MECHANICAL ENGINEERING

THE MAGAZINE OF ASME

No. 12

139

Technology that moves the world

EMERGING TECHNOLOGY AWARDS

RAISING THE CURTAIN ON INNOVATION

Bioengineering • Robotics • Manufacturing
Pressure Technology • Clean Energy

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CYBORG DRAGONFLY TAKES THE AIR

SWARMS OF TINY, INSECT-LIKE ROBOTS may someday do our dirty work, taking air samples in hazardous or inaccessible environments, searching out survivors in disasters, and maybe even hunting down an enemy. In recent years roboticists have made great strides in producing miniscule flyers that might perform such jobs. Now researchers at Draper Laboratories are manipulating the neurons of dragonflies and fitting them with a tiny guidance and navigation system to produce a bugborg.

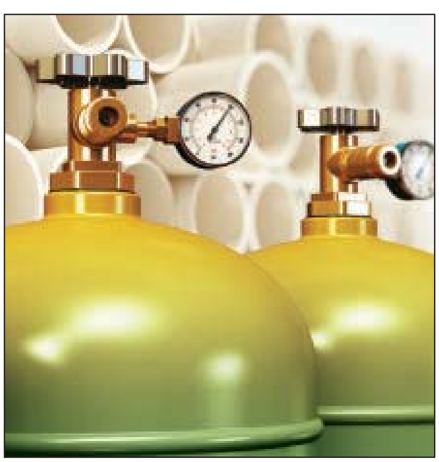

Image: ASME.org

TURNING CO_2 INTO A GOOD GUY

Manufacturing polyethylene terephthalate (PET) and other plastics produces significant amounts of carbon dioxide, a greenhouse gas that contributes to climate change. For example, using fossil-fuel feedstocks generates more than four tons of CO_2 for every ton of PET that is manufactured. To improve this situation, scientists are turning the gas into a manufacturing asset by using it as a feedstock for plastics, thereby reducing greenhouse gas emissions.

ROBOTIC TECHNOLOGY COMES TO HOMEBUILDING

3-D PRINTING, AUTO-ROUTING, ARTIFICIAL INTELLIGENCE, and other technologies are transforming the work of home contractors and construction workers, disrupting what has long been a very traditional field. This is changing the day-to-day work of professionals in fields that have been seen as averse to digital technology.

SENSORS ARE MAKING CYCLING SAFER

A TEAM CURRENTLY WORKING at the University of Minnesota hopes to create a warning system to protect bicycles from motor vehicles, providing a respectful and safe transportation environment.

Rajesh Ramani, a professor of mechanical engineering at the school, says just as some cars have collision-prevention systems, there isn't a reason why there can't be a corresponding one for bikes.

Image: ASME.org

NEXT MONTH ON ASME.ORG

HUMAN-ROBOT COLLABORATION AT BMW

Five years ago, automaker BMW began letting down some of the protective fences that separated robot from human. Now, about 60 collaborative robots do heavy lifting and repetitive tasks to save wear and tear on human muscles.

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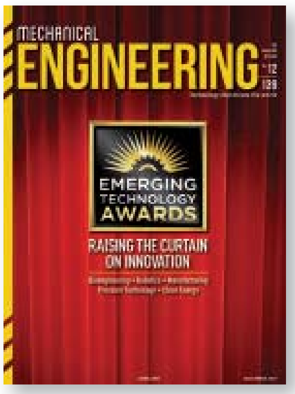

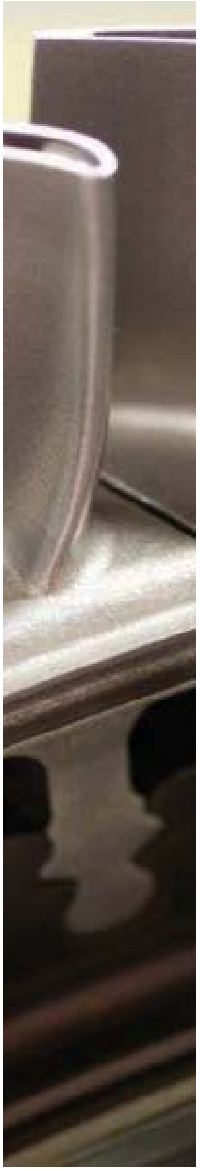

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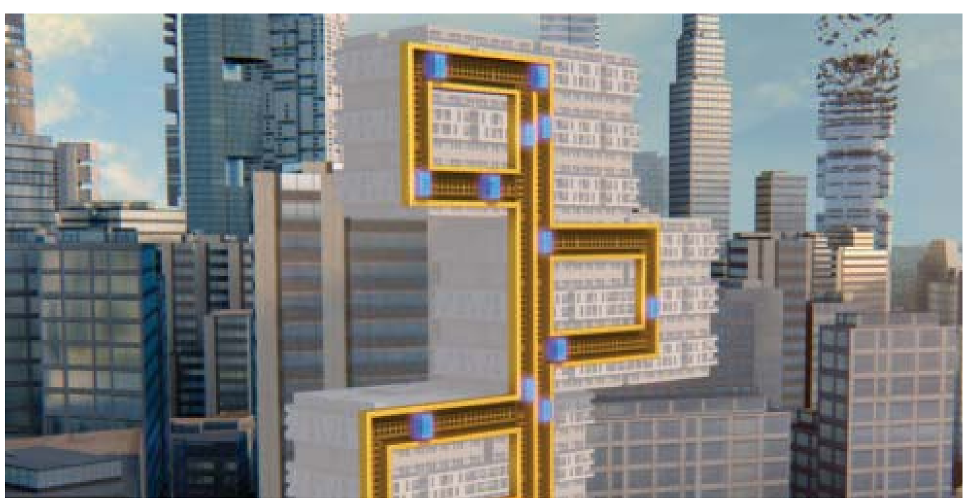

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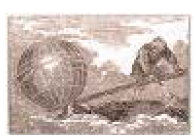
Give me the place to stand, and I shall move the earth
—Archimedes



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John G. Falcioni
Editor-in-Chief

OUR FIRST EMERGING TECHNOLGY AWARDS

Next month, we begin volume 140 of *Mechanical Engineering* magazine. Yet, for a publication with such a long history, we take pride in our steady focus on the future. Every month, we write about emerging technology and its impact on society.

In presenting our first-ever Emerging Technology Awards this month, we've taken the bold step of celebrating five ascending technologies that we believe will revolutionize the world.

Since the start of this year, our editorial team has researched, debated, and ultimately decided on the companies and individuals to spotlight in this issue. The project lead was Senior Editor Jeffrey Winters, who masterfully juggled assigning articles—including an essay by celebrated author Henry Petroski—with video, illustration, and editing deadlines.

The achievements we have selected are not the only ones in the world breaking new ground, as numerous companies and individuals are doing work that is transformative. With these awards we focus on the areas that ASME's Board of Governors identified as important for the organization: manufacturing, robotics, bioengineering, clean energy, and pressure technology. Those we call out in this issue have stirred our imagination this year and make us curious of the impact they will have for years to come.

The *Mechanical Engineering* magazine Emerging Technology Award for Manufacturing goes to Siemens, for its revolutionary 3-D printed turbine blade that can withstand the heat and stress found inside a gas turbine.

The award in the area of Bioengineering goes to MIT innovator Hugh Herr for his powered foot-ankle prostheses with multiple tendon-like actuators. His advanced prosthetic limbs may one day enable people to exceed the capabilities of their natural body parts.

The award in the area of Robotics goes to Mobileye, now part of Intel. Its technology provides the capability for autonomous vehicles to detect and avoid obstacles and other vehicles, with a system so small that it fits on a single silicon chip.

The award in the area of Pressure Technology goes to Babcock & Wilcox for its ultra-supercritical boiler, which withstands very high pressure and temperatures, enabling the plant to operate at a net efficiency of better than 39 percent. That means it burns less fuel than standard coal-fired boilers while releasing 17 percent fewer CO_2 emissions.

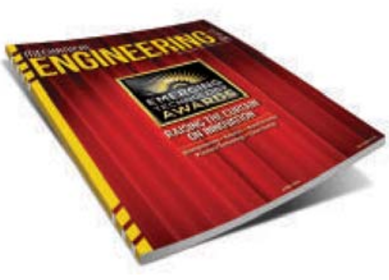
The award in Clean Energy goes to Tesla Motors for optimizing the chemistry and manufacturing process to bring down the cost of lithium-ion battery packs. Improved energy storage will help speed electric-powered cars and trucks to the mass market, and may profoundly alter the automotive industry.

Please visit ASME.org to view the videos we've produced on this year's emerging technologies. They will leave you inspired and motivated, much as they've left us. We salute each innovation and innovator. ME

FEEDBACK

Tell us which projects, individuals, and companies we should keep an eye out for next year's awards. Email me.

falcionij@asme.org



LETTERS & COMMENTS

OCTOBER 2017

Reader Vreeman says forecasting is valuable even if the projection is off.

« One reader extols the benefits of a waste-burning reactor, while another finds great value in outdated technological projections.

FUZZY PROJECTORS

To the Editor: Thank you for continuing to publish past contributions to *Mechanical Engineering* in the Vault. Your look back 40 years in the October 2017 issue ("New Career Paths in Engineering: Applications of Solar Energy" by Lloyd O. Herwig) provided a great reminder of how often the economic viability of up-and-coming technologies are only 10 to 20 years away, to which an experienced engineer might add with a smile, "And they always will be."

Acknowledging that forecasts of economic viability are often wrong is not a criticism of such projections per se. To his great credit, Herwig stated that the projections he cited in 1977 were themselves based on forecasts of "technology development and competing alternative fossil and nuclear-fueled plants."

Absent a crystal ball, how would he or anyone else at the time have imagined the events that would lead to a generations worth of low cost energy at the very height of a widely perceived energy crisis?

What is so frequently misunderstood about projections is that their benefit lies less in their accuracy a decade or two later, but rather in the work of developing and maintaining the projections in the first place.

Forecasting requires gathering data, challenging assumptions, and estimating risks, which can then be used to develop contingency plans, enabling us to respond quickly in the face of uncertainty. At the same time, we do ourselves a disservice when we either unquestioningly believe our projections, investing too much in their accuracy over the long haul, or dismiss them outright because "they are always wrong."

Studying what our predecessors assumed, what they believed, and the choices they made, is a great way to honor their contributions. It is also a great way to keep us grounded in the face of a predictably uncertain future.

Chris Vreeman, *Greenville, S.C.*

SPENT FUEL AS A RESOURCE

To the Editor: I am always amazed by the endless number of Rube-Goldberg clean energy schemes that scientists and engineers come up with. A prime example is "Electrofuels" by F. Todd Davidson, Kazunori Nagasawa, and Michael E. Webber in the September 2017 issue.

We already possess an existing non-carbon energy source that has been mined, processed, and can easily be converted into a 500 year supply of electricity to power our country and our transportation systems. That energy resource is the spent nuclear fuel that resides at each and every nuclear power plant in the U.S.

That resource can be tapped via the GE-Hitachi PRISM reactor, a fourth-generation advanced reactor system that can convert spent nuclear fuel into electricity while consuming 95 percent of it in the process.

PRISM technology is a perfect waste-to-energy system that has been proven at the 24 MW pilot scale at Argonne West in Idaho using billions of our tax dollars. PRISM technology is—and has been—ready for commercial-scale demonstration since 1994.

What are we waiting for? This is a question that all of us need to ask our Senators and Congressional representatives.

Bob Balhiser, *Helena, Mont.*

OUT OF GAS

To the Editor: In the August 2017 Trending ("By the Numbers: Born to Run," by Jeffrey Winters) the Honda Civic performance history is inaccurate. For example, the current Civic has either a 1.5 l turbo 174 hp engine that gets a combined 36 mpg gas mileage or a 2.0 l non-turbo 158 hp engine that gets 36 mpg. This is not consistent with the 1.0 l 127 hp engine at 59 mpg that you listed.

Aaron Tanzer, P.E, *Glendale Heights, Ill.*

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

3-D DESIGN WITH A TWIST

TELESCOPING OBJECTS COULD TAKE ON MYRIAD SHAPES AND TASKS

Imagine a little robotic dinosaur that shrinks down small enough to fit through a gap at the bottom of a wall and then redeploys at full scale on the other side. Or, perhaps a curved claw that stretches out over a mound of rubble to save a teddy bear trapped in a fire.

Those are just some of the many possibilities for a new way of making collapsible devices based on curved telescoping parts. Think of them as the unexpected progeny of a pirate's telescope and Marvel superhero Wolverine's retractable claws.

"Telescope" entered the English language around 1650 as a noun to describe an optical instrument that magnifies distant objects. Once sailors began using easily stored telescopes, the noun became a verb to describe the linear extension of any set of nested cylinders into a longer object. Today, telescoping parts are used in everything from camera tripods and antennas to baskets, and, of course, telescopes.

Seeing Wolverine's retractable claws at a Maker Faire inspired Keenan Crane and Stelian Coros to put a new twist on telescoping parts.

The two are assistant professors of computer science and members of the Robotics Institute at Carnegie Mellon University. After seeing the claws retract, they began to wonder how many different types of objects they could make by using curved parts that bend and rotate as they telescope.

"It was an interesting moment for us," Crane said. "The artist had figured out one way to do it, but we wanted to know all the possible ways you could possibly hope to do it."

The answer, it turns out, is a lot.

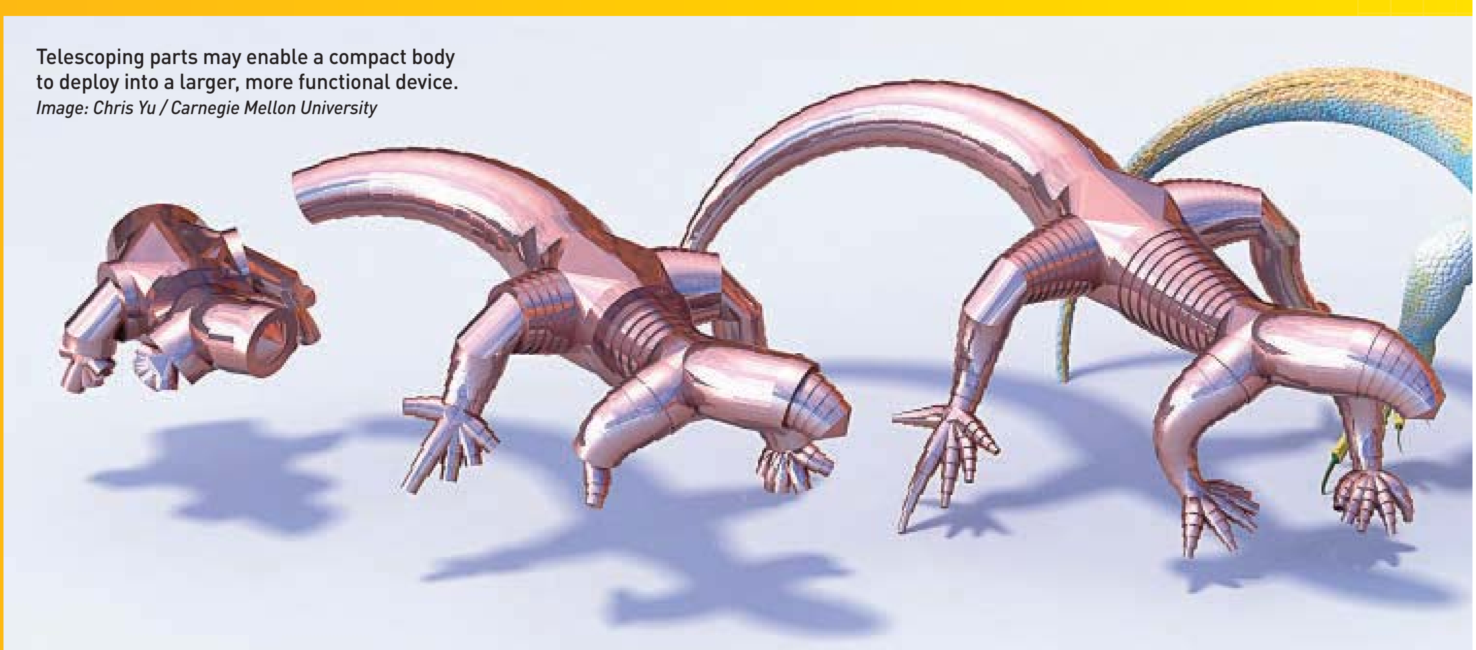
"Any space curve of constant curvature can be a telescope," Crane said.

Working with Christopher Yu, a doctoral candidate, Crane and Coros developed a way to automate the design of telescoping structures.

Their mathematical model for telescoping structures started with a few assumptions: Each shell must be manufacturable from rigid material such as metal; it should extend and contract without bumping into itself; and there should be no empty wasted space between nested pieces.

Their work on the model led to a key geometric insight. Both simple pirate telescopes and the most complicated telescoping objects can be defined by simple geometric curves that exhibit a constant amount of bend and one or more arbitrary twists.

Crane likens that to a clump of instant



Telescoping parts may enable a compact body to deploy into a larger, more functional device.
Image: Chris Yu / Carnegie Mellon University

ramen. All the noodles curl and bend by roughly the same amount, but they all twist in lots of different ways. This accounts for their bountiful variety of shapes.

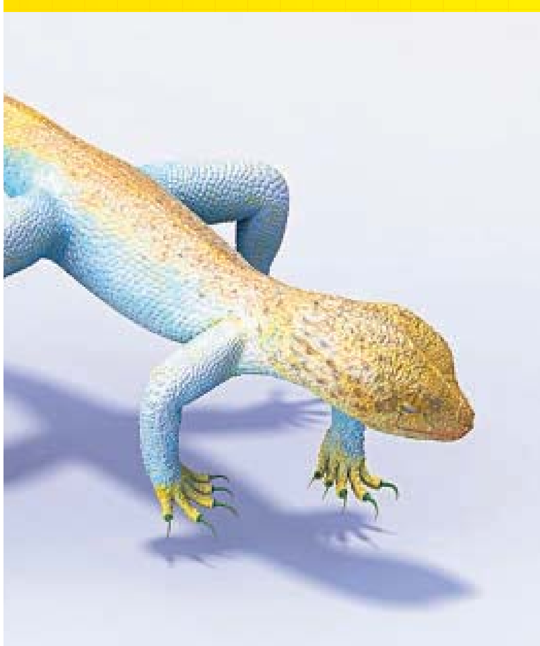
They tested the model by simulating a metal salamander-like lizard that collapses into a package that looks something like a complex gear box. Other simulations included the shrinking dinosaur and teddy-bear-saving claw.

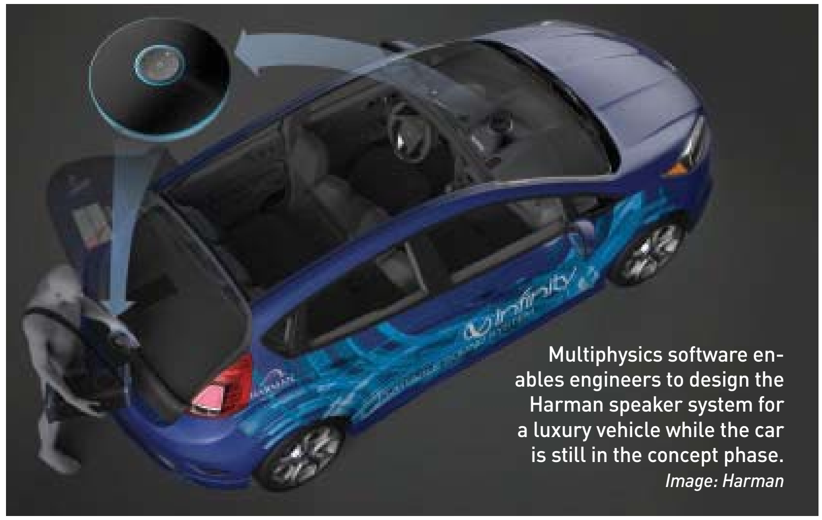
They also prototyped several structures using a 3-D printer, including a flexible robotic arm and a hard-surfaced tent that expands to several times its original volume.

Telescoping structures also expand the production capacity of 3-D printers. "You can print a much bigger structure than your normal 3-D printer would allow, because when you take it out, it deploys to a greater volume," Crane said.

With so many possibilities, Crane and Coros are looking for collaborators with ideas about how to control these devices. Because, thanks to their simulations, it does not take a telescope to see that potential applications are closer than ever. **ME**

MEREDITH NELSON is a technology writer in New York City.





Multiphysics software enables engineers to design the Harman speaker system for a luxury vehicle while the car is still in the concept phase.
Image: Harman

ENGINEERING THE PERFECT SURROUND SOUND

No doubt you've been surrounded by a subpar automotive sound system at some time in your life. You know how it goes: the speaker in the driver's-side door vibrates with a plastic sound, another speaker buzzes and sizzles when the bass kicks in.

Engineers at Harman take every step possible to provide an immersive automotive sound experience, with the goal of keeping the music rich and resonant. Harman, of Paris, equips more than 80 percent of the world's luxury cars with audio systems, said Michal Bogdanski, Harman's project leader for virtual product development.

To determine how its automotive customers should configure their sound systems for the best acoustical performance, the Harman team calls upon physical experiments and numerical analysis in conjunction with multiphysics modeling tools from Comsol. These tools allow engineers to virtually "tune" the acoustics systems, even before they have access to an actual automotive prototype.

Engineering the perfect automotive surround sound is difficult due to the number of parts that come together to create the overall acoustical system and its sound. If they're not in sync, distortion, vibration, and other jarring noises result, said Michael Strauss, Harman's senior manager of virtual product development and tools.

"Car cabin simulations are among the most challenging because they include many different areas of physics," he added.

Interactions that could create unwanted noise can happen at many points of contact: between speaker components, including the motion and acceleration of the speaker membrane; between the speaker and its enclosure; between the speaker and the car door and its components. To study those interactions, engineers must run mechanical, electrical, and acoustical models, said Francois Malbos, senior acoustics engineer at Harman.

Along with component interactions, another element comes into play: engineers need to determine how to best configure the system, including the placement and orientation of speakers. Each vehicle model calls for a different configuration for what Malbos calls the best "sound feel" inside the car.

The acoustical model depicts the objective sound feel: the pleasant

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VINE-LIKE ROBOT GROWS TO THE RESCUE

Robots leap, robots creep, robots fly, robots crawl. It seems that every robot to emerge from a robotics lab is inspired by the locomotive method of one of the world's clever beasts, be it bee, galago, cheetah, or octopus. But each of these machines has its limitations. If they are large they are stymied by smaller crevices. If they are small, they are limited by the power they can carry.

To overcome the difficulties faced by the fauna-inspired robots of the world, researchers in the department of mechanical engineering at the University of California, Santa Barbara, have turned to other life forms: plants and fungi. Rather than traverse ground and space as a single unit, their robot grows from place to place.

"IT CAN GROW THROUGH NAILS BECAUSE THE BODY DOES NOT MOVE."

ELLIOT HAWKES, UC SANTA BARBARA

"I remember watching, over many months, an ivy plant on my bookshelf grow around the corner, seeking the sunlight," said Elliot Hawkes, the project's lead researcher and a professor of mechanical engineering at the university. "I thought that, in a certain, very slow way, it was going somewhere. At the same time, I was working on pneumatic artificial muscles in the lab, and I was able to modify the standard stretching behavior to get tip-based extension. I realized we were on to something when I attempted to grow an early prototype through the complete mess that is my desk, and against all odds, it easily passed through the clutter."

Hawkes' ultimate creation looks something like an absurdly long version of one of those slippery, slightly disturbing water snake toys. "We found these after the fact, but the eversion at the tip is very similar. Unlike the toy, it is not a loop though, so we are actually able to change length and 'grow,'" he said. Hawkes' tube extends at the closed end and is filled with air at the open end. As the tube elongates, new material appears at the tip from the inside of the tube, while the outer walls stay put. By altering the pressure, either side of the tip can be lengthened, allowing it to turn. A small camera that stays at the tip enables the navigators to tell it where to go.

Made of polyethylene, the winding robot can squeeze into the tightest of corners.
Image: L. H. Blumenschein and E. W. Hawkes

Made of polyethylene, the winding anguine bot can squeeze into the tightest of corners and take all kinds of abuse. "It can grow through nails because the body does not move with

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These solar panels help power a school in Malawi.

A VISUAL INSPECTION GUIDE TO DETECT FAULTY SOLAR PRODUCTS

Stores in Malawi and likely other developing countries carry defective, and even fraudulent, solar photovoltaic panels. In places where quality standards are not enforced or do not exist, stores and suppliers can sell faulty products to poorly informed consumers. Used solar panels, broken panels, poorly constructed panels, and even fake panels with paper made to look like PV cells can have price tags that equal those of new panels in good condition.

Kristine and Michael Sinclair noticed the problem during a trip to Malawi.

"I'm an engineer and my wife is a solar physicist, both with a specialization in solar technology. We spent three months in Malawi and were astonished at the poor quality of the modules for sale," Michael Sinclair said.

"We met with government officials in charge of customs control to see if there were any quality standards in place, any systems in place to help them mitigate this problem of people selling modules that are of a predatory quality. And the answer is there's nothing," Sinclair said.

Fortunately for consumers, solar panels are unusually well-suited for visual inspection.

"That works for solar because panels are transparent to light so you have to be able to see in. This wouldn't apply to a battery or a solar home system because in a panel the guts are on display," Michael Sinclair said.

The Sinclairs created a visual inspection guide to help protect consumers.

"Anybody without a formal education could look it over and tell a good module from a bad one. Ideally, if you had no education in this you might want to attend a seminar, and we did that with students. At the end they felt able to use the guide to tell good modules from bad modules," Michael Sinclair said.

The International Electrotechnical Commission (IEC), which assesses standards for electrotechnologies, is in the process of publishing this guide as a publicly available specification.

The guide is designed for the visual inspection of front-contact poly-crystalline and monocrystalline silicon solar PV modules, helping the inspector detect major defects. The Sinclairs wrote that their guide should supplement international testing standards, but not replace them.

"A lack of visually observable defects is necessary but not sufficient to determine if a module would pass IEC 61215 testing," the Sinclairs wrote.

"Many consumers and retailers are not aware of the presence of significant visually observable defects that may limit performance and/or lead to premature product failure... This document was designed with the intention of being a quick tool that is inexpensive to implement, as it does not require any test equipment. Although helpful, no prior knowledge of solar photovoltaics is required to benefit from this guide, and an inspector should be able to be trained in its use in two days or less," the Sinclairs wrote. ME

ROB GOODIER is managing editor at Engineering for Change. For more articles on global development visit www.engineeringforchange.org.

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ENGINEERING THE PERFECT SURROUND SOUND

acoustical sounds—the thrilling highs and lows—users are likely to get when driving or riding in a particular car.

To gauge how the system will work and sound, engineers needs to virtually simulate and model how the three physical phenomena would act, together, in the real world.

For this, Harman uses Comsol multiphysics software, which simulates the way the phenomena act independently and interact together. All this is done digitally. After running an initial simulation, engineers perfect design elements and layout, then resimulate until they've found the perfect component design and layout, Malbos said.

"Then, during the development of the full sound system, we support different divisions or engineering teams in optimizing specific components like a loudspeaker," he added. "We help the system engineers find the perfect location for the subwoofers or other transducers.

"We can explore how the acoustic behavior of a loudspeaker relates to any part of a vehicle structure—for example, the stiffness of a door—and then provide design guidelines to our customer," Malbos said.

The multiphysics tool is important because engineers can begin acoustical and mechanical modeling when the car is still in the "concept phase," meaning "when the complete physical prototype isn't yet available," Malbos said.

Then there's what Malbos called the "third bubble," the subjective feedback Harman engineers and the automakers get by actually listening to the acoustical setup, even if the car hasn't yet been produced.

Engineers can set up a playback system based on simulation results and signal processing to let engineers and clients listen, evaluate, and compare any optimized audio system, including subwoofers, midranges, and tweeters, Malbos said.

These listening tests have shown that this approach to modeling and playback can successfully replace actual in-situ listening, he added.

So next time you're driving with the radio blasting—whether it's classical or talk—remember the details that have gone into attaining your listening experience. **ME**

JEAN THILMANY is a writer based in St. Paul, Minn.

RE-ENGINEERING THE FUTURE

Codes and Standards in an age of technology ecosystems

ASME published its first Boiler & Pressure Vessel Code (BPVC) more than 100 years ago, and we have been updating it ever since. Yet even the seemingly staid BPVC—as well as many other codes and standards—must race to keep up with rapid changes in applications and technology. In fact, the BPVC illustrates how ASME is reimagining the way our codes and standards might spur the adoption of new technologies while ensuring safety and reliability.

ASME adopted the BPVC to prevent boiler explosions at a time when small boilers powered individual factories, generators, and trains. Since then, boilers have grown larger and more complex as they strain to achieve greater efficiency.

This is especially true for the boilers that generate electricity in today's densely packed cities, which are growing in both wealth and size—China's Pearl River Delta, for instance, has more residents than Britain or Italy. Urban residents demand more and more power to heat, cool, move, and inform. Moreover, the cities themselves are growing smarter, using cloud analytics and IoT sensors to manage traffic, lighting, and water and deliver services autonomously.

Electricity is the lifeblood of the modern city. Yet when it comes to energy sources, there are more options than ever. These range from coal and natural gas to nuclear and renewable technologies. Aligning and balancing this mix with a fluctuating demand will remain an ongoing challenge.

Because the output of renewables often varies with wind speed or sunlight, reliable baseload power will remain crucial for many years to come. Coal will remain part of that baseline mix—as long as engineers continue to boost efficiency and slash pollution.

Supercritical boilers, which operate at temperatures and pressures high enough to transmute water into steam without boiling, address some of these needs. They push efficiency levels above 40 percent, compared with 33 percent for coal-fired plants globally, and reduce carbon emissions by 3 percent for every 1 percent gain in efficiency.

To accommodate the extreme conditions in supercritical and ultra-supercritical boilers, there are projects underway to revise the BPVC to address continued and expanded use of design by analysis methods at elevated temperatures, and assemblage and analysis of data for elevated temperature materials properties. This will provide a firm foundation to support initiatives such as advanced ultra-supercritical fossil power generation and Generation IV high temperature nuclear reactors. ASME is building on this work to set standards for the next generation of ultra-supercritical boilers, whose higher temperatures and pressure could lift plant thermal efficiencies to 50 percent.

In the past, this might have been the end of the story. But disruptive technology, chiefly digital, means mechanical engineers must think more broadly. After all, real-time digital controls make next-generation efficiency targets possible. One such system lifted Germany's RDK-8 ultra-supercritical power plant to a world record 47.5 percent thermal efficiency in 2015. Other facilities near those efficiency levels by combining cloud analytics with real-time digital controls.

Even more changes loom over the horizon. Digital controls and sensors, for example, enable Denmark's Avedøre Power Station to switch between such fuels as coal, natural gas, oil, and biomass. They keep 600 mirrors reflecting sunlight onto pressurized columns to generate supercritical steam at Australia's CISRO Energy Center.

Digital technology, in the form of high-fidelity computer models, is also blurring the divide between the digital and physical worlds. Designers already use realistic models to simulate thermomechanical behavior over a broad range of operating conditions. They hope to one day use similar models to verify and validate boiler and pressure vessel designs.

In the past, standards-making organizations like ASME focused on the things we knew best, like material and weld properties and thermal transfer. Today, we need to broaden our outlook to include new and disruptive technologies.

Whether it is pressure technology, clean energy, bioengineering, robotics, or manufacturing, disruptive technologies ranging from Big Data to IoT and nanoscience, are reshaping all of ASME's core technologies. Our best response is to think of these fields, not as individual technologies, but as ecosystems of rapidly evolving interrelated technologies.

Codes and standards like BPVC will continue to remain important. Yet we must also embrace ways to serve our members faster, whether with best practices and interim guidelines or training and technical events. Only then can we fulfill the promise behind ASME's first boiler code: a safer and more reliable way to engineer the future. ME

THOMAS G. LOUGHLIN, CAE, is Executive Director of ASME.

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VINE-LIKE ROBOT GROWS TO THE RESCUE

respect to the environment," Hawkes said. "This means that if a nail pokes it, the hole is sealed by the nail. This is in contrast to a body that locomotes, which would be gashed by the nail." It can also squeeze between a sandwich of flypaper, expand through a trough of glue, and travel through a slit less than a sixth of its inflated size. To make their "grow-bot" even more indestructible, Hawkes and his team are experimenting with other materials such as kevlar and rip-stop nylon.

These feats make it the ideal rescue tool. Hawkes' lab has already demonstrated how the robot can be used to sneak under a door and into a room, where it can bend like a hook to shut off a valve. It's also wormed its way into a closed room and successfully put

THE SOFT ROBOT CAN GROW INDEFINITELY BUT FOR NOW, IT STOPS AFTER ABOUT 100 YARDS.

out a fire there. A smaller version may someday guide catheters during surgery.

In theory, the soft robot can grow indefinitely: As one roll of tubing comes to an end, it could be attached to a fresh roll. But, at the moment, the robot stops growing around 100 yards, regardless of how much tubing is available. "The friction of pulling the new material through starts to get hard to overcome," said Hawkes. "We are looking at new, lower friction options that can hold higher pressures, so we might be able to go quite a bit further in the near future."

With a stronger, longer, growing robot, there may be no emergency that can't be reached. Hopefully, the rescued won't be terrified by the appearance of a cycloptic, ever-extending, polymer digit. ME

MICHAEL ABRAMS is an independent writer. For more articles on robotics visit www.asme.org.

"MOOCs are a failed product, at least for the goals we had set for ourselves. Our mission is to bring relevant education which advances people in careers and socio-economic activities, and MOOCs aren't the way."

Clarissa Shen, vice president and managing director for the Asia Pacific region at Udacity, as reported in the Economic Times of India *on October 6, 2017.*

Q&A
ROBERT LANGER

MIT'S ROBERT LANGER is arguably the world's most celebrated engineer. In addition to winning nearly every major engineering award in the world, he pioneered controlled release drugs, transdermal drug delivery, targeted cancer medications, and tissue engineering. He is one of a handful of leaders who turned engineering into an integral part of biology and medicine. Yet it was never easy.

ME: How did you wind up working on cancer?

R.L: I wanted to make an impact. While earning my Ph.D. at MIT, I taught chemistry at an alternative school and saw that curricula made a tremendous difference. But schools give degrees in curriculum development, and no university would hire me because I didn't fit in the box. Then someone at the lab suggested I contact Judah Folkman at Harvard who was trying to starve cancer tumors.

ME: Folkman hired unusual people. Why did he hire you?

R.L: Folkman was trying to prevent tumors from growing blood vessels. He thought he could find an inhibitor in bone marrow, where blood vessels did not grow, but he couldn't isolate it. Several excellent physicians and biologists had tried, so it made sense to try someone with a different background.

ME: You eventually isolated hundreds of potential inhibitors and developed a timed release system for large molecules to test them. These were major breakthroughs published in leading journals such as *Nature* and *Science*. You must have had your choice of jobs then.

R.L: Not at all. People didn't believe large molecules could move through a coating. It was like walking through a wall. And researchers had trouble duplicating my work, which made the coatings by controlling many variables. No chemical engineering department would hire me because I was doing experimental biology, and it didn't fit in with what chemical engineers did back then. Nevin Scrimshaw, who had founded MIT's Department of Nutrition and Food Science, found a place there for me without asking the faculty. When he left a year later, I was isolated. At a faculty meeting, one famous professor in our department blew cigar smoke in my face and told me I ought to start looking for another job.

ME: Was your reception better on the biomedical side?

R.L: My first nine grant applications were rejected. One reviewer wrote, "Dr. Langer is an engineer. He knows nothing about biology and he knows even less about oncology." There was an inherent prejudice against engineers. I was one of the few engineers doing experimental biology work anywhere, maybe the only one. I didn't fit into the box, and they turned me down for that reason.

ME: So what turned things around?

R.L: Researchers began to duplicate my results, and two companies licensed the technology. But when the experiments did poorly, they gave up. So a colleague suggested that we start a company to commercialize the coatings. It made the technology readily available and companies started using it.

ME: Since then, you have founded 40 successful companies. What advice would you give engineers seeking to commercialize their research?

R.L: It's not an easy answer. You should make sure your research is solid and not rush to commercialize it. Your intellectual property should be very strong, with patents that include reduction to practice, good examples, and an explanation of the claim terms. I look for investors who treat people well. Picking a CEO is really hard because you want someone who can do deals and really understand the science.

ME: With so many achievements, what do you think will be your legacy?

R.L: My students. As well as I've done scientifically, they've done well too. My lab's had 800 to 900 trainees, and they are CEOs and professors at some of the best schools all over the world.

ALAN S. BROWN

SYNTHETIC LIQUID FUELS IN THE UNITED STATES

BY W.C. SCHROEDER, OFFICE OF SYNTHETIC LIQUID FUELS, BUREAU OF MINES, WASHINGTON D.C.

Faced with tight petroleum supplies, an engineer sketches out the potential to produce artificial oil.

LOOKING BACK

Engineers were considering options to increase the national fuel supply when this article was first published in December 1947.

The disappearance of the reserve capacity to produce natural crude oil in the United States is the most important difference between the country's prewar and postwar economic and security situation. Prior to the war, a reserve of 20 to 21 billion barrels would have permitted domestic production of about 5 million barrels daily at the maximum efficient rate, while actual production was less than 4 million barrels. In essence, there was a cushion of 1 million barrels a day to soak up the heavy war demand and to provide time in which the civilian consumption could be curtailed to provide even greater supplies for military uses.

Now, a domestic crude production of nearly 5,100,000 barrels daily is barely sufficient to meet the country's needs.

Exploratory effort will undoubtedly find billions of barrels of oil, and this work should be carried forward vigorously. Deeper horizons, as well as drilling on the continental shelf, should help to maintain the oil reserves. Secondary recovery, that is, the attempt to rework old fields which have been exhausted by ordinary pumping methods, is assuming greater importance. In some oil sand it is estimated that 30 to 50 percent of the original oil may still be unrecovered. How far this work will go will depend to a considerable extent on the cost of recovering oil by these methods, as compared to the cost of producing it from other sources. It is estimated that postwar costs for discovering new oil are about three times prewar costs, partly the result of a generally higher price level, but also because of the greatly increased drilling and exploration work necessary to find the oil.

Importation of foreign oil is another possible source of large supplies. ... From some economic viewpoints, this might be the best means for meeting any shortages of crude oil which may occur in the United States.

In a broad chemical sense, it is probable that most carbonaceous material could be used for the production of oil. Practically, however, since huge volumes of raw material must be available at low cost near the synthetic-oil plants, the choice is limited to natural gas, oil shale, and coal, and in some circumstances possibly agricultural waste.

To establish a synthetic-fuel industry furnishing a considerable fraction of this country's oil needs will impose heavy demands on these raw materials, and the choice of the ones to be used will be determined by at least four major factors, as follows: Raw material available; water supply; predominant type of products wanted, i.e., fuel oil, diesel oil, or gasoline; and location of market and transportation costs for products. ME

SPRUCE GOOSE

While Wilburn Schroeder's article was in press, another wartime project was culminating in California. During World War II, transatlantic shipping was vulnerable to attack from German U-boats, and planners were looking for alternative means to transport men and equipment. Shipbuilder Henry J. Kaiser and aircraft designer Howard Hughes proposed building the world's largest aircraft, a 218-foot long flying boat with a 320-foot wingspan capable of carrying either 750 fully equipped troops or two 30-ton M4 Sherman tanks. Because of wartime material shortages, the aircraft—designated the Hughes H-4 Hercules—was constructed from laminated wood. By the time it was finished, the war was over, but as a stubborn demonstration of the concept, Hughes flew the so-called Spruce Goose once for about a mile on November 2, 1947.

The Spruce Goose on the day before it made its only flight.
Image: Bettmann/CORBIS

WATER WORKS IN SURP

WATER IS ALL AROUND US, but new ways of measuring it—or measuring with it—are opening some surprising doors. This month, we look at one lab peeling away the dynamics of turbulent fluids that bubbles often hide, and another that uses water to imagine the hidden features of complex objects that laser scanners cannot see.

What do you get when you combine an array of high-speed cameras with fast-turnaround research projects? In the case of Utah State University's Splash Lab, which studies fluid behaviors, the answer may provide a way to smooth the ride of inflatable boats on choppy waters.

"We often study things on a very short basis, sometimes only a few days,"explained Randy Hurd, a mechanical engineering doctoral candidate at the lab. "We'll gather some data to see if there's anything there, and if we don't think we can answer the question, we move on. We just had a study about cookie-dunking and another about urinal splashback. We'll study absolutely anything that makes us curious."

The lab's interest in inflatable boats began several years ago, when lab members began asking why a squishy toy ball, called the Waboba, skipped over water as well as, or better than, a flat stone.

Fortunately, lab director Tadd Truscott pioneered a technique to answer this type of question. It is called synthetic aperture imaging. It uses high-speed cameras to create tightly focused images of one narrow plane within the flow. When an algorithm combines the views from five or more cameras, each from a different perspective, into a single, high-resolution image, it also removes the bubbles that block individual cameras from seeing into the turbulence.

"High-speed imagery is the world's best measuring tape," Hurd said. "It's non-invasive, provides concrete evidence, and drastically speeds up the scientific process."

The researchers used the method to study the Waboba's impact with water. They found its surface deformed into a disk that bounced off the water surface, just like a flat, skidding rock. The smoother the surface, the longer the skips. These findings led to a surefire method for predicting at what points the ball would skip.

The lab continued to study the elastic spheres by dropping them into water and measuring their deformation. This enabled Splash Lab to model and predict the ball's behavior, based on its speed and composition.

Ultimately, they believe their research could help build inflatable speedboats that ride smoothly by absorbing energy from waves in the water.

"It seems so simple, you'd think someone would have done it before," Hurd said. ME

Splash Lab uses an array of high-speed cameras to measure turbulence through bubbles. *Photo: Splash Lab*

VISUALIZING BUBBLY WATER

THE LAB Splash Lab, Utah State University, Logan. Associate professor Tadd Truscott, director.

OBJECTIVE Untangling the mechanisms of fluid behaviors using a novel 3-D measurement method called synthetic aperture imaging.

DEVELOPMENT Using predictions of how an elastic ball hitting the water deforms to develop an inflatable boat that rides more smoothly on choppy water.

RISING WAYS

To reverse-engineer a part, people usually start by scanning it with a laser. This creates a point cloud—a map of the surface defined by each spot the laser touches.

This works fine, but only for features within the laser's line of sight. Engineers must add cavities and other obscured or hidden features by hand.

That could change, thanks to a very modern application of a 2,300-year-old principle that enables researchers to image complex parts, hidden features and all.

The story began when Kfir Aberman, a professor of electrical engineering at Tel Aviv University, visited the Advanced Innovation Center for Future Visual Entertainment in Beijing and saw a small figurine of elephants standing in a circle with their heads raised to the center.

"One of our researchers noticed all the hidden areas that an optical scanner wouldn't be able to reach," Aberman said. "Then we sought to answer one simple question: 'Could water be used to penetrate those areas and more effectively scan the object?' It was a moment of pure inspiration that helped us imagine this method."

The team turned to Archimedes' law of buoyancy, which states that the volume of water displaced by a submerged object is equal to the object's volume. By slowly dipping an object into water along an axis, the researchers could measure the volume of water displaced as it went under.

Slow dipping produced a series of thin slices of the object's volume along the dipping axis. Changing the axis produced a different set of slices. By using several axes, the researchers could generate enough data to reconstruct the shape of the part—interior cavities and all—based on an algorithm they call a "dip transform."

To realize the concept, they built a robot to dip parts. This posed some engineering challenges.

ARCHIMEDES AIDS 3-D SCANNING

THE LAB Advanced Innovation Center for Future Visual Entertainment, Beijing. Charles Wang, deputy director. Kfir Aberman, professor of electrical engineering, Tel Aviv University, visiting scholar.

OBJECTIVE Developing new technologies for the visual arts via a university-industry collaboration led by Beijing Film Academy.

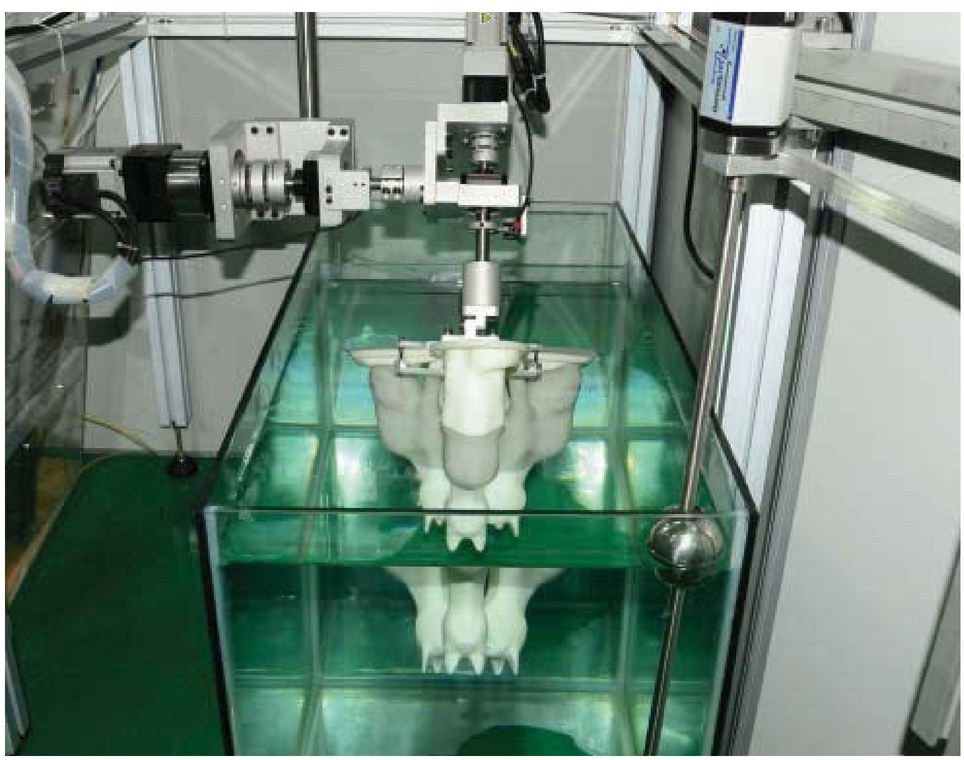
DEVELOPMENT Using submersion in water to uncover the hidden features of complex 3-D objects.

"When simulating the method, everything was smooth and elegant, but in reality, a dipping robot creates a lot of noise and vibration that causes the water to ripple, so measuring the height of the water becomes more difficult," Aberman said.

He has overcome many of those problems, and will continue to develop the technique.

"This work paves the way to an entire new world of optical scanning, so we can't stop now," he said. ME

CASSIE KELLY is a technology writer based in Columbus, Ohio.



Engineers can image hidden features by dipping objects in water.
Photo: Kfir Aberman

BY THE NUMBERS:

In the 1970s, smog blighted cities such as New York. The EPA documented pollution around the country, including oil spills and unlicensed dumping around the Statue of Liberty.

Photos: Getty (top); National Archive (below left and right)

WEALTH OUTPACES POLLUTION

As countries get richer, they produce less waste per capita.

In the 1970s, shortly after the Environmental Protection Agency (EPA) was established, the agency collected photographs documenting pollution across the United States. The images depicted illegal dumping grounds and skylines obscured by smog. The photographs, now digitized and kept by the National Archives, seem to come from not just a different era, but a different world.

EPA regulations have reduced pollution, but there are broader forces at work, too.

Researchers at the Federal Reserve Bank of St. Louis recently examined the connection between pollution and economic growth. Economists had previously hypothesized that the connection was complex; in early stages of industrialization, pollution increases matched growth in gross domestic product (GDP), but past a certain stage, rich countries were able to apply more resources to remediation and to less polluting technology.

Federal Reserve economist Guillaume Vandenbroucke and research associate Heting Zhu looked at data on GDP, carbon pollution, and emissions of small particles that are associated with ill health.

If the previous hypothesis held, the researchers would have found that in the United States pollution decreased at an ever-improving pace as the economy grew and increased during economic slowdowns, such as the Great Recession. Also, international data comparisons would show poorer countries increased their pollution as they grew and rich countries decreased pollution.

But that's not what Vandenbroucke and Zhu found. In the U.S., carbon emissions increased as the economy grew, but at a slower pace than economic growth. Between 1990 and 2005, for instance, greenhouse gas emissions grew by 15 percent while the economy grew 59 percent. What's more, from 2005 to 2010, when the economy was at a near standstill, greenhouse gas emissions declined.

"The United States still produced more CO_2 in 2014 than in 1990, and that rise is likely to have detrimental effects on climate," the researchers wrote. "The point here is that the increasing level of CO_2, which is detrimental to well-being, coincides with an even greater increase in GDP per capita, which advances well-being."

International comparisons of particulate emissions to GDP were even more telling. Poor countries pollute more per capita than richer ones, and for every factor of ten increase in per capita GDP, the rate of particulate emissions fell by about a third.

If American cities no longer have brown skies and filthy rivers, the EPA should get plenty of credit. But the fact that the U.S. is considerably richer than it was in the 1970s is also a major factor. No one, it seems, wants more pollution if they can afford to be without it. ME

JEFFREY WINTERS

THE EVOLUTION OF GREENHOUSE GAS EMISSIONS, U.S. GDP, AND POPULATION

INDEXES (1990=100)	1990	2005	2010	2011	2012	2013	2014
Greenhouse Gas Emissions	100	115	109	107	104	106	107
GDP	100	159	165	168	171	174	178
Population	100	118	124	125	126	126	127

SOURCE: EPA. "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014." EPA 430-R-16-002, April 15,2016, Table 2-14.

EMERGING TECHNOLOGY AWARDS

INTRODUCTION

INNOVATION ON THE RISE

We revel in the stories of eureka moments, including the first, when Archimedes ran naked and dripping wet through the streets of Syracuse, proclaiming his discovery of a way to measure the volume of an irregular object. Other vivid anecdotes of inspiration, such as the burrs latched onto a dog's coat that inspired Velcro, or the chocolate bar melted by a radio transmitter that led to the microwave oven, fire the imagination.

But new ideas by themselves are not enough to change the world.

Experts who study technology development describe an S-shaped path traced by successful breakthroughs. First, there is the research and development phase, a long gestation period when promising ideas are tested and improved. (Or not improved—many would-be innovations never make it out of R&D.) At the other end of the path, there is standardization and maturity, when technologies have shown their worth and industries work to turn them into profitable commodities.

Linking those two segments is the ascending phase: Technologies at that point on the S curve have escaped R&D, crossed the so-called commercialization valley of death, and are poised to remake the market.

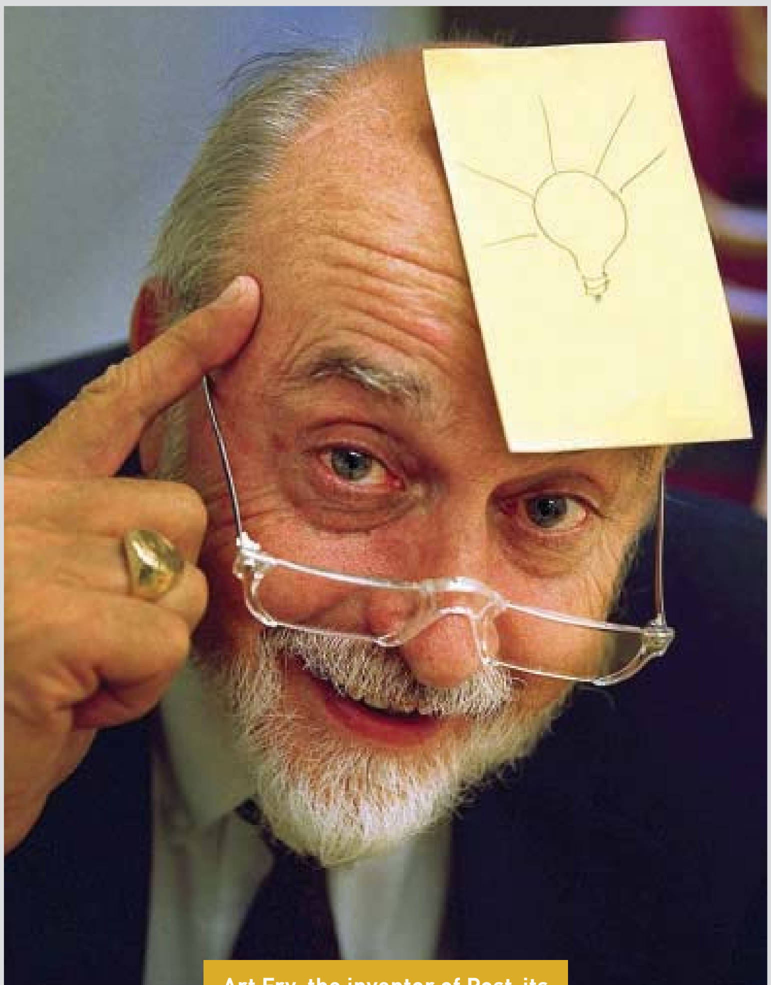
It is these ascending technologies that *Mechanical Engineering* magazine recognizes this month with our inaugural Emerging Technology Awards.

Our editors have examined ASME's core technological focuses—bioengineering, automation and robotics, manufacturing, pressure technology, and clean energy—and selected one innovation from each that has successfully moved from the lab to the cusp of commercialization. Some of these technologies are hidden away in the guts of power plants or the brains of automobiles, while others are as visible as powered prosthetic legs. But all share the distinguishing mark of finding insightful new ways of meeting society's most important challenges.

Please join us in celebrating the achievements of these innovators, starting on the next page with Henry Petroski's essay about the difficulties new ideas face in crossing the commercialization valley of death. ME

WATCH VIDEOS ON EACH OF THE TECHNOLOGIES HONORED ON ASME.ORG.

CROSSING THE VALLEY



Art Fry, the inventor of Post-its

As *Mechanical Engineering* magazine celebrates five emerging technologies this month, we should pause to consider how difficult it can be to get a potentially good idea from the laboratory to the marketplace. A classic example of this difficulty is the humble Post-it note.

The engineer and inventor Art Fry worked for the 3M Company, which allowed him to engage part time in intrapreneurship—meaning that in addition to doing his assigned work he was free to pursue his own research and development ideas and then attempt to promote them within the company. Fry employed a supposedly failed product off the laboratory shelf to give bookmark-size slips of paper the ability to remain in place yet be easily removed after they had served their purpose.

When Fry approached his superiors with his invention, the novel idea was not received with much enthusiasm. The market for sticky bookmarks did not seem to be very promising, and the idea that people could use what came to be known informally as “little stick ums” and “sticky notes” to write reminders and attach them to everything from refrigerator doors to appointment books seemed outlandish. After all, why would anyone pay for pads of a manufactured product whose purpose had long been served by recycled scraps of paper cut or torn from larger sheets?

Fry persistently pushed the idea until 3M relented and test-marketed “temporarily permanent” stick-and-remove notes, pads of which were distributed free to customers of other office products.

Before long, based on requests to reorder supplies of the notes, it was clear that the little slips of colored paper backed by a strip of so-called unglue “met an unperceived need.” Secretaries and other office workers found all sorts of uses for what came to be called Post-it notes, and as it is said, the rest is

OF DEATH

It's no mean feat to take a product from development to commercialization. Many great ideas never make it.

BY HENRY PETROSKI

history for the immensely successful product. But the process spanned about a decade.

If an intrapreneur like Fry had to work with such determination to achieve success within his own company, imagine how difficult it must be for an independent inventor to sell an idea to a large manufacturing firm. Not only must the "not invented here" syndrome be overcome but also the outright risk of having a very good idea become adapted—some would say stolen—by a company without recognition or remuneration of the inventor.

Stories are legion of lone inventors, having succeeded in getting their foot in the corporate door to demonstrate their invention, only to be disappointed in it not being embraced, and to find later their idea incorporated into some successful big-firm product. It is like rubbing salt in the wound of rejection.

The example of the intermittent windshield wiper falls into this category. Its inventor, Robert Kearns, encountered rejection at all the Big Three automakers. He found vindication, however, when patent infringement lawsuits against Ford and Chrysler were decided in his favor for tens of millions of dollars.

My books on invention and design have prompted many part-time inventors to approach me with their clever ideas, asking, "How can I get this to the marketplace?" They tend to know the stories of products like Post-it notes and the intermittent windshield wiper, but the potentially long and arduous path from invention through rejection to vindication does not discourage them. Some of my discussions and correspondence with these inventors has spanned well over a decade, during which time they have continued to work on and improve their product. Many have produced prototypes, and my bookcases and file drawers are full of artifacts that demonstrate the never-ending ingenuity of the inventive mind.

Of course, it is not just small office or consumer products and subcomponents of larger systems that are the stuff of legend and lesson. And getting an idea—good or bad—from the laboratory to the marketplace is no guarantee of commercial success. Perhaps the Edsel, the automobile with the vertically dominant grill centerpiece and push-button panel for gear selection, is among the most notorious failed automobile models.

Edsel was the name of Henry Ford's son,

Ford Edsel

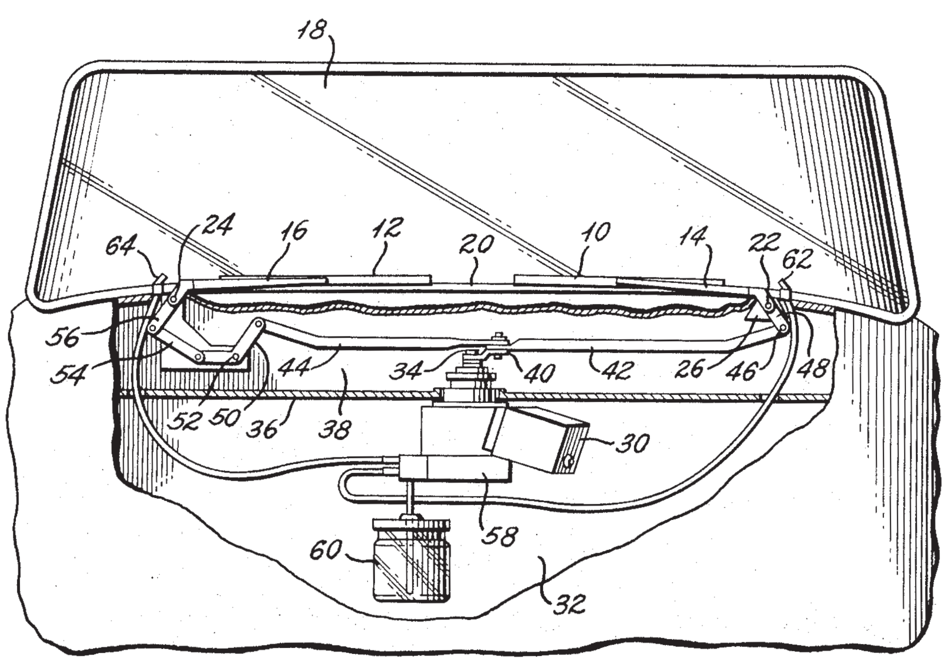
who served as president of the Ford Motor Company from 1919 (he was in his mid-20s at the time) until his death in 1943. Edsel had tried to convince his famous father to depart from the perennially conservative design of the Model T, but even a member of the family can have difficulty introducing new ideas into a company with an old mindset. It was mostly changing conditions—Ford was losing market share—that led eventually to Edsel's Model A being introduced in 1927.

The younger Ford also injected into the company's line the Lincoln and Mercury, the latter being named by Edsel himself. But what's in a name?

In the mid-1950s, when Ford was seeking a name that was "more than a label" for a new automobile, the company asked the poet Marianne Moore to make suggestions. Over the course of several weeks she offered more than 40 possibilities, ranging from the rhyming Ford Silver Sword to the risible Utopian Turtletop. None of her suggestions were taken. The new car was, instead, called the Edsel.

But that name for an automobile—even one made by Ford—may have been a marketing mistake. While the name Edsel may have been revered among some Ford decision makers, it was generally met with quizzical disregard by the car buying public. What's an Edsel? Is it as reliable as a Lincoln or as fast as a Mercury?

Another transportation story involves something that was widely hyped and anticipated as a means to change the way people move altogether—not only an invention but an innovation. As the time drew near to unveil the transformative device whose exact nature and name was held in strict secrecy, publicity and curiosity mounted. The innovative machine, developed from the self-balancing technology that made the iBot wheelchair able to climb stairs and raise its rider to eye level with a standing person, was code-named It and Ginger. The Segway, as it officially came to be known, was to be



Intermittent Windshield Wiper

The Segway

manufactured by an independent, dedicated company, which is another way to get an invention to market. But countless snags—technical, legal, and cultural—doomed the novel two-wheeler from achieving its full promise.

The Segway is among the products now on display in the recently opened Museum of Failure in Helsingborg, Sweden. Other exhibits include New Coke, which was an embarrassing effort to sneak by consumers a revised formula for a revered old soft drink, and the Betamax system of videotape recording. Superior in reproduction quality to what is known as VHS, the Betamax lost out to VHS by sheer marketing firepower. As with New Coke, you can lead consumers to market, but you can't force them to buy.

Among other product failures on display at the Swedish museum are the Bic for Her ballpoint pen and Harley-Davidson perfume, whose names should be as self-explanatory as their reasons for failing. Corporations, like people, can be guilty of overreach, being greedy to add new products when the market share of their flagship products plateau, decline, or even tumble off a cliff. Such experiences with seemingly promising products, whether invented within or outside the company, can lead to overly conservative corporate behavior when it comes to subsequent proposed products.

Just as the success and failure of products tend to follow cyclic paths—inventions being improved until they are overimproved, providing valuable lessons in their failure for renewed success—so can corporations move from open- to close-mindedness and back again as they welcome and then reject new ideas. Depending upon where inventors and staff researchers and developers alike catch a company in the cycle, they may or may not find it easy to sell their hoped-for innovations to the marketers and decision-making executives. ME

HENRY PETROSKI is the Aleksandar S. Vesic Professor of Civil Engineering and a professor of history at Duke. His latest book, *The Road Taken: The History and Future of America's Infrastructure*, has recently been issued in paperback.

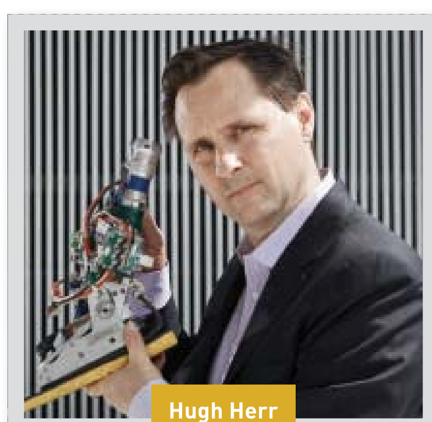
EMERGING TECHNOLOGY AWARDS

BIONIC LEG PROSTHESES

INNOVATOR Biomechatronics group, MIT Media Lab. Hugh Herr, group leader.

INNOVATION Powered foot-ankle prostheses with multiple tendon-like actuators controlled by multiple onboard computers.

IMPACT Advanced prosthetic limbs may one day enable people to exceed the capabilities of their natural body parts.



Hugh Herr

BIOENGINEERING

POWER PROSTHETICS

Hugh Herr designs bionic legs—including his own.

STORY BY SARA GOUDARZI • ILLUSTRATION BY THOMAS ROMER

Hugh Herr was already a top technical rock climber at age 17 when he set out with a partner to scale Mount Washington in New Hampshire. The two were caught in a blizzard and Herr suffered severe frostbite to his lower legs. Surgeons eventually had to amputate both of his legs below the knee.

"I was fitted with conventional prostheses that were wholly inadequate," Herr recalled, "and I really dedicated my life at that time to improving technology for people with disabilities."

Herr didn't have a rigorous engineering background but he knew his way around the machine shop. After a little tinkering, he designed prostheses especially for ice climbing. Each one weighed as little as a carbon tennis racket—that enabled Herr to pull up less weight and to do more work before experiencing fatigue.

"I was able to climb better after the accident," Herr said. "That experience was really inspirational and led me back to school, into a new realm where I was studying mathematics, science, engineering and loving that."

Today, Herr heads the Biomechatronics group at the MIT Media Lab, where he works to create improved prostheses—both to aid the more than 20 million worldwide who experience limb amputations and to extend human physicality beyond natural innate levels.

Herr has developed bionic limbs, specifically powered foot and ankle prostheses with multiple tendon-like actuators that stiffen and power gait. Each ankle holds three computers that perform various computations enabling one to walk at different speeds across different terrains. They're distinct in the prostheses world because these bionic limbs are powered, while all other foot ankle prostheses are energetically passive.

"You can say that conventional mechanical prostheses are like a bicycle and what I'm wearing is like a motorcycle—the motors actually inject mechanical energy into my walking gait, enabling me to move more efficiently," Herr said.

In effect, he's tried to mimic the mechanism of a natural limb: The human spinal cord receives sensory information from all the muscles and tendons. Then computation is performed on the spinal cord level and muscles are activated based on the sensing and calculation information. The bionic limb is running these spinal-like reflexes on a computer chip.

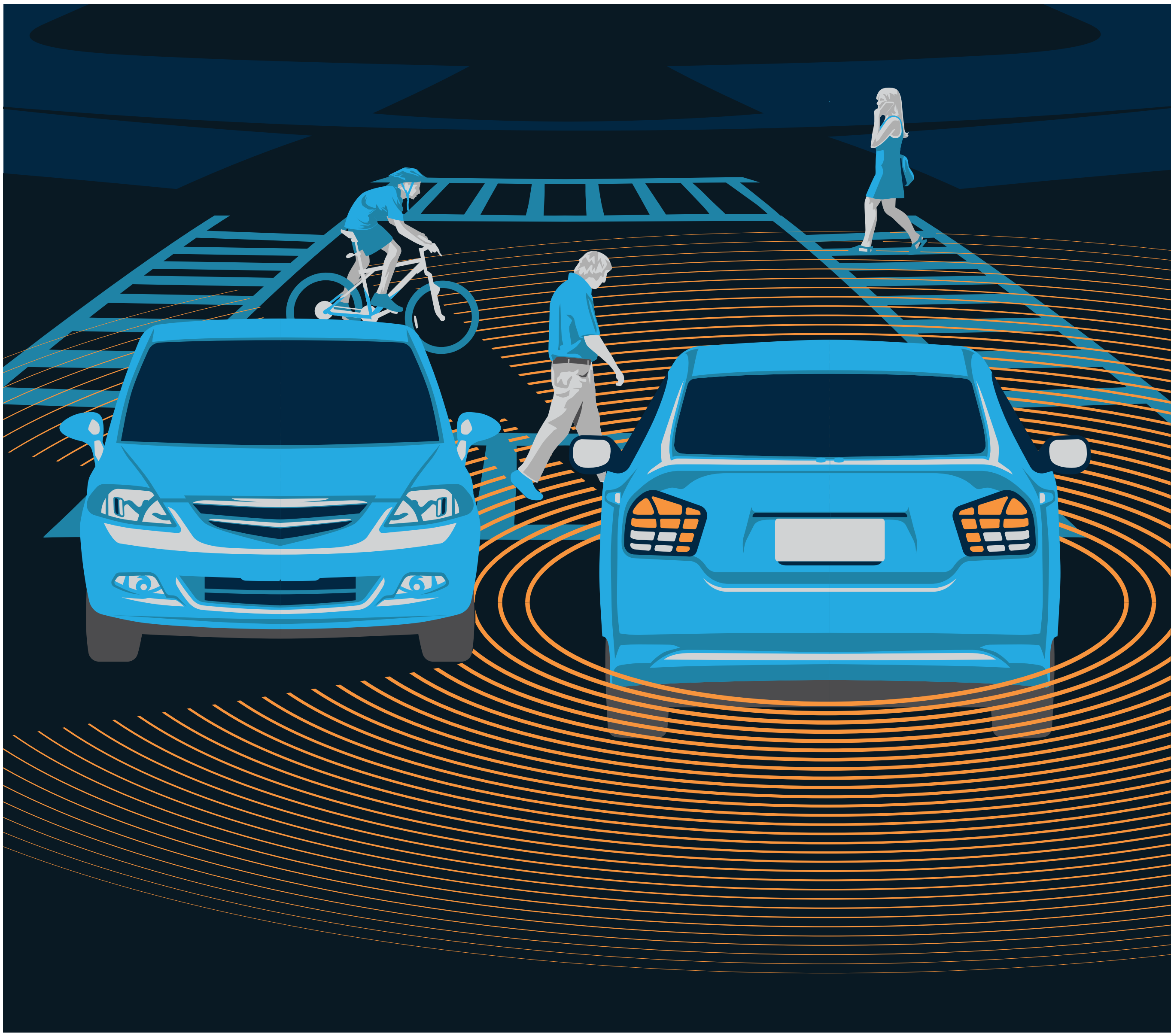
A commercial product—called emPOWER—is sold through Herr's startup called BioneX Medical Technologies. In the lab, Herr and his colleagues are working on developing neural interfaces, essentially connecting the bionic limbs to muscles and nerves so a person can think and move the limbs and also feel the movement as a feedback into the nervous system.

"The units that I wear day to day is the emPOWER foot ankle system," Herr said. "It is all intrinsic intelligence without the neural control but just in a year or two I'll be neurally linked to my limbs fulltime inside and outside the lab."

Currently, computer-controlled prostheses are more expensive than passive prostheses and run a few tens of thousands of dollars. However, Herr hopes that as they scale the product, manufacturing will become more efficient and the costs will go down, making smart prostheses available to the millions in need. ME

SARA GOUDARZI is a writer based in Brooklyn, N.Y.

EMERGING TECHNOLOGY AWARDS

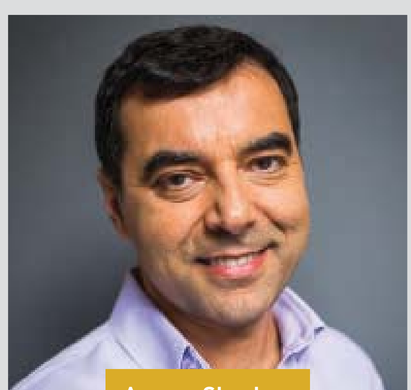


VEHICLE VISION SYSTEM

INNOVATORS Mobileye. Amnon Shashua, founder.

INNOVATION Hardware and software that help vehicles detect and avoid other vehicles, with the entire system miniaturized so that it fits on a single silicon chip.

IMPACT Improved vision systems will enable autonomous vehicles to navigate unexpected hazards more ably than human drivers.



Amnon Shashua

ROBOTICS

EYES ON THE ROAD

Mobileye puts a robotic vision system on a chip.

STORY BY MICHAEL ABRAMS • ILLUSTRATION BY THOMAS ROMER

The promise of autonomous cars is that they will be more attentive to the hazards than distractable human drivers. To make good on that potential, the Jerusalem-based company Mobileye has been designing hardware and training software algorithms to help vehicles detect and avoid other vehicles. In a major advance, the company has been able to shrink its Advanced Driving Assist System to fit on a single silicon chip it calls EyeQ.

When wired to a camera, the system offers superior cruise control, keeps its vehicle in lane, recognizes traffic signs, and can automatically brake for pedestrians and other dangerously close vehicles.

The company, which was founded by Amnon Shashua, a professor of computer science at the Hebrew University of Jerusalem, has already sold 20 million of its chips. The advantage of having so many of them already traveling the world's highways extends beyond the immediate safety they provide. Mobileye is mining the data those chips collect—24 million miles worth of video so far—to create a high definition mapping system that will work with real-time data to help vehicles navigate and eventually become fully autonomous.

"Several years ago, we identified mapping as one of the technical roadblocks to fully autonomous driving," said Dan Galves, the company's chief communications officer. "We developed a system that processes raw camera data into small chunks of relevant data that can be communicated to the cloud through normal LTE wireless."

However good the map, autonomous cars must be able to manage every tricky situation that human drivers can finesse. Some of those are trickier than others. When two lanes of traffic join with two other

lanes of traffic, for instance, the rules of vehicular behavior seem fuzzy at best, yet humans perform such merges with little difficulty. Mobileye is using AI to figure out how best to maneuver vehicles automatically through such thickets.

"We use semantic cues and reinforcement learning algorithms to train vehicles to negotiate with other agents in double-lane merge type situations," Galves said.

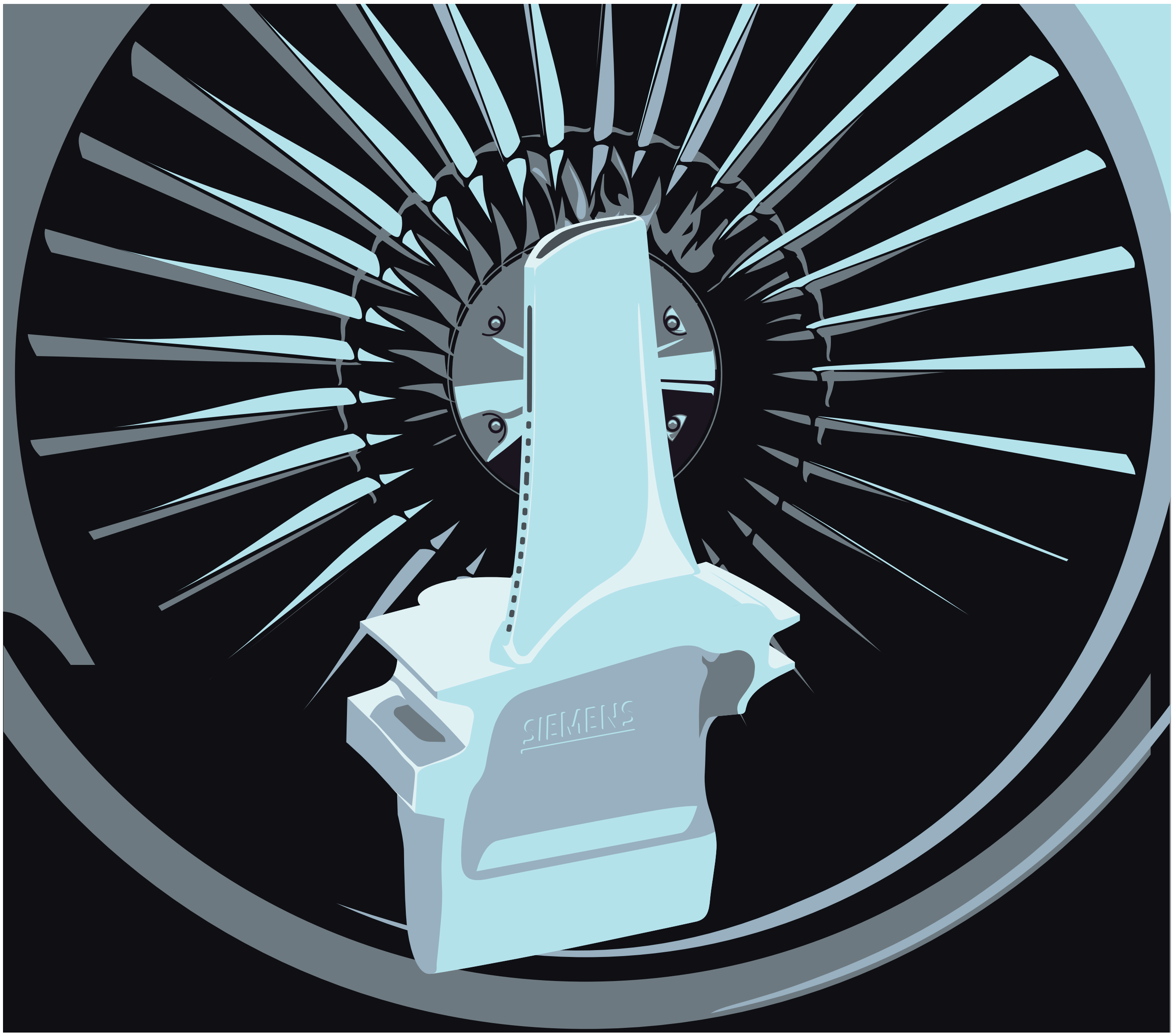
Another hurdle for the Advanced Driving Assist System is understanding which objects are actually on the road and which aren't. Humans instinctually distinguish the leaves and branches of an overhanging tree from a fallen branch in the path of a car. How do you teach a machine to do that? Mobileye intends to mate 8-megapixel cameras to a vision system chip that can analyze 250 million pixels a second, in hopes of crunching enough data to make distinctions between different kinds of obstructions.

In addition, a new version of its EyeQ chip will be able to recognize the front, rear, and sides of a vehicle—crucial information when it comes to knowing which direction a vehicle is going.

Shashua and co-founder Ziv Aviram took Mobileye public in 2014 and sold the company to Intel earlier this year. Now the company is working with more than 25 automakers worldwide. Thanks to Mobileye's mix of AI, software development, massive data collection, and general ingenuity, one day we may be able to travel safely with our eyes off the road and our hands off the steering wheel. ME

MICHAEL ABRAMS is a writer based in Westfield, N.J.

EMERGING TECHNOLOGY AWARDS

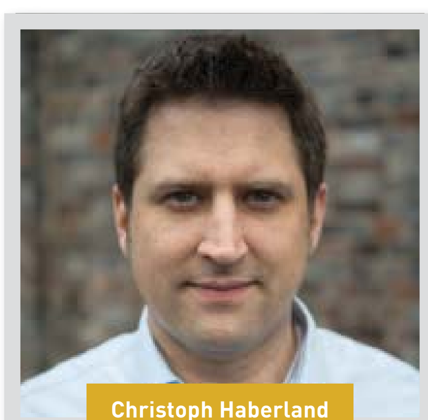


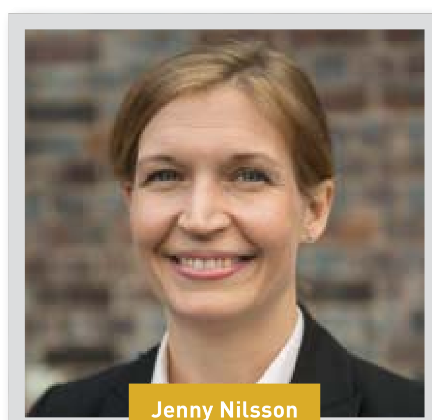
3-D PRINTED TURBINE BLADE

INNOVATORS Siemens. Christoph Haberland, Power and Gas Division; Jenny Nilsson, Additive Manufacturing Group.

INNOVATION A prototype blade made via additive manufacturing that can withstand the heat and stress found inside a gas turbine.

IMPACT Printed parts may cut the time to design new turbine blades by 75 percent.


Christoph Haberland


Jenny Nilsson

MANUFACTURING

ADDITIVE ADVANTAGE

Siemens prints a blade that survives inside a turbine.

STORY BY TOM GIBSON • ILLUSTRATION BY THOMAS ROMER

The rotating blades inside a gas turbine must stand up to intense heat and stresses. One small imperfection can cause the blade to rip apart—with catastrophic results. To achieve the necessary level of perfection, manufacturers have used investment casting, a complex, time-consuming, and costly procedure that requires building a mold for each blade.

Additive manufacturing could help speed blade development by eliminating casting, at least in the prototyping phase. One form of additive manufacturing, 3-D printing, has been used to build plastic models to show a design's fit and form.

Siemens has demonstrated the potential of 3-D printing by taking a printed gas turbine blade and successfully putting it through the paces of a turbine operating at high temperature, pressure, and centrifugal force.

Christoph Haberland, an engineer and expert in additive manufacturing for Siemens in Berlin, said, "It was a big success in proving that we can 3-D-print rotating parts that run on the machine. To our knowledge, nobody has tried this before."

The team behind the blade included project manager Jenny Nilsson, now a group manager for the design of additive manufacturing parts in Finspong, Sweden, as well as engineers at Material Solutions, a company Siemens later bought. "We started with an idea, and the vision was to print blades with different new designs and test and validate them in an engine," Nilsson said.

Team members developed better cooling designs to improve the gas turbine efficiency, designed the blade, and developed the whole manufacturing process to manufacture this type of component and geometry. "The whole purpose was to create an approach to rapid prototyping," Nilsson said.

Like all additive manufacturing, the team applied thin layers of material—one after the other—to build up a finished object. The main difference with Siemens' blade process was that layers were made of high-temperature-resistant, polycrystalline nickel-based superalloy powder, which was then heated and melted by a laser.

To prove the durability of the printed blades, they were installed in a 13-MW SGT-400-type industrial gas turbine at a Siemens test center for industrial gas turbines in Lincoln, U.K. At full power, turbine blades rotated at 13,600 rpm with a blade tip speed of 480 m/s and carried loads of 11 tons. The blades also had to withstand the heat from 1,250 °C gas moving through the turbine.

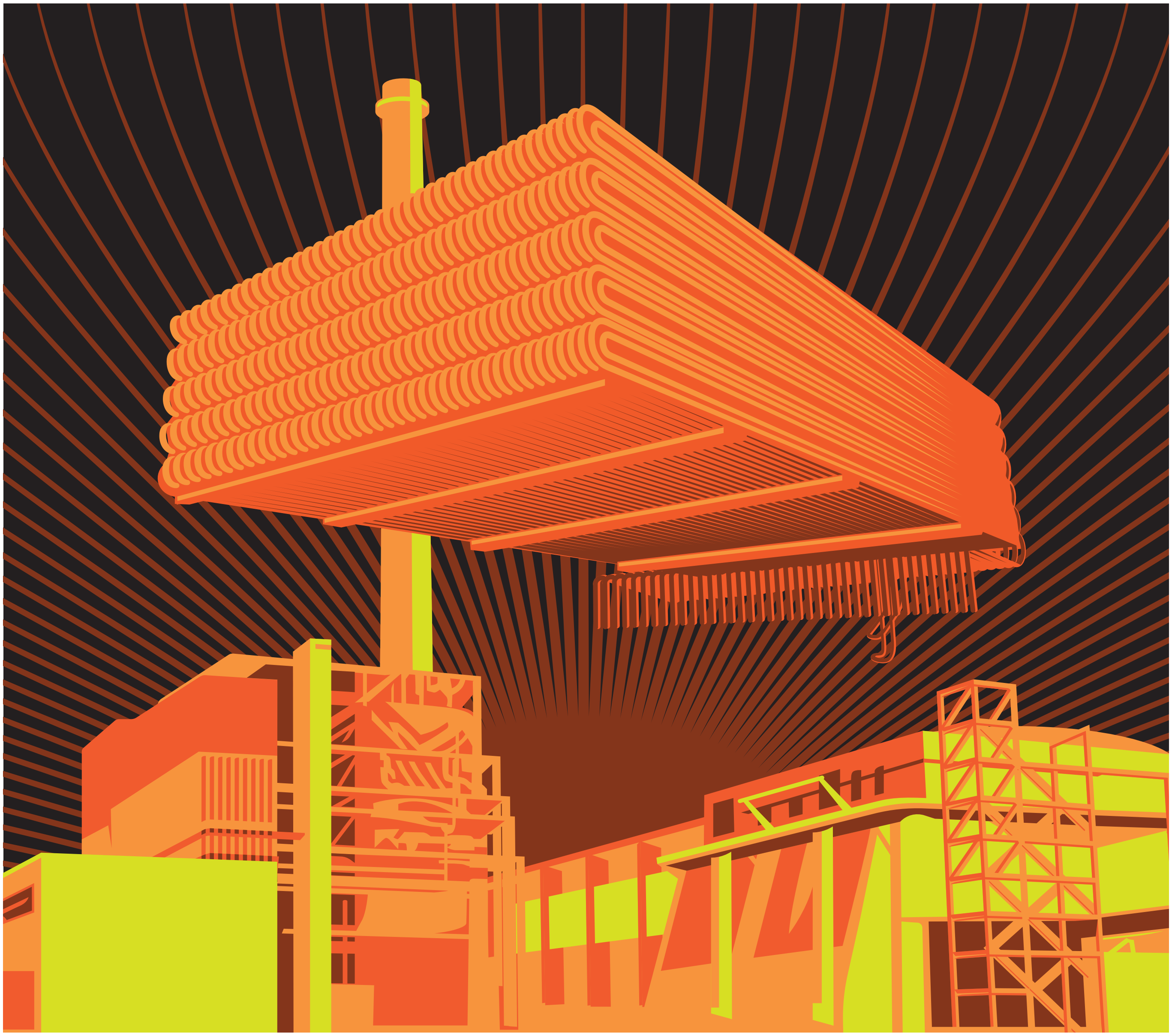
One advantage of 3-D printing turbine blades, Haberland said, was that "when you go with the conventional procedure, casting a design and testing it, this is a long lead time, and by using 3-D printing, we could reduce it by 75 percent." The team reduced the time from manufacturing the new design of a gas turbine blade to its validation from two years to two months.

Could 3-D printing go beyond prototyping and be used for production blades?

"The 3-D-printing processes and materials available today will not meet the long-term requirements of a blade," Haberland said. "However, we are developing new 3-D printing technologies, and we may end up being able to produce blades by 3-D printing in the future." ME

TOM GIBSON, P.E. is a writer based in Milton, Pa.

EMERGING TECHNOLOGY AWARDS



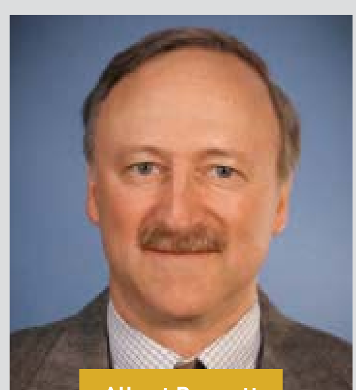
ULTRA-SUPERCRITICAL BOILER

INNOVATORS Babcock & Wilcox. Brandy Johnson, vice president, new build utility and environmental; Albert Bennett, technical consultant.

INNOVATION Ultra-supercritical boiler at John W. Turk Jr. Power Plant withstands very high pressure and temperatures, enabling the plant to operate at a net efficiency of better than 39 percent.

IMPACT Plant uses less fuel than standard coal-fired boilers and releases 17 percent fewer CO_2 emissions.

Brandy Johnson



Albert Bennett

PRESSURE TECHNOLOGY

INCREASING EFFICIENCY

Advanced Babcock & Wilcox boiler takes the heat.

STORY BY MARK C. CRAWFORD • ILLUSTRATION BY THOMAS ROMER

When engineers are challenged to extract more power from the fuel entering a Rankine cycle thermal plant, they have a few options. Among the most challenging are raising the steam temperature and increasing the pressure.

The technology demonstrated at the John W. Turk Jr. Power Plant in Fulton, Ark., tackles both challenges, raising the pressure and temperature of the steam to new heights. While other plants in the United States operate at supercritical pressure, the Turk plant is the first where the final steam conditions exceed both the critical pressure and a temperature of 1,100 °F. Operating as an ultrasupercritical boiler, the Turk Plant has the highest net plant efficiency of any solid fuel power plant in the U.S.

Plant owner Southwestern Electric Power Company tapped Babcock & Wilcox to design, supply, and erect the 600-MW advanced supercritical steam generator.

"B&W's full project scope included the engineering, design, supply, and installation of a 600 MW-net pulverized coal-fired spiral-wound universal pressure steam generator, a selective catalytic reduction system, a dry flue gas desulfurization system, pulse jet fabric filter, and associated auxiliary equipment," said Brandy Johnson, vice president, new build utility and environmental, for Babcock & Wilcox.

To best optimize efficiency, the design team selected a single reheat cycle with elevated steam pressure and temperature.

In designing high-temperature steam cycles, designing the interface between the stainless steel tubing (in the area exposed to hot flue gas) and the high-strength ferritic collection headers outside of the hot

gas is especially important. As the average design steam temperature increases, the temperatures of the individual superheater tubes can vary widely. Material fatigue places an upper practical limit on the steam temperature.

According to Albert Bennett, a technical consultant for Babcock & Wilcox who was significantly involved on the project, "Special attention was made to ensure that the steam temperatures were controlled such that early fatigue failure would not be an issue."

The team found new chrome- and nickel-based superalloys that could be used in the steam generator, piping, and other system. Those alloys should hold up for three decades or more.

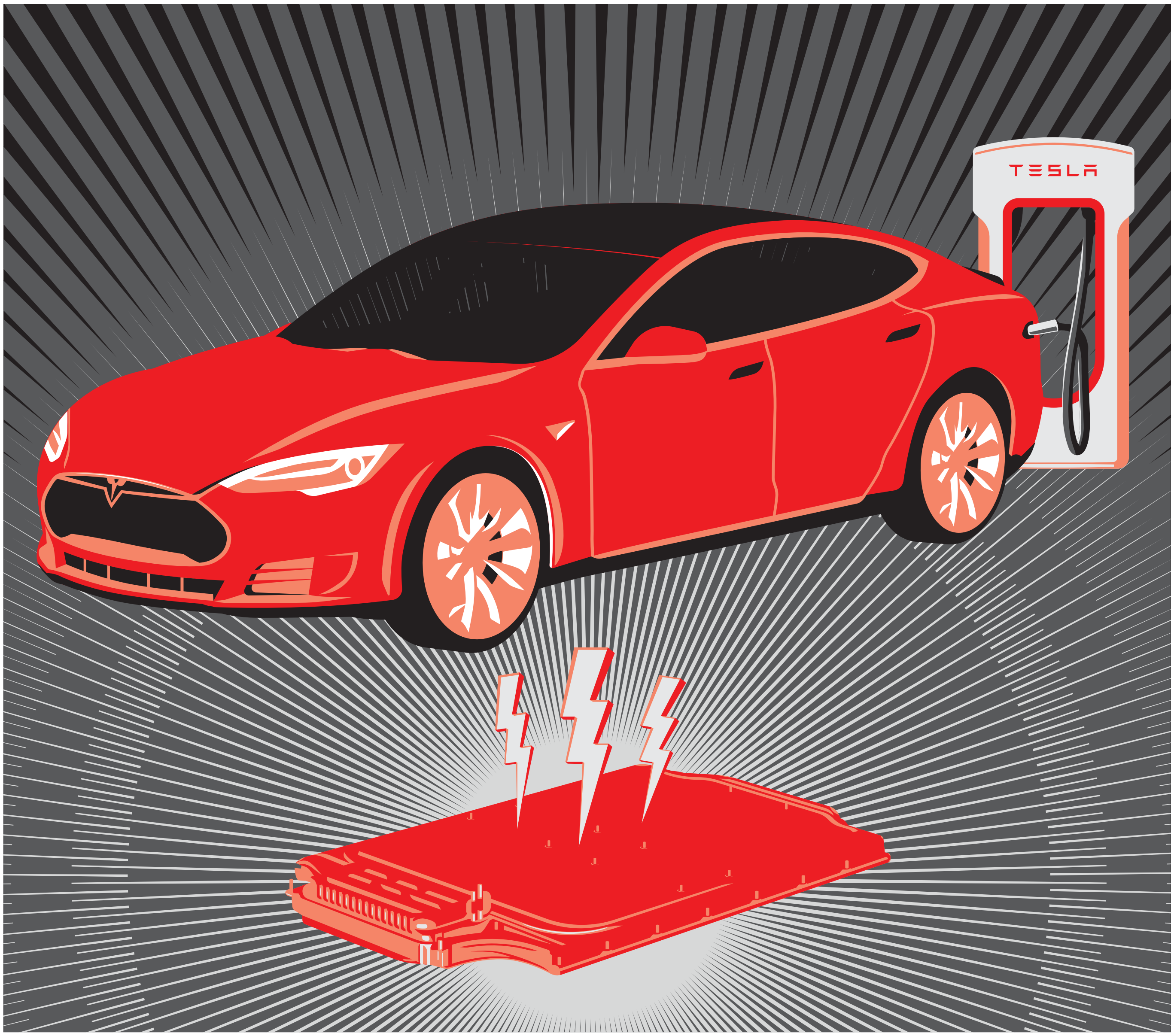
With a superheater outlet pressure of 3,789 psig—well above the critical pressure of 3,206 psig—an outlet temperature of 1,126 °F, and a steam flow of 4,419,400 lbs. per hour, the Turk plant has been able to produce a net plant heat rate of 8,730 Btu/kWh—equivalent to a net plant efficiency of 39.1 percent since it entered commercial operation in 2012.

By comparison, the fleetwide average for coal-fired boilers is 32.5 percent. That difference makes a substantial impact on emissions per megawatt-hour of power generated. The higher efficiency results in less overall coal consumption and fewer emissions, including carbon dioxide, per megawatt output.

Babcock & Wilcox engineers also employed computational fluid dynamics modeling to place burners and overfire air ports to make the best use of low-sulfur coal. ME

MARK C. CRAWFORD is a writer based in Madison, Wis.

EMERGING TECHNOLOGY AWARDS

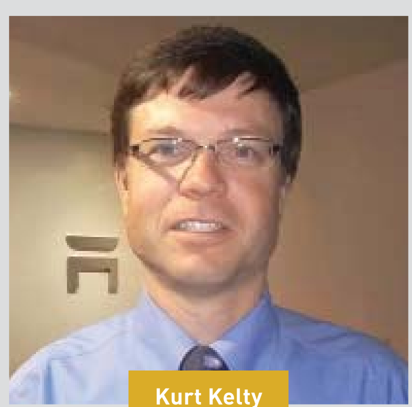


AFFORDABLE ENERGY STORAGE

INNOVATORS Tesla Motors; Kurt Kelty, former director of battery technology.

INNOVATION Optimizing the chemistry and manufacturing process to bring down the cost of lithium-ion battery packs.

IMPACT Less expensive energy storage will help electric vehicles reach the mass market, cutting tailpipe emissions from cars and trucks.



Kurt Kelty

CLEAN ENERGY

ELECTRIC ENABLER

Tesla batteries are making EVs affordable.

STORY BY JOHN KOSOWATZ • ILLUSTRATION BY THOMAS ROMER

In the last year, electric vehicles have broken through with their most skeptical audience: legacy automakers. In October, General Motors joined Ford, Volvo, Nissan, and others in announcing that a substantial portion of its future production will be powered in part or entirely by electricity.

The rush toward emission-free vehicles is only possible because of a dramatic drop in the cost of producing batteries to power them. That game-changing price cut is credited to a small automaker with a commitment to electric vehicles: Tesla Motors.

Tesla's battery revolution began when CEO Elon Musk declared that it would sell a mass-market EV for just \$35,000. To produce battery packs cheaply enough to reach that price point Tesla re-engineered not only the production process, but the factory in which the batteries are made.

The Reno, Nev., Gigafactory is not yet operating at full capacity but it is expected to produce 35 GW per year of lithium-ion batteries, about double the present-day global production. Costs are not released publicly but most industry observers believe the company already has brought them below \$200 per kWh.

Tesla partnered with Panasonic to revamp the production process, and ended up redesigning the chemistry of the battery itself. The standard "18-650" cell format used thousands of less expensive commodity cells, similar to lithium-ion batteries used in laptop computers. Tesla replaced individual safety systems built into each cell with an inexpensive fire-proof system for the entire battery pack. Now, they've begun producing the new "2170" cell, which is named after its dimensions of 21 mm by 70 mm. It delivers higher density through an automated system developed with Panasonic to further reduce costs.

For now, Musk says the 2170 will be used in the Model 3 and its Powerwall and Powerpack storage units for solar electricity.

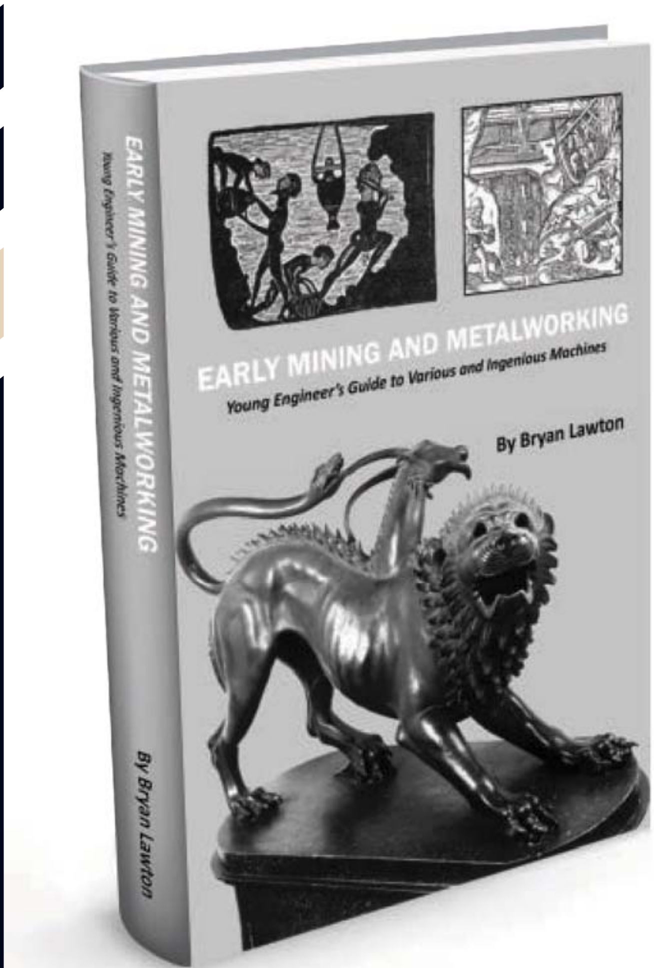
"We're doing our best to change the nomenclature of the industry," Kurt Kelty, Tesla's former director of battery technology, told an industry gathering last year. "We've been using the 18-650 because it existed but it is not the optimal size for EVs." The company thinks the new battery format improves sizing and energy density specifically for electric vehicles. But the challenge was to reduce production costs by 30 percent.

Tesla attacked that partly through partnering with mining companies to guarantee cost and supplies of raw materials, which Kelty says are the biggest cost drivers. Nickel is the largest raw material cost, Kelty said, followed by graphite, lithium, and cobalt. The firm believes the sourcing of needed raw materials will remain steady for the next five years, though resource constraints may crop up if the electric vehicle market surges.

Even better batteries may be on the horizon. A research partnership with NSERC/Tesla Canada Industrial Research has lab-tested battery cells capable of doubling the lifetime of Tesla's batteries. According to the group's chairman, pioneering battery researcher Jeff Dahn, the aluminum coating used by the group performed so well, he thinks the batteries could last 20 years.

That development has not yet been incorporated into Tesla's products, but it certainly holds out the promise of even greater efficiencies and a longer battery—and vehicle—life. ME

JOHN KOSOWATZ is senior editor at ASME.org.



FEATURED

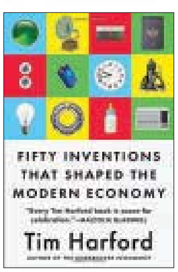
EARLY MINING AND METALWORKING: YOUNG ENGINEER'S GUIDE TO VARIOUS AND INGENIOUS MACHINES, VOLUME 2

BRYAN LAWTON

ASME Press, Two Park Avenue, New York, NY 10016. 2017

This is the second volume of Lawton's series of shortened, more affordable, and more accessible books spun off from his acclaimed *Various and Ingenious Machines*. (The first volume was featured in last month's Bookshelf column.) One of the main purposes of this new work is to deliver not only an outline of mechanical engineering history, but also an adequate mathematical treatment for each topic, without straying beyond the level of a first engineering degree. The hope is that the reader can enjoy a well-written history and can supplement it with a concise mathematical explanation in the appendices at the end of most of the chapters. As noted by Lee Langston in the foreword, in the chapter on mining in antiquity, Lawton provides a calculation of the solid rock tunneling rate with fire setting, using the same heat transfer error function solution used by Lord Kelvin in the 1890s to estimate the Earth's age.

175 PAGES. $29; ASME MEMBER, $23. ISBN: 978-0-7918-6142-4



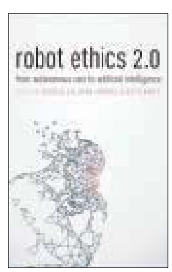
FIFTY INVENTIONS THAT SHAPED THE MODERN ECONOMY

Tim Harford

Riverhead Books, 375 Hudson St., New York, NY 10014. 2017

Economist Tim Harford treads on territory famously covered by James Burke: the history of inventions and how innovations change the society that innovates. But while Burke's *Connections* series and follow-up books linked inventions to one another, Harford groups them thematically, showing how the tally stick, the shipping container, and IKEA furniture all reinvented the global supply chain. "Each invention tugged on a complex web of economic connections," Harford writes. "Sometimes they tangled us up, sometimes they sliced though old constraints, and sometimes they weaved entirely new patterns." He's as careful to take note of those who lose out from innovation—from small farmers to mom-and-pop store owners—as he is of the more obvious winners.

336 PAGES. $28. ISBN: 978-0-7352-1613-6



ROBOT ETHICS 2.0: FROM AUTONOMOUS CARS TO ARTIFICIAL INTELLIGENCE

Patrick Lin, Keith Abney, and Ryan Jenkins, editors

Oxford University Press, 198 Madison Ave., New York, NY 10016. 2017

Robots are machines, but as their control systems become ever-more advanced, they are allowed to operate in increasingly autonomous ways. But with that autonomy come moral questions that were first recognized with the prospect of robotic war-fighting machines but now have been raised in many fields where autonomous robots may contribute. The editors assembled two dozen chapters covering many dimensions of these ethical issues, ranging from whether courts can apply a "reasonable driver" standard to a self-driving vehicle to plumbing human-robot relationships. Will robotic police officers be able to take greater "physical" risks than their human counterparts, or will their lack of compassion lead to "shoot first" attitudes? Fantasy? Maybe, but the future is approaching fast.

440 PAGES. $39.95. ISBN: 978-0-1906-5295-1

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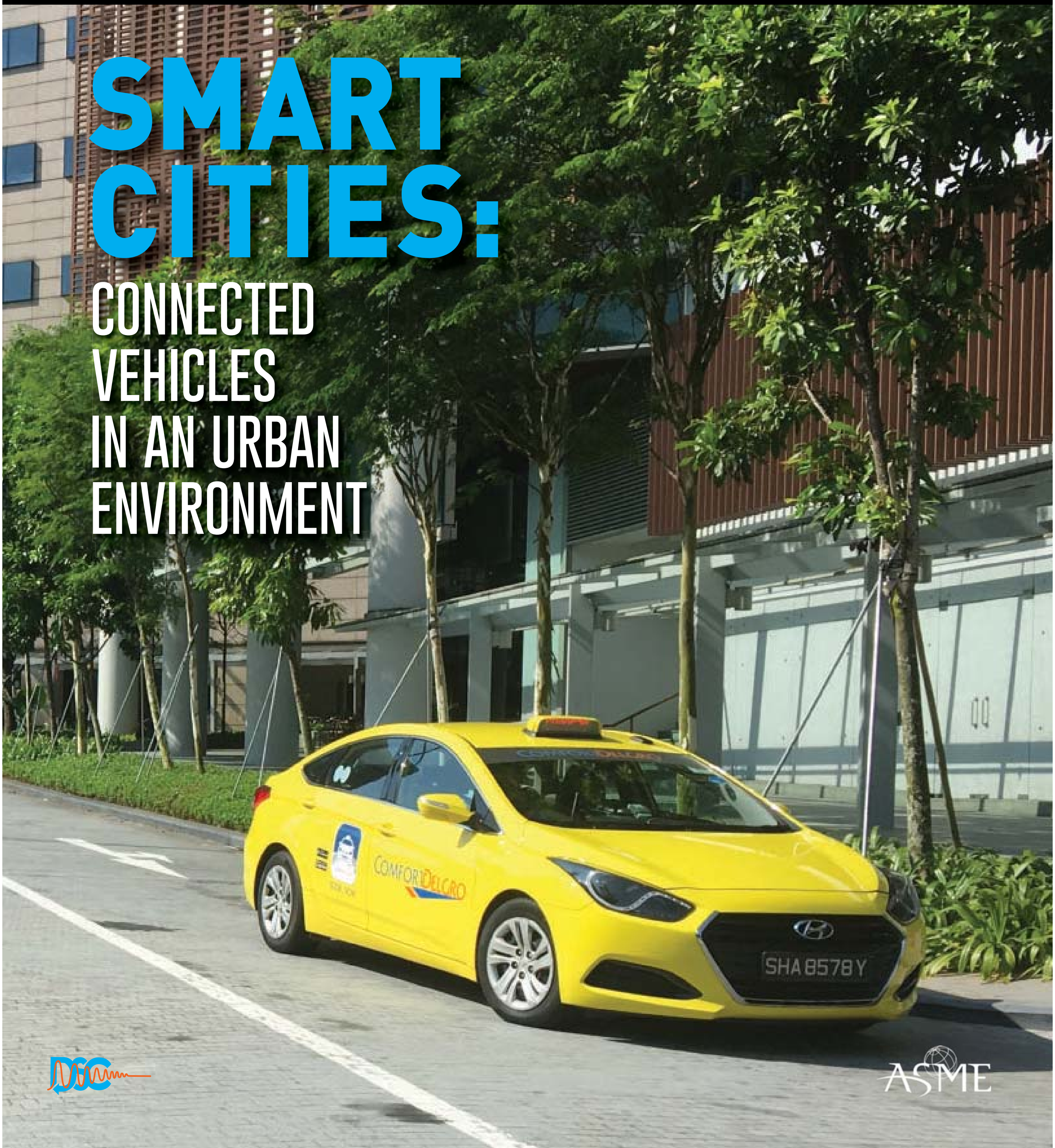
DYNAMIC SYSTEMS & CONTROL

DECEMBER 2017 VOL. 5 NO. 4

SMART CITIES:

CONNECTED VEHICLES IN AN URBAN ENVIRONMENT



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Smart Cities: Connected and Automated Vehicles in an Urban Environment

The **Smart City** vision seeks to realize intelligent, interconnected, self-aware, self-optimizing systems-of-systems in urban settings, leveraging the ongoing revolutions in information and communication technology (ICT) and Internet of things (IoT). Tangible exemplars of this vision now include Connected and Automated Vehicles with Vehicle-to-anything (V2X) connectivity operating within such a Smart City.

Significant new capabilities (e.g., improved spatio-temporal preview) enter the realm of possibility by merger of information-fusion and real-time connectivity of traditionally localized information to distributed non-traditional recipients. Enhanced situational awareness benefits both human and automated drivers to better understand the operational environment and to plan actions. However, realizing reliable, robust and secure deployments faces numerous challenges, including increased infrastructure requirements as well as operational complexity. In this twentieth issue of the DSC magazine, we bring you five thought-provoking articles from leading experts that showcase the impact of dynamic systems and control theories, methodologies and implementation on this front.

The first article, "Connected Cooperative Control of Autonomous Vehicles During Unexpected Road Situations" from researchers at the National University of Singapore/MIT highlights urban driving challenges stemming from both varied vehicle densities and area-specific traffic rules. V2X communication not only facilitates but also enhances urban driving, especially in the face of unexpected real-life variations/violations.

The *computational clairvoyance* ensuing from both enhanced perceptual ranges and automated multimodal information processing can significantly improve both safety and efficiency by facilitating earlier decision-making. Orosz, *et al.* from the University of Michigan showcase their efforts in exploring this frontier in the second article entitled, "Seeing Beyond the Line of Sight–Controlling Connected Automated Vehicles".

In their provocatively-titled article, "A Driver's License Test for Driverless Vehicles," Mangharam, *et al.* from the University of Pennsylvania argue the case for adapting a formal methods paradigm (employed in VLSI or software realms) to augment empirical AV performance testing. They address the formidable task of ensuring reliability, robustness and safety by advocating for a continuum treatment of lifecycle testing (simulation-and hardware-in-the-loop) coupled with adoption of formal methods (correct-by-construction, robustness-guided scenarios).

The open-architecture, open-standard nature of V2X communications makes them vulnerable to attacks, which can substantially degrade the efficiency and safety benefits afforded by the expanded situational awareness. In the fourth article, researchers from Clemson present a resilient Cooperative Adaptive Cruise Control (CACC) scheme that can both detect and gracefully degrade (to ACC) to mitigate deleterious effects of both natural imperfections (range-and band-limitations, noise) but also malicious intent (Denial of Service or False Data Injection attacks).

The availability of talent with this skillset to realize intelligent, interoperable self-aware and self-optimizing systems-of-systems is proving to be one of the critical bottlenecks for deployment of connected and automated vehicles (and the longer-term Smart City vision). The final article from McKenzie and McPhee entitled "Research and Educational Programs for Connected and Autonomous Vehicles at the University of Waterloo" makes the case for comprehensive programmatic development of "in-vehicle" and "systems-engineering" based education to prepare the next generation of engineers.

I would express my deep appreciation to all authors who made contributions to this magazine.

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

Venkat N. Krovi, PhD
Guest Editor, *DSC Magazine*

COVER IMAGE: HANS ANDERSEN

CONNECTED COOPERATIVE CONTROL OF AUTONOMOUS VEHICLES DURING UNEXPECTED ROAD SITUATIONS

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Autonomous driving in urban environments has been of great interest to researchers due in part to the high density of vehicles and various area-specific traffic rules that must be obeyed. The DARPA Urban Challenge [1], and more recently the V-Charge Project catalyzed the launch of research efforts into autonomous driving on urban roads for numerous organizations. Referring to **Figure 1**, the problem of urban driving is both interesting and difficult because it encompasses both increased operating speeds of autonomous vehicles as well as increased environmental complexity. A mature solution in one environment may not work in another due to different traffic rules and human driving characteristics that are unique in each urban area. A particularly difficult problem arises when unexpected situations happen during the autonomous run, and may require the unmanned system to break the corresponding traffic rule in order to progress along its own course. Vehicle-to-Vehicle (V2V) communication offers the promise of enhancements on both urban driving fronts, especially when faced with unexpected situations.

An overview of autonomous vehicle software architecture [2] is shown in **Figure 2.** The subsystems of an autonomous vehicle can be broadly grouped into three categories: perception, planning and control.

Perception is the ability of an autonomous system to extract relevant knowledge and understanding about itself and its environment through internal sensing and external environmental sensing. Internal sensing is essentially to observe the states of current sensors, switches, and actuators, which are mainly used for self-diagnosis. The external sensing includes estimation of the current location, map features, and dynamic objects, which are used for localization, mapping, and obstacle detection, respectively. The detected obstacles are considered in both path planning and speed control.

Planning for autonomous driving is usually performed in a hierarchical manner. The mission planner (or route planner) considers high-level objectives, such as assignment of pickup/drop-off tasks and which roads should be taken to achieve the tasks. The behavioral planner (or decision-maker) makes ad-hoc decisions to properly interact with other agents and follow rules restrictions, and thereby generates local objectives, e.g., change lanes, overtake, or proceed through an intersection. The motion planner generates a locally-optimal path that avoids unexpected obstacles. The planned path is then fed into the motion control module.

The motion control module consists of several subsystems. The longitudinal controller outputs brake or throttle signals to the actuation system so that the speed of the vehicle tracks the desired speed. The lateral controller outputs a steering signal to the actuation system so that the vehicle follows the desired path. In case of any emergency situations, the emergency module will be enabled to stop the vehicle appropriately.

Autonomous driving on urban roads has seen tremendous progress in recent years, with several commercial entities pushing the research boundaries alongside academia. Google has perhaps the most experience in the area, having tested its fleet of autonomous vehicles for more than 2 million miles [3]. Tesla is early to market their work, having already provided an autopilot feature in their 2016 Model S cars. Uber's mobility service has grown to upset the taxi markets in numerous cities worldwide, and has furthermore recently indicated plans to eventually replace all their human-driven fleet with self-driving cars. Nutonomy is the first company in the world to introduce autonomous taxi service, which hit the roads of Singapore in August 2016 [4]. Nutonomy's success can also be attributed to the Singapore Government's initiative in opening some of the roads in one-north (**Figure 3**), a technology business district for autonomous vehicle testing.

FIGURE 1 **Complexity and operating velocity for various driving scenarios.** *Source: [1]*

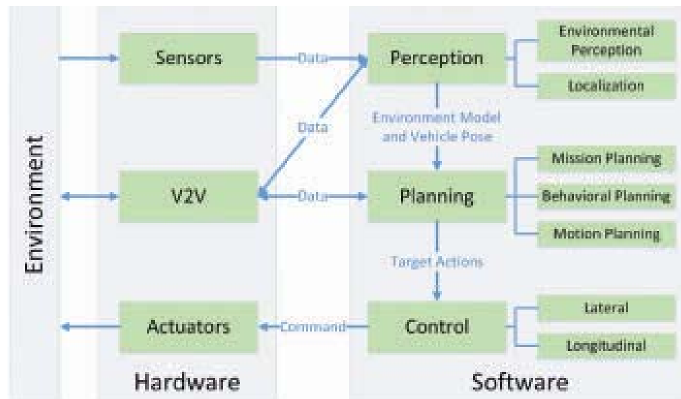

FIGURE 2 **A typical autonomous vehicle system overview, highlighting core competencies.** *Source: [1]*

However, all of the above-mentioned companies have reported accidents while driving autonomously. A preliminary analysis in 2015 by Schoettle and Sivak [5] has shown that autonomous vehicles have a higher crash rate per million miles traveled compared to conventional vehicles, and similar patterns were evident for injuries per million miles traveled and for injuries per crash. The report also concluded that none of the accidents reported thus far has been the fault of the autonomous vehicles, as their vehicles have been programmed to follow the traffic rules conservatively.

UNEXPECTED SITUATIONS

Reacting to potentially hazardous unexpected situations is one of the key issues in autonomous driving in urban environments. An example scenario that we encounter very frequently during our autonomous vehicle deployment at the One-north area in Singapore is depicted in **Figure 4**. In this scenario, a car is illegally parked on the vehicle's ego lane, and therefore has to be overtaken. In this case, a human driver may have to move slightly into the opposite lane in order to clearly see in front of a car ahead. Once he has gathered enough information about the road ahead, then he can safely overtake. However, as this is two-way traffic, the overtaking implies that the vehicle invades to the opposite lane, and therefore will take the traffic head-on, causing a safety hazard.

A few different approaches have been proposed in recent literature to handle this kind of unexpected dilemma. Sampling-based methods, such as RRT* and its variants, are popular for trajectory planning. One notable variant, Minimum Violation RRT* (MVRRT*), has been proposed by Reyes Castro, et. al [6]. The authors express traffic rules as formulas using Linear Temporal Logic (LTL), and propose an incremental algorithm to generate a trajectory of a dynamical system that systematically picks which safety rules to violate and minimizes the level of risk involved. The system assumes a static environment, and that the environment is known a priori. The proposed system also relies on a carefully designed set of rules and formulations.

Guo, et al. [7] proposed a solution to circumventing the illegally parked vehicle by finding a lead vehicle in the ego lane and following its behavior to generate a trajectory that is based on a cubic spline model with mass-spring-damper system. However, this approach may fail if there are no leading vehicles in the ego lane or if the intention of the vehicle is unknown, as the urban traffic rules can be complicated and very dynamic.

Lee and Seo [8] have proposed another learning-based method for such circumstances. They proposed a framework based on inverse reinforcement learning and a Gaussian process. Real-world data collected from expert drivers are used to train a trajectory generator. Using the pre-trained weight, an optimal trajectory can be evaluated online. This approach also relies on manually defined and engineered features that have to be carefully chosen. The method also suffers from discretization error due to discontinuity in the problem formulation and training. In general, learning-based motion planning methods often act as black boxes that are very difficult to systematically analyze and therefore prove safety. Learning-based methods also rely on availability of valid expert data and feature engineering. Acceptable driving styles under unexpected situations can differ from one place to another, and therefore a network that has been trained under one circumstance may not be applicable in the other.

Such problem is often formulated as a constrained optimization problem and the locally-optimal solution to the problem is computed with a receding horizon. This controller is referred to in the literature as a Model Predictive Controller (MPC). Compared to learning-based methods, MPC requires more in-depth understanding of the problem, and accurate problem modeling and formulation. However, in contrast to learning methods, there is a huge literature on the analytical aspects of the optimization problem, and therefore it is possible to design a controller that balances safety and complexity.

MPC has a few other attractive features. First, it is possible to intuitively incorporate vehicle dynamics into the problem formulation. Second, the problem can be formulated in continuous time, and therefore does not possess the problems that probabilistic motion planning methods possess, including inherent inaccuracy due to discretization limits, and the computational complexity that rises exponentially as the dimensionality of the planning state space increases.

Probabilistic motion planning methods' main strength is its probabilistic completeness, and global optimality. However, due to the limitation in the sensor range and the uncertain nature of driving in an urban environment, re-planning with a receding horizon is always necessary, and therefore it may be more practical to plan a locally-optimal solution within the prediction horizon.

Researchers have also approached this problem from the philosophical point of view, which argues whether autonomous vehicles have to be programmed to take the action that causes the least damage. Gerdes and Thornton [9] attempt to answer the ethical question for handling such dilemmas by formulating the motion planning as an MPC problem. They argue that ethical autonomous vehicles must obey traffic rules, except where obeying the traffic rules could cause a collision with human agents, other vehicles or the environment. Therefore, traffic rules have to be formulated as a cost term in the MPC formulation.

In recent work [10], we have formulated the problem of overtaking an illegally parked vehicle on a 2-way street as an MPC problem. Referring to **Figure 5**, unexpected objects on the ego lane will cause occlusion and therefore the vehicle has to move out of its ego lane to gather sufficient information before making the decision whether to overtake the obstacle or not. We have observed the following behavior of human drivers facing the described scenario: they will first decelerate the vehicle, and move closer to the center of the lane and assess the traffic on the opposite lane as well as the distance that the driver has to overtake, before finally overtaking the obstacle and merging back to the ego lane. Based on this observation, we have designed a behavior planner with costs and constraints of the MPC problem. In contrast to previous works, we also consider visibility maximization (blind spot minimization), to generate overtaking trajectories that take into account the perception limitations of the ego vehicle.

Simulation results have shown that the proposed method is capable of making a safe decision when deciding and overtaking the obstacles. However, there are risks associated with the limited perception range of the on-board sensors of the vehicle. These risks can be mitigated by having an inter-vehicle communication system, which will be discussed next.

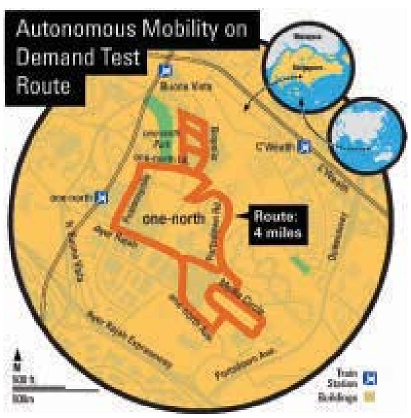

FIGURE 3 Autonomous vehicle testing area in One-north, Singapore. *Image: Delphi.*

FIGURE 4 Unexpected static obstacle in the form of an illegally-parked car on a two-way street. *Image: Hans Andersen.*

CONNECTED VEHICLES

Cooperation between multiple autonomous vehicles (AVs) is possible with the development of vehicular communication. In particular, state estimation can be improved with multiple sources of information gathered from different vehicles. Cooperative state estimation can also improve robustness against communication failure. With future trajectories shared among nearby vehicles, the motion can be coordinated to make navigation safer and smoother for AVs.

VEHICULAR COMMUNICATION

Vehicular communication technology has been progressing rapidly, enabling connection between vehicles via wireless networks. The bandwidth and range of wireless communication are increasing rapidly while the latency is being significantly reduced. For example, the communication range of Dedicated Short Range Communications (DSRC) can be up to one kilometer, allowing a vehicle to connect to nearby vehicles even beyond line-of-sight and field-of-view. Furthermore, the information can be relayed and multi-hop connections are possible, which can significantly increase the connectivity. For vehicular communication, the IEEE 802.11p standard has been designed to allow information exchange between high-speed cars, and between vehicles and roadside infrastructure. Other wireless communication technologies, such as 3G, 4G and WiFi, are also suggested in [11].

COOPERATIVE LOCALIZATION

Global Positioning System (GPS) is a widely-used method for estimating a vehicle's location, however, it is generally unavailable or unreliable due to signal obstruction or multi-path effects, especially in urban environments. Cooperative information sharing and fusion enables significant improvement in vehicle localization, e.g., by installing transmitters in the infrastructure, correction messages can be shared so as to improve the estimation accuracy. In order to reduce the common GPS bias, the GPS coordinates can be shared with neighboring vehicles through vehicle to vehicle (V2V) communication and rectified by applying a constraint that the group of vehicles must all reside on the road. Usually, a digital map, i.e., the road network, is used for group map matching, however other approaches such as pairwise map merging using Simultaneous Lo-

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calization and Mapping (SLAM) methods [12] can also be utilized for estimating the relative pose between two vehicles. Relative observations are commonly used for cooperative localization, which can be categorized into four groups: relative range, relative bearing, relative position, and relative pose. Some sensors can only give the range information while others can only give bearing information. For instance, acoustic sensors can only measure the relative distance by measuring the Time of Arrival (TOA), while the monocular camera can only measure the bearing angle. If the sensor can measure both TOA and Angle of Arrival (AOA), it can provide the relative position.

After the shared information has been received, the remaining two steps of cooperative localization are data association and data fusion. Most of cooperative localization is performed in simulation, where vehicle identities are assumed to be known. The vehicle identity problem is solved by using a distinct transmitting signal [13]. The data association is a challenging problem due to combinatorial explosion. Some methods use topology information or symmetric measurement equation (SME) to avoid data association. Other methods use PHD filter, nearest neighbors assignment with validation gate, and multiple hypotheses registration. For the data fusion, various methods are proposed, such as standard Kalman filter, cubature Kalman filter, Covariance Intersection filter, particle filter, factor graph optimization, maximum likelihood estimation (MLE), and Maximum A-Posteriori Estimation (MAP).

The open problems of multi-vehicle cooperative localization should at least include the following: communication delay and failure [13]; data bandwidth and cluttered environment [14]; robust data association and scalability [15].

COOPERATIVE CONTROL

Planned future trajectories can also be shared so that the prediction of cooperating vehicles' future positions can be better facilitated. Potential motion conflicts can then be identified and mitigated with motion coordination algorithms, which can guarantee that decisions are jointly feasible.

With future trajectories shared among vehicles via vehicle to vehicle (V2V) communication, the collective vehicle motion can be coordinated in an optimal way to avoid conflicts. Multi-robot motion planning has been studied extensively to take into account the paths of other robots so as to avoid any possible collision, congestion or deadlock. A wide variety of methods have been proposed in the literature, which is often categorized along the spectrum between centralized and decoupled planning. Centralized approaches plan the path in the composite configuration space that is formed by the Cartesian product of configuration spaces of individual robots and then extracts the trajectories for the individuals to execute. Probabilistic motion planning algorithms, such as A*, D* and RRT*, can be leveraged to ensure completeness and optimality. The decoupled planning can be further classified into two, namely prioritized planning and path-velocity planning. The prioritized planning method plans the path sequentially, according to the predefined or online computed priorities, and robots with planned paths are regarded as dynamic obstacles in the configuration-time space for the remaining robots to avoid. Much of the related research work has focused on the assignment of priorities to improve the quality of the solution [16]. The path-velocity planning method plans the path concurrently while ignoring the mutual collisions in the first phase and resolves the conflicts by velocity planning in the second phase. A hybrid of prioritized planning and path-velocity planning is introduced in [17] where motion coordination is conducted in an incremental manner. Nonetheless, the decoupled planning sacrifices the completeness and optimality for efficiency and applicability.

While there are many multi-robot/multi-vehicle motion planning algorithms available, only some are actually applicable in multi-vehicle motion coordination. There is some uniqueness to the multi-vehicle motion coordination problem. The following four traits are specific to multi-vehicle motion coordination:

1) The goals are usually not interchangeable for vehicles because each vehicle has its own destination, and thus there is no need to maintain communication connectivity.

2) The vehicles need to stay in the middle of the lane, and thus the path is fixed in most circumstances.

3) The vehicles are usually moving fast and thus communication latency is a critical variable in collision avoidance.

4) Reverse motion is typically not allowed on the road because of traffic rules.

An example motion coordination algorithm that considers these aspects is proposed in [18]. In the proposed method, V2V communication is combined with graph search in the coordination diagram to resolve conflicts in future trajectories and minimize the total waiting time, and plan time-optimal trajectories.

CONCLUSION

Autonomous vehicles have come a long way from research labs to nearing full commercialization. However, we believe that its best days are still ahead. Many modern cars have been advertised to have autonomous driving capabilities, but these features are mostly demonstrated for automated highway driving, and still require human attention. Driving autonomously in urban areas poses a completely different challenge due to the complexity of the traffic rules as well as unexpected scenarios involved.

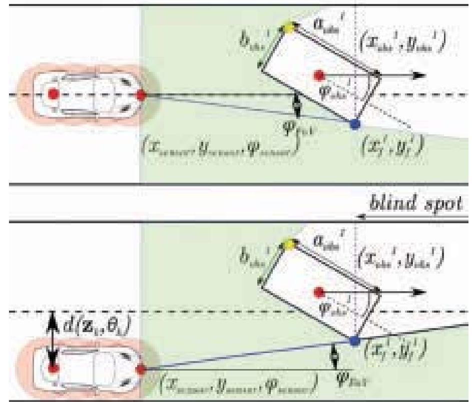

FIGURE 5 Complete occlusion (top) and blind spot (bottom) of a vehicle approaching an obstacle. *Source: [10]*

Reacting to these scenarios is still a very challenging topic, especially when the autonomous vehicle has to break traffic rules, or pick the best of two evils. The ultimate goal of deploying autonomous vehicles is to provide safe and comfortable mobility, and thus it is important to reduce the instances in which the system has to make such decisions by managing the unexpected risks associated with unenforced traffic rules.

Future research has to address these issues not only by planning safe behavior and motion, but also harnessing the superhuman perception that connected vehicles enable. Finally, it is then critical to carefully integrate all of the software components in the system, ensuring that the interactions between different software components are meaningful and valid. ■

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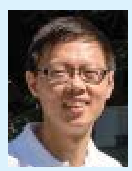

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SEEING BEYOND THE
CONTROLLING CONNECTED AUTOMATED VEHICLES

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During the last two decades, auto manufacturers and technology companies have been developing vehicles with high levels of automation. Many advanced driver assistance technologies have already been made available on production vehicles while OEMs are still working toward full automation. In the meantime, a new generation of vehicle-to-everything (V2X) wireless communication technologies have been introduced to allow vehicles to share information with each other and with the fixed infrastructure. Merging connectivity and automation has large potential benefits for safety, fuel economy, and traffic efficiency but it also poses many challenges for vehicle control design. In this article, we discuss some past, present and future research on connected automated vehicles and their impact on road transportation. We also describe some specific algorithms and show the related experimental results to highlight the benefits of using beyond-line-of-sight information in real-world traffic systems.

BRIEF HISTORY OF VEHICLE AUTOMATION AND CONNECTIVITY

The last few decades have witnessed increasing automation of automobiles and heavy-duty vehicles. From the 1980s, microcontrollers started to penetrate production vehicles through various subsystems such as engine control units, anti-lock braking systems, etc. Soon the need for different microcontrollers to communicate with each other led to the invention of the controller area network (CAN) bus. In the 1990s, we started to see the appearance of on-board sensors that were used to monitor the environment and the motion of neighboring vehicles. These sensors, combined with more powerful computers, allowed vehicles to perform lateral and longitudinal control such as lane keeping and car following. Some of these efforts culminated in demonstrations such as the 1997 California PATH experiment in which eight automated vehicles were driven from Los Angeles to San Diego using a dedicated highway [1]. These technologies started to appear on high-end production vehicles in the late 1990s and early 2000s. In the meantime, with more powerful on-board

LINE OF SIGHT –

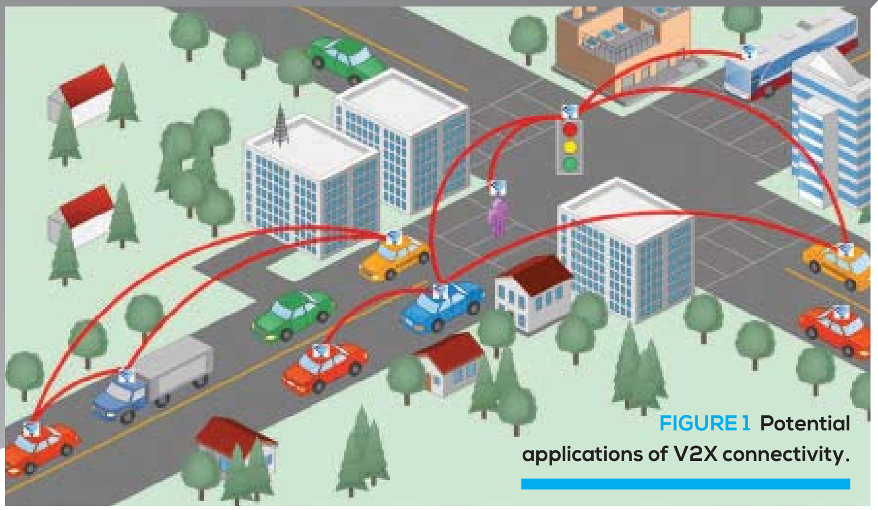

FIGURE 1 Potential applications of V2X connectivity.

computers and sensors such as GPS, lidar/radar, and cameras, researchers started to push toward higher levels of autonomy. These efforts were stimulated by events such as the DARPA Grand Challenges, where vehicles were given the task to drive autonomously in complex environments [2]. During the past decade, most major auto manufacturers have been investing in vehicle automation with the final goal of developing self-driving vehicles [3], while legislators have been making efforts to create an environment where such innovations thrive [4].

Starting from the mid-2000s, wireless communication technologies such as WiFi and 4G/LTE have been adopted in order to facilitate vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. These are often referred to as vehicle-to-everything (V2X) communication, where X also includes pedestrians, bicyclists, etc. In particular, in the US, dedicated short range communication (DSRC) has been standardized based on IEEE 802.11p protocol, which allows low-latency, ad-hoc, peer-to-peer communication with 10 Hz update frequency. Moreover, message sets such as the basic safety message (BSM) and the signal phase and timing (SPaT) message have been standardized during the last half decade. A set of new technological vendors have been developing and manufacturing on-board and roadside units, allowing the creation of V2X-based safety applications that warn drivers about impending dangers [5, 6]. These include V2V applications such as forward collision warning, blind spot warning, intersection movement assist and V2I applications such as red light violation warning, curve speed warning, and weather condition warning; see **Figure 1**. Most of these applications can be realized based on BSMs (that contain GPS position, speed, heading angle, and yaw rate) and SPaT messages, while customized information (such as pedal positions in the CAN data) may also be sent utilizing the WAVE short messages protocol (WSMP). Warnings can be communicated to the driver using visual, auditory or haptic cues. Due to the human limitations in processing a large amount of information within limited time, it is desirable to use computers to process and aggregate information. The synthesized control actions may be suggested to the driver or executed by an automated system.

CONNECTED AUTOMATED VEHICLES IN HUMAN-DRIVEN TRAFFIC

During the past five years, automated driving technologies have progressed through many milestones, such as accumulating millions of miles in real-traffic testing. While the driving automation is learning to deal with more complex environments, there remain a considerable number of disengagement incidents, where an automated vehicle is unable to safely navigate the traffic and calls for human intervention [7]. It is not only difficult to eliminate such disengagements, but also difficult to ensure safe human take-over, because current on-board sensors need higher reliability, more redundancy, and larger perception range [8]. For example, radar/lidar and cameras may be able to obtain the distance of a vehicle within the line of sight, but they often cannot provide information such as the heading angle or yaw rate [2]. This may lead to difficulties in predicting and tracking the motion of surrounding vehicles, and such difficulties have been observed to trigger disengagements of automated vehicles at intersections and highway ramps [7]. Similarly, many disengagement incidents happen due to non-ideal weather/road conditions where the sensors could not determine the color of traffic lights or the position of lanes.

Aside from limited information type and working conditions, the most fundamental limitation on-board sensors face is the line of sight: they cannot see through an obstructing object or see around a blind corner. This gives an automated vehicle a confined view of its surroundings, which can impact the safety margin of its driving strategies. Thus, it is desirable to equip an automated vehicle with V2X communication so that it utilizes information both within and beyond its line of sight for decision-making and motion-control. We refer to such a vehicle as a connected automated vehicle (CAV).

V2X connectivity can greatly enhance the capability of automated vehicles to perceive their environment. Connected automated vehicles are able to see around a blind corner when moving toward an intersection, and know whether any vehicle is approaching from other directions. They can see through dozens of cars when a car several hundred meters ahead is skidding on ice or applying harsh braking, and decide how to avoid the safety hazard [5, 6]. Even information within the line of sight available via sensors can be augmented by V2X connectivity. For example, a connected automated vehicle can obtain accurate heading angle and yaw rate from BSMs transmitted by a neighboring vehicle, and determine with higher confidence whether the other vehicle is turning or changing lanes. Similarly, a connected automated vehicle can obtain from SPaT

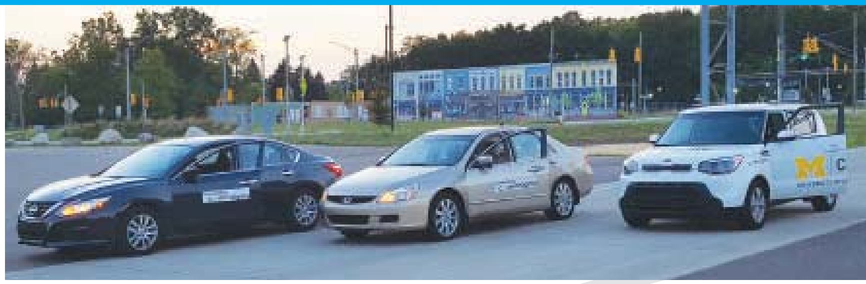

FIGURE 2 **Two connected (left and middle) and a connected automated vehicle (right).**

messages not only the exact color of the traffic lights, but also when the lights will change, which may help it to decide how to approach an intersection [9]. Perceiving events within and beyond the line of sight allows a connected automated vehicle to build up clairvoyance, so that it responds to situations earlier, makes better decisions, and avoids hazardous scenarios.

Because of the benefits that V2X connectivity promises, we are expecting a rapid increase in the penetration of V2X communication devices in the near future. On the vehicle side, multiple automakers are equipping new production vehicles with on-board units facilitating V2V and V2I communication, since the added cost is very small compared with the potential benefits [10-12]. On the infrastructure side, multiple US cities are piloting the deployment of roadside units [13, 14], while countries like Japan have already built such infrastructure in multiple areas.

Given the rapid expansion of V2X technology and the ambitious self-driving timeline from many automakers, a future where all vehicles are connected and automated seems within reach. Researchers are already designing sophisticated controllers for CAVs to cruise the highway in platoons [15-20] or cross intersections with no traffic lights [21-23]. However, as V2X devices and higher-level driving automation gradually penetrate the market, early generations of CAVs will need to operate in traffic systems where most vehicles are human-driven and only a fraction of those are equipped with V2X devices. Then a key question to answer is how connectivity can be utilized by a CAV so that it improves its own performance as well as the performance of the neighboring human-driven vehicles. This would lead to a paradigm shift in how we design the motion-control and decision-making algorithms: instead of passively responding to traffic perturbations created by human drivers, a connected automated vehicle may actively mitigate undesirable traffic behaviors propagating through the traffic flow.

LEARNING, ADAPTATION, AND CONTROL OF CAVS

By augmenting sensory information with V2X communication, connected automated vehicles are able to build up detailed knowledge of their driving environment and create data-based models for estimation, prediction, and control. However, a CAV needs to identify the constantly-changing configuration and driving behaviors of neighboring vehicles to be clairvoyant in real traffic. Such identification can be quite challenging, because a particular vehicle may only appear within the sensors' line of sight for a few seconds, and V2X information may not include every vehicle nearby. While algorithms based on a first-principle model can be used to identify the configuration of surrounding traffic, combining these with data-based methods may significantly enhance the robustness of estimation [24]. Similarly, in order to better describe and predict human driving behavior, important human parameters including driver reaction time can be identified using real-time V2X information [25]. Knowing the driving behavior of neighboring vehicles helps the CAV to adapt to different traffic environments, so that it can be better accepted by its human passengers as well as other road users.

While V2X communication allows connected automated cars to be clairvoyant, it also brings interesting challenges into decision-making and controller design through the highly-dynamic environment of vehicular traffic. For example, a connected automated vehicle and nearby human-driven vehicles (some of which are equipped with V2X devices) form an ad-hoc connected vehicle system that has time-varying configuration and network topology. Thus, a connected automated vehicle needs to be robust against uncertainties in the driving behavior of neighboring vehicles as well as against stochastic packet drops in wireless communication [25, 26]. Moreover, connectivity-based control algorithms need to be scalable and flexible, so that the macroscopic performance of a connected traffic system keeps improving as the penetration rate of V2X-equipped vehicles and connected automated vehicles increases [27]. In order to achieve this, one may identify beneficial motifs in vehicular networks and design connected automated vehicles to facilitate the formation of such motifs [28]. In particular, as the size of a connected vehicle system increases, algorithms with low computational costs will be needed to allow adaptation of connectivity topology with the limited sojourn time of V2X signals [29].

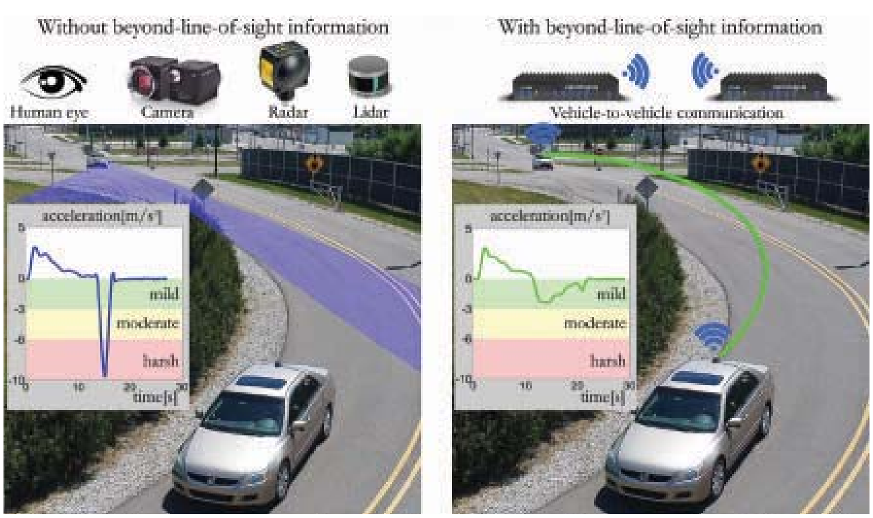

FIGURE 3 **Comparison of the behavior of a vehicle approaching a stationary vehicle.**

IMPROVING SAFETY AND EFFICIENCY OF TRAFFIC FLOW WITH CAVS

In order to demonstrate the benefits of utilizing beyond-line-of-sight information, we carried out a series of experiments using a connected automated vehicle that responded to the motion of multiple human-driven vehicles equipped with GPS and DSRC devices; see **Figure 2**. The results below show that connectivity, when utilized appropriately, may significantly improve the safety and efficiency of the CAV and the human-driven vehicles around it [30].

The first experiment is summarized in **Figure 3**, where a vehicle is approaching another vehicle stopped along the road. Due to the road geometry and elevation, the stationary vehicle only appears within the line of sight when the distance between the two vehicles is around 25 meters. Thus, harsh braking is required if the car was traveling close to the speed limit (35 mph). Indeed, a braking maneuver is recorded that reaches almost -10 m/s^2 (left panel of **Figure 3**). Such a deceleration not only adversely impacts passenger comfort, but may also lead to collisions under non-ideal road conditions. However, this potential hazard can be avoided when the line of sight of the human driver or on-board sensors (highlighted by the blue cones) is augmented by V2V information. In the right panel of **Figure 3**, the same scenario is handled by a connected automated vehicle that is aware of the stationary vehicle via V2V communication. In this case, its maximum deceleration only

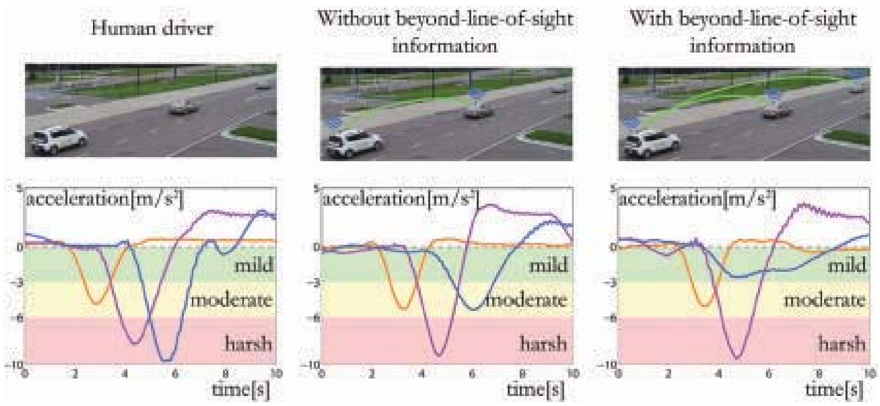

FIGURE 4 **Comparison of the behavior of a vehicle responding to a braking cascade.**

reaches -2 m/s^2, which would keep the vehicle safe even if the road surface was not ideal. We note that the connected automated vehicle starts braking when the stationary vehicle is around 70 meters away, well beyond the line of sight.

The second experiment is summarized in **Figure 4,** where three vehicles follow each other on a straight road and the human driver of the first vehicle applies moderate braking (around -5 m/s^2). In response to this perturbation, the human driver of the second vehicle brakes more severely (around -8 m/s^2). The left column shows that when the third vehicle is also driven by a human driver, its deceleration reaches a hazardous -10 m/s^2. The middle column shows the response of a connected automated vehicle in the same situation without beyond-line-of-sight information. That is, the CAV only responds to the motion of the human-driven vehicle immediately ahead (as a sensor-based automated vehicle might do). Due to smaller response time and better accuracy, it brakes less harshly with a peak deceleration around -5 m/s^2. Finally, the right column shows the scenario when the connected automated vehicle utilizes beyond-line-of sight information and responds to the motion of both vehicles ahead. Its peak

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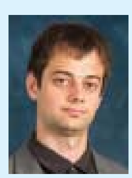

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deceleration is only $-2.5\ m/s^2$, indicating better safety and passenger comfort.

While the two examples above demonstrate that a CAV can be made safer by beyond-line-of-sight information, the robustness and scalability of connectivity-based control algorithms are also being experimentally validated. For example, when a non-transmitting vehicle is between the two DSRC-equipped human-driven vehicles ahead, the CAV is able to maintain a similar level of improvement without changing its controller. Moreover, when utilizing information from larger numbers of transmitting vehicles ahead, the CAV is able to further enhance its performance. Apart from safety improvements, beyond-line-of-sight information may be used to intercept the cascading perturbations among human-driven vehicles and alleviate stop-and-go traffic jams. This benefit can be realized through connected automated vehicle designs that are “head-to-tail string stable” [26]. Such a design was used in the right column of **Figure 4**, where the deceleration of the connected automated vehicle (tail) exhibits even smaller amplitude than the human-driven vehicle (head). Aside from smoother traffic flow, better energy efficiency has also been observed during road tests among real traffic [31]. The multiple experimental studies all indicate the positive impact of CAVs on the efficiency of the road transportation system.

OUTLOOK FOR CONNECTED AUTOMATED TECHNOLOGY

The results discussed in this article are only a small fraction of connected automated vehicle research. Many other interesting problems are being studied, especially regarding more diverse driving environments such as multi-lane roads, highway ramps, and traffic intersections with pedestrians and bicyclists. In these complex traffic scenarios, individual vehicles and other transportation participants may benefit more from harnessing V2X connectivity in decision-making and motion control. With automation and connectivity technologies increasingly integrated and validated on road vehicles, the road transportation system is stepping into a safer, more economical, and more efficient future. ■

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A DRIVER'S LICENSE TEST FOR DRIVERLESS VEHICLES

Autonomous vehicles (AVs) have already driven millions of miles on public roads, but even the simplest maneuvers such as a lane change or vehicle overtake have not been certified for safety. Current methodologies for testing of Advanced Driver Assistance Systems, such as Adaptive Cruise Control, cannot be directly applied to determine AV safety as the AV actively makes *decisions* using its perception, planning and control systems for both longitudinal and lateral motion. These systems increasingly use machine learning components whose safety is hard to guarantee across a range of driving scenarios and environmental conditions.

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New approaches are needed to bound and minimize the risk of AVs to reassure the public, determine insurance pricing and ensure the long-term growth of the domain. So what type of evidence should we require before giving a driver's license to an autonomous vehicle? To answer this question, consider the major components which make up an AV. An AV is typically equipped with multiple sensors, such as a LIDAR (a laser range finder) and several cameras (**Figure 1**(1)). The readings of these sensors are processed by algorithms that extract a model of the current scene, like object detectors, in order to understand *who's doing what and where*. This information is then fused together to provide the AV with its state estimate, such as position and velocity, and that of the other agents in the scene. The AV must then decide where to go next (a discrete decision taken by the behavioral planner), what continuous trajectory to follow to get there (a computation performed by the trajectory planner) and how to actuate steering and acceleration to follow that trajectory (performed by the trajectory tracker). Add to this the interaction with other vehicles, changing weather conditions and the respect of traffic laws, and it is clear that verifying correctness of AV behavior is a gargantuan task.

WHOLE-AV TESTING

Such considerations have led AV researchers to *formal methods* to provide a high level of assurance. This term encompasses a wide field of theory, techniques and tools for answering the following question: Given a *mathematical model* of a System Under Test (SUT), and a *formal specification* of correct system behavior, does the SUT model satisfy the specification? A formal tool's answer is *complete and sound*[1]. If the SUT model is incorrect, the tool *will* find an example violation, also called a *counterexample*. And if the tool returns that "The model is correct", then the model is indeed correct and does not violate the specification. Unlike testing, there is no question of 'Could we have found a bug if we had tested more?'

Formal methods applied to the problem of AV verification

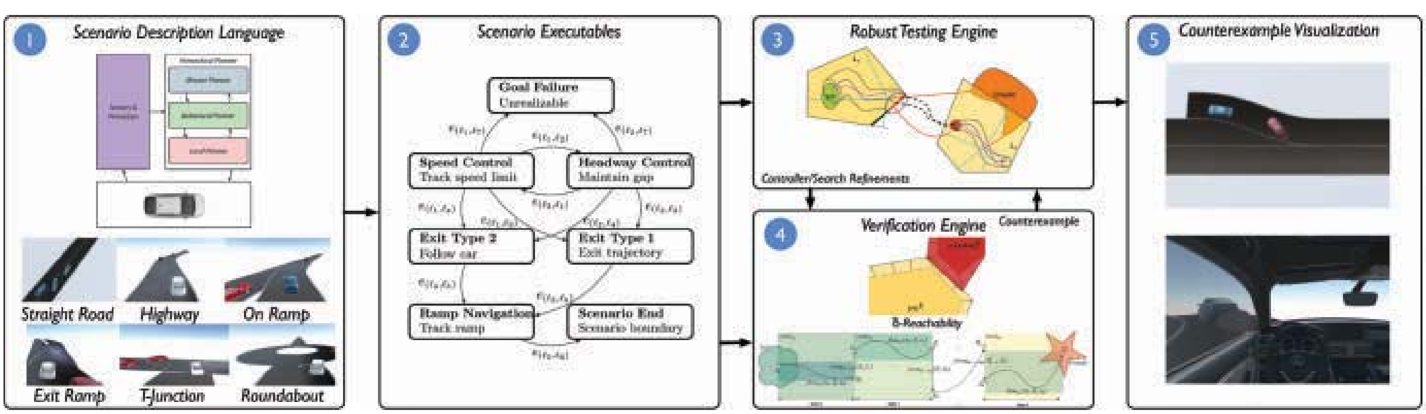

FIGURE 1 The AVCAD toolchain: (1) A Scenario Description Language allows quick creation of driving scenarios (2) The scenarios are translated into formats that can be processed by the testing and verification tools (3) Robust Testing [G. Fainekos] (4) Formal Verification Engine [S. Kong] (5) Requirement violations are visualized for an intuitive understanding of the violation.

[1] Though some provide approximate answers for more complicated models.

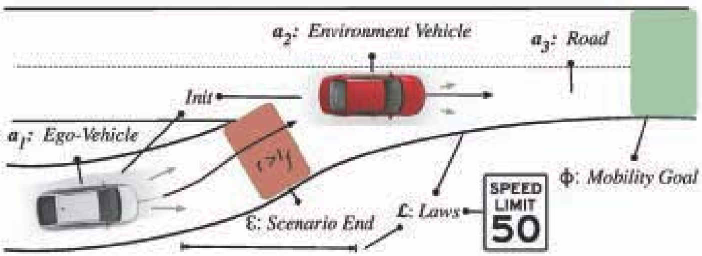

FIGURE 2 On-ramp scenario.

include theorem proving [1, 2], reachability analysis [3], synthesis [4, 5, 6], and maneuver design [7]. Theorem proving is an interactive technique in which the computer is largely responsible for demonstrating that the model satisfies the specification, with occasional help from the user. The latter provides lemmas and axioms that the tool leverages to advance the proof towards its conclusion. While this interactivity allows us to tackle more complex models, it also limits the scalability of the approach.Additionally, existing work such as [1] utilizes unrealistically conservative lemmas (such as, vehicle spacing of at least 291 feet) [8].

Reachability analysis is a popular formal technique where the reachable state space of the model is over-approximated and tested for intersection with a set of unsafe states. Reachability analysis is used in [9] to verify the operation of the AV *during navigation*. This provides an extension of on-board diagnostics to whole-AV operation, where the diagnosis does not concern one component's requirements, but the safety of the entire AV.

Another approach is to design *correct-by-construction* controllers from pre-verified maneuvers. The basic idea is that one builds a library of maneuvers, like Left-Turn and Right-Turn, and verifies (by Lyapunov analysis, say) that the car can perform these maneuvers from any initial state. Online, we restrict the AV's motion to be a composition of such maneuvers. This technique is closely related to motion planning algorithms and is limited to specific types of correctness criteria, like dynamical feasibility. Along these lines, a vigorous area of research concerns *controller synthesis from formal specifications* [4, 5], where formal verification techniques are adapted to *create* controllers that are correct relative to specifications in some temporal logic. Most of this work requires a discretization of the AV model's state-space and faces computational complexity barriers. Nonetheless, it forms the basis of a promising approach that divides the verification challenge into a design phase where correct-by-construction controllers are synthesized, and a post-design phase where these are used in a whole-AV verification effort.

COMBINING TESTING AND FORMAL VERIFICATION FOR WHOLE-CAR TESTING IN IDEALIZED ENVIRONMENTS

The guidance issued by NHTSA on the elements of a safety assurance case for AVs [10] is a starting point for standardizing the *type* of safety and correctness evidence needed for deployment of AVs. However, it does not prescribe *how* such evidence should be obtained. AV correctness, including safety, is a continuous spectrum: we should be able to rank vehicles by their relative safety, and compare one AV's performance across different scenarios. This is routinely done for human-driven cars, which receive safety ratings based, for example, on their crash performance and the technology they carry, like collision sensors. For AVs, such a continuous measure of correctness can and should be obtained *at design time, and measured throughout the design cycle*.

To illustrate the sorts of requirements that need to be formalized and measured, consider a Highway On-ramp scenario (**Figure 2**). The ego-vehicle, which is the AV under test, must merge while satisfying the following requirements:

1. At all times, stay at least 2 m from any fixed obstacle.

2. If the ego-vehicle is already in the merge point and an approaching vehicle on the highway is closer than 6 m, reach a speed of 45 mph within 6 sec.

3. Either reach the green rectangle within 20 secs or stay at the starting position until the road is clear.

These requirements increase in complexity: the first is a static no-collision requirement, the second adds a *reactive* element, and the third adds a pure *temporal* element. What are meaningful continuous measures of correctness for these requirements? For Req. 1, a meaningful measure ρ would be the minimum distance between the vehicle and any fixed obstacle over the course of the simulation. Req. 2 is more complicated since it involves different possibilities. It is reasonable to say that the correctness measure ρ in this case equals either the minimum distance

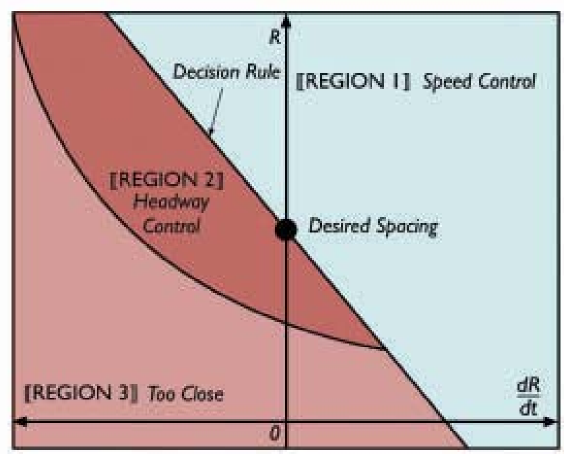

FIGURE 3 Hybrid Adaptive Cruise Controller. In Region 1 Speed Control, the AV tries to maintain a desired speed. It switches to Headway Control if a minimum time to collision constraint is violated. In Headway Control, the AV tries to maintain a given separation from the leading vehicle. R is the spacing to lead vehicle. In Region 3, the vehicle brakes to avoid collision.

between the two cars if it is above 7 m (so the minimum speed requirement is irrelevant), otherwise it equals the difference between the maximum car speed and 45 mph over the 6 sec window. What about the third requirement? Things are even more complicated because of the temporal 'until' component: should the correctness measure reward entering the intersection earlier? Should it differentiate between two different behaviors after the road clears? And what if *all* three requirements are part of the vehicle specification? How do we balance between all of them?

It becomes clear that we need a *systematic way* of calculating this correctness measure for *arbitrary* specifications involving reactive, spatio-temporal requirements. Such a measure of correctness is provided by the *robustness function* of Metric Temporal Logic (MTL) requirements [11]. Specifically, it is possible to express the AV requirements as a *formula* φ in MTL, which is a formal mathematical language for writing temporal specifications. Using a formal logic, like MTL, removes ambiguity from the requirements, and enables the use of *automatic* correctness checking tools that go a long way toward flushing out difficult bugs that could not be found by manually-created test cases.

Given a (reachability) MTL formula φ, the highest level of assurance is provided by *reachability analysis*, described earlier. To run such a powerful tool requires the development of an appropriate mathematical model of the *whole* AV, which is very challenging. Moreover, reachability tools can have very long runtimes.

To counter the second issue, the *robustness* ρ_φ of φ can be leveraged [12]. The robustness ρ_φ (x) of system execution x is a real number that measures two things about x: its sign tells whether x satisfies the spec ($\rho_\varphi(x) > 0$) or violates it ($\rho_\varphi(x) < 0$). Moreover, the trajectory x can be disturbed by an amount $|\rho_\varphi(x)|$ without changing its truth value (e.g., if it is correct, the disturbed trajectory is also correct). Thus, robustness is a continuous measure of correctness of the AV relative to the desired properties: if $\rho_\varphi(x_1) > \rho_\varphi(x_2) > 0$, this means x_1 is more robustly correct than x_2 since it can sustain a greater disturbance without violating the correctness specification.

The idea behind *robustness-guided verification* [13] is that we can first search the set of behaviors to find those executions with low robustness. Assuming continuity of behavior, low-robustness executions are surrounded by other low-robustness executions, and possibly by executions with negative robustness (**Figure 4**). The latter, then, are violations of φ. The reachability tool is run on a neighborhood of these low-robustness executions: rather than waste time on robustly-correct behavior, we focus on behavior that may reveal bugs. Formal verification and robustness, and the tools that implement them, are illustrated in the following example from the AV testing tool AVCAD [14].

***Scenario 1** (On-Ramp, **Figure 2**) There are two cars, the AV a_1 and an environment vehicle a_2. The AV is getting on the highway via an on-ramp, which is a cubic spline. The shape of the on-ramp matters because the tracking performance of the AV is altered by sharp curvatures. The AV uses a hybrid Adaptive Cruise Controller (ACC) shown in **Figure 3**. This ACC design has been utilized extensively on real vehicles, but is designed for operating conditions involving highway driving tasks with straight roads.*

*AVCAD, **Figure 1**, supports two tools:* S-TaLiRo *[12] and dReach [15].* S-TaLiRo *is a specification-guided automatic test generator for cyber-physical systems. By minimizing ρ_φ over the space of AV behaviors* x, S-TaLiRo *can find many different ways in which the AV violates the specification, thus promoting good coverage of the test space. dReach is a formal reachability tool that can exhaustively determine whether a dynamical system violates its specification.*

Robust testing in S-TaLiRo *was able to identify a design flaw within 8 seconds. In contrast, dReach also returned UNSAFE, but ran for 5+ hours. This raises the general point that when analyzing new controller designs, robust testing produces interpretable results more quickly than reachability. Once major design issues have been addressed in testing, then reachability can be used to certify the scenario as error-free, or find to corner case errors.*

*Additionally, robust testing can quickly identify potential safe sub-regions. **Figure 4** shows the robustness of system trajectories as a function of the initial velocity of the environment vehicle, its x-coordinate, and the goal region of the AV. Green points denote safe executions. **Figure 4** suggests that the system is robust on longer ramps (AV goal between 39 and 50 meters). dReach is able to prove that this region is safe in about 3 minutes, which should be contrasted with the 5+ hours it took to process the entire set of behaviors. This approach is useful because it can precisely answer regulatory questions such as: under what conditions is the system safe to operate?*

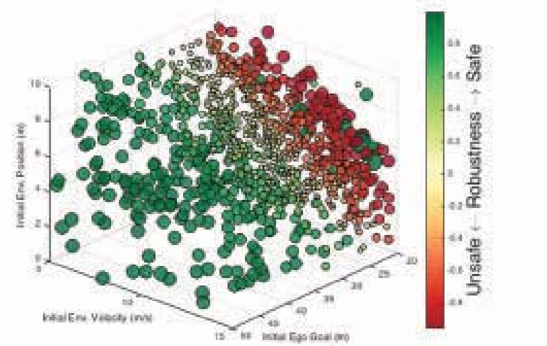

FIGURE 4
Robustness of On-Ramp scenario as a function of 3 initial state variables (1000 runs).

INCORPORATING A WORLD SIMULATOR INTO WHOLE-AV TESTING

An idealized mathematical model of the environment and other cars is not required for a testing tool like S-TaLiRo. The latter only requires the ability to execute the system under test (SUT). The SUT, in fact, could be the actual AV software that will execute on the physical hardware. Therefore, we can leverage advanced simulators that provide the AV perception pipeline with realistic input, such as video and depth data. The

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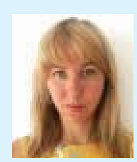

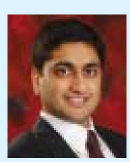

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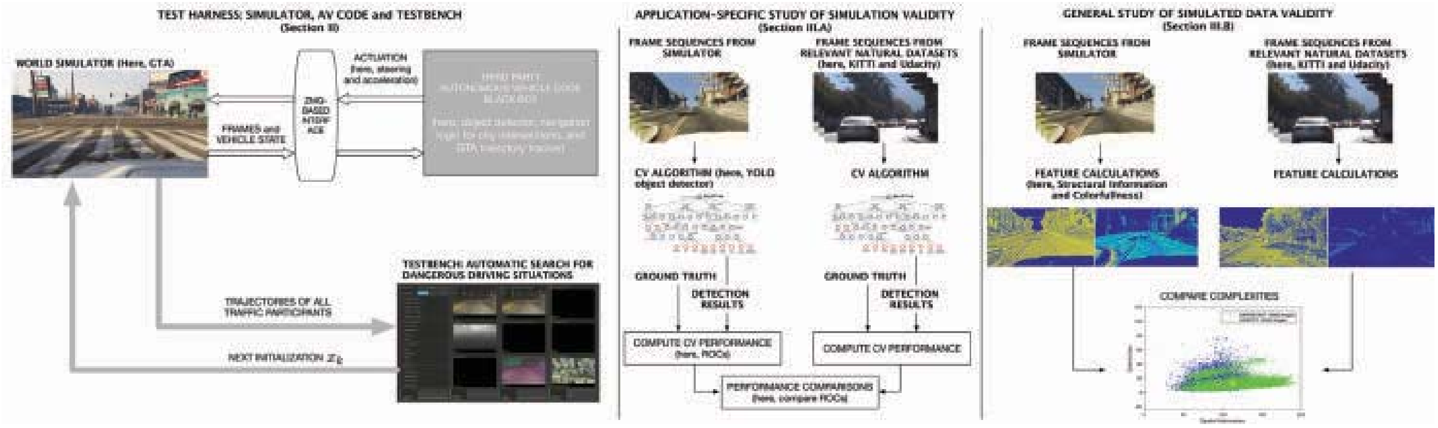

FIGURE 5 **The test harness. *(Left)* Robustness-guided search for unsafe behavior. The harness selects the initial position and velocity of the AV. It also selects initial environment conditions: positions and velocities of other cars, and time of day, which allows control of the illumination conditions. This initialization is sent to the world simulator (here, GTA), which simulates the scenario in lock-step with the AV code. Every frame produced by the game is sent to the AV to be processed by its perception pipeline. The AV controllers then compute the next actuation that is sent to the game to move the AV. *(Middle)* To validate simulation results, the perception code is run on simulated frames (from the world simulator) and on real datasets, and the performances are compared. *(Right)* The visual complexity of simulated and real datasets are compared to further assess whether simulated data can act as proxy for real data.**

perception code then processes this input and extracts from it information for the AV's controllers, such as position and speed of obstacles in the environment.

In [16], a test harness is presented that allows an AV to drive in a simulated world in real-time, as illustrated in **Figure 5**. A notable aspect of this harness is that it allows weather conditions to vary, thus stressing the perception pipeline. This is very important: the 2016 fatal accident in Florida involving a Tesla Auto-Pilot was partially due to a failure of the car's visual sensors to detect the truck blocking the AV's path against the bright sky. Issues like validity of simulated data are also addressed in [16].

Scenario 2 *The game Grand Theft Auto V (GTA) is used as a world simulator. At a T-junction in the GTA city map, the objective of the AV is to make a safe right turn, and obey the Stop Sign. Robust testing automatically found a non-trivial accident between the AV and another car in under 100 simulations. This was due to the right combination of poor lighting (robust testing automatically chose twilight conditions) and similar speeds for the AV and another car.*

MOVING FORWARD: TOWARD RISK ANALYSIS FOR AUTONOMOUS VEHICLES

Ultimately, after all the testing and verification, non-technical issues like insurance and liability must be settled for autonomous vehicles to become a commercial reality. Insurance speaks the language of risk: what is the probability of a terrible accident in this city? How often is this car model involved in minor collisions? With autonomous vehicles, we have a chance to answer these questions *before* the AV hits the road: by a careful choice of simulations, and with large amounts of traffic data, we can build a *risk profile* of an AV to guide the insurance pricing. The above techniques, from formal verification to testing, further this goal by giving complementary ways of quantifying the likelihood of an accident and its severity. An autonomous vehicle thus brings together disparate fields of inquiry, and may well be the first autonomous robot that deals directly with social questions like "What level of risk are we prepared to explicitly accept, and for what benefit and to whom?" ■

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A CONTROL-ORIENTED PERSPECTIVE FOR SECURITY IN CONNECTED AND AUTOMATED VEHICLES

Advanced connectivity features in today's smart vehicles are giving rise to several promising intelligent transportation technologies. Connected vehicles are one such technology where a set of vehicles can communicate with each other and the infrastructure via dedicated communication networks. Connected vehicles have the potential to improve the traffic throughput, minimize risk of accidents and reduce vehicle energy consumption. However, despite these promising features, vehicular communication networks endure several challenges from reliability and security perspectives. These challenges can occur due to cyberattacks with purposes of disrupting the performance of the connected vehicles system. In order to improve safety and security, advanced vehicular control systems must be designed to be resilient to cyberattacks. This article describes a resilient control architecture that consists of several control strategies for different network attacks, and a decision-making system to select the best countermeasure.

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V2V COMMUNICATION AND VULNERABILITIES IN CONNECTED VEHICLES

Connected vehicles (CV) present a significant advancement in transportation for improvement of safety, mobility, and energy consumption. Connected vehicles are able to communicate with other vehicles or the Department of Transportation (DOT) network resources through vehicular application and network (VANET). A variant of Wi-Fi referred to as Dedicated Short Range Communications (DSRC) is a candidate for use in a VANET that supports both public safety and private communication [1]. The communication environment of DSRC is both vehicle-to-vehicle (V2V) and vehicle-to/from-roadside infrastructure (V2I). DSRC aims to provide a high data rate and at the same time minimize latency within a relatively small communication zone. The broadband access speed can be up to 27 Mbps along with low latency (less than 50ms) over a range of up to 1 km, and uses a 75MHz block of spectrum in the 5.9 GHz band, which has been allocated by the FCC for automotive applications [2]. However, the DSRC communication network has not yet been fully evaluated and analyzed through field experiments in a systematic manner and has some issues regarding packet delivery and reliability of network specifically in real experimental scenarios [3]. The packet delivery ratio is affected by the velocity of mobile nodes. Experimental results show that the ratio of successful packet delivery (DSRC IEEE 802.11p) drops significantly (as large as 10 percent) as the relative velocity between the sender and receiver is about 60 mph, and this rate increases exponentially when the velocity increases further. These losses may be acceptable for cellular and stream applications, but pose a great challenge for networked control and diagnosis, which are typically vulnerable to message losses. Also, the communication delay is affected by the network interaction topology, which can increase exponentially with an increase in the size of the network. CVs have to constantly communicate with the infrastructure to acquire information for their maneuver actions. The accuracy requirement of networked control and diagnosis becomes difficult to maintain as vehicle speed increases [4]-[5]. A typical vehicle application utilizing DSRC communication is Cooperative Adaptive Cruise Control (CACC), where each individual vehicle automatically accelerates and decelerates to keep a desired distance from its preceding vehicle utilizing onboard sensors, such as radar, to measure the inter-vehicle distance and relative velocity while information of the preceding vehicle(s), such as their acceleration, is broadcast through the DSRC network. This enables vehicles to obtain information beyond the line-of-sight of onboard

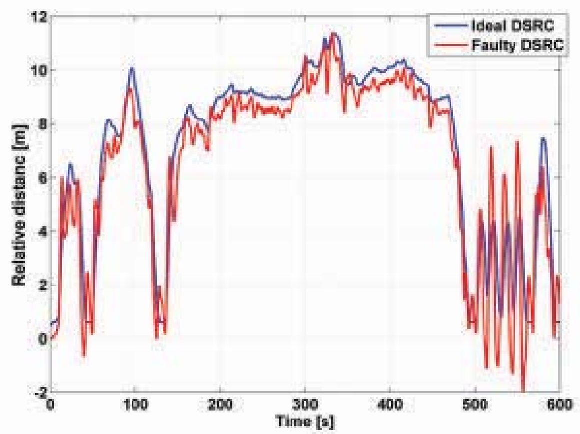

FIGURE 1 Impact of communication delay on relative distance between two connected vehicles.

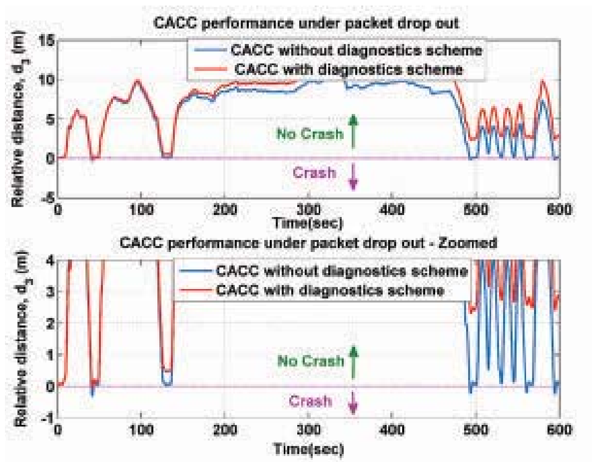

FIGURE 2 Impact of intermittent communication on relative distance between two connected vehicles.

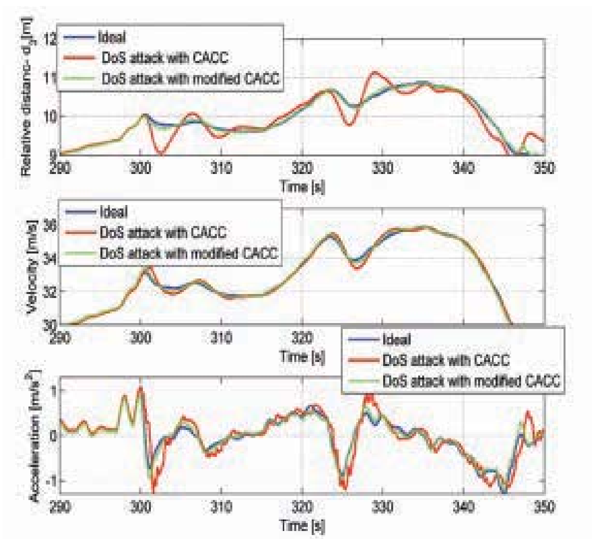

FIGURE 3 Impact of Denial of Service attack on relative distance between two connected vehicles, velocity, and acceleration of vehicles.

sensors and to obtain information of other vehicles that cannot be retrieved otherwise. As a result, short inter-vehicle distances can be realized, thus increasing traffic throughput, without compromising safety. Hence, the performance in terms of minimizing the inter-vehicle gap is enhanced, while guaranteeing string stability and disturbance attenuation in the platoon [6], specifically compared to conventional adaptive cruise control (ACC), which is operated without wireless communication [7]. Sharing information through the wireless communication network makes connected vehicles vulnerable to cyberattacks and network failures as well as physical faults. In [8], the capability of attackers to intrude vehicles is explored. It is shown that the attacker is theoretically able to take control over the individual position and velocity of other vehicles in the platoon.

Figure 1 shows the effect of network failure in cooperative adaptive cruise control (CACC). Here a platoon of connected vehicles is considered while their acceleration information is exchanged through the DSRC network. The leader vehicle follows the US06 driving cycle (a particular velocity profile defined by the Environmental Protection Agency for emissions testing) and the relative distance between two vehicles is considered as a criterion of vehicle performance while the network communication has some imperfection due to random transmission delay. In an ideal DSRC-based system, the relative distance between vehicles could potentially be as small as 0.5 meters. However, in real systems that include network impairment and possibly physical and software failures, the optimal distance between two vehicles would likely vary over time making the vehicles subject to crash. A way to avoid this issue is to improve robustness and capabilities of connected vehicle applications by enhancing safety and vehicular control.

EFFECTS OF ATTACKS ON COOPERATIVE CONTROL

Intermittent communication

Wireless links are known to be prone to errors and failures. Packet dropping is the most common failure in communication networks, causing intermittent communication, and occurs due to a number of factors including occasional hardware failures, degradation in link quality, and channel congestion. Although many network protocols have re-transmission mechanisms embedded, for real-time feedback control data, it may be advantageous to discard the failed packets on their first transmission because re-transmitted packets may have too large latency to be useful [9]. Re-transmission may also delay the transmission of new packets. In connected vehicles, due to limited computing power of the communication modules, error correction techniques are not common on the lower network levels. **Figure 2** shows the effect of packet dropping in the DSRC network in a platoon of vehicles equipped with CACC. To illustrate the effect, we have plotted the relative distance of two vehicles in a platoon. Without modifications, the CACC algorithm with intermittent communication will have degraded performance particularly if it doesn't switch to ACC algorithm. To enhance the performance of the CACC under packet dropping, an observer-based algorithm that estimates the lost information can be utilized [10]. The results are shown in **Figure 2** with the red curves.

DOS Attack

Cyberattacks are different from network failures because they are designed smartly by attackers. Hence, modeling the cyberattacks from a control perspective is more challenging than network failures, and requires detailed analysis over network and attacker capabilities.

Denial of service (DoS) attacks are perhaps the most detrimental attacks that affect the packet delivery because they have been proven capable of shutting off an organization from the Internet or dramatically slowing down network links [11]. The definition of DoS attack may vary in different studies; however, all describe the effect of DoS attack as the same. The violation of availability of sensor and control data is known as denial-of-service. DoS attacks can be classified into several different types, among which the packet flooding attack and data jamming, induced by a malicious adversary, are prevalent [12]-[13]. Attackers may flood a network with a large volume of data to deliberately consume the limited resources, such as CPU cycles, memory, network bandwidth, and packet buffers. Consequently, time delay and packet loss of transmitted information in connected vehicles become worse under such attacks, which in turn may significantly impair the system performance. In the existing literature, there are two main methodologies to model Denial of Service attack from a control perspective: time delays or packet loss [11]-[12]. Indeed, based on the network communication protocol and attacker capabilities, DoS attacker can flood the network with data, creating congestion and consequently packet loss. However, if the attacker does not make the attack too obvious on the network, it may flood the packets randomly on the network and try to increase the service time on the communication network [13]. **Figure 3** shows the effect of DoS attack, which is modeled as a time delay in the DSRC network. By developing a resilient strategy for DoS attack [14], the effect of the attack can be compensated (**Figure 3**, green line).

False data injection

In connected vehicles, false data injection attacks refer to a class of cyberattacks in which the attacker wishes to alter the integrity of a system by compromising either a subset of sensors and sending inaccurate readings to the controller or actuators data from the controller [15]. To carry out the attack, the input to the controller needs to be carefully designed since abnormal sensor measurements will generally trigger an alarm [16]. In the control literature, false data injection attacks are typically modeled as an additive sensor or actuator fault on the original data. Hence, existing fault detection algorithms, including Kalman filter [15], [16] and observer design [17], are capable of detecting the false data injection attack in the system. However, there are cases in which these types of attacks are not diagnosable with standard fault detection methodologies. To illustrate an example of this case, consider a smarter false data injection attack where the attacker uses fake identity to inject fake vehicle data into the DSRC network to disrupt the performance of the whole platooning of vehicles. The attacker provides fake vehicle information to increase or decrease the inter-vehicle distance, which can degrade the platoon performance and disrupt the stability of the string. Indeed, the attacker has the capability to develop a fake identity to insert fake cars into the platoon. Having a fake vehicle in the platoon (see **Figure 4**), makes decisions difficult for the follower car due to the conflict between physical observations and network observations. In this case, it is not clear if the following car should fill the physically open gap or follow the ghost injected vehicle. In [18] a solution is proposed based on a partial differential equation (PDE) model of a platoon of cooperating vehicles using PDE observer design for the identification of the fake data injection attack.

DECISION-MAKING RESILIENT CONTROL

The previous sections have explained how different attacks can affect the cooperative control in connected and automated vehicles

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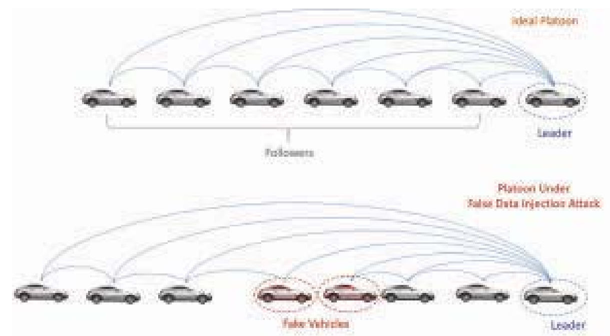

FIGURE 4 False data injection attack in a platoon of connected vehicles as ghost vehicle impacting density of the traffic.

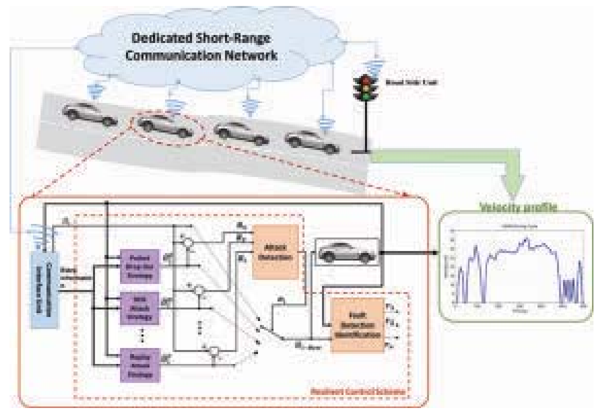

FIGURE 5 Developed CACC attack-resilient control scheme.

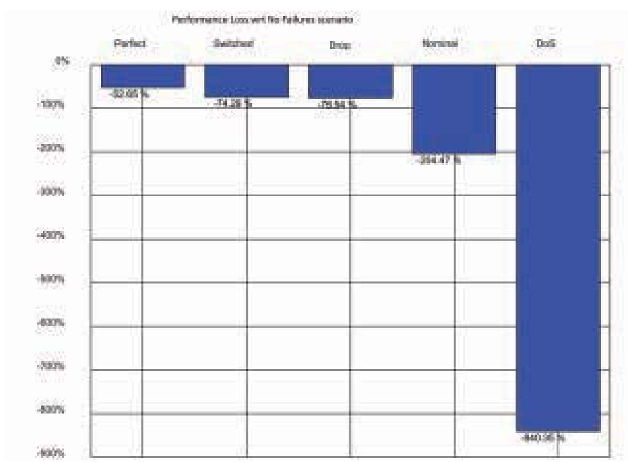

FIGURE 6 Performance loss associated with selection of the wrong strategy.

and how appropriate resilient control strategies can avoid collision and maintain functionality as long as safety can be guaranteed. Now the question is how to combine the aforementioned strategies in an integrated control scheme capable of selecting the appropriate strategy under unknown attack conditions. A hybrid format controller is required to determine which type of cyberattack is happening in the system and what are the corresponding actions to minimize the effect of that specific attack. In this section, an example of a decision maker using an optimum control algorithm to select the best control signal among the available choices is shown [18].

The attack detection and switching strategy in **Figure 5** is formulated as an MPC-like optimization problem where the control variable is constrained to one of the three strategies described in the previous section and applied in a receding horizon fashion. The choice of the cost function plays an important role in the performance of the system. In this case, the problem was formulated to penalize aggressive driving while maintaining safe distance from the preceding vehicle. **Figure 6** shows the results of the switching strategy with respect to the case with no networks attacks or failures using the RMS of the jerk as measure of comfort (performance index). By comparison with the perfect case, in which the attacks are perfectly identified and the correct strategy selected immediately, there is approximatively a 22 percent strategy improvement that could still be achieved by changing the switching strategy.

CONCLUSIONS

Network attacks are a real potential threat to the deployment of cooperative control functions in CVs. This article provides an overview of potential attacks that can impact CV technologies and highlights how a resilient control scheme can be effective to mitigate the effect of these attacks by allowing the system to safely operate with reduced performance. Further research in this area can offer more mature solutions to implement such strategies in a real production vehicle. ■

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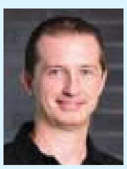

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RESEARCH AND EDUCATIONAL PROGRAMS FOR CONNECTED AND AUTONOMOUS VEHICLES AT THE UNIVERSITY OF WATERLOO

There are numerous challenges to overcome to advance from the current offering of automobiles with limited connectivity and partial automation, to a fully connected, highly automated vehicle that ultimately offers fully autonomous driving. University of Waterloo Centre for Automotive Research (WatCAR) faculty, staff and most importantly students are contributing to the development of in-vehicle systems education programs for connected and autonomous vehicles (CAVs) at Waterloo.

Waterloo's anechoic chamber, part of the Centre for Intelligent Antenna and Radio Systems (CIARS), offers both near-field and far-field testing capabilities, a world first.

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The UWaterloo programs take advantage of geographical location in undertaking CAV research. Waterloo is uniquely positioned within clusters for both automotive and information technology. The school is at the centre of Canada's 260-mile (415 km) automotive industry running from Detroit to east of Toronto, with 16 OEM facilities and over 700 Tier-1, -2, -3 parts manufacturers and materials suppliers. Meanwhile, the Toronto-Waterloo innovation corridor covers 60 miles (110 km) and is home to over 15,000 information technology companies.

UWaterloo is Canada's largest engineering school, with 9,500 engineering students and 309 engineering faculty. Co-operative education, which is mandatory for all Waterloo engineering undergraduates, is differentiated from other co-op programs by its four-month study/four-month work sequence. As a result, it takes five years to complete a four-year degree with co-op at Waterloo. Graduate student workplace experience is also a priority at Waterloo, with numerous internships in place at CAV partner companies.

Over 130 Waterloo faculty, 110 from engineering, are engaged in WatCAR's automotive and transportation systems research programs. The school's CAV efforts leverage WatCAR research expertise from 5 areas: (i) Connected and Autonomous; (ii) Software and Data; (iii) Lightweighting and Fabrication; (iv) Structure and Safety; and (v) Advanced Powertrain and Emissions. Foundational and operational artificial intelligence (AI) expertise from the University of Waterloo Artificial Intelligence Institute complements the autonomous driving efforts, in disciplines that include neural networks, pattern analysis and machine learning.

Faculty researchers lead teams of graduate students, post-doctoral fellows, undergrads, engineers in training, research technicians and research engineers to enhance and integrate CAV technologies in facilities across the campus, notably at WatCAR's 10-bay autonomous vehicle garage. WatCAR research is further enabled by preferential all-season access to the Region of Waterloo test track, a 3/4-mile (1.2 km) loop with a 220-yard (200 m) skid pad, instrumented traffic intersection, and vehicle-to-infrastructure (V2I) sensors, all supporting Waterloo's CAV research. The University of Waterloo was the first organization in Canada approved to test and operate self-driving vehicles on public roadways.

Industry partnerships are a strong, valued element of all automotive research projects at Waterloo. In connected vehicle projects, current partners include BlackBerry QNX, General Motors, Magna, Miovision and Toyota. Autonomous vehicle project work presently involves Applanix, Clearpath Robotics, Denso, Ford, General Motors, Maplesoft, NovAtel and Renesas Electronics. For example Renesas Electronics, the world's leading automotive semiconductor processor supplier, has engaged Waterloo to contribute key software elements to their Renesas autonomy vehicle in an ongoing capacity for the past two years.

DEMONSTRATOR AND TEST PLATFORMS

Connected Lexus Demonstrator

WatCAR researchers took their first deep dive with connectivity on a full-scale vehicle in 2013. As technology integrator for a demonstrator project, Waterloo's Real-time Embedded Software Group seamlessly connected 12 disparate technologies from 12 separate companies, making them fully functional on a Lexus SUV. Working through a QNX operating system, individual kernels were created for each installed technology.

Initiated by the Canadian Automotive Parts Manufacturers' Association (APMA), with lead partners BlackBerry QNX and Toyota, the Connected Lexus Demonstrator was taken directly to company offices and exhibited at select conferences, including ASME's 2014 Advanced Design and Manufacturing Impact Forum in Buffalo, simultaneously showcasing each company's technologies on the enhanced, fully functional SUV. The vehicle travelled throughout Michigan and Ontario as well as to California, New York, Kentucky and Quebec, completing demonstrations extensively for three years, while also profiling the collaborative result of a collective effort from all project partners.

WATonomous

In April 2017, Waterloo was selected as one of just eight schools from across North America to participate in AutoDrive, a newly established three-year autonomous driving competition. The team, named WATonomous, will use a Chevrolet Bolt provided by General Motors as their autonomous vehicle platform. Faculty supervisors for the team come from Engineering's Computer and Mechatronics programs, who will work with the team to identify and facilitate Capstone Design projects from elements of the AutoDrive competition. Graduate students serve as mentors and project managers, furthering the educational connection between the real world (competition) and academics.

The WATonomous team is based in the Sedra Student Design Centre, a 20,000 sq. ft. (1,860 sq. m) space that is home to 20 student competition teams and a hub for engineering experiential learning labs. Undergraduates, who may initially join a team based on personal interest, have the option to pursue a tie-in to their academic studies, which academic programming and the Student Design Centre both facilitate.

Autonomoose

Waterloo's first autonomous vehicle, Autonomoose, uses a Lincoln MKZ hybrid sedan as the platform. Currently in year two of a three-year research program, Autonomoose, named by graduate students working with the vehicle, is being modified to autonomous drive-by-wire operation. The program involves seven academic researchers from six Engineering programs (Computer, Electrical, Mechanical, Mechatronics, Software, and Systems Design) as well as two academic researchers from the Cheriton School of Computer Science, which is based in the world's largest faculty of Mathematics.

When completed, the Autonomoose research platform will feature a full suite of radar, sonar, lidar, inertial and vision sensors. Additional feature sets involve GPS, wireless vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication, machine learning, mobile security, vehicle control and power management.

Throughout every phase of the Autonomoose platform's development, safety is paramount. The use of real-time embedded software provides security and safety monitoring of the vehicle while in operation, contributing to the operating system

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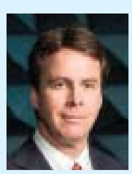
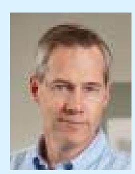


John McPhee is the Canada Research Chair in System Dynamics at the University of Waterloo. He has pioneered the use of linear graph theory and symbolic computing to create dynamic system models and model-based controllers, with applications ranging from autonomous vehicles to rehabilitation robots. He has won 5 best paper awards and his research algorithms are a core component of the MapleSim modeling software.

Dr. McPhee is a Fellow of the ASME, where he has served on a technical committee, a journal board, and conference committees. In 2014, he received the prestigious NSERC Synergy Award from the Governor-General of Canada.



Ross McKenzie is the Managing Director of WatCAR at the University of Waterloo. He is responsible for facilitating collaborative research between industry partners and faculty. Ross has served on the board of ITS Canada since 2011 and as chair of Electric Mobility Canada's annual student competition since its inception in 2013.

In 2016 Ross addressed the G7 Transport Ministers in Japan, summarizing Canada's activities and initiatives in connected and autonomous vehicles. In 2017 he was presented with the Ontario Ministry of Transportation Partnership Award, recognizing significant contributions to road safety.

(ROS) that runs the on-board autonomy stack. Powerful computers have been installed to run a complete autonomous driving system, integrating sensor fusion, path planning, and motion control software. To support the required integration, a custom autonomy software stack is being developed at Waterloo.

RESEARCH AND EDUCATIONAL DIRECTIONS

WatCAR researchers are focusing on specific open problems essential for Level 5 autonomy, namely: (i) robust perception, (ii) integrated planning and control, and (iii) safety assurance. Advances in deep learning, multi-sensor fusion, and onboard 3D geometric scene modeling are being used to improve driving perception reliability in the presence of adverse weather conditions, degraded road surfaces and highly dynamic environments [1,2]. Tightly integrated planning and control algorithms have been created using a combination of machine learning and model-based techniques [3,4]. These algorithms exploit the enriched sensor and environment data to enable the AV to operate efficiently and safely throughout their operating envelope [5]. The researchers are establishing minimal hierarchical safety requirements for autonomous functions, fidelity-aware simulations that can rapidly evaluate large numbers of challenging driving scenarios, and safety assurance methods for systems that rely on machine learning [6,7].

Two specific projects currently underway highlight the intertwining of these facets as well as the need for simultaneous engagement on both the research and development fronts.

Improve self-driving in all-weather conditions that are specific to Canada

Improvements to self-driving in all-weather conditions is utilizing simultaneous localization and mapping (SLAM) as well as undergoing autonomous maneuvers under extreme conditions. During initial winter driving tests in 2016, the lidar unit interpreted glare ice on the roadway as a pothole.

The varied refraction level of the ice was 'viewed' by the lidar's laser beams to be six inches lower than the adjacent roadway of bare asphalt. Researchers subsequently enhanced the on-board software of Autonomoose to scrutinize and evaluate lidar data, factoring in variables such as external temperature, recent weather conditions and time of year on the calendar.

Safe, robust computer-based controls for self-driving vehicles.

Methods to design safe, robust computer-based controls for self-driving vehicles are being provided with the introduction of: (i) Feature-oriented engineering (FOE); (ii) Runtime monitoring and reconfiguration infrastructure for autonomous driving; (iii) Fault-tolerant electric/electronic (E/E) architectures for autonomous vehicles; and (iv) Functional safety for software and components of autonomous vehicle systems.

Autonomoose in the GAIA Vehicle Test Cell strapped down and ready to drive-by-wire on the 4-wheel chassis dynamometer. Autonomoose, a Lincoln MKZ hybrid, is Canada's first autonomous vehicle.

In autonomous driving, feature-oriented engineering (FOE) refers to a required multitude of distinct behaviors, called features (such as lane changing and self-parking). FOE promotes independent development of the features, ultimately leading to feature interactions. Feature interactions are a fundamental challenge in FOE.

RESEARCH INFRASTRUCTURE ENABLERS

Waterloo has unique labs and equipment utilized in their CAV research, three of which are outlined in this section. These are in addition to the 10-bay autonomous vehicle garage and 3/4-mile (1.2 km) test track discussed previously.

GAIA vehicle test cell: The Green and Intelligent Automotive (GAIA) facility, has the capacity to simultaneously validate advanced driver assistance systems (ADAS), V2I communications and next-generation powertrain systems in a full vehicle test cell. A full 4-wheel chassis dynamometer is the cell's main component alongside a millimeter-wave signal generator combined with a traffic simulator to allow for ADAS validation activity. In 2018, a 270° screen wrap-around driving simulator will be added, integrated with sensor and traffic simulation software to support safe CAV testing prior to deployment on a test track.

Anechoic chamber: As part of the Centre for Intelligent Antenna and Radio Systems (CIARS), the anechoic chamber is capable of holding a full-size pick-up truck. Looking like a gigantic isolation booth, the chamber is part of the Centre for Intelligent Antenna and Radio Systems (CIARS). The chamber is used for many aspects of vehicular connectivity testing, including signal validation and antenna placement.

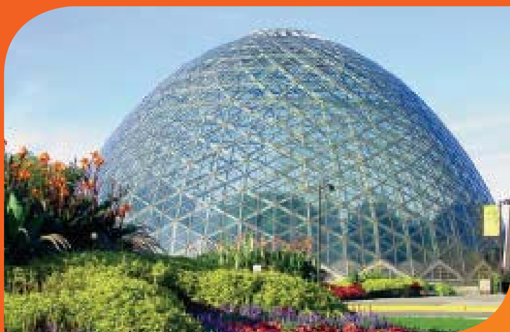
RoboHub: Waterloo will open an advanced robotics testing facility in 2018. A two-story glass cube, the RoboHub, will serve as a development lab and demonstration zone for robots, scaled autonomous passenger vehicles, autonomous delivery vehicles and unmanned aerial vehicles. The facility will bridge the laboratory and the real world, where researchers and students will simulate complex real-world environments and explore the potential of combined robotic technologies, many of which are targeted for CAV application.

CONCLUSION

The parallel pursuit of research and education programs for CAV activity at the University of Waterloo is succeeding. Industry partners are engaged, with several already integrating Waterloo advancements into their product portfolios. As discoveries continue to unfold, the next generation of engineers is learning about tomorrow's technologies in an experiential environment. Waterloo graduate and undergraduate students alike are receiving real-world training to become highly qualified personnel and will graduate equipped to further technological discoveries and their integration into connected and autonomous vehicles. ■

2018 AMERICAN CONTROL CONFERENCE

MILWAUKEE, WI
JUNE 27-29, 2018



DETAILS CAN BE FOUND ON THE CONFERENCE WEB SITE AT HTTP://ACC2018.A2C2.ORG

The 2018 AMERICAN CONTROL CONFERENCE will be held Wednesday through Friday, June 27-29, at the Hilton Milwaukee City Center Hotel in the heart of Milwaukee, Wisconsin – mere steps from the Lake Michigan shoreline. The conference venue is near nightlife, restaurants, shopping, and entertainment, including the Henry Meir Festival Grounds - host to the world's largest music festival, SummerFest, which will celebrate its opening day alongside the ACC.

The ACC is the annual conference of the American Automatic Control Council (AACC), the U.S. national member organization of the International Federation for Automatic Control (IFAC). National and international society co-sponsors of ACC include American Institute of Aeronautics and Astronautics (AIAA), American Institute of Chemical Engineers (AIChE), Applied Probability Society (APS), American Society of Civil Engineering (ASCE), American Society of Mechanical Engineers (ASME), IEEE Control Systems Society (IEEE-CSS), International Society of Automation (ISA), Society for Modeling & Simulation International (SCS), and Society for Industrial & Applied Mathematics (SIAM).

The 2018 ACC technical program will comprise several types of presentations in regular and invited sessions, tutorial sessions, and special sessions along with workshops and exhibits. Submissions are encouraged in all areas of the theory and practice of automatic control.

Photographs courtesy of VISIT Milwaukee

DSCC 2018

ATLANTA

THE ASME 2018 DYNAMIC SYSTEMS AND CONTROL CONFERENCE
OCTOBER 1-3, 2018
HYATT REGENCY ATLANTA
ATLANTA, GEORGIA

The DSC conference is the showcase technical forum of the ASME Dynamic Systems and Control Division. It provides a focused and intimate setting for dissemination and discussion of the state of the art in dynamic systems and control research, with a mechanical engineering focus. The 2018 DSC Conference Technical Program will consist of sessions in all of the usual areas of interest to the Division that include, but are not limited to, automotive and transportation systems, bio-systems and health care, energy systems, mechatronics, modeling, identification, intelligent systems, robotics, vibrations, and smart structures.

SUBMISSION OF PAPERS FOR REVIEW: APRIL 9, 2018

https://www.asme.org/events/dscc

ADVANCED ANALYTICS

SMARTUQ, MADISON, WIS.

SMARTUQ, PROVIDER OF PREMIUM PREDICTIVE ANALYTICS and uncertainty quantification software tools, has released its latest version, intended to push the boundaries of digital engineering and uncertainty quantification. The new tool can quantify and manage uncertainties and reduce the computational burden from performing advanced analytics on large data sets, while maintaining accuracy. The product can be integrated into a digital engineering platform and can handle more complex data sets than previously. For very large data sets, SmartUQ's new intelligent sampling tools can subsample or divide the data set into subsets. The company claims incorporating its tools into the workflow may enable engineers to better quantify the risk in each step of a product life cycle and could provide significant savings of both time and money.

MODELING

SIEMENS, MUNICH, GERMANY

Parasolid 29.1 delivers numerous enhancements to both B-rep modeling and convergent modeling technology. B-rep enhancements focus on high-value workflow automation, enabling application developers to deliver functionality more effectively. Convergent modeling improvements to working with imported facet data and the architectural foundations will back fully integrated convergent modeling in the future. Parasolid operations will support models containing arbitrary combinations of classic B-rep geometry and facet B-rep geometry. Among many upgrades, potential workflow bottlenecks in tapering and sweeping have been removed to deliver successful operations on more complex configurations and provide better diagnostic information when an operation is not possible on a specific configuration.

IGNITION SCADA SUPPORT

SEEQ, SEATTLE

Seeq's connection module for California-based Inductive Automation's Ignition SCADA system simplifies integration of the Seeq Workbench into Ignition displays and server gateways. Ignition customers in manufacturing, mining, pulp and paper, food and beverage, and other process industries use the Seeq Workbench to rapidly find insights in their data leading to better production outcomes including improved asset availability, product quality, and process efficiency. The easier deployment of Seeq and integration into Ignition Vision displays is designed to help Inductive Automation's system integrator partners get more value from their Ignition SCADA systems. Users can achieve insights to improve production results, a task that was often too time-consuming.

3-D CAD VIEWER

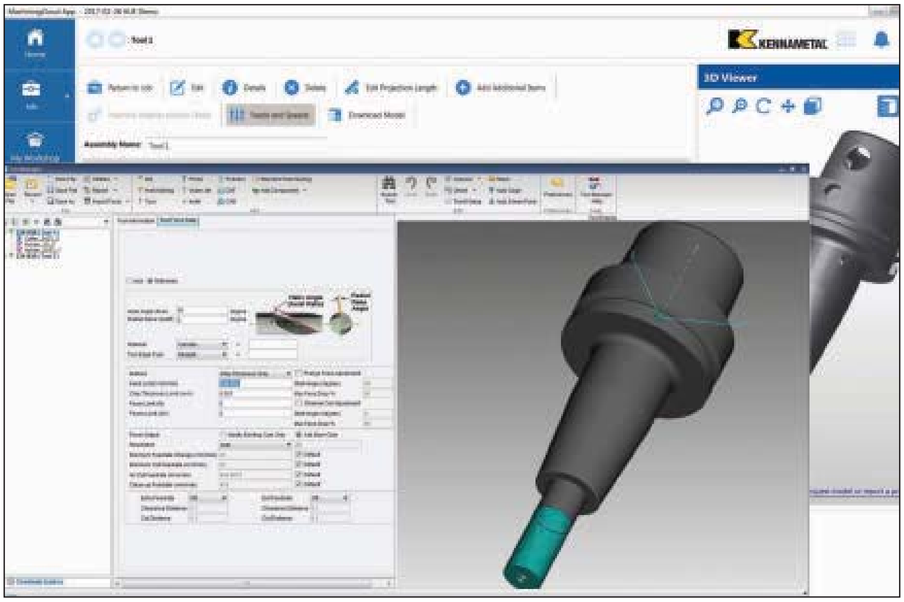
CORETECHNOLOGIE, FRANKFURT, GERMANY

Developed specifically for the plastics industry, the viewer assesses wall thicknesses, undercuts, draft analysis, and the bounding box. It also calculates projected areas of components and assembly groups of complex plastic parts. The software's unique innovation is the analysis report in PDF or HTML format. Analysis functions are supplemented by geometric model comparison, to indicate differences between models from two different CAD formats or revisions of the same CAD. The module creates captures of the variances with the ability to write to a 3-D PDF. For digital mock-up (DMU) examinations, a function determines collisions in assemblies and calculates clearances between single parts or components and all surrounding parts. It also creates exploded views that can be animated for BOM.

CUTTING TOOL PARAMETERS

CGTECH, IRVINE, CALIF.

An enhancement in the MachiningCloud connection enables VERICUT customers to import cutting parameters from cutting tool manufacturers from within MachiningCloud directly into VERICUT. VERICUT CNC machine simulation, verification, and optimization software detects CNC programming errors as well as potential collisions from the same NC code that drives the CNC machine. MachiningCloud is a product data provider for cutting tool manufacturers, CNC machines, and work holding. After defining a tooling package on the MachiningCloud and directly downloading all the tool assemblies into VERICUT, customers can obtain the cutting parameters of the tool to verify that it was programmed correctly.



EFFECTIVE CALCULATIONS

PTC, NEEDHAM, MASS.

PTC's Mathcad Prime 4.0 allow users to show, solve, and secure the company's specialized engineering calculations more effectively. Content protection provides area protection and locking to control the degree of access and visibility for other users. Interoperability with third-party applications enables users to embed content from other applications into worksheets, as well as copy and paste multiple regions of a worksheet into MS Word. Equation wrapping offers more control over the presentation.

COMPUTER-AIDED MANUFACTURING

DP TECHNOLOGY, CAMARILLO, CALIF.

ESPRIT 2017 aims to deliver a smarter, simpler, faster machining process with an expert toolpath, streamlined user control, and accelerated processing power. It features an upgraded three-axis global finishing cycle that provides a comprehensive solution for steep/shallow milling of complex part geometries that optimizes machining by applying the most appropriate toolpath to complex parts based on an analysis of the model and a single-threshold angle. Z-level cutting passes are applied to steep areas and boundary offset passes to shallow areas using a sophisticated logic that gives priority to continuity of the toolpath.

MOTION SIMULATION

DESIGN SIMULATION TECHNOLOGIES, CANTON, MICH.

SimWise version 9.8 integrates with the Onshape CAD system, opening its parts and assemblies. Onshape assembly constraints are converted to SimWise Motion constraints and can be used for multibody dynamic simulation, structural and thermal finite element analysis, durability (fatigue) analysis, and in optimization studies. Changes made to Onshape can be automatically applied to the SimWise model. A new capability exports a SimWise Motion model to ADAMS, a widely used, high-end, multibody dynamics analysis tool from MSC Software. The motion model built and simulated in SimWise is transferred to ADAMS, including all of the motion-specified objects, where it can be immediately used in an ADAMS simulation.

VIRTUAL TRAINER

EON REALITY, IRVINE, CALIF.

With the Enterprise Virtual Trainer, users administer training remotely via the web and collaborate with a trainee via VoIP, touch, or a mouse. EVT can be integrated with ERP and MRP solutions (such as SAP and Oracle), learning solutions, and Learning Record Stores using SCORM or xAPI. It also leverages the EON AVR platform's functionality. 3-D industrial environments and equipment can be either selected from the EON Experience AVR Enterprise Library (thousands of AVR models) or imported from the customer's CAD repository, using EON Raptor's import functionality. Training interactions and customization of the user interface are implemented using EON Professional development tools after the collaborative publishing formats are determined.

ROBOT CONTROLLER

FANUC, ROCHESTER HILLS, MICH.

The R-30iB Plus robot controller features a new iPendant with screen resolution and processing capability. The user interface, iHMI, has an icon-based screen that provides a familiar format with intuitive guides for setup and programming. It includes tutorials from the main home page, which has a design common to FANUC CNCs, enabling easier use of robots. With the help of the programming guide, even first-time robot users can create a program for a simple handling task and execute it in just 30 minutes. Easier use also facilitates the system setup and maintenance.

SUBMISSIONS

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

In This Issue

Global Gas Turbine News

Volume 57, No. 4 • December 2017

ASME INTERNATIONAL GAS TURBINE INSTITUTE

ASME Gas Turbine Segment | 11757 Katy Frwy., Ste. 380 | Houston, TX 77079 | go.asme.org/IGTI

ASME Turbo Expo 2018

ASME Turbo Expo is recognized as the must-attend event for turbomachinery professionals. The technical conference has a well-earned reputation for bringing together the best and brightest experts from around the world to share the latest in turbine technology, research, development, and application. ASME Turbo Expo offers unrivaled networking opportunities with a dedicated and diverse trade show floor. The 3-day exhibition attracts the industry's leading professionals and key decision makers, whose innovation and expertise are helping to shape the future of the turbomachinery industry. In addition, the Student Poster Session, presented by the Student Advisory Committee, will provide students an opportunity to display their research outside of a technical paper while still contributing to the continuing advancements in the turbomachinery community.

Targeted Maintenance, Repair and Overhaul (MRO) at the right time is key to ensuring efficient, reliable and affordable operation of turbomachines throughout their lifetime. Given the developments in digitalization, the overall theme of the 2018 edition of the ASME Turbo Expo is MRO in the Light of Digitalization featuring specifically focused keynotes, plenaries, as well as panel and technical paper sessions. This year's focus track on Additive Manufacturing is continued, along with the traditionally broad spectrum of latest thermal turbomachinery research and technology.

Make plans now to join over 3,000 turbomachinery colleagues from around the world at ASME Turbo Expo, ASME's premier turbomachinery technical conference and exposition, set for June 11 - 15, 2018 in Lillestrøm, Norway.

Keynote Theme

MRO in the Light of Digitalization

Thermal turbomachines are key to our modern society providing reliable power in air, at sea and on land. Wear, deterioration or damage may easily lead to disruptive operation having a major impact on operating costs and reliability. Planning the Maintenance, Repair and Overhaul (MRO) of turbomachinery thoroughly and instantly, be it by means of predictive or preventive maintenance, allows operators to ensure efficient, continuous and reliable operation as well as to reduce operating costs significantly. The advances in digitalization, ranging from the creation of exact digital replicas of real machines over the reliable acquisition of real-time monitoring data to advanced data processing, are currently revolutionizing the field of MRO. The degree of sophistication reached in advanced simulations paired with the computational power of modern computers allows analyzing digital replicas at a high level of details giving new insights into previously poorly understood phenomena. Advanced analyses of relevant operation data may give an unprecedented view on actual machine conditions, opening up for accurately scheduling precise MRO measures. Furthermore, the technology of Additive Manufacturing is a true game-changer, not only in the manufacturing but also in the repair of components. Using this technology, worn components can often be repaired rather than replaced and in the best case, even exceed operating condition standards.

The unique experience of the ASME Turbo Expo community combined with the conference theme MRO in the Light of Digitalization and the focus track of Additive Manufacturing make the 2018 ASME Turbo Expo a must-attend event. Use this opportunity to meet with the best and brightest experts from around the world in Lillestrøm, Norway, right outside Oslo, the capital of Norway, to open new chapters in turbomachinery.

Plenaries

Keynote Panel: MRO in the Light of Digitalization
The ASME IGTI Awards Program commences after the Keynote.
Monday AM, June 11, 2018
Hall B4, First level at the Norway Trade Fairs

Plenary: Additive Manufacturing in MRO
Tuesday AM, June 12, 2018
Hall B4, First level at the Norway Trade Fairs

Plenary: Big Data in MRO
Wednesday AM, June 13, 2018
Hall B4, First level at the Norway Trade Fairs

Exposition

We understand that you need return on investment for your sponsorship, exhibiting, and advertising dollars. Partnering with ASME Turbo Expo gives you strategically focused access to an influential audience of commercial, governmental and academic engineers in the field of turbomachinery This alliance offers many key opportunities, including high visibility, hospitality, and networking.

Kicking off the conference on a positive note, the Keynote and Luncheon on Monday allows for establishing connections with the attendees prior to the Exhibit opening on Tuesday. Monday evening, in a casual atmosphere with attendees, the Welcome Reception is an opportunity for exhibitors to establish new connections and strengthen existing ones. During the exhibit, Tuesday through Thursday, industry leading exhibitors showcase their innovative and essential products. Afternoon hall receptions allow for more networking with the attendees and casual engagement time to showcase their products and services to the over 3,000 attendees.

Maximize your return on investment! By optimizing your dollars through partnering with ASME Turbo Expo, you ensure that your exhibit will get the attention of the attendees at the conference and throughout the year. Your company will be front and center with our influential community.

This partnership provides you with an exclusive opportunity to cultivate mutually beneficial relationships with our attendees in ways that are best suited to meet the individual needs of your business. Combine any of the Conference sponsorship opportunities with an exhibit booth to maximize your exposure at Turbo Expo and customize your experience. Complement the professional technical sessions by enabling attendees to see, hear, examine, question, and evaluate the latest developments in equipment, supplies and services which are recommended for use in the field of turbomachinery! Contact igtiexpo@asme.org today for exhibition, sponsorship and advertising opportunities for ASME Turbo Expo 2018.

ASME Gas Turbine Segment Welcomes New Leaders

ASME Gas Turbine Segment is pleased to announce the appointment of three new leaders: Paul Garbett, Siemens Power & Gas Division; Eisaku Ito, MHI; Nicole Key, Purdue University; and Mark Turner, University of Cincinnati.

Paul Garbett joined Ruston Gas Turbines in 1989 as a Graduate Trainee after leaving university. He specialized in stress methods working on existing and new industrial gas turbine models such as the Typhoon and Tempest (now the SGT-100 and SGT-300). He moved to Westinghouse in the USA in 1996 as a turbine blade design engineer. He later moved to Hamilton, Ontario to head the Product Manufacturing Engineering department. After returning to Orlando, Florida in 2003, he led the development of the SGT5-8000H gas turbine culminating in validation at the Ulrich-Hartmann power plant in Irsching, Germany. In 2010, Paul became the head of development for all Siemens Large Gas Turbine frames produced globally by Siemens factories. The frame teams are responsible for managing overall engine development projects and meeting budget, schedule and technical objectives. Since October 1, 2013, Paul assumed responsibility as the global head of Core Engineering for Siemens Large Gas Turbines.

Eisaku Ito is a senior general manager in marketing and innovation at the headquarters of MHI. He had extensive experimental and numerical simulation experience while working at MHI R&D Center in Takasago. He successfully applied Computational Fluid Dynamics analyses for the development of three dimensional design systems for multi-stage turbines. The resulting systems are widely used by MHI and MHPS to evaluate Gas Turbine designs from the Aero, Heat Transfer, Vibration, Structure and Strength point of view. Deeply involved with design teams as a turbine aero design lead, he led R&D teams and coordinated key activities required for the development of high turbine inlet temperature gas turbines, including a 1,700ºC TiT Gas Turbine project funded by the Japanese Government. He also applied leading edge technology to the design of a 1,600ºC TiT Gas Turbine. He was the recipient of the 2017 IGTI Industrial Gas Turbine Technology Award and was given the ASME Best Paper award 2010 IGTI (GT2010-23233).

Nicole Key is a Professor at Purdue University's School of Mechanical Engineering. She obtained her Bachelors degree from the School of Aeronautics & Astronautics at Purdue in 2000 and her Masters from the School of Mechanical Engineering at Purdue in 2002. She then spent a year in Brussels completing the Diploma Course at the von Karman Institute for Fluid Dynamics working on turbine tip flows. She returned to Purdue and completed her PhD in 2007, focusing on vane clocking effects in a multistage compressor. Dr. Key's experimental research focuses on understanding the underlying flow physics associated with primary and secondary flow phenomena in axial and radial compressors to enable more efficient, robust designs. Her research has been sponsored by NASA, Rolls-Royce, Honeywell, Siemens, Pratt & Whitney, GE, and the GUIde Consortium. She was the recipient of the 2014 IGTI Dilip Ballal Early Career Award and also serves as an Associate Editor for the ASME Journal of Turbomachinery and the AIAA Journal of Propulsion and Power.

Mark Turner is a Professor in the Department of Aerospace Engineering at the University of Cincinnati. He received his BS in Mechanical Engineering from Virginia Tech in 1979, his MS in Aeronautical Engineering from the University of Cincinnati in 1986, and his Doctor of Science in

...Continued on pg. 49

As the Turbine Turns...

#32 December 2017

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

Performance and Endurance Enhancement by Means of Turbine Cooling

Large Brayton-Rankine combined cycle electrical power plants are now at record setting thermal efficiencies of 62%, the most efficient heat engines yet perfected by engineers. These have been made possible by modern efficient (as high as 45%) electric power gas turbines whose exit gas path temperatures have been increased enough to allow ample high pressure steam production for the Rankine cycle. Aviation jet engine advances have provided much of the leading edge technology that underlies this power plant revolution.

Gas turbine thermal efficiencies increase with higher temperatures of the gas flow exiting the combustor and entering the work-producing component - the turbine. Turbine inlet temperatures in the gas path of modern high-performance commercial jet engines can reach 3000˚F (1649˚C), while electric power gas turbines typically operate at 2700˚F (1482˚C) or lower, and military jets can be in the 3600˚F (1982˚C) range. (The turbine designer must accommodate for excursions above these nominal temperatures, due to combustor hot streaks, etc.)

In the highest-temperature regions of the turbine, special high-melting-point nickel-base alloy cast blades and vanes are used because of their ability to retain strength and resist hot corrosion at extreme temperatures. These so-called superalloys, when conventionally vacuum cast, soften and melt at temperatures between about 2200˚F (1204˚C) and 2500˚F (1371˚C).

This means blades and vanes closest to the combustor can be operating in gas-path temperatures far exceeding their melting point. To endure these temperature excesses of 500 to 1400 F˚ (278 to 778 C˚), they must be cooled to acceptable service temperature (typically eight-to-nine-tenths of their lower melting point) to maintain integrity.

Thus, turbine airfoils subjected to the hottest gas flows take the form of elaborate superalloy investment castings to accommodate the intricate internal passages and surface hole patterns necessary to channel and direct cooling air (bled from the compressor) within and over exterior surfaces of the superalloy airfoil structure. By turbine design conventions, internal airfoil cooling is usually termed "convective cooling", while the protective effect of cooling air over external airfoil surfaces is called "film cooling".

A New Turbine Cooling Guide

This past June, at ASME Turbo Expo '17 in Charlotte, the biennial International Gas Turbine Institute Scholar Lecture was given by Ronald Bunker. Ron, a Past IGTI Chair and recently retired General Electric gas turbine heat transfer expert, presented his scholar paper "Evolution of Turbine Cooling" [1].

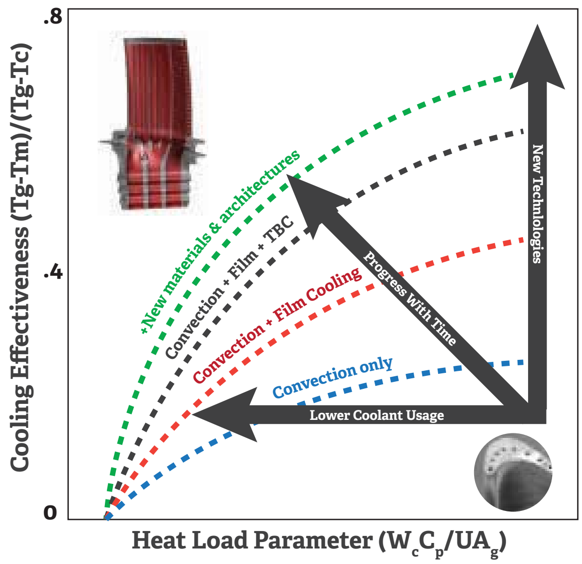


Figure 1: Evolution of Turbine Cooling

Dr. Bunker's paper can now serve as an up-to-date overview of turbine cooling, complete with a listing of 123 references. His 26-page paper treats the evolution of turbine cooling in three broad aspects, including background development, the current state-of-the-art, and prospects for the future. This is indeed a seminal work by an expert, reflecting his direct research and design OEM experience over a period of several decades.

The author posits that the fundamental aim of a turbine heat transfer designer is to obtain the highest overall cooling effectiveness for a blade or vane, with the lowest possible penalty on thermodynamic performance. In Fig. 1 (taken from his Fig. 3 [1]) this is shown in the form of notional (i.e., expressing a notion) cooling technology curves.

On the Fig. 1 ordinate, the cooling effectiveness of a turbine blade or vane is made up of its bulk metal temperature (Tm), the hot gas path temperature (Tg), and the coolant fluid temperature (Tc). (A value of 1.0 would represent "perfect" cooling.)

The Fig. 1 abscissa is the heat load parameter which is the external airfoil heat loading (UAg , where U is an overall hot gas path convective and radiation heat transfer coefficient and Ag is an external surface area), divided into the coolant flow rate (Wc) and the thermal capacity coefficient of the coolant fluid (Cp).

Bunker points out that in the last 50 years, advances have led to an overall increase in turbine and vane cooling effectiveness shown in Fig. 1, from 0.1 to 0.7. It started with convection only (e.g., the convectively cooled turbine airfoils of the German jet engines of WWII) and has progressed with film cooling, thermal barrier coatings (TBCs) and new materials and architectures (e.g., directionally solidified and single crystal turbine blades, which entered service in the 1970-90s).

In Fig. 2 (taken from his Fig. 4 [1]) are five conventional investment casting cooling geometries in use today. They range from convection only (i.e. internal passage heat transfer only), to film cooling and the combination of both. The reader is referred to Bunker's paper for a detailed discussion of each.

An Evolution Theme

In writing his ASME IGTI Scholar paper covering this fascinatingly important topic of turbine cooling, Bunker used evolution as a theme. He wrote that the evolution of turbine cooling (since the gas turbine's invention in 1939) is loosely analogous to that of the Darwinian theory of evolution for animals, starting from highly simplistic forms and progressing to increasingly more complex designs having greater capabilities. Let me continue his evolution theme to end here, with a view of the importance of film cooling for present and future gas turbine technology.

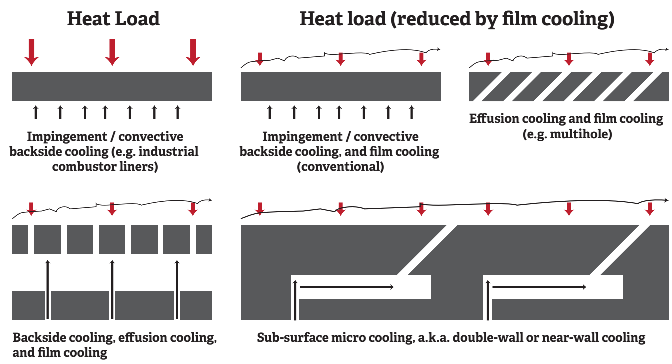


Figure 2: Conventional modes of turbine blade and vane cooling.

Lieberman [2] reviews current research in human evolutionary biology on the fundamental role our unique sweat cooling system has played in human evolution. Human sweating probably emerged sometime around 2 million years ago, in order to help meat-eating hominids compete with other carnivores. Eating meat led to larger body and brain size than chimpanzees. Sweat cooling allowed our ancestors to forage safely during peak heat in a hot, dry African climate, when heat-dump limited predators were unable to hunt them. Evaporative cooling also allowed persistence hunting, where hominids (well before the bow and arrow) could wear down prey, not by superior speed, but by a sustained pace causing hyperthermic state in the hunted.

An analogy can be made between the role of sweat cooling in human evolution to that of the evolution of gas turbine performance and endurance enhancement due to film cooling. Earlier, we saw what temperature excesses are now in turbines - as high as 1400 F° (778 C°) above alloy melting points. Film cooling is key to attaining these levels, and to increasing them in the future, for yet higher gas turbine efficiencies. (Bunker [1] discusses "micro cooling", an advance form of film cooling, akin to sweat cooling.)

Four centuries ago, Ben Jonson wrote: "Who casts to write a living line, must sweat." Today, a turbine designer who casts to perfect a more efficient gas turbine, must film cool.

References

1. Bunker, Ronald S., 2017, "Evolution of Turbine Cooling", Proc. ASME Turbo Expo 2017, GT2017-63205, June 26-30, Charlotte, NC, USA, p 1-26.

2. Lieberman, Daniel E., 2015, "Human Locomotion and Heat Loss: An Evolutionary Perspective", Comprehensive Physiology, January, Vol. 5, pp. 99-117.

Engineering And Validating A World Record Gas Turbine

Christian Vandervort[1], Todd Wetzel[2] & David Leach[3] | [1]GE Power, 1 River Road, Schenectady, NY 12345
[2]GE Global Research | 1 Research Circle, Niskayuna, NY 12309 [3]GE Power | 300 Garlington Road, Greenville, SC 29615

Introduction

Whenever you turn on a light-switch in your home, there is a strong likelihood that those electrons were generated by a gas turbine combined cycle (GTCC) power plant. These jet-engines-on-the-ground represent the most efficient conversion of natural gas into electricity. In April 2016, under the auspices of the Guinness Book of World Records, a 9HA.01 GTCC set a world record for combined cycle efficiency of 62.22%. Achieving this new record, and setting new ones in the years to come, involves the science and inventions of hundreds of engineers.

H-Class Gas Turbine Heritage And Evolution Of 7/9HA Gas Turbines

Gas turbine technology level is commonly identified by letter designation, with higher letters representing increased combustion temperatures and higher efficiencies. Development of H-class technology began in the early 1990's leading to the first commercial operation (COD) in 2003. This original H-class gas turbine pioneered many technologies, including the 4-stage, steam-cooled turbine section and 4 stages of variable guide vanes at the compressor inlet.

Experience and knowledge gained from operation and maintenance of the original GE H-machines paved the way for a new set of H-class products, designated the 7HA and 9HA. The 7/9HA gas turbine hot gas path is entirely air-cooled, facilitated by technological advances in turbine cooling, sealing, materials, and coatings. The "H" signifies H-class firing temperature with the addition of "A" denoting air-cooling.

The 7HA and 9HA are speed and geometric scales with factors of 0.83 (versus 9HA) and 1.2 (versus 7HA), respectively. The 7HA serves the 60 Hz market while the 9HA serves the 50 Hz market. Scaling based upon this approach has been routinely applied for industrial gas turbines, including the 7/9E's and 6/7/9F's offered by GE Power.

The 7/9HA family of gas turbines offers two output sizes for both 7HA and 9HA. The ".02's" are flow scales of the ".01's". The process of flow scaling can be summarized by increasing compressor inlet and turbine exit annulus areas to accommodate higher air flow with resultant increase in power output. Pressure ratio is increased to maintain aerodynamic flow function in the mid-to-later compressor and first and second turbine stages. Overall length increases by about one meter for both the 7HA.02 and 9HA.02. Fuel supply capability and fuel nozzle sizing are increased to maintain constant firing temperature.

Table 1 provides today's output and efficiency for simple-cycle and combined-cycle configurations of the HA products. These performance values are shown on a net basis at ISO with boundary conditions per the Gas Turbine World (2017) standard. SS is an abbreviation for 1x1, single-shaft configuration.

Honors and Awards

Young Engineer Turbo Expo Participation Award

Nomination deadline - February 1, 2018: https://www.asme.org/wwwasmeorg/media/ResourceFiles/Events/TurboExpo/YETEP-Award-Application_1.pdf

ASME IGTI Student Scholarship

Student application deadline is June 15, 2018 for the 2018-2019 School Year. Scholarship winners will be notified by the end of October 2018. Scholarships will be dispersed in November.

Application is available at: https://community.asme.org/international_gas_turbine_institute_igti/w/wiki/4029.honors-and-awards.aspx.

Student Advisory Committee Travel Award

To apply for the Student Advisory Committee (SAC) travel award, **please submit all documents in one PDF file to sac.igti@gmail.com by February 1, 2018.** All applicants will be notified of the decision on their application by March 2018. Application can be located at: https://www.asme.org/events/turbo-expo/program/students.

For more information on the Gas Turbine Segment Honors and Awards Opportunities, visit https://community.asme.org/international_gas_turbine_institute_igti/w/wiki/4029.honors-and-awards.aspx.

	Gas Turbine Output (MW)*	SS Combined Cycle Output (MW)*	Combined Cycle Efficiency *
7HA.01	289	436	62.1%
7HA.02	372	560	63.1%
9HA.01	446	659	63.4%
9HA.02	544	804	63.5%

*Net, ISO, Gas Turbine World (2017)

Table 1. 7/9HA Product offerings

1. Compressor

The 7/9HA compressor is a direct evolution from the 7F.05 gas turbine. The 7F.05 compressor has a 14-stage architecture with inlet guide vanes followed by three stages of variable guide vanes. There are two extraction points for supply of cooling air to the hot gas path. This compressor incorporates the latest aerodynamic and durability enhancements. Features include 3D aerodynamics, field replaceable blades and application of 'super-finishing' or coating of blades. These elements combine to provide high efficiency, wide operability, minimal degradation, optimal reliability and maintainability. The 9HA.01 compressor is shown by Figure 1.

Figure 1. 7/9HA Gas turbine compressor

2. Combustor

The 7/9HA gas turbines operate with lower than 25/15 ppm NOx/CO from 30 to 100 percent load. Even lower emissions can be guaranteed for both 7HA and 9HA via reduction in firing temperature or inclusion of exhaust Selective Catalytic Reduction (SCR). The 9HA.01 gas turbine was introduced with DLN 2.6+ combustion technology. This system employs multiple fuel circuits supplying 6 fuel nozzles with five arranged circumferentially around a center nozzle. The operational strategy uses fuel staging to achieve low emissions with robust maneuverability.

The 7HA.01 and 7HA.02 gas turbines incorporate combustion improvements enabling further reduction in emissions levels and improved turndown capability. "Axial Fuel Staging" (AFS) system enables lower NOx emissions with improved turndown. It also reduces thermal loading that combines with advanced materials and coatings to deliver state-of-the-art durability. The 7HA combustor is shown in Figure 2 along with a photograph of the flame from full-scale laboratory testing.

9HA.01 and 9HA.02 gas turbines with shipment dates from 2018 and onward can incorporate an evolutionary improvement to the premixing fuel nozzles, in addition to AFS. The 5 around 1 fuel nozzles can be replaced by an equivalent number of arrays with smaller, tubular premixers., shown by Figure 3.

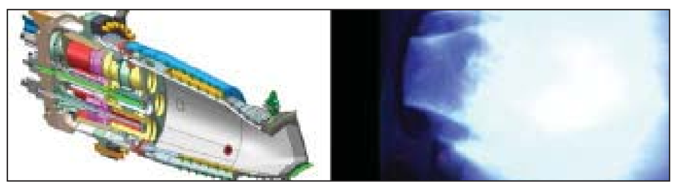


Figure 2. 7HA GT combustor (left) and flame image from combustion laboratory testing (right)

...Continued from pg. 45

the Department of Aeronautics and Astronautics from MIT in 1990. Mark worked for GE Aviation for 20 years. He joined UC in 2001, first as a Research Professor, and then tenure track. He is the Co-director of the UC Gas Turbine Simulation Lab. His lab has created and distributed several turbomachinery design codes through their website. He has worked with NASA Glenn Research Center, the Air Force Research Labs, and many companies on Multistage Turbomachinery Design Methods, supersonic inlets, propellers and renewable devices. He is currently the Undergraduate Program Chair, and teaches Fluids-Propulsion Classes including a Turbomachinery Flows class, a Senior Capstone Design Class, Numerical Methods, and Rocket Propulsion. Mark is a Fellow in the ASME. He has two patents, and has written 24 journal articles, 35 refereed conference papers (including 3 best-paper awards), and 40 non-refereed papers. He has graduated five PhD students and 13 MS students, and taught 42 courses.

ASME Gas Turbine Segment would like to thank the outgoing Segment Leadership Team Members for their participation and contribution to the organization.

Thank you Segment Leader, Piero Colonna, Full Professor, Chair of Propulsion and Power at the Faculty of Aerospace Engineering, Delft University of Technology; Special Advisor, Karen A. Thole, Distinguished Professor and Department Head, Mechanical and Nuclear Engineering, Pennsylvania State University; and Segment Member and TEC Representative Timothy C. Lieuwen, Professor in the School of Aerospace Engineering and the Executive Director of the Strategic Energy Institute at Georgia Institute of Technology, who will stay on the Segment Leadership Team as a Special Advisor. Your dedication to the industry is greatly appreciated.

Figure 3. Enhanced premixing section for 9HA combustor

3. Turbine

The 7/9HA turbine is based upon the original H-class 4-stage gas turbine with exception of simplification by eliminating steam cooling. Metals chosen for the 7/9HA are proven alloys with over 50 million hours of operation on F and H-class gas turbines. Turbine cooling was enhanced based upon combination of this experience coupled with use of state-of-the-art computational and experimental methods. Development benefited from use of Computational Fluid Dynamics (CFD), and component testing, aided by partnerships with multiple Universities and National Laboratories. The turbine section and corresponding velocity field as generated by CFD are shown in Figure 4. Engineers and researchers advanced the understanding of near-wall flow physics to allow optimization of the turbine aerodynamic and cooling architectures. The inner and outer turbine shell applies passive measures for optimization of clearances. Abradable and honeycomb shrouds and shorter shank buckets were carried forward from the original H-class gas turbine, while near-flowpath seals were leveraged from GE's Aviation products.

Figure 4. 7/9HA Turbine (left) and velocity field from computational fluid dynamics (right)

4. Full-Speed, Full-Load Validation

In 2008, GE developed the world's largest and most comprehensive full-speed, full-load (FSFL) gas turbine test facility in Greenville, South Carolina, USA. This off-grid, world-class facility provides full-scale, full load validation of 50 and 60 hertz gas turbine systems. The first usage of this facility was for the 7F.05 compressor in 2011 followed by the 7F.05 gas turbine in 2012. The facility was subsequently used for validation of the 9HA.01, 7HA.01 and 7HA.02 gas turbines.

The FSFL facility enables operation independent of the grid. Key elements of the FSFL train are the gas turbine, a load compressor, and starting means. The facility was developed to allow for the load compressor to utilize a production version of the gas turbine compressor. The load compressor can be operated at different points on the map versus the actual gas turbine compressor. Instrumentation of the load compressor also enables doubling the amount of compressor validation data. Nearly 6,000 sensors and instruments collect data on all aspects of operation and components of the gas turbine during validation. Gas turbine performance is mapped over a broader operating envelope: isolation from the grid facilitates off-speed (90%-110% speed) operation over a range of loaded conditions. Variable speed also enables testing at ambient temperature equivalent over a range from -37°C to 50°C.

Compressor aeromechanics are validated through use of strain-gauges and light probes applied along the flow-path. Loaded speed sweeps greater than +/-10% provide parametric sensitivities to frequency and operating condition variation. Surge margin is quantified by intentionally maneuvering the load compressor into a surge condition and monitoring the response. Multiple surge events are performed for each platform. Gas turbine transient events including grid disturbances, fuel transfers, and load rejections are performed under highly monitored conditions.

The standard FSFL validation test plan is portioned into three sections: validation, demonstration, and growth. Validation includes extensive testing to provide measurements to support comparison with analytical predictions to validate the methods. The demonstration phase leverages off-grid capabilities to exercise operational capability. Significant testing is dedicated to exploring the growth capability of the HA gas turbine technology for future upgrades. Aeromechanic, combustor and aerothermal data are collected for operations up to 115 percent of rated output.

9HA.01 World Record At EDF Bouchain

The first 9HA.01 entered commercial operation on June 17, 2016 at the Électricité de France (EDF) Bouchain plant, located in the Nord Pas-de-Calais region of France. GE followed the Guinness Book of World Records' definition for a consistent and traceable operating condition for establishing efficiency world records. Under the oversight of Guinness World Records staff, GE set the record for the world's most efficient combined-cycle power plant with an efficiency of 62.22% while producing more than 605 MW of electricity.

Summary

GE's HA gas turbines represent the most reliable, and efficient machines in the world for converting natural gas into electricity. In a combined cycle arrangement, these turbines provide cost-effective and clean generation that offers reliable electricity to an expanding, global population.

Innovations from aerodynamics, to combustion, to heat transfer, to materials, and many other areas, representing the work of hundreds of dedicated engineers, made this world-record machine possible. And those same engineers are busy at work preparing to set a new world record...stay tuned!

MOISTURE METER

PAUL N. GARDNER COMPANY, POMPANO BEACH, FLA.

PROFESSIONAL PTM 2.0 is a hand-held, digital, pin-type resistance moisture meter designed to take precise measurements of moisture content in wood, relative drywall readings, and comparative WME (wood moisture equivalent) readings in wood byproducts and other building products. With built-in standard calibrations, specific calibration for more than 500 wood species, and adjustable temperature correction, the meter has a wide moisture content range of 6 to 46 percent and digital readout to 0.1 percent accuracy. Convenient features include a reading "Hold" facility; the capacity to save up to 100 readings for maximum, minimum, average, and standard deviation statistics; a color LCD screen with brightness adjustment for low-light operation; and a heavy-duty but lightweight aluminum construct.

MOTORS AND DRIVES

ABM DRIVES, LOVELAND, OHIO.

Modular motors and gearbox drives from ABM Drives are tailor-made in-house specifically for each application, whether it requires compact design, low noise operation, or maximum operating safety. A flexible modular design system allows cost-effective, low-volume production runs. Custom motors and drives are available for forklifts, electric vehicles, lifting technology, biomass heating systems, textile machines, wind power control, warehouse logistics, high-speed doors, air compressors, construction equipment, packaging machinery, and vehicle-inspection equipment. The high overall efficiency of ABM Drives' helical and parallel shaft gearboxes reduces power input and energy consumption. Vertical integration of manufacturing includes tool-and-die engineering and aluminum die-casting to guarantee best implementation and integration of components to a compact drive unit.

TEENY-TINY SPRINGS

SMALLEY, LAKE ZURICH, ILL.

With a fitting name for a company that produces minuscule wave springs, Smalley points out that engineers around the world are looking for ever more compact components to support their designs in the medical, computer, and robotics industries. Smalley's answer is its expanded Crest-to-Crest Wave Spring Series. Standard sizes in the C (imperial) and CM (metric) are now available from stock down to 0.188 in. and 5 mm in diameter. "How small do you need?" the company asks, reporting that its engineering and manufacturing teams can design a custom solution for your application down to 0.157 in. or 4 mm in diameter.

SUBMISSIONS

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

HARDWARE

TOOL MANAGEMENT

BALLUFF, NEUHAUSEN, GERMANY

Tool identification using Balluff Industrial RFID increases production efficiency by making incorrect tool allocation and missing tools a thing of the past and eliminating scrap and rework due to excessive use of tools. It is simple to retrofit, install, and configure. All that is required is a USB port on the machine tool and a presetter. The data are written via RFID technology from the presetter to the tool and then passed on through the Easy Tool-ID system to the machine tool. Manual entry is eliminated. Setup times and the risk of incorrect entries are significantly reduced. The system consists of a tool stand with an integrated read/write head, a processor unit, a microcontroller, and the power supply.

BLUETOOTH PROTOCOL ANALYZER

SAELIG, FAIRPORT, N.Y.

The BPA from Teledyne LeCroy is a powerful, portable protocol analyzer for wireless transmissions that adhere to Bluetooth low-energy specifications. Ideal for field or lab use, the BPA is USB-powered, eliminating the need for an external power supply. This analyzer supports all of the mandatory Bluetooth low-energy features through Bluetooth version 4.2, and ships with Frontline software allowing Bluetooth developers the ability to see events as they occur live, decoding and decrypting the Bluetooth data for full analysis and troubleshooting issues. Smaller than a deck of cards (3.5 in. x 1.75 in. x 0.71 in.), the BPA analyzer decodes all Bluetooth low-energy traffic, including advertising packets, data packets, and LL control packets.

ENCODER DIGITIZED RESOLVER

EMPIRE MAGNETICS, ROHNERT PARK, CALIF.

The Encoder Digitized Resolver (ERD) is designed for beamline facilities, but can be used for any multi-station automated system with centralized control. The ERD reduces cabling costs through its ability to provide feedback from each station/device into an Ethernet network. Each device has selectable addressing, so the control room can easily track multiple units on a single cable and display current data with certainty of its origin. This greatly reduces the number of cables needed to connect work stations to the control room. The ERD unit includes an isolated 110 to 220 V power supply and has a memory to keep track of its last location, eliminating the concern of losing positional information in the event of a power failure or other disruption.

PRECISION TOOLHOLDERS

SCHUNK, MORRISVILLE, N.C.

The TRIBOS-Mini, designed for micro-machining, can be used for high-speed spindle interface HSK-E 20. The HSK-E 20 ensures exact contact of the toolholder, which enables outstanding change and positioning accuracy. In addition, the close tolerances of the tapered seat result in maximum precision and running smoothness at high speeds. Both the TRIBOS-Mini and TRIBOS-RM series with the interfaces HSK-E 25 and HSK-E 32, starting with clamping diameters of 0.5 mm, are optionally available in fine-balanced versions with a balancing grade of G 0.3 at 60,000 rpm. For multi-axis machining centers, SCHUNK has modified the robust TRIBOS-RM with an extended L1 dimension of 78 mm. The extra length can be used for many different tasks. In addition to direct clamping, it is suitable for clamping of smaller shank diameters.

LINEAR MOTORS

MOTICONT, VAN NUYS, CALIF.

Moticont's SDLM Series of high-speed, direct-drive linear motors, also known as electric cylinders, features two compact drives with a 1.0-in. (25.4-mm) stroke that are just 1.0 in. (25.4 mm) in diameter and 3.75 in. (95.3 mm) long. These motors have resolutions of 5 μm (0.000197 in.) and 1.25 μm (0.000049 in.) The integral, linear optical quadrature encoder is directly connected to the shaft for the greatest possible accuracy. Each motor provides a continuous force rating of 20.1 oz. (5.82 N) and a peak force of 66.3 oz. (18.4 N). This motor is designed with a larger air gap of 0.059 in (1.5 mm) that allows the motor myriad uses, including for vibration, noise cancellation, photonics, gimbals, antenna positioning, and medical devices.

RESOURCEFILE

- Instrumentation & Control
- Power Transmission & Motion Control
- Fluid Handling
- Materials & Assembly
- Engineering Tools
- Other Products & Services

A bimonthly listing of the industry's latest technical literature and product information available FREE to *Mechanical Engineering* readers.

MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Chair, Department of Mechanical Engineering
University of Michigan

The Department of Mechanical Engineering (ME) at the University of Michigan (U-M) seeks applicants and nominations for the position of Department Chair. The University of Michigan Mechanical Engineering Department is home to 68 tenured/tenure-track faculty, 21 research faculty, 56 staff, over 450 graduate students (including over 250 Ph.D. students) and 800 undergraduate students. U-M ME is well known for its outstanding strengths in major mechanical engineering core disciplines, as well as in interdisciplinary and emerging thematic areas. The Department is consistently ranked among the top nationwide and worldwide by various ranking systems, such as the QS World rankings, *U.S. News and World Report*, and the National Research Council Ph.D. Program Assessments. More information about the Department can be found at: *http://me.engin.umich.edu/*.

The successful candidate will be an outstanding scholar with an earned doctorate in a research field related to Mechanical Engineering and will have an exemplary record of achievement in research, teaching and service at a level commensurate with appointment as a tenured full professor. The person must also possess visionary leadership abilities, a broad appreciation for the diverse perspectives within Mechanical Engineering, and a strong interest in promoting sponsored research programs and mentoring faculty. The qualified candidate should be able to lead and support the faculty to ensure that learning of the highest quality flourishes at all levels, from undergraduate education to graduate and post-doctoral research. The candidate must be able to work with a diverse group of faculty, staff, students, and administrators to achieve common goals, to build upon a supportive and inclusive climate and to maintain and enhance rapport with alumni and industry representatives.

Michigan Engineering's vision is to be the world's preeminent college of engineering serving the common good. This global outlook, leadership focus, and service commitment permeate our culture. Our vision is supported by a mission and values that, together, provide the framework for all that we do. Information about our vision, mission and values can be found at: *http://strategicvision.engin.umich.edu/*.

The University of Michigan has a storied legacy of commitment to Diversity, Equity and Inclusion (DEI). The Michigan Engineering component of the University's comprehensive, five-year, DEI strategic plan—with updates on our programs and resources dedicated to ensuring a welcoming, fair, and inclusive environment—can be found at: *http://www.engin.umich.edu/college/about/diversity*.

The University of Michigan is a non-discriminatory/affirmative action employer. Underrepresented minorities and women are strongly encouraged to apply. The College of Engineering is especially interested in qualified candidates who can contribute, through their research, teaching, service and administrative leadership activities to the diversity and excellence of the academic community and who will build collaborative ties with other departments within the College of Engineering and the University. The University of Michigan is responsive to the needs of dual-career families.

Applicants should electronically submit a detailed curriculum vitae and cover letter describing professional background, qualifications, and leadership experience, as well as a two-page synopsis of their views on the current challenges and opportunities facing mechanical engineering education and research. The deadline for ensuring full consideration of an application is December 1, 2017. The search will be conducted in confidence until finalists are invited for campus visits at which time professional references will be contacted.

Please submit your application to the following:
https://apply.interfolio.com/44562

If you have any questions regarding the web application submittal process or other inquiries, please contact Professor André L. Boehman, Chair, ME Search Committee, at boehman@umich.edu.

THE UNIVERSITY OF UTAH®

Faculty Positions in Mechanical Engineering
University of Utah

The Department of Mechanical Engineering at the University of Utah (**http://www.mech.utah.edu/**) invites applications for three tenure track positions at all ranks with a Fall Semester 2018 starting date. Candidates with interest and expertise in the areas of i) solid mechanics, ii) robotics, and iii) thermal sciences are strongly encouraged to apply. Candidates are expected to develop and maintain an active, externally-funded research program that complements existing research and should be qualified to teach core courses in a mechanical engineering program. Applicants are expected to have an earned Ph.D. or Sc.D. in Mechanical Engineering or a closely related field prior to start date. The Department of Mechanical Engineering currently has 38 tenure-line faculty members, over 1000 undergraduate and 245 graduate students. The University of Utah is a tier 1 research institution that has ranked in the top 5 nationally for start-up companies in the last 5 years. The University of Utah campus is situated in Salt Lake City, a diverse, cosmopolitan city with a population of 1M nestled against the backdrop of the beautiful Wasatch Mountains. Salt Lake City residents have unparalleled access to national parks (8 within a few hours drive), skiing/snowboarding (7 resorts within 30 minutes), hiking, fishing, biking, rafting/kayaking, NBA basketball, MLS soccer, and numerous cultural events including opera, dance, symphony, theatre, and outdoor concerts, amongst others. Review of applications will begin on December 4, 2017 and continue until positions are filled. For further information on these positions and the application process see **http://mech.utah.edu/department/open-positions/**.

The University of Utah is an Equal Opportunity/Affirmative Action employer and educator. For additional information about the University's commitment to equal opportunity and access see: **http://www.utah.edu/nondiscrimination/**.

Department of Mechanical Engineering Faculty Positions

The Department of Mechanical Engineering at Virginia Tech invites applications for **seven faculty positions** in the general areas listed below. These tenure-track or tenured positions could be filled at the Assistant, Associate, or Full Professor level as designated below. Exceptional candidates will be considered for named professorships.

1. **Dynamic Systems and Control** (open rank): Robotics and autonomous systems, control and information theory, perceptions and intelligent systems, signal processing and estimation, mechatronics, and system dynamics. Particularly desirable are areas such as control theory, human-machine interaction, modeling and control of social and behavioral systems, bioinspired robotics, and social robotics. Job number **TR0170140**. Search committee chair: Prof. Pinhas Ben-Tzvi (bentzvi@vt.edu)
2. **Robotics Perception** (open rank): Perception in robotics, autonomous systems, and intelligent infrastructures. Job number **TR0170141**. Search committee chair: Prof. Pinhas Ben-Tzvi (bentzvi@vt.edu)
3. **Computational Design and Analysis Methods**, (Assistant and Associate Professor level): computational mechanics, multiscale (nano-micro-macro scale) modeling, design automation, design optimization, design reliability, design methodology, advanced material modeling, and design for (additive) manufacturing. Job number **TR0170139**. Search committee chair: Prof. Chris Williams (cbwill@vt.edu).
4. **Materials and Manufacturing for Energy Systems** (Assistant and Associate Professor level): materials, design, and manufacturing with a preferred emphasis in energy storage and batteries, battery technology from a manufacturing perspective that encompasses the automation of the materials, mechanical, and chemical processes involved. Job number **TR0170138**. Search committee chair: Prof. Chris Williams (cbwill@vt.edu).
5. **Bio, Micro, and Nano-systems** (Assistant and Associate Professor level): emerging areas of mechanical engineering including mechanobiology, interface of mechanics and biology and medicine, BioMEMS/NEMS, cellular mechanics, biomedical micro/nano-devices, biotransport, modeling of biological systems ranging from molecular to genes, organelle, cell, and tissue level. Job number **TR0170135**. Search committee chair: Prof. Amrinder Nain (nain@vt.edu)
6. **Energy Engineering and Sciences/Combustion** (Open rank): turbomachinery, aerospace propulsion systems, gas turbine heat transfer, electronic cooling and thermal management, diagnostic systems, and thermoelectric power generations, biofuels, combustion diagnostics and dynamics, and automobile engine systems. Job number **TR0170133**. Search committee chair: Prof. Wing Ng (wng@vt.edu).
7. **Nuclear Engineering and Sciences** (Open rank): nuclear materials and fuels, particle transport methods, radiation detection, reactor physics, reactor safety, reactor shielding, reactor design, medical and imaging applications, nuclear security and safeguard, nuclear non-proliferation and policy. This position is directly related to VT's Intelligent Infrastructure Destination Area (a transdisciplinary initiative across many colleges.) To apply for this position, please refer to Virginia Tech's cluster hire ad at https://listings.jobs.vt.edu/postings/80315 and select Mechanical Engineering Department and mention applying to Nuclear Engineering position.

Positions 2 through 7 contribute to the University's transdisciplinary Destination Area in Intelligent Infrastructure and Human Centered Communities. Please find more information on the departmental web site for details.

Virginia Tech is committed to diversity and seeks a broad spectrum of candidates including women, minorities, and people with disabilities. Virginia Tech is a recipient of the National Science Foundation ADVANCE Institutional Transformation Award to increase the participation of women in academic science and engineering careers (www.advance.vt.edu).

Applicants must hold a doctoral degree in engineering or a closely related discipline. We are seeking outstanding candidates committed to a career in research and teaching. The successful candidates will be responsible for mentoring graduate and undergraduate students, teaching courses at the undergraduate and graduate levels, and developing an internationally recognized research program. Candidates should apply online at www.jobs.vt.edu to the appropriate posting number given above. Applicants should submit a cover letter, a curriculum vitae including a list of published journal articles, a one-page research statement, a brief statement on teaching preferences, and the names of five references that the search committee may contact. Review of applications for all positions will begin on **December 4, 2017** and will continue until the positions are filled. Please visit the departmental web site at http://www.me.vt.edu/ for more information about the department and each position.

ILLINOIS

Professor (Faculty Rank)
Department of Mechanical Science and Engineering
College of Engineering
University of Illinois Urbana-Champaign

The Department of Mechanical Science and Engineering at the University of Illinois at Urbana-Champaign invites applications for multiple faculty positions in all ranks. Candidates are sought in all technical subdisciplines of mechanical science and engineering including design, thermosciences, solid and fluid mechanics, and dynamics and control, with particular interest in the broad areas of manufacturing, energy and sustainability, and robotics and cyber-physical systems.

Qualified senior candidates will also be considered for a named appointment as part of the Grainger Engineering Breakthroughs Initiative, supported by a $100-million gift from the Grainger Foundation.

A doctoral degree is required, all opportunities are full-time, tenure or tenure-track, 9-month appointments paid over 12 months, with salary commensurate with qualifications and experience. Applications received by December 1, 2017, will receive full consideration. Early applications are strongly encouraged. Interviews may take place before the given date; applications received after December 1, 2017 may be considered until positions are filled. The expected start date of a position offered/accepted through this search is August 16, 2018, but other start dates will be considered.

A full position description and information on how to apply can be found at on the University of Illinois at Urbana-Champaign online jobsite: **http://jobs.illinois.edu**.

For further information regarding application procedures, please address questions to: **mechse-facultyrecruiting@illinois.edu**.

The University of Illinois conducts criminal background checks on all job candidates upon acceptance of a contingent offer.

The U of I is an EEO Employer/Vet/Disabled **www.inclusiveillinois.illnois.edu**

香港中文大學
The Chinese University of Hong Kong

Applications are invited for:-

Department of Mechanical and Automation Engineering
Professors / Associate Professors / Assistant Professors

(Ref. 170001DV)

The Chinese University of Hong Kong (CUHK) is ranked one of the top 50 universities worldwide according to the QS World University Rankings of 2016/17. It is also named the Most Innovative University in Hong Kong by Thomson Reuters in their survey of August 2016. In the 2014 Research Assessment Exercise, the mechanical engineering discipline of CUHK was ranked first among its counterparts of all universities in Hong Kong in terms of the ratio of world leading research (top category of 4*). Further information about the Department is available at http://www.mae.cuhk.edu.hk.

The Department of Mechanical and Automation Engineering (MAE) at CUHK is seeking excellent candidates in the following areas:
- robotics and automation;
- systems and control;
- design and manufacturing, in particular, in areas of 3D printing and CAD.

Applicants should have (i) a PhD degree in mechanical engineering or a related discipline; and (ii) a proven record of academic scholarship and high potential for excellence in teaching and research.

The appointees will (a) teach undergraduate and postgraduate courses; (b) develop an externally funded high impact research programme; (c) supervise postgraduate students; and (d) provide service to the department, professional organizations and the community.

Similar to tenure tracked positions at universities in USA, appointments will normally be made on contract basis for up to three years, which, subject to mutual agreement, may lead to longer-term appointment or substantiation later. Outstanding candidates with substantial experience for Professor rank may be considered for substantive appointment forthwith. The exact start date will be negotiated with the successful applicants.
[Those who have responded to the previous advertisement for the post (Ref. 160001SC) are under consideration and need not re-apply in this instance.]

Applications will be accepted until the posts are filled.

Application Procedure
Applicants please upload the full CV, copies of academic credentials, publication list with abstracts of selected published papers, details of courses taught and evaluation results (if available), a research plan, a teaching statement, together with names, addresses and fax numbers/e-mail addresses of three to five referees to whom the applicants' consent has been given for their providing references (unless otherwise specified). For more information, please contact Ms. YL Kan at ylkan@mae.cuhk.edu.hk.

The University only accepts and considers applications submitted online for the posts above. For more information and to apply online, please visit http://career.cuhk.edu.hk.

The Department of Mechanical Engineering at the University of Minnesota-Twin Cities invites applications to fill two full-time, tenure-track positions beginning Fall 2018. The appointment is expected to be at the Assistant Professor level, but applicants may be considered for a tenured appointment if they have a particularly strong record of research and teaching accomplishments, scientific leadership, and creativity. We seek individuals with an interest in building strong research programs, teaching, and service activities in (1) Building Energy Sciences and (2) Reactive Flows. Additional information and application instructions can be found at http://www.me.umn.edu. The University of Minnesota is an equal opportunity educator and employer.

University Of Michigan-Shanghai Jiao Tong University Joint Institute The University of Michigan-Shanghai Jiao Tong University (UM-SJTU) Joint Institute invites applications for tenure-track and tenured positions in all emerging fields related to Mechanical Engineering. UM-SJTU Joint Institute is committed to building a world-class research and educational institution based on the US university model. The Mechanical Engineering Program is ABET accredited. The students are among China's best. Successful candidates are expected to establish vigorous research programs, mentor students, participate in the international research community, and teach undergraduate and graduate classes. Salary will be highly competitive and commensurate with qualifications. Applicants should send a CV, statement of research interests, three publications, and contact information for five referees as a single PDF file to: Prof. Xudong Wang, Chair of the Search Committee, wxudong@sjtu.edu.cn and ji-search@sjtu.edu.cn. More information is available at http://umji.sjtu.edu.cn/en/.

Mechanical And Aerospace Engineering Department At Missouri University Of Science And Technology Assistant Professor Position (Ref #00030916) The Department of Mechanical and Aerospace Engineering at the Missouri University of Science and Technology (formerly the University of Missouri – Rolla) invites applications for a full-time tenure-track Assistant Professor position in the general area of autonomous systems, such as small spacecraft systems, unmanned air vehicles, mobile robots, and swarms. Areas of interest include, but are not limited to, embedded intelligence, large interconnected systems and coordinated control, and human interaction with autonomous systems. Applications are invited from candidates that possess an earned Ph.D. in Mechanical or Aerospace Engineering or closely related fields. The successful candidates will demonstrate the potential to establish and grow a strong research program and will participate in all aspects of the Department's mission, which includes research, teaching and service. The Department currently has 41 faculty members, including 37 tenured and tenure-track faculty, over 950 undergraduate and approximately 250 graduate students, and offers the B.S., M.S., and Ph.D. degrees in Mechanical and Aerospace Engineering. Details regarding the department can be found at http://mae.mst.edu/. Candidates should include the following with their letter of application: current curriculum vitae, a list of graduate courses taken, statement of research plans including areas in which the candidate has an interest in collaborating with other faculty, statement of teaching philosophy, and names and contact information for at least three references. Review of applications will begin on January 2, 2018 and applications will be accepted and reviewed until the position is filled. All application materials must be electronically submitted to the Missouri University of Science and Technology's Human Resource Office using the following address: http://hr.mst.edu/careers/academic/. Acceptable electronic formats that can be used include PDF and Word. Missouri S&T is an AA/EEO employer and does not discriminate on the basis of race, color, religion, national origin, sex, sexual orientation, gender identity, gender expression, age, disability, or status as a protected veteran. Females, minorities, and persons with disabilities are encouraged to apply. The university participates in E-Verify. For more information on E-Verify, please contact DHS at: 1-888-464-4218.

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Director of the Center for Energy Research

The Department of Mechanical Engineering at the University of Nevada Las Vegas seeks applicants for a tenured faculty position [18523] with a research emphasis in Solar Energy, Renewable Energy and/or Energy Systems who will serve as the Director of the Center for Energy Research (CER). The ideal candidate will be hired as a Full Professor. Candidates at the Associate Professor level with exceptional research and leadership qualifications will also be considered. The candidate is expected to lead the Center for Energy Research activities which include: securing extramural funding, promoting interdisciplinary research initiatives, mentoring junior faculty, encouraging high quality research, providing teaching excellence in energy related areas, as well as the recruitment of future students, faculty, and staff.

For more information, please visit **https://hrsearch.unlv.edu**

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The Department of Aeronautics and Astronautics at Stanford University invites applications for a tenure track faculty position at the Assistant or untenured Associate Professor level.

Research advances in the fundamental areas of aerospace engineering are critical for future air and space transportation systems that will provide efficiency, safety, and security, while protecting the environment. We are seeking exceptional applicants who will develop a program of high-impact research, contribute to an innovative undergraduate curriculum, and develop graduate courses at the frontier of areas such as aerospace system design, autonomous vehicle technologies, and breakthroughs in aerospace propulsion concepts. We will place higher priority on the impact, originality, and promise of the candidate's work than on the particular area of specialization within Aeronautics and Astronautics.

Evidence of the ability to pursue a program of innovative research and a strong commitment to graduate and undergraduate teaching is required.

Candidates whose research programs in Aeronautics and Astronautics will involve the development of sophisticated computational and/or mathematical methods may be considered for an appointment with an affiliation with the Institute for Computational and Mathematical Engineering (**https:/ /icme.stanford.edu/**).

All candidates should apply online at **https://aa.stanford.edu/job-openings**. Applications should include a brief research and teaching plan, a detailed resume including a publications list, three letters of reference, and the names and addresses of at least two more potential referees. Applications will be accepted until the position is filled; however, the review process will begin on January 1, 2018.

Stanford is an equal employment opportunity and affirmative action employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability, protected veteran status, or any other characteristic protected by law. Stanford also welcomes applications from others who would bring additional dimensions to the University's research, teaching and clinical missions.

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FUTURE ENGINEERS CELEBRATE 3-D DESIGN AND CREATIVITY

Trumpeting the message, "If you can design it, you can print it!" recent launch events held to promote the ASME Foundation's latest Future Engineers challenge opened up the 3-D design world to students and encouraged them to explore its infinite possibilities.

More than 400 students and guests gathered at the Smithsonian National Air and Space Museum in Washington, D.C., on Sept. 27 for the official announcement of the sixth Future Engineers challenge, "Two for the Crew." Joining representatives from the ASME Foundation and NASA, these aspiring engineers had a chance to flex their creative digital design skills while exploring Tinkercad software and watching MakerBot 3-D printers in action.

Following this 3-D design-and-print "show and tell," Future Engineers founder **Deanne Bell** facilitated a panel discussion featuring ASME Foundation Interim Executive Director **Paul Scott**. The discussion focused primarily on the opportunities to positively impact K-12 STEM education through non-traditional collaborative partnerships.

A similar approach was on display at the ASME Foundation's Future Engineers booth at the 2017 Girl Scout Convention in Columbus, Ohio, from Oct. 3 to 5.

Building on a theme of G.I.R.L.—Go-getter, Innovator, Risk-taker, and Leader—the convention hosted some 10,000 scouts, delegates, and parents who enthusiastically camped out at the Future Engineers exhibit to render their 3-D designs and get the red-carpet treatment at a corresponding step-and-repeat photo booth. ME

The Future Engineers Challenge event featured a panel session on K-12 STEM education.
Image: Patti Jo Rosenthal

Young visitors had the opportunity to try out Tinkercad software.
Image: Patti Jo Rosenthal

ASME MEMBER SPEAKS AT INDIA'S ENGINEER'S DAY

ASME member **Emamul Haque** was invited to be the guest of honor at an event commemorating Engineer's Day in India that was held at the University of Petroleum & Energy Studies (UPES) in Dehradun, India, on Sept. 25.

Haque, who served as the 2015-2016 ASME Early Career Leadership Intern Program to Serve Engineering (ECLIPSE) intern to the Board of Governors, was the featured speaker during the special Engineer's Day orientation session, which was arranged by the UPES ASME student section.

Nearly 130 students and faculty members filled the university's auditorium to listen to Haque's presentation, "Quality Mechanical Engineering: Transforming the World Through Technology," in which he discussed the disparity between what engineering students learn in school and the skills that are required in industry once they graduate, as well as how ASME can help provide students and early career engineers with opportunities to acquire these necessary skills.

After his speech, which included a lengthy Q&A session with the audience, Haque met with the students and faculty from the university at an ASME information booth that had been set up for the occasion. By the end of the event, more than 90 students and 12 UPES professors had registered to become members of ASME. ME

ASME member Emamul Haque was the guest of honor at a special Engineer's Day event. *Photo: Yash Shukla*

APPLICATIONS NOW BEING ACCEPTED FOR THE 2018 WISE INTERNSHIP PROGRAM

ASME is currently accepting applications from engineering students who are interested in representing the Society in the 2018 Washington Internships for Students of Engineering (WISE) program. The WISE program offers third- and fourth-year engineering students the opportunity to spend the summer in Washington, D.C., learning how government officials make decisions on complex technological issues and how engineers can contribute to the decision-making process. ASME will sponsor one WISE internship during the 2018 WISE term, which will take place from June 3-Aug. 4, 2018. At the end of the nine weeks, each intern will complete a public-policy paper on a topic of interest and present his or her findings on Capitol Hill. ME

HONORING THE ACHIEVEMENTS OF THE PROFESSION'S FINEST

The careers and achievements of eight leaders of the engineering profession—including **Adrian Bejan**; **Paul D. Edwards**; **John Staehlin, P.E.**; **Evelyn N. Wang**; **Zdenék P. Bažant, P.E.**; **Ramesh K. Agarwal**; **John W. Cipolla**; and **Michael F. Modest**—were highlighted on Nov. 6 at the annual ASME Honors Assembly, held during the ASME 2017 International Mechanical Engineering Congress and Exposition in Tampa, Fla.

Bejan, the J.A. Jones Distinguished Professor of Mechanical Engineering at Duke University, was presented the Ralph Coats Roe Medal during the event. The medal recognizes an outstanding contribution toward a better appreciation of the engineer's worth to the society.

Edwards, vice president and construction manager for ASME programs at WECTEC Global Project Services Inc. in Canton, Mass., received ASME Standards & Certification's Melvin R. Green Codes and Standards Medal. The award pays tribute to the extraordinary contributions of Green, a dedicated supporter of industrial standards.

Staehlin, president emeritus of Volunteers for Medical Engineering (now known as V-LINC) in Baltimore, Md., received the Hoover Medal at the ceremony. The medal is presented to an engineer whose professional achievements and personal endeavors have advanced the well-being of humankind.

Wang, the Gail E. Kendall Professor in the mechanical engineering department at MIT, was presented the Gustus L. Larson Memorial Award, given to an engineering graduate who has demonstrated outstanding achievements within 10 to 20 years after graduation.

Bažant, the McCormick Institute professor and W.P. Murphy professor of civil and mechanical engineering, and materials science at Northwestern University, received the Society's highest award, the ASME Medal.

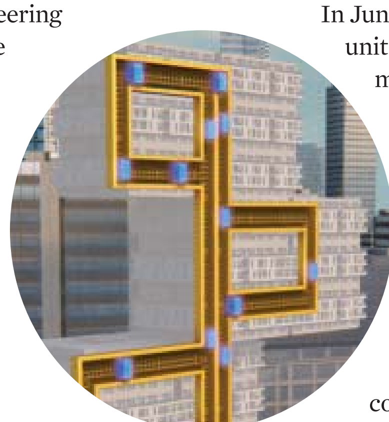
Agarwal, Cipolla, and Modest each received ASME Honorary Membership—the highest level of Society membership, which is conferred upon persons who have made distinctive contributions to engineering, science, industry, research, or other pursuits allied with the engineering profession. ME

The cable-less elevator system moves multiple cars in a single shaft.
Images: Thyssenkrupp

ELEVATING THE FUTURE

Roald Dahl's classic children's book *Charlie and the Chocolate Factory* was considered a work of fantasy when it was published in 1964. After all, along with nut-sorting squirrels and teleportation via television, the book describes the eccentric Willy Wonka's ingenious glass elevator that "goes up, down, sideways, and every other which way you can think of going."

Now over five decades later, German engineering firm Thyssenkrupp Elevator AG is turning the "Wonkavator" into reality. The company has developed the Multi, a rope-free elevator that can travel both horizontally and vertically in a single shaft.



Elevators may not be an obvious venue for innovation, as the business is very conservative. "But as buildings are growing higher and higher, it becomes obvious more and more that the traditional elevator is a limiting factor and a bottleneck for the constructors of visionary buildings," said Markus Jetter, head of product development at Thyssenkrupp Elevator.

To avoid those bottlenecks, Thyssenkrupp's technology enables multiple elevator cabins to run in a loop and the cars move via a magnet-based linear motor drive system, similar to that found in Maglev trains. The elevators have an "exchanger," which can switch from vertical to horizontal to allow for sideways movement.

The system, Jetter said, activates only those sections where the cars are located, so energy is consumed only where cars are accelerating, moving steadily, or decelerating.

"The absence of ropes may give a different first impression but that isn't true in any respect," he said, adding that the linear motors are safe because they need to be energized before they move. Without electricity, the cabins won't move.

The cabins also include emergency batteries so they can continue to run in the case of a blackout.

In June, Thyssenkrupp displayed a fully functional unit in an 870-foot test tower in Rottweil, Germany. The company is now working on getting international certifications. OVG, the developer of smart office buildings, will be installing the elevator system in the East Side Tower in Berlin.

Besides being one of the first new innovations in the elevator industry since the invention of the safety elevator some 165 years ago, the Multi promises to reduce peak power demand by as much as 60 percent, compared to conventional elevator systems.

"Multi offers a 50 percent higher transportation capacity. That means the same amount of people can be commuted with half the number of shafts. This is particularly important as elevator shafts can occupy up to 40 percent of the floor space in a typical tall building," Jetter said.

The Multi won't have all the features of the Wonkavator. In the book's sequel, the Great Glass Elevator flew to an orbiting space hotel. **ME**

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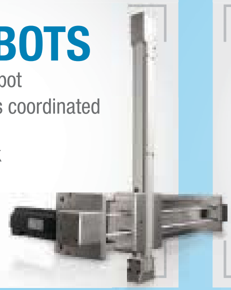

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