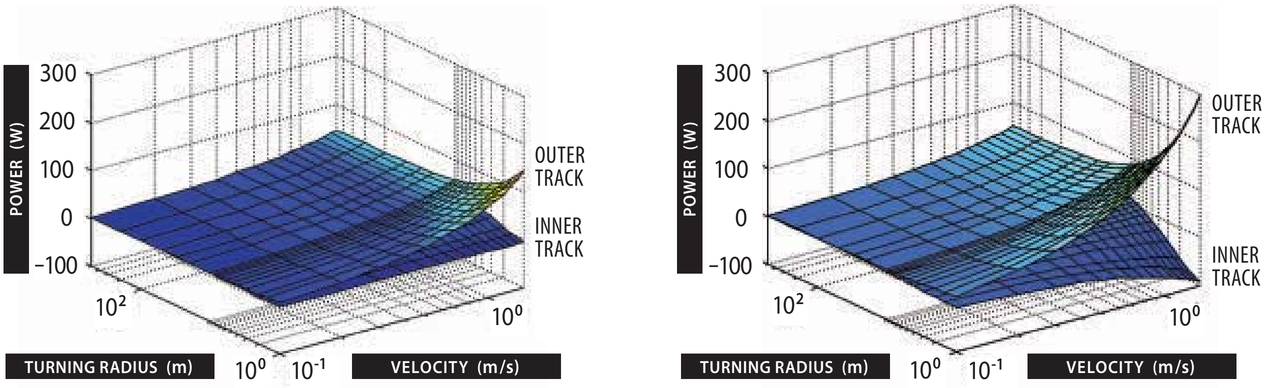

FIGURE 3 Simulation of power consumption of a tracked robot running on dry sand (left) and sandy loam (right).

tances lead to a predicted voltage constraint violation. This predicted violation activates the power limiting algorithm so that the terminal voltage can be kept above the minimum limit of 3.2 V. As the cell temperature approaches the maximum temperature limit, 45°C in this case, the power capability begins instead to be determined by the maximum temperature limit. This helps the battery temperature to be kept at the limit. Finally, the SOC constraint becomes active and the battery eventually turns off. This performance highlights that the proposed method can estimate the power capability accounting for thermal and electrical constraints. Thus, safe and reliable operation of the battery is achievable.

ONLINE ENERGY TRACKING

The previous two sections have discussed models for the thermo-electric dynamics of the battery and the interactions between the tracks and terrain. These models are useful to plan a mission as seen in the Energy Efficient Coverage Planning section, or develop the power management techniques of the Battery Power Management section. However, there may be a difference between the conditions during the execution of the mission, and those assumed in the planning stage. A method to track the available energy online and predict potential mission failures due to energy limitations is needed. This does not necessarily negate the simulation results. In fact, the method highlighted in this section combines prior knowledge from simulations (and/or prior experiments) with real-time data collected as the mission is run to predict whether it can be completed with the remaining energy. If failure is predicted, the Energy Efficient Coverage Planning task can be re-visited and the coverage mission can be re-planned taking the remaining available energy into account.

In this approach, a Bayesian regression model is used to predict mission power when prior knowledge of road segments is available. A road segment has a consistent average grade and surface condition. The model parameters are recursively updated based on real-time measurements of the robot velocity and energy consumption. The updated model is used to predict the future power consumption by leveraging an experimentally validated, linearized vehicle longitudinal dynamics model. The probability of accomplishing the mission can be adaptively estimated during its execution. Details of the approach are given in references 9 through 11. In the example mission of **Figure 5**, the Bayesian approach outperforms that of the traditional linear regression, which ignores prior knowledge and can under or over estimate the mission energy requirement.

ABOUT THE AUTHORS

Tulga Ersal is an Assistant Research Scientist in the Department of Mechanical Engineering at the University of Michigan. His expertise is in modeling, identification, simulation, and control of system dynamics, including hardware-in-the-loop simulation, with applications to batteries and vehicle powertrains among others.

Youngki Kim is a Ph.D Student in the Department of Mechanical Engineering at the University of Michigan. His research interests include design and control of hybrid electric vehicles and lithium-ion battery modeling and estimation.

John Broderick is a graduate student in the Department of Electrical Engineering at the University of Michigan. His research interests include modeling and control of ground robots to increase reliability.

Tianyou Guo is a graduate student in the Department of Mechanical Engineering at the University of Michigan. His research interests include vehicle dynamics modeling and control, robotics, terramechanics and sizing and design of hybrid vehicles. His current research focuses on power modeling and control of small unmanned ground vehicles.

Amir Sadrpour is a graduate student in the Department of Industrial and Operations Engineering at the University of Michigan. His research focuses on energy-based mission reliability assessment for unmanned ground vehicles.

Anna Stefanopoulou is a Professor in the Department of Mechanical Engineering at the University of Michigan and the Director of the Automotive Research Center. Her research interests include estimation and control of internal combustion engines and electrochemical processes such as fuel cells and batteries.

Jason Siegel is an Assistant Research Scientist in the Department of Mechanical Engineering at the University of Michigan. His research interests cover electrochemical energy storage

INTEGRATED CASE STUDY

We combined the models and algorithms described above into a single simulation framework and performed a case study to highlight the importance of an integrated solution to the problem of making ground robots more energy and power aware.

The case study started with defining an area to cover. The coverage planning algorithm generated a path and planned the most energy efficient velocity trajectory to follow along that path. A trajectory tracking controller then drove the robot dynamics model along this path while the terramechanics model predicted the loads due to the interaction between the tracks and terrain and the battery dynamics model predicted the thermo-electric implications of this trajectory for the battery. Two simulations were run.

The first simulation represented the pre-mission analysis and showed that if the terrain type is dry sand and the mission starts with a fully charged battery at 35°C ambient temperature, then the mission can be completed successfully with 60% remaining SOC and 40°C final battery temperature, 20°C below the assumed maximum allowed limit of 60°C.

The second simulation represented the actual mission scenario, where the mission actually starts with 70% SOC in the battery, which is different from what was assumed for the pre-mission analysis, but would still be sufficient to finish the mission, if the soil type was dry sand throughout the entire area. However, the actual mission scenario also assumed that the terrain type switched from dry sand to sandy loam approximately 1/3 of the way into the mission. When this simulation was run, shortly after the terrain type switched, the mission energy prediction algorithm correctly predicted failure; i.e., if the simulation had continued as is, the battery would have run out of energy before the mission was competed due to the increased power requirements for the sandy loam type of terrain. When failure was predicted, the coverage planning algorithm was re-run to cover as much area as possible with the remaining available energy. The simulation then continued with the updated path and velocity trajectory, and showed another implication of the change to a more power-demanding terrain type; namely, the battery reaching its temperature limit of 60°C. When this happened, the power management algorithm described above prevented the battery temperature from exceeding 60°C

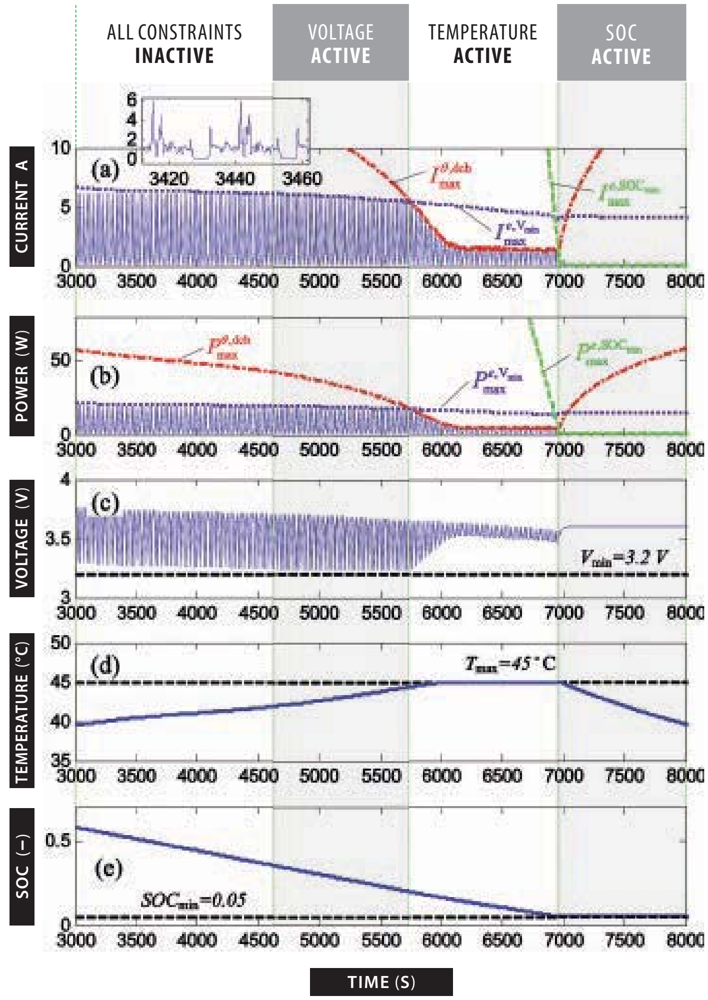

FIGURE 4
Performance of power capability estimation method during repeated operations at 30 °C ambient temperature and natural convection (6 W/m²/K): (a) current; (b) power; (c) voltage; (d) temperature; (e) SOC.

and conversion for automotive applications.

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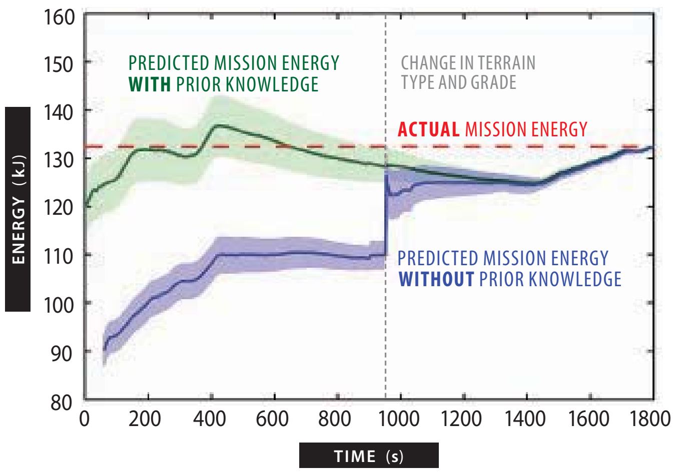
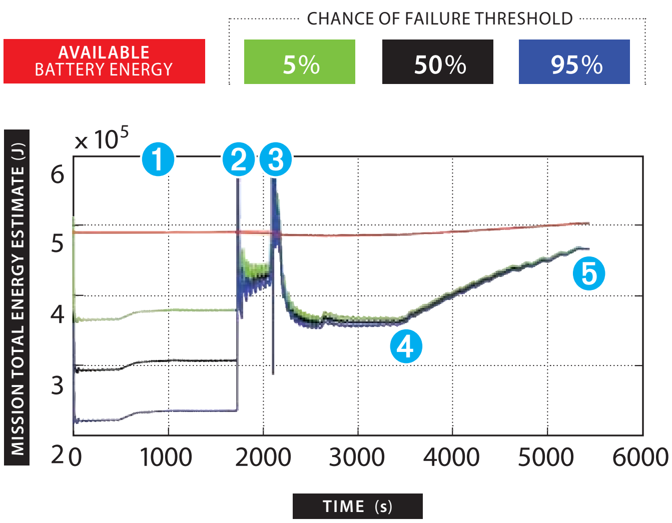


FIGURE 5 **Mission energy predictions with prediction confidence intervals (shown as shaded regions) using the Bayesian (green) and linear regression (blue) approaches. Unlike the Bayesian approach, the linear regression approach ignores the prior knowledge and initially underestimates the mission energy requirement.**



by limiting the power that can be drawn from the battery. This, however, also prevented the robot from following the optimal velocity trajectory and caused it to operate under inefficient conditions. Inefficient operation caused the mission energy requirement predictions to gradually increase. Nevertheless, the mission was completed before another failure was predicted. **Figure 6** shows the mission energy requirement predictions during this second simulation.

CONCLUSIONS

Using a coverage problem as an example, this article shows that managing the battery and the mission properly is critical for ground robots to successfully complete given tasks and make maximum use of their capabilities. To this end, the problems of energy efficient coverage planning, predicting the locomotion power requirements, controlling the battery power with thermal and electrical constraints, and tracking the mission energy requirements online based on a combination of prior knowledge and real-time data are all tightly connected to each other. Therefore, the best answers to the question of how a ground robot should most effectively utilize its battery are more likely to come from such integrated solutions. The collaboration presented here is a first demonstration of such an integration. ■

FIGURE 6 **Tracking mission energy during a simulated coverage task mission execution.**

1 Mission starts as predicted. Robot has sufficient energy to complete the mission.

2 Terrain type changes unexpectedly. Predicted energy requirement starts increasing.

3 Failure is predicted. Mission is re-planned with the remaining available energy.

4 Battery temperature reaches the maximum allowable limit. Battery power is constrained to regulate temperature. Lower speeds lead to inefficient motor operation. Mission energy prediction starts increasing.

5 Mission is completed without overheating and before the battery runs out of charge.

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THE LITHIUM-ION BATTERY MODELING CHALLENGE:

A DYNAMIC SYSTEMS AND CONTROL PERSPECTIVE

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Electrochemical batteries are central to the portable consumer electronics market. They power critical biomedical devices such as cardiac pacemakers. They help improve the fuel economy, performance, and emissions characteristics of hybrid electric vehicles by enabling regenerative braking, component right-sizing, and optimal power management. They have the potential to lessen the variability of large data centers' electric power demand through *peak shaving* and *valley filling*. In the electricity market, they are gaining attention as means for addressing the intermittencies associated with renewable generation from photovoltaics and wind power plants.

Batteries are challenged by competing energy storage technologies. This competition can be appealing for business, as in the case of heavy vehicles potentially benefiting from hydraulic hybrid powertrains. To remain commercially viable, batteries must compete with rival technologies on multiple fronts/metrics. These include monetary/societal/environmental cost, safety, efficiency, longevity, scalability, and specific power/energy. Today, we have a large portfolio of battery chemistries, each of which is a tradeoff among the above criteria. This portfolio can be subdivided into *primary* versus *secondary* batteries. Primary batteries are intended for single-use applications as they release energy through an irreversible chemical reaction. The lithium-iodine battery found in cardiac pacemakers is an example: it gradually releases energy over a period of years, after which it must be surgically replaced. Secondary batteries are rechargeable. They release energy through a reversible chemical reaction. Examples include lead-acid, nickel-metal-hydride, and lithium-ion batteries.

LITHIUM-ION BATTERIES: INTERNAL STRUCTURE AND OPERATION

Much of the progress in secondary battery technology has been driven by applications requiring mobility, such as portable electronics and transportation. The need for mobility creates impetus for higher *specific power/energy* (i.e., higher rated power/energy per unit mass). Lithium's position on the periodic table makes it light and highly reactive. Thanks to these two properties, lithium-ion batteries provide an attractive combination of specific power and specific energy. This is illustrated by the *Ragone plot* in **Figure 1**.

To construct a lithium-ion battery, one needs positive and negative electrodes, as shown in **Figure 2**. Each electrode contains active material particles, brought together into a porous mix using a binder, and infused with an electrolytic solution or gel. A porous separator allows the electrodes to exchange lithium ions through the solution. Electrons cannot travel through this separator, and must go through the electrodes' metallic current collectors plus outside circuitry to travel from one electrode to another. The negative electrode's active material is often a carbon substance, such as graphite. Popular choices of active positive electrode materials include lithium iron phosphate (LFP), lithium cobalt oxide (LCO), and lithium manganese oxide (LMO)[1].

Regardless of the choice of electrode materials, the basic principles of lithium-ion battery operation are the same. Lithium can reside in *interstitial sites* within the crystal structures of both electrodes, but has a higher affinity for the positive electrode. During battery charging, external current pulls electrons from the positive electrode and injects them into the negative electrode. External work is done on the battery, since current is forced uphill against an electric potential. Inside the battery, energy is stored through the transfer of ions to the negative electrode, for which they have less affinity. Lithium's journey during this charging process proceeds as follows. Solid-state diffusion transfers lithium from interstitial sites inside the positive electrode's active material crystals to the surfaces of these crystals. A *de-intercalation* reaction then transfers lithium ions from the positive electrode crystals to the electrolyte. The ions diffuse within the electrolyte, through the separator, and into the negative electrode. An *intercalation* reaction transfers lithium into the crystal structure of the negative electrode's active material. Finally, lithium diffuses within the negative electrode's crystal structure and settles within its interstitial sites. Separating lithium ions from electrons in the positive electrode is an *oxidation* process. Re-uniting them in the negative electrode is a *reduction* process. This oxidation-reduction reaction stores energy in the battery. Should the external power source be replaced by a load, the lithium ions will trace the journey backwards, releasing energy to the load.

This description raises a few important questions. *What role does instrumentation and control have in improving battery performance, safety, and health? To what extent are electrochemistry-based models important for battery management? What are the underlying physics in lithium-ion batteries, and how does one model them? What insights can one gain from electrochemistry-based models regarding battery behavior in the time/frequency domain? How easy is it to obtain lithium-ion battery parameter values from experimental data? Finally, what role can education and outreach play in lithium-ion battery modeling and control?* The remainder of this article is an attempt to examine these questions from a high-level vantage point, with the scientific literature serving as a guiding light.

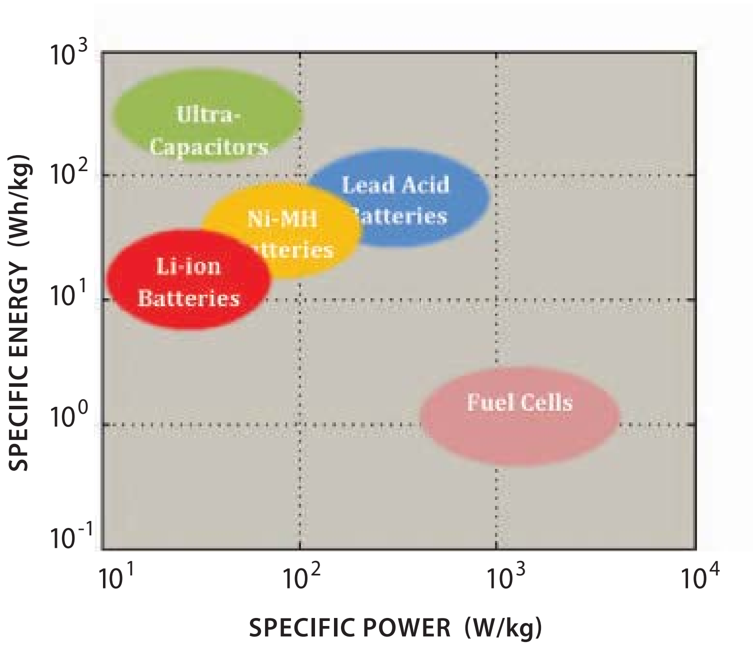

FIGURE 1 Ragone plot showing specific power vs. specific energy for different battery chemistries, in comparison to fuel cells and ultra-capacitors.

HOW DO LITHIUM-ION BATTERIES AGE, DEGRADE, AND FAIL?

It would be ideal to maximize a lithium-ion battery's power and energy through cycles of deep charge/discharge at a high current over a broad temperature range. This is crucial for applications such as electrified transportation, as in a hybrid car's resilience to both Arizona summers and Alaskan winters. But this ideal temperature-blind, deep, and aggressive battery charging/discharging is difficult to achieve for at least three reasons:

- Aggressive battery use may not be efficient. The higher currents result in larger dissipative losses which diminish efficiency.
- The tradeoff between a battery's useful power and energy capacity is partly the result of internal diffusion dynamics. When a lithium-ion battery is charged or discharged at high currents, lithium ions do not have sufficient time to spread evenly throughout its electrolyte and crystal structure. Substantial lithium concentration gradients build inside the battery and cause it to appear "full" or "empty" prematurely from an input-output perspective, as terminal voltages hit their upper and lower bounds more quickly than during less aggressive operation. In order to prevent battery damage, charging or discharging prematurely

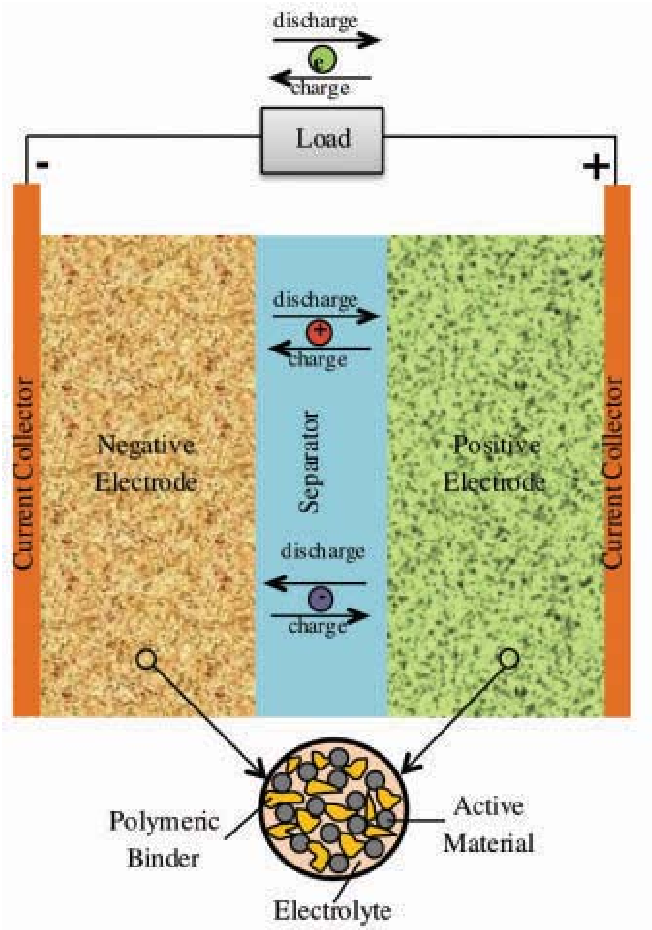

FIGURE 2 Internal structure of a lithium-ion battery.

must then be curtailed. This results in the *Peukert effect*, where larger battery charge/discharge currents diminish useful capacity.

- Aggressive use of a lithium-ion battery can also reduce the life of its useful power, as it accelerates aging and degradation.

Lithium-ion battery control is an exercise in degradation constraint management. It helps to have a physical understanding of how lithium-ion batteries age and degrade in order to achieve this control. Although surveys of battery degradation exist [1–4], the goal here is to provide an introduction to four damaging phenomena: solid electrolyte interphase growth, dendrite growth, mechanical fatigue, and thermal runaway.

Damage Mechanism #1: SEI Layer Growth

The *solid electrolyte interphase* (SEI) is a protective layer that coats the negative electrode's active material particles as soon as they come in contact with the electrolyte. The degree to which lithium-ion batteries contain SEI layers is chemistry-dependent, and our discussion here focuses on batteries where carbon is the active negative electrode material. The presence of an SEI layer is desirable in moderation: the SEI layer coats the negative electrode particles and protects them from further reaction with the electrolyte. Moreover, the SEI layer allows lithium ions to travel between the electrolyte and negative electrode particles during battery charging and discharging. Over the lifetime of the battery, the SEI layer tends to grow, consuming lithium ions in an irreversible manner and reducing the battery's ability to store charge and energy. This results in visible *capacity fade*. In addition, the growth of the SEI layer can contribute to the battery's *power fade,* which results from growing internal resistance that diminishes the its ability to provide high levels of power. SEI layer growth continues throughout the life of lithium-ion batteries with carbon-based negative electrodes—even while unused batteries are sitting in storage—and greatly affects battery longevity. Limiting SEI layer growth can be key to prolonging lithium-ion battery life. From a control-theoretic perspective, this growth can be limited by managing the input variables contributing to it in addition to the battery state. It is especially important to note the acceleration of SEI layer growth at higher *states of charge* (SOCs), during faster charging, and at elevated temperatures.

Damage Mechanism #2: Lithium Plating

Lithium plating is a damage phenomenon that occurs when metallic lithium precipitates on the surfaces of a battery's active negative electrode particles. Lithium plating can be very damaging, especially when the precipitated metallic lithium forms dendrites that pierce the battery's separator, thereby creating an internal short circuit. To understand the main cause of lithium plating, consider the following hypothetical experiment. Imagine creating a lithium-ion battery with a very small amount of metallic lithium buried inside the separator. This lithium deposit is called a third electrode. One can hypothetically connect this third electrode to an external current source or sink. Depending on whether that source/sink provides positive or negative current, the third electrode could either release lithium ions into the electrolyte

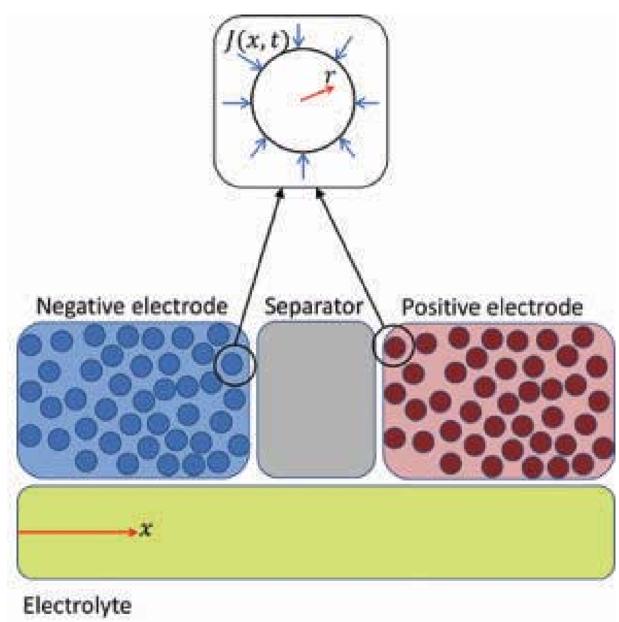

FIGURE 3
Schematic of the DFN lithium-ion battery model.

solution or gain lithium from the solution. This explains the battery community's convention of referring to this electrode as the Li\Li+ electrode: it is an electrode that represents the ionization and precipitation of pure lithium. In our hypothetical experiment, we will not utilize this third electrode for battery charging or discharging. Instead, we will use it as a reference electrode, and measure different battery potentials relative to it. One quickly discovers through this experiment that carbon-based negative electrodes in lithium-ion batteries operate at potentials very close to zero relative to Li\Li+ reference electrodes. This is especially true at high overall battery states of charge. Because of this fact, lithium-ion batteries with carbon-based negative electrodes tend to be quite vulnerable to lithium plating. Plating is particularly likely to occur when one attempts to exceed the physical limitations on intercalation rates in the negative electrode: in that scenario, lithium begins to plate the surfaces of negative electrode particles instead of intercalating into the particles. The achievable intercalation rate in a battery electrode is temperature-dependent: lower temperatures translate to slower intercalation rates. This explains the fact that lithium plating is particularly worrisome when batteries are operated at low temperatures.

Damage Mechanism #3: Mechanical Degradation

Inserting lithium into the interstitial sites in an electrode can cause the electrode to expand in volume, and removing ions can cause it to shrink. The process of charging and discharging a lithium-ion battery therefore creates cycling mechanical stresses that can induce mechanical fatigue. Deep charge/discharge cycles produce larger swings in internal battery stress with cycling, thereby resulting in higher levels of mechanical degradation. The way in which a battery is used therefore has a significant impact on the degree to which it degrades mechanically. Compared to plug-in electric vehicles, for instance, the fact that hybrid electric vehicles cycle their batteries over much narrower ranges of state of charge is attractive from a mechanical degradation perspective.

Damage Mechanism #4: Thermal Runaway

Most battery degradation mechanisms, such as SEI layer growth, progress slowly over years of battery life and thousands of battery charge/discharge cycles. Thermal runaway is an exception. As its name suggests, this is a phenomenon where battery temperature rises in a very rapid manner, leading to catastrophic failure. Thermal runaway typically begins in an already-overheated battery: one whose temperature has risen above roughly $90^{\circ}C$, perhaps because of an internal short circuit. From that point onwards, the battery experiences a sequence of exothermic damage reactions. If these reactions generate heat faster than the battery can dissipate it, internal battery temperature rises to the point of catastrophic failure. The thermal runaway of one cell in a battery pack could potentially trigger a domino cascade of thermal runaways in neighboring cells. The degree to which this occurs in practice depends on the care taken in overall battery pack construction, design, and thermal management.

Thermal runaway can be catastrophic, but is often a manifestation of underlying damage mechanisms, and involves cascading stages of battery failure. Instrumentation, estimation, and control technologies may perhaps be able to: *(1)* lessen the likelihood of thermal runaway by monitoring and controlling the factors leading to it (e.g., cell temperature); *(2)* detect the inception of thermal runaway early enough to be able to at least manage the resulting damage.

ELECTROCHEMICAL MODEL-BASED LITHIUM-ION BATTERY MANAGEMENT

There is growing evidence in the literature suggesting that model-based battery management grounded in the fundamentals of electrochemistry can help expand the envelope of lithium-ion battery performance, efficiency, longevity, and perhaps even safety. A recent study by Rahimian *et al.*, suggests that one can tailor a battery's charge/discharge trajectory to prolong useful life by up to 29% without compromising performance[5]. Research by Smith and Wang suggests that electrochemical model-based health management can potentially improve useful lithium-ion battery power density by as much as 50% without compromising longevity[6]. Research by Bashash *et al.* suggests that there is an opportunity to achieve a Pareto-optimal tradeoff between overall energy cost and long-term SEI growth in plug-in hybrid electric vehicle (PHEV) battery packs by optimizing the timing and rate with which PHEVs charge their battery packs with grid electricity[7]. Boovagaravan *et al.* and Methekar *et al.* provide an elegant physical explanation for why model-based battery management can potentially help expand the envelope of lithium-ion battery performance[8, 9]. Specifically, they use electrochemistry-based battery simulations to suggest that optimal battery charging/discharging utilizes active battery electrode materials more effectively than traditional battery cycles. An experimental study by Zhang presents the finding that the shape of a lithium-ion battery's charge/discharge cycle does indeed have a significant impact on internal degradation via impedance growth, even if the time-averaged charge/discharge current is held constant[10]. Model-based lithium-ion battery management is clearly an unfolding research topic, with much need for additional study and discovery. However, the emerging literature in this field appears to lend credence to the exciting conclusion that model-based estimation and control, grounded in the fundamentals of electrochemistry, can perhaps lead to substantial improvements in lithium-ion battery performance, efficiency, longevity, and safety.

There is a sharp distinction between this research and the traditional battery management system (BMS) design mindset. In a traditional BMS, strict safety limits are imposed on battery current, SOC, voltage, and temperature. There is freedom to operate the battery within these safety limits. In sharp contrast, the model-based battery control literature attempts to minimize battery degradation and damage by managing the internal battery state variables contributing to degradation and damage, rather than imposing ad-hoc limits on measured battery input/output variables. Implicit in this literature is the belief that this electrochemistry-based approach leads to less conservative and better-optimized battery management. Understanding the electrochemical processes occurring inside lithium-ion batteries is of great importance, and necessary in order to model these processes, and train new generations of engineers on how to use them for monitoring and control.

MODELING THE DYNAMICS OF A LITHIUM-ION BATTERY

The literature presents a large family of lithium-ion battery models, with varying degrees of fidelity and complexity. Some of these models abstract a lithium-ion battery into an equivalent circuit, while other models express battery dynamics using coupled algebraic and differential equations grounded in the discipline of electrochemistry. The mindsets behind these models are very different: equivalent circuit modeling tends to emphasize simplicity, and often involves fitting low-order approximations to empirically-measured input/output battery behavior. Electrochemical modeling, in contrast, tends to emphasize predictive ability, and focuses on describing a battery's underlying physics. This difference in mindset can be misleading: it can potentially exaggerate the contrasts between equivalent circuit models and electrochemical models. One goal of this article is to emphasize the commonalities between equivalent circuit and electrochemical battery models, particularly the degree to which both reflect the fundamental physical processes inside a lithium-ion battery.

Much of the literature on lithium-ion battery modeling has roots in the seminal work of Doyle, Fuller, and Newman (DFN)[11]. **Figure 3** provides a schematic representation of the DFN model's structure. The model describes the evolution of two quantities inside a battery: *electric potential*, ϕ, and the *volumetric concentration of lithium ions, c*. The model idealizes the active electrode material inside the battery as an infinite assortment of homogeneous spherical particles, distributed evenly across the thickness of the battery. There are two spatial axes in this model: an r axis representing radial distance inside the battery's spherical particles, and an x axis representing distance perpendicular to the battery's electrode layers. This choice of axes reflects the fact that variations in ion concentrations and electric potentials tend to be relatively small along the length and width of the electrode layers. DFN model construction is a three-step process:

STEP 1 Modeling potential distributions using Ohm's law

Elementary circuits textbooks present a lumped-parameter version of Ohm's law, $V=IR$, with V being the voltage across a resistor, I being the current through it, and R beings its resistance. If the resistor has a uniform cross-section, then its resistance can be expressed in terms of its cross-section area, A_r, effective conductivity, σ, and length. Here we are interested in an infinitesimal resistor of vanishingly small length δx. The voltage V, in this case, is the difference in potential, ϕ, between the two ends of the resistor, and the current, I, flows in the positive x-direction. Applying Ohm's law gives:

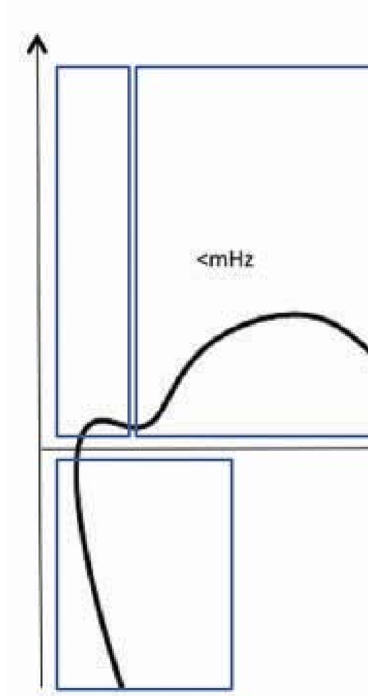

FIGURE 4
Sketch of lithium-ion battery EIS plot.

$$\phi(x+\delta x)-\phi(x) = -I\,\frac{\delta x}{\sigma A_r} \quad (1)$$

Rearranging the above equation and taking the limit as $\delta x \longrightarrow 0$ results in the following differential equation:

$$\sigma\frac{\partial \phi}{\partial x} = -I\,\frac{\delta x}{\sigma A_r} \quad (2)$$

Equation 2 assumes that the same current that enters the resistor at location x leaves the resistor at location $x+\delta x$. If the above resistor represents, say, one of the solid electrodes of a lithium-ion battery, then this assumption is not true. Current travels along the x-axis in the electrode, but additional current also enters the electrode via intercalation from the electrolyte. If the intercalation current density (i.e., intercalation current per unit volume) is J, then the following equation enforces conservation of charge:

$$I(x+\delta x)-I(x) = J A_r\,\delta x \quad (3)$$

Rearranging Equation 3 and taking the limit as $\delta x \longrightarrow 0$ gives:

$$J A_r = \frac{\partial I}{\partial x} = \frac{\partial}{\partial x}\left(-\sigma A_r\frac{\partial \phi}{\partial x}\right) \quad (4)$$

Finally, canceling the area A_r from both sides of Equation 4 yields Ohm's law as it applies to the solid material of a lithium-ion battery electrode:

$$J + \frac{\partial}{\partial x}\left(-\sigma A_r\frac{\partial \phi}{\partial x}\right) \quad (5)$$

The above derivation can be used to relate solution-phase potential gradients to intercalation current density, with only two minor changes. First, one must change the sign associated with intercalation current density, J, to ensure conservation of charge between the electrodes and electrolyte. Second, one must also account for the impact of lithium ion concentration gradients on solution-phase potentials: a phenomenon known as *concentration polarization*.

STEP 2 Modeling concentration dynamics using Fick's law

During charging and discharging, the electrodes of a lithium-ion battery exchange ions via diffusion. Fick's law of diffusion—analogous to the law of conduction heat transfer—states that diffusion proceeds opposite to concentration gradients. For a prismatic medium of cross-sectional area A, Ficks's law states that the total ion flow rate, Q, is related to concentration gradient, $\frac{\partial c}{\partial x}$, as follows:

$$Q = -AD\frac{\partial c}{\partial x} \quad (6)$$

The quantity D represents diffusivity. Treating diffusivity as a constant parameter furnishes a linear diffusion model. This can lead to some inaccuracy if the underlying diffusion dynamics are nonlinear. Additional modeling complexities arise when solid-state lithium ion diffusion induces a crystal structure phase change: a phenomenon that occurs in lithium iron phosphate electrodes.

Using Fick's law of diffusion to model battery dynamics involves imposing an ion conservation law, analogous to Equation 3. Consider, for example, an element of the electrolyte of infinitesimal thickness δx. Diffusion causes lithium ions to enter this infinitesimal element at a rate equal to $Q(x)-Q(x+\delta x)$. Moreover, if the volumetric intercalation current density is J, then ions leave this electrolyte element at a rate $JA\delta x\,\frac{(1-t^+)}{F}$. The constants t^+ and F are a *transference number* and Faraday's number, respectively. Dividing intercalation current by Faraday's number converts it to an ionic transfer rate. Furthermore, multiplying by $(1-t^+)$ accounts for the fraction of intercalation current transmitted via lithium ions. Altogether, the net rate at which lithium ions enter this infinitesimal electrolyte element equals the rate of charge accumulation within the element, i.e.:

$$Q(x)-Q(x+\delta x)-\frac{J(1-t)A\delta x}{F} = \frac{\partial}{\partial t}[\varepsilon c A\delta x] \quad (7)$$

The symbol ε in the previous equation represents battery porosity: a quantity that is important because the electrolyte only occupies the pores within a lithium-ion battery. Substituting Equation 6 into Equation 7 and taking the limit as $\delta x \longrightarrow 0$ gives:

$$\nabla.(D\nabla.c) - \frac{J(1-t)}{F} = \varepsilon\frac{\partial c}{\partial t} \quad (8)$$

Equation 8 is Fick's law of diffusion, written specifically for the electrolyte in a lithium-ion battery. This is a partial differential equation which, when discretized in space, yields state equations for solution-phase ion concentrations as state variables. The "driving force" in this PDE is intercalation current density. A similar derivation, omitted for brevity, yields a partial differential equation for ion concentration dynamics over the spherical coordinate system for the active electrode particles.

STEP 3 Modeling intercalation using the Butler-Volmer equation

Intercalation current density appears in all of the above battery model derivations. Intercalation is a chemical reaction, driven by a difference in potential between the solution and solid phases in a lithium-ion battery. Depending on lithium ion concentration at the surface of a given solid particle, there is an *equilibrium potential* U_{ref} at which intercalation and de-intercalation reactions occur at equal rates, denoted as i_o. When the potential difference between the solid and solution phases equals that equilibrium potential, there is no net transfer of charge via intercalation. Suppose we increase the difference between solution-phase and solid-phase potentials relative to this equilibrium, by some *overpotential* η. This overpotential will accelerate the intercalation reaction by the factor $e^{\frac{\alpha F}{RT}\eta}$, where F is Faraday's number, R is the ideal gas constant, T is absolute temperature, and α is a constant known as a charge transfer coefficient. Furthermore, de-intercalation slows down by the factor $e^{-\frac{(1-\alpha)F}{RT}\eta}$. The end result is that the *net intercalation rate* grows to some nonzero value, J, governed by the *Butler-Volmer equation*:

$$J = i_o\left(e^{\frac{\alpha F}{RT}\eta} - e^{-\frac{(1-\alpha)F}{RT}\eta}\right) \quad (8)$$

Overpotential, in the Butler-Volmer law, is the difference between solution-phase and solid-phase potential computed relative to equilibrium:

$$\eta = \phi_{solution} - \phi_{solid} - U_{ref} \quad (9)$$

The Butler-Volmer equation is central to the DFN battery model. It couples all the other major elements of the model, bringing together the phenomena of solid- and solution-phase diffusion and Ohmic resistance into an integrated whole. To complete the DFN model, one needs to incorporate boundary conditions representing the fact that potential gradient is zero at interfaces where current is zero (e.g., the interface between the solid electrode and separator), and is proportional to total battery current at the interface with external circuitry. Furthermore, modeling the thermal dynamics of the battery requires additional equations capturing reversible and irreversible heat generation, thermal energy storage, heat transfer, and the dependence of battery parameters such as diffusivities and equilibrium reaction rates on temperature.

THE NEED FOR CONTROL-ORIENTED LITHIUM-ION BATTERY MODELING

From a control-theoretic perspective, the DFN battery model is very complex. It captures the evolution of battery state variables as a function of time, transverse distance within the battery material (*x* axis), and radial distance within the battery particles (*r* axis). It consists of coupled ordinary differential equations, partial differential equations, and algebraic constraints. Reasonable discretizations of the DFN model can yield thousands of lumped-parameter differential algebraic equations (DAEs).

The scientific community has been actively developing different tools for balancing the fidelity and complexity of electrochemical battery models such as the DFN model. Examples of these tools include the use of orthogonal collocation methods, proper orthogonal decomposition, pole residue grouping, and Padé approximation to reduce the number of state variables needed to model battery dynamics[1]. These model reduction techniques are valuable, but it is equally important to build an intuitive understanding of which electrochemical phenomena are important to model for different battery operating conditions. Towards this goal, consider the problem of extracting appropriate simplifications of the DFN model for different battery *C-rates*. A battery's C-rate is defined as its charge/discharge current, in Amperes, divided by its charge capacity in Ampere-hours. A 1-C charge rate, for instance, represents an attempt to charge the battery in exactly 1 hour, whereas a 2-C charge rate represents an attempt to charge it in 30 minutes. The question, here, is: *which components of the DFN model are important at different C-rates?* Examining the literature reveals the following insights:

- At extremely slow C-rates measuring less than C/100, the relationship between state of charge and open-circuit voltage defined battery behavior. The corresponding relationship in the DFN model is between solid-phase ion concentrations and equilibrium potential, U_{ref}, for each of the two electrodes.

- As C-rates increase to roughly 1-C, the battery's Ohmic resistance and solid-phase diffusion dynamics become more important. This motivates the literature's development of the single-particle model: a simplification of the DFN model where solution-phase ion concentration is assumed to be constant. By neglecting spatial variations in solution concentration, the single particle model is able to: *(1)* represent each battery electrode by a single spherical diffusion particle (hence the model's name), *(2)* eliminate the need for solving Fick's law of diffusion for the solution, *(3)* replace Ohm's law for both the solid and electrolytic media by lumped equivalent resistors.

- At C-rates higher than 1-C, the need for the DFN model to fully incorporate thermal behavior increases substantially.

LITHIUM-ION BATTERY BEHAVIOR IN THE FREQUENCY DOMAIN

When developing physics-based battery models such as the DFN model, electrochemists are typically looking to capture battery behavior over a reasonable range of frequencies, for a broad range of charge/discharge currents and temperatures. The need for accurate models of frequency-domain battery behavior motivates *electrochemical impedance spectroscopy* (EIS): the process of measuring and plotting the complex impedance of a battery for different excitation current frequencies. An EIS plot is essentially a Nyquist plot, with one small caveat: while the real axis represents battery resistance, the imaginary axis represents imaginary battery impedance multiplied by -1. An EIS plot of an RC circuit, for instance, lies in the first quadrant of the complex

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plane. EIS plots are an excellent means for emphasizing the connections, as opposed to contrasts, between electrochemistry-based and equivalent circuit battery modeling.

Figure 4 presents a sketch of a lithium-ion battery's EIS plot. As battery excitation frequency increases from zero to infinity, one traces this EIS plot from the top right corner to the bottom left. The DFN model excels at matching the low-frequency portion of this plot. At very low frequencies, the battery acts as a pure integrator. The battery's output voltage at these frequencies is a function of state of charge, which is proportional to the integral of input current. The DFN model represents this fact through the static relationship between electrode equilibrium potentials and solid-phase ion concentrations. The EIS plot shows this integral behavior by curving upwards to become almost vertical at frequencies in the sub-mHz range. As excitation frequency increases, diffusion dynamics become relatively important. Consider Fick's law of diffusion for a spherical solid electrode particle. Fick's law can be discretized spatially to furnish a set of lumped-parameter state-space equations that physically represent cascades of resistive-capacitive dynamics. The corresponding EIS plot curves with frequency such that its slope approaches 45°. This model-based insight is typically visible in an EIS plot, particularly as frequency increases from the mHz range to the Hz range. At higher excitation frequencies, the interfaces between the electrode particles, electrolyte, and current collectors become more important to model. Phenomena such as the double-layer capacitance of the SEI layer, the charge transfer resistance of the SEI layer, and the impedance of the passivation film at the heart of the SEI begin to reveal their own RC dynamics at the battery's input/output ports. We did not incorporate these RC dynamics in the DFN model presented here, but this can be done fairly easily, pushing the model's bandwidth to the neighborhood of 100Hz. As excitation frequencies push into the kHz range, inductive phenomena and *skin effects* come into play, causing the EIS plot to drop into the fourth quadrant.

CONCLUDING REMARKS

The overarching messages of this article have been that: *(1) Lithium-ion batteries have a key role to play in mobile energy storage. (2) One can potentially expand the envelope of lithium-ion battery performance, efficiency, safety, and longevity by using fundamental electrochemistry-based models for battery control. (3) There are clear tradeoffs between battery model fidelity and complexity, and a significant literature addressing these tradeoffs. (4) Electrochemistry-based battery models can be effective at capturing frequency-domain battery dynamics, especially at lower frequencies. When they are examined in this light, the commonalities between them and equivalent-circuit models become more visible.*

We refer in the title of this article to the lithium-ion battery modeling *challenge*. Constructing lithium-ion battery models certainly takes effort, and so does reducing these models for control design purposes. One important open challenge in lithium-ion battery modeling is the matching of sophisticated battery models to experimental data. Fortunately, with full charge/discharge, duty cycle, and EIS testing there is considerable input/output data available for validation. Half-cell testing or insertion of a third reference electrode in a feul cell can separate the contributions of the negative and positive electrodes, and researchers are pursuing other novel technologies for in-cell instrumentation and measurement. Most importantly, there is a need to educate the next generation so that they can contribute to the community's growing efforts to tackle the lithium-ion battery modeling challenge. ■

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BETTER BATTERIES

THROUGH ELECTROCHEMISTRY

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Batteries are everywhere: in our smart phones, laptops, electric vehicles (EVs), and electric grids. Energy storage is a critical enabling technology for enhancing energy sustainability. Although battery materials science has seen rapid advances, the systems are underutilized and conservatively designed. Consumers purchase batteries with 20-50% excess energy capacity, leading to added weight, volume, and upfront cost. Intelligent battery control can lead to faster charge times, increased energy and power capacity, as well as a longer life. The key to realizing such advanced battery management systems is electrochemistry and controls—a fusion of modern control theory and electrochemical models that allows batteries to operate safely at their physical limits.

This article introduces key concepts in ElectroChemical-based Control (ECC) systems for batteries, and highlights the fundamentals of battery electrochemistry, state-of-charge/state-of-health estimation, and constrained control.

BATTERY FUNDAMENTALS

Jumping Frog Legs: A Brief History of the First Battery

Italian physicist Alessandro Volta invented the first battery cell in 1800. The so-called voltaic pile consisted of two metals in series, zinc and copper, coupled by a sulphuric acid electrolyte. Volta's inspiration came from experiments performed by his colleague Luigi Galvani who was interested in the interaction between electricity and biological nervous systems. During his experiments, Galvani discovered that a dead frog's legs would kick to life when in contact with two dissimilar metals. Volta reasoned that the different metals caused this behavior, and demonstrated this to be true with his voltaic pile.

Principles of Operation

A battery, put simply, converts between chemical and electrical energy through oxidation-reduction reactions. As shown by the zinc-copper Galvanic cell in **Figure 1**, it consists of two dissimilar metals (electrodes) immersed in an electrolyte. The cathode and anode materials are selected to have a large electrochemical potential between each other. This provides the desired electrochemical energy storage property. The electrodes are electrically isolated from each other via a separator. Hence, electrons are forced through an external circuit, powering a connected device, while cations flow between the electrodes within the electrolyte.

Electrode and electrolyte materials are selected for their voltage, charge capacity, weight, cost, manufacturability, etc. For example, lithium-ion cells are attractive in mobile applications because lithium is the lightest (6.94 g/mol) and most electropositive (-3.01V vs. standard hydrogen electrode) metal in the periodic table. Lead acid cells feature heavier electrodes (Pb and PbO_2), yet provide high surge currents at cost effective prices. Lithium-air batteries feature cathodes that couple electrochemically with atmospheric oxygen, thus producing energy densities that rival gasoline fuel.

In battery energy management, we are interested in maximizing performance and longevity. This requires a detailed understanding of the underlying electrochemistry. However, the electrochemical variables are not directly measurable. At best, one can measure voltage, current, and temperature only. Consequently, modeling and control are necessary to extract the full potential from batteries.

State-of-Charge (SOC) Estimation

SOC indicates the remaining charge, analogous to a fuel tank level indicator. Unlike fuel tanks, SOC is not measurable—it is estimated by combining models and measurements.

To motivate the particular challenges of SOC estimation consider **Figure 2**, which provides the relationship between voltage and SOC at different C-rates (*see sidebar below "What is C-rate?"*) for a $LiFePO_4$ cell. In principle, one may measure voltage and invert the nonlinear relationship shown in Fig. 2. Two challenges are immediately visible. First, voltage shifts with C-rate, thus complicating inversion. Second, function inversion is highly sensitive to measured voltage errors, since the slope is nearly zero in the 5% – 95% SOC range. In addition, this relationship varies with temperature, age, and cell chemistry. Accurate models and estimation theory are needed to address this problem, especially in highly dynamic and safety critical environments such as electric vehicles.

State-of-Health (SOH) Estimation

Battery SOH metrics indicate a battery's relative age. The two most common SOH metrics are charge capacity fade and power capacity fade. Charge capacity fade indicates how charge capacity has decreased relative to its nameplate value (e.g., a 2 Ah cell may hold 1.6 Ah after two years of use). Power capacity fade indicates how power capacity has decreased relative to its nameplate value (e.g., a fresh cell may provide 360W of power for 10 seconds, but only 300W after two years of use). Gradual changes in SOH metrics can be related to changes in a mathematical model's parameters. A rich body of literature on parameter identification is readily available to address SOH estimation. Several interesting challenges arise within the context of electrochemical models, including derivations of parametric models, nonlinear parameter identifiability, and persistency of excitation.

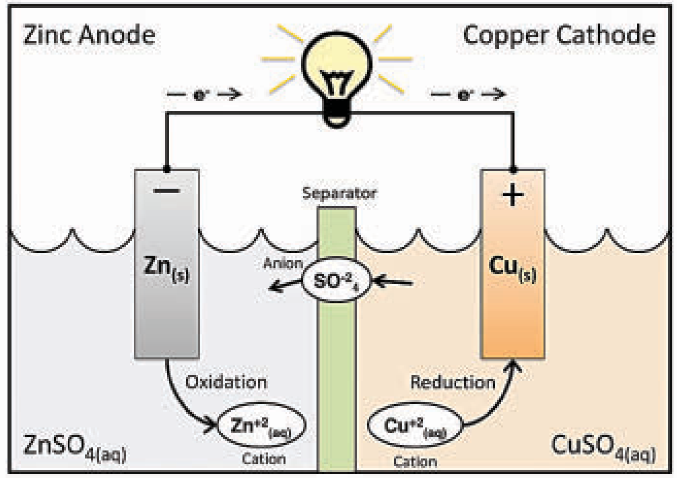


FIGURE 1 Zinc-copper Galvanic cell demonstrating the principles of operation for an electrochemical cell.

Controlled Charging/Discharging

In current applications, additional capacity is added to mitigate cell imbalance, capacity/power fade, thermal effects, and estimation errors. This leads to larger, heavier, and more costly batteries than required. ECC alleviates oversizing by safely operating batteries near their physical limits. Today, operation is defined by voltage, current, and temperature limits—all measurable variables. Battery degradation, however, is more closely related to limits on the immeasurable electrochemical states, such as overpotentials and surface concentrations. Consequently, we seek a paradigm-shifting architecture that expands the operating envelope by constraining internal electrochemical states instead of voltage, current, and temperature, as seen in **Figure 3**. This combines SOC/SOH estimation with control algorithms to form a comprehensive ECC battery management system.

MATHEMATICAL MODELING

Equivalent Circuit vs. Electrochemical Models

Mathematical battery models generally fall into two categories: equivalent circuit models (ECM) and electrochemical models (EChem); see **Figure 4**. ECMs predict the input-output behavior of cells via electric circuits. The simplest ECM, shown in Fig. 4(a), considers a battery as a nonlinear voltage source in series with an internal resistor. This is written in state-space form as

WHAT IS C-RATE?

C-rate is a normalized measure of electric current that enables comparisons between different sized batteries. Mathematically, the C-rate is defined as the ratio of current, I, in Amperes (A) to a cell's nominal capacity, Q, in Ampere-hours (Ah). For example, if a battery has a nominal capacity of 2.5 Ah, then C-rates of 2C, 1C, and C/2 correspond to 5A, 2.5 A, and 1.25 A, respectively. **Note that C-rate has dimensions of [A] / [Ah] = [1/h].**

$$S\dot{O}C\,(t) = -\frac{1}{Q}I\,(t) \quad (1)$$

$$V(t) = OCV\,(SOC\,(t)) - R\,I\,(t) \quad (2)$$

where $I\,(t)$ is current, Q is charge capacity, $OCV\,(\cdot)$ is the open circuit voltage function, R is internal resistance, and $V(t)$ is voltage. These models become more complex and accurate by considering additional circuit components (e.g. RC pairs) and more parameterizations[1]. Although ECMs are intuitive to formulate, they are insufficient for controlling the electrochemical states. Many researchers have recently focused solely on EChem models.

EChem models capture the spatiotemporal dynamics of lithium-ion concentration, electric potential, and intercalation kinetics. Most models in the battery controls literature are derived from the Doyle-Fuller-Newman (DFN) model[2], which is based upon porous electrode and concentrated solutions theory. Fig. 4b shows a cross section of the layers described in Fig. 1. At full charge most of the lithium exists within the anode solid phase particles, typically lithiated carbon Li_xC_6, that are idealized as spherically symmetric. During discharge, lithium diffuses from the interior to the surface of these spherical particles. At the surface an electrochemical reaction separates lithium into a positive lithium ion and electron.

$$Li_xC_6 \rightleftharpoons C_6 + xLi^+ + xe^- \quad (3)$$

Next, the lithium ion migrates from the anode, through the separator, and into the cathode. Since the separator is an electrical insulator, the corresponding electron travels through an external circuit, powering the connected device. The lithium ion and electron meet at the cathode particles' surface, typically a lithium metal oxide $LiMO_2$, and undergo the reverse electrochemical reaction.

$$Li_{1-x}MO_2 + xLi^+ + xe^- \rightleftharpoons LiMO_2 \quad (4)$$

The produced lithium atom then diffuses into the interior of the cathode's spherical particles. This entire process is reversible by applying sufficient potential across the current collectors – rendering an electrochemical storage device. In addition to lithium migration, this model captures the spatial-temporal dynamics of internal potentials, electrolyte current, and current density between the solid and electrolyte phases.

Although EChem models predict battery operation over broad conditions, they are mathematically complex. **Table 1** summarizes the main equations, including partial differential equations (PDEs), ordinary differential equations (ODEs) in space, ODEs in time, and nonlinear algebraic constraints. This complexity prohibits estimator and control design. As a result, there is a focus on reduced-order models that facilitate control design while predicting the dynamics of interest.

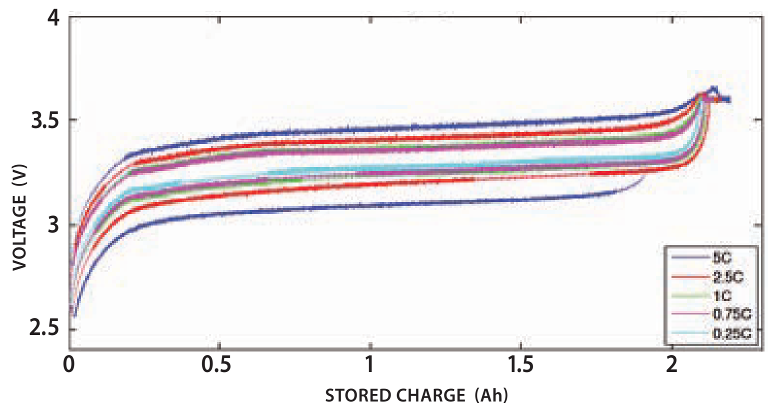


FIGURE 2
Relationship between terminal voltage, storage charge, and C-rate for a LiFePO4 cell.

Reduced-Order Models

A rapidly growing body of literature is establishing a spectrum of EChem models that achieve varying balances of mathematical simplicity and accuracy. The most fundamental reduced EChem model is the single particle model (SPM). The SPM idealizes each electrode as a single aggregate spherical particle. This model results if one assumes the electrolyte Li concentration $c_e(x,t)$ from[11] is constant in space and time. This assumption works well for small currents, yet produces errors at large C-rates. Mathematically, the model consists of two diffusion PDEs governing each electrode's concentration dynamics,

$$\frac{\partial c_s^-}{\partial t}(r,t) = D_s^-\left[\frac{2}{r}\frac{\partial c_s^-}{\partial r}(r,t) + \frac{\partial^2 c_s^-}{\partial r^2}(r,t)\right] \quad (5)$$

$$\frac{\partial c_s^+}{\partial t}(r,t) = D_s^+\left[\frac{2}{r}\frac{\partial c_s^+}{\partial r}(r,t) + \frac{\partial^2 c_s^+}{\partial r^2}(r,t)\right] \quad (6)$$

where input current enters as Neumann boundary conditions

$$\frac{\partial c_s^-}{\partial t}(0,t) = 0, \qquad \frac{\partial c_s^-}{\partial t}(R_s^-,t) = \frac{I(t)}{D_s^- F a^- A L^-} \quad (7)$$

$$\frac{\partial c_s^+}{\partial t}(0,t) = 0, \qquad \frac{\partial c_s^+}{\partial t}(R_s^+,t) = \frac{-I(t)}{D_s^+ F a^+ A L^+} \quad (8)$$

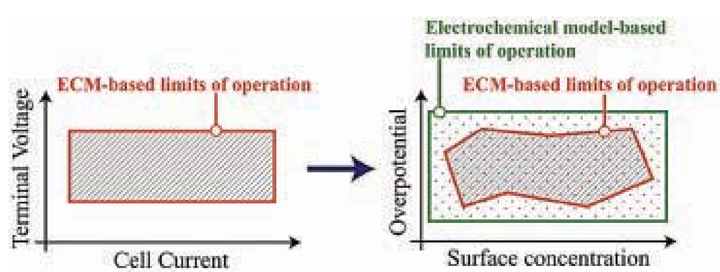
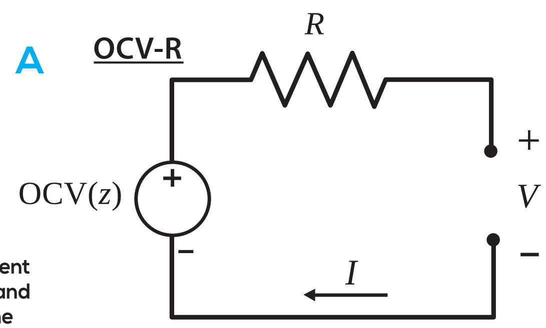


FIGURE 3 Current battery management systems regulate operation by limiting measurable quantities (e.g. voltage and current). An ECC approach expands the operating regime by regulating the immeasurable electrochemical states within safe limits.



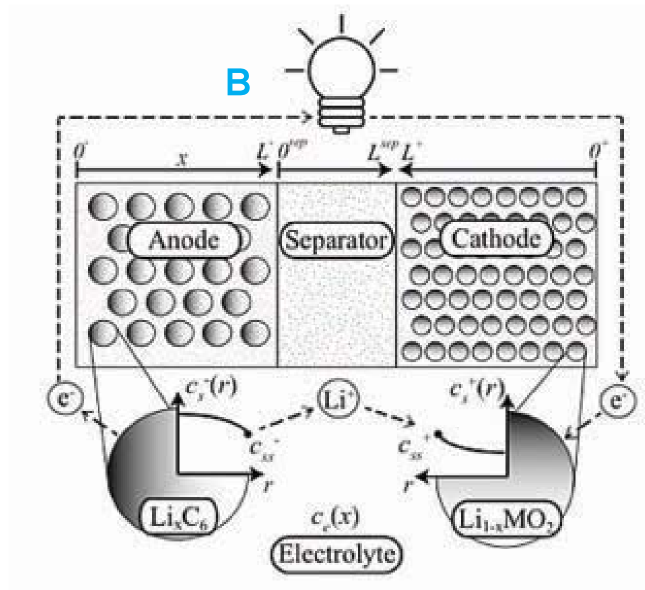


FIGURE 4 Example equivalent circuit model **A** and a schematic of the electrochemical battery model **B**.

The boundary conditions at $r = R_s^+$ and $r = R_s^-$ signify that flux is proportional to input current $I(t)$. Output voltage is given by a nonlinear function of the state values at the boundary $c_{ss}^+(t)$, $c_{ss}^-(t)$ and the input current $I(t)$ as follows

$$V(t) = \frac{RT}{\alpha F}\sinh^{-1}\left[\frac{I(t)}{2a^+AL^+i_0^+(c_{ss}^+(t))}\right] - \frac{RT}{\alpha F}\sinh^{-1}\left[\frac{I(t)}{2a^-AL^-i_0^-\left(c_{ss}^-(t)\right)}\right] + U^+\left(c_{ss}^+(t)\right) - U^-\left(c_{ss}^-(t)\right) + R_f I(t) \quad 9$$

where the $i_0^j(\cdot)$ is the exchange current density and $c_{ss}^j(t) = c_{ss}^j(R_s^j, t)$ is the surface concentration for electrode $j \in \{+,-\}$. The functions $U^j(\cdot)$ are the equilibrium potentials of each electrode material, given the surface concentration.

The SPM reduces the DFN model to two linear state equations and a nonlinear output mapping. This model is amenable to control/observer design, however its predictive capability is limited to low C-rates. Other researchers have developed higher-fidelity reduced EChem models via a swath of numerical methods[4–8]. Nonetheless, these models are not always oriented towards controller/observer synthesis, thus motivating further research.

A critical property for state estimation is observability. The DFN model is not completely observable (in the linear sense) from voltage, current, and temperature measurements. Several heuristics have been successfully applied to render complete observability, which are associated with reduced-order modeling[3,4,7]. However, exploitation of nonlinear observability or PDE observability remains an open opportunity.

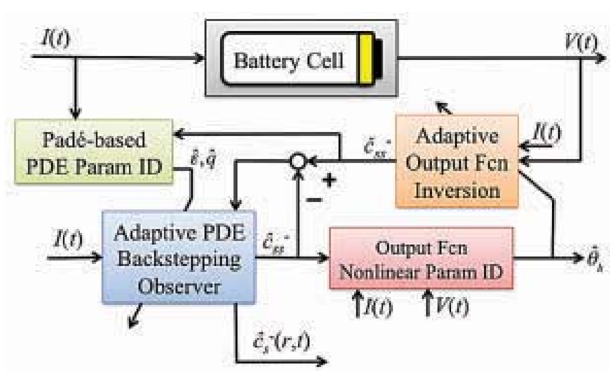


FIGURE 5 Block diagram of the adaptive observer composed of the backstepping state observer (blue), PDE parameter identifier (green), output function parameter identifier (red), and adaptive output function inversion (orange). The observer furnishes estimates of SOC (i.e. $\hat{c}_s^-(r,t)$) and SOH (i.e. $\hat{\varepsilon}, \hat{q}, \hat{\theta}_h$) given measurements of I(t) and V(t), only.

STATE-OF-CHARGE/STATE-OF HEALTH ESTIMATION

Research on battery SOC/SOH estimation has experienced considerable growth, and can be categorized under ECM or EChem model-based algorithms.

The first category considers estimators based upon ECMs. For example, the seminal work by Plett[9]. applies an extended Kalman filter to simultaneously identify the states and parameters of an ECM. The key advantage of ECMs is their simplicity. However, they are unable to predict relevant electrochemical states and parameters. The second category considers electrochemical models. Although these models can predict internal states, their complex mathematical structure prohibits controller/observer design. These approaches employ model reduction with estimation. Some of the first studies within this category used the SPM in combination with an extended Kalman filter[10]. Another approach uses residue grouping for model reduction and Kalman filters for observers[11]. The authors of reference 6 apply approximations to the electrolyte and solid concentration dynamics to perform SOC estimation. More recently, simultaneous SOC and SOH estimation was performed on a SPM using PDE-theoretic techniques[3]. Simultaneous SOC and SOH estimation using electrochemical models is in infancy, and represents a rich problem for dynamic systems and control researchers.

Adaptive PDE Observer for Single Particle Models

We present a simultaneous SOC/SOH estimation algorithm using adaptive PDE observer designs based upon a SPM. The SOC and SOH estimation problems can be cast mathematically as state and parameter estimation problems, respectively. That is, SOC can be defined in terms of the anode solid concentration $c_s^-(r,t)$ and SOH can be defined in terms of electrochemical parameters, such as moles of cyclable lithium n_{Li} and electrolyte resistance R_f.

Figure 5 summarizes the complete algorithm. Although the SPM is a relatively simple electrochemical model, it

Description	Equation	Eqn.
Solid phase Li concentration	$\frac{\partial c_s^{\pm}}{\partial t}(x,r,t) = \frac{1}{r^2}\frac{\partial}{\partial r}\left[D_s^{\pm} r^2 \frac{\partial c_s^{\pm}}{\partial r}(x,r,t)\right]$	(10)
Electrolyte Li concentration	$\varepsilon_s \frac{\partial c_e}{\partial t}(x,t) = \frac{\partial}{\partial x}\left[\varepsilon_e D_e \frac{\partial c_e}{\partial x}(x,t) + \frac{1-t_c^0}{F} i_e^{\pm}(x,t)\right]$	(11)
Solid potential	$\frac{\partial \phi_s^{\pm}}{\partial x}(x,t) = \frac{i_e^{\pm}(x,t) - I(t)}{\sigma^{\pm}}$	(12)
Electrolyte potential	$\frac{\partial \phi_e}{\partial x}(x,t) = -\frac{i_e^{\pm}(x,t)}{\kappa} + \frac{2RT(1-t_c^0)}{F}\left(1 + \frac{d \ln f_{\frac{c}{a}}}{d \ln c_e}\right)\frac{\partial \ln c_e}{\partial x}(x,t)$	(13)
Electrolyte ionic current	$\frac{\partial i_e^{\pm}}{\partial x}(x,t) = a_s F j_n^{\pm}(x,t)$	(14)
Butler-Volmer kinetics	$j_n^{\pm}(x,t) = \frac{2}{F} i_0^{\pm}(x,t) \sinh\left[\frac{\alpha F}{RT}\eta^{\pm}(x,t)\right]$	(15)
Temperature	$\rho c_P \frac{dT}{dt}(t) = h[T^{\infty}(t) - T(t)] + I(t)V(t) - \int_{0^-}^{0^+} a_s F j_n(x,t) \Delta T(x,t) dx$	(16)

TABLE 1 Main equations for the electrochemical model.

contains several notable challenges. These include *(1)* the PDE dynamics, *(2)* the nonlinearity imposed by estimating states and parameters together, and *(3)* the output function's nonlinear relationship with respect to both states and parameters. We take a cascaded design approach to address these issues. That is, we synthesize identification algorithms for uncertain parameters in the PDE state equation and output function. These estimates are then applied to a backstepping PDE state observer algorithm, using the certainty equivalence principle[3].

To demonstrate, we consider a vehicle-like charge/discharge cycle generated from two concatenated urban dynamometer driving schedule (UDDS) drive cycles. This signal is highly transient with large C-rate magnitudes, producing a sufficiently rich signal for parameter estimation. **Figure 6** portrays the state and parameter estimates using data generated from the DFN model summarized in Table 1. The state estimates are represented by bulk SOC and surface concentration, which converge to their true values. The PDE parameter estimates $\hat{\varepsilon}, \hat{q}$ and output function parameter estimates $\hat{n}_{Li}\ \hat{R}_f$ (normalized to one in Fig. 6) also converge near their true values. Similar results are achievable for various other initial conditions and charge/discharge cycles. The relative complexity of combined SOC/SOH estimation for the simplest of electrochemical models highlights the problem richness. Open research opportunities include algorithms based on higher-fidelity models, nonlinear estimation, novel sensing, and experimental verification.

TABLE 2 Electrochemical states to be constrained within upper/lower limits.

Variable	Definition	Constraint
$I(t)$	Current	Power electronics limits
$c_s^{\pm}(x,r,t)$	Li concentration in solid	Material saturation/depletion
$\frac{\partial c_s^{\pm}}{\partial r}(x,r,t)$	Li concentration gradient in solid	Diffusion-induced stress/strain
$c_e(x,t)$	Li concentration in electrolyte	Material saturation/depletion
$T(t)$	Temperature	High/low temp. accelerate aging
$\eta_s(x,t)$	Side reaction overpotential	Li-plating, SEI-layer growth

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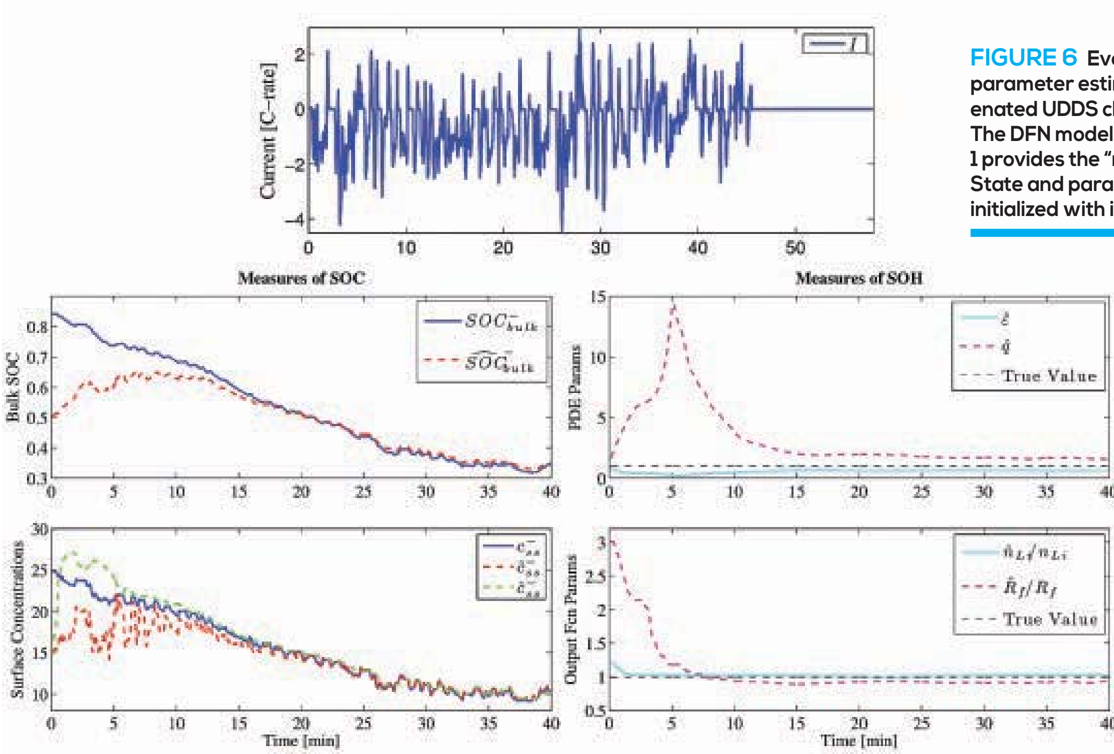

FIGURE 6 Evolution of state and parameter estimates for two concatenated UDDS charge/discharge cycles. The DFN model summarized by Table 1 provides the "measured" plant data. State and parameter estimates were initialized with incorrect values.

CONTROLLED CHARGING/DISCHARGING

Battery packs are typically oversized and underutilized to ensure longevity and robust operation. Indeed, oversizing mitigates degradation mechanisms, such as lithium plating, lithium depletion/over-saturation, overheating, and stress fractures by reducing C-rates. However, oversizing can be overly conservative. In this section we discuss concepts for eliminating this conservatism. Namely, constrained optimal control methods, such as reference governors (RG), enable smaller-sized batteries whose electrochemical states satisfy safe operating constraints.

Constrained Control

Ensuring safe operating constraints is a basic requirement for batteries. Mathematically, this can be abstracted as a constrained control problem for which RGs provide one promising solution. We seek to maintain operation subject to electrochemical state constraints. This protects the battery against catastrophic failure and maintains longevity, an issue underscored by the recent Boeing 787 Dreamliner battery failures[12]. A list of relevant state constraints is provided in **Table 2**. These limits are associated with material saturation/depletion, mechanical stress, extreme temperatures, and harmful side reactions, such as lithium plating and solid/electrolyte interphase film growth.

A reference governor is an add-on device that guarantees state constraint satisfaction pointwise-in-time while tracking a desired reference input[13]. In our "modified" reference governor (MRG) implementation, the applied current $I^r[k]$ and reference current are related according to

$$I[k+1] = \beta[k] I^r[k], \qquad \beta \in [0,1] \tag{17}$$

where $I[k] = I(t)$ for $\in [k\Delta t, (k+1)\Delta t]$, $k \in Z$. The goal is to maximize β such that the state stays within an admissible region over some future time horizon,

$$\beta^*[k] = \max\{\beta \in [0,1]: x(t) \in O\} \tag{18}$$

Variable $x(t)$ represents the electrochemical model state at time t and O is the set of initial conditions that maintain the state within the constraints listed in Table 2, over a future time horizon $\tau \in [t, t+T_s]$. See reference 14.

Figure 7 compares the standard constant current-constant voltage (CCCV) protocol, to an MRG that utilizes perfect estimates of the constrained states. CCCV applies 1C charging until voltage reaches a manufacturer-specified "maximum," 4.2V in this case. Next, CCCV regulates terminal voltage at the maximum voltage, 4.2V, while current diminishes toward zero. The value of 4.2V is selected to avoid lithium plating caused by overcharging. Mathematically, this corresponds to $\eta_s \geq 0$ in Fig. 7. Indeed, the side reaction overpotential remains positive, however it is conservative. Specifically, the side reaction overpotential can be regulated closer to zero. The MRG applies 1C charging subject to the constraint $\eta_s \geq 0$. In Fig. 7 the MRG maintains $\eta_s \geq 0$ despite voltage exceeding 4.2V. Moreover, the cell attains 95% SOC in 24min vs. 38min for CCCV. Note that CCCV reaches a final SOC of 96%, whereas the MRG achieves 100% SOC. Consequently, charging time is decreased by 37% and energy capacity is increased by 4%. Note that initial C-rates above 1C in the constant current region can further enhance performance beyond what is shown here.

One combines this MRG design with a state observer to form a complete output feedback ECC system (**Figure 8**). Several questions remain, such as robustness to estimation errors, forecasting reference current, optimal charge/discharge current trajectories, and experimental validation.

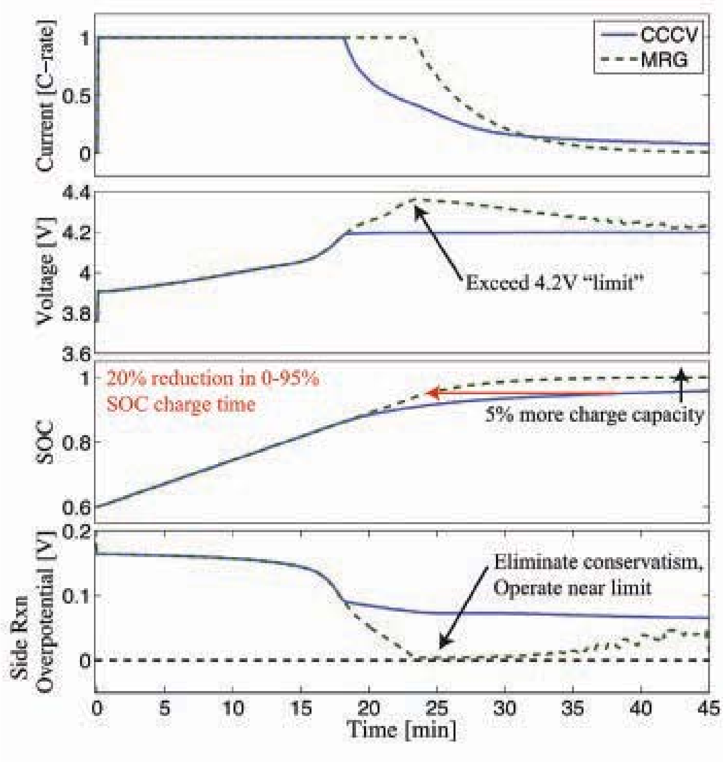

FIGURE 7 Comparison of CCCV and modified reference governor (MRG) charging. The MRG regulates near its limit, thereby achieving 95% SOC in 24min vs. 38min for CCCV, despite voltage exceeding 4.2V.

FUTURE OUTLOOK

Batteries play a prominent role in developing technologies to ensure energy security, enhance sustainability, and lower greenhouse gases. However, today's reality is that batteries are expensive and conservatively designed. Advanced control systems that optimize battery performance and longevity are a key enabler for reducing costs and catalyzing deeper penetration into transportation fleets and electric power grids. Namely, promising solutions exist at the nexus of electrochemical modeling and advanced control theory. The dynamic systems and control community is uniquely positioned to play a significant role, as batteries provide a rich opportunity for advancements in fundamental control science and emerging energy application areas.

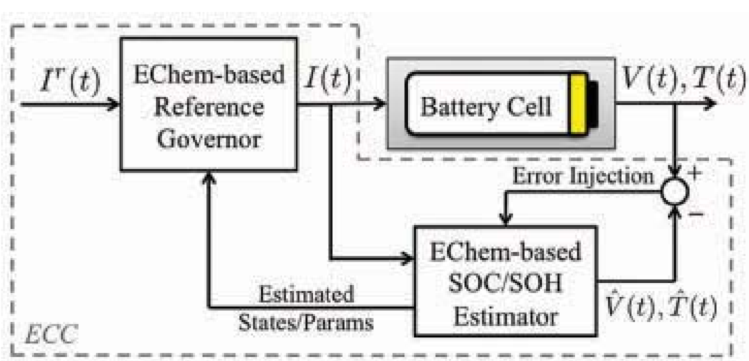

FIGURE 8 Block diagram of the ECC system comprised of a SOC/SOH estimator to determine the electrochemical states/parameters, and a reference governor to apply controlled charging/discharging.

ABOUT THE AUTHORS

Scott Moura is an Assistant Professor at the University of California, Berkeley (UCB) and Director of the Energy, Controls, and Applications Lab. He earned a Ph.D. (2011) and M.S.E. (2008) degree from the University of Michigan, and the B.S. degree from UCB in 2006 - all in Mechanical Engineering. He received the NSF Graduate Research Fellowship, a UC Presidential Postdoctoral Fellowship and has been honored as a Semi-Plenary speaker at the ASME Dynamic Systems and Control Conference. His research interests include optimal and adaptive control, PDE control, demand side management, and batteries.

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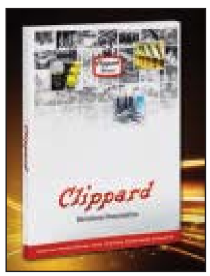

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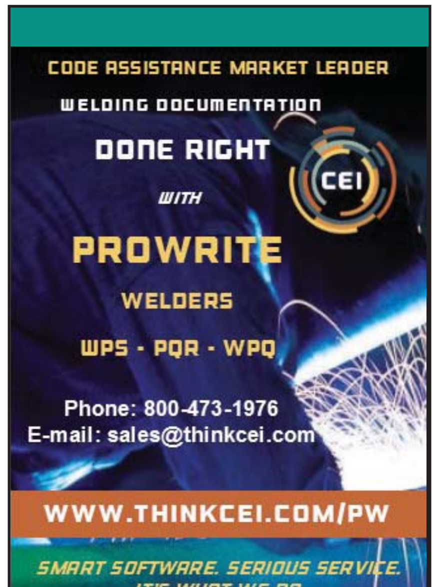

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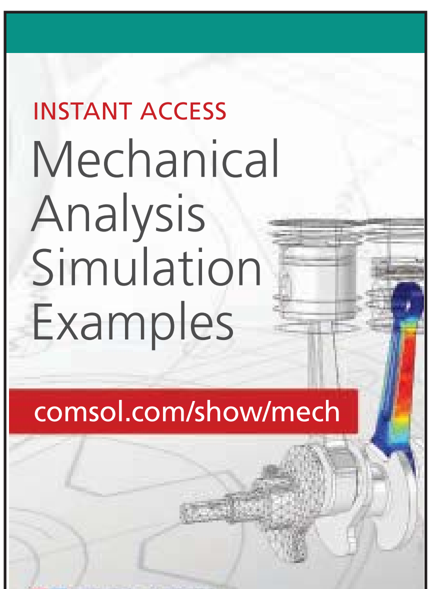

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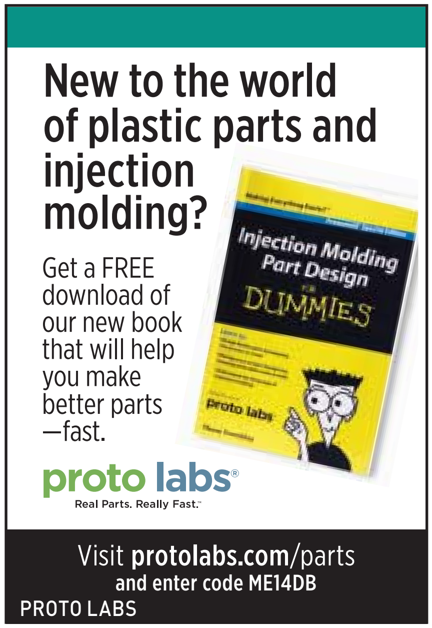
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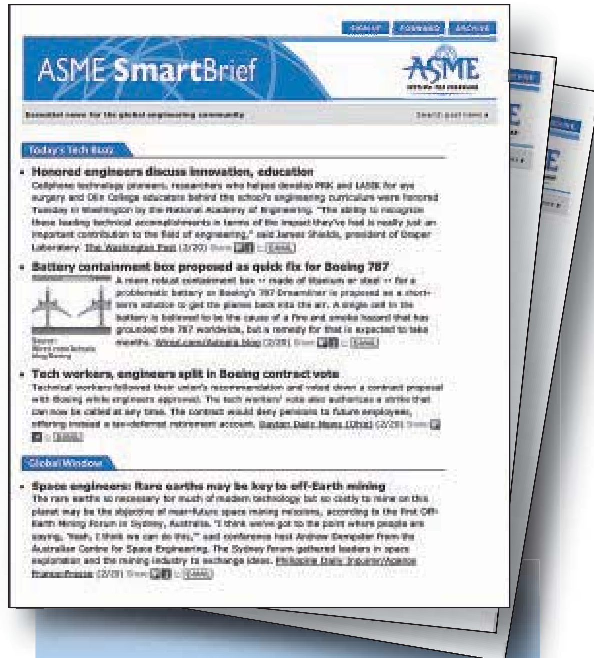

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UMASS TEAM WINS TOP

A TEAM CALLED NONSPEC FROM THE University of Massachusetts at Lowell won the top prize of $25,000 at the 2014 ASME Innovation Showcase. The team designed a low-cost, adjustable prosthetic limb for use in developing countries.

Team BiliQuant from Rice University won the $15,000 second prize, and the SmarTummy team from the University of Hawaii placed third for $10,000.

The event, also known as IShow, was held in April at the Newseum in Washington, D.C.

Now in its eighth year, IShow is supported by the ASME Foundation. The annual competition requires teams not only to engineer a useful product design, but also to deliver presentations and have entrepreneurial plans for marketing it. Cash awards are seed money to help the teams develop into companies.

Team Nonspec's design is a mass-producible limb that can be adjusted to individual patients. Because it is adjustable, the limb is particularly useful for children. It can be adapted as they grow, so they will need fewer replacements during their growing years.

SmarTummy is a medical training device, a manikin that simulates a number

ASME President Madiha Kotb (center) with members of the winning Nonspec team.

DISTINGUISHED ENGINEER OF THE YEAR: AL-MASOUD

NIDAL AL-MASOUD WAS PRESENTED ASME'S 2014 Distinguished Engineer of the Year Award upon the recommendation of the Central Connecticut State University Department of Engineering and the ASME Hartford Section. The event was sponsored by Pratt & Whitney and Belcan Engineering Group and hosted by Aaron Danenberg, a CCSU mechanical engineering alumnus and the chair of the ASME Hartford Section.

The annual award recognizes exemplary achievement and professionalism in the field of engineering.

Al-Masoud has a long record of dedicated service within the engineering department at Central Connecticut State University. He had a leading role in the creation of CCSU's mechanical engineering program—the first baccalaureate engineering program in the Connecticut State Colleges and Universities system.

Nidal Al-Masoud, left, receiving the award from Peter Baumann. Photo: ASME Hartford Section

Al-Masoud remodeled and developed engineering labs that focused on fluids, dynamics, and controls, and collaborated with fellow faculty members on a variety of publications.

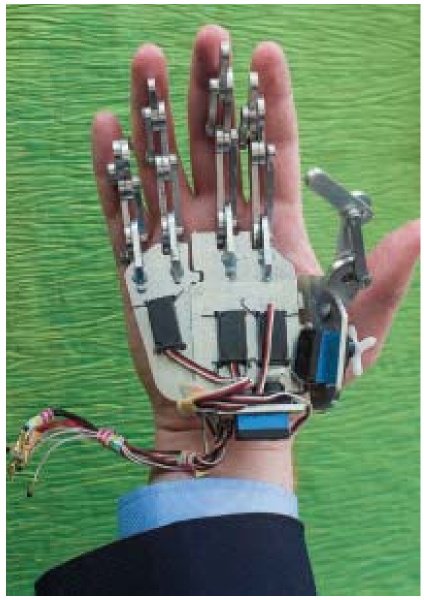
An active member of the Hartford section's scholarship committee, Al-Masoud remains the section's principal liaison with CCSU. **ME**

ISHOW PRIZE

of abdominal ailments. It can be used in training health care students to perform palpation exams.

Team BiliQuant developed a system combining microfluidics and optics in a device that can make low-cost diagnoses of jaundice.

A total of 10 teams from nine universities competed in the event. Information about IShow is available online at www.asme.org/events/competitions/asme-ishow. **ME**



This prosthetic hand is part of the low-cost, adjustable artificial limb system for use in developing countries that won first prize in the 2014 IShow.

BARRIER-BUSTING CAR NOW ASME LANDMARK

The *Thrust SSC* supersonic car was designated a historic mechanical engineering landmark at a ceremony in Coventry, England, in March.

The landmark designation recognizes the jet-powered car for being first land vehicle to surpass the speed of sound. In 1997, Royal Air Force pilot Andy Green raced the car to an average speed of 763.04 miles per hour over two mile-long runs at Black Rock Lake in Nevada, breaking the previous land speed record by 30 mph.

The vehicle was conceived by Richard Noble and designed by a team of British engineers led by Ron Ayers, Glynne Bowsher, and Jeremy Bliss, using computational fluid dynamics programs and wind tunnel testing. According to the plaque presented by ASME, the team "solved novel mechanical, aerodynamic, and control problems to design a car that properly managed complex dynamic forces, including those from reflected shock waves." About 100 people attended the event at the Coventry Transport Museum, including ASME President Madiha El Mehelmy Kotb, Executive Director Thomas Loughlin, and members of the Society's History and Heritage Committee and United Kingdom Section.

Addressing the audience during the presentation of the landmark plaque, Kotb emphasized the value of highlighting engineering innovations.

"I'm sure you will all agree that landmark programs are an important reminder of the heritage of engineering. They play an important role in promoting a greater public understanding of engineering and its place in civilization," Kotb said.

"By joining with fellow engineers, such as yourselves, and our partner societies in recognizing the historic importance of the *Thrust SSC*, we're reminded of how human ingenuity and the will to advance knowledge and innovation can impact the speed, evolution, and design of modern machines, while accelerating the progress and inspiration of modern industry and technology." ■

For more details, see: www.asme.org/about-asme/who-we-are/engineering-history/landmarks.

METROPOLITAN SECTION HEARS ABOUT MEGACITIES

NEARLY 100 ASME MEMBERS ATTENDED the President's Night Meeting of the Metropolitan Section in March, held at the National Grid building in Brooklyn, N.Y. Guest of honor President Madiha El Mehelmy Kotb discussed the continued growth of city populations worldwide. More than half the world's people live in cities, and 60 percent are expected to live in metropolitan areas by 2030.

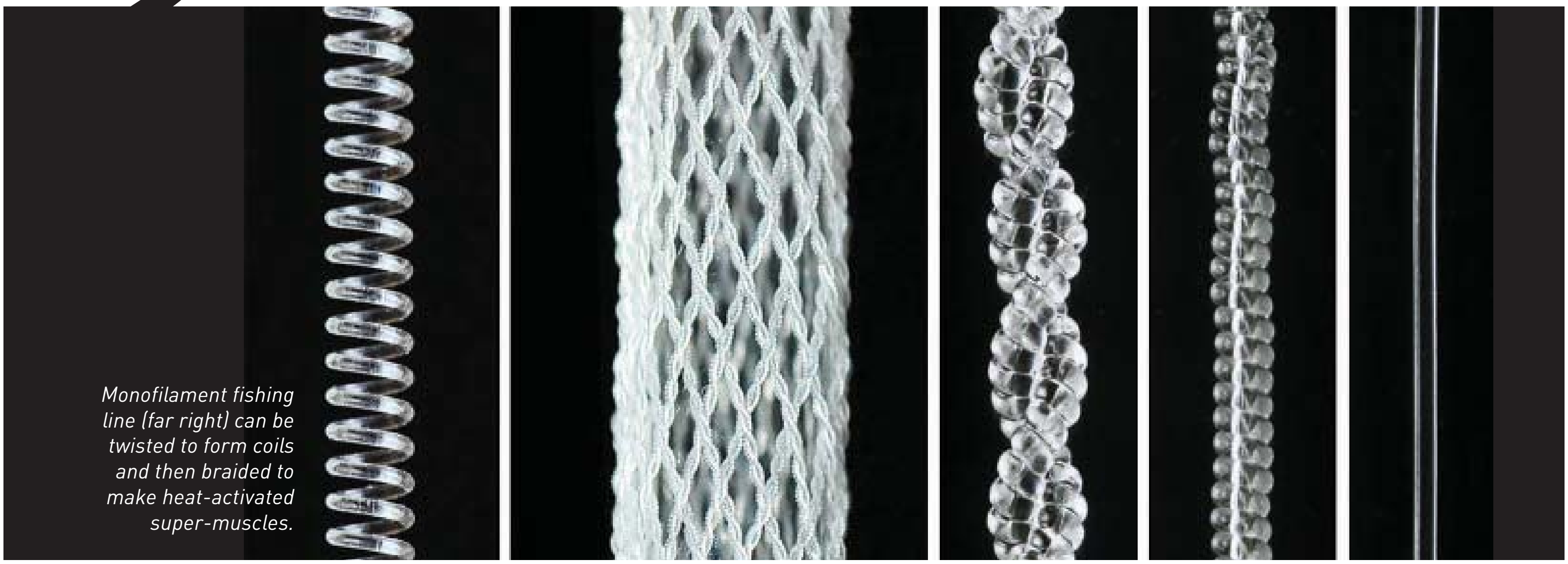
"As new cities emerge and existing cities reach high density, integration into smart grids, merging all systems for transportation, energy, water, and sewage is essential," Kotb said. "That's how we live and that's how engineers design. Preparing for the integration of future technologies is a challenge for existing cities."

Kotb spoke from experience about geographic diversity. She said that as an engineer born and raised in Egypt, currently living in Canada, and the first ASME president not from the United States, encouraging diversity within membership was a natural choice for an objective as president of ASME.

"Building geographic diversity is achievable through opening global access to ASME activities and also by building better interaction among sectors," Kotb said, pointing to the Society's work providing global access to its standards-setting process as an example of an activity that encourages greater international participation.

ASME is engaged in global initiatives such as international work groups and partnerships with organizations like the World Federation of Engineering of Organizations and the United Nations Educational, Scientific, and Cultural Organization. In addition, it provides translations of its standards and courses in Spanish, Chinese, French, Japanese, Korean, and Portuguese.

Other important society efforts to encourage global participation include the multi-society Engineering for Change partnership for solving global development problems, and ASME.org, which enables engineers around the world to make new connections, share information, collaborate in ASME Groups, and remain informed and up-to-date with advances within the profession, Kotb said. ■



Monofilament fishing line (far right) can be twisted to form coils and then braided to make heat-activated super-muscles.

IN THE MOVIE *THE TERMINATOR*, WHAT MADE THE LETHAL CYBORG NEAR INVINCIBLE— some sort of advanced hydraulics, shape memory alloys, or a currently undreamt-of nano-whatever—is left to the imagination. Recently, however, researchers unveiled a real-life artificial muscle material that pound-for-pound is 100 times more powerful than Arnold Schwarzenegger's right bicep.

It's made from fishing line.

After years of toiling with other, newer, higher-tech materials, researchers at the University of Texas at Dallas have shown the world how to make a powerful, cheap, artificial muscle out of the same stuff we use to build mobiles for our kids or, yeah, haul trout out of the creek.

POWER LINES

For decades researchers have searched for a material to make cheap but powerful artificial muscles. They've found it in a tackle box.

Ray Baughman, the lead researcher on the project, had been studying all sorts of exotic material in search of a perfect artificial muscle. His team had been toying with carbon nano-fibers (price tag: $10,000 a pound) when he decided to try the sportsman's polymer line.

"We never thought it would work," Baughman said. "The idea that you can take something cheap and readily available and immediately convert it to a muscle that gives wonderful performance is contrary to reason."

Turns out the trick is how you coil the stuff.

Twist fishing line, or any other stringy thing, and you'll get some torsional energy back when it untwists. That's what powers a rubber band airplane. Keep twisting and the strands start to loop over on themselves to become a coil. (Remember a telephone handset cord? It looks like that.)

Heat the coil, and the added energy causes the helix to tighten and compress. As it cools, the coil relaxes again and gets longer.

The power of the contraction is startling: 16 horsepower per pound, about five times what's produced by an internal combustion engine, more in line with a jet engine. An artificial muscle made from coiled polymer filament—not just fishing line, but also polyester thread and similar stuff—would produce 100 times more power than meat muscle of the same weight and length.

The polymer coils also beat biology in another way: The more weight being lifted, the stronger the pull. "With most muscles, their stroke decreases with increasing load," Baughman said. "The work we can do increases as we apply higher loads—until we break the muscle."

Baughman said the list of possible applications for such mega muscles is long. The coils could recover energy from any system where there's waste heat to be harvested. The heat rejected from a car's engine could be converted right back to mechanical energy. In other situations, macro and micro, a wire or chemical reaction could activate the springs. Labs on chips, for example, need tiny pumps and valves—soon they could be activated with tiny artificial muscles. Exoskeletons, remote control surgical devices, and automatic window blinds and vents are just a few of the places likely to profit.

And, of course, there are the robots. "When I was in Korea I met a very beautiful woman," Baughman said. "When I got close to her she wasn't that beautiful. She was Eve, a humanoid robot, but she didn't have enough muscles in her face to smile or frown properly. How do you do that with motors? With muscles it's trivial."

While there are few parts of a robot that couldn't use the fishing line muscle, don't expect to find it replacing any biceps, triceps, or masticatorii in the human body any time soon.

"There is this problem—you have to dissipate the heat," says Baughman.

"You've got blood. You can't heat up the blood very much." ME

MICHAEL ABRAMS is a frequent contributor to *Mechanical Engineering*. He lives in New York City.

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