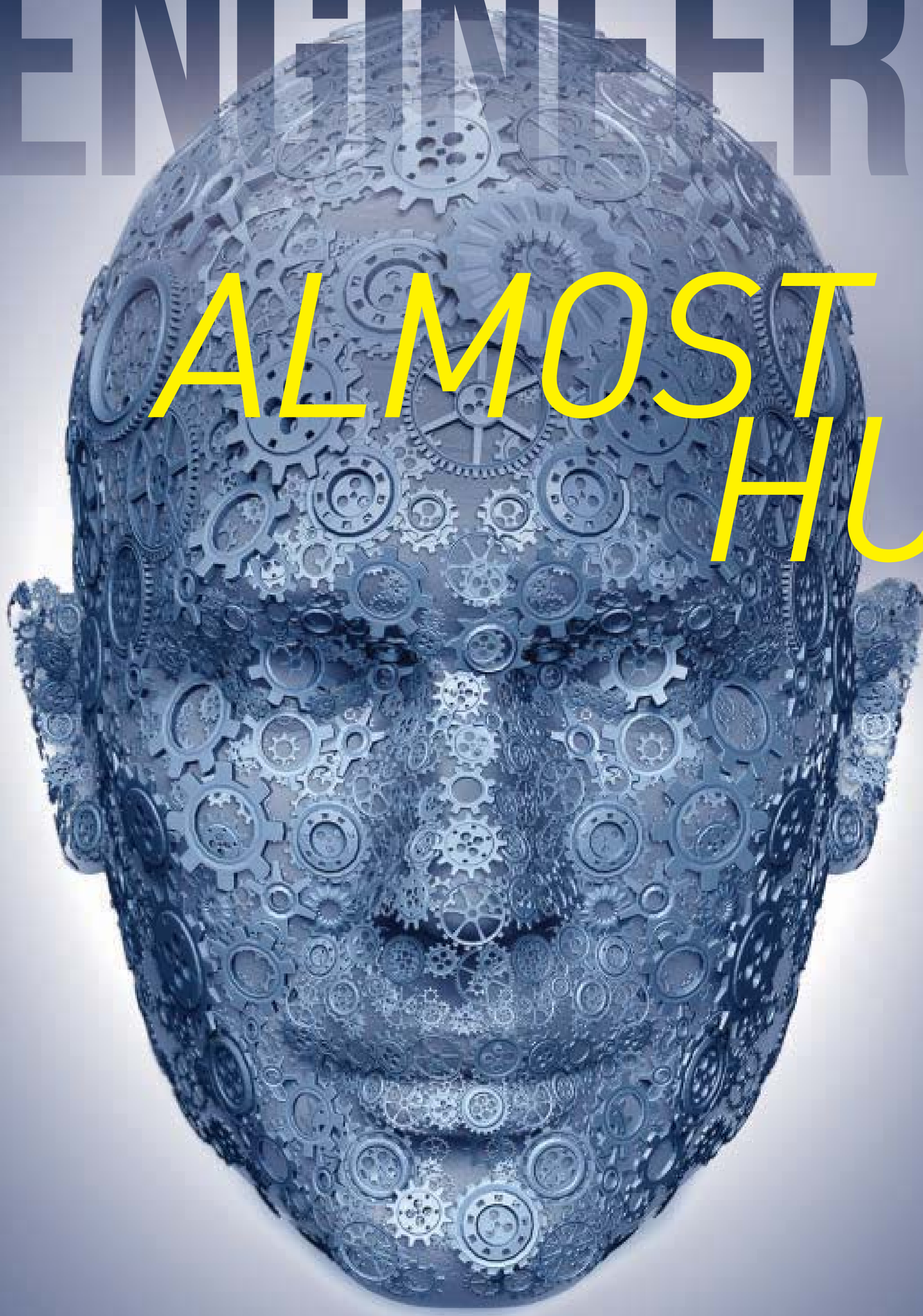
MECHANICAL ENGINEERING
Technology that moves the world
THE MAGAZINE OF ASME
No. 09
136



ALMOST HUMAN

MACHINES ARE APPROACHING THE AGE OF REASON

join us for this free webinar!

MECHANICAL ENGINEERING WEBINAR SERIES

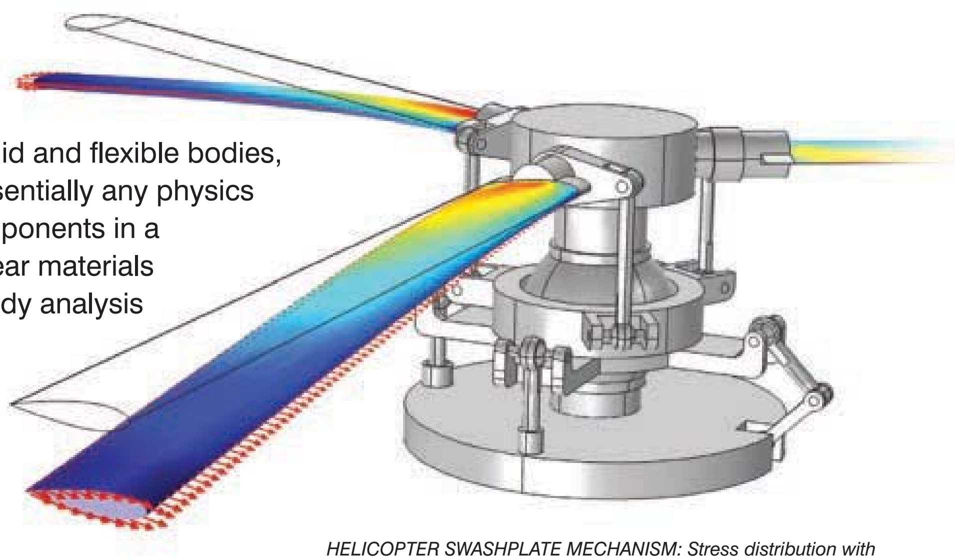
Multibody Dynamics Simulation with COMSOL Multiphysics

September 18, 2014 • 2:00 p.m. ET / 11:00 a.m. PT

Register today at: http://bit.ly/me-webinar-sept18

The Multibody Dynamics Module, an add-on to the Structural Mechanics Module for COMSOL Multiphysics, offers powerful tools for designing and optimizing multibody systems. With the module, simulate systems containing rigid and flexible bodies, various joint types, and add essentially any physics to a model. Design flexible components in a multibody system using nonlinear materials and use the results of a multibody analysis to evaluate fatigue.

This webinar will introduce you to the capabilities of the module and features a live demonstration followed by a Q&A session.



HELICOPTER SWASHPLATE MECHANISM: Stress distribution with magnified deformation shown in the flexible rotor blades of a helicopter.

Sponsored by:

COMSOL

MODERATOR:	SPEAKER:
JOHN FALCIONI	PAWAN SOAMI
Editor-in-Chief	Technical Product Manager
MECHANICAL ENGINEERING	COMSOL

Register today at http://bit.ly/me-webinar-sept18

Tesla factory building a Model S chassis. The company plans to build a plant that will turn out batteries in quantities that can reduce prices.

WAITING FOR THE GIGAFACTORY

THE MAN IN CHARGE OF SPACEX AND TESLA MOTORS, ELON MUSK, aims to bring electric-powered vehicles to the masses via his estimated $5 billion Gigafactory, a manufacturing plant to produce lithium ion batteries at a scale projected to sharply reduce costs and enable production of a lower-cost electric car. Musk's ambitious plan to produce some 500,000 vehicles annually by 2020 depends on building a factory that can produce a large enough number of batteries to drive down production costs.

OFFSHORING NUCLEAR PLANTS

An MIT professor, Jacopo Buongiorno, has designed a nuclear power plant that cuts costs and increases safety by operating at sea.

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

HELPING BABIES BREATHE EASIER

Students at Brigham Young University are developing a ventilator to assist babies in the developing world, where often the only option is a hand pump.

VIDEO: THE NEW TAPPAN ZEE BRIDGE

With twin cable-stayed spans and piles reaching deep into the river bed, New York's new Tappan Zee Bridge promises to be a true engineering marvel when complete in 2018.

NEXT MONTH ON ASME.ORG

MANAGING DIABETES WITH WEARABLE PANCREAS

Engineers from Boston University have developed a bionic pancreas system and are testing the technology, which is intended to automate the regulation of glucose in patients with diabetes.

TECHNOLOGY TAKES TATTOOS INTO THE FUTURE

Technology is decreasing the pain and increasing the possibilities of tattooing, bringing a new generation of customers into the nation's tattoo parlors.

CONTENTS

09 136

ASME
SETTING THE STANDARD

42

COLD START DEAD SENSOR

Electrostatic discharge from lubricants can destroy sensitive, and crucial, engine components. BY BEHROUZ ABEDIAN

49

DYNAMIC SYSTEMS & CONTROL

Four papers examine research in a growing field: Robots designed for rehabilitation.

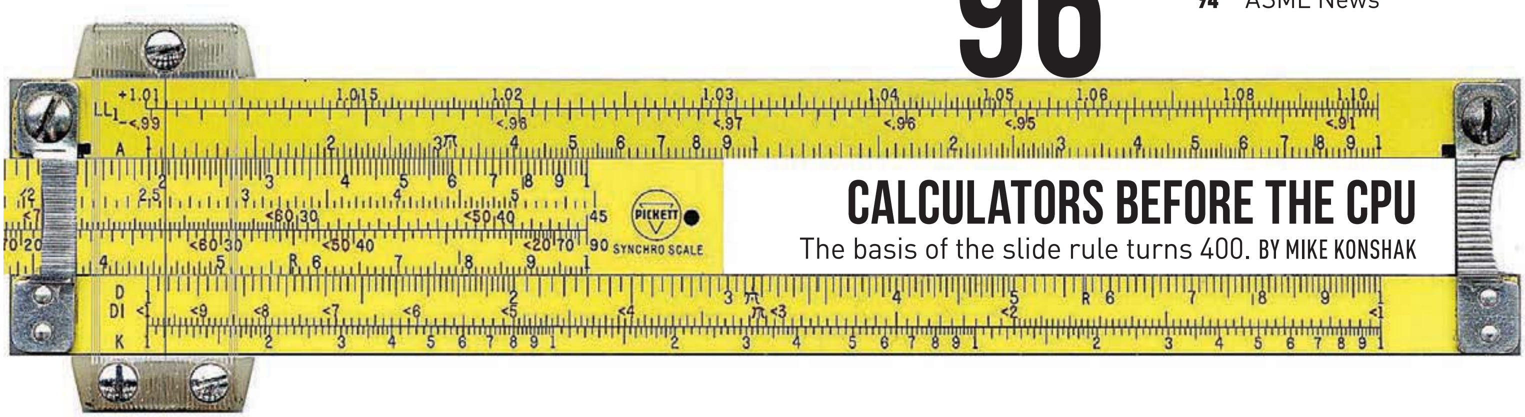
73

INTERNATIONAL GAS TURBINE NEWS

Turbo Expo: Curbing life cycle costs.

INSIDE

96



CALCULATORS BEFORE THE CPU

The basis of the slide rule turns 400. BY MIKE KONSHAK

MECHANICAL ENGINEERING // THE MAGAZINE OF ASME

Editor in Chief
John G. Falcioni

Executive Editor
Harry Hutchinson

Senior Editor
Jeffrey Winters

Associate Editors
Alan S. Brown
Jean Thilmany

Art and Production Designer
Dorothy Szemiot

Contributing Writers
Michael Abrams, Benedict Bahner, Richard Benson, Rob Goodier, Lee Langston, Bridget Mintz Testa, Andrew Reynolds, Kirk Teska, Jack Thornton, Michael Webber, Frank Wicks, Amos Winter, Robert O. Woods

Design Consultant Bates Creative Group

ASME.ORG

Editor
David Walsh

Managing Editor
Chitra Sethi

Senior Editor
John Kosowatz

Managing Director Publishing Philip V. DiVietro

Managing Director Conformity Assessment & Publishing Michael Merker

Contact *Mechanical Engineering*

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

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

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

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

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

President J. Robert Sims
President Nominee Julio C. Guerrero
Past President Madiha El Mehelmy Kotb

Governors
John F. Elter; Urmila Ghia; John E. Goossen; Stacey E. Swisher Harnetty; Bernard E. Hrubala; Richard T. Laudenat; Andrew C. Taylor; John M. Tuohy; William M. Worek

Executive Director Thomas G. Loughlin
Secretary and Treasurer Warren R. Devries
Assistant Secretary John Delli Venneri
Assistant Treasurer William Garofalo
Second Assistant Treasurer June Ling

Senior Vice Presidents
Standards & Certification Laura Hitchcock
Technical Events & Community Robert E. Grimes
Public Affairs & Outreach William J. Wepfer
Student & Early Career Development Cynthia M. Stong

***Mechanical Engineering* magazine Advisory Board**
Robert E. Nickell, chair; Harry Armen; Leroy S. Fletcher; Richard J. Goldstein

ASME offices

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

Customer Sales & Service
e-mail customercare@asme.org
p. 973.882.1170 f. 973.882.1717
22 Law Drive, Fairfield , NJ 07007
In U.S. toll-free 800 THE ASME
international 973.882.1167

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

Int'l Gas Turbine Institute http://igti.asme.org
p. 404.847.0072 f. 404.847.0151
6525 The Corners Parkway, Suite 115; Norcross, GA 30092-3349

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

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

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

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

Publisher
Nicholas J. Ferrari

Manager, Integrated Media Sales
Greg Valero

Marketing and Promotion Manager
Anthony Asiaghi

Circulation Coordinator
Marni Rice

Advertising & Sponsorship Sales Coordinator
Michelle Lewitinn

Media Sales Assistant
James Pero

Classified and Mailing List
212.591.7534

Advertising Sales Offices

East Coast Michael Reier; **reierm@asme.org**
p. 410.893.8003 f. 410.893.8004
900-A South Main Street, Suite 103; Bel Air, MD 21014

Southeast Bob Doran **doranb@asme.org**
p. 770.587.9421 f. 678.623.0276
8740 Glen Ferry Drive, Alpharetta, GA 30022

East Central Thomas S. Bednar
bednart@asme.org
p. 440.933.4746 f. 440.933.2319
391 Long Pointe Drive, Avon Lake, OH 44012

West Central Thomas McNulty
mcnultyt@asme.org
p. 847.842.9429 f. 847.842.9583
P.O. Box 623; Barrington, IL 60011

Southwest and West Phoebe Klein
phoebe.klein@husonmedia.com
p. **212.268.3344 f. 917.210.2989**
13-17 Laight St., Suite 401, Box 7, New York, NY 10013

UK/Europe Christian Hoelscher
christian.hoelscher@husonmedia.com
p. +49 89.9500.2778 f. +49 89.9500.2779
Huson International Media
Agilolfingerstrasse 2a, 85609 Aschheim/Munich, Germany

James Rhoades-Brown
james.rhoadesbrown@husonmedia.com
p. +44 (0) 1932.564999 f. +44 (0) 1932.564998
Huson European Media
Cambridge House, Gogmore Lane, Chertsey, Surrey, KT16 9AP, England

Rachel DiSanto
Rachel.disanto@husonmedia.com
+44 (0) 1625.876622 fax +44 (0) 1932.564998
Huson European Media
Cambridge House, Gogmore Lane, Chertsey, Surrey, KT16 9AP, England

Mechanical Engineering (ISSN 0025-6501) is published monthly by The American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990. Periodicals postage paid at New York, N.Y., and additional mailing offices. POSTMASTER: Send address changes to Mechanical Engineering, c/o The American Society of Mechanical Engineers, 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300. Return Canadian undeliverable addresses to P.O. BOX 1051, Fort Erie, On, L2A 6C7. PRICES: To members, annually $32 for initial membership subscription, single copy $7; subscription price to nonmembers available upon request. COPYRIGHT © 2014 by The American Society of Mechanical Engineers. Canadian Goods & Services Tax Registration #126148048. Printed in U.S.A. Authorization to photocopy material for internal or personal use under circumstances not falling within the fair use provisions of the Copyright Act is granted by ASME to libraries and other users registered with the Copyright Clearance Center Transactional Reporting Service, 222 Rosewood Drive, Danvers, MA 01923. Request for special permission or bulk copying should be addressed to Reprints/Permissions Department.

Your one-stop source for INDUSTRIAL ELECTRONICS

Schneider Electric

For Industrial Automation and Control, we have the products & solutions you need from the most trusted brands.

newark.com | 800.463.9275

Featured product:
ZB4BA731347 Actuator, Harmony XB4 Pushbutton
(28W5544)

Newark™ element14

John G. Falcioni
Editor-in-Chief

SETTING THE STAGE FOR A LEADING ROLE

Rosie the robot had a mind of her own. She held a prominent role in *The Jetsons*, the futuristic and animated family television sitcom. She spent her days being part-time housekeeper, part-time babysitter and—more often than not—a prominent family sage. *The Jetsons* was set in the Space Age world of 2062, when robots serve as servants, flight is the preferred means of transportation, and people use video chatting to communicate. Imagine that.

Some said the show, which first aired in 1962, was ahead of its time. It went off the air after one season but returned to a more successful run from 1984 to 1987. Hollywood's fascination with robots, however, predates Rosie and the Jetsons. Since the early days of B movies there has been an allure in giving mechanical objects the ability to think for themselves and act autonomously. In most of these obscure and often dark films, chaos occurs, predictably, when the machine, armed with the power to act under its own volition, wreaks havoc, turns on humans, and occasionally kills innocent women and children. In essence, it gets ugly.

Sans all the death and destruction, the fascination to give robots something akin to cognitive aptitude has not been lost on a long list of researchers throughout the years. They've been at work trying to promote robots from the assembly line and into useful aides that can interact with humans in positive and helpful ways. One of the many intriguing examples we have written about in the past is the work to turn robots into caregivers to help the elderly.

Because much of yesterday's science fiction has become today's technology, our editors have relied on the likes of technologists such as Ahmed Noor to keep us honest about the line between science fiction and reality. In his articles over the past decade or so, Noor has taken us inside technologies that are burgeoning and others so advanced you wouldn't be surprised to see them on *The Jetsons*. We've closely monitored Noor's work and we've kept a keen eye on the Center for Advanced Engineering Environments that he runs at Old Dominion University in Norfolk, Va.

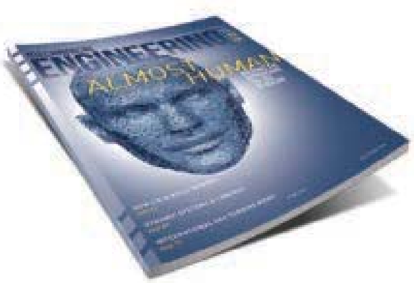
"Game Changers," the article Noor penned for us this month (plus a related article, "Robot See, Robot Do," written by a group from the University of Maryland) leads us on a path showing that machines are approaching the age of reason. Noor tells us about some serious explorations conducted here at home in places such as the U.S. Defense Advanced Research Projects Agency, commonly known as DARPA, and others farther away, such as the Neurorobotics Research Lab of Humboldt University in Germany, where an early generation cognitive robot called Myon is learning to respond to human emotion. Myon is so advanced, in fact, that it will play the lead in Berlin's Komische Oper production of "My Square Lady," a take on Frederick Loewe's musical, *My Fair Lady*. (No, I'm not kidding.)

The unique production will probe the question of what makes a person a person, and whether an object such as a robot can be transformed into one.

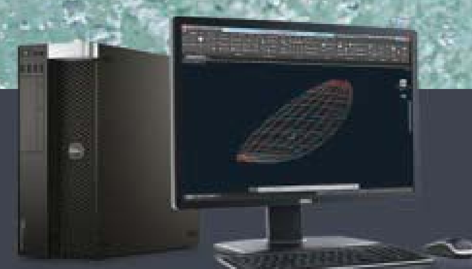
In spirit—figuratively speaking of course—Myon is more Rosie the robot than its distant relatives who play the menacing machines of modern warfare in *Transformers: Age of Extinction*. Just the same, I'm glad we've got the likes of Ahmed Noor to tell us just how long we have until technology fully catches up with science fiction. **ME**

FEEDBACK:

Do you envision the day when robots will have cognitive aptitude? Email me.
falcionij@asme.org



The perfect wave deserves the perfect board.



Screen image simulated. Monitor not included.
Wired keyboard and mouse come standard.

KKL engineers the complex design behind every surfboard with AutoCAD® and the power of Dell Precision workstations.

KKL supplies custom-built surfboards to competitors around the world. But competitors need more than just one board. So the challenge is to build dozens of boards for a client – each perfectly identical to the other. To meet this challenge, KKL relies on workstations such as the Dell Precision T3610 with the latest Intel® Xeon® processors and Windows 8.1 to deliver precise, uniformly designed boards for consistent performance when and where it counts.

Watch KKL engineer some of the world's best surfboards at Dell.com/CAD

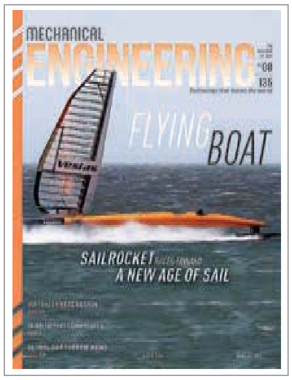
Dell Precision T3610: Optimized for performance and reliability

Intel® Xeon® processors and Windows 8.1 team with high-end graphics options for astounding results. Peak performance is easy to maintain with Dell Precision Performance Optimizer.

Starting at $1,029

Intel, the Intel logo, Xeon, and Xeon Inside are trademarks or registered trademarks of Intel Corporation in the U.S. and/or other countries. © 2014 Dell Inc. All rights reserved. Dell, the DELL logo, the DELL badge and Precision are trademarks of Dell Inc.

LETTERS & COMMENTS



AUGUST 2013

Reader Ghorashi says metals, not just composites, can be anisotropic.

« A reader adds new letters to STEM. Others take issue with hard-to-read colors and an apparent error in a graphic figure.

ISOTROPIC ILLUSION

To the Editor: The article titled "Unknown Qualities" (August 2013), on the properties of composites and the way they compare with metals, is interesting and informative.

However, it assumes that anisotropic behavior is limited to composites, and metallic pieces only behave isotropically. The article states, "Metals behave in the same way no matter where a force is applied."

It is a well-known fact that metals are commonly anisotropic (see B.J. Moniz, *Metallurgy*, fifth edition, American Technical Publishers, 2012). As Moniz explains, cold work results in anisotropic behavior in metals. The greater the amount of cold work, the greater the anisotropy.

Mechanical properties become distinctly different in the directions parallel and perpendicular to the cold-work direction. In the cold work direction, the metal exhibits an increase in tensile and yield strength, as well as hardness. The percent elongation, percent reduction in area, and notch toughness are reduced. The opposite is true of mechanical properties in the transverse direction. If the metal should have uniform properties in all directions (i.e. be isotropic), it needs annealing heat treatment to fully soften and restore uniformity.

Mehrdaad Ghorashi, P.E., *Gorham, Maine*

COLORS IN DEMAND

To the Editor: I recommend that whoever designs the *DEM+ND* supplement never print the supplement in the same colors as used in May 2014.

The colors made reading the material nearly impossible. Examples include the information on the Editorial Review Board and the authors of the articles, the excerpts in the articles, and elsewhere where orange and white were used as contrast. The color contrast on the world map in the "Remobility" [sic] article was close to illegible.

ASME is an organization that communicates technical and related information. The print design of the May supplement did not support that effort.

Sanford L. Pearl, *Palm Beach Gardens, Fla.*

COMMENT

WHAT I DID DURING MY YEAR IN D.C.

With the end of the Cold War the national laboratories were struggling to justify their own existence. They could no longer depend purely on defense work. In some quarters of Congress the question was being asked whether the United States needed them at all. The search for new energy sources provided an opportunity to demonstrate the utilitarian value of the laboratories.

As a Congressional Fellow in the 1991-92 term, I had managed to attach myself to the Senate Committee on Governmental Affairs, chaired by Senator John Glenn. The committee was very aware of the fact that the federal government is the largest consumer of energy in the nation. I was involved in an effort to assemble "Tiger Teams" which, when invited, could descend on government facilities and perform audits aimed at improving the efficiency of their power consumption, particularly in heating or cooling.

Another hot topic that touched on the labs was the mechanics of nuclear disarmament. This was particularly relevant to me since my work at Sandia had been in research aimed at better understanding the atmosphere in case the Soviets violated the Limited Test Ban Treaty and again started testing weapons above ground. Other aspects of disarmament included properly dismantling the existing stockpile of nuclear weapons, verifying that the ex-Soviets were really doing the same, and cleaning up the radioactive remains of the Manhattan Project.

There was plenty of latitude for an engineer in the committee. For example, dismantling a nuclear device involved far more than simply taking it apart. Many mechanical components were highly classified and had to be decommissioned in such a way that they could be disposed of in unclassified waste without any nation reverse engineering them and using their technology against us. In addition to the active parts of the weapon itself, a very elaborate set of circuit boards, explosive actuators, and radioactive components had to be salvaged and treated individually.

The burgeoning field of robotics was well suited to selecting small parts of a complex assembly. It opened a new field of engineering development.

BATTERY SWITCH

To the Editor: On the occasions that I read your magazine (I am not an ASME member), I have been impressed by the quality of articles and range of material covered.

I was thus surprised by Figure 1 in the article "The Lithium-Ion Battery modeling challenge ..." on page 8 of the special section in the June 2014 issue.

The figure seems to indicate, counter to the relevant text, that lead acid batteries would be ideal candidates for portable application batteries due to their superior combination of specific power and specific energy. Methinks that perhaps the balloons for Li-ion and lead acid were transposed in the figure.

R. Brian Peters, *Knoxville, Tenn.*

ADDING ARTS TO STEM

To the Editor: A recent local newspaper article brought me back to your April editorial in which you said, "The point is not to force-feed STEM over subjects like history, art, and literature, but to even out the level of instruction. ..."

Your point is already being taken. In the Pontiac, Mich., schools, the arts community has decided that it will be STEAM. Which will be next, SHTEAM or STEALM?

Roy Salisbury, Jr., *Rochester, Mich.*

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.

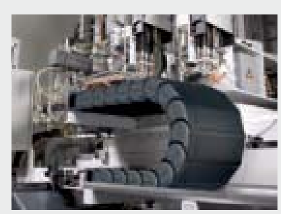
Cleaning up radioactive waste was a universe in itself. The most notorious case was the waste tanks at the nuclear production facility at Hanford, Wash. There, large underground tanks were filled with an ill-assorted collection of radioactive components and simple mechanical junk. A lot of innovative engineering involved creating remote sensors and cameras that could map the rubbish heap and provide data for robotic manipulators. All of this required engineering judgment and was done under contract to the Department of Energy and overseen by the Committee on Government Affairs. The Hanford cleanup goes on today unabated. ME

ROBERT O. WOODS, an ASME Fellow, is a frequent contributor to the magazine.

INNOVATIVE SOLUTIONS FOR ANY OPERATION

Why go to Extremes for the Ultimate Protection?

Looking for optimal protection for your application? Look no further, Tsubaki KabelSchlepp has the best option for any application with debris. TKA Series Cable Carriers are completely sealed regardless of the carrier's position, to ensure the utmost protection of your Tsubaki KabelSchlepp cables as well as your entire operation. No need to take extreme measures to protect your application from flying debris, metal chips, wash down contaminants or any other particulates that may get in your way. Call it a wrap on your old carriers because TKA has got you covered. www.ustsubaki.com or 800-443-4216



Be sure to stop by our booth at the 2014 IMTS show Sept. 8-13, Chicago, IL Booth #E-5823

TSUBAKI KABELSCHLEPP

© 2014 U.S. Tsubaki Power Transmission, LLC. All Rights Reserved.

NYLON • STEEL • HYBRID • TUBE • 3D • SILENT

Nymann Teknik, a Danish machine shop, uses a Universal Robots robotic arm to handle tooling.

WORKER-FRIENDLY ROBOTS

A NEW GENERATION OF LOW-COST ROBOTS HANDLES SHORT RUNS IN TIGHT quarters. With so much attention focused on driverless cars, package-delivering drones, and scrambling, stomping, and slithering automatons, industrial robots remain mechatronics' blue collar guys. They work several shifts each day, no complaints, doing the same repetitive job quickly and accurately.

"That's the equation that generates high ROI from robots in automotive and electronics mass production," said Ed Mullen, national sales manager for Universal Robots.

"But the other half of the world consists of small and medium sized factories that don't run on that model. They do short product runs with quick changeovers, and can't justify spending a lot of money for a machine that bolts into place and does only one thing."

Universal Robots is one of several firms developing robots for this emerging market. It has more than 3,000 robots up and running, mostly in Europe. Another notable contender is Rethink Robotics, which was founded by iRobot innovator Rodney Brooks.

Their robots have several characteristics in common. They are affordable (Universal's UR-5 lists at $34,000). They need little or no maintenance. They swap grippers rapidly. And they are flexible.

Most technicians learn to program one within a few hours, teaching tasks by moving the arm through each motion, much like a parent teaching a child to swing a bat. The robots then optimize the routines as they learn on the job.

This makes them flexible enough to move from line to line, loading lathes one day and assembling housings the next.

Perhaps most important is that these new robots are built to work safely around people.

Most heavy-duty industrial robots are not. Many industrial robots lack collision sensors. All work behind barriers to keep people out.

Even so, the U.S. Occupational Safety and Health Administration has counted about one industrial death by robot every year for the past 31 years. Most of them occurred on lines where people worked near robots.

Universal's six-axis robots are built to collaborate with people, and 80 percent of them do not

QUICK FACTS:

WHAT THEY ARE:
Low-cost, easily programmed robots that can operate in close quarters with people.

KEY DEVELOPERS:
Universal Robots, Odense, Denmark. Rethink Robotics, Boston.

TARGET MARKET:
Small and medium-size manufacturers making short product runs and quick changeovers.

work behind barriers. This is not because they are slow. While Universal's largest robot, the UR-10, only handles loads of 10 kilograms, it moves at speeds of 1 meter per second. That's fast enough to cause some damage, especially when handling hard or sharp objects.

Universal uses a grab bag of engineering tricks to keep that from happening. The robot is equipped with force sensors, which trip the control system when they reach 150 newtons (33.7 pounds force), a number referenced in several standards for human-friendly robots.

The control system sends the message to each of the arm's six Kollmorgen servomotors (one for each axis). Because they are oversized when compared with their loads, they decelerate rapidly to a stop. Because the motors are linked to harmonic drives with 100:1 gear ratios, the deceleration takes place even faster than if the motor was connected directly.

Mullen recommends that factories program robot speed based on their own safety assessments. In the past, when users wanted a greater margin of safety, they slowed down the robot. Universal's new third-generation robots let users select shutdown impacts below the previous 150 newton set point.

The robots now reaching the market from Universal and its competitors represent a new revolution in shop floor robotics, because they make robotics more affordable for everyone. Mullen said the typical customer receives a payback in six months.

"If you buy something like a gantry, it can only be as productive as the line you install it on," he said. "But with our system, you can move it to a busy line today and a busier line tomorrow. You get your payback by keeping that thing in production all the time."

Now, small shops can do it because they no longer have to fear injuries. ME

ALAN S. BROWN

From left, (a) unpurified sand, (b) purified sand, and (c) vials of unpurified sand, purified sand, and nanosilicon. The latter is used in the lithium ion battery developed at U.C. Riverside.

AN ANODE BUILT ON SAND

RESEARCHERS AT THE UNIVERSITY OF CALIFORNIA, Riverside's Bourns College of Engineering have developed a lithium ion battery that outperforms the current standard by three times. The improved performance could mean an increase in the lifespan of silicon-based electric vehicle batteries up to three times or more, they said.

The key to making this superbattery is sand—well, sand that can be turned into pure silicon and then, from there, pure silicon at the nanoscale.

"This is the holy grail—a low cost, non-toxic, environmentally friendly way to produce high performance lithium ion battery anodes," said Zachary Favors, a graduate student who works with Mihrimah and Cengiz Ozkan, both of whom are engineering professors at the university.

The idea came to Favors on the beach in San Clemente, Calif. He picked up some sand, took a close look at it and saw it was made up primarily of quartz, or silicon dioxide, he said.

Favors's research focuses on the anode, or negative side of the lithium ion battery, where graphite is the most commonly used material. But as electronics have become more powerful, graphite's ability to be improved has been virtually tapped out, Favors said.

Researchers are now focused on using silicon at the nanoscale as a replacement for graphite. But the problem with nanoscale silicon is that it degrades quickly and is hard to produce in large quantities, Favors said.

After his beach epiphany, Favors did some looking to find a spot where sand contains a high percentage of quartz. That took him to the Cedar Creek Reservoir, east of Dallas, where he grew up.

Back in the lab, Favors milled the sand down to the nanometer scale and followed with a series of purification steps changing its color from brown to bright white, similar in color and texture to powdered sugar. Then, he ground salt and magnesium into the purified quartz and then heated the resulting powder. With the salt acting as a heat absorber, the magnesium worked to remove the oxygen from the quartz, resulting in pure silicon.

The Ozkan team found the pure nanosilicon had formed into a very porous 3-D silicon that had a sponge-like consistency. That porosity has proved to be the key to improving the performance of the batteries built with the nanosilicon.

Feedback from sensors embedded in two fingertips of this prosthetic hand enabled Dennis Aabo Sørensen to grasp objects with appropriate force.

GETTING A GRIP

THE CYBORG LIMBS OF TODAY ARE PRETTY CRUDE APpendages. With their ability to grasp and hold, they're far more sophisticated than the hooks and pegs of yesteryear's pirates. But it's still an all-or-nothing affair: despite the number of sensors and degrees of freedom the contemporary bionic arm may have, the host knows only that a grip is either on or off. The grip lacks the feeling for whether the object held is hard or soft, round or square. Without looking at what's in their artificial hands, amputees have no more knowledge of an object's pliability than excavator operators have of the rubble they're scooping.

As a result, amputees have no sense of how much force is appropriate for an object. Hand them an orange to cradle and you might get orange juice. Now a consortium of engineers, scientists, doctors—and one patient—has managed to create a prosthetic arm with a sense of touch.

The patient, Dennis Aabo Sørensen, lost his forearm when toying with fireworks some ten years ago. Researchers at Switzerland's Ècole Polytechnique Fédérale De Lausanne hooked him up to a prosthetic with a robotic hand. The tips of two of its fingers have sensors, as do the artificial tendons of the hand. Signals from those sensors were sent to "transversal intrafascicular multichannel electrodes" planted in nerves in the remaining part of Sørensen's arm.

An undamaged biological arm senses the stiffness of an object with a feedback loop—the appropriate grip is determined by the sensation of the grip (think "Don't squeeze the Charmin"). In the middle of the loop there's a crucial element: the person. The "Real-Time Bidirectional Hand Prostheses" include this component.

"It's not a closed-loop control," said Marco Capogrosso, a biorobotics engineer at the institute. "The feedback is not to the robot. We actually put the brain into the middle. It's the brain that receives the signal and decides on how to control the robot."

The key to the "real-time" part of the system's name, and the chief engineering challenge, was keeping the gap between sensation and response to less than 100 milliseconds. Any longer and Sørensen would feel the delay.

"WE ACTUALLY PUT THE BRAIN INTO THE MIDDLE. IT'S THE BRAIN THAT RECEIVES THE SIGNAL AND DECIDES HOW TO CONTROL THE ROBOT."

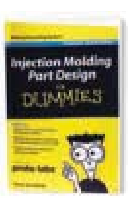
Sørensen did not feel a delay. Nor was there any delay to his putting the arm to use, once suited up, and he outperformed the researcher's expectations. Blindfolded and headphoned, he could tell the shape of a baseball, a bottle, and an orange (producing no juice as he held it) as well as its orientation. Handed a piece of hard wood, a stack of plastic cups, and a package of cotton, he appropriately tightened his grip each time. "He didn't train to use the robot," Capogrosso said. "He was just using the natural sensations he had from 10 years before. It was immediate and natural."

To achieve that naturalness, the researchers had to integrate a number of disparate commercial parts. The hand itself, for instance, was a Prensilia IH2 Azzurra, the arm socket made by Ortopedia Italia, and the TIME electrodes originally developed for another project. "The challenge was integrating all this technology in the human and continued on page 14»

Building Bright Ideas

At Proto Labs, we accelerate innovation by turning brilliant concepts into real parts in days.

Proto Labs serves as a catalyst for product designers and engineers when high-quality prototype parts are needed fast. Just upload a 3D CAD model for an interactive quote within hours. When ready, our molding, machining and additive services can produce 1 to 10,000+ plastic, metal and liquid silicone rubber parts in as quick as a day. That means you can fail fast, iterate faster (and more often), and confidently launch your product to market before competitors.



Injection Molding
Part Design for Dummies
Request your free book at
go.protolabs.com/ME4B

Major Credit Cards Accepted | ISO 9001:2008 Certified | ITAR Registered
© 2014 Proto Labs, Inc. | protolabs.com | 877.479.3680

proto labs®
Real Parts. Really Fast.™

continued from page 12 »

GETTING A GRIP

making it work for the first time," Capogrosso said.

After making it work for a month, though, Sørensen had to be unplugged—thanks to laws about such experimentation. "It requires a lot of psychological strength to feel your hand after ten years and then have that stolen from you," Capogrosso said.

But Sørensen knew what he was getting into. And for that, Capogrosso said, he deserves much of the credit. "It's like Apollo 11, the astronauts who went to the moon. After all the engineers have done their work, take an electrode and implant it in your nerve. A lot of things can go wrong. He was a pioneer in a way." ME

MICHAEL ABRAMS / ASME.ORG

The SunJack foldable solar power pack weighs less than 3 pounds—light enough to carry most places.

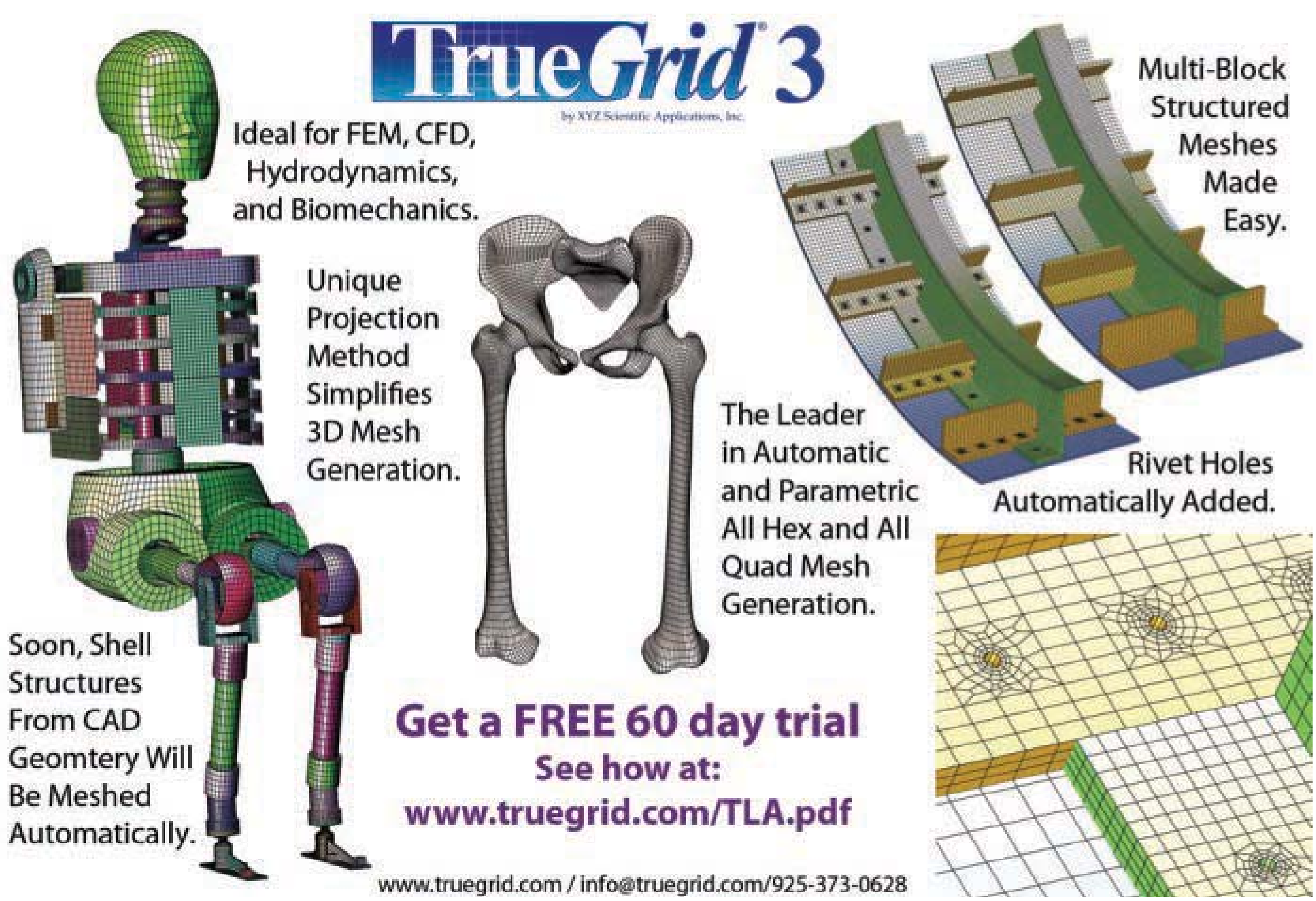
FOLDABLE

IF THERE'S AN ENERGY REVOLUTION afoot, then Harold Tan is working the front lines. He recently led development of a foldable, portable solar panel.

Tan teamed with Gigawatt Inc. to create SunJacks, which are 14-watt and 20-watt monocrystalline panels with battery packs that deliver quick charges and work even in cloudy weather. Gigawatt Inc. of Placentia, Calif., develops and distributes solar technologies.

To pay for their first run, the SunJack design team asked for crowdfunding via a Kickstarter campaign and soon met its $33,000 goal.

It has plans to sell the SunJack kits via retail



SOLAR PANELS

venues later this year.

Each SunJack kit includes a 14- or 20-watt foldable solar panel with two USB ports, a lithium-polymer battery, a battery cable, and an instruction manual.

The kits should cost $150 for the 14-watt kit and $250 for the 20-watt kit, Tan said.

The SunJack team also plans to give panels away to communities in Papua New Guinea that are off the grid or only have intermittent power supplies. It also allows consumers to buy panels as gifts for people in developing areas, Tan said.

Giving things away versus selling them can be controversial in global development. Tan said giveaways help if the product is right.

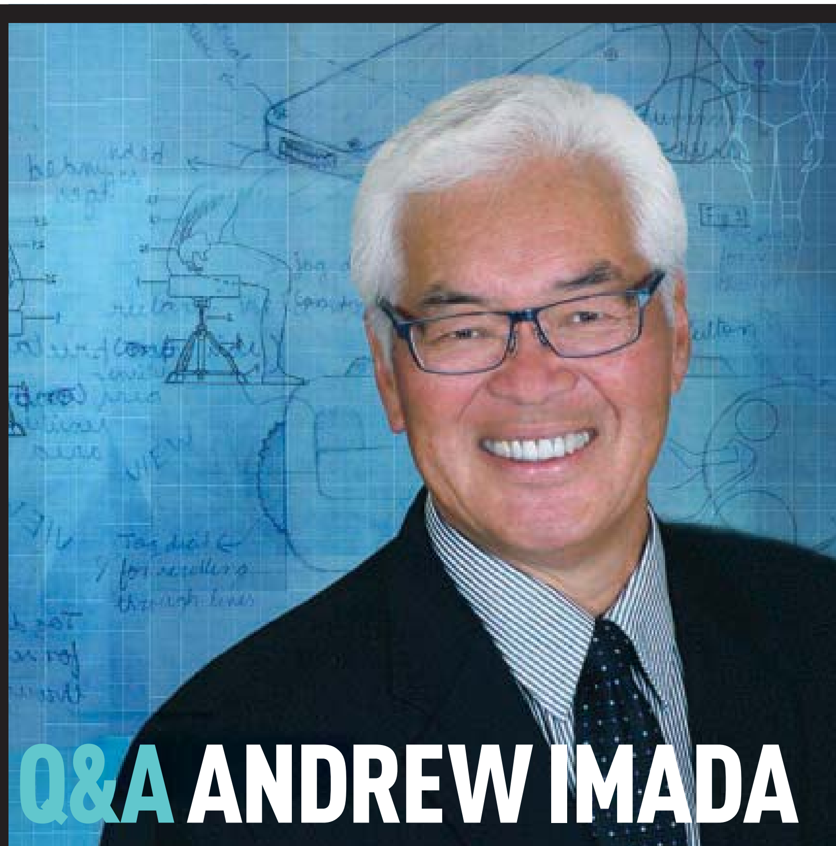
The output from each USB port provides enough power to charge small electronics such as a tablet computer.

"With solar power, we're actually helping cultivate the economy by providing renewable energy that can be used to power life and business," he said.

SunJacks and other micro power generators could have a powerful impact among the families who get to use them. They could save hours of walking for a mobile phone charge, they could allow kids to study at night by electric light, and they could supplement small businesses by entrepreneurs who sell charges, according to Tan.

Solar cells and lights can improve businesses, communication, and medical service, and they're durable, Tan said. In 25 years, the SunJack panels might still operate at 80 percent capacity. **ME**

ENGINEERINGFORCHANGE.ORG



Q&A ANDREW IMADA

AS PRESIDENT OF THE HUMAN FACTORS AND ERGONOMICS Society, Andrew Imada brings a wealth of experience to the role, which he assumes in October. Imada is president of A.S. Imada & Associates in Carmichael, Calif., and was a professor of ergonomics and safety sciences at the University of Southern California for 19 years. He directed USC's Safety Science Center and was international distance-learning liaison at the university's Center for Scholarly Technology. He's a specialist in human and organizational change and a certified professional ergonomist.The Human Factors and Ergonomics Society in Santa Monica, Calif., is a multidisciplinary professional association of more than 4,500 members.

ME: How did you become interested in the profession?

A.I: I came from a traditional academic environment to the University of Southern California where the human factors department was housed in a multidisciplinary unit with engineering, safety, and management faculty. This environment gave me a fuller appreciation of how human factors and ergonomics fit and contribute to the world.

ME: How have your work and your profession evolved since you entered the field?

A.I: Moving from a research university to a consulting practice changes the kinds of questions that you ask and answer. Human factors and ergonomics were once confined to physical and cognitive dimensions. Now we consider them in a larger context where humans interact with technology. A macroergonomics approach considers organizational, psychosocial, and the larger systems context. This approach is vital to achieving sustainable change.Broadening the interface between people and the technologies they use is a move toward human systems integration. This allows us to understand the causes and remedies for accidents, productivity, user satisfaction, usability, and general effectiveness.

Our organizations and systems are more technologically interdependent and therefore require more robust perspectives than any single discipline can provide. The human factors and ergonomics profession uses a multidisciplinary approach—requiring engineering, psychology, management, and medicine to name a few perspectives—to solve real-world problems.

ME: In what way is the work rewarding?

A.I: The goal of the human factors and ergonomics discipline is to optimize human well-being and overall system effectiveness simultaneously. While different professions can improve one or the other, few can claim to make a difference in both areas. Improving systems and allowing people to live improved lives are certainly worthwhile goals.

ME: What are your plans for the presidency in the Human Factors and Ergonomics Society?

A.I: Like many professional societies, the Human Factors and Ergonomics Society faces important challenges to make a value proposition that today's professionals find attractive. Engaging professionals in ways that are natural and consistent with the way we work, think, and interact today is the key to creating collaboration in research and practice. We are exploring different ways to remain relevant to the membership we serve and to advancing the discipline we represent.

ME: What are the most pressing issues in human factors work today?

A.I: The rapid rate of change has created many opportunities, as well as challenges, because people are interacting with technologies and each other differently. Creating a knowledge base about how these changes affect people and applying this information in a timely fashion is challenging.

ME: What are the biggest misperceptions about the field?

A.I: The biggest misconception is that human factors and ergonomics professionals are exclusively time-and-motion experts or office workstation designers. The discipline has three fundamental characteristics. First, it is design driven. Second, it focuses on two related outcomes—system performance and human well-being. Finally, it takes a systems view of the problem.

ME: What are your guilty pleasures?

A.I: My red bicycle, red wine, and fantasy baseball with my son, Mark; not necessarily in that order, or at the same time. I started a fantasy baseball league where parents and adults co-managed a team with their child or a relative to give them something to talk about over breakfast. This avoided one-word answers to lame adult questions such as, "How was school?" "What did you learn today?" **ME**

Proto Labs now offers low-volume metal injection molding and liquid silicone rubber molding in less than three weeks.

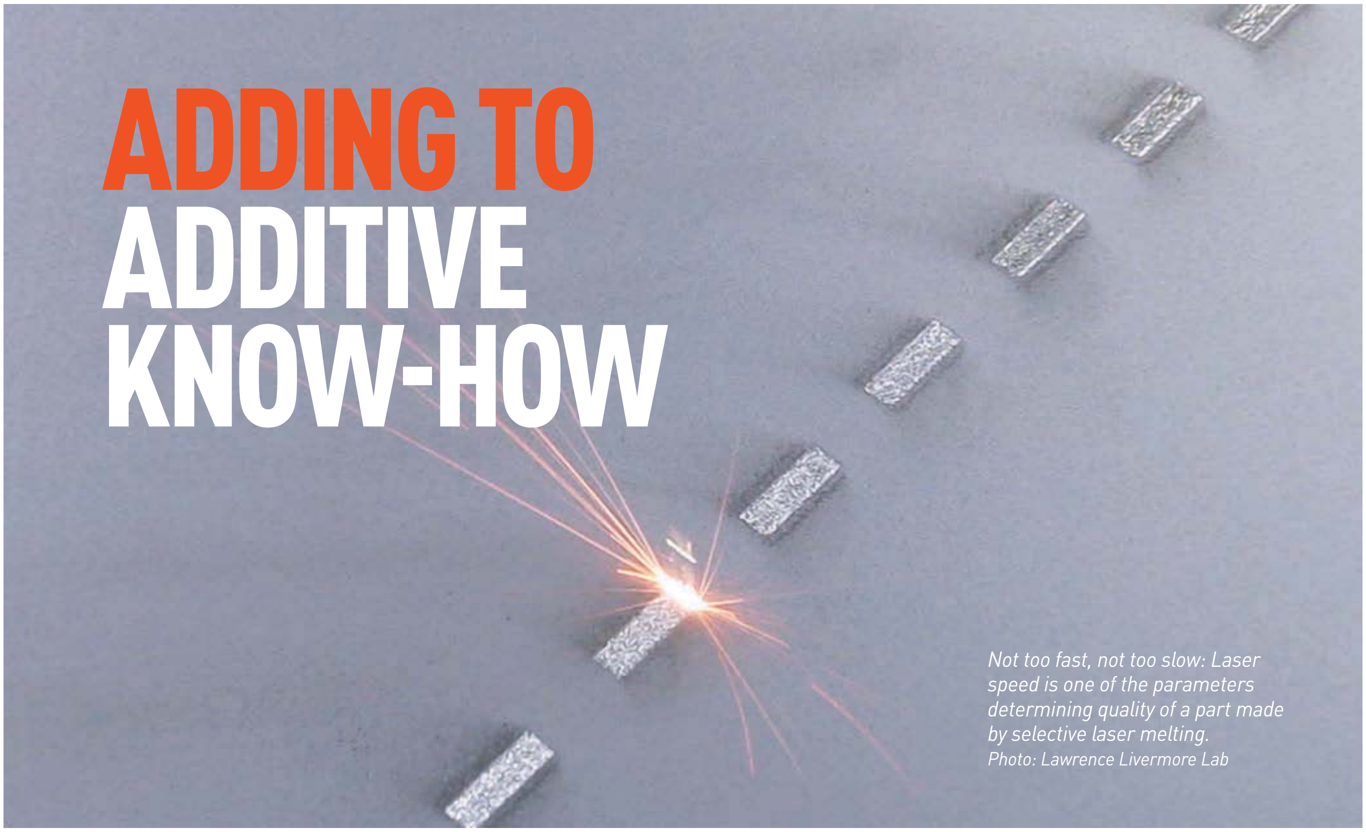
Proto Labs has applied its advanced manufacturing capabilities to a pair of quick-turn injection-molding processes that provide product designers and engineers with liquid silicone rubber and stainless steel parts really fast. Whether you need 25 prototypes or a small run of 5,000+ parts, we'll have them shipped in less than three weeks.

LSR Takes The Heat
Request your free whitepaper at
go.protolabs.com/ME4C

Major Credit Cards Accepted | ISO 9001:2008 Certified | ITAR Registered
© 2014 Proto Labs, Inc. | protolabs.com | 877.479.3680

proto labs®
Real Parts. Really Fast.™

ADDING TO ADDITIVE KNOW-HOW



Not too fast, not too slow: Laser speed is one of the parameters determining quality of a part made by selective laser melting.
Photo: Lawrence Livermore Lab

The phrase "additive manufacturing" refers to the making of a three-dimensional part by building up material layer after layer. The term covers a number of technologies, including three-dimensional printing, stereolithography, and selective laser melting. With roots in the 1980s, the process continues to be driven forward by researchers around the globe.

PROGRAMMING FOR DENSITY

THE LAB Lawrence Livermore National Laboratory's Center for Applied Scientific Computing; Lori Diachin, division leader.

OBJECTIVE To create computer tools and programs to take advantage of new computing applications.

DEVELOPMENT A way to calculate the optimal parameters for selective laser melting.

Researchers at the Lawrence Livermore Center for Applied Scientific Computing have developed a method to predict the best process parameters for parts made via selective laser melting, an additive manufacturing process.

In selective laser melting, or SLM, a high-energy laser beam fuses metal powder particles, layer by layer, to create a 3-D structure. According to Chandrika Kamath, a member of the center's research staff who helped develop the prediction method, density of a finished product can be an issue in SLM.

"We found that the metal density reduces if the speed is too low, due to voids created as a result of keyhole mode laser melting, where the laser drills into the material" Kamath said. "At the same time, too high a speed results in insufficient melting. The key is to find the right parameters where the melting is just enough."

Because pores or voids create weaknesses that can lead to failure, some SLM applications call for very dense parts with less than 1 percent porosity, she said.

But building parts and components to such specifications can be challenging because of the number of parameters that need to be set correctly, she said. Parameters besides laser speed can include laser power, distance between laser scan lines, scanning strategy, and powder layer thickness.

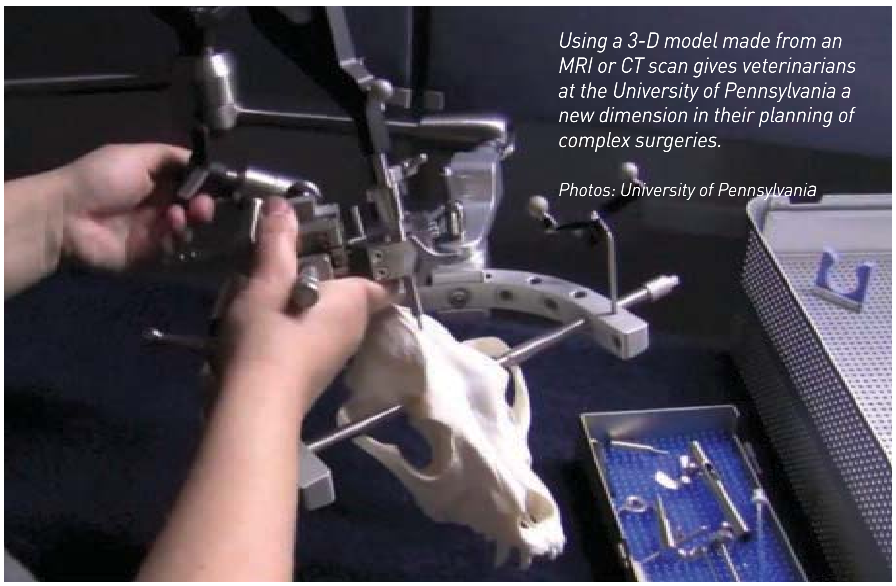
The SLM community needed a reliable and cost-effective way to determine the right parameters for parts with desirable properties, such as high density, Kamath said.

The center's approach uses computational simulations, which can compute the dimensions of the melt pool, which is the pool of liquid formed when the laser melts the metal powder particles.

"We mine the simulation output to identify important SLM parameters and their values such that the resulting melt pools are just deep enough to melt through the powder into the substrate below," Kamath said. "By using the simulations to guide a small number of single-track experiments, we can quickly arrive at parameter values that will likely result in high-density parts."

Kamath said she and her colleagues have used the simulations successfully to gain insight into optimal processing parameters.

The research is the first step in understanding how to use computer simulations along with a small number of experiments to find the best processing parameters for selective laser melting, she said.



Using a 3-D model made from an MRI or CT scan gives veterinarians at the University of Pennsylvania a new dimension in their planning of complex surgeries.

Photos: University of Pennsylvania

SURGERY MODEL

THE LAB Penn School of Veterinary Medicine and PennDesign Fabrication Lab, University of Pennsylvania, Philadelphia; Joan Hendricks, dean of the school of veterinary medicine; Dennis Pierattini, lab manager.

OBJECTIVE To improve animal care and to provide a place for design students to construct their work.

DEVELOPMENT Printed 3-D models of animal injuries and deformities to better understand the animals' conditions before surgery.

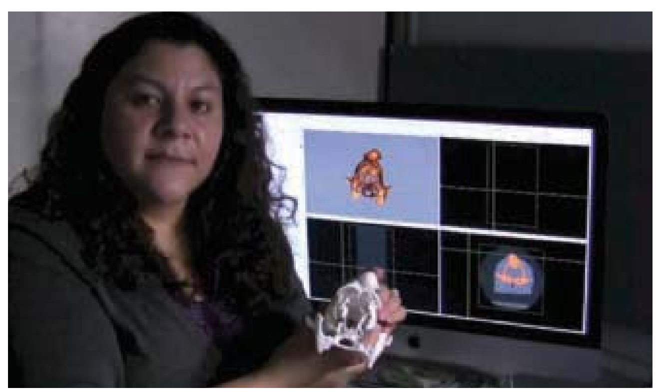
Veterinary medicine researchers at the University of Pennsylvania recently teamed with faculty in the university's Fabrication Lab to print an exact replica of a dog's skull. The dog, named Millie, has a cranial deformity and the 3-D copy of her skull gave veterinarians a better understanding of her condition before they operated.

After examining Millie, Evelyn Galban, a neurosurgeon in Penn Vet's Department of Clinical Studies in Philadelphia, thought it would be useful to physically handle a replica of the dog's skull.

"It's difficult to fully understand the malformation until we have it in our hands," she said. "That usually doesn't happen until we're in surgery."

Dennis Pierattini, the Fabrication Lab leader, and Stephen Smeltzer, a lab member, partnered with Galban to produce a model of Millie's skull. They've also helped Galban create other models that precisely replicate injuries or deformities of pets. Such applications have the potential to improve training and patient care at the veterinary school, Galban said.

To create the model, veterinarians transformed computed tomography files into a format compatible with a 3-D printer. Using the scan files, the printer built the model layer by layer from gypsum powder bound by acrylic and sealed with a glue-like substance to make it rigid, Smeltzer said.

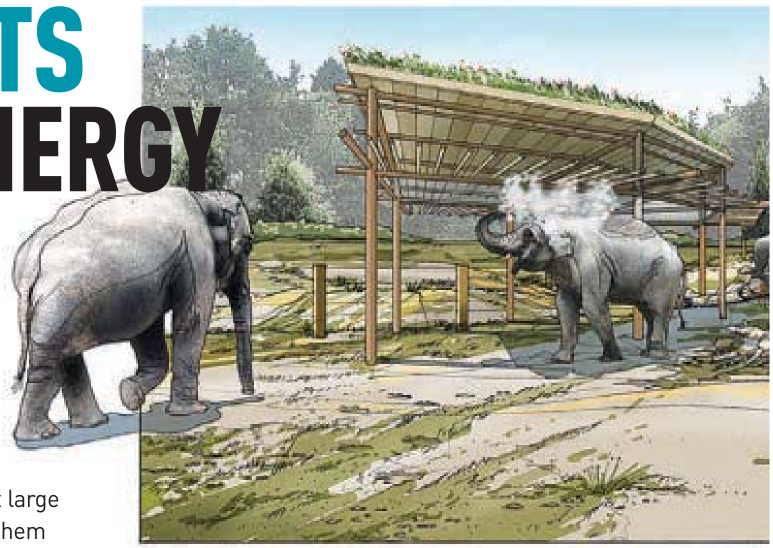


Evelyn Galban, a Penn Vet neurosurgeon, holds a replica of a dog's skull. Behind her is the scan from which the model was made.

Models like these could help veterinarians plan more of their surgical procedures in advance of an operation. Full-color models may even allow for testing new approaches that avoid contact with critical blood vessels and other tissues, he added.

"Last week I had no idea that this was going to be happening, and now all of a sudden I have a vested interest in Millie," Smeltzer said. ME

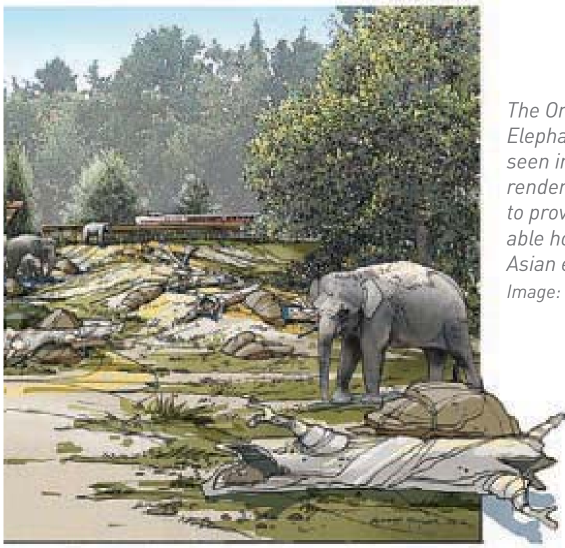
SAVING ELEPHANTS AND SAVING ENERGY



ELEPHANTS ARE ONE OF THE WORLD'S ICONIC animals, but they are struggling. Their numbers in the wild are dwindling as poachers kill them for ivory and humans encroach on a shrinking habitat.

In captivity, by contrast, their exhibits commonly draw the most visitors. Now, zoos are rethinking care and building exhibits that mimic life in the wild, giving the animals much more space to enable them to live in herds. Increasingly, those exhibits rely on a finely tuned design incorporating mechanical systems that efficiently cool and heat large living areas, and allow them to achieve LEED designation for green buildings.

At the Smithsonian National Zoological Park in Washington, D.C., curators have replaced antiquated structures and systems, along with antiquated thinking, in reworking care of their Asian elephants. The zoo spent some $65 million to refurbish a 1930s-era building into a LEED-Gold-certified facility that, along with a quarter-



The Oregon Zoo's Elephant Land exhibit, seen in this artist's rendering, is designed to provide a comfortable home for eight Asian elephants.
Image: Oregon Zoo

mile outdoor "trek" and associated exhibit, provides enough space to house up to ten Asian elephants and their young.

"We're rebuilding the matriarchal structure," said zoo director Dennis Kelly.

On the other side of the country, officials at the Oregon Zoo in Portland are investing $57 million in a similar project. They are building a new Elephant Land exhibit covering more than six acres. It will include outdoor trails and areas where the zoo's eight Asian elephants can forage and exercise. Its focus will be Forest Hall and an adjacent indoor holding facility totaling 32,000 square feet. A 1,850-square-foot curtain wall will provide natural lighting and allow visitors to see the adjoining outdoor complex.

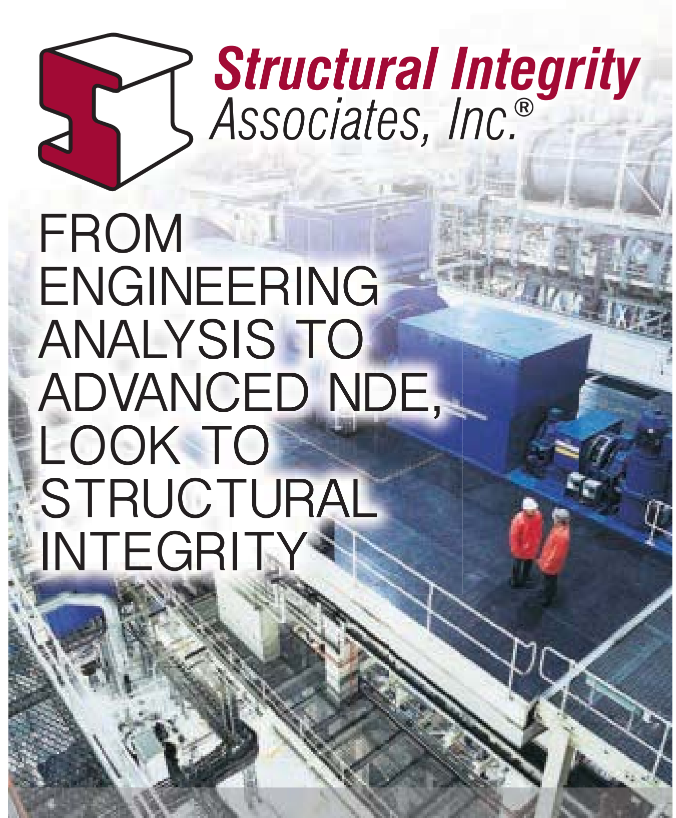
"A TYPICAL BUILDING OF THIS SIZE WOULD USE ABOUT $100,000 PER YEAR IN ENERGY COSTS. THIS BUILDING IS DESIGNED FOR ABOUT $60,000."

The design includes skylights and a green roof (studded with solar panels) that allows for natural ventilation. An air curtain prevents heat from escaping the building while permitting elephants to enter and exit at will.

The exhibit, scheduled to open in 2015, will depend on geothermal wells to provide much of the project's energy. There will also be energy to share with a future upgrade of a polar bear exhibit and possibly with other projects.

"It is an energy-efficient design that allows energy transfer and eliminates the need for large and expensive cooling equipment for the polar bears," said Tim Elley, engineer with the job's mechanical engineering consultant, PAE Engineers in Portland. "Otherwise you'd need a large cooling tower and chillers."

Metro, the regional governmental agency that operates the zoo, insisted the overall zoo expansion meet its goal to



We Connect the Dots

Over the past 30 years, Structural Integrity has built a team of over 200 industry experts providing comprehensive solutions to the energy industry. We connect the dots from problem to resolution, from regulations to compliance, from nondestructive examination, to engineered solutions, even custom equipment.

You can look to us for our:

- Knowledge of power plants, codes, and how things work.
- Extensive experience and leadership.
- High quality, hard work, and responsiveness.

Call us today and we'll connect the dots for you.

Scan the QR Code for more information

877-474-7693
(877-4SI-POWER)
www.structint.com/asme

continued from page 21 »

SAVING ELEPHANTS AND SAVING ENERGY

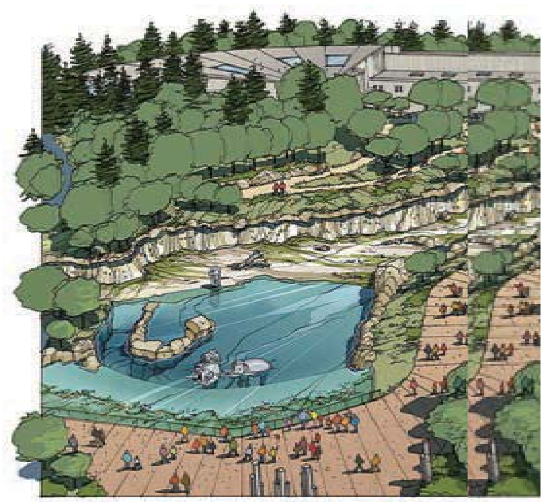
reduce direct and indirect greenhouse gas emissions 80 percent below 2008 levels by 2050.

"It is a very sustainable government organization," said Jim Mitchell, the zoo's construction manager. "There were a list of items that were nonnegotiable, the first being animal care [during construction] and energy efficiency."

For the first phase, the result was an elephant house design by CLR Design of Pittsburgh. It will use 60 percent less energy and save 40 percent of the energy costs compared to a similar building built to the Oregon Energy Code baseline, said PAE's Tim Elley. The building meets LEED Silver requirements.

"A typical building of this size would be expected to use about $100,000 per year in energy costs," he said. "This building is designed for about $60,000 to $62,000 per year."

Much of the savings is in heating energy. Three heat-recovery units are being installed with the building's ventilation units to account for a better than 80 percent reduction in the heating load, according to PAE. The geothermal



plant accounts for about a 75 percent reduction in energy required to meet the remaining load, resulting in a 95 percent overall reduction in heating energy compared to the baseline code.

In Washington, the National Zoo drilled 40 geothermal wells to heat and cool its elephant exhibit. In Oregon, designers took advantage of an available 1.5 acre site to place a coiled, 12-zone geothermal "slinky" system that can provide 850,000 Btu of heating capacity for the elephant house as well as 70 tons of cooling capacity for the polar bears.

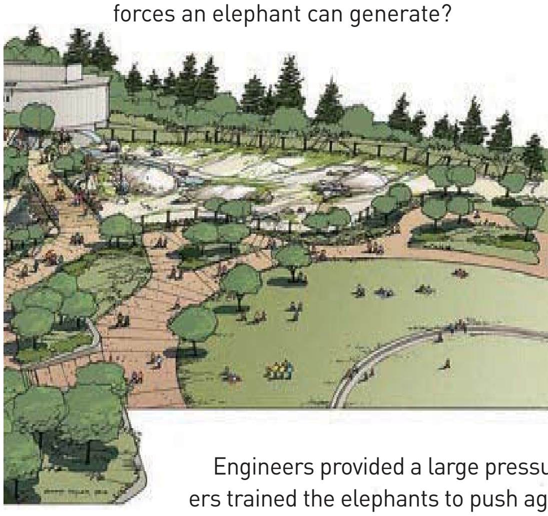
Natural gas-fired boilers will generate a small portion of heating and cooling needs.

Solar panels will generate up to 30 kW to heat water for the elephants and rainwater will be collected from the 14,000-square-foot roof to a 5,000-gallon underground tank. Rainwater will be disinfected with an ultraviolet system for internal use, such as flushing toilets or pressure washing.

Zoo officials will rely on the heat-recovery exhaust fans to move air through the building for ventilation. But design revolves around the elephants. The air curtain allows for the animals to come and go at will from the structure to the outdoors, which in Portland's mild climate, Mitchell said, may happen much of the year.

To contain and protect both animals and keepers, the buildings use reinforced concrete walls and steel barriers. As in Washington, concrete floors are being eliminated and replaced with a four-foot layer of sand, which provides a softer, more natural surface for the animals.

"But elephants are naturally curious, and they like to move and push things," Mitchell said. So how do you design for the forces an elephant can generate?



In addition to six acres of outdoor area, the exhibit will house a shelter sporting geothermal heaters and solar panels.
Image: Oregon Zoo

Engineers provided a large pressure plate and keepers trained the elephants to push against it. Mitchell said they topped out at 3,500 pounds of push, but engineers designed for a force of 7,000 pounds at seven feet.

But they were met with an unanticipated issue after a simple steel shade structure was completed.

"We wanted to keep the elephants on site during construction," Mitchell said. When the elephants were allowed back to the structure, one of them "pushed at about 10 feet and wrapped its trunk around the post, pushing in a back-and-forth motion," he said. It moved the post about four inches, and cracked the foundation from what engineers describe as "earthquake-type motions." They had to reinforce the shelter with steel-plate H-columns.

According to Mitchell, "There's really no standard for this." ME

JOHN KOSOWATZ is the senior editor of ASME.org.

Complete Solutions for Process Measurement and Control at omega.com

Temperature/Process Controller Panel
Single Input

CNI-CB120-K Series Starts at $800

- **Easy-to-Use Digital Controller with On/Off, PID and Ramp/Soak**
- **Optional Ethernet Control with Built-In Web Server**
- **120V Operation (240V optional)**

Visit omega.com/CNi-CB120-K

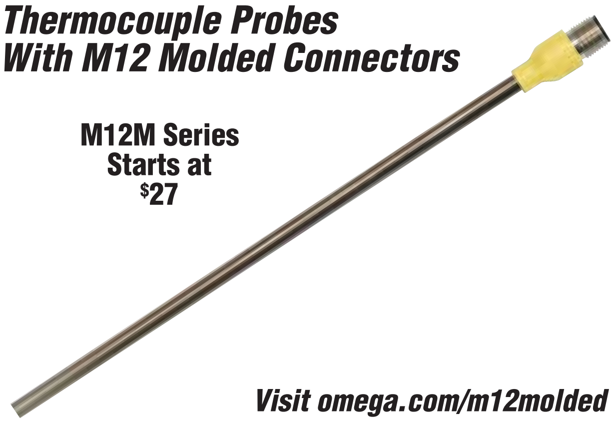
Temperature, Process and Strain Controllers

CNi Series Starts at $195

Visit omega.com/cni_series

Thermocouple Probes With M12 Molded Connectors

M12M Series Starts at $27



Visit omega.com/m12molded

1-888-826-6342 **omega.com**

OMEGA®

© COPYRIGHT 2014 OMEGA ENGINEERING, INC ALL RIGHTS RESERVED

Prices listed are those in effect at the time of publication and are subject to change without notice. Please contact OMEGA's sales department for current prices.

LOOKING BACK

Reducing auto emissions and increasing mileage were already national concerns when this article appeared in September 1974.

POLLUTION-CONTROL ENERGY COSTS

ERIC HIRST, RESEARCH ENGINEER, OAK RIDGE NATIONAL LABORATORY, OAK RIDGE, TENN.

A Department of Energy engineer 40 years ago looked at ways to make cars more efficient, especially considering the fuel penalties due to increasing emission controls.

Automobile Pollution Control. The federal Clean Air Act of 1970 established air pollution emission standards for automobiles designed to reduce hydrocarbon, carbon monoxide, and nitrogen oxide emissions by about 90 percent after 1976 (relative to uncontrolled autos). Meeting these standards will probably worsen auto fuel economy (relative to uncontrolled, pre-1968 vehicles) by about 15-30 percent. According to recent tests the fuel penalty due to emission controls on 1973-model autos is 8 percent.

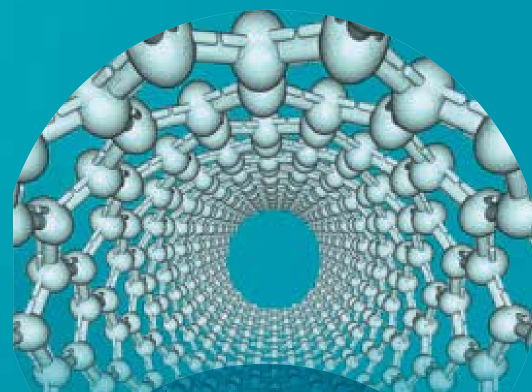
We assume an average fuel penalty of 20 percent for all cars manufactured after 1976. Applying this penalty to 1970 urban auto traffic shows an increase in fuel use of 1,100 trillion Btu (1,200 quadrillion J). This represents a 19 percent increase in total energy use for that year.

Redesign of Automobiles. Because of concerns over impending domestic oil shortages and the need to import large quantities of petroleum, there is considerable interest in improving the energy efficiency of our transportation system. Since the automobile consumes a larger share of the transportation energy budget than all other modes combined, an examination of this mode for potential efficiency improvements is important. A second reason for focusing on autos is to seek ways to counteract the expected fuel penalties discussed in the foregoing.

The single most important determinant of auto fuel economy is vehicle weight. Fuel economy in the *Consumer Reports* test trip ranged from 35 mpg (15,000 km/m^3) for the 1,600-lb (720 kg) Datsun 1200 to 11 mpg (4,700 km/m^3) for the 4,600-lb (2,100-kg) Mercury Marquis. The 1971 average auto fuel economy, as reported by the Federal Highway Administration, was 13.7 mpg (5,830 km/m^3). A recent study estimated a 30 percent potential fuel savings through a shift to small cars.

Other methods to reduce fuel use include redesign of auto shapes to reduce aerodynamic drag, use of low-loss tires such as radials, use of cars with lower horsepower-to-weight ratios, redesign of the internal-combustion engine, and use of alternative power sources. ... The diesel engine (which met the 1975 standards) and the prototype stratified-charge engine (which met the 1976 standards) provided fuel savings of 44 and 15 percent, respectively, relative to the 1973 internal-combustion engine.

Combining the aforementioned energy-conserving options could cut auto fuel use by as much as one-half, but this is unlikely. A more likely scenario is that average auto fuel economy would be improved sufficiently to offset the expected fuel penalty due to emission control. Such an improvement could be achieved by a 25 percent shift to small cars weighing one-half the average, plus a 25 percent shift to diesel engines. **ME**



BIRTH OF A TERM

The year 1974 saw the birth of a technical term that has since entered the popular lexicon. Norio Taniguchi, a professor at Tokyo University of Science, presented a paper at the International Conference on Production Engineering in which he wrote: "The finishing technology aimed to get the preciseness and fineness of 1 nm would be called '**nano-technology**.'" He was referring to advanced manufacturing processes including thin film deposition that could maintain control on the order of one nanometer. His paper was the first recorded use of the term "nanotechnology."


1
Flows to 100 l/min!
2
3
A-ET-2M-6
4
5
Clippard
6
1 Next Gen Electronic Valves with Flows to 100 l/min!
2 "GV" Series High Flow Poppet Valves
3 Electronic Valves for Analytical Industries
4 "HV" Toggle & Stem Valves
5 "EGV" Electronic High Flow Poppet Valves
6 "PQ" In-Line & Elbow Flow Controls
7 High Flow "E" Electronic Valves
8 Manifold Mount Multi-Check Valves
9 Electronic Valves for Oxygen Applications
Introducing
new products new solutions
7
8
Clippard
Minimatic
9
Clippard
Clippard Instrument Laboratory, Inc.
Providing innovative solutions for today's engineering challenges.
877-245-6247 • www.clippard.com
more info

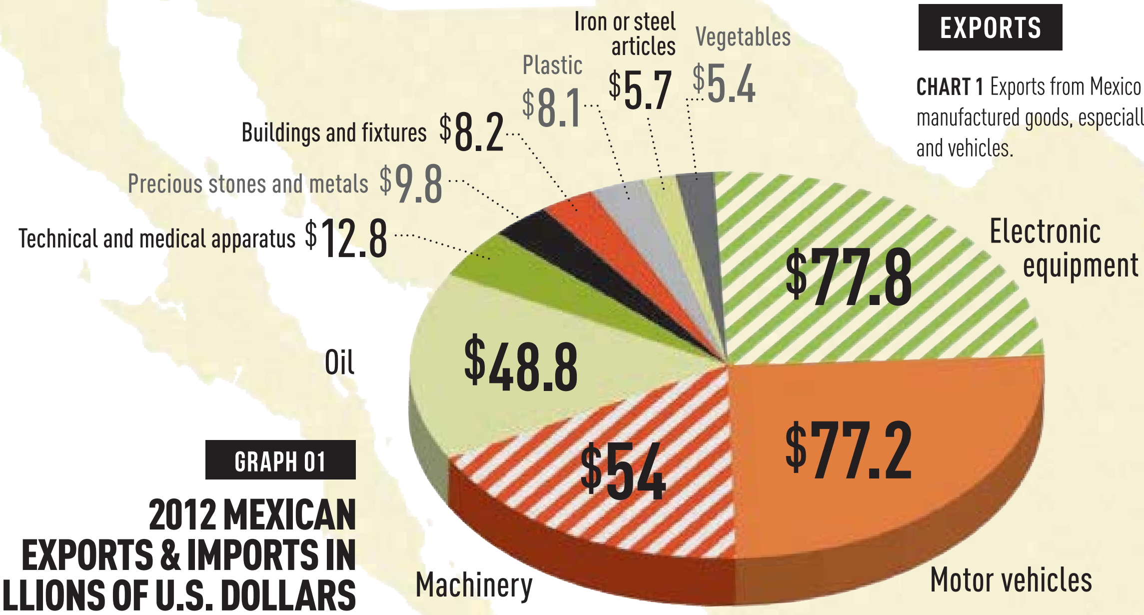
GRAPH 01

2012 MEXICAN EXPORTS & IMPORTS IN BILLIONS OF U.S. DOLLARS

SOURCE: *UN Comtrade*

EXPORTS

CHART 1 Exports from Mexico are dominated by manufactured goods, especially electronics and vehicles.



In 2009, Mexico became the world's largest producer of flat-panel television sets and two-door refrigerators. It has a vibrant aerospace sector. Last year, it built 2.9 million motor vehicles to become the eighth largest automaker.

Exports doubled between 2003 and 2012, making Mexico the 10th largest exporter in the world. More than three-quarters of those exports go to the U.S., but Chrysler plans to export some Mexican Fiat 500s to China.

There are lots of reasons for Mexico's resurgence. NAFTA integrates Mexico with the U.S. and Canadian economies (one reason why Bombardier makes aircraft outside Mexico City). Mexico also signed free trade agreements with 44 countries, twice as many as China and four times more than Brazil.

Mexico's open economy lets factories import the raw materials and components needed for production. Like exports, Mexican imports doubled between 2003 and 2012.

Mexican trade benefits from China's diminished luster. China's labor costs are rising, its workforce is aging, and its long supply chains are costly.

In fact, according to AlixPartners, a trade consulting firm, the landed cost of Mexico's products in the U.S. are significantly lower than China's, and the gap is likely to increase. AlixPartners looks at a variety of products, including fabricated parts, assemblies (including electronics), and consumer

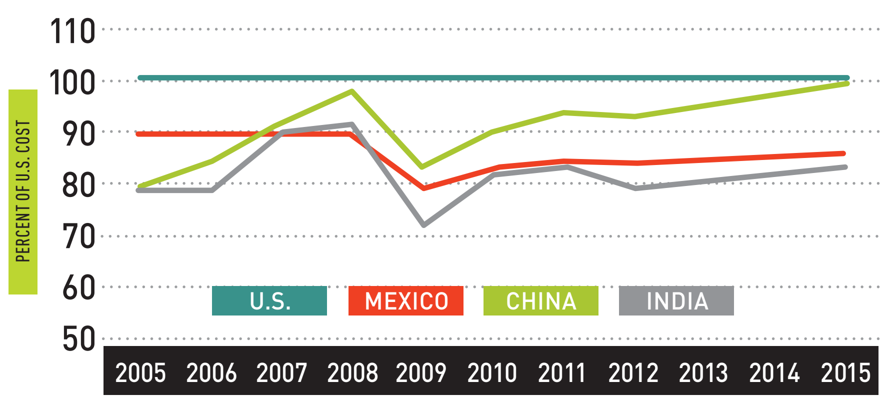
For many years, Mexico had a reputation for manufacturing labor-intensive, low-value-added components, like wire harnesses, auto seats, and plastic goods. A lot has changed in the past decade.

BY THE NUMBERS:

GRAPH 02

LANDED COSTS OF MANUFACTURED GOODS

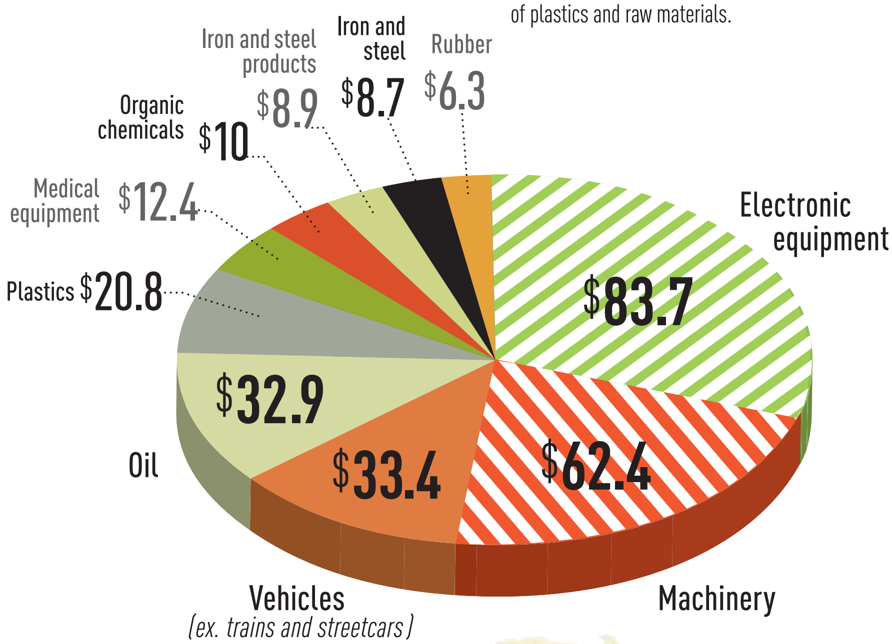
SOURCE: *AlixPartners Manufacturing Sourcing Cost Index*



GRAPH 2 As recently as 2005, the cost of manufactured goods being imported to the United States from China and India were significantly cheaper than those coming from Mexico. Now, factors such as labor costs, factory overhead, and logistics have made Mexican imports relatively cheaper.

IMPORTS

CHART 2 Mexico actually imports more electronics and machinery than it exports. It also imports a lot of plastics and raw materials.



products. It then analyzes costs for labor, raw materials, factory overhead, logistics, inventory, tariffs, and exchange rates.

Bangladesh and the Caribbean come out on top for clothing and fabrics. China's infrastructure makes it a dominant player in sophisticated consumer electronics. But Mexico comes out ahead in industrial products that require casting, assembling, and welding. It is also making headway in smartphones, computers, and other consumer electronics.

With its open border, Mexico integrates tightly with U.S. manufacturers, said AlixPartners managing director Foster Finley. For example, HVAC companies often make compressors and motors in Mexico because they are compact and easy to ship, then integrate them with more bulky components made in the United States. In fact, 40 percent of the parts in the products that Mexico exports to the United States were originally made in the U.S.

There are other reasons why American companies want to bring manufacturing nearer to home. A big driver is faster speed to market, which allows companies to improve products on the fly instead of waiting months for inventory to move through the system. Manufacturers also like lower freight costs, improved customer service, and fewer supply disruptions.

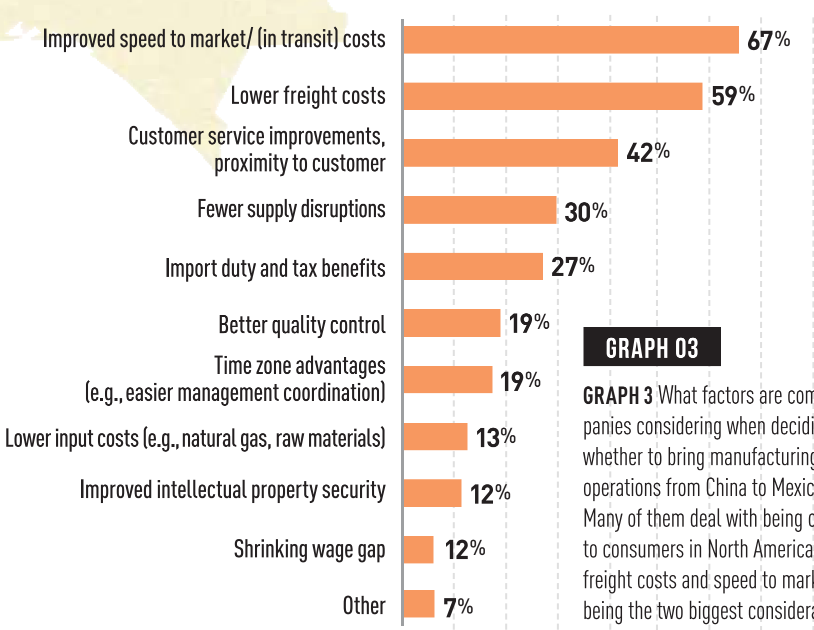
Mexico is clearly the top near-sourcing destination in Latin America, but it faces clear competition—from the United States itself. AlixPartners found 42 percent of large manufacturers would build U.S. plants to make products destined for the domestic market, thanks to low-cost energy, reasonable wages in some regions, and very short supply chains. **ME**

ALAN S. BROWN

THE MAKING OF MEXICO

EXPECTED ADVANTAGES FROM NEAR-SOURCING

SOURCE: *AlixPartners, 2014 survey of manufacturers*



GRAPH 03

GRAPH 3 What factors are companies considering when deciding whether to bring manufacturing operations from China to Mexico? Many of them deal with being closer to consumers in North America, with freight costs and speed to market being the two biggest considerations.

ASME
SETTING THE STANDARD

2014

JOIN US AT THIS YEAR'S

ASME INTERNATIONAL MECHANICAL ENGINEERING CONGRESS AND EXPOSITION (IMECE)

November 14–20, 2014
Palais des Congres
Montreal, Canada

ASME's International Mechanical Engineering Congress and Exposition (IMECE) will focus on today's technical challenges, research updates and breakthrough innovations that are shaping the future of engineering. This year's conference features 3,300 technical presentations among 19 tracks on more than 245 topics. In addition to the breadth and depth of technical content for industry, IMECE offers unique opportunities to network with engineering leaders and colleagues from around the world.

ADVANCE REGISTRATION DEADLINE: November 9

Questions? Contact us at imece@asme.org.
To sponsor or exhibit, contact
Joyce Ginsburg at ginsburgj@asme.org or
phone 1-773-456-2153

Conference Theme:
Engineering for Global Development

JOHN HOCKENBERRY

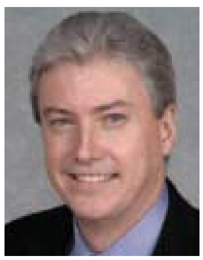
KEYNOTE EVENT - Monday, 11/17 8:00am-9:30am

Through a unique program based on ASME's successful Decision Point Dialogues series, renowned journalist John Hockenberry-host of the public radio program The Takeaway-will moderate a fascinating conversation with distinguished thought leaders on the critical role engineers play in helping people who work and live in the developing world find solutions to problems related to accessing affordable energy, clean water, sanitation, and the delivery of healthcare.

CONGRESS-WIDE PLENARY SPEAKERS

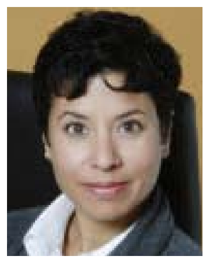
CHRIS VAN BUITE
Vice President,
Sikorsky Innovations

Taking on the 'Impossible': The Sikorsky Innovations Story
Tuesday, 11/18, 8:00am - 9:30am



DENNIS O'DONOGHUE
Vice President, Boeing Test & Evaluation

Testing the Future of Flight — Boeing's ecoDemonstrator Program
Wednesday, 11/19, 8:00am - 9:30am



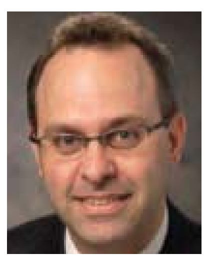
ANN MARIE SASTRY
Co-Founder and CEO, Sakti3

The Next Energy Storage Revolution — Cheap, Clean, Solid State Devices
Thursday, 11/20, 12:00pm – 12:45pm

FEATURED INDUSTRY PRESENTERS

BRIAN NOLAN
Chief Engineer of Engine Development Programs,
Rolls-Royce Energy

Extension of the Natural Gas Envelope on Rolls-Royce Industrial Engines and Development of the Industrial Trent DLE
Tuesday, 11/18, 1:00pm – 1:45pm



YVES RABELLINO
Director, Research & Technology, Strategic Cost Reduction and Support to Operations
Pratt & Whitney Canada

Trends of the 21st Century in Aero Engines Trent DLE
Wednesday, 11/19, 1:00pm – 1:45pm

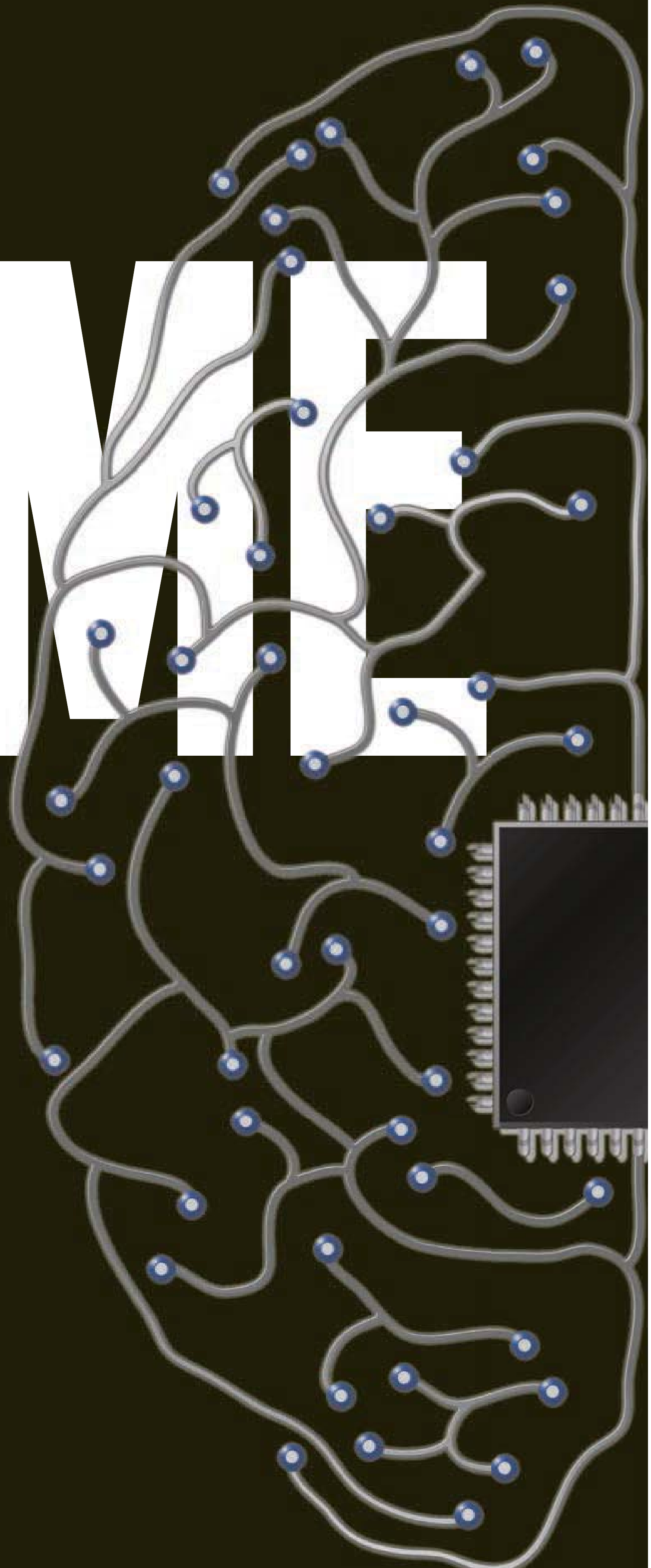
FASSI KAFYEKE
Strategic Technology,
Bombardier Aerospace

Bombardier Strategic Technology: The Future of Business and Commercial Aviation
Thursday, 11/20, 1:00pm – 1:45pm

REGISTER AT:

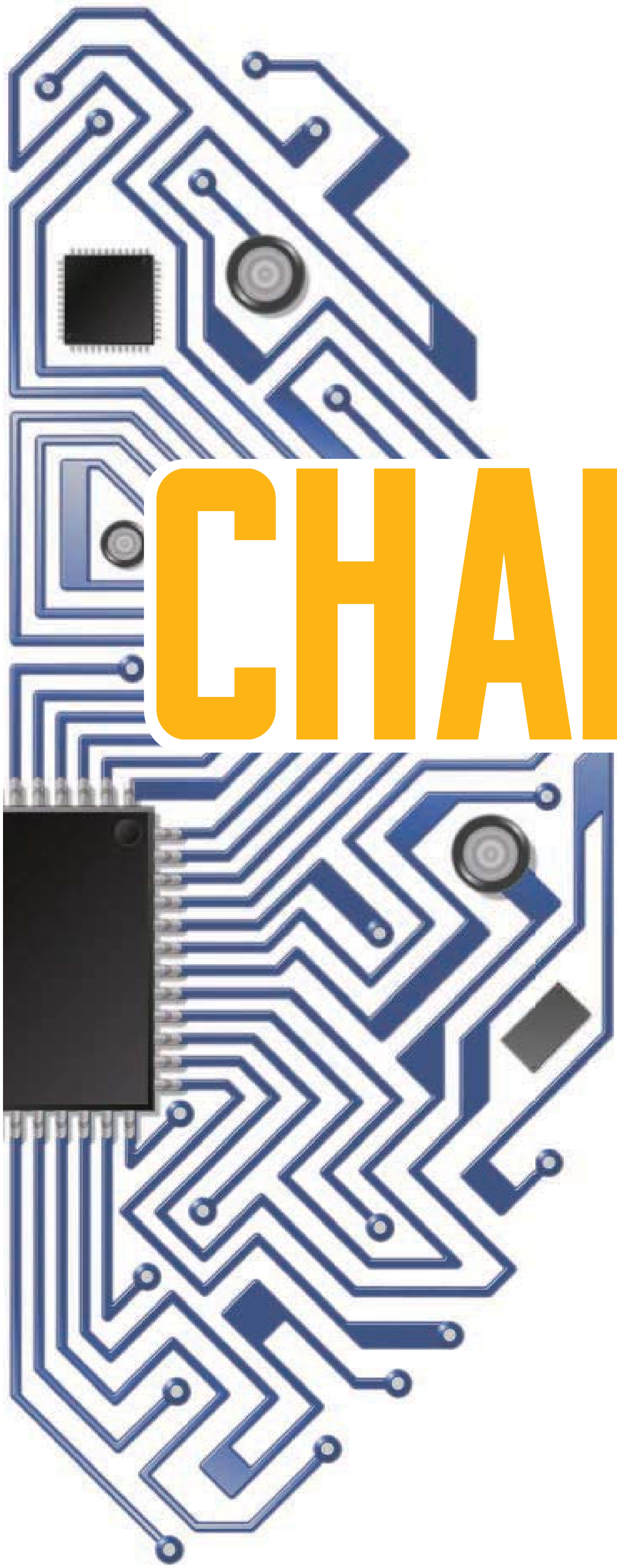
www.asmeconferences.org/congress2014

GAME



SYSTEMS THAT CAN LEARN, REASON, EVEN FIND MISTAKES IN DATA ARE COMING TO THE AID OF PROFESSIONALS IN AN EVER-MORE-COMPLEX WORLD.

Cognitive systems, which take on some of the activities of the human brain, promise a powerful new generation of engineering tools.



CHANGERS

By Ahmed K. Noor

THE QUIZ SHOW *JEOPARDY* ALWAYS engaged a very human mind. Contestants benefit from encyclopedic knowledge, but they also need logic, intuition, and a bit of luck. Even grammar is involved. The game isn't question and answer. Instead, the player is given an answer, and has to respond by phrasing an appropriate question.

For instance, a contestant may be told, "When Apple sued for iPad patent infringement, Samsung cited this 1968 movie as the originator of the design."

The response is: "What is *2001: A Space Odyssey*?"

It requires contributions by different parts of the brain. That was a challenge of a very human sort. But then, along came Watson.

IBM's supercomputer played against two *Jeopardy* champions in 2011 and won. Watson was able to respond directly and precisely to natural language prompts with relevant, correct responses. It had access to 200 million pages of structured and unstructured information consuming four terabytes of disk storage including the full text of Wikipedia, but was not connected to the Internet during the game.

It was like Captain Kirk's interaction with Computer on the *Enterprise*. Watson was science fiction brought to real life.

Of course, IBM didn't develop Watson to win game shows. The goal was to have computers start to interact in natural human terms across a range of applications.

The computer has moved on to address bigger and more serious issues now. For instance, it has a role in health care in which it helps physicians overwhelmed by the herculean task of both treating patients and keeping up with an exponentially expanding body of medical research.

The term we give to this kind of technology is "cognitive computing." Unlike expert systems of the past, which required inflexible hard-coded expert rules, cognitive computers interpret unstructured data (sensory information, images, voices, and numbers), navigate through vast amounts of information, learn

> *They were hoping against hope that the humans would screw up. … They were right. Watson won handily.*

From "The Obsolete Know-It-All," a TED talk by Ken Jennings, who won more than 70 times at Jeopardy. *Pictured, from left, are Jennings, a stand-in for Watson (which was in its climate controlled room), and Brad Rutter, the show's top cash winner.*

by experience, and participate in dialogues with humans using natural language to solve extremely complex problems.

IBM isn't alone in pursuing cognitive computing.

The U.S. Defense Advanced Research Projects Agency is funding a program called SyNAPSE (Systems of Neuromorphic Adaptive Plastic Scalable Electronics) to develop machine technology that will function like biological neural systems. IBM, Hughes Research Labs, and several universities are working on this program. The aim is to build an electronic system that matches a mammalian brain in function, size, and power consumption. It would recreate 10 billion neurons and 100 trillion synapses, consume one kilowatt (same as a small electric heater), and measure less than 2,000 cubic centimeters.

The Human Brain Project of the European Union was initiated in 2013. It aims, among other things, to build information and computing technologies by mapping the inner workings of the brain and mimicking them in computing. As part of the project, researchers in Germany used a neuromorphic chip and software modeled on insects' odor-processing systems to recognize plant species by their flowers.

Computing itself is only one element in the broader pursuit of cognitive engineering. "Cognitive" means that a system can perform some functions of human cognition. The system would have natural language processing capability, learn from experience, interact with humans in a natural way, and help make decisions.

Most of the work engineers do is cognitive in nature. So many see a potential in cognitive systems as very powerful tools to support engineers and other professionals.

In its health care role, for example, IBM Watson will help a New York-based genome research center in developing treatments for glioblastoma, the most common type of brain cancer in U.S. adults.

What makes Watson unique is that it isn't programmed like most computers. Instead of relying on information put into it, Watson learns by reading vast amounts of information and combining it with the results of previous work to solve problems.

Researchers at the Rensselaer Polytechnic Institute are at work on cognitive technologies with similar abilities that can be applied to data streams, particularly those used to control and guide aircraft. They are funded by the Air Force Office of Scientific Research to develop "active data" technologies, known as smart analytics.

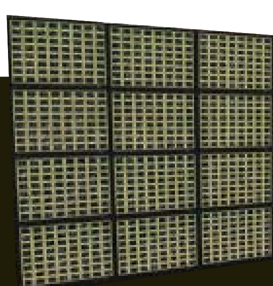
The technologies would enable otherwise passive data systems to search for patterns and relationships and to identify incorrect data generated by faulty sensors, or other hardware failures, such as those that contributed to the Air France 447 crash in June 2009. During that flight, important sensors failed, and reported erroneous airspeed data. But the autopilot didn't know that and acted as if the data were correct.

The system uses mathematical and programming elements that search for patterns and relationships that indicate hardware failure. Active data has been incorporated into a software system called the Programming Language for spatiO-Temporal data Streaming applications, or PILOTS, which treats air speed, ground speed, and wind speed as data streams that sometimes exhibit errors, which can be automatically corrected so that the pilot receives the correct readings and can adjust accordingly.

In addition to its benefits in making flight systems safer, smart analytics could also be helpful in other applications that rely on sensors, such as health care. Analyzing the patterns of data collected from sensors on the human body could detect early signs of seizures or heart attacks.

GAME CHANGER

THE BRAIN WALL



A NEURAL NETWORK VISUALIZATION TOOL BUILT BY SYNAPSE RESEARCHERS AT IBM

The display gives researchers an overview of neuron activation states in a large-scale neural network.

ROBOTS, CARS, AND FACTORIES

Projects are also under way to apply cognitive technology to robotics, cars, and production systems.

As interaction of robots with humans increases, so does the demand for sophisticated robotic capabilities associated with deliberation and high-level cognitive functions. Future robots will be endowed with higher-level cognitive functions to interact with humans, reason, and perceive so they can function in unpredictable environments.

Cognitive robots have the processing architecture to reason how to accomplish complex goals.

An early-generation cognitive robot is the human-like Myon, developed by the Neurorobotics Research Lab of Humboldt University in Germany. All the body parts of Myon can be removed and mounted again. The body parts retain their separate functionality because each one has its own energy supply and computational ability. The neural network is distributed over the decentralized robot.

Myon is learning to respond to human emotion. The humanoid robot will be playing a lead role in "My Square Lady" in Berlin's Komische Oper in the 2014-15 season, as an experiment.

A European consortium, led by the University of Graz and including both biological and technical institutions, is creating a swarm of cognitive, autonomous underwater robots. The goal of the project is to develop robotic vehicles that can interact with each other and cooperate in tasks. They could be used for ecological monitoring, or for searching, maintaining, and even harvesting in underwater environments.

The swarm will need the robustness and stability to function under dynamically changing conditions. The vehicles will interact with each other and exchange information, resulting in a cognitive system that is aware of its environment, of local individual goals and threats, and of global swarm-level goals and threats.

As shown by natural swimming fish swarms, such mechanisms are flexible and scalable. The usage of cognition-generating algorithms can allow robots in the swarm to mimic each other's behavior and to learn from each other adequate reactions to environmental changes.

The plan includes investigating the emergence of artificial collective pre-consciousness, which leads to self-identification and further improvement of collective performance. In this way, several gen-

IBM and the Watson Ecosystem

Watson is ushering a new era of computing, the cognitive computing era. In addition to programmatic computing (used in the current programmable systems era), Watson uses a combination of three capabilities that make it unique: namely, it can understand and process natural language; it can generate and evaluate hypotheses to provide evidence-based responses, with a confidence level; and it can be trained (i.e., have dynamic learning capability).

Watson communicates more like a human in both query and reply, and uses probability to reason out the best answers, and it can do this with speed and precision. It can process 500 gigabytes, the equivalent of a million books, per second. The sources of information for Watson include encyclopedias, dictionaries, thesauri, newswire articles, and literary works. Watson also uses databases, taxonomies, and ontologies.

Watson's hardware integrates massively parallel POWER7 processors. It is composed of a cluster of 90 IBM Power 750 servers, each of which uses a 3.5 GHz POWER7 eight-core processor, with four threads per core. In total, the system has 2,880 POWER7 processor cores and has 16 terabytes of RAM.

Watson, above, has many connections. Developers, for instance, access it through the cloud, and soon classes of university students will do so as well.

In November 2013, **IBM announced the formation of the Watson Ecosystem for creating a complete environment for fostering new business** opportunities and driving innovation. The environment supports a community of interconnected partners, which include cross-industry application developers and content providers. They are provided access to the Watson platform, technologies, and tools through the Watson developer cloud. They are also supported by a collaborative community of IBM technical, marketing, and sales resources. The developer cloud is used for building and testing applications of the business partners.

An Unstructured Information Management Architecture framework to support distributed computing is being developed.

In September 2014, IBM will launch the Cognitive Systems Institute to advance the development and deployment of cognitive computing systems. Like IBM's Watson, these systems can learn, reason, and help human experts make complex decisions involving extraordinary volumes of data. The institute will comprise universities, research organizations, and IBM clients.

Also, **IBM is partnering with a number of universities to launch new cognitive computing courses**, which provide students with access to Watson via the cloud. The courses will include building ideas for cognitive innovations, creating cognitive apps, and developing entrepreneurial know-how. ■

GAME CHANGER

GOOGLE SELF-DRIVING CAR

GOOGLE'S SELF-DRIVING CAR ELIMINATES STEERING WHEEL, ACCELERATOR, AND BRAKE PEDALS

According to Google, "Seniors can keep their freedom. ... And drunk and distracted driving? History."

eral principles of swarm-level cognition will be explored to assess their importance in real-world applications. These studies complement earlier studies led by Naomi Leonard at Princeton University.

The results can be exploited for improving the robustness, flexibility, and efficiency of other technical applications in the field of information and computing technology.

In June 2014, the European Commission, along with 180 companies and research organizations (under the umbrella of euRobotics), launched the world's largest civilian research and innovation program in robotics. Covering manufacturing, agriculture, health, transport, civil security, and households, the initiative is called SPARC and aims at developing technologies including smart industrial robots, autonomous cars, and drones.

Cognitive cars are equipped with integrated sensors, cameras, GPS navigation systems, and radar devices that provide coordinates and information gathered on the road to other cars, equipped with the same car-to-car communication system. The new technologies are intended to serve and protect drivers and passengers, and ultimately render human drivers superfluous.

The advanced technologies that make cognitive and self-driving cars have been filtering into commercial products at a fast rate.

In April 2014, the Google self-driving cars surpassed 700,000 autonomous accident-free miles. This was done by improving the software that can detect hundreds of distinct objects simultaneously.

The self-driving cars can ingest massive amounts of data in a very short amount of time, explore multiple scenarios, and eventually run simulations to insure that their decisions are as safe as possible. The cars pay attention to pedestrians, buses, stop signs, and a cyclist making gestures that indicate a possible turn, in a way that a human driver cannot, and they never get tired or distracted.

Google has unveiled a fully autonomous, two-seat electric car prototype without steering wheel, accelerator, or brake pedal. The cars can go up to 25 mph. Google is building about 100 prototypes of this sort and plans to conduct initial tests in versions that retain the manual controls.

Meanwhile, a new autopilot tool, Cruise Rp-1, which enables hands-free driving on highways, has been advertised and is slated for use in California starting in 2015. It can be fitted for nearly any vehicle. It includes two cameras, a radar mechanism, GPS, inertial sensors, and an on-board computer, as well as actuators that control the car's steering, acceleration, and braking. Using this software/hardware combination, the Cruise RP-1 constantly scans the road to keep the car operating within safe parameters in relation to other cars and the boundaries of the driving environment.

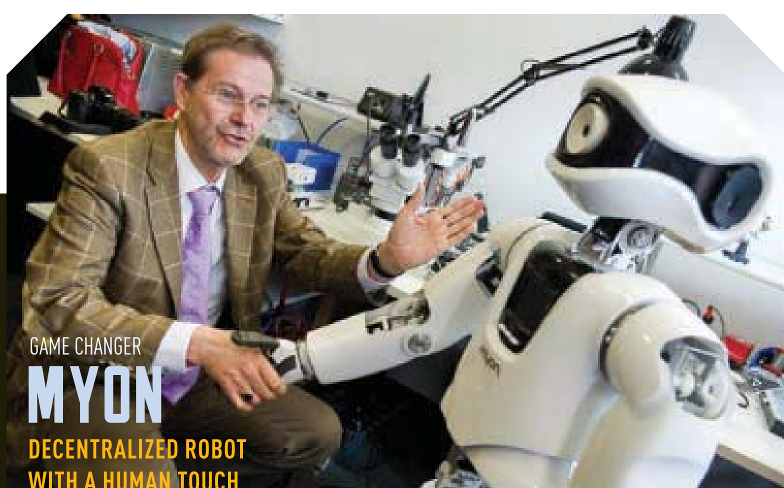
The cars can deal with changing environments and some level of dynamic uncertainty. However, it is impossible to plan ahead for every single scenario that a fully autonomous car might have to handle. Therefore, one of the key requirements of autonomous cars is to have human-like cognitive capabilities (being able to learn and make decisions on the fly).

A cognitive system with implications for factory production is being developed by researchers at Kings College in London. It is a cognitive robotic hand with vision system.

The robotic hand uses a Kinect depth-sensing camera to analyze a 3-D object, builds a 3-D computer model of it, and determines how the robotic hand can securely grasp it.

That kind of autonomy and flexibility gives rise to the concept of cognitive factories. Possible systems include autonomous machining, automated programming of industrial robots, human-robot cooperation, knowledge-based quality assurance, and process control.

As part of the SkillPro project funded by the European Commission, researchers at the Karlsruhe Institute of Technology in Germany are developing cognitive tools for smart reconfigurable manufacturing systems and mass customization. The project considers a modern production system as a combination and collaboration of



GAME CHANGER

MYON

DECENTRALIZED ROBOT WITH A HUMAN TOUCH

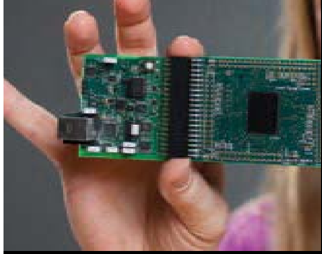
Myon—shown shaking the hand of Jan-Hendrik Olbertz, president of Humboldt University—can respond to human emotions.

GAME CHANGER

CO•CO•RO

A SWARM OF COGNITIVE ROBOTS DEVELOPED BY A PROJECT IN THE EUROPEAN UNION

The autonomous vehicles will interact to perform such tasks as ecological monitoring or harvesting resources in underwater habitats.

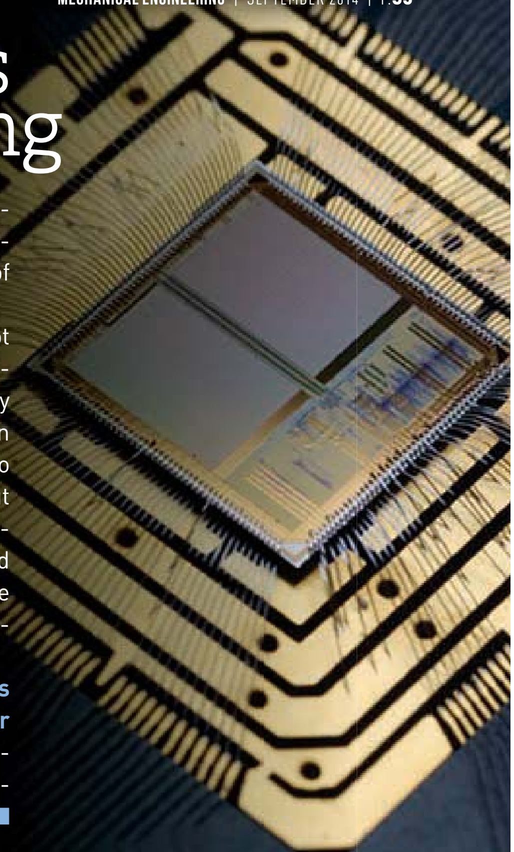


Neuromorphic Chips and Machine Learning

Today's computers use the so-called von Neumann architecture. They shuttle data back and forth between a central processor and memory chips in linear sequences of calculations. While that method is appropriate for crunching numbers and executing precisely written programs, it is not efficient for processing images, or for detecting and predicting patterns. By contrast, **neuromorphic chips process sensory data**, such as images and sound, **and respond to changes in data in ways not specifically programmed**. They attempt to model in silicon the massively parallel way the brain processes information as billions of neurons and trillions of synapses respond to sensory stimuli. The neurons also change how they connect with each other in response to changing images, sounds, or patterns. Neuromorphic chips have the potential of overcoming the physical limitations and considerably reducing the power requirements of the traditional von Neumann processors.

Qualcomm demonstrated a small robot powered by a neuromorphic chip and specialized software that simulate the activity in the brain. Simply telling the robot when it has arrived in the right spot allows it to figure out how to get there later without any complex set of commands. The company plans to partner with researchers and startups, offering them a platform to create neural architectures very quickly with Qualcomm's tools.

Potential **applications include computers that draw on wind patterns, tides, and other indicators to predict severe storms** more accurately, or glasses for the blind that use visual and auditory cues to recognize objects. ■



Jennifer Hasler holds a board, above, with bio-based neuron structures; right, a neuromorphic chip from Heidelberg. Photo: Heidelberg University, Germany

cyber-physical assets that offer different skills.

Having completed one order, manufacture of any new product ordered mostly requires a modification of the production process. When manufacturing small series, preparation, setup, and programming of the machinery often take much longer than manufacture proper. Machines equipped with cognitive capabilities and communicating with each other are expected to significantly reduce the changeover time.

A machine equipped with cognitive tools and camera sensors, for instance, can recognize any workpiece even in the case of changing products. Having examined the workpiece's shape and position, the machine can decide how to apply its gripper or suction cups and where to place the workpiece. Depending on the product, machines with gripping, welding, or bonding skills can determine their next task or production step.

They communicate with neighboring machines and know whether they have to ask for a mobile robot to transport the product to the next workstation or the shipping department of the company.

POWER TO THE ENGINEER

Cognitive computing and cognitive technologies can be major game changers for engineering systems, practice, and training. The confluence of cognitive systems with such technologies as cloud, mobile, wearable devices, Internet of Things, Big Data, and visual analytics will amplify their impact.

Future cognitive engineering systems will be designed to handle various tasks in a flexible manner and adapt to the user's needs. They should also be reasonably easy to instruct and affordable. They will incorporate a variety of sensors, interacting reasoning modules, and actuators.

With the use of cognitive systems, engineers will be able to perform highly sophisticated search within a dynamic domain, find relevant information and patterns, see the bigger picture outside their immediate expertise, and harvest insight from data that is constantly being updated. The result will let engineers explore large numbers of alternative designs and make better decisions in large multidisciplinary projects. All this promises to reduce both the time and cost of the development process.

The aim is to create a partnership in which cognitive devices and facilities will support the thinking of the human brain. This form of partnership will think better than any human brain by itself, and will process data in a way better than current information handling machines.

Such interactions can amplify human capabilities and help engineers in creating more innovative products in powerful new ways. ME

AHMED K. NOOR is Eminent Scholar and William E. Lobeck Professor of Modeling, Simulation and Visualization Engineering at Old Dominion University in Norfolk, Va.

To Learn More **For more information on cognitive computing and cognitive engineering systems, go to: www.aee.odu.edu/cognitivecomp. The website, created as a companion to this *Mechanical Engineering* magazine feature, contains links to material on cognitive computing, cognitive technologies and systems, current activities, educational programs, and research projects.**

robots are getting smarter all the time. Developments in hardware and processing power have made it possible to automate tasks much more complex than spot welding or pick-and-place.

Robots at EPFL learn to feel the difference between skilled and unskilled welders so they can provide assistance when needed.

Indeed, we live in an age when society may soon have to decide how to integrate autonomous aircraft with conventional air traffic. Personal service robots may one day set the table for us or pour our drinks.

In industry, machines and their artificial intelligence can be productive at ever-more-complex tasks, but the cost of programming them can be prohibitive, especially to small and mid-size enterprises. It is not just a one-time cost of developing the large computer code. Smaller manufacturers are frequently producing short runs and so face a need for frequent reprogramming.

Current manual programming approaches rely on formulating a simple version of the problem and applying a search-based planning algorithm to discover a solution. To generate a problem within the conceptual grasp of a human programmer, the simplifying assumptions might include considering all objects being manipulated to be rigid and ignoring dynamics.

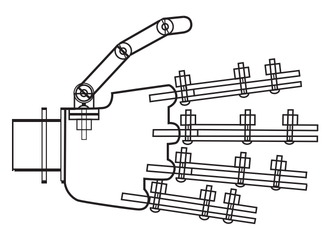
The challenge and cost of programming can increase significantly when the process involves the management of deformable or fluid materials, typically encountered in many routine tasks in industry as well as in our daily lives. But imagine an alternative that can eliminate the need to write lengthy programs that try to foresee the numerous variations possible in a complex task. Suppose you could program a robot by showing it how to do the job.

RESEARCH IS MAKING GREAT STRIDES IN IMITATION LEARNING—**THE PROGRAMMING**

robot see

OF AUTONOMOUS MACHINES BY INDIVIDUAL AND CROWD DEMONSTRATIONS.

robot do



BY KRISHNANAND N. KAIPA, JOSHUA D. LANGSFELD, AND SATYANDRA K. GUPTA

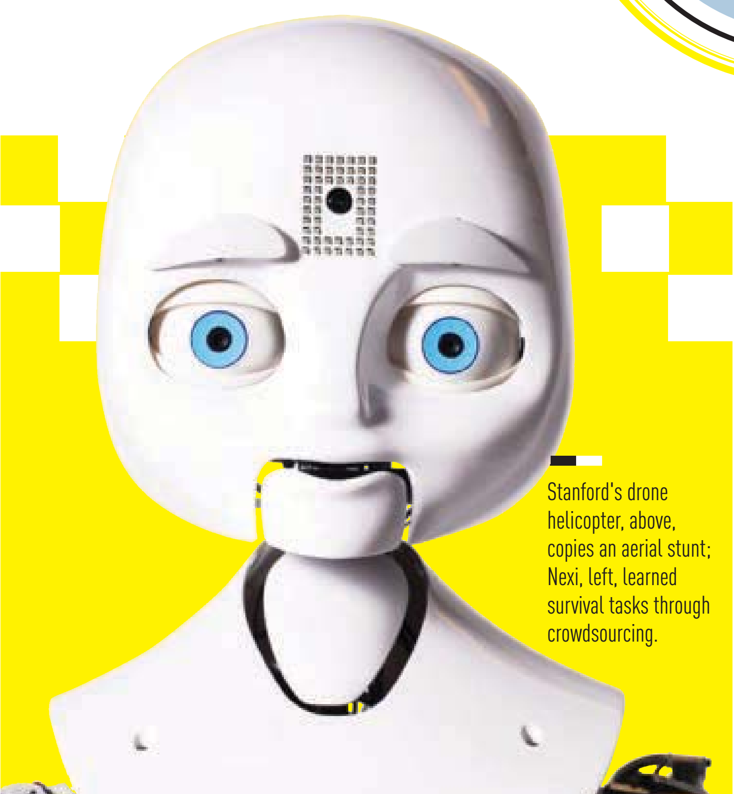
The core idea is that humans cannot spontaneously perform challenging tasks; instead, they gain experience and improve their performance over time as they execute repeated trials.

This is often called "learning from demonstrations" or "imitation learning." And it isn't a far-fetched idea. Labs at several institutions—for example, the Swiss Federal Institute of Technology at Lausanne, the University of Maryland, Massachusetts Institute of Technology, and Worcester Polytechnic Institute—are experimenting with technology that may one day make imitation learning common for machines.

The underlying idea of this approach is to allow an agent to acquire the necessary details of how to perform a task by observing another agent (who already has the relevant expertise) perform the same task. Usually, the learning agent is a robot and the teaching agent is a human. Often, the goal of imitation learning approaches is to extract some high-level details about how to perform the task from recorded demonstrations.

Research into imitation learning has achieved some impressive results ranging from training unmanned helicopters to perform complex maneuvers to teaching robots general-purpose manipulation tasks.

One early implementation reported in 2004 was focused on teaching a helicopter to hover in place and perform a few maneuvers.



Stanford's drone helicopter, above, copies an aerial stunt; Nexi, left, learned survival tasks through crowdsourcing.

Learning of more complex maneuvers like in-place flips from human demonstrations was reported in 2010. Researchers at the Stanford AI Lab led by director Andrew Ng were able to train the small helicopter to perform complex stunts by observing the behavior of an expert pilot performing them.

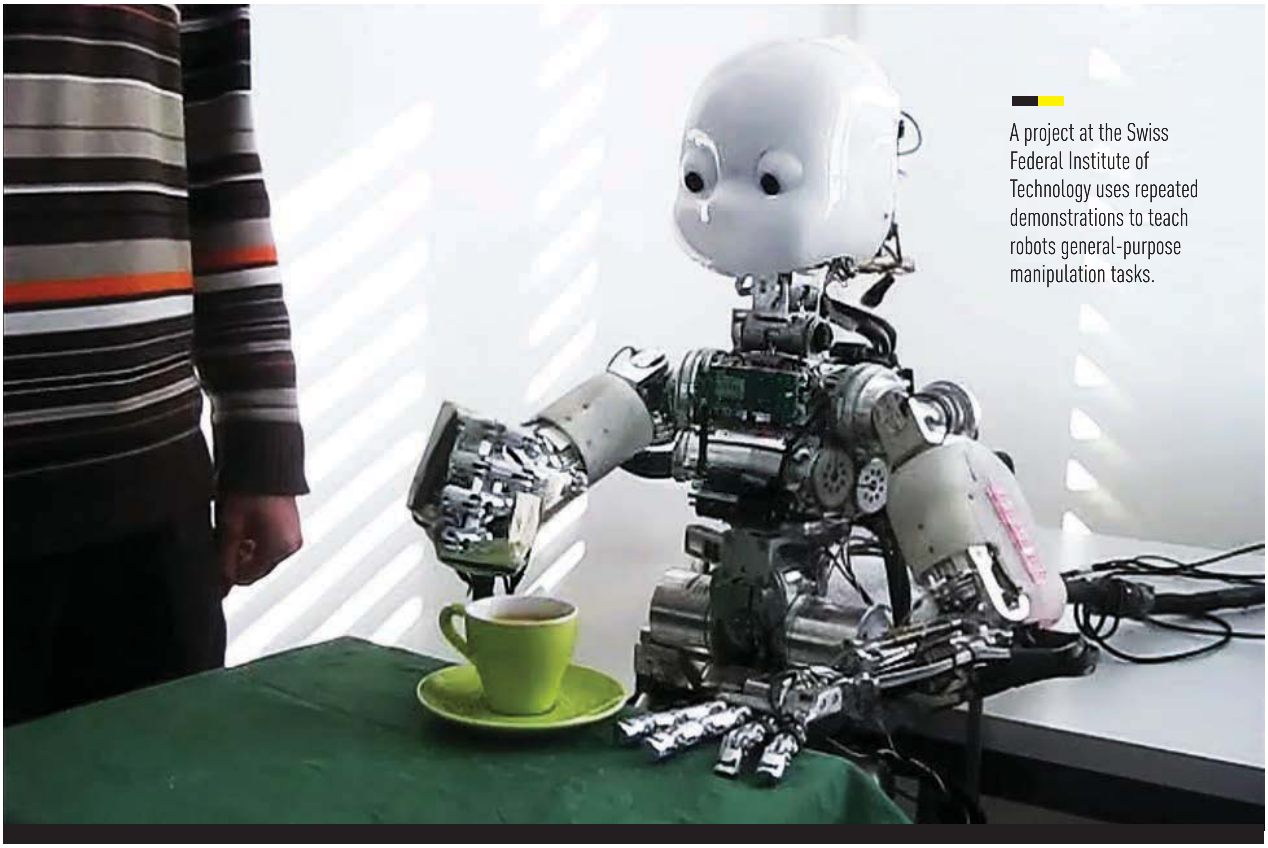
The robot could not simply copy the inputs given by the pilot since no two runs of a stunt are exactly equal. The pilot is continually compensating for disturbances while performing the task. Successful replication of a stunt by an autonomous robot requires a learning algorithm to extract the desired characteristics of the task from one or more demonstrations and to develop a policy to reproduce those characteristics at an acceptable level of performance.

The apprenticeship learning approach has the advantage of not requiring any input from a human programmer to define the stunt motions. This is difficult to do, as helicopter dynamics are complicated and often only known implicitly, assuring that any hand-coded control algorithm is likely to fail on maneuvers that require capabilities of the helicopter close to its limits. Learning from expert demonstrations serves as a feasible option in such cases.

The general approach used by the Stanford researchers involves the assumption that the pilot is demonstrating a noisy version of the desired trajectory to execute the stunt. Multiple demonstrations of the same stunt have differing amounts of noise in different sections, and so a good averaging algorithm is able to extract an appropriate trajectory. Using an expectation maximization algorithm, the system is able to produce the average trajectory by simultaneously aligning the demonstrations temporally and finding trajectory elements that can be achieved by the helicopter, given its dynamics.

The net result is that the helicopter can perform the stunts with a consistency comparable to that of the expert pilot. The helicopter was able to transition between learned stunts without returning to neutral flight state between stunts.

Researchers at the Learning Algorithms and Systems Laboratory of the École Polytechnique Fédérale de Lausanne, led by Aude Billard, have been incorporating learning from demonstrations for a variety of robot tasks. They are primarily concerned with teaching humanoid robots various general-



A project at the Swiss Federal Institute of Technology uses repeated demonstrations to teach robots general-purpose manipulation tasks.

purpose manipulation tasks, from setting a table with cutlery and flatware to putting objects into a container. These tasks may involve learning when to grasp, how to grasp, and what trajectories to follow.

The researchers have developed algorithms that are able to extract the desired characteristics of a task from repeated demonstrations. The approach enables different demonstrators to illustrate different aspects of a manipulation task and generalizes the demonstrations into a single cohesive model for achieving the task goals. They use a probabilistic framework to encode the demonstration data and extract important constraints for achieving the task.

Most traditional approaches to imitation learning in the robotics area only utilize a small number of successful human demonstrations. These demonstrations are used to construct a model that identifies parameters to be used by the robot in doing the same task. If the robot is unable to do the task using the parameters prescribed by the model, then the approach fails.

The reasons for failures are often insufficient number of demonstrations or the subtle differences between the robot and the human that are not modeled. This phenomenon is generally referred to as the correspondence problem in the imitation learning and cognitive science communities.

Relying on demonstrations or a model that captures all the differences between the human and the robot is impractical. We need a robust approach to imitation learning that anticipates failures in the transfer of skills from the human to the robot and has built-in features to recover from it.

Human operators often need to perform challenging tasks multiple times in order to be able to reach an acceptable level of performance. Typically, humans make a lot of errors during early phases of learning.

They learn the appropriate coordination by using the motor error to adjust their neural command over repeated trials. This provides a different approach to imitation learning: In addition to learning from successful demonstrations, robots can also learn from errors made by human operators and how they recovered from these errors in subsequent trials.

We and our collaborators in the Maryland Robotics Center at the University of Maryland in College Park are working on developing imitation learning algorithms, with a particular emphasis on learning from failures. The core idea is that humans cannot spontaneously perform challenging tasks; instead, they gain experience and improve their performance over time as they execute repeated trials.

Accordingly, all demonstrations, whether successful or not, can be recorded and learned from. The robot learns a model of the human's behavior which can provide a means to act in a novel variation of the task and a strategy to adjust its behavior when failure occurs. It imitates how the demonstrator converged to a successful trial.

We are currently focused on the problem of pouring liquid into a moving container placed on a rotating platform. This scenario takes inspiration from an assembly line at a small or medium-size manufacturing firm, where task requirements might change rapidly and purchasing specialized automation hardware for each variation would be too expensive.

The goal is to use general-purpose robotic manipulators that can be easily trained. The task of pouring a liquid into a container while it is moving is a challenging problem for current autonomous planners because it is difficult to accurately model the fluid dynamics in real time. The task is therefore relatively more amenable to directly learning from human demonstrations.

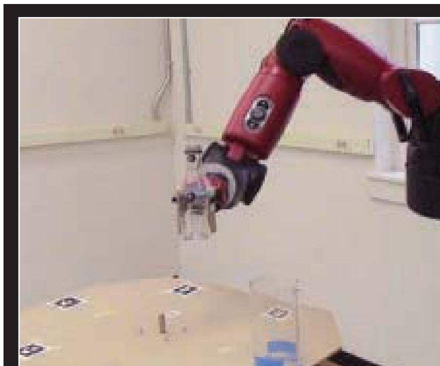
During experiments, we observed that humans approach this task with no experience and rapidly converge to a successful behavior. Initial results indicate that there is valuable information in a trial where the demonstrator failed at performing the task, primarily in terms of how that experience affected their behavior in the next trial.

Our approach involves extracting this adjustment strategy as a function of current performance in order to imitate not just the task itself, but how to improve and succeed in cases of failed attempts. The algorithm developed on these ideas was illustrated using a robotic arm that failed initially, learnt from its failures, and eventually succeeded at performing the pouring task.

People often wonder how well the learned components of autonomy will perform in situations not encountered during demonstrations. Extensive physical experiments to predict reliability would be costly in time and money. Clearly a demonstration that might pose a threat to the human or the robot has to be avoided. So conducting demonstrations in the virtual world is emerging as an attractive alternative.

Over the last few years, tremendous progress has been made in the area of physics-based robot simulators. For example, the DARPA Robotics Challenge is making an extensive use of simulation technology to test autonomy components.

By combining advances in multi-player online games and accurate robot simulations, new games can be developed in which humans can compete and collaborate with each other by teleoperating virtual robots. This advancement means that demonstrations need not be confined to a few experts. Instead, anyone with an Internet connection can participate in the training of a new robot. That is how



The robotic arm is taught by successful and unsuccessful

DARPA used a publicly distributed Anti-Submarine Warfare game to learn how to track quiet submarines.

Integrating virtual world demonstrations with advances in crowdsourcing takes imitation learning to a new level.

At the MIT Media Lab, in conjunction with Worcester Polytechnic Institute, Cynthia Brazeal and Sonia Chernova are working on enabling large-scale robot learning from crowdsourcing of demonstrations. Their work is inspired by the Restaurant Game project, where thousands of human players were able to interact with each other in the form of virtual avatars inside a restaurant, generating example behaviors of how customers and waiters behave.

This large amount of data could then be mined to produce generalized behavior models that respond appropriately to previously unseen contexts. The concept was extended to a virtual survival game on Mars, where a

A demonstrator at the Maryland Robotics Center pours liquid into a container on a revolving platform. The arrangement is intended to simulate some of the challenges of a factory assembly line.

human and a robot must collaborate on a physical task of salvaging items and escaping to a spaceship.

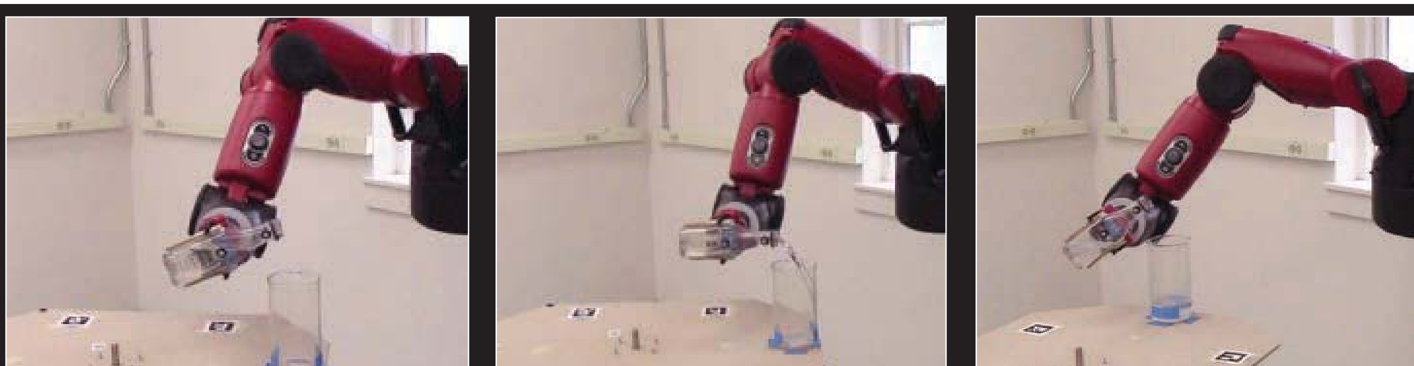
In this scenario, physical constraints on the robot—such as an inability to traverse stairs when only wheeled locomotion is available—are modeled. Both the robot and human virtual agents would be controlled by human players, producing a database of samples that illustrate how the two agents should collaborate given the motion and task constraints.

The results from this virtual interaction were extracted and applied to a physical version of the survival scenario where Nexi, a mobile, dexterous, and social robot assisted a human participant in performing the survival tasks of gathering needed items. Their results indicated that the robot was able to incorporate crowd-sourced knowledge in its behavior to perform the collaborative task at a comparable level of ability as a predefined behavioral script, executed by a teleoperator.

The researchers report seeing spontaneous collaborative behavior between the human and robot solely based on the crowdsourced data. They conclude that using the ability of crowds to generate the behavior policy of the robot is promising, but still requires significant work with several open challenges. For example, they must determine how to assure that the player of the virtual game will act in the same manner as with a physical robot, given that the two scenarios have substantial differences that change human behavior.

Crowdsourcing provides a rich diversity in demonstrations and hence enhances the probability of generalization. Some of the participants are likely to exhibit unconventional thinking and demonstrate a highly creative or innovative way of doing a task. This is great news for optimizing robot performance.

For some people, this way of training robots might serve as a means to earn money by performing demonstrations (basically acting as robot tutors). Playing games that involve robots is likely to be entertaining for at least a segment of the population.



demonstrations. It learns from its own failures, much as humans do, and adjusts its behavior to pour the liquid with reasonable accuracy into the moving container.

This paradigm can also be used in situations where a robot is stuck during a difficult task and needs a creative solution to get out of the bind.

We expect demonstrators recruited via crowdsourcing to be non-experts and therefore to fail, but robots can still learn from those failures, just as humans do. Imitation learning methods that make use of both successful and failed demonstrations are suited to exploiting the benefits of crowdsourced demonstrations.

Automatically learning reasoning rules and skills from a vast amount of demonstration data is an interesting challenge and will keep the research community busy for many years to come. But this seems to be the much-needed crucial advancement to reduce the cost of autonomous robots. ME

KRISHNANAND N. KAIPA is a research assistant professor and **JOSHUA D. LANGSFELD** is a graduate student in the Department of Mechanical Engineering at the University of Maryland. **SATYANDRA K. GUPTA** is a professor in the Department of Mechanical Engineering and the Institute for Systems Research at UMD.

TO LEARN MORE

"A Survey of Robot Learning From Demonstration," B. D. Argall, S. Chernova, M. Veloso, and B. Browning. (2009). *Robotics and Autonomous Systems*, 57(5): 469–483.

"Autonomous Helicopter Aerobatics Through Apprenticeship Learning," P. Abbeel, A. Coates, and A.Y. Ng. (2010). *The International Journal of Robotics Research*, 29(13): 1608-1639.

"Catching Objects in Flight," S. Kim, A. Shukla, and A. Billard. (2014). *IEEE Transactions on Robotics*, 30(5), In press.

"Crowdsourcing Human-Robot Interaction: New Methods and System Evaluation in a Public Environment," C. Breazeal, N. DePalma, J. Orkin, S. Chernova, and M. Jung. (2013). *Journal of Human-Robot Interaction*, 2(1): 82-111.

"Towards Imitation Learning of Dynamic Manipulation Tasks: A Framework to Learn From Failures," J. Langsfeld, K.N. Kaipa, R. J. Gentili, and S.K. Gupta. (2014). *Simulation Based System Design Lab Technical Report.*

"Keyframe-Based Learning From Demonstration," B. Akgun, M. Cakmak, K. Jiang, and A.L. Thomaz. (2012). *International Journal of Robotics Research*, 4(4): 343-355.

"Active learning From Demonstration for Robust Autonomous Navigation," S. David, J.A. Bagnell, and A. Stentz. (2012). *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 200-207.

COLD START

WE HAVE ALL SAT IN AN AIRPORT WAITING FOR A PLANE THAT FAILS TO ARRIVE OR TAKE OFF ON TIME. SOMETIMES THE FLIGHT IS DELAYED; SOMETIMES IT IS CANCELED. THERE CAN BE MANY REASONS FOR THAT, INCLUDING ONE THAT HAS ONLY RECENTLY BECOME CLEARLY UNDERSTOOD.

In the past two decades, the U.S. Federal Aviation Administration has compiled numerous reports on jet engine shutdowns during cold start-ups. The cause of these accidents has been attributed to burnt-out electronic components inside the engine due to electrical discharge. The connection between the start-up at low temperatures and the electronic-component failure has only recently come to light.

All thermomechanical power systems contain a dielectric fluid—namely the circulating lubricant oil—where its circulation can create friction and cause a static electric charge to build up. The charge can induce voltage spikes in portions of the circulation manifold during the initial warm-up period. The spike can destroy a sensitive component such as a sensor or microprocessor, and if that component is critical to operation, the engine will shut down.

When a power system is cold (lower than -10 °C), its circulating oil has a very high viscosity and very low electrical conductivity. The oil will warm as the engine heats up, but for a period after a cold start, there will be a hazard of static electric build-up in the oil and of potentially damaging spontaneous discharge.

Flow electrification of liquids has been a source of numerous industrial hazards, primarily in the petroleum and power industries. This effect occurs in improperly grounded systems carrying fuels, lubricating oils, and other hydrocarbon liquids. That's why some commercial gasoline fuel hoses in the United States have an attached ground wire to dissipate electric charge accumulation during fueling operations and there exist regulations to shut off the engine when pumping fuel into a vehicle.

DEAD SENSOR

THE CULPRIT IS HIDING IN THE LUBRICANT SYSTEM: ELECTROSTATIC DISCHARGE FROM OIL CAN DESTROY SENSITIVE AND CRUCIAL ENGINE COMPONENTS.

BY BEHROUZ ABEDIAN

STATIC ELECTRIFICATION of a dielectric liquid is due to the presence of some trace elements in the oil products. Examples of substances that can carry electric charge in a non-conducting liquid are various oxidized oil components (as a result of processing), contaminating agents (acquired during processing and handling), metal salts, and other ionized additives. The concentration of any of these substances at which liquid electrification occurs can be as low as 1 part per billion. Because of such low concentration, it is impractical to remove these trace elements and even if one does so successfully, subsequent handling can reintroduce the elements through recontamination.

Even with the presence of trace elements, stagnant undisturbed oil is uncharged in the bulk and charged only very close to the solid surfaces with which it is in contact. The liquid motion and the convection of the trapped charges in the liquid give rise to a convective electric current often referred to as streaming current.

The ability of a liquid to retain its electrical charge depends on its electrical conductivity. In dielectric liquids, the time that an isolated liquid mass can remain electrified is known as its electrical relaxation time. It is inversely proportional to its electrical conductivity. For different commercial oils, this time constant is in the range of 1 microsecond to 1,000 seconds for higher to lower conductivities. For any lubricating oil, at very low temperatures during a cold start, the relaxation time of the liquid is closer to the upper limit, whereas under steady-state operation, it has values closer to the lower limit. Accordingly, during a cold start, the electrified oil will remain charged and if moved can give rise to charge accumulation in the circulating system.

Once electrified, the distance that the oil can carry the charges depends on its electrical relaxation time as well as the bulk velocity of the flowing oil. In the warm-up phase of a power system, the velocity and the electrical conductivity of the circulating oil both increase with time. At the start, the velocity and conductivity of the oil are low and therefore the electrification is limited to regions close to charge source without electric charge build-up or any potential damage.

On the other hand, with normal operations, any static electrification in the moving oil can travel very short distances (less than 1 mm). The oil will get neutralized, and the electrical charges dissipate to the adjacent walls.

However, as the engine warms up from a cold start, there can be a time interval in which the oil velocity is high enough and the conductivity is still low enough such that moving oil will give rise to charge accumulation with the potential to do damage.

Yet another temperature effect has to do with the induced charge concentration behind a charge source such as a filter. In the most general case, filter electric charging depends on a number of parameters that have to do with filter geometry and flow conditions. These and other parameters were discussed in a 1977 paper by Peter Huber and Ain Sonin in the *Journal of Colloid and Interface Science*.

PREHEATING THE ENGINE BLOCK **IS UNLIKELY TO MITIGATE THE HAZARD.**

A SYSTEM TO WARM THE OIL **AND NOT THE BLOCK WOULD BE A SOLUTION.**

For industrial filters used in power systems, the charging behind the filter is often saturated and proportional to the liquid electrical conductivity. So as the temperature rises during a cold start, the filter charging will also increase with time during the warm-up period.

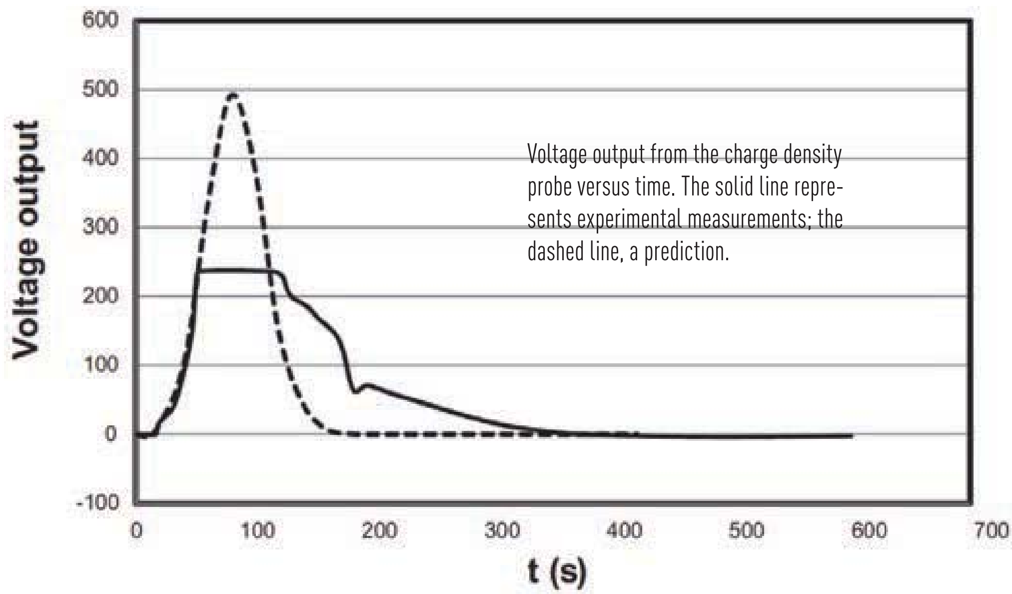
Accordingly, as the temperature rises with time, downstream of a charge source, there is an exponential increase in the induced electrification of the liquid and a decrease in the convective length of the electrified oil. The combination of these two counter-effects will be a transient charging effect in the form of a voltage spike in the downstream of the charge source where the oil flows.

How low must the starting temperature be for this hazard to pose a practical problem? In general, the severity of this transient effect is influenced by a wide range of variables such as the size and arrangements of the compartments in the circulation system, the base electrical conductivity of the circulating oil, the types of filters and pumps used in the system, the flow-volume rate, and the temperature profiles of the system during the warm-up phase as well as the starting temperature. Therefore, a complete system analysis is needed to answer the question.

In the system that my colleagues and I have analyzed, the starting temperature in the experimental setup was -41 °C and the estimated maximum voltage of 500 V was estimated at about -10 °C. For this particular system, any starting temperature below -10 °C can induce a severe spike. However, during experiments at higher temperatures, we observed a similar but milder response. For example, after starting the system at 0 °C, we measured a maximum voltage of 150 V.

PREHEATING THE ENGINE BLOCK is unlikely to mitigate the hazard of a voltage spike. While preheating might help the engine to start, it may, in fact, potentially amplify the voltage spike. Engine oil is often stored in an oil pan that is not in contact

VOLTAGE OVER TIME



Reed Elsevier, used with permission.

with the main engine block. So if the engine components are warm and the circulating oil is very cold, oil electrification will be enhanced.

Experimental data on the use of single-block heating for different engines for an extended period of time, detailed initially by E.W. Wiens in a 1972 paper in *Canadian Agricultural Engineering*, show that the engine oil may rise only between 3 and 6 °C while the temperatures of the engine blocks and the coolant change 30 to 60 °C.

A system that can warm up the engine oil and not the engine block would be a solution, and there exist several proposed systems for particular engines, but this solution can't be practical for all power systems because oil in the pan may not be easily accessible.

Another solution is to use a by-pass system for some of the components such as filters that can be triggered by a differential pressure across the component.

While this can be a promising technology and filter manufacturers have begun to utilize this by-pass system, there are still a few drawbacks. One is that the system is now more complex and more susceptible to failure. The other is that if new oil is used, the settings for the by-pass condition should also be changed accordingly. Moreover, this technology can't be used for other components such as an oil pump, which can also induce charging in the oil.

One might envision a change to the arrangement of an engine to put the oil storage unit within the engine block. This is somewhat analogous to systems that exist in some hybrid-engine automobiles that store the hot coolant inside the engine for better start-stop performance.

The most robust option will be well-electrical grounding of the engine compartments during the early stages of a cold startup to prevent charge accumulation.

TO ASSESS THIS POTENTIAL HAZARD for a given power system, the charging sources in the oil circulation system such as the filter and the pump need to be characterized in terms of the magnitude and the polarity of the charge they induce in the liquid. Once such data is available, one can utilize recently developed analysis on unsteady charging in circulation systems to predict the severity of charging during a cold start. The analysis was included in a paper written by David S. Behling and this author, "Transient electric charging of dielectric liquids in recirculation systems," published in October 2013 by the *Journal of Electrostatics*.

Flow-induced electrification of dielectric liquids has been studied extensively since World War II. By and large, all these studies, theoretical and experimental, have been restricted to steady charging under ambient temperatures. The electrostatics of a startup circulating oil is both unsteady and critically dependent on temperature.

While, we are not aware of any open report on cold start-up problem of this sort for automobiles, as advanced engines continue to include more electronics, this hazard could potentially pose a problem for them, too.

This is a practical problem and new studies are needed to shed light on this phenomenon with respect to temperature effects and other transitory behavior of a system. **ME**

BEHROUZ ABEDIAN is an associate professor in the mechanical engineering department of Tufts University.

ASME
SETTING THE STANDARD

Training & Development

Setting the Standard for Workforce Learning Solutions

TRAINING COURSES FOR ENGINEERS AND TECHNICAL PROFESSIONALS

2014 AUTUMN

SEPTEMBER - OCTOBER 2014 – BARCELONA, SPAIN

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

Visit go.asme.org/barcelona1

OCTOBER 2014 – ATLANTA, GEORGIA USA

PD107	Elevator Maintenance Evaluation	6-7 Oct
PD391	ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids *ASME Code Course*	6-7 Oct
PD539	Bolted Joints and Gasket Behavior	6-7 Oct
PD690	Economics of Pipe Sizing and Pump Selection	6-7 Oct
PD077	Failure Prevention, Repair and Life Extension of Piping, Vessels and Tanks *ASME Code Course*	6-8 Oct
PD370	B31.8 Gas Transmission and Distribution Piping Systems *ASME Code Course*	6-8 Oct

CONTINUED, OCTOBER 2014 – ATLANTA, GEORGIA, USA

PD506	Research and Development Management	6-8 Oct
PD513	TRIZ: The Theory of Inventive Problem Solving	6-8 Oct
PD571	The Taguchi Design of Experiments for Robust Product and Process Designs	6-8 Oct
PD597	Risk-Informed Inservice Testing	6-8 Oct
PD618	Root Cause Analysis Fundamentals	6-8 Oct
PD683	Probabilistic Structural Analysis, Design and Reliability-Risk Assessment	6-8 Oct
PD394	Seismic Design and Retrofit of Equipment and Piping	6-9 Oct
PD632	Design in Codes, Standards and Regulations for Nuclear Power Plant Construction *ASME Code Course*	6-9 Oct
PD675	ASME NQA-1 Lead Auditor Training	6-9 Oct
PD432	Turbo Machinery Dynamics: Design and Operation	6-10 Oct
PD601	Bolting Combo Course **SAVE UP TO $1,260!**	6-10 Oct
PD386	Design of Bolted Flange Joints	8 Oct
PD449	Mechanical Tolerancing for Six Sigma	8-9 Oct
PD698	Predictive Maintenance Technologies **NEW!**	8-10 Oct
PD575	Comprehensive Negotiating Strategies®: Engineers and Technical Professionals	9-10 Oct
PD577	Bolted Joint Assembly Principles Per PCC-1-2013 *ASME Code Course*	9-10 Oct
PD591	Developing Conflict Resolution Best Practices	9-10 Oct
PD706	Inline Inspections for Pipelines	9-10 Oct

Visit go.asme.org/atlanta4

OCTOBER 2014 – HOUSTON, TEXAS USA

PD115	The Gas Turbine: Principles and Applications	20-21 Oct
PD313	Fundamentals of Fastening Systems	20-21 Oct
PD624	Two-Phase Flow and Heat Transfer	20-21 Oct
PD146	Flow Induced Vibration with Applications to Failure Analysis	20-22 Oct
PD231	Shock and Vibration Analysis	20-22 Oct
PD395	API 579-1/ASME FFS-1 Fitness-for-Service	20-22 Oct
PD410	Detail Engineering of Piping Systems	20-22 Oct
PD442	BPV Code, Section VIII, Division 1: Design and Fabrication of Pressure Vessels *ASME Code Course* **TOP SELLER**	20-22 Oct
PD619	Risk and Reliability Strategies for Optimizing Performance	20-22 Oct

REGISTER NOW: United States and Canada 1.800.843.2763 / Europe +32.2.743.1543

CONTINUED, OCTOBER 2014 – HOUSTON, TEXAS, USA

PD633	Overview of Codes and Standards for Nuclear Power Plant Construction *ASME Code Course*	20-22 Oct
PD702	Process Safety and Risk Management for Mechanical Engineers **NEW!**	20-22 Oct
PD010	ASME A17.1 Safety Code for Elevators and Escalators *ASME Code Course*	20-23 Oct
PD014	B31.3 Process Piping Design *ASME Code Course*	20-23 Oct
PD672	BPV Code, Section XI, Division 1: Inservice Inspection 10-Year Program Updates for Nuclear Power Plant Components *ASME Code Course*	20-23 Oct
PD679	Selection of Pumps and Valves for Optimum System Performance **NEW!**	20-23 Oct
PD443	BPV Code, Section VIII, Division 1 Combo Course **SAVE UP TO $645!** *ASME Code Course* **TOP SELLER**	20-24 Oct
PD581	B31.3 Process Piping Design, Materials, Fabrication, Examination and Testing Combo Course *ASME Code Course* **SAVE UP TO $575!**	20-24 Oct
PD665	BPV Code, Section I: Power Boilers *ASME Code Course*	20-24 Oct
PD699	Reliability Excellence Fundamentals **NEW!**	22-24 Oct
PD441	Inspections, Repairs and Alterations of Pressure Equipment *ASME Code Course*	23-24 Oct
PD634	Comparison of Global Quality Assurance and Management System Standards Used for Nuclear Applications *ASME Code Course*	23-24 Oct
PD457	B31.3 Process Piping Materials Fabrication, Examination and Testing *ASME Code Course*	24 Oct

Visit **go.asme.org/houston5**

NOVEMBER 2014 – SAN DIEGO, CALIFORNIA USA

PD382	How to Predict Thermal-Hydraulic Loads on Pressure Vessels and Piping	3-4 Nov
PD445	B31 Piping Fabrication and Examination *ASME Code Course*	3-4 Nov
PD531	Leadership and Organizational Management	3-4 Nov
PD539	Bolted Joints and Gasket Behavior	3-4 Nov
PD567	Design, Analysis and Fabrication of Composite Structure, Energy and Machine Applications	3-4 Nov
PD077	Failure Prevention, Repair & Life Extension of Piping, Vessels and Tanks *ASME Code Course*	3-5 Nov
PD190	BPV Code, Section IX: Welding, Brazing and Fusing Qualifications *ASME Code Course*	3-5 Nov
PD349	Design and Applications of Centrifugal Pumps **NEW!**	3-5 Nov
PD389	Non-Destructive Examination -- Applying ASME Code Requirements (BPV Code, Section V) *ASME Code Course*	3-5 Nov
PD513	TRIZ: The Theory of Inventive Problem Solving	3-5 Nov
PD674	International Business Ethics and Foreign Corrupt Practices Act	3-5 Nov
PD359	Practical Welding Technology	3-6 Nov
PD448	BPV Code, Section VIII, Division 2: Alternative Rules - Design and Fabrication of Pressure Vessels *ASME Code Course* **TOP SELLER**	3-6 Nov
PD601	Bolting Combo Course **SAVE UP TO $1,260!**	3-7 Nov
PD665	BPV Code, Section 1: Power Boilers *ASME Code Course*	3-7 Nov
PD681	International Business Ethics and Foreign Corrupt Practices Act Combo Course **SAVE UP TO $635!**	3-7 Nov
PD386	Design of Bolted Flange Joints	5 Nov

CONTINUED, NOVEMBER 2014 – CALIFORNIA, USA

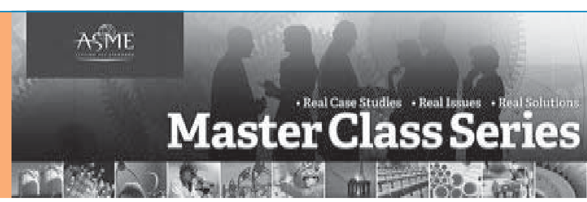
PD449	Mechanical Tolerancing for Six Sigma	5-6 Nov
PD621	Grade 91 and Other Creep Strength Enhanced Ferritic Steels	5-7 Nov
PD700	Risk-Based Asset Management **NEW!**	5-7 Nov
PD575	Comprehensive Negotiating Strategies®: Engineers and Technical Professionals	6-7 Nov
PD577	Bolted Joint Assembly Principles Per PCC-1-2013 *ASME Code Course*	6-7 Nov
PD673	Design and Selection of Heat Exchangers	6-7 Nov
PD680	Understanding the Foreign Corrupt Practices Act	6-7 Nov
PD692	Communication Essentials for Engineers	6-7 Nov

Visit **go.asme.org/sandiego2**

NOVEMBER 2014 - AMSTERDAM, NETHERLANDS

PD634	Comparison of Global Quality Assurance and Management System Standards Used for Nuclear Applications *ASME Code Course*	3-4 Nov
PD714	BPV Code, Section VIII, Division 2: Pressure Vessels *ASME Code Course*	3-5 Nov
PD720	Layout of Process Piping Systems **NEW!**	3-5 Nov
PD616	API 579 /ASME FFS-1 Fitness-for-Service Evaluation	3-6 Nov
PD622	BPV Code: Plant Equipment Requirements *ASME Code Course*	3-6 Nov
PD632	Design in Codes, Standards & Regulations for Nuclear Power Plant Construction *ASME Code Course*	3-6 Nov
PD642	ASME B31.1 Power Piping *ASME Code Course*	3-6 Nov
PD643	B31.3 Process Piping Code *ASME Code Course*	3-6 Nov
PD644	Advanced Design and Construction of Nuclear Facility Components per BPV Code, Section III *ASME Code Course*	3-6 Nov
PD686	Layout of Process Piping Systems and Managing 3D CAD/CAE Systems Combo Course **NEW! SAVE UP TO €750!**	3-7 Nov
PD721	Optimisation of Plant Layouts Utilising 3D CAD/CAE Systems **NEW!**	6-7 Nov

Visit **go.asme.org/amsterdam2**



Register Now to Attend the ASME MasterClass Series on

Boiler, Pressure Vessel and Piping Technologies and Standards

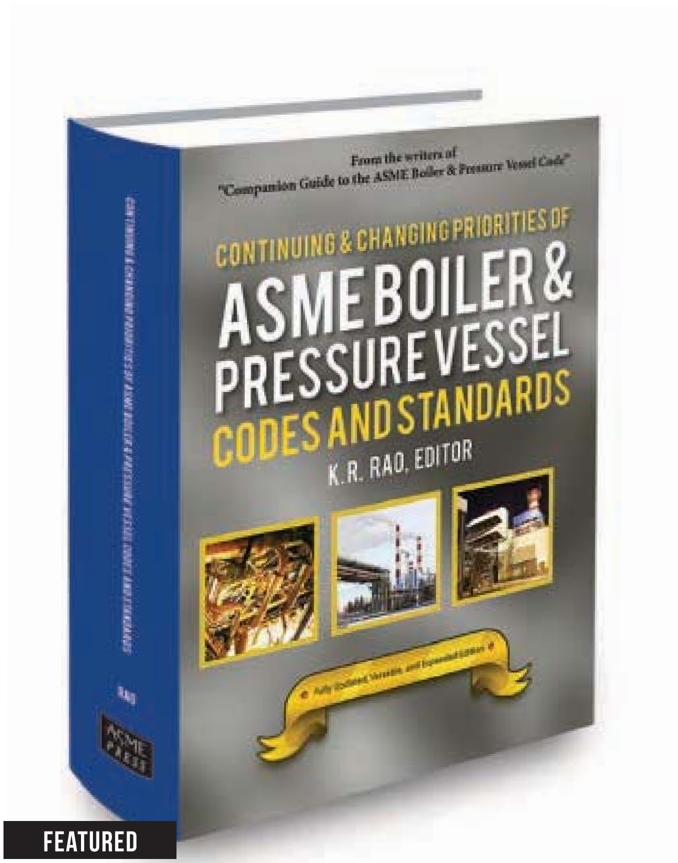
November 10-13, 2014 • New Orleans, LA

Led by industry experts and Codes & Standards leaders, the ASME MasterClass Series on Boiler, Pressure Vessel and Piping Technologies examines proven techniques and strategies to explain application of critical design rules and technologies to address current issues in today's industry. The MasterClass Series will be held from November 10-13, 2014 at the Hyatt Regency in New Orleans, Louisiana.

Register Now and Save $200. Early Bird discount expires on October 13, 2014.

For full descriptions of MasterClasses offered during this event and to register, visit

go.asme.org/MCseriesNov2014



FEATURED

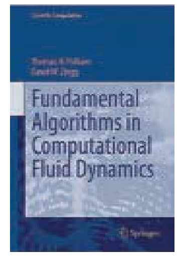
CONTINUING AND CHANGING PRIORITIES OF THE ASME BOILER AND PRESSURE VESSEL CODES AND STANDARDS

K.R. RAO

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

This work was originally published as part of Volume 3 of the *Companion Guide to the ASME Boiler & Pressure Vessel Code*. The text has been updated and expanded to serve as a stand-alone publication that addresses topics including next-generation nuclear reactors and internals, license renewal, public safety, PRA, and spent fuel pool-related issues. The book has four parts, the first dealing with continuing priorities of the ASME Boiler and Pressure Vessel Code and the remaining three parts dealing with changing priorities of the code. The first part has 14 chapters written by 16 code authorities with updated information pertaining to continuing priorities. A new chapter on "seismic protection for pressure piping systems" reflects the importance of the topic especially in regard to aging nuclear reactors.

800 PAGES. $259; ASME MEMBERS, $207; ISBN: 978-0-7918-6019-9.



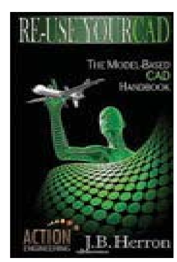
FUNDAMENTAL ALGORITHMS IN COMPUTATIONAL FLUID DYNAMICS

Thomas H. Pulliam and David W. Zingg

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

Intended as a textbook for courses in computational fluid dynamics at the senior undergraduate or graduate level, this book is a follow-up to *Fundamentals of Computational Fluid Dynamics* by the same authors, which was published in the series Scientific Computation in 2001. The earlier book concentrated on the analysis of numerical methods applied to model equations, while the new book concentrates on algorithms for the numerical solution of the Euler and Navier-Stokes equations. It focuses on some classical algorithms as well as the underlying ideas based on the latest methods. A key feature of the book is the inclusion of programming exercises at the end of each chapter based on the numerical solution of the quasi-one-dimensional Euler equations and the shock-tube problem. These exercises can be included in the context of a typical course. Sample solutions are provided in each chapter, so readers can confirm that they have coded the algorithms correctly.

211 PAGES. $89.99. ISBN: 978-3-3190-5052-2.



RE-USE YOUR CAD

J.B. Herron

CreateSpace Independent Publishing. 2013.

This handbook can be used to learn how to create, deliver, and re-use CAD models in compliance with model-based standards. It provides CAD format-neutral techniques for compliance with ASME Y14.41 and MIL-STD-31000A model-based definition and technical data packages. The 3-D model protocols provided are intended to enable businesses to save time, reduce risk, and improve products. Through use of CAD best practice and modeling rules from relevant standards, Herron hopes to provide a means for CAD users to reap the full benefits of their design software.

150 PAGES. $49. ISBN: 978-1-4948-7717-0.

A forum for emerging systems and control technologies.

DYNAMIC SYSTEMS & CONTROL

SEPTEMBER 2014 VOL. 2 NO. 3

EDITOR

A. Galip Ulsoy, University of Michigan, *ulsoy@umich.edu*

DYNAMIC SYSTEMS AND CONTROL MAGAZINE
EDITORIAL BOARD

Jordan M. Berg, Texas Tech University, *Jordan.berg@ttu.edu*

Jaydev P. Desai, University of Maryland, *jaydev@umd.edu*

Hans DeSmidt, University of Tennessee, *hdesmidt@utk.edu*

Kiriakos Kiriakidis, United States Naval Academy, *kiriakid@usna.edu*

Venkat Krovi, SUNY Buffalo, *vkrovi@buffalo.edu*

Alexander Leonessa, Virginia Tech, *leonessa@vt.edu*

Peter H. Meckl, Purdue University, *meckl@pudue.edu*

Gregory M. Shaver, Purdue University, *gshaver@purdue.edu*

Guoming Zhu, Michigan State University, *zhug@egr.msu.edu*

SUBMIT ARTICLE IDEAS TO:

A. GALIP ULSOY, UNIVERSITY OF MICHIGAN, ulsoy@umich.edu
(734)-936-0407

SUBMIT DSCD NEWS ITEMS TO:

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

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

December 2014
Advanced Manufacturing

Robots that Heal

Welcome to the seventh issue of ASME *Dynamic Systems and Control (DSC) Magazine*, for which I am serving as guest editor. This month's issue, which is devoted to robots used for rehabilitation, features four papers by experts in this growing field.

Since their development in the early 1960's for industrial applications, robots have usually been heavy, bulky machines that were considered dangerous when humans came too close. The thought of having a close interaction between robot and human was never even contemplated. However, with pioneering work by Neville Hogan and others, new control strategies were developed that allowed the interaction impedance to be regulated. This meant that the robot could be made to represent a desired dynamic behavior that would allow it to respond to human inputs, acting much like a spring in response. Thus, instead of the robot blindly moving to set positions as instructed by its controller, a human operator could take the robot by the hand and guide it to follow a desired trajectory. In addition, the robot could be designed to favor some positions more than others, so that the human operator would feel more resistance at some points than at others. It was therefore natural that such human-robot interactions would eventually be exploited for physical rehabilitation.

In the first paper, Neville Hogan describes the rationale behind using robot therapy for healing stroke victims. Traditional therapy for stroke involves a physical therapist assisting the patient in performing repetitive limb movements. Neville explains how these motions allow the brain to reestablish neural connections for limb movement and how robot-assisted movement therapy can help to accomplish this healing. He also describes the requirements for the robot controller to achieve a gentle assistive function and lists challenges that remain to be solved.

Marcia O'Malley and colleagues, in the second paper, describe two different robot designs to exercise the elbow, forearm, and wrist for motor rehabilitation. They also describe a novel control strategy that adapts the feedback gains so that the amount of assistance that the robot provides for the patient to execute the motion is reduced as the patient gets more proficient.

The third paper, by Michael Goldfarb and collaborators, shifts the focus to robotic lower-limb prostheses. In their paper, they describe two different impedance-based controllers to achieve locally passive control both during ground interaction and during the swing phase of a walking gait. They also demonstrate the efficacy of their control approach on a powered knee and ankle prosthesis tested by an amputee walking on a treadmill.

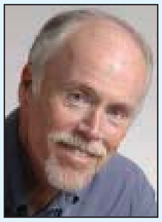
The final paper, by Homayoon Kazerooni and collaborators, describes a bio-inspired mechanical hip-knee coupling mechanism for a powered lower-extremity exoskeleton, which is used to provide gait assistance for individuals with spinal cord injury. The resulting design minimizes the required number of actuators by using a single actuator to power both hip and knee motions simultaneously, thereby enabling a lighter, more compact exoskeleton.

In this issue, we also feature a tribute to Suhada Jayasuriya, written by his student, Matt Franchek. Suhada, who passed away unexpectedly on July 12, was a dear friend, mentor, and colleague who provided immense leadership to the Dynamic Systems and Control Division in various capacities. He will be sorely missed.

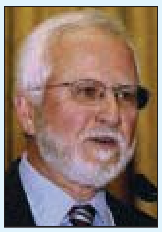
In the next issue of this magazine, the focus will turn to Advanced Manufacturing. As always, if you have any ideas for articles, please contact the Editor of *DSC Magazine*, **A. Galip Ulsoy** (**ulsoy@umich.edu**).

Peter H. Meckl
Guest Editor, *DSC Magazine*

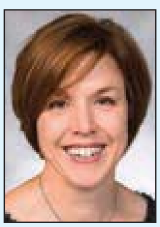
RECOGNITION OF ASME DSC DIVISION MEMBERS



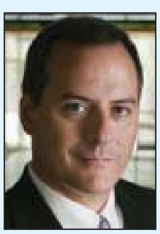
ASME DSCD member **J. Karl Hedrick** was elected to the National Academy of Engineering. Professor Hedrick is the James Marshall Wells Academic Chair Professor of Mechanical Engineering at University of California, Berkeley.



ASME DSCD member **A. Galip Ulsoy** was recently elected IEEE Fellow. In July, he was presented with the Hideo Hanafusa Outstanding Investigator Award in Flexible Automation at the 2014 International Symposium on Flexible Automation, held in Japan on the island of Awaji. Professor Ulsoy is the C.D. Mote, Jr. Distinguished University Professor and William Clay Ford Professor of Manufacturing at the University of Michigan.



ASME DSCD member **Marcia K. O'Malley** was recently elected ASME Fellow. She is an associate professor of mechanical engineering at Rice University.



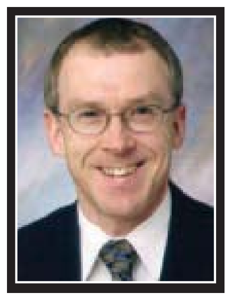
ASME DSCD member **Robert G. Landers** was elected ASME Fellow. Landers is professor of mechanical engineering in the Mechanical and Aerospace Engineering Department at the Missouri University of Science and Technology.

ASME DSCD member **Rifat Sipahi**, an associate professor in the Department of Mechanical and Industrial Engineering at Northeastern University, was elected ASME Fellow.

CONTINUED ON THE NEXT PAGE

Professor Meckl joins the ASME DSCD Executive Committee

Peter H. Meckl is a professor at Purdue University's School of Mechanical Engineering, where he has served since 1988. Peter obtained his B.S.M.E. from Northwestern University, and M.S.M.E. and Ph.D. degrees from MIT. His research interests are primarily in dynamics and control of machines, with emphasis on vibration reduction, motion control, and engine diagnostics.

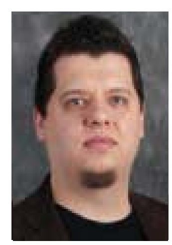


Professor Meckl's teaching responsibilities include courses in systems modeling, measurement systems, and control. He also teaches a course, *Technology and Values*, which introduces students to the social and environmental impacts of technology through a series of readings and discussions.

Peter received the Ruth and Joel Spira Award for outstanding teaching in 2000. He spent a semester in the Institute of Measurement and Control Engineering at the University of Karlsruhe, Germany, in spring 2005, conducting research and teaching on autonomous vehicles. Since 2011, he has served as one of the faculty advisors for the Purdue EcoMakers, who competed as part of the EcoCAR 2 competition, sponsored by DOE, GM, and other sponsors. In year 3 of the competition, they placed 4th out of 15 teams with a parallel plug-in hybrid electric vehicle.

Peter has been involved with the Dynamic Systems and Control Division for over 20 years, having served as chair of the Technical Panel on Vibration, a member of the Honors and Awards Committee, and as chair of the Conference Editorial Board. He said he is excited to have been selected to serve on the Executive Committee.

Control Systems Forum



Assistant professor **Tansel Yucelen** (Missouri University of Science and Technology MS&T) is leading the **Control Systems Forum**, dedicated to the dissemination and discussion of new research results, education perspectives, and applications of automatic control, decision-making, and dynamical systems.

The forum enables individuals from academia, government and industry to follow the state-of-the-art approaches from experts in control systems. Please take a moment to visit the forum at **http://consys.forum.mst.edu/** and if you wish, you can sign up for any webinars of interest to you at no cost. Professor Yucelen is the principal investigator of the Advanced Systems Research Laboratory at MS&T, and a member of the ASME DSC Division.

A TRIBUTE TO

Professor Suhada Jayasuriya

A colleague, leader, and friend.

It is with sincere regret and sorrow that we remember the untimely passing of our dear friend Suhada Jayasuriya on July 12th in Phoenixville, Pa., at the age of 61. Suhada is survived by his wife, Bodhini Rasika; his children Ruvin, Nilan, and Sashinie; his mother, Eva; and his siblings.

Dr. Jayasuriya, an ASME Fellow, was the department head of the Mechanical Engineering and Mechanics Department at Drexel University. His previous positions included distinguished professor and chair of the Department of Mechanical and Aerospace Engineering at the University of Central Florida, program director of the CMMI Division at the National Science Foundation, and Kotzebue Endowed Professor and head of mechanical engineering at Texas A&M. He received a B.Sc. in mechanical engineering (1977) from the University of Sri Lanka (Peradeniya), and his M.S. (1980) and Ph.D. (1982) in mechanical engineering from Wayne State University. Dr. Jayasuriya's career-long research, leadership, and citizenship have been recognized in many forms including the 1997 Gustus L. Larson Memorial Award, the 2002 Henry Paynter Outstanding Investigator Award, and the 2008 Michael J. Rabins Leadership Award.

Over his career, Suhada has made significant contributions to the knowledge base of automatic controls. His initial work advancing the concept of tracking in the sense of spheres led to an L_∞ or l_1 framework for synthesizing controllers for nonlinear uncertain systems. In the late 1980s and early 1990s, Suhada focused on developing frequency domain controller design methodologies under bandwidth limitations for maximizing the tolerable size of an unknown-but-bounded disturbance without violating hard time-domain constraints imposed on inputs, outputs, and states.

Suhada's most recent work had been in the area of multi-agent systems. His focus has been on developing efficient algorithms for distributed, real-time control of cooperating multi-agent systems that incorporate actual hardware constraints, dynamic constraints, and configuration constraints. The main objective of his work in this area is to advocate a change in paradigm in the approach to multi-agent formation control by addressing the key issues of dynamic feasibility and computational complexity.

Beyond his scholarship, Suhada was a tireless contributor to professional societies. For the American Automatic Control Council, he served as general chairman (2005), program chair (2000), and the ASME representative (2004-2009). He was a major leader within the ASME Dynamic Systems and Controls Division serving as chair of the Executive Committee (2002-2003), editor-in-chief of the ASME *Journal of Dynamics Systems, Measurement, and Control* (2004-2008) as well as on countless advisory and honors committees. Most recently, Suhada was serving as the general chair for the upcoming 2014 ASME Dynamic Systems and Controls Conference (DSCC) to be held in San Antonio this October. Colleagues, who are planning a special event at the conference honoring his life, contributions, and memory, will feel his absence.

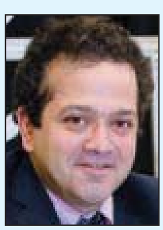
He is deeply missed by his friends and colleagues. On a personal note, I have known Suhada since August of 1986 where he served as my graduate advisor at Texas A&M University. I continued to work closely with him on a variety of conference committees and other professional society activities, including the 2014 ASME DSCC. I spoke with him the week before his passing. At that time, Suhada was extremely excited about the recent engagement of his son, Ruvin. He had such joy in his voice when speaking to me about Ruvin. The name Suhada means "kind hearted" and that is exactly the way I shall remember him. ■

Professor Matthew A. Franchek
Professor of Mechanical Engineering
University of Houston, July 25, 2014.

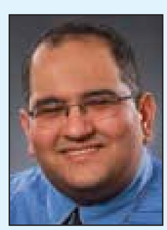
...CONTINUED FROM THE PREVIOUS PAGE

■ ASME DSCD member **Dumitru I. Caruntu** received the 2013-2014 Research Excellence Award from the University of Texas-Pan American where he is an associate professor of mechanical engineering.

ASME DSCD members receive NSF CAREER Awards



Mo Rastgaar, an assistant professor of mechanical engineering at Michigan Technological University, was recognized for his work ***CAREER: Steerable Powered Ankle-foot Prostheses for Increased Mobility in Amputees***.



Hosam Fathy, an assistant professor of mechanical engineering at Pennsylvania State University, was awarded the honor for his work ***CAREER: Identifiability Optimization in Electrochemical Battery Systems.***

by Neville Hogan

ROBOT-AIDED NEURO-RECOVERY

Stroke—cerebral vascular accident, or CVA—is the leading cause of lasting disability in the developed world. It is considered a paradox of modern health care—a disorder whose widespread growth is the result of continuous medical progress and advancement. As most of us are living longer, we grow increasingly susceptible to disorders such as stroke. Although there is some degree of spontaneous, unaided recovery, about 90% of stroke survivors are left with residual disability that requires treatment. Although hundreds of pharmacological agents have been tried, no drugs exist to aid recovery. Only one has been FDA-approved for neuro-protection, helping the brain survive a stroke, but none have been FDA-approved for neuro-recovery, restoring brain function after a stroke.

Robots help people recover after neurological injury.

Care usually involves some form of movement training, delivered by physical or occupational therapists, which creates both a challenge and an opportunity. The challenge is how the physical medicine and rehabilitation (PM&R) community can manage the rapidly growing burden of treatment. The opportunity is that physical and occupational therapy are labor-intensive, manual procedures, ripe for augmentation by technology. Properly designed robots can help people recover after neurological injury.

HOW CAN ROBOTS HELP?

There are two types of stroke: haemorrhagic, caused by bleeding in the brain; and ischemic, the more common, caused by blocking blood flow. An ischemic stroke occurs because a blood clot finds its way into the blood supply to the brain, where it impedes blood flow and starves "downstream" nerve cells of the oxygen they require to live and function. The brain consumes almost a third of the oxygenated blood supplied by the heart. Because of the way this blood is transported to the brain (i.e. the "plumbing") the parts most vulnerable to blockage tend to be those most rostral (Latin for "towards the head"). The most rostral parts of the central nervous system (CNS: brain plus spinal cord) are the cerebral hemispheres (the parts inside your head), which include areas of cerebral cortex (the wrinkled part just inside the skull) involved in sensory-motor coordination. In general, the aftermath of surviving a stroke is that some parts of your brain do not work properly, often in the upper reaches of the CNS where sensory-motor coordination is managed.

How does movement experience provided or assisted by a human therapist help to heal what is essentially a "hole in the brain"? How might a robot augment this process and alleviate an injury to the brain? The answer is found in the slowly emerging (and as yet incomplete) understanding of how the brain works. For most of the 20th century, the adult CNS was considered to be a stable, fixed entity. Only in the last few decades has evidence emerged that, in fact, the adult brain is highly plastic (i.e. susceptible to change). The basic mechanism of neural plasticity was initially proposed by neuropsychologist Donald O. Hebb and confirmed many decades later by careful experimentation. To paraphrase Hebb's law: "Nerves that fire together wire together."

FIGURE 1 Robot-aided neuro-rehabilitation for the shoulder and elbow.

The most successful robot-administered therapy to aid neuro-recovery is based on several principles of learning. A visual display indicates a target location to which the patient should attempt to move.

FIGURES 2 & 3
Robot-aided neuro-rehabilitation for the wrist.
***Far right:* Robot-aided neuro-rehabilitation for the hand.**

The robot sets up a virtual channel between the current location of the patient's limb and the target location. If the patient moves along that channel, no forces are experienced. However, if the patient's motion deviates to either side of that channel, those aiming errors are permitted but resisted by a programmable damped spring. If the patient moves too slowly (or does not initiate movement at all) the back wall of the channel (the end at the patient's starting location) moves smoothly towards the target location, nudging the patient to the target.

The result of all this is that: 1) the visual display evokes the intent to move; 2) that intention generates neural activity (possibly incoordinated) descending from the higher CNS through cortico-spinal pathways to the muscles; 3) that activity generates a corollary discharge or efference copy of the descending command that is routed back up to areas of the brain associated with learning and coordination; 4) a short time later, a movement occurs that roughly approximates an unimpaired, properly-coordinated response; 5) that movement generates sensory neural activity that ascends the cortico-spinal pathways back up to the cerebral hemispheres, where 6) it may be compared with the efference copy of the command. According to Hebb's law, those commands that correlate well with the appropriate movement are reinforced; those that do not are attenuated.

Repeating this process with high intensity—a typical session of robot-aided therapy involves over a thousand movements, whereas a typical session of human-administered therapy involves about eighty—provides the stimulus and statistics for the brain to re-acquire movement control and coordination. This account is confirmed by the observation that the patient's active participation is essential. Passively moving a patient's limbs may help improve joint mobility but it yields no improvement of motor function.

Other principles of learning are also built into the therapy algorithm. Visual feedback about progress, based on several measures computed by the robot, is provided to the patient, but not continuously. That is because intermittent feedback provides the greatest retention of acquired skill. In addition, the assistance provided by the robot is continually adapted based on the patient's performance. Specifically, if the patient becomes better at aiming, the stiffness of the channel sidewalls is progressively reduced; as the patient needs less help, less help is provided. Similarly, as the patient moves faster, the speed with which the back wall of the channel converges to the target is progressively increased; as the patient can move faster, faster movements are encouraged. These parameters are continuously updated to keep the patient at a "challenge point" where their success rate is about 80% ± 10%—not too successful, to maintain engagement; not too much failure, to avoid discouragement. This robot therapy algorithm is like coaching: assistance is provided, but only as needed; and "the bar is raised" but only to a level the patient can achieve.

Aside from its theoretical underpinnings, this form of robot-administered treatment works well. The American Heart Association periodically issues recommendations for rehabilitative care of stroke patients. The most recent issue gave robot-aided neuro-rehabilitation for the upper extremities its strongest recommendation based on the strongest level of evidence[1]. The U.S. Veteran's Administration similarly endorsed upper-extremity robot-aided neuro-rehabilitation[2]. Remarkably, this technology-based treatment is less expensive than usual care, at least within the Veteran's Administration health-care system[3].

HOW HARD CAN THIS BE? THE NEED FOR GENTLE ROBOTS

At first glance, administering therapy using robots might seem trivial; just move the patient's limbs. However, robot-administered treatment requires physical contact and dynamic interaction with the patient, and that's a challenge. There's the obvious requirement for 100% safety. A related but subtler challenge is coupled (in)stability. Due to physical interaction, the dynamics of an object—in this case, a patient—coupled to the robot may profoundly affect the robot controller's stability. This challenge was identified in the earliest days of research in robotics. Given a sufficiently detailed knowledge of the object's dynamics, the controller might be structured to preserve stability, but in this application, the "object" is a neurologically-impaired human. Unfortunately, we know very little about the dynamic behavior of unimpaired humans and vastly less about the dynamic behavior of neurologically-impaired humans.

One simple solution to this problem emerged from studying the interaction of dynamic physical systems. If the robot's interactive behavior is structured to approximate that of an energetically passive object (any collection of springs, dampers and masses, connected in any configuration) then connecting the robot to a passive object cannot induce instability. Almost all observations of unimpaired humans show that their interactive dynamic behavior is also energetically passive. Structuring the control system so that the robot's interactive dynamic behavior (its mechanical impedance) approximates that of a passive object is sufficient to ensure stability when coupled to unimpaired humans. To date, that has also proven sufficient to ensure stability when coupled to neurologically-impaired patients.

Beyond the obvious requirement for stability, a therapeutic robot must also be gentle. The human skeleton is often modeled as a collection of kinematic pairs, but in fact its integrity requires muscle activity. For example, the shoulder joint is held together by the activity of the shoulder muscles. Neurological disorders such as stroke weaken those muscles and compromise the skeleton's integrity. As a result, even moderate forces (that an unimpaired joint would readily withstand) may cause discomfort or injury. Joint pain and a disorder known as shoulder-hand syndrome are common side-effects of post-stroke therapy. Remarkably, their incidence appears to be lower with robot-administered therapy. The key is that the robots are highly back-drivable (they have low mechanical impedance); large displacements may evoke small forces. Maintaining low mechanical impedance ensures gentleness—the robot never generates large forces, however far the patient's motion deviates from nominal.

WHAT CHALLENGES REMAIN?

Despite the success of upper-extremity robot-aided therapy, much remains to be done. Most important is the application of robot technology to lower-extremity disorders. Some encouraging results have been reported, but robotic lower-extremity therapy has overall been less successful than its human-administered counterpart. The Veteran's Administration strongly recommended against it, while the American Heart Association described it as "still in its infancy"[1,2].

But lower-extremity robot-aided neuro-rehabilitation ought to work—the same mechanisms of neural plasticity in response to high-intensity movement experience should operate. The problem does not lie in the several robots that have been developed; many are elegant examples of mechatronic design. Instead, the challenge lies in our collective ignorance of how unimpaired human locomotion is controlled, and our even deeper ignorance of how it may be recovered after neurological injury.

Underlying the success of upper-extremity robot-aided therapy is a quantitative knowledge of how humans coordinate and control their upper extremities. Decades of study have shown that unimpaired upper-extremity movements are primarily controlled by first specifying the kinematics of hand motion. Exposure to visual distortions or perturbing forces (including Coriolis accelerations) evokes a rapid adaptation that largely restores the unperturbed hand motion, showing that joint actions and muscle forces are subordinated to the kinematic specification of hand motion. Independent of movement duration and any load carried, that kinematic specification is well-approximated as the smoothest movement subject to task constraints (i.e. acquiring a target). This is precisely the specification at the core of the successful robot-aided therapy described above.

A corresponding quantitative knowledge of unimpaired human locomotion has yet to emerge. One reason is that humans are exceptional. For excellent reasons, almost all of more than a century of neuroscience research into the control of locomotion has been based on animal studies. While that research has provided deep insight about the evolution of the nervous system, its relevance to human locomotion is unclear. In addition to the more obvious factors that make humans exceptional (vastly more elaborated cerebral cortex, superior tool use, language, laughter) there are several factors specific to locomotion. While other mammals can walk upright on two legs, humans are the only mammals to do so preferentially. We walk plantigrade (foot flat on the ground during the stance phase) whereas other mammals walk digitigrade (on their toes). We walk with much straighter legs than our nearest cousins, chimpanzees and apes. As a result, mechanisms known to play a prominent role in mammalian locomotion may not apply to humans.

For example, neural networks capable of self-sustaining oscillation, known as central pattern generators (CPGs), contribute to the locomotion of several species, and coordinated rhythmic locomotion is preserved even after the cerebral hemispheres of the brain are surgically disconnected. However, there is very little evidence of a CPG in humans, and none so far in the context of upright walking. It may be that locomotor CPGs have been largely suppressed in humans, replaced by more direct control from the vastly-enlarged cerebral hemispheres.

This is important because most robot designs for lower-extremity therapy are based on imposing rhythmic patterns of lower-limb movement. Steady walking is clearly rhythmic but we also make discrete steps and smoothly integrate them with other actions such as throwing, at which humans are again exceptional. Recent studies of humans learning to compensate for visual distortion have shown that practice based on discrete movements leads to rapid learning that transfers well to rhythmic execution of the same movements. In contrast, rhythmic practice leads to slower learning and, more important, does not transfer to discrete execution of the same movement. Thus the emphasis on rhythmic motion in lower-extremity robot-aided neuro-rehabilitation may account for its lack of success.

PROSPECT

This is where the synergy between biology and engineering can be most productive. In the past few years, major advances in robotic locomotion have been achieved, including that of humanoid bipeds. While human locomotion may be controlled entirely differently, robotic research clearly identifies the major challenges of biped locomotion.

Those challenges—for example, rapid foot-placement—may prove to be effective targets for robot-aided locomotion therapy. Conversely, the emergence in the past few years of exoskeletal assistive technologies may provide the means to deliver this kind of treatment. At the same time, these technologies, which can interact with humans in a realistic context of upright locomotion, may enable critical experiments to establish how unimpaired human locomotion is controlled and—most important—how it may be restored after injury. ■

REFERENCES

1 E. L. Miller, L. Murray, L. Richards, R. D. Zorowitz, T. Bakas, P. Clarck, and S. A. Billinger, "The Comprehensive Overview of Nursing and Interdisciplinary Rehabilitation Care of the Stroke Patient: A Scientific Statement from the American Heart Association," *Stroke*, vol. 41, pp. 2402-2448, 2010.

2 "VA/DoD Clinical Practice Guideline for the Management of Stroke Rehabilitation," D. o. V. Affairs and D. o. Defense, Eds., 2.0 ed: The Management of Stroke Rehabilitation Working Group, 2010.

3 T. H. Wagner, A. C. Lo, P. Peduzzi, D. M. Bravata, G. D. Huang, H. I. Krebs, R. J. Ringer, D. G. Federman, L. G. Richards, J. K. Haselkorn, G. F. Wittenberg, B. T. Volpe, C. T. Bever, P. W. Duncan, A. Siroka, and P. D. Guarino, "An Economic Analysis of Robot-Assisted Therapy for Long-Term Upper-Limb Impairment After Stroke," *Stroke*, vol. 42, 2011.

ACKNOWLEDGEMENTS

The work reported here is the product of many students and colleagues supported by public funding and private foundations, all too numerous to list in detail.

UPPER EXTREMITY EXOSKELETONS

BY FABRIZIO SERGI, AMY BLANK, AND MARCIA O'MALLEY DEPARTMENT OF MECHANICAL ENGINEERING, RICE UNIVERSITY

Neurological injuries, including stroke and spinal cord injury, typically result in significant motor impairments. These impairments negatively impact an individual's movement coordination, in turn affecting their ability to function independently. It is well understood that intensive motor rehabilitation is necessary to restore functional use of the impaired limbs. For example, recent research in stroke rehabilitation has emphasized a need for more effective therapy than the current standard of care. A key motivation for effective therapy is to restore stroke survivors' independence and reduce the cost of therapy and care, with one objective being the restoration of arm functions so that individuals can again perform normal activities of daily living.

Intensively repetitous motion training has proven to restore some motor function after neurological injuries. This training is often labor-intensive and costly. By enabling therapists to train their patients intensively through consistent, repeatable movements, robotic rehabilitation systems offer a cost-effective solution requiring less labor and effort. These systems have demonstrated therapy outcomes comparable to those of intensive training without robotic aid. This means that it is possible to reduce the amount of labor for the therapist without sacrificing therapy effectiveness. Given the potential for robotics to positively affect the delivery of rehabilitation, researchers have focused efforts to optimize rehabilitation through the development of hardware and control algorithms.

The design of upper limb robotic therapy devices has been a topic of research for over two decades. Early devices were end-effector based, and guided the motion of a patient's hand to desired positions. These devices focused on rehabilitation of elbow and shoulder movement, typically immobilizing the patient's wrist to ensure that the desired arm motions were produced. Hardware and software designs emphasized the safety of the robotic devices, using control methods specifically designed to ensure safe interaction forces between the user and the device. Later devices aimed to expand the capabilities of robotic therapy devices by targeting the wrist and hand as well. However, when the end-effector based device targets many degrees of freedom, the redundancy of the human arm makes it possible for patients to compensate for impaired motion of one joint by using a different set of joints to complete a given task (for example, compensating for impairment in the wrist with extra shoulder and elbow motion). Therefore, exoskeleton type devices have been developed to isolate the motion of individual joints. These devices tend to have higher complexity and reduced range of motion as compared to endpoint manipulators, but they target more selectively the desired joint(s), and they enable more precise data collection about the motion of the patient's limb. Recent designs have focused on systems that match the full range of motion of the targeted joints, aiming towards actuated systems that have both high torque output, to assist patients with muscle tone, and low intrinsic impedance, to minimally perturb independent arm movements. Satisfying all of these requirements while simultaneously maintaining a high priority on patient safety is still an active area of research.

Recently, the focus of robotic therapy research has shifted towards improving treatment methods. It has long been known that motor learning is more effective if the learner is actively engaged in the learning process. This general feature of motor learning holds true in stroke and spinal cord injury therapy as well. Active

FOR ROBOT-AIDED REHABILITATION

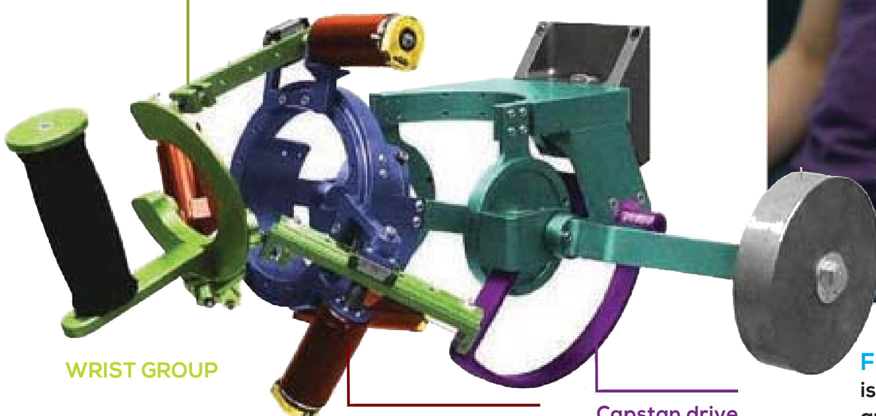


FIGURE 1 The MAHI EXO-II robotic exoskeleton is designed for rehabilitation of the elbow, forearm, and wrist after stroke or spinal cord injury.

therapy, in which the patient is actually attempting to move his or her own arm, results in greater improvements to motor function than passive therapy. Therefore, robotic therapy efforts are moving towards systems that encourage active patient participation by continually challenging the patient to the edge of his or her abilities.

One example of promoting more active engagement is the notion that the rehabilitation robot should change its behavior and physical interactions with the user based on real-time assessment of patient capability. Adaptive robotic training protocols called "assist-as-needed" algorithms focus on providing the minimal amount of robotic assistance necessary for a patient to complete a movement, thus requiring significant effort from the patient. These algorithms range from simple controllers designed to gently guide the patient's hand along a particular path, to more complex, interactive algorithms that estimate the current ability of the patient and apply just enough assistive force for the patient to complete the desired movement.

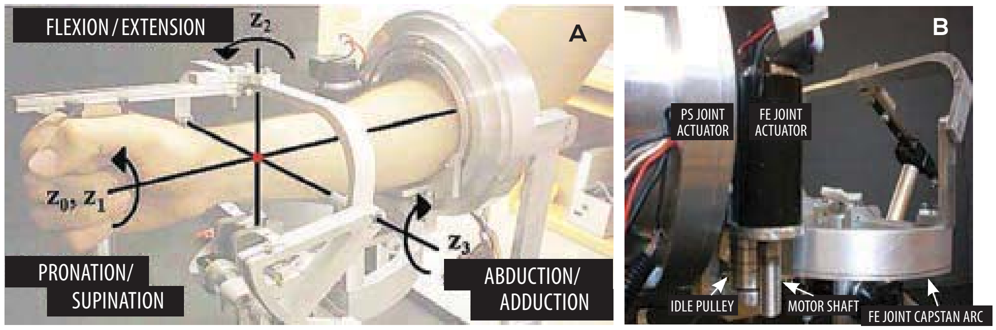
CASE STUDIES IN THE DESIGN OF UPPER EXTREMITY EXOSKELETONS

As an example of exoskeleton type upper limb rehabilitation robot systems offering adaptive assist-as-needed control, we consider the MAHI EXO-II and the RiceWrist-S, two upper limb exoskeletons for rehabilitation after neurological injury developed in the Mechatronic and Haptic Interfaces (MAHI) Laboratory at Rice University.

The MAHI EXO-II[1], shown in **Figure 1**, is an exoskeleton with four active DOF, including elbow flexion-extension (F/E), forearm pronation-supination (P/S), wrist F/E and radial-ulnar (R/U) deviation, and one passive DOF (shoulder abduction and adduction for the user's comfort). The basic kinematic structure of the wrist portion of the exoskeleton is a 3-revolute-prismatic-spherical (RPS) mechanism with additional degrees of freedom (both active and passive) for the more proximal joints of the upper limb. The elbow DOF consists of a revolute joint that is actuated by a brushed motor attached via nylon coated cable to a capstan arc. The forearm DOF also consists of a revolute joint actuated by a DC motor and cable drive.

Figure 2 shows the RiceWrist-S—an improvement of the design of the wrist module of the MAHI EXO-II, recently presented in reference 2. This design uses a serial, spherical mechanism with cable-drive actuation to address limitations of the parallel mechanism design of the MAHI EXO-II wrist module, namely limited range of motion and torque output capabilities in wrist

FIGURE 2 The RiceWrist-S. (A) Schematic of the anatomical axes of the wrist joint. (B) Cable routing mechanism for the RU joint: power is transferred from the motor shaft to the transmission rod via a steel cable. The transmission rod drives the RU joint capstan arc that is coupled with the handle support. (C) Cable routing mechanism for the FE joint: an idle pulley is employed to transfer actuation to the FE joint capstan arc via a steel cable



flexion/extension and radial/ulnar deviation. The design achieves the goals of 1) covering the complete workspace of the human wrist, 2) providing high torque output that enables both assistance and resistance training, and 3) introducing minimal friction, gravitational and inertial loading in the haptic display of forces to the user. To minimize reflected gravitational and inertial loading and provide acceptable torque output, DC motors are located remotely and connected to the respective output shaft through aluminum capstan arcs. The system also features a customized force sensing handle, used for assessment of grip force before and after the therapy session.

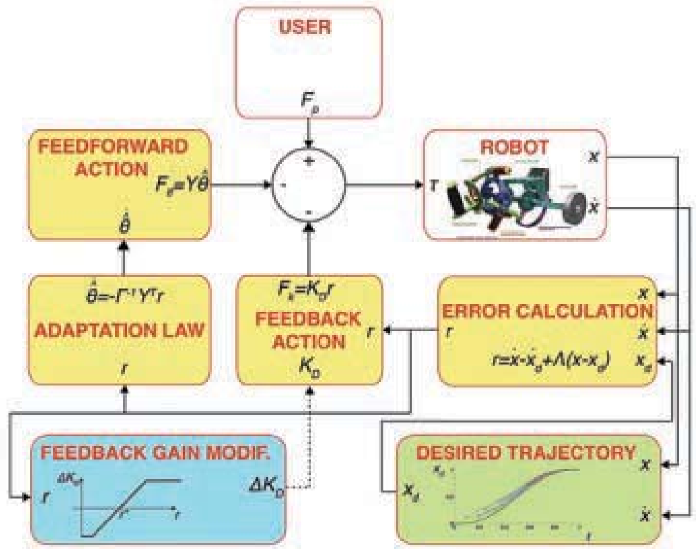


FIGURE 3 AAN controller block diagram. Blocks used for the adaptive controller are with a yellow background, while blocks introduced for the rehabilitation robotics application are shown in blue and green. The dashed line represents a non-continuous transfer of signals (the feedback gain is changed only between different tasks).

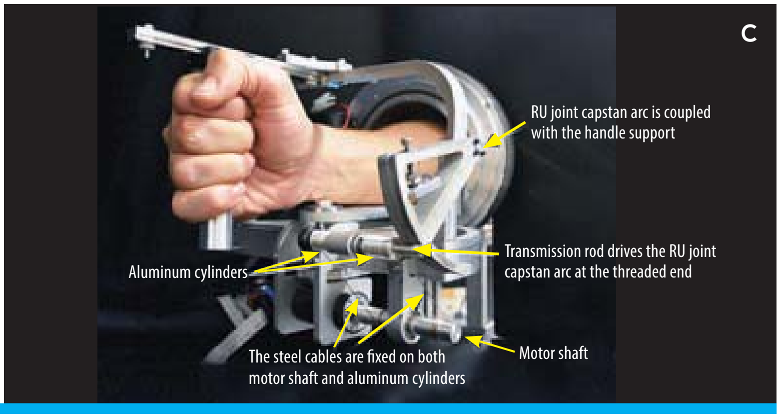
DYNAMIC CHARACTERIZATION OF REHABILITATION ROBOTS

Before any clinical implementation can take place, a thorough analysis of a robot's performance is necessary to validate it as a suitable platform for rehabilitation. The MAHI EXO-II and RiceWrist-S have capabilities comparable to other state-of-the-art serial wrist exoskeletons[3]. In comparison to the RiceWrist-S, the parallel mechanism of the MAHI EXO-II offers lower inertia, viscous coefficient, and static friction, but has reduced torque output and workspace. Both devices offer favorable static friction characteristics, both in magnitude and as a percentage of maximum continuous torque output, and a relatively constant magnitude of friction throughout the workspace enables effective compensation via feed-forward techniques. Both the inertial and viscous friction characteristics of the devices are suitable for administering high quality therapy; however, future designs would benefit from the use of advanced composites in the distal elements of the exoskeleton, along with a less inertial method for elbow DOF gravity compensation. Closed-loop bandwidth tests showed that the devices have capabilities to match healthy human movement.

Table 1 summarizes the range of motion and torque requirements for activities of daily living (ADL). Where the workspaces of our devices exceed the necessary ranges, we use redundant software and hardware stops to ensure the safety of the patient. We present the experimentally determined performance characteristics of the MAHI EXO-II and RiceWrist-S in **Table 2**, including static friction, inertia, viscous friction, and closed-loop position bandwidth. Note that the torque values listed are the maximum torque values.

	RANGE OF MOTION (*deg*)			TORQUE (*Nm*)		
Joint	ADL	ME-II	RW-S	ADL	ME-II	RW-S
Elbow F/E	150	90	—	3.5	7.35	—
Forearm P/S	150	180	180	0.06	2.75	1.69
Wrist F/E	115	65	130	0.35	1.45	3.37
Wrist R/U	70	63	75	0.35	1.45	2.11

TABLE 1 Range of motion and torque characteristics of the MAHI EXO-II and RiceWrist-S



SUBJECT ADAPTIVE, ERROR TOLERANT THERAPY

A crucial area of rehabilitation robotics involves the definition of a therapeutic protocol, capable of maximizing recovery and promoting neural plasticity. Here, "protocol" refers to the combination of movement type, visual interface, number of repetitions, sequence, number and type of joints addressed and, most important, the mechanical action applied by the robot. In this regard, preliminary evidence gathered to date (primarily for stroke rehabilitation) demonstrates that maximum therapeutic benefit is obtained when the implemented control algorithms promote the participant's active engagement in their therapy. Addressing these needs, we have contributed to the development of controllers that enable the so-called assist-as-needed (AAN) paradigm to be used for robot-aided rehabilitation therapy[4].

The main novelty of our implementation of AAN control is the resulting ultimately bounded stability property that allows errors within a known bounded region, as opposed to asymptotic stability, which corresponds to errors approaching zero. We aim to obtain this global property motivated by studies of human motor control that show that error is likely to be a driving signal for motor learning. Through this scheme, we do not provide assistance to minimize errors, but rather we tolerate error and manipulate the error bound in a performance-adaptive way. The developed controller, whose block diagram is depicted in **Figure 3**, consists of three main components: i) an adaptive controller based assistance scheme, ii) a performance-based feedback gain modification algorithm, and iii) an online trajectory recalculation.

The control action is given by:

$$F_r = F_{ff} - K_D r = \hat{G}(x) - \hat{F}_P(x) - K_D r,$$

where $\hat{G}$ is the estimate of the gravitational term, $\hat{F}_P$ is the estimate of interaction forces, K_D is a feedback gain matrix, and $r = \dot{x} - \dot{x}_d + \Lambda(x - x_d)$ is the error term, calculated through the combination of position and velocity errors. Through the assumption of linear parameterization of the feedforward contribution, we define:

$$F_{ff} = Y\hat{\theta}$$

where Y is a regressor matrix containing known functions of the state x, and $\hat{\theta}$ is a vector that contains the parameter estimates. To model the feedforward contribution, we use the superposition of Gaussian radial basis functions with amplitude θ, evenly distributed in the n-dimensional robot workspace. Through the use of the adaptation law $\dot{\hat{\theta}} = -\Gamma^{-1} Y^T r$, we could demonstrate that the controller is uniformly ultimately bounded, i.e. the error is guaranteed to stay within a certain bound that can be modulated through proper selection of the feedback gain. The other blocks exploit this particular feature of our control approach.

In particular, the feedback gain modification algorithm analyzes performance in the previous tasks, and changes the feedback gain for the next task by comparing the error in the observed movement profiles with the variability of healthy subjects' movements during unperturbed movements. Instead of increasing the feedback gain until the error is minimized, we decrease the feedback gain until the measured error is within an acceptable range defined as repeatability error in similar tasks executed by healthy subjects (r^* variable in the block diagram). This algorithm creates a continuous and dynamic challenge to the user, reducing the amount of robotic assistance when movements are characterized by below-physiologic error levels. When instead the assistance is excessively decreased, resulting in the user lagging behind the desired trajectory, the feedback gain is increased to provide additional support.

As a final step in the formulation of our subject-adaptive therapeutic protocol, we include a performance-adaptive desired trajectory generation algorithm. The algorithm is used to avoid the transfer of forces that resist the subject's movement, in the case when the subject is actually performing better than the previously defined nominal trajectory. We implement an explicit on-line recalculation routine that guarantees that the desired trajectory is both continuous and time-differentiable, and does not lag the subject's movement. Through the online trajectory recalculation algorithm, we also modulate the time allocated to complete a task if the subject was ahead of the desired trajectory in the previous task. Through the combination of the feedback gain modification algorithm and the desired trajectory definition and recalculation algorithms, the subject is continuously challenged to perform more repetitions, increasing his effort in the therapeutic protocol. Clinical evaluation of this protocol is currently underway in Houston, in collaboration with our clinical partners at TIRR-Memorial Hermann Hospital and UTHealth.

	STATIC FRICTION (*Nm*)		INERTIA (*kgm*^{2})		VISCOUS FRICTION (*Nms/rad*)		CLOSED-LOOP POSITION BW (*Hz*)	
Joint	**ME-II**	**RW-S**	**ME-II**	**RW-S**	**ME-II**	**RW-S**	**ME-II**	**RW-S**
Elbow F/E	0.95	—	0.27	—	0.12	—	2.8	—
Forearm P/S	0.14	0.22	0.026	0.026	0.017	0.43	4.2	3.5
Wrist F/E	0.11	0.20	0.002	0.012	0.028	0.085	13.3	6.0
Wrist R/U	0.11	0.21	0.003	0.005	0.023	0.14	10.6	8.3

TABLE 2 **Dynamic characteristics of the MAHI EXO-II and RiceWrist-S**

DEMONSTRATING EFFICACY

The clinical evaluation of our exoskeleton-based upper limb rehabilitation robots has been conducted primarily with individuals with incomplete spinal cord injury (SCI). We first evaluated our MAHI EXO-II wrist module for rehabilitation of the upper limbs (UL) of two tetraplegic persons with incomplete SCI[5]. Two pilot experiments were conducted. First, we demonstrated that we could administer treatment to the left UL of a tetraplegic subject during seven therapy sessions with the device. The subject's feedback and the investigator's observations were used to enhance the robotic device and the corresponding graphical interface. Then, a second tetraplegic subject underwent ten three-hour training sessions administered by a physical therapist. Efficacy of the treatment was evaluated using both clinical assessments often conducted by physical therapists in a rehabilitation setting and robotic measures of motor impairment that quantify the characteristics of movements using data collected from the exoskeleton during movement execution with the device unpowered and backdriven by the subject. At the conclusion of this pilot study with our exoskeleton, the subject was able to more quickly complete basic activities of daily living with the treated limb. The smoothness of the individual's unassisted movements in each degree of freedom was also evaluated pre- and post-therapy and showed significant improvements.

Based on these promising pilot results, we conducted a more extensive case study with the full MAHI EXO-II device[6], with robotic training provided to both upper limbs of a participant with chronic incomplete SCI. For this participant, the right UL was more affected, such that she was unable to initiate or sustain independent movement. The left UL was less affected by the injury, and as a result, she was able to initiate movements independently. We observed gains in performance only for the more engaging control mode (only used with the less affected limb), and these findings are in agreement with the literature noting the need for patient engagement and simultaneous intent of movement with sensorimotor feedback in order to realize treatment gains. The extension of this study to a population of 10 SCI survivors has recently concluded, with results currently undergoing analysis for publication.

We have also validated the RiceWrist-S as a tool to deliver robotic rehabilitation therapy through a case study with a subject affected by chronic incomplete (AIS level C) SCI at the C3-5 level[2]. The subject, a 45-year-old male, participated in ten sessions of robot-assisted arm training over twenty days, approximately four times per week. At each session, the subject's movements were evaluated with the robot programmed to apply no forces, but only measure the subject's visually cued, point-to-point movements. After evaluation, the subject was visually cued to execute the same movements, with the robot providing active resistance, by means of a velocity-dependent resistive force field. The analysis of robotic data measured during the evaluation sessions supports the hypothesis that robotic training increased movement smoothness, as assessed through two metrics, the Movement-Arrest-Period-Ratio (MAPR), which quantifies the amount of time movements are above a threshold velocity, and the Normalized Sum of Jerk (NSOJ), which directly assesses the jerk of the executed movements. Although

ABOUT THE AUTHORS

Fabrizio Sergi received his Ph.D. degree in biomedical engineering from Università Campus Bio-Medico di Roma, in Rome, Italy, and is currently a postdoctoral research scientist in the mechanical engineering department at Rice University. His research interests span multiple aspects of human-robot interaction, including the design and subject-adaptive control of high-performance robots for rehabilitation and human augmentation and the use of robots as scientific tools to investigate motor learning. He is a member of the American Society of Mechanical Engineers.

Amy Blank received a Ph.D. in mechanical engineering from the Johns Hopkins University in 2012. She is currently a postdoctoral research associate at Rice University in the department of mechanical engineering. Her research interests are in theory and application for design, modeling, and control of robotic manipulators and human-robot interaction. Specific areas of interest include upper-limb prosthetics and rehabilitation, biologically inspired robotic sensing and control strategies, variable-impedance robot control, and user feedback for prosthesis control and teleoperation.

Marcia O'Malley received her mechanical engineering Ph.D. in 2001 from Vanderbilt University. She is an associate professor of mechanical engineering and computer science at Rice University. In addition, she is director of rehabilitation engineering at TIRR-Memorial Hermann Hospital. Her research addresses the issues that arise when humans physically interact with robotic systems, with a focus on training and rehabilitation in virtual environments. In 2008, she received the George R. Brown Award for Superior Teaching at Rice University. She is a Fellow of the American Society of Mechanical Engineers.

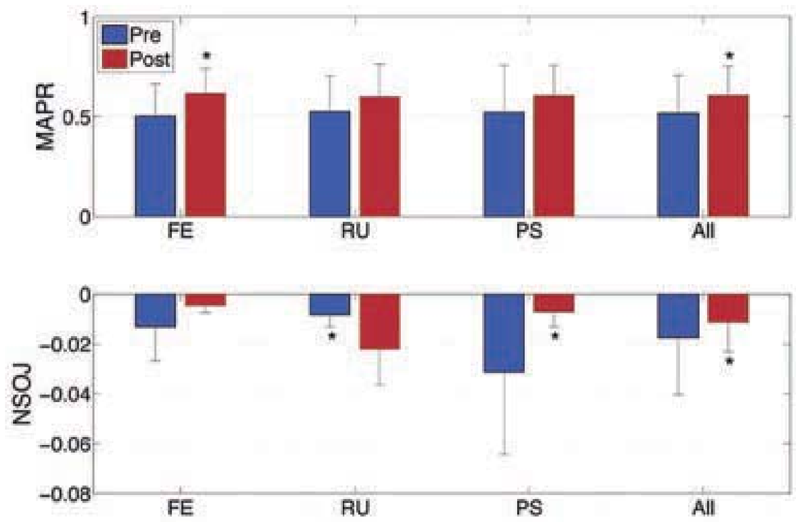


FIGURE 4 Bar plot describing the two measures of smoothness computed during the first (Pre) and last (Post) session of therapy with the RiceWrist-S, representing mean and standard deviation of the movements for each degree of freedom during evaluation. Asterisks indicate statistical significance ($p<0.05$).

not every DOF-specific comparison showed a statistically significant difference, the pre-therapy vs. post-therapy comparison involving the combination of movements in all directions demonstrated a statistically significant increase of smoothness of subject's reaching movements, as shown in **Figure 4**.

NEXT STEPS

Robotic exoskeletons designed for rehabilitation of the upper limb after neurological injury aim to promote neural plasticity and recovery of motor coordination through high intensity and high repetition of reaching movements. The design of these devices requires consideration of the therapeutic application in terms of range of motion, torque requirements, and dynamic performance that ensures safe patient-robot interactions. Further, the development of these systems must consider the control algorithms that govern the nature of the patient-robot interaction. The importance of engaging the patient in therapy has been clearly demonstrated through studies of both active and passive movements assisted by robotic systems, and therefore recent research has focused on the ability of robotic systems to engage the patient using assist-as-needed strategies. Assist-as-needed strategies have moved towards adaptive controllers that estimate patient effort and impairment in real time based on movement data collected by the robot, thus changing the level of assistance provided even during a single movement. Though feasibility and positive functional gains have been shown for many of these methods that encourage patient engagement, it is still unclear which methods are most appropriate for different situations and levels of patient impairment. While small clinical studies have demonstrated the viability of robotic rehabilitation after neurological injury, carefully controlled, large-scale clinical studies are needed to compare available treatment methods across patient populations and to determine how the efficacy of the methods depends on the characteristics of specific patients. The results of such studies will enable therapists to optimize treatment methods for restoring upper-limb function after neurological injury in patients with a variety of needs and abilities. ■

REFERENCES

1 Pehlivan, A.U., O. Celik, and M.K. O'Malley. "Mechanical Design of a Distal Arm Exoskeleton for Stroke and Spinal Cord Injury Rehabilitation," *Proceedings of the IEEE International Conference on Rehabilitation Robotics (ICORR)*, Zurich, Switzerland, June 29-July 1, pp. 633-637, 2011.

2 Pehlivan, A.U., F. Sergi, A. Erwin, N. Yozbatiran, G. Francisco, and M.K. O'Malley. "Design and Validation of the RiceWrist-S Exoskeleton for Robotic Rehabilitation after Incomplete Spinal Cord Injury," accepted for publication, *Robotica*, CJO 2014, DOI:1017/S0263574714001490.

3 Krebs, H., B.T. Volpe, D. Williams, J. Celestino, S.K. Charles, D. Lynch, and N. Hogan. "Robot-aided neurorehabilitation: a robot for wrist rehabilitation," *IEEE Trans. on Neural Systems and Rehabilitation Engineering*, 15(3), pp. 327–35, 2007.

4 Pehlivan, A.U., F. Sergi, and M.K. O'Malley. "A subject-adaptive controller for wrist robotic rehabiltation," *IEEE/ASME Transactions on Mechatronics*, DOI: 10.1109/TMECH.2014.2340697.

5 Kadivar, Z., J.L. Sullivan, D.P. Eng, A.U. Pehlivan, M.K. O'Malley, N. Yozbatiran, and G.E. Francisco. "RiceWrist Robotic Device for Upper Limb Training: Feasibility Study and Case Report of Two Tetraplegic Persons with Spinal Cord Injury," *Intl. Journal of Biological Engineering*, 2(4): 27-38, 2012.

6 Yozbatiran, N., J. Berliner, M.K. O'Malley, A.U. Pehlivan, Z. Kadivar, C. Boake, and G.E. Francisco. "Robotic training and clinical assessment of upper extremity movements after spinal cord injury; a single case report," *Journal of Rehabilitation Medicine*, 44:186-188, 2012.

ACKNOWLEDGMENTS

We wish to acknowledge the invaluable input of our collaborators **Dr. Gerard Francisco** and **Dr. Nuray Yozbatiran**, and contributions of the students and post-docs who have been involved in this work, **James French, Zahra Kadivar, Ali Utku Pehlivan**, and **Chad Rose**. This research was supported in part by Mission Connect, a project of the TIRR Foundation, NSF, and NIH.

BY BRIAN E. LAWSON AND MICHAEL GOLDFARB
DEPARTMENT OF MECHANICAL ENGINEERING, VANDERBILT UNIVERSITY

IMPEDANCE & ADMITTANCE-BASED COORDINATION CONTROL FOR ROBOTIC LOWER LIMB

Robotic prostheses have been emerging in the engineering literature recently. Such prostheses have the ability to better reproduce the variety of behaviors exhibited by the healthy limb during locomotion [1-5], relative to passive prostheses. Powered prostheses require a controller to coordinate the movement of the prosthesis with that of the user; accordingly, various control approaches have been recently described [6-12]. Such controllers should provide to the user safe, intuitive, and well-coordinated interaction with the prosthesis. This article presents and compares two different control systems for a powered knee and ankle prosthesis for transfemoral amputees that were constructed to provide such functionality (i.e., to enable power delivery from the prosthesis in a manner that is safe, natural, and coordinated with the motion of the user). The first controller utilizes only impedance-like behaviors, while the

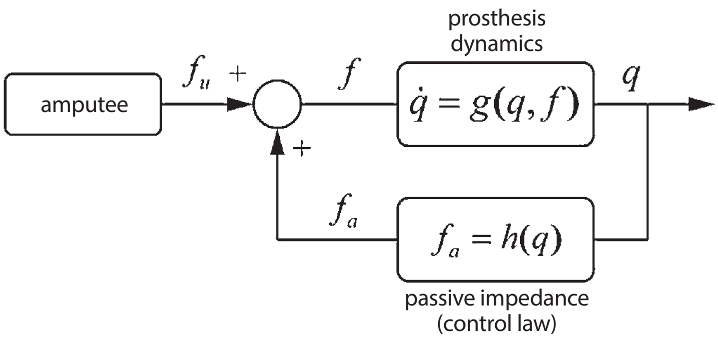


FIGURE 1 Amputee/prosthesis dynamic system with passive impedance control law.

STRATEGIES PROSTHESES

second utilizes both impedance-like and admittance-like behaviors in a hybrid approach. The controllers were implemented on a powered knee and ankle prosthesis and tested in walking trials by a transfemoral amputee. Data from these trials indicates that both controllers achieve comparable performance with respect to healthy subject data, despite some substantial structural differences between the two.

A PIECEWISE-PASSIVE IMPEDANCE CONTROL FRAMEWORK

A control structure for providing local passivity

Prosthesis motion can be decomposed into two components: movement associated with the internal configuration of the prosthesis, and movement of the prosthesis through space. The former can be described by the prosthesis joint angles, and the latter by joint angles combined with a set of generalized coordinates locating the center of mass and principal axes of the prosthesis relative to an inertial reference frame. For the control problem considered here, the control of movement of the prosthesis through space is assumed to be primarily governed by the user, in the same manner that a user would control movement of a passive prosthesis. As such, the control framework described here considers only the dynamics associated with the internal configuration of the prosthesis, hereafter referred to as the prosthesis dynamics (i.e., the dynamics described by the set of generalized coordinates consisting of prosthesis joint angles).

Two distinct sources of power can impart energy to the prosthesis: the amputee and the prosthesis actuators. The generalized forces associated with the user, f_u, are typically imparted at the mechanical interface between the user and prosthesis, and/or at the interface between the foot and ground. The generalized forces associated with the actuators, f_a, are the set of torques imparted by each joint actuator on the respective joints of the prosthesis. If the vector f describes the union of user and actuator generalized forces, the state equations describing the prosthesis dynamics can be expressed as

$$\dot{q} = g(q, f) \qquad (1)$$

where q is the state vector corresponding to the internal configuration of the prosthesis. The set of generalized forces associated with the user, f_u , cannot be controlled by the prosthesis control system, and so it is regarded as a vector of exogenous inputs. The set of generalized forces associated with the actuators, f_a, however, is governed by the prosthesis control system, and can be constructed as

$$f_a = h(q) \qquad (2)$$

such that the function $h(\cdot)$ ensures strict passivity between the state inputs and the torque outputs. In particular, considering an actuated joint on the prosthesis, let the actuator torque be given by τ and the associated joint angle and angular velocity by θ and $\dot{\theta}$, respectively. The prosthesis will exhibit passive behavior if the actuator torque output is controlled according to

$$\tau = z(\theta, \dot{\theta}) \qquad (3)$$

where $z(\cdot)$ is a diagonal, odd function of its arguments. Although a number of functions will satisfy this requirement, one simple form is the polynomial

$$\tau = \sum_{n=1}^{N} k_{2n-1}(\theta - \theta_0)^{2n-1} - \sum_{m=1}^{M} b_{2n-1}\dot{\theta}^{2n-1} \quad (4)$$

where N and M define the highest order of each odd polynomial, and k_n and b_m are coefficients associated with each of the polynomial terms. In the case of a first-order polynomial, the actuator torque simplifies to

$$\tau = k(\theta - \theta_0) + b\dot{\theta} \quad (5)$$

Defining the prosthesis controller in this form (i.e., a strictly passive impedance function), the system dynamics can be reformulated as shown in **Figure 1**. Since $h(\cdot)$ is energetically passive by selection, and since the dynamics described by $g(\cdot)$ are also passive, the system is comprised of two passive interconnected systems, and thus the closed loop is also passive (i.e., as described by the passivity theorem). As a result, the feedback-controlled prosthesis can be reduced to a single passive system that interacts with the user in a manner similar to a passive prosthesis. Among other properties, this characteristic of passivity ensures that the powered prosthesis is stable, and in the absence of excitation from the user, the prosthesis will come to rest in a known state. The control structure therefore possesses inherent characteristics that foster safe human-robot interaction.

Despite these desirable properties, a control structure that maintains strict passivity defeats the point of a powered prosthesis, which (like the healthy neuromuscular system) should be capable of power generation (in addition to storage and dissipation). In order to provide net power generation, the prosthesis control structure is modified such that (exogenous) input generated by the user is used to switch $h(\cdot)$ between successive passive behaviors. Such an approach can be implemented as a finite state machine (FSM), where state transitions are selected based upon biomechanical events. With mindful selection of state transitions, the user must be actively engaged in a given activity in order to maintain the succession of switching between passive behaviors. In this manner, the powered prosthesis is globally active (i.e., is able to generate net power over time), but locally passive (in the absence of excitation from the user, switching will not occur, and the prosthesis will come to rest).

Emulating biomechanical functionality of the healthy limb

The previously presented control structure was described without regard to its ability to emulate the biomechanical functionality of the healthy limb. Consider the example of level ground walking. **Figure 2** shows the (averaged) knee joint angle, angular velocity, and torque for a group of healthy subjects during normal level walking. Within the context of the passive control structure, the biomechanical behavior of the joints is characterized by the relationship between the joint motion (i.e., angle and angular velocity) input and the joint torque output. Therefore, the proposed control structure should emulate the biomechanical behavior of the healthy joint if a passive function of the general form given in Reference 3 can be constructed such that, given the (healthy) angle and angular velocity profiles shown in **Figure 2** as input, the function will result in the (healthy) torque profile also shown in Figure 2. Since the biomechanical behavior of the healthy joint is in general not passive, such construction will in general require the construction of $h(\cdot)$ with a series of *piecewise* passive functions. Using the data shown in Figure 2 as an example, and incorporating six linear passive functions of the form 5 with the parameters listed in **Table I** to construct $h(\cdot)$ over one period of the gait cycle, the control method will generate an approximation of healthy knee joint torque as indicated by the red circles in the torque plot. As indicated in Figure 2, the set of simple linear passive functions provides a reasonably faithful representation of healthy joint behavior. In the implementation described subsequently, the Piecewise Passive Impedance (PPI) controller is implemented as an FSM with the states as labeled in Figure 2.

A Hybrid Impedance-Admittance Control Framework

Although the PPI controller provides desirable control behavior, it also requires a potentially large number of selectable parameters. In an effort to maintain many of the desirable characteristics of the PPI controller while also reducing the number of selectable control parameters, the authors modified the control approach with a hybrid impedance-admittance

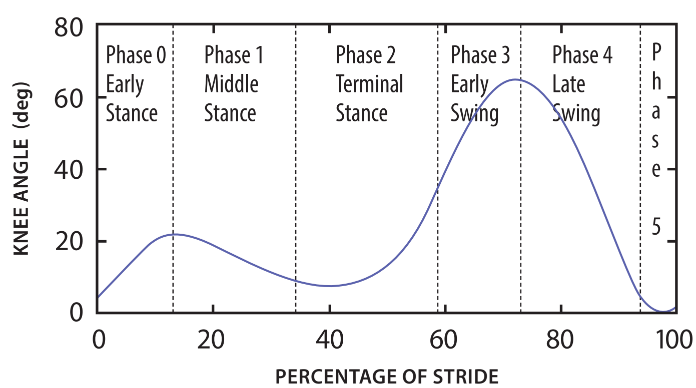


FIGURE 2 Healthy knee kinematics reprinted from Reference 2. The knee torque has been scaled for a 79 kg subject (the mass of the subject used in the subsequent experiments). The red circles overlaid on the knee torque plot indicate the torque reference that would be generated from the piecewise linear fit using parameters specified in Table I. It is clear from these data that the knee behavior is well modeled in middle and early stance, and in swing, by the impedance model, although the behavior during late stance (ankle push off) is not as well represented by the model.

FIGURE 3
A subject walking with the powered prosthesis.

TABLE 1 Knee Level Walking Parameters from Healthy Subject Data

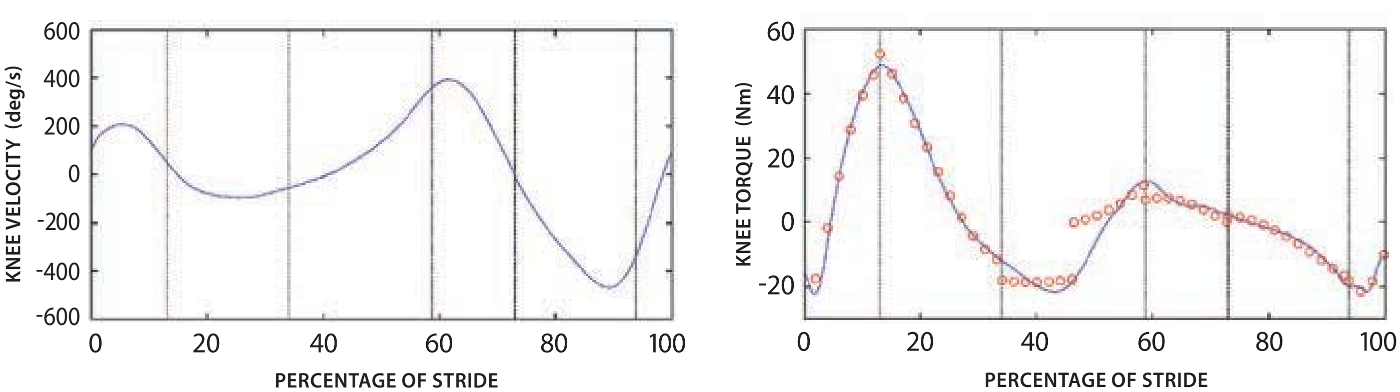
	k $\left(\frac{Nm}{deg}\right)$	b $\left(\frac{Nm\cdot s}{deg}\right)$	θ_{eq} (deg)
Early Stance	4.47	0.00	11.0
Middle Stance	4.28	0.10	10.6
Late Stance*	0.42/0.50	0.00	51.5/10.0
Early Swing	0.00	0.20	0.00
Late Swing	0.32	0.00	58.1
Pre-Landing	2.26	0.04	7.61

*** Because the knee joint is not well modeled by a single, linear impedance in this state, a sub-state has been integrated allowing a change in stiffness and equilibrium parameters once the knee passes a threshold angle.**

(HIA) approach. The HIA approach essentially incorporates the PPI control structure during the early and middle stance phases of gait, and a trajectory-tracking control approach in terminal stance and swing.

With this approach, both the passivity and naturalness aspects of the PPI controller are compromised, but neither in a substantial manner. With regard to passivity, the swing phase is a time-based trajectory, and therefore is transient and bounded by nature, so it does not substantially compromise the previously described inherent passivity of the PPI control structure. With regard to naturalness, although the trajectory control is characterized by a high joint impedance, the impedance is high during a period of interaction in which the user is relatively insensitive to the joint impedance. Specifically, the mechanical impedance interacting with the user is comprised of the internal impedance of the leg (i.e., the impedance imposed by the controller), in series with the impedance of the environment. In the stance phase, when the leg is on the ground, the impedance felt by the user is approximately the impedance of the joints of the leg (since the ground impedance is high). In the swing phase, when the leg is in the air, the impedance felt by the user is approximately the inertial impedance of the leg (since the impedance of air is essentially non-existent). Since the user is relatively insensitive to the nature of joint impedances in swing phase, implementing a high-impedance (i.e., admittance-type) trajectory-tracking controller in swing does not substantially compromise the naturalness properties of the PPI controller.

In the implementation described subsequently, the HIA controller consists of two superstates: an impedance-based state in the majority of the stance phase (early and middle stance), and an admittance-based state during terminal stance (powered push off) and swing phase. Note that the ability to change the impedance between early and middle stance is primarily used for slope walking (i.e., the two states share a single impedance in level walking).



IMPLEMENTATION, DEMONSTRATION, AND COMPARISON OF CONTROLLERS

Powered Prosthesis Prototype

The PPI and HIA controllers were each implemented on a self-contained powered prosthesis prototype previously developed by the authors. A photograph of the powered prosthesis is shown on a transfemoral amputee in **Figure 3**. Both the knee and ankle units are actuated by the combination of a brushless DC motor and a three-stage belt/chain speed reduction transmission. The knee is capable of generating a maximum torque of approximately 85 Nm, and the ankle approximately 110 Nm. The actuator output at the ankle joint is supplemented by a parallel carbon-fiber leaf spring (stiffness of 6 Nm/deg, engagement angle of 0 deg). The mass of the current prosthesis prototype, configured for a 50th percentile male, is approximately 5 kg.

Walking Trials

Each controller was implemented in the powered prosthesis prototype and tested in walking trials by a transfemoral amputee subject. Prior to the experiments, informed consent was obtained in accordance with the requirements set forth by the Vanderbilt University Institutional Review Board. For each controller, the controller parameters were tuned during treadmill walking at a self-selected treadmill speed of 0.89 m/s (2.0 mph). The control parameters corresponding to the PPI controller are given in **Table 2.** The impedance parameters for the first two phases of the HIA controller are the same as those used in the stance phases of the PPI controller. Following controller parameter selection, knee and ankle joint angle and motor current data from 20 consecutive strides were logged internally by the embedded system on the prosthesis for assessment and comparison.

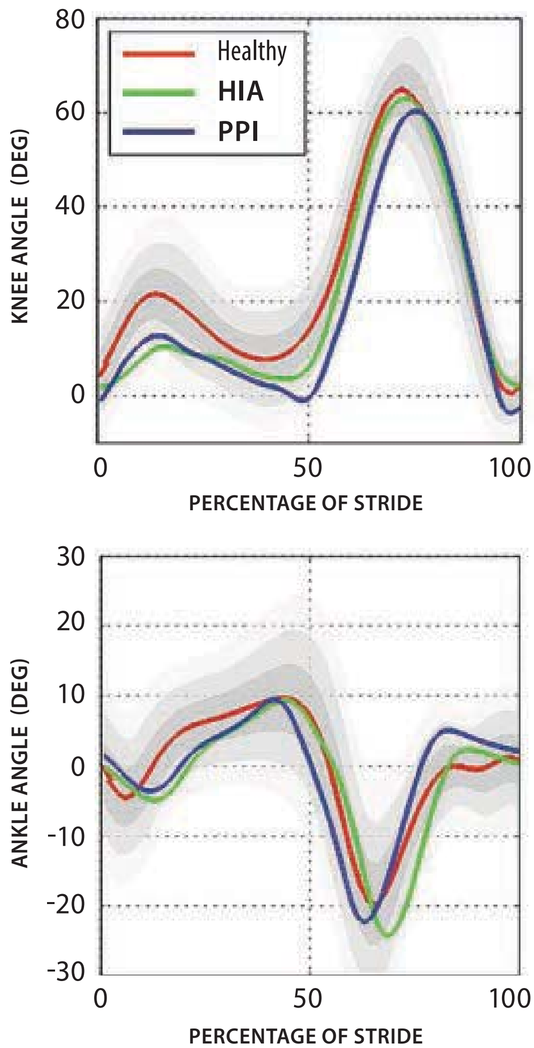


FIGURE 4
Knee and ankle kinematics for both controllers as compared to healthy subject data from Reference 2. The gray areas represent ±1, 2, and 3 standard deviations from the mean of healthy subjects.

Results and Discussion

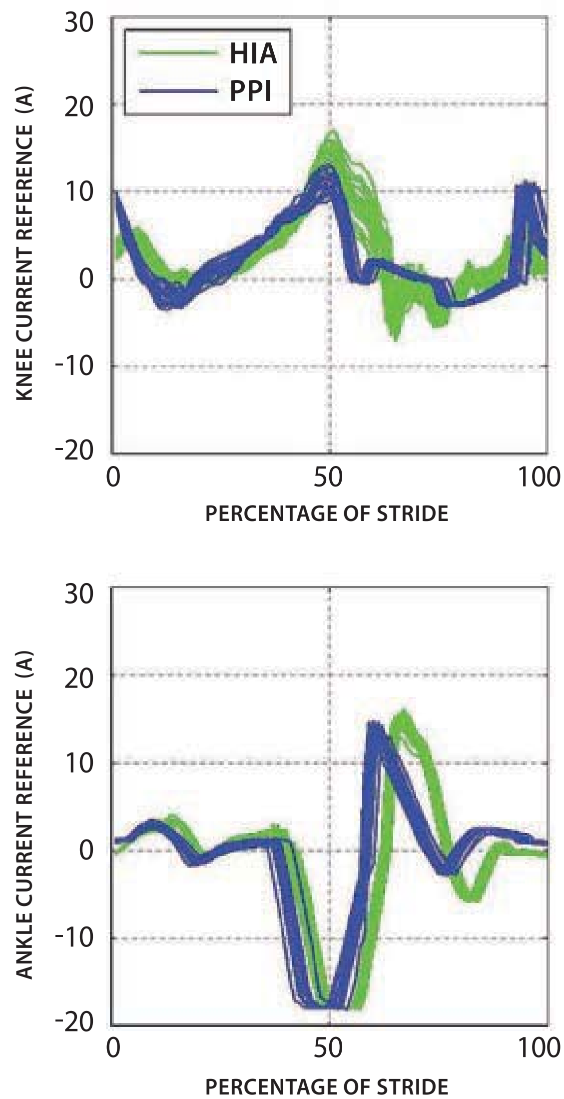
The kinematics of the prosthetic joints in the sagittal plane are plotted in **Figure 4**, along with averaged data from 19 healthy subjects. The nature of control activity is indicated by the corresponding motor current references for each joint, shown in **Figure 5**. Both controllers achieve knee and ankle kinematics that contain the salient features of healthy level ground walking. The current references in Figure 5 best illustrate the (minor) differences in the behavior of these two controllers. Because the first two phases have identical impedance parameters in both controllers, any differences in the current references in these two states are due to reactions and interactions with the user. Such differences are small, however, and they appear to be due to slightly varied timings relative to the rest of the stride. At push off, however, it is clear that the HIA controller is more active at the knee, generating a flexive torque that better resists the knee's tendency to hyperextend during the initial portion of push off.

TABLE 2
Impedance Parameters for the PPI controller

	KNEE PARAMETERS			ANKLE PARAMETERS		
	$k\left(\frac{Nm}{deg}\right)$	$b\left(\frac{Nm\cdot s}{deg}\right)$	$\theta_{eq}\,(deg)$	$k\left(\frac{Nm}{deg}\right)$	$b\left(\frac{Nm\cdot s}{deg}\right)$	$\theta_{eq}\,(deg)$
Early Stance	4.00	0.10	10.00	4.00	0.20	0.00
Middle Stance	4.00	0.10	10.00	4.00	0.20	0.00
Late Stance*	5.50/0.10	0.03	10.00	7.00	0.15	-20.00
Early Swing	0.30	0.00	45.00	3.00	0.15	0.00
Late Swing	0.30	0.00	20.00	3.00	0.15	0.00
Pre-Landing	3.00	0.15	5.00	4.00	0.15	0.00

* Because the knee joint is not well modeled by a single, linear impedance in this state, a sub-state has been integrated allowing a change in stiffness parameters once the knee passes a threshold angle.

FIGURE 5 **Knee and ankle current references for the finite state-based impedance controller and the impedance/admittance controller as functions of percentage of stride. Positive currents indicate positive motor torques, where a positive torque, should it be the net torque on a joint,**



In swing, the HIA controller generally matches healthy norms better than the PPI controller. The knee joint in the HIA controller is leading the trajectory, and so the controller behaves essentially as a damper in swing, while the PPI controller provides active torque in the form of virtual springs to generate sufficient knee flexion. Although this behavior could perhaps be altered with a different set of controller parameters for the PPI controller, it was in this case achieved inherently with the HIA controller. Finally, as one might expect, the high-gain nature of the HIA controller requires increased electrical power relative to the PPI, although for the walking trials shown, the increase was small (~5%).

Conclusion

Powered lower limb prostheses are emerging, and in theory they have the capacity to better emulate the functionality of the healthy limb. In order to be useful, such prostheses must provide biomechanical levels of torque and power. Consequently, these prostheses are powerful robots that are firmly attached to a human. It is imperative to provide a control structure that coordinates the movement of the prosthesis with the movement of the user in a safe and natural manner. The authors describe here a control structure that provides these characteristics, and a modified version of it that maintains favorable characteristics, while greatly reducing the number of required control parameters. The authors additionally showed that both controllers provide similar behavior and provide biomechanics representative of healthy walking.

COMPETING INTERESTS *B.E.L. and M.G. hold patent applications through Vanderbilt University that have been licensed to Freedom Innovations, a United States-based prosthetics manufacturer.*

REFERENCES

1 B. J. McFadyen, and D. A. Winter, "An integrated biomechanical analysis of normal stair ascent and descent," *J Biomech*, vol. 21, no. 9, pp. 733-44, 1988.

2 D. A. Winter, *The biomechanics and motor control of human gait: Normal, elderly and pathological*, Waterloo, Ontario, Canada: University of Waterloo Press, 1991.

3 R. Riener, M. Rabuffetti, and C. Frigo, "Stair ascent and descent at different inclinations," *Gait Posture*, vol. 15, no. 1, pp. 32-44, Feb. 2002.

4 A. Forner Cordero, H. F. Koopman, and F. C. van der Helm, "Multiple-step strategies to recover from stumbling perturbations," *Gait Posture*, vol. 18, no. 1, pp. 47-59, Aug. 2003.

5 A. S. McIntosh, K. T. Beatty, L. N. Dwan, and D. R. Vickers, "Gait dynamics on an inclined walkway," *J Biomech*, vol. 39, no. 13, pp. 2491-502, 2006.

6 S. Au, M. Berniker, and H. Herr, "Powered ankle-foot prosthesis to assist level-ground and stair-descent gaits," *Neural Netw*, vol. 21, pp. 654 - 666, 2008.

7 S. K. Au, J. Weber, and H. Herr, "Powered Ankle-Foot Prosthesis Improves Walking Metabolic Economy," *IEEE Transactions on Robotics*, , vol. 25, no. 1, pp. 51-66, 2009.

8 E. C. Martinez-Villalpando, and H. Herr, "Agonist-antagonist active knee prosthesis: a preliminary study in level-ground walking," *J Rehabil Res Dev*, vol. 46, no. 3, pp. 361- 73, 2009.

9 J. K. Hitt, T. G. Sugar, M. Holgate, and R. Bellman, "An Active Foot-Ankle Prosthesis With Biomechanical Energy Regeneration," *Journal of Medical Devices*, vol. 4, no. 1, Mar. 2010.

10 M. A. Holgate, A. Bohler, and T. G. Sugar, "Control algorithms for ankle robots: A reflection on the state-of-the-art and presentation of two novel algorithms," *Biomedical Robotics and Biomechatronics*, pp. 97-102, 2008.

11 C. D. Hoover, G. D. Fulk, and K. B. Fite, "Stair Ascent With a Powered Transfemoral Prosthesis Under Direct Myoelectric Control," *IEEE/ASME Trans on Mechatronics*, vol. 18, no. 3, 2013.

12 M. F. Eilenberg, H. Geyer, and H. Herr, "Control of a powered ankle-foot prosthesis based on a neuromuscular model," *IEEE Trans Neural Syst Rehabil Eng*, vol. 18, no. 2, pp. 164-73, Apr. 2010.

DESIGN OF A MINIMALLY ACTUATED MEDICAL EXOSKELETON WITH MECHANICAL SWING-PHASE GAIT GENERATION AND SIT-STAND ASSISTANCE

BY WAYNE YI-WEI TUNG,
MICHAEL MCKINLEY,
MINERVA V PILLAI, JASON REID,
AND HOMAYOON KAZEROONI
DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF CALIFORNIA BERKELEY

The AUSTIN exoskeleton (**Figure 1**) is an accessible lightweight system that enables individuals with paraplegia to walk. A single actuator per leg and a mechanical hip-knee coupler power the knee during swing phase and provides assistance for sitting and standing. The suit's design embeds gait generation into hardware, decreasing controller complexity.

In 2012, an estimated 270,000 individuals in the U.S were afflicted by spinal cord injury (SCI), according to the National Spinal Cord Injury Statistical Center (NSCISC). Forty-three percent of the estimated 12,000 new spinal cord injuries sustained each year result in paraplegia.

Because they are confined to a wheelchair, SCI patients risk developing secondary injuries and medical complications such as acute pressure ulcer development, osteoporosis, decreased range of joint motion, urinary tract infection, and impaired respiratory and cardiovascular functions [2, 3].

DEVICES TO REDUCE SECONDARY INJURIES

Passive orthoses are commonly prescribed by doctors as means of delaying the onset of secondary injuries [4]. Devices such as the knee-ankle foot orthosis (KAFO) or reciprocating gait orthoses (RGO), as shown in **Figure 2**, are designed to enable users to achieve a quasi bipedal gait by swinging one leg in front of the other using upper body strength. Although passive orthotics are available for personal ownership, studies have shown that the majority of RGO users discontinued use within 5 years due to rapid fatigue and sluggish ambulation.

FIGURE 1 Austin Exoskeleton system overview

FIGURE 2 Examples of common passive orthoses. KAFO (left) and RGO (right).

Powered Exoskeletons

In an effort to improve walking energetics, several research groups have developed powered exoskeleton systems that use actuators to assist with locomotion. **Figure 3** shows four of the most well-known powered exoskeletons today. ReWalk, eLEGS and Vanderbilt University Exoskeleton use four electric motors to power the knee and hip joint motions along the sagittal plane. The Rex exoskeleton uses ten joint actuators to power the hip, knee, and ankle [6]. The more involved actuation scheme of the Rex generates a very slow walking gait that puts the user through a series of quasi-statically balanced postures.

FIGURE 3 **Powered exoskeleton systems.**

COUPLING INSPIRED BY BIOMECHANICS

By using a bio-inspired coupling mechanism, the Austin system is able to power both the hip and knee joints using a single hip actuator. Hip-knee joint coupling refers to motion where the knee flexes simultaneously with hip flexion and extends simultaneously with hip extension. Biologically, this happens partially due to biarticular muscles. Biarticular muscles such as the hamstrings act across multiple joints to produce coupled motion. Various examples of this coupling behavior during walking, sitting, and standing are described in the literature [7–9]. To more clearly illustrate this coupling relationship, **Figure 4** shows a simulated human leg motion with a fixed hamstring length while flexing the hip.

Joint Coupling Walking Mechanics

The human gait cycle is commonly divided into stance and swing phase. Swing phase can be further divided into two phases: *swing-flexion* and *swing-extension* as illustrated in **Figure 5** [10].

PHASE I: ***Stance*** During stance, the person's foot is in contact with the ground and the leg is bearing weight. The hip goes through extension while the knee stays locked.

PHASE II: ***Swing-flexion*** At maximum hip extension, swing-flexion phase begins. In this phase, both the knee and hip flexes to achieve toe clearance.

PHASE III: ***Swing-extension*** At maximum knee flexion, swing-extension phase begins and the knee re-extends to prepare for heel strike.

Mechanical Gait Generation

Knee actuators can be replaced by a joint coupling system so that only a single actuator per leg is required to produce the three-phase gait cycle. In this system, knee motion becomes a function of hip motion and the knee has two states. In the *coupled state*, activated during swing-flexion, the knee will flex and extend with the hip, powered by a coupling mechanism that transfers power to it from the hip. During the *uncoupled state*, the knee is locked against flexion but still free to extend, allowing the knee-spring to fully extend the leg during swing-extension and provide locking during stance.

A walking gait is generated by toggling between the coupled and uncoupled states, in the following three steps (see Fig. 5).

1 During stance, the hip and knee are uncoupled and the knee stays locked while the hip goes through extension.

2 Going into swing-flexion, the hip and knee are coupled to flex simultaneously as observed in a natural human gait.

3 At the point of maximum toe clearance, the coupling mechanism is deactivated, allowing the knee to extend and prepare the leg for stance.

SYSTEM ARCHITECTURE

The gait generation hardware of the Austin exoskeleton suit consists of three major components: hip actuation, a hip-knee coupler, and a controllable locking knee. Users operate the exoskeleton with a simple wireless user interface consisting of two push buttons that are installed on the handle of the stability aid. Electrical components are located on the back of exoskeleton as shown in **Figure 6**.

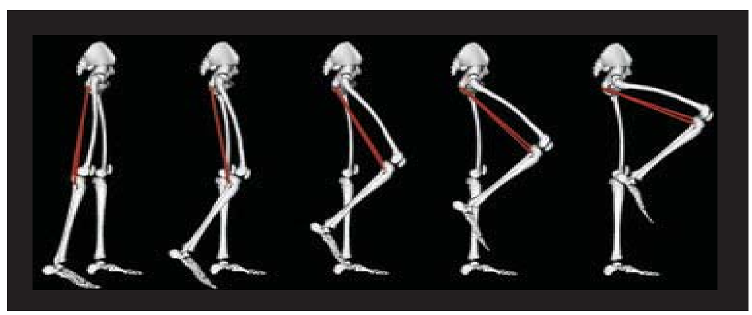


FIGURE 4 **Fixed hamstring length with hip flexion.**

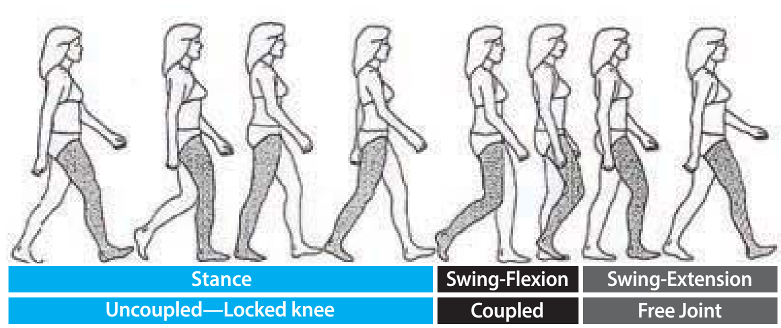


FIGURE 5 **Three-phase walking cycle and the corresponding coupling states.**

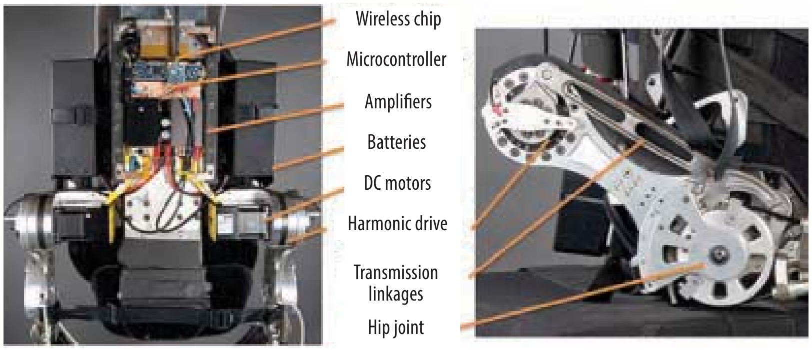


FIGURE 6
Austin exoskeleton hardware.

FIGURE 7
Coupling mechanism comparison to biarticular leg muscles.

Hip Actuation

The hip actuator is a Parker BE231D brushless DC motor mounted at the lower back of the exoskeleton. The motor is connected to an 80 to 1 transmission linkage system that moves motor torque to the hip. This system can provide 53 Nm of continuous and about 160 Nm of maximum intermittent hip torque.

Coupling Mechanism

The coupling mechanism (**Figure 7**) consists of a pulley at the hip (*hip pulley*) that is 4 inches in diameter and a smaller pulley, 2 inches in diameter, at the knee (*knee pulley*). The hip pulley freely rotates coaxially to the hip joint. The knee pulley is fastened to the tibia link of the exoskeleton, generating knee rotation from the knee pulley. A pair of wire ropes connects the two pulleys: rotating the hip pulley rotates the knee at twice the angular velocity.

Coupled motion of the exoskeleton leg is generated when a mechanical brake fixes the hip pulley relative to the torso of the exoskeleton. In this state, the hip pulley becomes analogous to the pelvis where the hamstring and rectus femoris are attached. The pair of wire ropes connecting the pulleys now spans across both the hip and knee joint—in effect acting as two very stiff antagonistic biarticular muscles. Just like their biological counterparts, these wire ropes become able to generate knee flexion during hip flexion and knee extension during hip extension. The coupling ratio is determined by the relative diameter of the pulleys. The two states of the coupling system are used to produce a walking cycle (**Figure 8**).

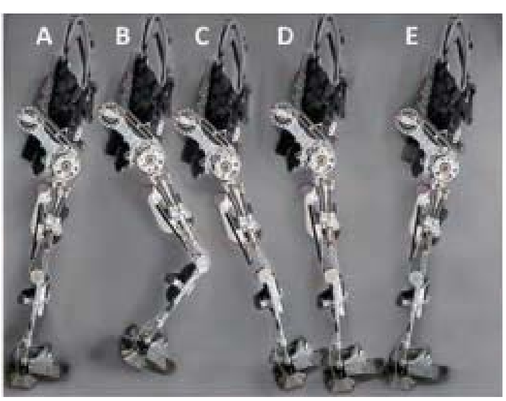


FIGURE 8 **A) toe off B) swing-flexion C) swing-extension D) heel strike E) toe off.**

Knee Design

The exoskeleton knee plays a critical role in gait generation since the locking and unlocking behavior of the knee needs to work in concert with the hip coupling mechanism. The knee has three basic functions. First, it automatically locks against flexion at heel strike. Secondly, it smoothly unlocks when coupled to the hip mechanism during swing-flexion phase, and thirdly, it is free to extend during swing-extension phase.

By default, the knee in this system is free to extend and locked against flexion. This behavior is achieved by using an off-the-shelf one-way locking gas spring controlled by a cam coupled to the knee pulley. The lockable gas spring constant can be tuned to provide knee extension torque for individuals with knee joint spasticity and contractures.

Determining Coupling Gait Trajectory

As previously described, the walking gait of the exoskeleton is generated through the activation and deactivation of the hip-knee coupling system, in other words, through engaging and disengaging the hip pulley. The synchronization of hip pulley engagement as a function of hip angle defines the gait trajectory. Clinical gait analysis (CGA) data published by Winter was used as reference to determine the

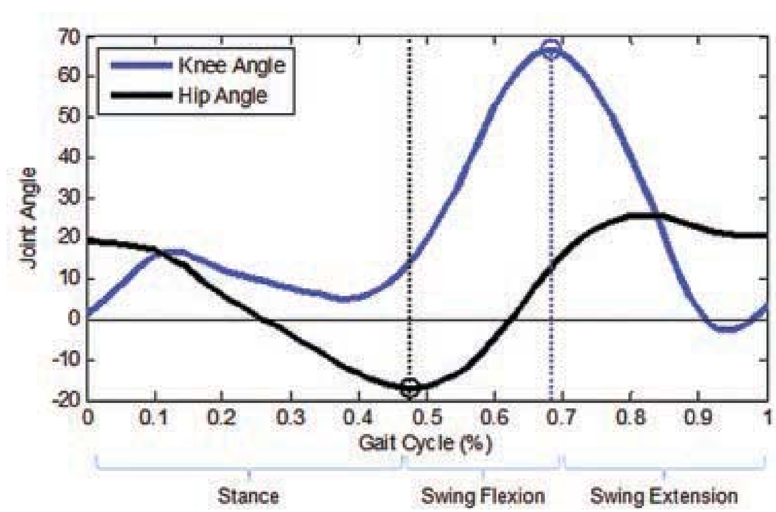


FIGURE 9
Superimposed Winter knee and hip CGA data with corresponding gait phase.

FIGURE 10 Frames from point tracking software tracker©. Video from a canon powershot sx40 hs.

optimal walking trajectory[11].

By superimposing hip joint data on top of knee joint data, the coupling gait trajectory can be determined. This reveals regions of stance, swing-flexion, and swing-extension. The vertical dashed lines in **Figure 9** mark the point of maximum hip extension and maximum knee flexion. The segment between the dotted lines is the swing-flexion phase of the gait cycle when the hip and the knee are both flexing. Based on this data, the swing-flexion phase of the gait begins when the hip is extended to approximately -17° and ends after approximately 30° of hip flexion, when the hip angle reaches 13°.

At maximum knee flexion, the coupling system can be deactivated, allowing the knee to freely re-extend with the assistance of gravitational force and a knee extension spring. As shown in the swing-extension segment of Fig. 9, knee angle returns to zero while the hip joint can be controlled to follow an independent and arbitrary trajectory. During stance phase, the hip is driven through a desired trajectory while the knee remains uncoupled (knee angle remains constant).

DISCUSSION OF EXPERIMENTAL DATA

Preliminary experiments using hip-knee coupling for ambulation assistance were conducted with the Austin exoskeleton on a 21 year-old male test pilot, who weighed 200 lbs at six foot two, and who had sustained a complete T12 injury 3 years prior. Video point tracking data (**Figure 10**) of the subject walking with the exoskeleton was collected for comparison with published CGA data.

Figure 11 plots point tracking data of two steps, with markers indicating the moment of "heel-off" for each step. The plot provides a comparison between CGA data and the full gait cycle of the Austin system. As expected, the data shows that the paraplegic pilot spends more time in double-stance getting ready for the next step. However, if the moments of heel-off are superimposed onto one another, the data shows that the mechanical gait generator produces a swing phase gait trajectory very similar to the CGA reference.

CONCLUSION AND FUTURE WORK

The Austin exoskeleton illustrated the feasibility of using a mechanical gait generator to mimic a natural human gait. Eliminating knee actuation by embedding knee control into intelligent hardware design, allows the Austin system to become more compact and lightweight than some existing powered exoskeletons. ■

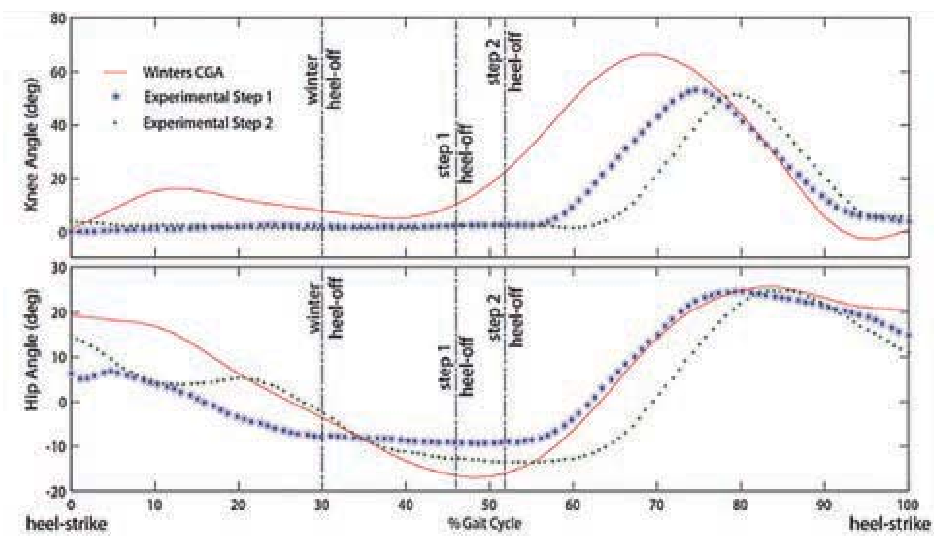


FIGURE 11 Knee and hip angles during the gait cycle. Starting and ending with heel strike.

REFERENCES

1 NSCISC, 2012, "Spinal Cord Injury Facts and Figures at a Glance," 35(4) https://www.nscisc.uab.edu.

2 Brown-Triolo, D.L., M. J. Roach, K. Nelson, and R.J. Triolo, 2002, "Consumer perspectives on mobility: implications for neuroprosthesis design.," *J. Rehabil. R&D*, 39(6), p. 659–69.

3 Phillips, L., M. Ozer, P. Axelson, and J. Fonseca, 1987, *Spinal Cord Injury: A Guide for Patient and Family*, Raven Press.

4 Center for Orthotics Design, 2013, "Isocentric RGO," http://www.centerfororthoticsdesign.com/isocentric_rgo/index.html.

5 Sykes, L., J. Edwards, E.S Powell, and E.R. Ross, 1995, "The reciprocating gait orthosis: long-term usage patterns.," *Arch. Phys. Med. Rehabil.*, 76(8), pp. 779–83.

6 Little, R., and R. Irving, 2011, "Self contained powered exoskeleton walker for a disabled user," U.S. Pat. App. 12/801,809.

7 Doorenbosch, C.A., J. Harlaar, M.E. Roebroeck, and G.J. Lankhorst, 1994, "Two strategies of transferring from sit-to-stand; the activation of monoarticular and biarticular muscles," *J. Biomech.*, 27(11), pp. 1299–307.

8 Kumamoto, M., T. Oshima, and T. Yamamoto, 1994, "Control properties induced by the existence of antagonistic pairs of bi-articular muscles—Mechanical engineering model analyses," *Hum. Mov. Sci.*, 13, pp. 611–634.

9 Schenau, G. van I., 1989, "From rotation to translation: constraints on multi-joint movements and the unique action of bi-articular muscles," *Hum. Mov. Sci.*, 8, pp. 301–337.

10 Sutherland, D. H., K.R. Kaufman, and J.R. Moitoza, 1994, "Kinematics of normal human walking," *Human Walking*, Williams & Wilkins, pp. 23–44.

11 Winter, D. A., 1990, *Biomechanics and Motor Control of Human Movement*, 2nd ed., John Wiley & Sons.

2014

ASME DYNAMIC SYSTEMS AND CONTROL CONFERENCE

SAN ANTONIO, TEXAS • OCTOBER 22–24

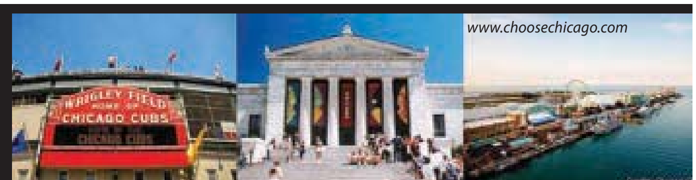
The **ASME Dynamic Systems and Control Conferences (DSCC)** are organized and led by the members of the ASME DSC Division to provide an intimate and focused setting for dissemination and discussion of the state of the art in the broad area of dynamic systems and control, from theory to industrial applications, and innovations in dynamical systems and control education.

Technical themes to be featured in special tracks at this year's DSCC include advanced manufacturing, renewable and traditional energy, bioengineering and biomedical engineering, as well as cyber-security for critical infrastructure. The program will also include contributed sessions, invited sessions, tutorial sessions, special sessions, workshops, and exhibits.

River Walk at Dusk / San Antonio Convention and Visitor Bureau

For more info on the 2014 DSCC, visit: **http://www.asmeconferences.org/DSCC2014/index.cfm**

JULY 1–3
CHICAGO



www.choosechicago.com

2015 AMERICAN CONTROL CONFERENCE

Led by General Chair **Richard D. Braatz** (*Massachusetts Institute of Technology*) and Program Chair **Alessandro Astolfi** (*Imperial College and University of Rome*), the **2015 American Control Conference (ACC)** will be held **July 1–3** in **Chicago**.

ACC 2015
Chicago
July 1–3, 2015

The ACC is the annual conference of the **American Automatic Control Council (AACC)**—the U.S. member organization of the **International Federation for Automatic Control (IFAC)**, and is co-sponsored by professional societies, including **ASME**.

The event's technical program includes regular and invited sessions, as well as tutorials, workshops and exhibits. *Submissions are encouraged in all areas of theory and practice of automatic control.*

Featured topics at this year's ACC include **energy, biomedical,** and **transportation systems**—subjects of three plenary/semi-plenary lectures that open full days of topical sessions.

Manuscripts and session proposals are due Sept. 26.
Workshop proposals are due Oct.17.

Details about the conference can be found at :
http://www.a2c2.org/conferences/acc2015/

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

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

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

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

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

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

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

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

PUBLIC REVIEW DRAFTS

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

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

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

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

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

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

INTRODUCING THE NEW ASME JOB BOARD + CAREER CENTER. LIKE THE *MECHANICAL ENGINEERING* MAGAZINE CLASSIFIEDS, IT'S ORGANIZED. EASY TO USE. AND DESIGNED WITH ENGINEERS IN MIND.

Top-notch engineering jobs may be difficult to get, but they shouldn't be difficult to find. That's why ASME has launched the new and improved Job Board + Career Center – to give engineering professionals and students another tailored marketplace for job opportunities and professional advice.

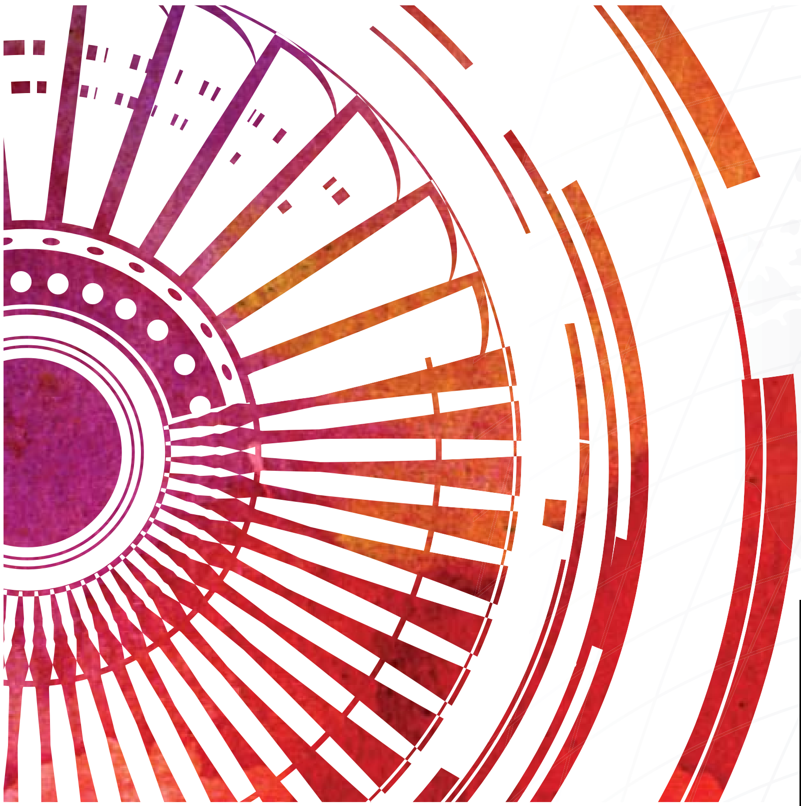
Whether you're looking to take the next step in your career, or exploring ways to make your current job better, you can find it at the new ASME Job Board + Career Center.

ASME
SETTING THE STANDARD

GET STARTED AT jobboard.asme.org

The American Society of Mechanical Engineers (ASME)

A SUPPLEMENT TO MECHANICAL ENGINEERING MAGAZINE



Global Gas Turbine News

Volume 53, No. 7 • September 2014

In this issue

go.asme.org/IGTI
Email: igti@asme.org

Welcome to the September 2014 edition of the Global Gas Turbine News. This edition will provide a comprehensive review of ASME Turbo Expo 2014, as well as glimpse into the launch of the 2015 show in Montreal.

ASME Turbo Expo is officially entering into its 60th year of operation as the premier turbomachinery conference in the world. In this issue, the familiar Turbo Expo prestige, knowledge and community will be on display as another successful conference is completed. Reflection on the past, pondering of the present, and eager anticipation of the future is the current theme within the community. Germany was the ideal location for TE14 as the Gas Turbine celebrated its 75th anniversary in its home country. It was a great occasion for the gas turbine industry to reflect on its humble beginnings 75 years ago.

ASME Turbo Expo 2014 in Düsseldorf, Germany

Technology Reduces Life Cycle Cost

Situated at the border of the Rhine River, Düsseldorf is the capital of the highest populated German state, North-Rhine Westphalia. The Düsseldorf area contributes significantly to the German landscape of turbo-engine builders, which has been shaped by organizations like Siemens, Alstom, MAN Turbo & Diesel, ABB and Atlas Copco for energy generation and process engineering. In the aerospace sector, the best known companies are MTU and Rolls-Royce Germany. Lufthansa Technik and N3, a joint venture of the former with Rolls-Royce, provide repair and overhaul services. All of the previous and many smaller companies benefit from a rich network of world leading, specialized technical universities and research institutions. This vibrant environment was the perfect backdrop for the turbomachinery industry, which is equally engaged in pushing the limits and challenging existing solutions to create better, even more efficient turbo engines.

...Continued on next page

ASME TURBO EXPO 2014 Opening Session

The conference began with three leading figures in the industry addressing the 2014 conference theme, "Technology Reduces Life Cycle Cost." Pratyush Nag of Siemens, Dr. Karsten Mühlenfeld of Rolls-Royce Deutschland, and Charles Soothill of Alstom Switzerland, examined the changes that are occurring in the industry and discussed the current development needs and the conflicts that can arise in meeting the goal of life cycle cost reduction. Whether the application is on land, at sea or in the air, the life cycle cost has a direct impact on the profitability of the power plant's operation. "To look at turbo engines only from the perspective of lower energy consumption or higher reliability would mean to stop short of what can be achieved. It is only when we appreciate the whole product life cycle, the hardware and related services that our task as engineers is given full justice. Optimizing even the piece part level maintenance, understanding the actual state of the hardware by intelligent health monitoring, and selecting the right means to optimize overhaul cycles are tasks which apply to all types of turbo engines – no matter if in the air, at sea, or on land. The difference lies less in the particular type of turbine we look at, but more in the attitude and business concept for running it. Outstanding mechanical engineering is just the beginning, the entry ticket to compete. Meeting current customer requirements is the basis; always thinking into the future makes the difference, for the city of Düsseldorf as well as for the industry."

> "To look at turbo engines only from the perspective of lower energy consumption or higher reliability would mean to stop short of what can be achieved..." Karsten Mühlenfeld, Rolls-Royce

Over 3,000 turbomachinery professionals from over 50 countries attended ASME Turbo Expo 2014

...Continued on page 83

AWARDS

R. Tom Sawyer Award

Gas Turbine Award

Aircraft Engine Technology Award

Early Career Award

Industrial Gas Turbine Technology Award

John P. Davis Award

ASME IGTI Board Chair & ASME President

Application Of An Industrial Sensor Coating System On A Rolls-Royce Jet Engine For Temperature Detection

J.P. Feist, P.Y. Sollazzo, S. Berthier, B. Charnley, J. Wells

INTRODUCTION

Engineers have continuously sought to increase fuel efficiency in gas turbines, more than halving fuel consumption over the last 3-4 decades. This was achieved mainly by increasing firing temperatures. Apart from new alloys and cooling methods, thermal barrier coatings (TBC) have played a major role in this development. These coatings were first used on jet engines in the 70's and are now a common feature on power generation turbines. TBCs allow components to survive higher temperatures and have acceptable service times. TBC technology will continue to play a dominant role in future energy solutions. TBCs are refractory coatings, usually based on yttria stabilized zirconia (YSZ), that are used to provide thermal insulation and indirectly provide oxidation protection on turbine blades, vanes and combustion chamber liners in gas turbines used in power generation and aviation. They offer the potential to allow end-users to operate at substantially higher temperatures than uncoated components could withstand. This leads directly to an increase in efficiency and a consequent reduction in CO_2 emission. The life expectancy of a TBC is known to be inversely proportional to the absolute temperature experienced by the coating. Close control of component temperatures cannot currently be achieved due to the absence of any reliable means to measure in the hot section of the engine. As a result, TBCs have, to date, been used conservatively, to extend the life of turbine components rather than to realise the full potential increase in operating temperature. Over the past 9 years Southside Thermal Sciences (STS) has pioneered the method of implementing luminescence materials into TBCs [2,5-7]. This novel approach promises optical, accurate, in-situ temperature detection and health monitoring. The basic concept is to take phosphorescent materials, as used in TV screens and energy efficient light bulbs, and embed those into standard TBC materials such as zirconia, consequently creating a 'smart' material. When illuminated with UV light this class of material starts to phosphoresce ('glow') and the observation of this light with specifically tailored instrumentation gives the engineer valuable information on temperature and structural damage such as erosion, corrosion and ageing effects as the phosphor particles act as embedded atomic sensors inside the ceramic. This paper will describe the implementation of a sensor coating system for the first time on an operating turbine providing temperature data from modified TBCs in the hot section of an operating engine.

REVIEW

The use of phosphorescent materials as temperature indicators is well known and this is an established laboratory technique and is well documented. The following references give good reviews about what is generally known as the thermographic phosphor technique [8,9]. However, the embedding of the optically active ions – namely Lanthanides and transition metals – into functional ceramics such as TBCs or even the mixing of a secondary phosphor phase into a primary material phase is a rather new concept and requires a different approach. The main consideration here is the integrity of the primary phase or primary host or the material system as such. Early failure due to the additional dopant being added is not an option as it would compromise the primary function. In the case of a TBC this is the protection of the component for many thousands of hours (e.g. 24,000 operating hours!). Choy, Feist and Heyes [1] introduced the notion of a "thermal barrier sensor coating" (sensor TBC) for temperature detection in 1998. This technique enabled surface temperature measurements, but also could provide a means to measure temperature within the TBC and at the metal/topcoat interface, hence enabling the manufacturing of an integrated heat flux gauge. The relatively low dopant levels insured no adverse effects on the coating stability. First results were published on YSZ co-doped with europium (I) powders in 2000 [10] and subsurface temperatures were measured for the first time looking through a 50µm undoped YSZ layer from a thin (≈10 µm) YSZ:Eu layer underneath [11].

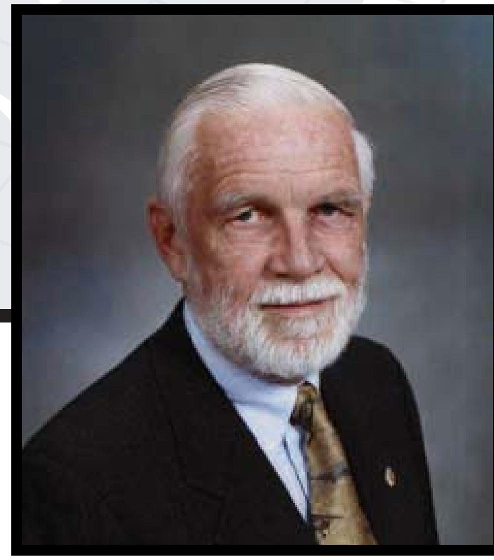
Publications on industrial relevant robust coatings produced by standard production techniques appeared shortly after. The first electron beam physical vapour deposition (EBPVD) sensor coating was reported in 2001 [12] using YSZ:Dy applied with an industrial coater at Cranfield University. A more important coating technology for power generation engines, however, is the atmospheric plasma spray process (APS). First work on industrial air plasma sprayed sensor coating systems commenced around 2002 and were first published in 2005 [5,13] and later in 2006 [14]. Heyes et al. demonstrated the capabilities of APS sensor coatings for in-situ two-dimensional temperature measurements in burner rigs using a high speed camera system [13]. Further, high temperature measurement capabilities in APS coatings up to 1674K with a two material phase architecture were published by Feist et al. [14] using an industrial thermal spray coater at the Research Centre Jülich, Germany.

EXPERIMENTAL ASPECTS

TBCs are used on combustion components, the hotter rotating blades and fixed vanes in the hot gas path section of industrial gas turbines. The thermal barrier coatings on these turbines usually consist of an oxidation resistant bond coat and a ceramic insulating layer. The bond coat is normally an MCrAlY (M for metal) coating and the top coat is normally YSZ. The main function of the MCrAlY coating is to form a stable passive alumina (Al_2O_3) layer which prevents oxidation of the main components. The primary function of the YSZ layer is to prevent heat flow into the part giving a lower metal temperature thus enabling the firing temperature of the turbine to be raised without significantly degrading the mechanical properties of the base alloy of the components.

...Continued on page 78

Turbine AS THE TURNS



Gems of Turbine Efficiency

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

This year marks the diamond jubilee for the gas turbine. Seventy five years ago, in 1939, the first jet engine aircraft flew, and the first gas turbine powering an electric generator was successfully tested.

This is also the approximate golden jubilee for the invention of turbine single crystal blades for use in gas turbines. These gas turbine "Crown Jewels" [1] were being developed and perfected at Pratt & Whitney Aircraft, when I joined the company, fresh out of graduate school, in 1964. Their first real engine test was in 1967-68 on Pratt's J58 engine, which powered the SR-71, Lockheed's supersonic reconnaissance aircraft. At that time, single crystal technology wasn't yet ready for this early application. Later, single crystal (SX) turbine blades were first used in military engines on Pratt's F100 engine, which powered the F16 and F15 fighter aircraft. Their first commercial use was on P&WA's JT9D-7R4 engine, which received FAA certification in 1982, powering Boeing's 767 and the Airbus A310 [2].

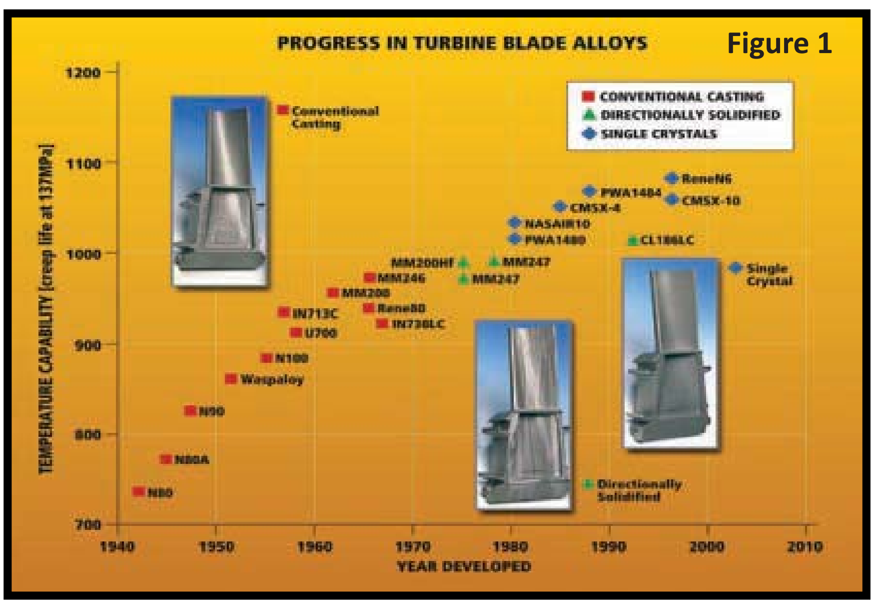


Figure 1: Progress in temperature (Celsius) creep rupture limits for various superalloys (Photos are of non-aviation turbine blades. Courtesy of NASA.)

Since these first applications, SX turbine blades have become standard on many high performance jet engines. They are also being used more recently on high performance non-aviation gas turbines, generating electric power with SX turbine blades in sizes as much as ten times larger than their aviation counterparts. (My research shows that Siemens was the first to use non-aviation SX turbine blades in their .3A series machines in the early 1990s.)

As we know, gas turbine thermal efficiency increases with greater 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 jet engines can exceed 3,000 °F, while non aviation gas turbines operate at 2,700 °F or lower. In high-temperature regions of the turbine, special high-melting-point nickel-base superalloy blades and vanes are used, which retain strength and resist hot corrosion at extreme temperatures. These superalloys, when conventionally vacuum cast, soften and melt at temperatures between 2,200 and 2,500 °F. This means blades and vanes closest to the combustor may be operating in gas path temperatures far exceeding their melting point and must be cooled to acceptable service temperatures (typically eight-to-nine-tenths of the melting temperature) 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. To eliminate the deleterious effects

...Continued on next page

of impurities, investment casting is carried out in vacuum chambers. After casting, the working surface of high-temperature cooled turbine airfoils are coated with ceramic thermal barrier coatings to increase life and act as a thermal insulator (allowing inlet temperatures 100 to 300 Fahrenheit degrees higher).

Grain Boundary Phenomena

Conventionally cast turbine airfoils are polycrystalline, consisting of a three-dimensional mosaic of small metallic equiaxed crystals, or "grains", formed during solidification in the casting mold. Each equiaxed grain has a different orientation of its crystal lattice from its neighbors'. Resulting crystal lattice misalignments form interfaces called grain boundaries.

Untoward events happen at grain boundaries, such as intergranular cavitation, void formation, increased chemical activity, and slippage under stress loading. These conditions can lead to creep, shorten cyclic strain life, and decrease overall ductility. Corrosion and cracks also start at grain boundaries. In short, physical activities initiated at superalloy grain boundaries greatly shorten turbine vane and blade life, and lead to lowered turbine temperatures with a concurrent decrease in engine performance.

One can try to gain sufficient understanding of grain boundary phenomena so as to control them. But in the early 1960s, researchers at Pratt & Whitney Aircraft (now Pratt & Whitney, owned by United Technologies Corp.) set out to deal with the problem by eliminating grain boundaries from turbine airfoils altogether, by inventing techniques to cast single-crystal turbine blades and vanes.

ANSYS

Thank You
2014 ASME IGTI Sponsor

The Result

In jet engine use, single-crystal turbine airfoils have proven to have as much as nine times more relative life in terms of creep strength and thermal fatigue resistance and over three times more relative life for corrosion resistance, when compared to equiaxed crystal counterparts. Modern high turbine inlet temperature jet engines with long life (that is, on the order of 25,000 hours of operation between overhauls) would not be possible without the use of single-crystal turbine airfoils. By eliminating grain boundaries, single-crystal airfoils have longer thermal and fatigue life, are more corrosion resistant, can be cast with thinner walls — meaning less material and less weight — and have a higher melting point temperature. These improvements all contribute to higher gas turbine thermal efficiencies.

Figure 1 shows creep life progress in turbine blade alloys, as given by NASA [3]. In the plot, the abscissa shows the year of alloy development and the ordinate shows temperature capability in degrees Celsius, for a variety of turbine blade superalloys. The temperature capability is the temperature for creep life posed as the time (1000 hours) the alloy reaches a certain elongation/strain (1%) under a given stress (137MPa = 20,000 psi). As shown, single crystal blades are clearly superior.

* * * * * * *

About fifty years ago, a small group of gas turbine industry researchers set out to eliminate grain boundaries in superalloy turbine blades. Today, the result is a whole class of single crystal turbine blades that have increased thermal efficiencies and have unmatched resistance to high-temperature creep and fatigue.

References

1. Langston, Lee S., 2006, "Crown Jewels", *Mechanical Engineering Magazine*, February, pp. 31-33.

2. Gell, M., Duhl, D.N., and Giamei, A.F., 1980, "The Development of Single Crystal Superalloy Turbine Blades", *Superalloys 1980*,

Element	Co	Ni	Cr	Al	Y
Amdry995	38.5	2.0	21.0	8.0	0.5

Table 1: Nominal composition of the Amdry 995 MCrAlY coating

When using the after-market for coatings, the choice is more limited as only MCrAlY coating compositions not controlled by patents can be used. One of the most common is the composition known as Amdry 995. The same composition can be obtained from other powder suppliers under different names. The composition of Amdry 995 is given in Table 1. Such a coating would be a suitable coating to be used with a metal temperature of 1073-1123K. To provide suitable life for a 24,000 hours of service interval (3 years) on an industrial gas turbine it would be applied with a thickness of 250µm. The APS TBC can have a thickness from 200-1000µm depending on the component, with combustion components tending to have thicker TBCs than blades and vanes. TBC's thicker than 750µm are more prone to early failures unless pore sizes are carefully controlled. On blades and vanes for industrial gas turbines the TBC is normally 250µm.

The finished coating chosen was an Amdry 995 MCrAlY coating 250µm thick covered with an APS TBC, also 250µm thick. A back scattered scanning electron microscope image of such a coating is shown in fig. 1.

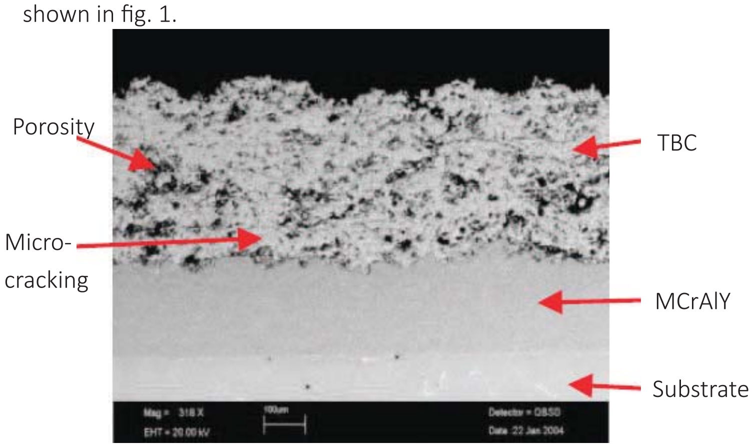


Figure 1: Example of an MCrAlY + APS TBC coating system on a large indistrial gas turbine component

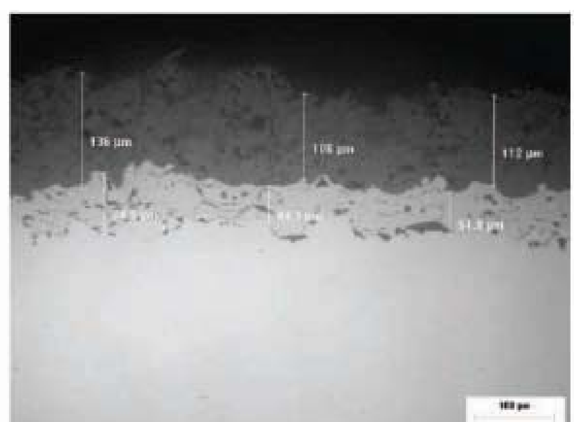
With large industrial gas turbine components, adding a 250µm thick MCrAlY coating and a 250µm coating does not significantly alter the dimensions, the weight or the natural frequency of the component. On an aero-engine component such a coating could make a major difference to all of these affecting turbine performance and potentially risking a component failure. To minimise these sort of risks a much thinner coating was specified for the Viper engine. The MCrAlY was specified as being Amdry 995 or an equivalent, and the nominal MCrAlY thickness was set as 100µm. The TBC was specified as being SN_20_4NS or an equivalent standard TBC material with modified sensor TBC powders being supplied by STS, and the nominal TBC thickness was set to between 50µm and

...Technical Article continued from page 75

100µm, depending on application. The method for depositing the MCrAlY was specified as high velocity oxygen fuel for the blades and vanes, and APS for the combustor. All TBC variations were specified as being prepared by APS. The array of TBC variations trialled is shown in Table 2. Heat treatments on the parts were carried out after application of the MCrAlY. The blades were given the standard heat treatment for Nimonic 105. A spark analysis of the vanes showed the composition to be quite different from Nimonic 105 and Cranfield University identified the vanes as being manufactured from alloy G39. No standard heat treatment was available for this, and so a heat treatment typical of this type of alloy was used. The solution heat treatment was carried out at 1448K for two hours followed by ageing heat treatments of 4hrs at 1373K and 16 hours at 1023K to diffuse the coating and optimise the microstructure for operation. Even though there was a difference in deposition efficiency between the modified sensor powders and off the shelf commercial YSZ powders, all powders were found to feed well through the APS gun.

Component	Number	TBC Variation
Vane	2	Dual layer system (standard *YSZ* on the bottom 50µm thickness; STS mix on the top)
Vane	2	Dual layer system (undoped *YSZ* at bottom 50µm - 75µm thickness; doped *YSZ* on top thickness 50µm -75µm)
Vane	2	Single layer (*YSZ* doped 100µm)
Vane	2	Single layer (STS specs; 60µm) no heat treatment
Vane	2	Single layer (STS specs; 60µm) inclusive heat treatment
Blade	2	Dual layer system (standard *YSZ* on the bottom 50µm thickness; *YSZ-YAG* mix on the top)
Blade	2	EBPVD multi layer – not covered in this article
Blade	2	Single sensor layer (*YSZ* doped 100µm)
Blade	2	Single layer (STS specs; 60µm)
Blade	2	Single layer (STS specs; 60µm) inclusive heat treatment
Combustor	strips	Dual layer system (standard *YSZ* on the bottom 50µm thickness; STS mix on the top) inclusive heat treatment
Combustor	strips	Single sensor layer (*YSZ* doped 100µm)

Table 2: Array of TBC variations specified for the coating trials.



Coating layer	Specified Thickness (µm)	Actual Thickness (µm)
Key coat / bondcoat	25-50	40-70
Standard *YSZ*	50-75	50-70
STS Mix	50-75	40-60

Figure 2: Optical microscope image showing the microstructure of the top 3 layers of coating achieved for the STS Mix coating for the blade qualification (from the manufacturer coating qualification report).

One example of an APS bondcoat and APS TBC is shown in fig. 2. Parallel tests at Didcot power station revealed survivability of specific coatings in excess of 4,500 EOH. It is expected that the capability of these coatings is in the range of normal maintenance schedules of industrial gas turbines of 24,000hrs or even longer. Based on what the manufacturer learned about the powders and deposition rates during the development and production work, the manufacturer expects that with a small amount of additional development work it would be possible to improve on the current spray process.

INSTRUMENTATION AND DATA COLLECTION

The optical instrumentation for a phosphorescent thermometry system consists of the excitation optics delivering the light of a Nd:YAG laser and the collection optic. The objective was to maximize delivery power while maintaining a large distance to the actual target. This is a significant design decision as the actual optical probe can be operated outside the extreme hot section to avoid extra cooling requirements and avoid the risk of failing parts potentially jeopardizing the engine integrity.

In order to maximise the delivery energy it was decided to operate with open beam optics instead of using fibre guides. The coupling of high energy pulsed UV lasers into silica fibres is limited to relatively low power compared to an open beam. A further benefit of avoiding fibres is the absence of additional optics which would be required to refocus the light when the light exits at the fibre end. This is undesirable as the optic would decrease the delivery power on one hand and on the other hand requires additional housing making it more complex to install the probe on an engine and hence less cost-effective. The aim for the collection optic design was to achieve a large field of view with an uncooled housing. The solution came in the form of a non-imaging optic designed by STS called optical energy transfer system (OPETS) and illustrated in fig.3. The delivery of the excitation light was achieved through a beam splitter housed in a cube which is robustly attached to the front of the collection optic, hence forming a single unit. The collected phosphorescence is coupled into a 2m fibre bundle delivering the light to the remote photomultiplier tube (PMT). The collection optic also may be equipped with several wavelength selecting filters to tailor it to the observation requirements. The system maximizes light collection regardless of the distance of the source. No refocusing is needed for different distances and hence enables the operator to measure the signal without the need to adjust the optics for the right stand-off distance which would be required for a conventional optic. This is a significant advantage as it reduces the need for precise alignment in an environment where precise alignment is difficult or impossible to achieve. Another most important design feature is the large 'flat hat' transfer function guaranteeing a uniform light collection across a large field of view (Figure 4; 8 degrees). This transfer function enables the scanning or observation of moving objects across the specified field of view with very little distortion of the intensity as would potentially occur in a conventional imaging optic. The laser pulse generates a phosphorescent spot on the component shown as position 'A' in fig. 3. In case of a fast moving component such as a turbine blade the slow decreasing phosphorescence will travel with the component across the field of view (from A to C). Hence the current probe design enables the observation of the undistorted life time decay. Figure 4 shows the variation in intensity of a constant light source when moving across the field of view (FOV) of the OPETS. Between -4 and +4 degrees the probe uniformly collects light. The graph was recorded using a specialised optical bench with a LED light source. The solid lines are created using a simple interpolation. The positions A, B and C correspond to the equivalent positions in fig. 4 symbolizing a moving phosphorescent signal.

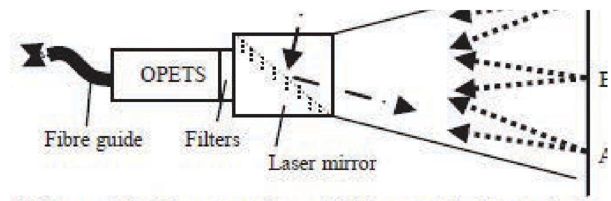


Figure 3: Illustration of the optical probe.

ROLLS-ROYCE VIPER 201 TEST BED

Two Rolls-Royce Viper Mk 201 engines were purchased by STS and a hot end instrumentation facility was designed and built at Cranfield University's Gas Turbine Engineering Laboratory. One engine was installed and commissioned as a test bed while the second engine was stripped down to remove a number of hot end components in preparation for coating by a commercial coatings company. Following the initial performance runs the first engine was dismantled, the coated components were installed and six windows were mounted on the engine enabling optical access to the main hot end components including the combustion chamber inner flame tube, nozzle guide vanes and the turbine rotor blades.

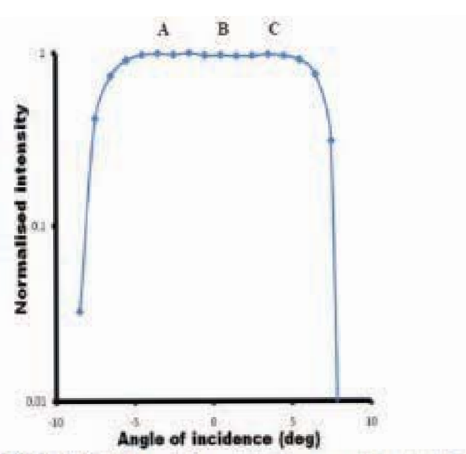


Figure 4: OPETS FOV. The positions A, B, C are equivalent to the positions in Figure 3. The flat hat function permits undistorted detection across a wide FOV.

Optical Windows

A method was required to provide clear optical access to all the hot end components; the combustion chamber, nozzle guide vanes (NGV) and turbine rotor blades. These were viewed in order of difficulty with the NGV access requiring that the window access pass through both the combustor outer casing and the outer flame tube at the correct angle onto the vane surface. The rotor window mounting plate was positioned on the downstream exhaust tube which was a more complex shape and required coordinate measuring machining and electrical discharge machining to give the necessary fit. During the design of the combustor windows it was discovered that it was possible to use dilution holes in the outer flame tube to provide sufficient FOV onto the inner flame tube surface. As it was intended to apply two different coatings to the inner flame tube, the window mounts were further adapted to extend the FOV and exploit the scanning capability of the sensor system. The extreme environment required that sapphire windows were installed and the support tubes were manufactured with a high aspect ratio to reduce issues associated with the ingress of combustion material or particles onto the optics. As the rotor windows were facing into the flow they included a purge system. Three of the six available windows are shown in fig. 5. With a view through the rotor window shown in fig. 6. The coated NGVs are shown in position in fig. 7.

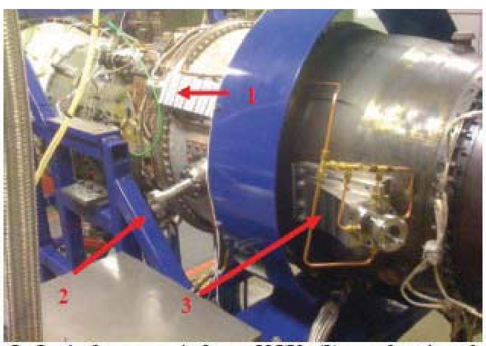


Figure 5: Optical access windows: NGVs (1), combustion chamber (2), and rotor windows with air purge (3).

Figure 6: View through the rotor window showing the turbine blades

Figure 7: Coated NGV in position on the engine.

CALIBRATION

When a sensor TBC is excited by a short laser pulse (5ns) it starts to emit phosphoresent light. The phosphorescence decays exponentially and this decay time is usually much longer than the laser excitation pulse and is typically of the order of micro- or milliseconds. Several publications have shown the dependency between the life time decay of this phosphorescence and the temperature [5,7-11,15,16]. Figure 8 shows the phosphorescent signal at different temperatures. The life time decay is extracted by applying a single exponential fitting routine on the measured signal.

$$I(t) = I_0 e^{\left(\frac{-t}{\tau}\right)} + B_0 \quad (1)$$

(1 is the mathematical representation of the signals illustrated in fig. 8. I_0 is the initial intensity, *t* is the life time decay, B_0 is the base line, and t is the time.)

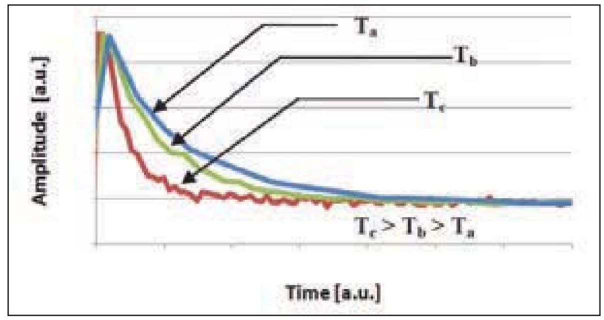


Figure 8: Phosphorescent signals at different temperatures.

In order to measure the temperature on the Viper, a correlation between the life time decay and the temperature is needed in the form of a calibration curve. The calibration curve is obtained by placing a sample inside a box furnace. The sample used for the calibration is a 30mm diameter disk coated with the same coating as the one used on the Viper components. The life time decay is measured for different temperature settings. The OPETS was placed in the front of the observation window of the furnace. Figure 9 shows a specific set-up. The Nd:YAG 355nm laser pulse is steered onto the sample by being reflected by the dichroic mirror located in the OPETS. The OPETS collected the phosphorescence signal from ca 350mm distance and the signal was guided by an optical fibre to a remote PMT. The phosphorescence signal was filtered by a band pass filter centred at 590nm. The PMT signal was amplified and digitalized. Using a computer the digitalized signal was fitted by a Levenberg-Marquardt algorithm to extract the life time decay. To automate the calibration curve measurement, the computer also controlled the furnace temperature set point. Typically the temperature of the furnace was set 20 minutes prior the measurement, providing sufficient time for the temperature to stabilise. For the Viper measurement system several calibration curves have been averaged. Each of the calibration curves were detected using slightly different settings such as: laser power, different quality phosphorescent filters, sample orientation (fig.10) and changes in the fitting routine. This was done to understand the sensitivity of the system and to estimate errors in the calibration. Figure 11 shows the resulting calibration curve which was used for the temperature detection on the Viper engine. The uncertainty associated with the

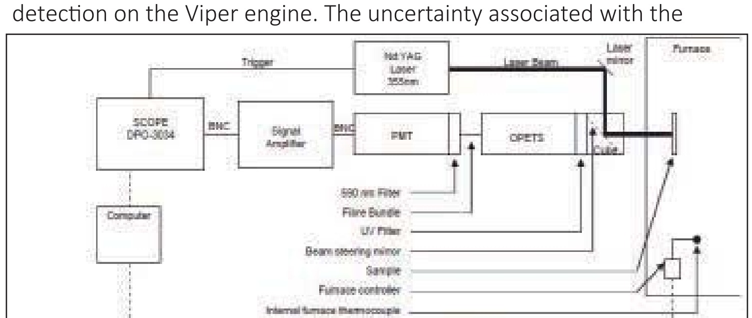


Figure 9: Calibration procedure experiment.

changed settings (laser power, filter quality, etc.) was defined as the difference between the average calibration curve and the specific curve generated for each setting. For the Viper operational regime (673K to 973K) the maximum error was determined to be ±4K, but typically was less.

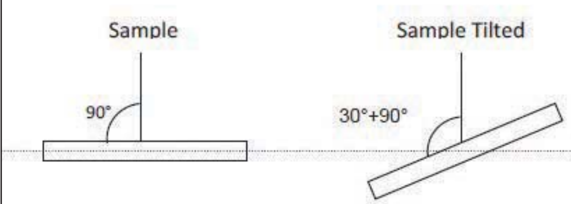


Figure 10: Sample orientation during calibration.

From fig. 11 it can be seen that the calibration curve is divided in three distinctive regimes. The first part (regime 1) from room temperature to 673K is constant and hence cannot be used for temperature detection as the life time decay does not change with temperature. The second part (regime 2), from 673K to T_Q (Q=quenching) has a low sensitivity to temperature. T_Q is defined as the temperature where the thermally activated quenching of the energy level starts to significantly dominate any other quenching process. Errors in the determination of the life time decay can result in larger errors for temperatures below T_Q as the slope is shallow (regime 2). This changes when the temperature is above T_Q as the gradient becomes very steep (range from T_Q to 1073K; regime 3). Here an error in the life time decay causes only a small error in the temperature. However, for the Viper measurements, regime 2 and 3 were both utilized.

RESULTS

The first measurement performed on the Viper was realized on a NGV as this was considered the easier task compared to the combustion chamber and the rotating blades and helped to configure the initial measurement system. Figure 12 illustrates the data collected during Run A. T_1 represents the Viper inlet temperature, T_2 the Viper compressor delivery temperature, T_3 is measured in the gas stream 40mm in front of the NGV and T_4 represents the Viper Jet pipe exhaust temperature. T_1 to T_4 were all measured using K-type thermocouples. T_s is the temperature measured on a NGV coated with the novel sensor TBC and using STS's detection technology. Data is recorded typically every second.

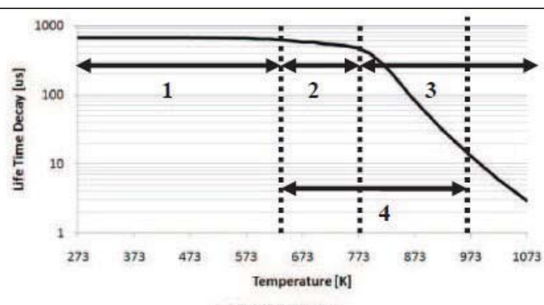


Figure 11: Calibration curve used for the *Viper* measurements using *YSZ:Dy*. (1) no temperature sensitivity, (2) low temperature sensitivity, (3) high temperature sensitivity, (4) temperature regime used for the *Viper* engine.

Most importantly T_s shows a strong correlation to the different operating conditions during the run. Under maximum load conditions at 13,500 RPM the maximum NGV temperature is detected at ca 1074K which is close to the maximum component temperature stated by the engine manual. In comparison T_3 – the gas stream temperature in the vicinity of the NGV – shows very high noise levels and it is almost impossible to detect a reliable value or follow rapid transients. The noise is probably caused by the extreme gas stream turbulences. In contrast to T_3, T_4 shows a very stable behavior throughout the test. It is significant to observe that the NGV coating temperature T_s detected by this novel sensor system correlates to the T_4 data, except for slight variations at 12k RPM. This correlation demonstrates the exceptional potential of phosphorescence sensor measurements in operating engines.

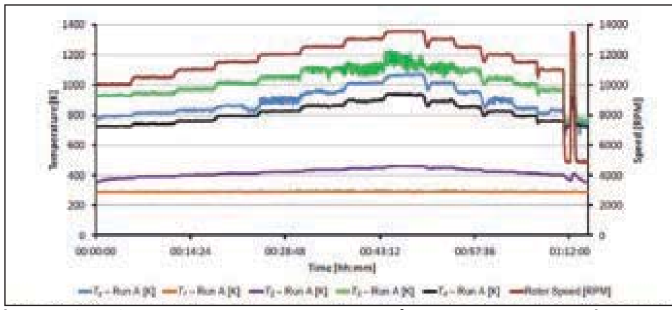


Figure 12: NGV measurements; Run A. The new sensor coating system follows the engine operating conditions well and shows very little noise.

COMBUSTION CHAMBER MEASUREMENTS

The second surface measured in the Viper was the combustion chamber inner flame tube. This measurement, Run C, was performed with the same operating conditions as shown for Run A (see fig.12) and with the same experimental setup. Optical access is provided through a window of less than 1 inch diameter. The distance between the probe and the liner surface was ca 400mm. The measurement is conducted on the inner lines therefore the signal is detected through the combustion flame. In contrast to the previous NGV

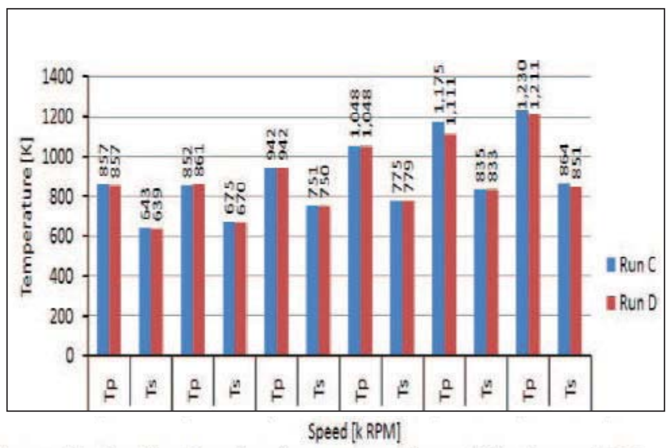


Figure 13: Combustion chamber; comparison of the Sensor TBC system with a commercial pyrometer for different speed conditions. T_p = pyrometer temperature reading; T_s = sensor coating temperature reading. The graph shows the average temperatures recorded for different operating conditions from 7,000 RPM to 13,500 RPM for two different runs. Both instruments show a remarkable repeatability.

measurements the background noise is substantially higher. This environment is very hostile for optical techniques and in particular for pyrometric measurements. As two observation windows were available for the combustion chamber, the second observation window was used to record the temperature measured by a pyrometer. This window was located directly opposite the first window looking at the equivalent position of the inner liner wall at 180°. The pyrometer was a LAND SOLOnet SN11 with a measurement range between 823K and 2023K. The pyrometer operates at a wavelength of 1mm, has a response time of 10ms and its emissivity was set to 1. Run C and D were performed using the exact same engine and instrumentation settings. The averaged temperature data for the pyrometer T_p and the sensor coating system T_s for both runs are plotted for different operating regimes indicated by different speeds in fig.13. Each operation regime lasted about 5 minutes. The commercial pyrometer T_p and the novel sensor system T_s show a high repeatability over the two runs for each operating regime. Further, in Run C and D the measured temperatures vary on average by 5K for T_s, the sensor coating system and by 15.6K for T_p, the commercial pyrometer.

At highest load the pyrometer indicates temperatures in excess of 1210K which is most unlikely as the surface of the inner liner is cooled with compressor air. The temperature of the compressor delivery air T_2 is well below 500K (see fig. 12) and hence will have a major impact on the liner temperature. An emissivity correction of the pyrometer for the ceramic surface would deliver even higher temperature readings. Further, it was observed that the gas stream temperature T_3 shows a lower temperature than T_p for the liner which is most unlikely. The authors conclude that the pyrometer data is unreliable. This is most probably due to stray light from the flame contributing to the total intensity detected by the pyrometer. Hence the pyrometer translated the extra intensity into a higher, but false, temperature reading for the liner. When comparing the T_s data recorded for the inner flame tube and for the NGV it appears that the NGV is hotter than the combustion chamber. This is not that surprising as the inner flame tube and the extreme ends of the NGV are significantly cooled using the compressor delivery air T_2.

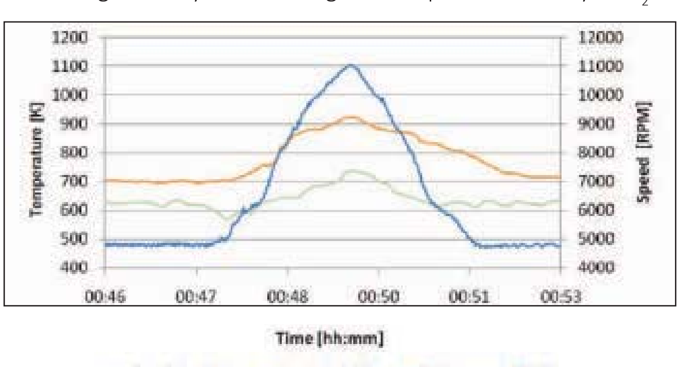


Figure 14: Rapid load increase: T_s is detected looking through a flame. The data from the inner liner can follow the strong temperature increase and shows a temperature peak at 750K.

However, the central part of the NGV where the measurements for T_s were taken is not cooled. Further the NGV takes the full load of the hot gas stream and this could explain the higher temperatures measured for T_s on the NGV in comparison to the combustion chamber.

An extra feature was introduced at the end of Run C as a rapid load increase from 5k to 11k RPM was performed (Figure 14). It can be seen that the STS system was able to follow this rapid temperature variation even when there is a high level of background noise caused by the flame. However, a noisy background above 11k RPM required an increase in integration time to ca 8 seconds for the sensor coating system. T_3 shows the gas stream temperature data is higher than the liner temperature and a difference of 190K is indicated at the peak load in fig. 14. This again is most likely an effect of the active cooling of the liner.

Turbine Blade Signal Detection

The final and most challenging task was the detection of a signal from a rotating turbine blade. The rotor disk included 113 blades of which 10 blades were coated with a sensor TBC. These ten blades consisted of five groups of two blades each. Each group received a different type of coating composition tailored for different possible operating conditions. (see Table 2). The turbine blades in the Viper engine can rotate at 13,500 RPM and this equates to ca 350m/s component velocity. The system was set to continuously fire the laser and record the resulting signal. An infrared blade detector was installed on the second optical window which enabled the tracking of individual blades – uncoated and coated. The STS system measured through the first observation window placed at 180° from the infrared blade detector. The signal from the STS measurement system could be correlated to the appropriate blade utilizing the signal from the infrared detector.

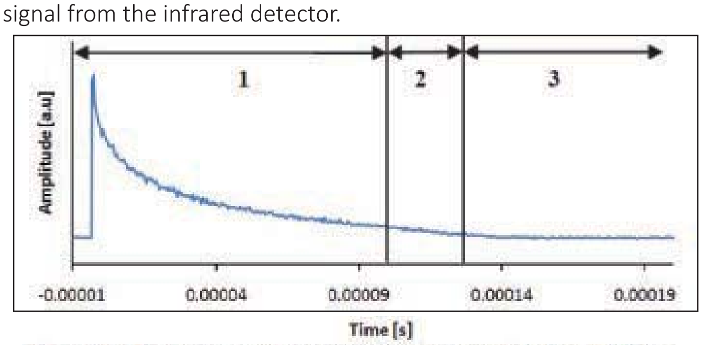


Figure 15: Life time decay phosphorescence signal from a turbine blade at a speed of 13,000 RPM using the OPETS probe. The signal from *YAG:Eu* is a single shot exposure and shows very low noise.

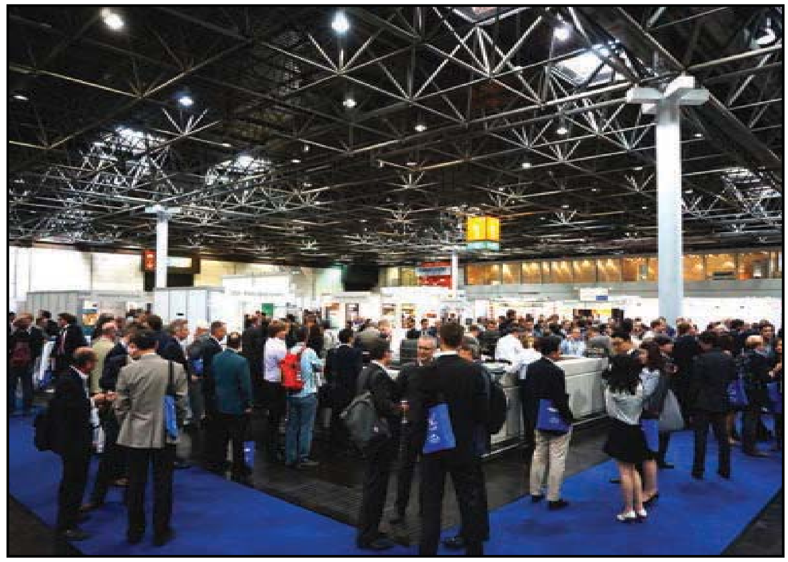
In order to measure the temperature on a moving part the right coating for the right temperature range and speed needs to be selected. As the temperature range in the Viper was expected to be below 1173K seven of the ten blades were equipped with ‘low temperature’ detection coatings. The correct sensor TBC is defined as having a phosphorescence decay lifetime short enough to be entirely observed while the measured component passes through the field of view of the OPETS. In the current case a YAG:Eu based phosphor was used with 532nm excitation wavelength to achieve short life time decays at low temperatures. The observation wavelength was 620nm. Utilizing the OPETS an undistorted life time decay signal was observed while the object moves across the FOV. A demonstration of the signal quality is given in fig.15 at a speed of 13k RPM. The signal can be divided in three parts. The first part (marked 1 in fig.15) is the signal viewed by the OPETS when the phosphorescence spot is entirely in the FOV. The length of the observation corresponds to 50mm observation path. The observation distance is ca 400mm. In the second part (marked as 2 in fig.15) the phosphorescence spot starts to leave the FOV and this can be observed as a more rapid drop in intensity. In the last part (marked as 3 in fig.15) the phosphorescence spot was totally outside the OPETS FOV and only a base line can be observed. The temperature associated with the life time decay shown in fig. 15 was 733K. This appears too low, but corresponds very well with the 723K reading of a thermocouple buried inside the edge of a NGV which was located only 40mm upstream of the rotor and was subjected to a stream of cooling air. The validation of the data is still in progress and will be reported at a later stage.

SUMMARY AND CONCLUSION

This paper has demonstrated for the first time the feasibility of implementing an entire sensor coating system on an operating engine and successfully detecting highly precise measurements. This was only possible by pushing technical boundaries in instrumentation design and algorithm development. **Sensor coating production:** the coating is of TBC architecture and is tailored to power generation applications. It was shown that these coatings can be produced on a production line without any difficulties. The coating structure is designed to survive many thousands of hours. **Instrumentation**: an advanced optical probe was specifically designed, manufactured, characterized and implemented to enable remote detection of a moving phosphorescent spot at speeds up to 350m/s. **Precision**: the comparison of the sensor coating system with a standard thermocouple measuring the temperature in the exhaust gas stream revealed that the precision of the new system was similar to that of the thermocouple and was of the order of 5K. The calibration error was estimated to be of the same order. However, the sensor coating system detects the temperature inside the coating which is related to coating life and engine performance. The Viper engine results demonstrate the capability of such a system to provide precise temperature readings in the most difficult environment of a gas turbine. However, for temperatures reaching 1773K other types of sensor coatings would need to be adopted and have been successfully tested already [7,14].

Paper GT2012-69913, Copyright 2012 by ASME, References and Acknowledgements available by request (igtinews@asme.org).

 ...Continued from page 74



“I am attending ASME Turbo Expo 2014 because it is the place to learn new technologies, research and expand my professional career.”

Turbo Expo Attendee

EXHIBIT HALL

Between sessions, attendees had the opportunity to visit the ASME Turbo Expo Exhibition Hall. From Tuesday through Thursday, the exhibit hall featured the latest technology offered by leading companies in the industry. Lunches and receptions occurred the exhibit hall each day and provided a relaxed, yet focused networking environment.

A VIEW FROM THE CHAIR

Dr. Seung Jin Song
ASME IGTI
Board Chair

Welcome back to the Global Gas Turbine News (GGTN), the quarterly news and events letter of the ASME International Gas Turbine Institute. We have had yet another record-breaking Turbo Expo in Dusseldorf with 1230 final papers (compared to 1154 papers at Turbo Expo in Copenhagen). Such sustained success is possible only with the dedication of our volunteers and staff, and I take this opportunity to thank all of you. Over the years, I have benefitted much from Turbo Expo and IGTI, and, therefore, I am particularly honored to take over the leadership of IGTI from Professor Karen Thole. She has selflessly served our community throughout her tenure on the Board, especially during the past year as the Chair. Thank you, Karen.

Recently, the IGTI Board reorganized itself to focus more on strategic issues and to develop additional leadership positions within IGTI to enable more of our members to contribute to the organization. The new five-member IGTI Board will retain focus on Turbo Expo but also look for new strategic opportunities, including regional/user-oriented IGTI events and joint efforts with other ASME groups or societies. This year's members are Piero Colonna, Howard Hodson, Allan Volponi, Vinod Philip, and myself. Reporting directly to the IGTI Board will be the newly formed Turbo Expo Executive Committee which is focused solely on organizing Turbo Expo. It will consist of the Past Chair of Conferences, Chair of Conferences, Executive Conference Chair, Technical Program Chair, Review Chair, three Vice Review Chairs, Chair of the Local Liaison Committee, and Exhibitor Representative. The Past Chair of Conferences will serve as the liaison between the IGTI Board and the Turbo Expo Executive Committee. As of now, 2015 Turbo Expo Committee members include, respectively, Howard Hodson, Geoff Sheard, Edward Hoskin, Damian Vogt, Tim Lieuwen, Jaroslaw Szwedowicz, John Chew, Anestis Kalfas, and Hany Moustapha.

Looking ahead, the Board will focus on the following :
1) Ensuring continued excellence at IGTI and Turbo Expo, starting with Turbo Expo's 60th Anniversary in 2015
2) Converting successful tracks to Committees after the recent expansion of the technical scope of IGTI (Fans & Blowers and Supercritical CO_2 tracks are planning to become Committees.)
3) Expanding globalization efforts, including more regional events (e.g. GT Latin America)
4) Strengthening support for students and early career engineers via scholarships, travel support, tutorials, and a student poster session at Turbo Expo.

For any questions regarding ASME Turbo Expo 2015, please contact Tim Graves at gravest@asme.org. If you have comments or questions, please feel free to contact me at sjsong@snu.ac.kr.

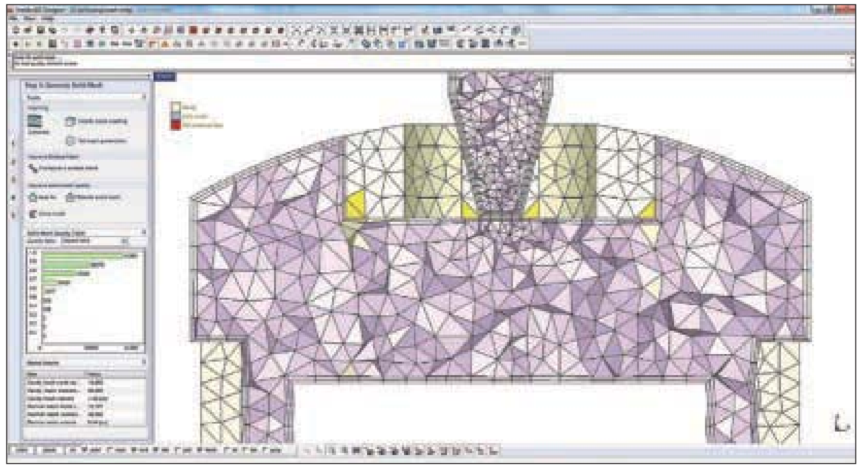
Women in Turbomachinery Event during ASME Turbo Expo this past June.
Join us in Montreal for ASME Turbo Expo 2015!

Turbo Expo Sponsors
PLATINUM
SILVER
BRONZE
ADDITIONAL

ANALYZE PLASTIC MOLDS

CORETECH SYSTEM, HSINCHU, TAIWAN.

Moldex3D revision 13 is a validation and optimization application for industrial design and manufacturing using plastics. With the simulation software, customers can visualize the plastic melt front behavior inside the mold cavity and predict potential molding problems before manufacturing. It also helps users validate design or process changes to work more efficiently. The application aids users in achieving specific industrial or environmental targets, such as lightweight design for automotive frame structure, according to the developer.



The plastic mold optimization software Moldex3D generates high-resolution solid meshes for complex model designs. It supports industry-specific molding simulation and validation.
Image: CoreTech Systems

CMM PROGRAMMING

VERISURF, ANAHEIM, CALIF.

Verisurf Automate has a 3-D CAD measurement platform that programs and automates all types and brands of coordinate measuring machines—portable CMM arms, scanners, laser trackers, optical trackers, and programmable stationary CMMs. The 3-D environment includes an object-oriented operations manager, CAD feature extraction, and solid model associativity. Ease of use is enhanced with file recognition, customizable user configurations, and drag-and-drop operations reordering.

ANTENNA DATABASE

MAGUS, STELLENBOSCH, SOUTH AFRICA.

Magus has teamed with Computer Simulation Technology of Darmstadt, Germany, to release Antenna Magus version 5.0, which gives engineers access to a database of 250 antenna types and now includes a "smart design" function. This feature automatically suggests practical design objectives and, as needed, can convert information provided by the designer into various antenna representations. A new feature of version 5.0 includes the library of specifications. This library incorporates the properties of typical design specifications used in various industries. Specification information can be added to the application by the user and can be stored and recalled for re-use in later design projects. All elements of a design, such as parameter values and 3-D images, can also be saved to file or clipboard in various text and image formats, providing easy access to resources for reporting.

CAPTURE MANUFACTURING DATA

HEXAGON METROLOGY, NORTH KINGSTOWN, R.I.

The measurement software PC-DMIS 2014 is used for the collection, evaluation, management, and presentation of manufacturing data. It is compatible with a range of available measurement equipment from various vendors. This update includes tools to increase performance of measurement devices and the effectiveness of inspection planning time. Completing complex inspection routines has been made easier than in past versions of the software. Highlights include the capability, with one click, to create features from CAD. Users can also create these features by hovering their mouse over a CAD model to highlight CAD elements. A quick-align capability allows users to select combinations of features to create a quick alignment.

PUMP SYSTEM SIMULATIONS

OPTIMIZED THERMAL SYSTEMS, COLLEGE PARK, MD.

The advanced vapor compression cycle design and analysis tool VapCyc can be used to simulate refrigeration, air conditioning, and heat pump systems. Multiple configurations are possible, with the ability to change and customize components. Connecting tubes, suction-line heat exchangers, two-stage compressors, inter-coolers, and fans can also be modeled. The parametric analysis capability incorporated in the program can help in developing catalog data. The optimization feature allows the user to explore a complete design space with multiple variables and constraints, but with reduced computation time.

PLATFORM DEVELOPMENT

OPEN DESIGN ALLIANCE, PHOENIX

Teigha, a software development platform for engineering applications, has been upgraded to version 4.0. The developer is a nonprofit consortium of software developers involved in design. Members commit to open industry-standard formats for the exchange of CAD data. The Teigha platform gives developers tools to create a variety of applications. The upgraded version contains the alpha release of Teigha Cloud, the developer's framework for cloud-based rendering of .dwg (drawing) and .dgn (design) files. This cloud framework is intended to give users access to information and processing on mobile devices in order to minimize development time. It also enables users to deploy their applications without obligation to a hosting service. To that end, Teigha 4.0 contains enhanced support for mobile platforms, including Java support for Android. ME

SUBMISSIONS

Submit hard copy or e-mail memag@asme.org, using subject line "Software Exchange." *ME* does not test or endorse software described here.

EXPLOSION-PROOF MOTORS

WEG ELECTRIC CORP., ATLANTA.

THE COMPANY IS ADDING FRACTIONAL horsepower models to its line of NEMA premium and high-efficiency explosion-proof motors. The new fractional hp motors are available in single-phase and three-phase versions. Two-pole motors range from 1/3 hp to 2 hp; four-pole models, from 1/3 hp to 1.5 hp.

TEMPERATURE TRANSMITTER

MOORE INDUSTRIES- INTERNATIONAL INC., NORTH HILLS, CALIF.

The THZ WirelessHART temperature solution combines the company's THZ Smart HART temperature transmitter and the BULLET WirelessHART adapter by MACTek into a self-powered package. The new WL housing includes a battery case that takes off-the-shelf D-type lithium batteries to power the transmitter and the BULLET. This saves on installation, maintenance, and repair costs associated with wiring, and eliminates the need to stock special batteries.

HIGH-AMPERAGE CLIPS

MUELLER ELECTRIC CO., AKRON, OHIO.

High-amperage clips incorporate a heavy duty, glass-filled polyamide handle. A high-impact glass filled nylon clip body also offers a cleaner look. Each bus bar within these high-amperage clips has been designed and field-tested to ensure effective heat dissipation. The BU-102B clips feature serrated jaws, created from stamped 100 percent copperplate and the BU-102W welding jaws are machined from 100 percent copper slugs with serrated teeth, ensuring their reliability in welding applications. The clips have been tumble tested to withstand thousands of cycles.

TEMPERATURE DATA LOGGER

OMEGA ENGINEERING, STAMFORD, CONN.

The new wireless RTD temperature data logger features a digital display that shows data in real time along with a battery life indicator and audible and LED alarm indicators. The OM-CP-RFRTDTEMP200A has wireless two-way communication, is field upgradeable, and has a cumulative alarm delay feature. This data logger is used for applications that require high-accuracy temperature monitoring, not only in laboratories but also in chemical, pharmaceutical, and food processing environments.

SOLENOID VALVES

GEMS SENSORS & CONTROLS, PLAINVILLE, CONN.

The Gems BL Series is designed to support fluid control requirements, such as those common to natural gas separation, natural gas plunger lifts, gas chromatography equipment, irrigation systems, and pneumatic pipelines. Offered with choice of either two-way or three-way design, the BL Series allows a user to pulse the valve itself. This facilitates its change of state into a closed or open position, depending upon requirement, with fast response times.

RETAINING MAGNETS

J.W. WINCO INC., NEW BERLIN, WIS.

Retaining magnet assemblies with rubber jackets are suitable for applications where a surface is easily marred. The magnets have an increased coefficient of friction, which creates high lateral retaining force. The RoHS-compliant magnet assemblies have a zinc-plated steel housing and a magnet of neodymium, iron, and boron. The rubber jacket is made of black elastomer. Assemblies are offered with matte black ball knob or nickel-plated steel.

PROCESS CONTROLLERS

SPIRAX SARCO INC., BLYTHEWOOD, S.C.

The SX80 temperature controller provides a universal process input and universal output making the SX80 a controller that can be used for multiple applications. The SX90 has been developed for processes that demand a high level of functionality with multiple inputs and outputs. The SX90 provides universal input, three logic inputs, remote set point, potentiometer input, two analog outputs, valve motor drive output and three relay outputs.

LED LUMINAIRES

CROUSE-HINDS BY EATON, SYRACUSE, N.Y.

New Champ LED luminaires range from 13,000 to 25,000 lumens—400 W to 1,000 W high-intensity discharge equivalents—and are designed for mounting heights of up to 60 feet. The luminaires are suitable for use in oil and gas, mining, and other heavy industrial applications where vibration and harsh environmental conditions are common. Available in both hazardous area and ordinary location versions, the fixtures provide an energy-efficient option for areas that require continuous and consistent light levels.

BORE GAUGES

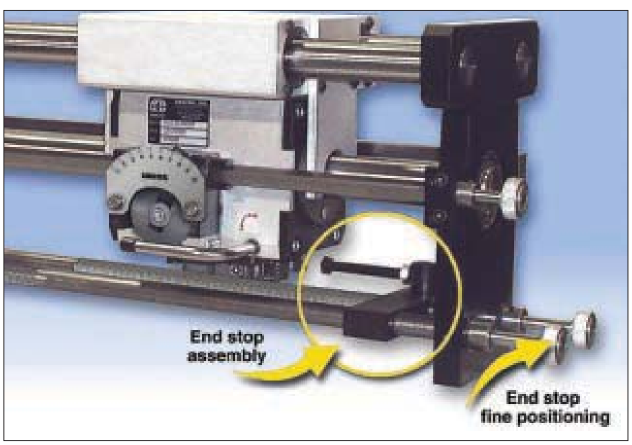
SUNNEN PRODUCTS CO., SAINT LOUIS.

GR-2245/2241 bore gauges combine rugged design with precise measurement to 0.0001 inch for heavy-duty large-part machining. Standard models are capable of checking bore diameters from 2 to 12 inches (50.8 to 300 mm) and bore lengths up to 24 inches (600 mm) with appropriate attachments. Special-order models can measure bores up to 65 inches (1,650 mm) long. GR-2245/2241 gauges are good for energy industry components, such as flow meter tubes, liner hangers, drill pipe, mud pump liners, and sucker rod pump barrels.

HEAVY-DUTY ALTERNATORS

PRESTOLITE ELECTRIC INC., PLYMOUTH, MICH.

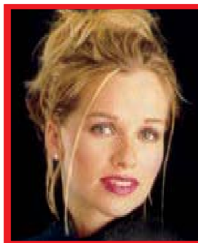
A new AVi2800 alternator from Leece-Neville replaces the division's 2800 series, which has been used in heavy-duty applications since the 1990s. The new alternator at 7.4 kg (16.3 lbs.) is 33 percent lighter than the original 2800 and provides 30 additional amps—190 A vs. 160. It has a compact, internal fan design, and a working temperature range from -40 to 125 °C. It is intended for heavy-duty use, including trucks and school buses.



FINE TRAVEL ADJUSTMENT

AMACOIL INC., ASTON, PA.

The Model RG linear drive assemblies now feature an option for fine adjustment of travel distance. The option enables more precise location of the drive unit reversal points. This is useful in linear motion applications where precision setting of the reversal points enhances process accuracy and integrity. The Model RG drive is used in various types of production equipment including packaging machinery, wire and cable spooling equipment, and other automated machinery with a linear motion component.



Always The Best Values In Small Vibration Test Systems And Digital Vibration Controllers!

SINCE 1974

100 lbf Vibration Testing System $7,128
Complete with Vibrator, Trunnion, low-noise Blower, low-distortion Linear Amplifier.

500 lbf Vibration Testing System $23,977
Complete with Vibrator, Trunnion, Blower, low-distortion Linear Amplifier, Instrument Cabinet.

NEW! **Accelerometer Cal System**
Complete with Vibrator, low-distortion Linear Amplifier, and a calibration standard Accelerometer.
40 lbf Vibration System $7,429

NEW! **Digital Vibration Controller Systems**
Each includes an Expansion Card and Software Package to convert your PC to a Digital Vibration Controller. (computer not included)
Sine $5,995 **Random** $5,995
NEW! **4-Channel Swept-Sine, Random & Classical Shock** with Built-In Current Sources $7,990
Head Expander 7x7 $1,105

Vibration Stress Screening Systems for production lines
Please download demo disk from our website.


25 - 600 lbf Electrodynamic Vibrators


Low-Distortion Linear Amplifiers


Digital Controllers

Digital Controllers Programmed For Windows Operation!

VTS
VIBRATION TEST SYSTEMS
10246 CLIPPER COVE, AURORA, OHIO 44202
330/562-5729 Fax 330/562-1186
www.VTS2000.com

Vibration Systems for modal testing, research and development, product qualification, vibration screening and vibration demonstration.

Made in the U.S.A.

TORMACH® Personal CNC

Shown here is an articulated humanoid robot leg, built by researchers at the Drexel Autonomous System Lab (DASL) with a Tormach PCNC 1100 milling machine. To read more about this project or to learn about Tormach's affordable CNC mills and accessories, visit www.tormach.com/mem.

www.tormach.com/mem

SILICONE CURATIVE

SIVANCE LLC, SPARTANBURG, S.C.

C1008 Curative is a new silicone curative that improves the durable flexibility of epoxy polysiloxane protective topcoats in marine and infrastructure applications, without sacrificing weatherability. The development of this new curative technology solves a challenge common to epoxy polysiloxanes: brittleness and cracking that can develop over time as the coating cures. In addition to demanding marine topcoat applications where resistance to sea water, ultraviolet light, and chemicals is critical, SiVance's new curative technology is designed for coating piping, bridges, and wind turbines.

COMSOL CONFERENCE 2014 BOSTON

October 8-10
Boston Marriott Newton
Newton, MA

The Multiphysics Simulation Event of the Year

- ✓ Keynotes from Boston Scientific, Ford, Oak Ridge National Laboratory, and WiTricity
- ✓ Application Builder hands-on training for designing COMSOL Applications
- ✓ 30 application-specific minicourses, including meshing, solvers, and postprocessing
- ✓ Over 150 presentations to attend
- ✓ Connect with COMSOL Users and Developers

Learn more at www.comsol.com/conference2014

GOLD SPONSORS

SILVER SPONSORS

MEDIA SPONSORS

© 2014 COMSOL.

COMSOL

INDUSTRIAL FAN

MACROAIR FANS, SAN BERNARDINO, CALIF.

AirVolution-D is powered by a motor technology called D-Drive, which can handle the torque requirements of a 24-foot diameter industrial fan. A smart processor called AirBrain can automatically adjust to different power sources and allow users to access real-time performance analytics. D-Drive eliminates the need for a gearbox, thus reducing weight and the number of moving parts. Fans are available in sizes from 6 to 24 feet.

WIRELESS PRESSURE SENSOR

TRANSDUCERS DIRECT, CINCINNATI.

The new TDWLB pressure/temperature sensor is powered with a coin-cell battery, controlled with a smartphone app, and certified as Bluetooth Smart. Developed for home automation, industrial, marine, and commercial applications, the TDWLB uses a patent-pending design and proprietary digital circuitry for high energy efficiency to provide an 18- to 24-month battery life and redundant sensing.

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.

R&D Engineers

Creare, a leader in cutting-edge R&D, conducts applied research, develops new technologies, and provides analysis, design, experimental, computational, product, and consulting services to industry and government. Project teams are small and engineer-led, and individuals have significant opportunity to pursue areas of technical interest.

At Creare's location in Hanover, NH, we have over 80 active R&D projects which span the following areas:

- **Fluid Mechanics/Heat Transfer**
- **Analog/Digital Electronics**
- **Structures**
- **Cryogenics**
- **Software Development**
- **Signal/Image Processing**
- **Biomedical**
- **Combustion**
- **Applied Mechanics**
- **Manufacturing Processes**

We are looking for exceptional engineers with the passion, creativity, and skills to pursue varied technical research in a multi-disciplinary environment.

Professional requirements: Ph.D. with exceptional academic achievement and/or Masters with the same plus 5 or more years of relevant industrial experience. Engineering degree majors include: Aeronautical, Biomedical, Chemical, Electrical, Mechanical, and Nuclear.

This position requires U.S. Citizenship or U.S. Permanent Residency.

Engineering Excellence Since 1961

Creare

Apply at www.creare.com

For assistance, email careers@creare.com

(Krē • är′• ē : from Latin "to create").

Creare is an equal opportunity employer M/W/D/V.

THE UNIVERSITY OF ALABAMA

DEPARTMENT OF AEROSPACE ENGINEERING AND MECHANICS

FACULTY POSITION IN SPACE AND ASTRONAUTICS

The Department of Aerospace Engineering & Mechanics at The University of Alabama invites applications for a tenure-track faculty position in areas related to space and astronautics. While all applications will be considered, highest priority will be given to candidates with expertise in guidance, navigation, and control (GNC). It is anticipated that the successful candidate will join the faculty at the rank of tenure-track Assistant Professor, although exceptional candidates may be considered for higher rank depending upon experience and qualifications.

With 17 tenured and tenure-track faculty members, the AE&M department enrolls 200+ undergraduate students in the ABET-accredited BSAE program and 50+ graduate students in the MS and PhD programs. The AE&M Department is currently experiencing an era of unprecedented growth and expansion. The AE&M department benefits from the University's rapid expansion in terms of facilities, including the recent construction of the $300 million Engineering and Science Quad. This four building complex provides over 900,000 square feet of state-of-the-art research and instructional space, the majority of which is devoted to the College of Engineering.

The University of Alabama is located on a beautiful 1,168 acre residential campus in Tuscaloosa, a dynamic and resilient community of over 150,000. The Tuscaloosa community provides rich cultural, educational, and athletic activities for a broad range of lifestyles. With technology-oriented government/industrial research centers (including the U.S. Army's Redstone Arsenal and the NASA Marshall Space Flight Center) in north Alabama and a growing aviation industrial sector (including Airbus aircraft manufacturing & engineering centers) in south Alabama, The University of Alabama is centrally located in Alabama's north-south aerospace corridor.

Applicants must have an earned doctorate degree in aerospace engineering or a closely related field. Applicants are to submit: a letter of application, a detailed CV, statement of teaching & research interests, and contact information for at least three professional references. Successful applicants are expected to develop a strong externally-funded research program, demonstrate a commitment to excellence in teaching & mentoring of students, and provide service to the profession, university, college of engineering and AE&M department. All application materials must be submitted via The University of Alabama's employment website (https://facultyjobs.ua.edu, requisition number 0808972). Review of applications will begin immediately and will continue until the position is filled. Inquiries should be addressed to Dr. John Baker, Department of Aerospace Engineering & Mechanics, Box 870280, The University of Alabama, Tuscaloosa, AL 35487-0280 or sent by e-mail to john.baker@eng.ua.edu.

Qualified women and minorities are encouraged to apply. The University of Alabama is an equal opportunity, affirmative action, Title IX, Section 504, ADA employer. Salary will be competitive and commensurate with experience level.

PENNSTATE 1855

NEW FACULTY SEARCHES IN MECHANICAL ENGINEERING AND NUCLEAR ENGINEERING

The Department of Mechanical and Nuclear Engineering at The Pennsylvania State University is pleased to announce a significant growth of faculty over the next three years. It is expected that the faculty will expand by 25% with ten new tenure-track positions in mechanical engineering. This year, the Department is seeking excellent applicants to fill five tenure-track positions in mechanical engineering and two tenure-track positions in nuclear engineering. The areas of interest for mechanical engineering include, but are not limited to: manufacturing and materials processing, cyber-physical systems, energy systems, multi-scale modeling, instrumentation and controls, biomechanics and biomedical devices, automation, and other emerging areas. The areas of interest for nuclear engineering include, but are not limited to: nuclear power and science, reactor physics, nuclear fuel cycle, nuclear materials, and other emerging areas. Applicants should have demonstrated outstanding scholarly research experience and teaching interests in mechanical engineering, nuclear engineering, or a related field.

The Department is home to 50 faculty, 270 graduate students, and 1000 undergraduate students. The faculty conduct in excess of $27M per year of funded research across a broad spectrum of traditional and emerging areas. Penn State actively encourages and provides resources for interdisciplinary research collaboration through university-level institutes primarily focused on materials, cyberscience, health, and energy. The Department offers separate B.S., M.S., and Ph.D. degree programs in both mechanical engineering and nuclear engineering, including distance graduate programs in both mechanical and nuclear engineering. Further information on the Department can be found at: http://www.mne.psu.edu/.

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

Nominations and applications will be considered until the positions are filled. Screening of applicants will begin on October 15, 2014. Applicants should submit a statement of professional interests, a curriculum vitae, and the names and addresses of four references. Please submit these three items in one pdf file electronically to job #52555 at http://www.psu.jobs.

Employment will require successful completion of background check(s) in accordance with University policies. Penn State is committed to affirmative action, equal opportunity and the diversity of its workforce.

POSITION OPEN
Toyota Technological Institute

Toyota Technological Institute has an opening for a professor position at Department of Advanced Science and Technology, Faculty of Engineering. For more information, please visit:

http://www.toyota-ti.ac.jp/english/employment/index.html

Position: Full professor or tenure-track professor

Research field: Fluid mechanics or fluid engineering

Qualifications: The successful candidate must have a Ph.D. degree in a relevant field, a record of outstanding research achievements, and ability to conduct both experimental and analytical research programs in the specified area. The candidate is expected to teach mathematics and mechanics in the basic course as well as fluid mechanics and fluid engineering in the advanced course. The supervision of undergraduate and graduate students in their research programs is also required.

Start date: April 1, 2015 or at the candidate's earliest convenience

Required documents:
1) Curriculum vitae
2) List of research activities
3) Copies of 5 representative papers
4) Brief summary and future plan of your research and education *(within 3 pages each)*
5) Names of two references including phone numbers and e-mail addresses
6) An application form *(available on our website)*

Deadline: October 31, 2014

Inquiry: Search Committee Chair
Professor Yasutake Ohishi

CONSULTING

Design Engineering Analysis Corporation

Stress Analysis • Strain Gage Testing
Fracture Mechanics • Failure Analysis
Dynamics • Vibration Measurements
Fluid Mechanics • Heat Transfer
FEA and CAD Services
ASME Code Calculations

Advanced Engineering Solutions

335 Morganza Road
Canonsburg, PA 15317
Phone: (724) 743-3322
Fax: (724) 743-0934
www.deac.com
info@deac.com

POSITIONSOPEN

THE UNIVERSITY OF BRITISH COLUMBIA Tenure-track Instructor position Sustainability Engineering and Public Policy The Departments of Mechanical Engineering and Chemical and Biological Engineering at the University of British Columbia-Vancouver seek an outstanding individual for a tenure-track position at the Instructor level in Sustainability Engineering and Public Policy. The starting date will be January 2015, or as soon as possible thereafter. Applicants will be expected to teach in, and help manage, Professional Masters programs including the Clean Energy Master of Engineering Program, and to teach courses at the undergraduate and graduate levels related to sustainability. The successful applicant will be expected to be highly engaged in curriculum development and pedagogical innovation at the Departmental and Faculty level. Applicants must have either demonstrated or possess a clear potential and interest in achieving excellence in teaching and learning, and in providing service to the University and community. Experience in areas such as engineering and the environment, engineering and public policy, sustainability education, and the impact of engineering on society is required. Entrepreneurial or industrial experience is an asset. She/he will hold a Ph.D. degree in a relevant area, and will be expected to register as a Professional Engineer in British Columbia. Further information on the departments is available at www.mech.ubc.ca and www.chbe.ubc.ca and information on the employment environment in the Faculty of Applied Science is available at www.apsc.ubc.ca/careers. The University of British Columbia hires on the basis of merit and is committed to employment equity. All qualified persons are encouraged to apply. UBC Applied Science especially welcomes applications from members of visible minority groups, women, Aboriginal persons, persons with disabilities, persons of minority sexual orientations and gender identities, and others with the skills and knowledge to engage productively with diverse communities. Applicants are asked to complete the following equity survey: https://www.surveyfeedback.ca/surveys/wsb.dll/s/1g3622. The survey information will not be used to determine eligibility for employment, but will be collated to provide data that can assist us in understanding the diversity of our applicant pool and identifying potential barriers to the employment of designated equity group members. Your participation in the survey is voluntary and anonymous. This survey takes only a minute to complete. You may self-identify in one or more of the designated equity groups. You may also decline to identify in any or all of the questions by choosing "not disclosed." Canadians and permanent residents of Canada will be given priority for the position. The position is subject to final budgetary approval. Applicants should submit a curriculum vitae, a statement of 1 to 2 pages in length detailing teaching interests and accomplishments, and the names and addresses (including e-mail addresses) of four references. Applications should be submitted online at http://www.hr.ubc.ca/careers-postings/faculty.php. Deadline for applications is October 1, 2014. Please do not forward applications by e-mail.

NANJING TECH UNIVERSITY FACULTY POSITIONS IN COLLEGE OF MECHANICAL AND POWER ENGINEERING This announcement invites applications for tenure-track faculty positions in: Mechanical Engineering, New Energy Science and Engineering, Welding Technology and Engineering, Mechanical Design Manufacturing and Automation, Vehicle Engineering, Process Equipment and Control Engineering. Required Qualifications: Ph.D. in Mechanical Engineering or a closely related field is required. Initial appointments are at the assistant professor level. Exceptionally qualified candidates at the associate or full professor level may also be considered. Rank and salary are commensurate with experience and accomplishments. To apply for a position, candidates should send applications and required materials to chunlei-shao@njtech.edu.cn. The following materials are required for submission of an application: A CV, a list of publications, statements of research and teaching plans are required. Applications received before December 31, 2015 will be guaranteed full consideration. Additional information is available at http://www.njtech.edu.cn.

FOR ALL

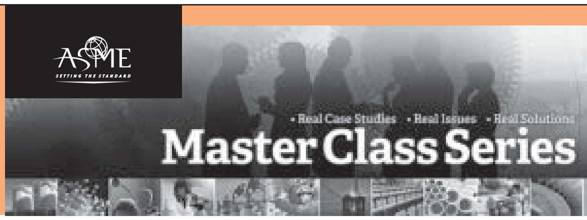
ADVERTISING AND SPONSORSHIP

OPPORTUNITIES

CONTACT

GREG VALERO

(212) 591–8356 valerog@asme.org



Register Now to Attend the ASME MasterClass Series on

Boiler, Pressure Vessel and Piping Technologies and Standards

November 10-13, 2014 • New Orleans, LA

Led by industry experts and Codes & Standards leaders, the ASME MasterClass Series on Boiler, Pressure Vessel and Piping Technologies examines proven techniques and strategies to explain application of critical design rules and technologies to address today's issues. This MasterClass Series will include:

- Design by Analysis Requirements in ASME Boiler & Pressure Vessel Code Section VIII, Division 2 (MC107)
- Techniques & Methods Used in API 579-1/ASME FFS-1 for Advanced Fitness-For-Service (FFS) Assessments (MC113) NEW
- Repair Strategies and Considerations for Pressure Vessels and Piping (MC114) NEW
- Application of Piping Flexibility Analysis to ASME B31 Codes (MC110) NEW
- Structural Materials and Design for Elevated to High Temperatures (MC112) NEW

... and more!

Register Now and Save $200. Early Bird discount expires on October 13, 2014.

For full descriptions of MasterClasses offered during this event and to register, visit

go.asme.org/MCseriesNov2014

FOR ALL
RECRUITMENT ADVERTISING INQUIRIES

CONTACT:
MICHELLE LEWITINN
(212) 591-8379
LewitinnM@asme.org

ADVERTISER INDEX

To purchase or receive information from our advertisers, go to **http://me.hotims.com**, visit the advertiser's website, or call a number listed below.

	PAGE	WEBSITE	PHONE
ASME Congress	28-29	asmeconferences.org/congress2014	
ASME Insurance	C3	ASMEInsurance.com/DIP	800-289-ASME
ASME Job Board	72	jobboard.asme.org	
ASME MasterClass Series	93	go.asme.org/MCseriesNov2014	
ASME Training & Development	46-47	go.asme.org/training	800-843-2763
ATI Industrial Automation	20	ati-ia.com/mes	919-772-0115
Clippard	25	clippard.com	877-245-6247
Computational Dynamics (CD-Adapco)	15	cd-adapco.com	919-772-0115
COMSOL, Inc.	C4	comsol.com/introvideo	
COMSOL (Conference)	90	comsol.com/conference2014	
COMSOL (Webinar)	C2	http://bit.ly/me-webinar-Sept18	
CRC Press/Taylor & Francis	87	CRCPRESS.COM	
Dell	7	Dell.com/CAD	
Forest City Gear	88	forestcitygear.com	815-623-2168
Master Bond, Inc.	86	masterbond.com	201-343-8983
Newark/element14	5	newark.com	800-463-9275
Omega Engineering, Inc.	23	omega.com	888-826-6342
Proto Labs, Inc.	13,17	go.protolabs.com/ME4B go.protolabs.com/ME4C	877-479-3680
Smalley Steel Ring, Inc.	22	smalley.com/getcatalog	847-719-5900
Structural Integrity Associates	21	structint.com/asme	877-4SI-POWER
Tormach	89	tormach.com/mem	716-645-2771
US Tsubaki	9	ustsubaki.com	800-443-4216
Vibration Test Systems	89	VTS2000.com	330-562-5729
XYZ Scientific	14	truegrid.com	925-373-0628

RECRUITMENT

CONSULTING

NAGANATHAN INTERIM PRESIDENT AT TOLEDO

ASME FELLOW NAGI NAGANATHAN HAS been appointed interim president of the University of Toledo. Naganathan has been dean of the university's College of Engineering.

Naganathan is the author and co-author of more than 100 publications in peer-reviewed journals and national and international conference proceedings, and as a principal and co-principal investigator has secured more than $6 million in sponsored research from outside agencies. He also has been awarded a U.S. patent on the use of piezoelectric devices in active suspension systems.

Naganathan's work with industry includes conducting vibration analysis and control studies on heavy-duty truck powertrains.

He earned his bachelor's degree with honors in mechanical engineering from India's National Institute of Technology at Tiruchirappalli, University of Madras; a master's degree in mechanical and industrial engineering from Clarkson University in Potsdam, N.Y.; and a Ph.D. in mechanical engineering from Oklahoma State University.

Naganathan has received a number of awards, including the ASME Outstanding Regional Faculty Advisor Award and the Society of Automotive Engineers Ralph R. Teetor Educational Award.

WARE RECEIVES THE ZAMRIK MEDAL

ARTHUR G. WARE, AN ASME FELLOW and active volunteer, received the 2014 S.Y. Zamrik PVP Medal in July during the ASME Pressure Vessels and Piping Conference in Anaheim, Calif.

The award recognizes Ware's numerous services to ASME and the Pressure Vessels and Piping Division, as well as his significant contributions to the design, analysis, licensing, and license renewal of nuclear power plants worldwide.

Ware has worked for Bettis Atomic Power Laboratory, the Naval Reactors Facility, Babcock & Wilcox Co., the Idaho National Laboratory, and Applied Engineering Services Inc.

His responsibilities have included analysis of naval nuclear plants, structural and safety analysis for Department of Energy test reactors, contributions to the development of ASME Code Case N-411 (nuclear piping

ASME FELLOW LARRY LEE

ASME FELLOW J. LAWRENCE (LARRY) LEE was featured in the season premiere of the television show *History Detectives: Special Investigations*, which airs on PBS stations throughout the United States.

The episode concerned itself with various theories surrounding the catastrophic boiler explosion on the steamship *Sultana* in 1865. The episode can now be viewed online on the television show's website.

Considered one of the greatest maritime disasters in U.S. history, the sinking of the *Sultana* resulted in the deaths of more than 1,800 people—many of them Civil War prisoners being transported home. Although the hosts of *History Detectives* considered several theories for the explosion of the *Sultana*, including whether it was an act of sabotage carried out by a Confederate agent, Lee said he believes that the disaster was an accident brought about by a series of bad decisions.

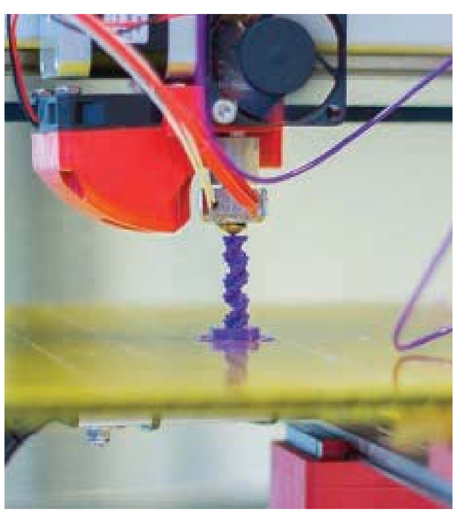
According to Lee, who is the immediate past chair of the ASME History and Heritage Committee, those errors in judgment included patching a boiler plate with one made of thinner iron than was used to build the boiler, and loading the ship with six times the number of people it was intended to carry.

Lee heats an improvised boiler to test a theory.

"The boat was very overcrowded, and this mass of people was out on the sides and up top," said Lee, engineer-historian for the National Park Service's Historic American Engineering Record program. "They were going to make the boat very easy to rock. As they navigated up the river, the boat was going to rock and roll. The boilers mounted on the boat did the same thing. They're going up and down," causing the water in those boilers to slosh back and forth.

This severe sloshing can lead to portions of the boiler shell to go "dry" for a period of time, Lee observed. The dry metal over the ship's firebox can become red hot and weaken within seconds. When the boat rolls back, the water coming in contact with the scorching metal turns instantly into steam, causing a spike in pressure beyond what the weakened

SEE THE EPISODE AT http://to.pbs.org/UkFVpt



CONGRESSIONAL

ASME, THE NATIONAL SCIENCE FOUNDATION, and *Discover* Magazine partnered to convene a briefing for Congress to address issues in advanced manufacturing.

The briefing, which was held in June, provided information to congressional staff on advances in manufacturing technology, especially as it deals with the "maker movement" and significant advances in 3-D printing. The briefing was held a day before the White House held its first-ever Maker Faire, a day to celebrate makers, innovators, and entrepreneurs of all ages who are using cutting-edge tools like 3-D printers and easy-to-use design software to

HELPS HISTORY DETECTIVES

Engineering historian Larry Lee (right) said water sloshing in a superheated boiler may have caused the Sultana *explosion.*

metal can withstand. Under such circumstances, a rupture is a near certainty, he said.

At the end of the 19th century, there were some 100,000 commercial boilers in service in the United States, but rules governing the manufacture, operation, and maintenance of steam boilers were non-existent, which greatly compromised the safety of these boiler operations. More than 2,000 boilers exploded in the United States from 1880 to 1890. Those accidents increased the urgency for boiler standards and the development of the Code for the Conduct of Trials of Steam Boilers by the American Society of Mechanical Engineers. Ultimately, this led to the first edition of the ASME Boiler Code. Published in 1914, the Code was a collaboration of manufacturers, operators, steel fabricators, utilities, and others that had a stake in boilers and boiler safety.

Lee said that he found filming the episode a very enjoyable experience and he was happy with the finished results. "It was a great gig—a lot of fun," he said. "It was a very professional deal. I didn't know quite how it was going to be edited. I was pleased when I saw the show, and glad that ASME received some recognition. All of the comments I've gotten on it have been very favorable.

"I hope they call back. I'd love it if some other opportunities like this came up." ■

damping), resolution of Generic Issue 113 (large bore hydraulic snubbers), and a license renewal procedure for fatigue analysis of reactor components under environmental conditions.

A private consultant since 2001, Ware has performed DOE seismic analyses, conducted engineering marketing, delivered seminars, and reviewed licensing and licensing renewal applications for the NRC.

Ware has been an ASME member since 1979 and a Fellow since 1995. He has served key roles in the ASME National Nominating Committee, the Seismic Engineering Committee of the Pressure Vessels and Piping Division, the PVP Executive Committee, and various PVP conferences. He is a member of the PVP Senate of Past Chairs and served on the PVP Financial Committee since 2001. He has received more than ten ASME Awards, including a Best Paper Award from the *Journal of Pressure Vessel Technology* and the Dedicated Service Award.

Ware has received degrees from Virginia Polytechnic Institute and Stanford University. He is a registered professional engineer in the state of Idaho.

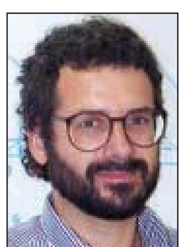
Established as the Pressure Vessel and Piping Medal in 1980, the award was renamed the S.Y. Zamrik PVP Medal in 2010. It is bestowed for outstanding contributions in the field of pressure vessel and piping technology.

BRIEFING ON ADVANCED MANUFACTURING

bring their ideas to life.

The speakers detailed how enabling "made to order" manufacturing is vital to the future of U.S. manufacturing. Manufacturing production is growing at its fastest pace in more than a decade, creating more economic value per dollar spent than any other sector. Adding to this surge is customization, the ability to quickly and efficiently make what you want, when you want it.

Steven Schmid, a professor from the University of Notre Dame and former ASME Foundation Swanson Fellow, opened the briefing by discussing the significant advances in manufacturing technology. He also showed how the United States is being out-invested by other countries around the world when it comes to manufacturing research. Schmid said that, if the United States is to remain an economic leader in the future, there is a great need for the U.S. to invest in the manufacturing sector now to ensure industry has the best technology moving forward.



Neil Gershenfeld

Another speaker during the briefing, **Neil Gershenfeld**, a professor at Massachusetts Institute of Technology, spoke about how large-scale customization is now possible due to a combination of Internet-based business platforms and technological advances in manufacturing. From 3-D printing to cyber-physical manufacturing systems, current and future engineering research holds promise to improve productivity in both production and the supply chain, benefiting suppliers and customers along the way. ■

FOR MORE INFORMATION

Primary sources for this article are Dieter von Jezierski's *Slide Rules, a Journey Through Three Centuries,* translated by Rodney Shepherd (Astragal Press, 2000) and Florian Cajori's *A History of the Logarithmic Slide Rule and Allied Instruments* and *On the History of Gunter's Scale and the Slide Rule*, published in 1900 and reprinted by Astragal Press in 1994. Cajori's book can be downloaded at http://www.sliderules.info/pdf/cajori.pdf.

CALCULATORS BEFORE THE CPU

THIS YEAR MARKS THE 400TH ANNIVERSARY OF THE INVENTION OF LOGARITHMS by John Napier. For most of that time—indeed, until 1976, when the TI-30 scientific calculator came out at $24.95—students, engineers, physicists, and mathematicians throughout the world relied on Napier's invention by using a slide rule.

Whether you were solving trig problems in high school or helping to hurl astronauts to the moon, the slide rule was your companion. In the early 1970s manufacturers in the United States, Japan, and Europe were selling a total of more than a million slide rules a year.

Mathematicians in Europe immediately began to study the tables and embrace the theories that Napier published in 1614. By 1620, Edmund Gunter, professor of astronomy in Gresham College, London, designed a logarithmic "line of numbers." Distances along the line from 1 through 10 were not proportional to the numbers on it, but to the logarithms of those numbers. He engraved it on a stick of wood.

Using a compass, one could add or subtract distances on the scale to find the products or quotients of the numbers.

William Oughtred, an English mathematician and Anglican priest, in 1622 placed two separate Gunter's rules together, side by side, and eliminated the compass with two "sliding rules." The slide rule was born. Oughtred also created "Circles of Proportions," the archetype of the circular slide rule.

Isaac Newton in 1675 described a method for computing cubic equations using three adjacent scales with an overlying hairline. This first rudimentary cursor would not be incorporated into slide rules for another hundred years.

The first technical slide rule was the Soho rule, made of boxwood, defined by James Watt and his associate, John Southern, in the 1790s. The T-shaped slide was captured in the routed well of the stock. Versions with two, three, and four sides were developed to hold scales in reference to each other. Not having a cursor was a big disadvantage.

A key contributor to the standardization of the slide rule was Victor Mayer Mannheim, a French student and later an artillery officer. In 1850, he defined a scale set and by 1890 had made a functional cursor. The "Mannheim Type" remained a template for slide rule design until the end of the slide rule era.

Slide rules were almost unknown in the United States before 1880. It was in 1844 that Aaron Palmer's Computing Scale, an 8-inch diameter circular slide rule, appeared in Boston, followed by a pocket version. John E. Fuller bought Palmer's copyright in 1846 and adapted the original designs. These instruments were unknown outside of Massachusetts and New York, however.

Wider interest in the slide rule was awakened about 1881, when Edwin Thacher, a bridge engineer, patented a cylindrical slide rule, and Robert Riddell published his book, *The Slide Rule Simplified*. When the Mannheim slide rule migrated to the United States in 1890, William Cox started promoting it in *Engineering News*. He subsequently designed and in 1891 patented (U.S. 460,930) the first duplex engineer's slide rule, which had a wrap-around cursor.

In 1900, only about half of the engineering schools in the United States included the use of the slide rule in their classes. By 1970 every math and engineering student had a slide rule, and by 1980 "slipsticks" were replaced by calculators and personal computers.

But nostalgia will outlive technology. The slide rule still enjoys a continued life as past users, who remember the warmth of celluloid and wood, and the simplicity of calculating with three significant figures, become collectors, and educators introduce the ultimate green calculator to today's students. **ME**

MIKE KONSHAK, a retired mechanical engineer, is the curator of the International Slide Rule Museum, www.sliderulemuseum.com.

Great engineering shapes the future.
So does great insurance.

As a mechanical engineer, you strive to identify solutions that will create a brighter future. The question is, does your financial plan do the same?

With the ASME Group 10-Year Level Term Life Insurance Plan, you can safeguard the financial future of the ones you love by **locking in the rate and benefit level that works best for your family — for 10 years.** Designed exclusively for engineers like you, this plan really helps put you firmly in control of your family's financial security.

While no one knows what tomorrow holds, one thing is for sure, our choices today help shape our tomorrow. Help protect your family now by locking in your family's financial security for 10 full years with the ASME Group 10-Year Level Term Life Insurance Plan.

Group 10-Year Level Term Life Insurance Plan

For information on features, costs, eligibility, renewability, limitations and exclusions, please call **1-800-289-ASME (2763)** or visit **ASMEInsurance.com/10YLT.**

ASME
SETTING THE STANDARD
ASME INSURANCE PROGRAM

ASMEInsurance.com/10YLT

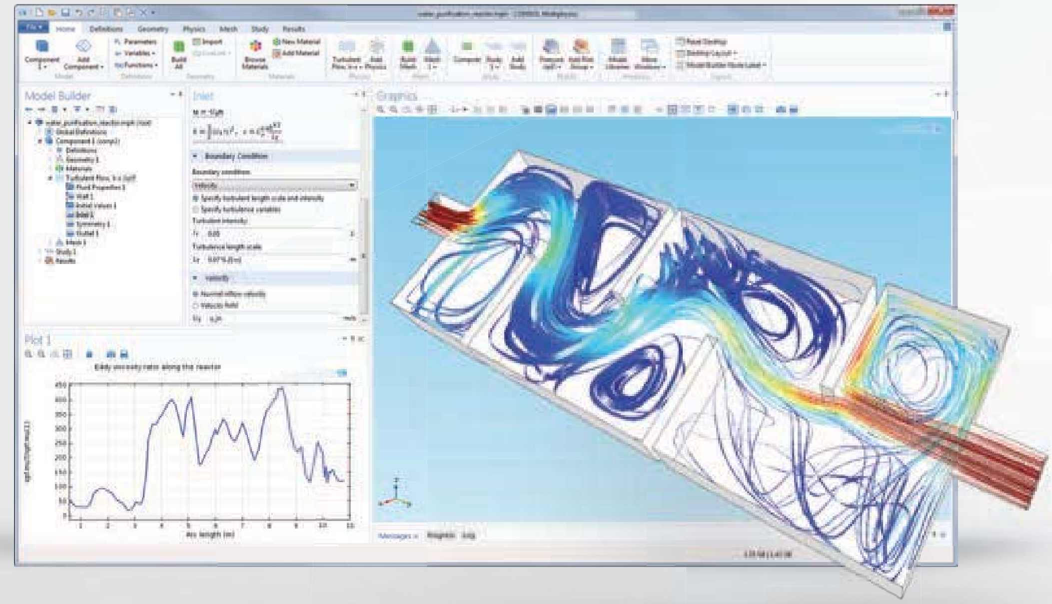
NEW YORK LIFE

The Group Term Life Plan is underwritten by New York Life Insurance Company, 51 Madison Ave., New York, NY 10010 on Policy Form GMR. Coverage may not be available in all states.

In CA d/b/a Mercer Health & Benefits Insurance Services LLC
AR Ins. Lic. #303439 | CA Ins. Lic. # 0G39709

65916 (10/14) Copyright 2014 Mercer LLC. All rights reserved.

WATER PURIFICATION: Model of a 6 m long ozone reactor. Simulation results give an overview of the turbulent flow field and allow estimation on residence time of chemical species.



VERIFY AND OPTIMIZE YOUR DESIGNS WITH

COMSOL MULTIPHYSICS®

Multiphysics tools let you build simulations that accurately replicate the important characteristics of your designs. The key is the ability to include all physical effects that exist in the real world. To learn more about COMSOL Multiphysics, visit www.comsol.com/introvideo

Product Suite

COMSOL Multiphysics

ELECTRICAL
AC/DC Module
RF Module
Wave Optics Module
MEMS Module
Plasma Module
Semiconductor Module

MECHANICAL
Heat Transfer Module
Structural Mechanics Module
Nonlinear Structural Materials Module
Geomechanics Module
Fatigue Module
Multibody Dynamics Module
Acoustics Module

FLUID
CFD Module
Mixer Module
Microfluidics Module
Subsurface Flow Module
Pipe Flow Module
Molecular Flow Module

CHEMICAL
Chemical Reaction Engineering Module
Batteries & Fuel Cells Module
Electrodeposition Module
Corrosion Module
Electrochemistry Module

MULTIPURPOSE
Optimization Module
Material Library
Particle Tracing Module

INTERFACING
LiveLink™ *for* MATLAB®
LiveLink™ *for* Excel®
CAD Import Module
ECAD Import Module
LiveLink™ *for* SolidWorks®
LiveLink™ *for* Inventor®
LiveLink™ *for* AutoCAD®
LiveLink™ *for* Creo™ Parametric
LiveLink™ *for* Pro/ENGINEER®
LiveLink™ *for* Solid Edge®
File Import *for* CATIA® V5

COMSOL

© Copyright 2013-2014 COMSOL. COMSOL, COMSOL Multiphysics, Capture the Concept, COMSOL Desktop, and LiveLink are either registered trademarks or trademarks of COMSOL AB. All other trademarks are the property of their respective owners, and COMSOL AB and its subsidiaries and products are not affiliated with, endorsed by, sponsored by, or supported by those trademark owners. For a list of such trademark owners, see www.comsol.com/trademarks