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About the Institute
Since its founding in 1947, Southwest Research Institute (SwRI) has contributed to the advancement of science and technology by working with clients in industry and government. Performing research for the benefit of humankind is a long-held tradition. The Institute comprises 11 divisions engaged in contract research spanning a wide range of technologies.

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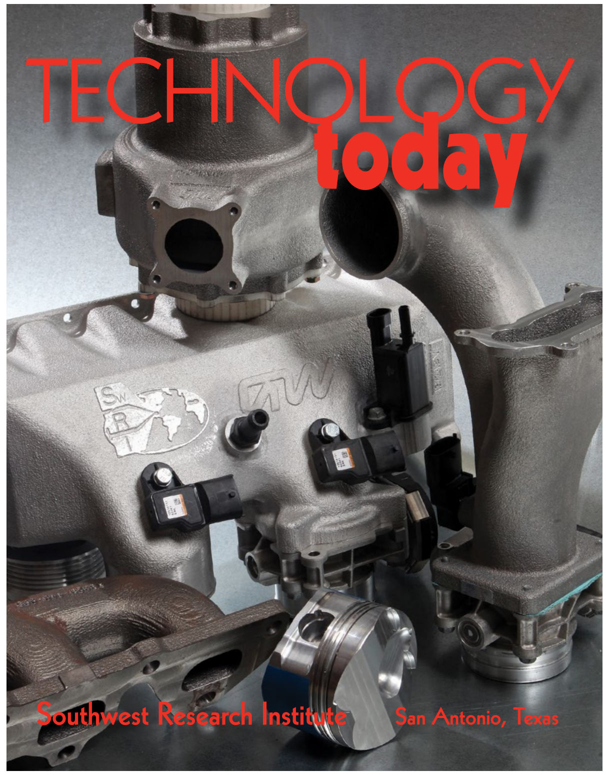
COVER



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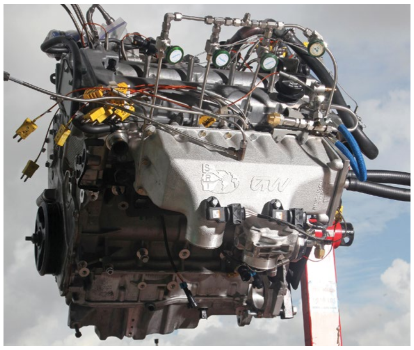
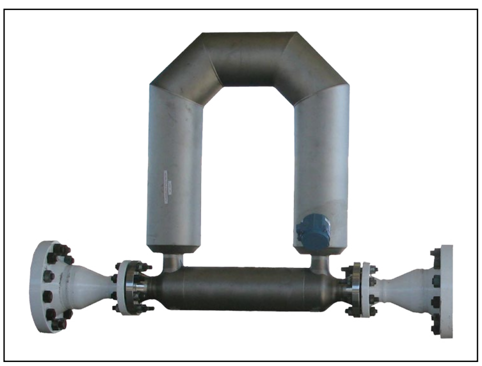
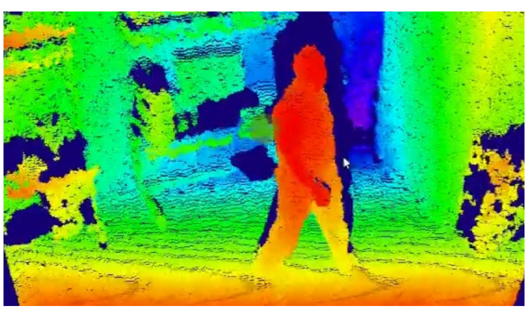
About the cover
SwRI-designed parts were created to modify a production gasoline engine for a prototype to demonstrate SwRI's Dedicated Exhaust Gas Recirculation (D-EGR) technology.

ARTICLES







Departments

Powering the Way to Better Fuel Economy

Dedicated EGR offers superior efficiency, emissions

D019108-5805

SwRI's high-efficiency D-EGR engine contains custom-designed airpath parts.

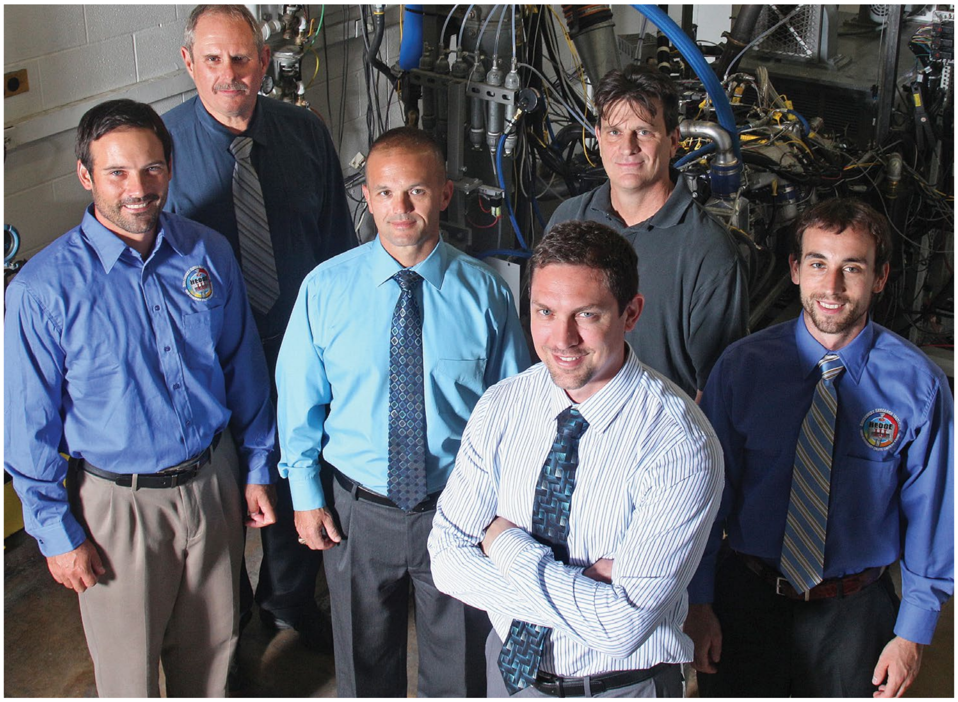
As engine manufacturers race to bridge the gap between current and future emissions and fuel economy regulations, a team of engineers at Southwest Research Institute (SwRI) has developed a new engine design that may quicken the pace.

The SwRI-developed Dedicated Exhaust Gas Recirculation (D-EGR™) gasoline engine is on average 10 percent more efficient than the next-best gasoline engine with certain operating conditions exceeding a 30-percent improvement. The engine, conceived under the High Efficiency Dilute Gasoline Engine (HEDGE®) research consortium managed by the Institute, is based on cooling and then re-circulating burned exhaust gases into the engine to improve the engine's thermal efficiency (see "Clean and Cool," Summer 2010 *Technology Today*). Dedicated EGR™ takes the technology a step further by using a subset of an engine's cylinders to re-circulate exhaust gases to the others. Tests at SwRI have shown that the engine has fuel economy comparable to a diesel engine of similar displacement, but at less than two-thirds the cost and with lower smog-forming and particulate emissions.

The cost-effective, high-efficiency, ultra-low emissions D-EGR engine combines the efficiency improvements of recirculated exhaust gas with the combustion benefits of reformed fuel. The fuel reformation process occurs inside a power cylinder that is operated with excess fuel. Rich combustion leads to the formation of large amounts of hydrogen (H_2) and carbon monoxide (CO), which are then recirculated to the engine. Since the fuel reformation occurs in a power-producing cylinder and all the combustion products are recirculated, the normal losses associated with fuel reformation in an external device are avoided. The synergy between cooled, recirculated exhaust gas and reformed fuel is at the crux of D-EGR technology.

The recirculated exhaust gas helps partially overcome engine limitations that have historically reduced spark-ignition engine efficiency, such as thermal losses, pumping work losses and engine knock. At low EGR levels, increasing the EGR rate leads to increased efficiency. Eventually, however, the engine reaches a limit where efficiency no longer improves with additional EGR. The efficiency limiting mechanisms are associated with combustion efficiency and flame speed. Recirculated exhaust gas at high levels slows combustion reaction rates, reducing knock but also reducing the flame speed. Slow flame speeds lead to unstable combustion, particularly at low power conditions. In a similar manner, the in-cylinder temperature reductions with cooled EGR that reduce heat transfer losses and improve efficiency also lead to a reduction in post-flame hydrocarbon oxidation rates and increased flame quench, which increases the emissions of unburned hydrocarbons and reduces combustion efficiency.

Addressing these deficiencies in cooled EGR is where the fuel reformation aspect of D-EGR is important. The reformate, primarily consisting of H_2 and CO, is recirculated with the rest of the exhaust gas. The combustion properties of the reformate mitigate some



The SwRI D-EGR development team (L to R): Principal Engineer Jess Gingrich, Principal Designer Douglas McKee, Assistant Director Dr. Terry Alger, Principal Engineer Mark Jones, Manager Christopher Chadwell and Research Engineer Raphael Gukelberger. Not shown are Research Engineer Jacob Zuehl and Research Technologist Roger Huron. All are within the Engine, Emissions and Vehicle Research Division.

of the drawbacks of cooled EGR alone. Reformate improves the engine's tolerance of recirculated exhaust gas, primarily by increasing burn rates, leading to improved stability at high EGR levels. The reformate also has a very low minimum ignition energy, which means that it has a reduced quench distance and improved fuel oxidation. This, in turn, leads to reduced emissions of unburned hydrocarbons and improved combustion efficiency. The combination of the two factors allows an engine with 25 percent dilution to operate with nearly the same combustion efficiency and identical stability as the baseline, non-dilute engine, but with a significant efficiency improvement.

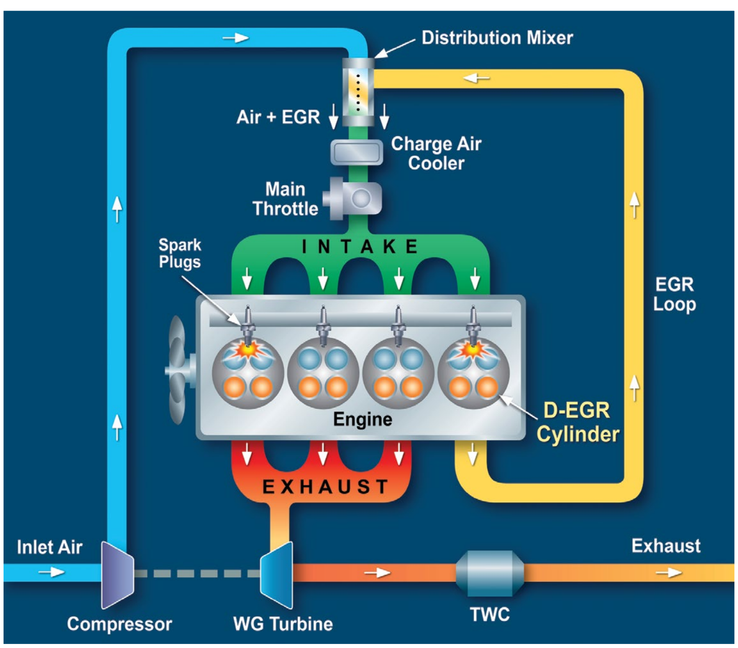
Because the air-fuel ratio differs among cylinders, D-EGR relies on a sophisticated control system to maintain optimum efficiency across the engine's combustion spectrum and to ensure that all cylinders produce the same power.

After exploring cooled EGR technology in the earliest phases of the HEDGE consortia, the latest phase has involved constructing a prototype D-EGR system in a modified four-cylinder engine to prove the performance gains indicated in earlier computer-generated analyses of D-EGR technology.

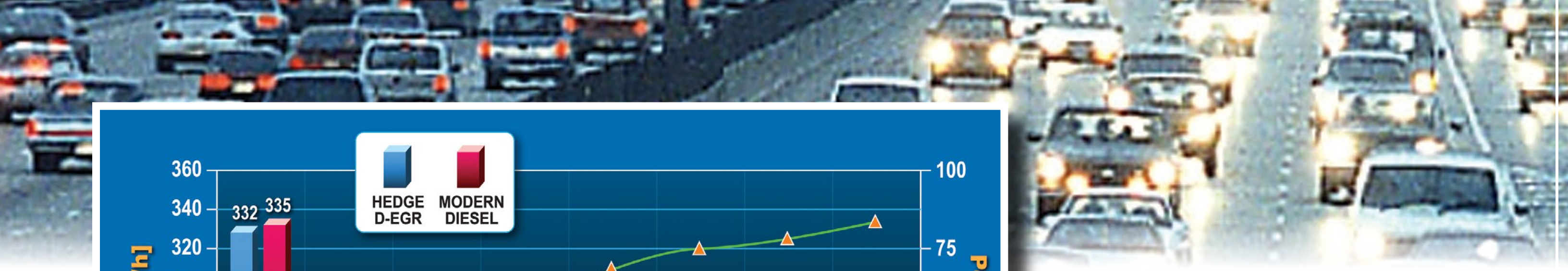
Other benefits of reformate

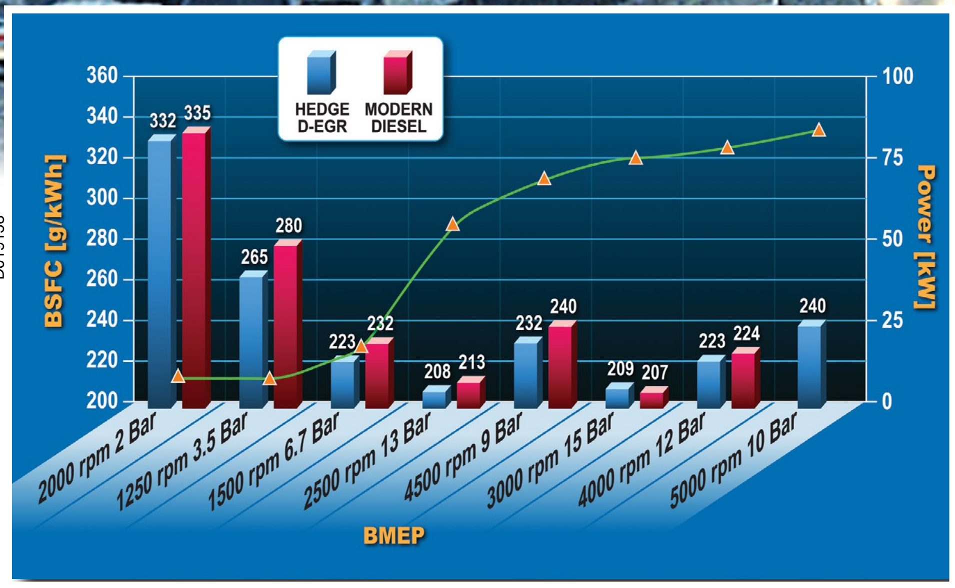
In-cylinder fuel reforming is used to convert a fuel-rich mixture of air and gasoline into a gas stream containing high levels of reformate in the form of hydrogen and carbon monoxide along with burned gas containing carbon dioxide, water vapor and nitrogen. Combusting reformed fuel (or, in chemical terms, converting complex hydrocarbons to a blend of hydrogen and carbon monoxide molecules) improves the efficiency and emissions of internal-combustion engines, especially in highly dilute spark-ignited engines. As mentioned above, reformate improves the combustion process by increasing flame speeds and enabling engine operation at higher dilution levels, creating more stable and complete combustion.

In addition to improving on the limiting factors associated with cooled EGR, the nature of reformate means that the engine charge is improved in several fundamental ways. First, both H_2 and CO have very high octane ratings — both have research octane numbers greater than 100 — and their presence in the fuel mixture increases the octane rating of the charge significantly. In a D-EGR engine, the knock response of the engine using regular-grade (87 AKI) gasoline is the same as for the baseline engine using super-premium (greater than 93 AKI) gasoline, which enables operation at very high (>11:1) compression ratios with high efficiency, even at very high specific power levels.



A schematic drawing of a D-EGR layout shows the path of air flow through the engine. Recirculated exhaust is shown in yellow.





A fuel consumption comparison shows the relative performance parameters of a D-EGR engine and a modern diesel. (BSFC = brake specific fuel consumption, a measure of how much fuel is required to achieve a given power level.)

In addition, since reformate is primarily diatomic molecules, it has a high ratio of specific heats. Because the ultimate efficiency potential of the engine increases as the ratio of specific heats of the charge increases, the presence of reformate improves the efficiency potential of the engine by increasing the charge's ratio of specific heats. The charge's ratio of specific heats is a function of both composition and temperature. By combining the composition-changing impact of reformate with the cooler combustion temperatures from cooled EGR, the D-EGR engine operates at a much higher ratio of specific heats over the cycle, increasing the efficiency potential over either reformate or cooled EGR alone.

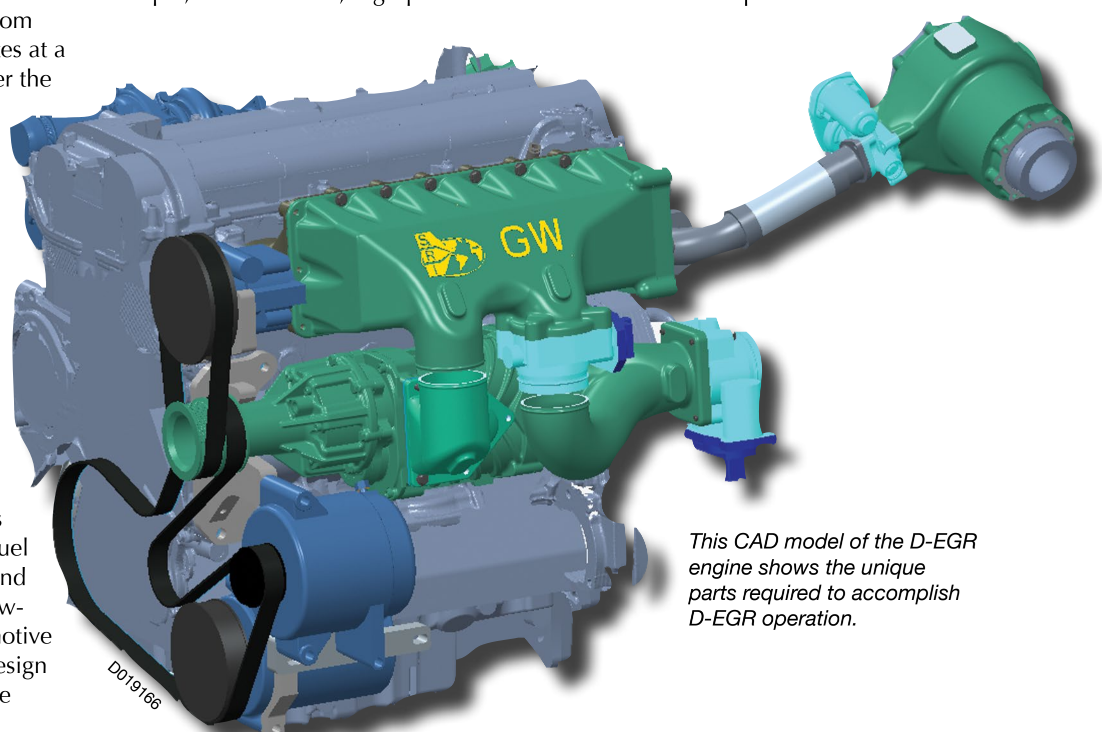
By improving the tolerance for dilution, D-EGR engines can run higher levels of recirculated exhaust gas and further reduce losses typically associated with throttled stoichiometric engines, which account for virtually all modern gasoline engines. Dedicating a cylinder to reformate production also ensures that while the dedicated cylinder runs with excess fuel, the rest of the engine can operate at stoichiometric air-fuel ratios (meaning the combination of air and fuel that results in complete combustion) and use the current, high-efficiency and low-cost aftertreatment available for automotive applications. The result is an engine design that has demonstrated very high engine efficiency with very low associated cost, delivering real-world engine efficiencies greater than 42 percent along with ultra-low emissions.

Reforming low-quality fuels

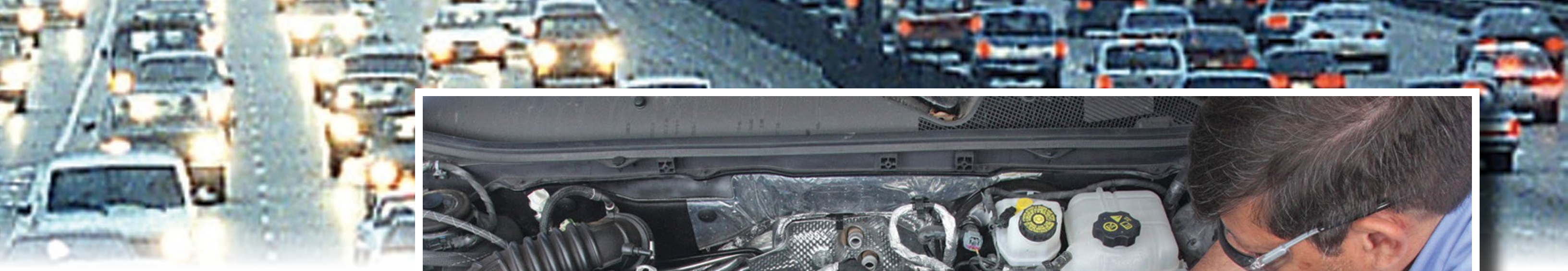
Historically, engines have been designed to operate within fairly narrow fuel quality parameters, any deviation from which might significantly limit engine efficiency. For example, some modern, high-performance engines require premium gasoline. However, the SwRI team discovered that D-EGR engines can operate on very low-quality fuels, whether liquid or gaseous, by reforming a portion of the fuel internally and thus improving its effective quality. By modulating the amount of in-cylinder fuel reformation, the D-EGR power plant in effect provides "octane on demand." With marketplace fuel costs generally directly proportional to quality, the lower the quality of fuel the engine can burn, the greater in-use cost benefit D-EGR can provide.

Superior emissions

Because nearly all the hazardous emissions of a modern engine are released before the catalyst becomes active, the combination of EGR and reformate, plus the ability of reformate to accelerate catalyst light-off, creates the potential for ultra-low emissions. Recent tests at SwRI indicate that cooled EGR reduces the emissions of particulates from gasoline engines. When D-EGR is employed, the particulate emissions are reduced even further from the cooled EGR baseline, indicating that it may be possible to meet future particulate emissions



This CAD model of the D-EGR engine shows the unique parts required to accomplish D-EGR operation.



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An SwRI technician installs the D-EGR engine in a demonstration vehicle.

standards without a costly particulate filter.

Torque is not necessarily compromised with D-EGR, because a turbocharger can be scaled and added to the engine to meet vehicle requirements. However, adding a turbocharger and other D-EGR components does increase costs, as does the requirement for higher cylinder pressures due to high compression ratios and improved combustion phasing. On the other hand, D-EGR may enable some potential cost-saving changes to engine architectures. Potentially, D-EGR eliminates the need for costly technologies such as a gasoline direct injection (GDI) fuel system because the EGR system, and the reformate that a dedicated EGR cylinder produces, both suppress knock to a far greater degree than the GDI system does. D-EGR also reduces the requirement for cam phasers to improve efficiency because it achieves part-load efficiency through dilution and in-cylinder fuel reformation.

D-EGR hardware and control

The D-EGR engine uses conventional low-cost and durable automotive components in a unique way to yield an elegant solution for high-efficiency engines. This technology uses cooled EGR and reformed fuel without requiring the hardware complexity and cost typically associated with such systems. The control system, integral to the product's high efficiency, is the final piece of this technology. The control system actively determines the amount of fuel that must be reformed to achieve best efficiency. In a transient environment, it can adapt the fueling rate independently for each cylinder. In addition to fueling, the controller adjusts ignition timing based on the reformate level to ensure optimal combustion phasing in each cylinder on a cycle-by-cycle basis. Finally, the control algorithms monitor the actual dilution in the system and continually adjust the airflow through the dedicated cylinder to maintain misfire-free operation in a transient environment. A sophisticated electronic control system enables the benefits of the technology to be realized in real-world conditions on a variety of platforms.

Non-automotive applications

While a Dedicated EGR engine's primary intended application is as either the sole powerplant for a vehicle or as part of a hybrid system, there are several other potential applications. In non-automotive applications, the engine can be used to generate electricity, pump fluids or power industrial machinery. In such applications, the D-EGR engine can produce more mechanical power per fuel input than other engines in its class, with potentially higher torque and power than a small, off-road certified diesel. This best-in-class efficiency is coupled with the capability to operate with super-ultra-low emissions (SULEV) using a conventional three-way catalyst aftertreatment system. As modern, emissions-compliant diesel engines have significantly increased in cost, the spark-ignition D-EGR engine for off-road or stationary applications also provides a significant cost reduction.

The engine can also be configured to produce high-quality heat for co-generation or combined heat and power (CHP) applications for large natural gas engines. Because the recirculated exhaust gas is cooled prior to introduction to the induction system, the heat extracted from this circuit can be coupled with exhaust heat to produce steam or preheat a subsequent power generating system. Conventional CHP systems that use lean-burn natural gas engines require emission control technologies that are more costly and less efficient than a three-way catalyst system. Also, lean-burn emissions control systems have a limited thermal operating range, which limits the thermal energy available for co-generation. D-EGR is less restricted by aftertreatment systems and can therefore increase the total energy recovered by a co-generation system.

Future development and applications

A major commercial automotive manufacturer has announced a D-EGR engine using HEDGE-developed technology for production in 2018 and several pre-development efforts with other companies are in progress. The HEDGE-III consortium will also continue work on the D-EGR concept, investigating additional ways of improving efficiency in the system. In addition, an internally funded research project is under way at SwRI to build a demonstration vehicle for D-EGR technology based on a 2012-model sedan platform.

Questions about this article? Contact Alger at (210) 522-5505 or talger@swri.org

D019149

Planetary Time Machine

An SwRI-developed geochronometer measures the age of rocks on the Moon and other planets without need to return samples to Earth

Dr. F. Scott Anderson is a principal scientist in the Planetary Science Directorate of SwRI's Space Science and Engineering Division. He is a planetary geologist interested in the geology, geophysics and chronology of planetary bodies, including Mars, the Moon and Venus. The main focus of his research is understanding the isotopic abundance of minerals and rocks using laser desorption resonance ionization mass spectrometry.

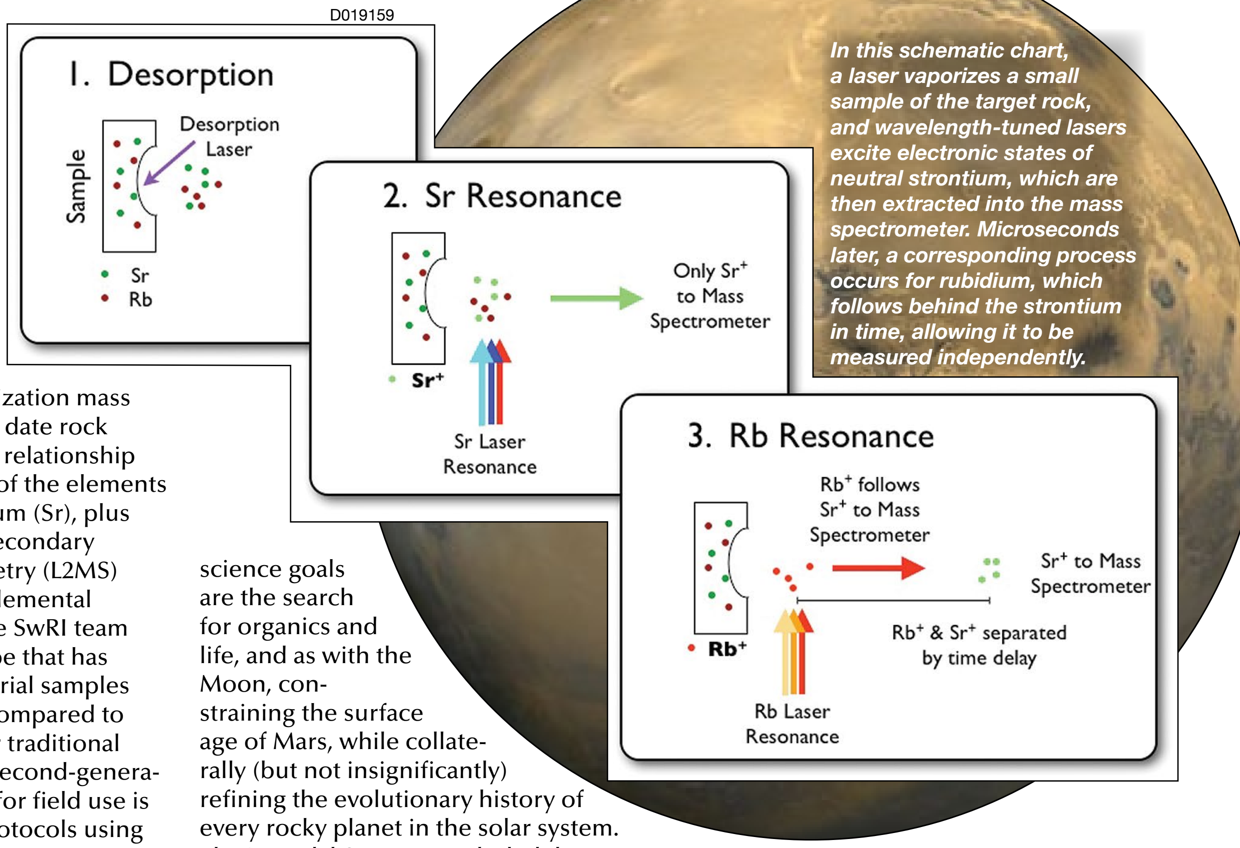
Photo by Matt Nager

By F. Scott Anderson, Ph.D.

The two highest science priorities for planetary exploration are searching for life and understanding our place in the history of planetary evolution. Straightforward as these goals may appear, however, they are anything but simple. Identifying life has proven to be complicated, requiring a wide range of laboratory techniques to identify the signatures of living or fossilized organisms. Furthermore, understanding the history of the scarred and cratered surfaces of other planets has been hindered by the difficult and time-consuming laboratory measurements required for radiometric dating. Worse, surface samples from bodies other than the Moon have yet to be brought home to Earth for study, due to difficulty and cost. In fact, the analytical challenges alone were considered so daunting that it was commonly assumed that samples must be returned to Earth for analysis. Besides costing much more than *in-situ* measurement, there is also the risk that some samples may prove to have been of little value once they have been analyzed. After all, how does one choose which few, thimble-sized samples to bring back to Earth to represent a whole planet?

All of this is about to change. A team of scientists from Southwest Research Institute (SwRI) is nearing completion of an instrument that can fit onboard a spacecraft rover to triage rock samples with a quick search for organic molecules — the building blocks of life — and also provide radiometric dates of samples before they are selected for return to Earth for detailed study. This development comes in the nick of time because NASA is expected to solicit instrument ideas for a 2020 rover mission to Mars sometime this fall, with additional calls for dating the oldest impact basin on the Moon in approximately 2015.

The SwRI-developed instrument uses laser desorption resonance ionization mass spectrometry (LDRIMS) to date rock samples by measuring the relationship between certain isotopes of the elements rubidium (Rb) and strontium (Sr), plus it has a laser desorption-secondary ionization mass spectrometry (L2MS) capability for measuring elemental and organic chemistry. The SwRI team built a bench-top prototype that has produced dates for terrestrial samples in as little as eight hours compared to many months required for traditional laboratory techniques. A second-generation, portable instrument for field use is testing organic analysis protocols using the secondary L2MS capability. The goal is to provide organic and dating measurements in a fast, portable package for use by both robotic and human missions to the Moon and Mars.



In this schematic chart, a laser vaporizes a small sample of the target rock, and wavelength-tuned lasers excite electronic states of neutral strontium, which are then extracted into the mass spectrometer. Microseconds later, a corresponding process occurs for rubidium, which follows behind the strontium in time, allowing it to be measured independently.

An opportune time

Every 10 years, the National Academy of Science solicits ideas from the planetary science community for a planning document for NASA called the Decadal Survey. The most recent National Research Council Decadal Survey for the Moon proposed a sample-return mission to improve our knowledge of the age of the lunar surface.

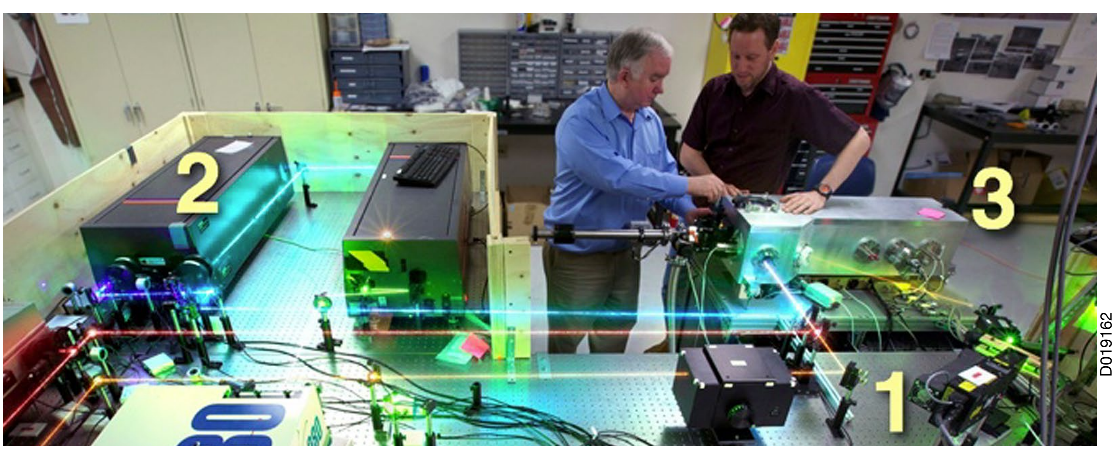
For Mars, the survey proposed a three-mission plan to cache and return samples from the surface, known as Mars Sample Return (MSR), at a total cost of approximately $11 billion, extending into 2020 and beyond. Primary science goals are the search for organics and life, and as with the Moon, constraining the surface age of Mars, while collaterally (but not insignificantly) refining the evolutionary history of every rocky planet in the solar system. The Decadal Survey concluded that these goals would best be achieved by instrumentation and analysis techniques available only on Earth.

Amid shrinking federal budgets, NASA last December made a surprising announcement of a new Mars flight opportunity for 2020. A Mars 2020 Rover Science Definition Team was formed, with a charter that supports caching samples in the search for organics and life, to be placed in geologic context according to both age and chemistry.

Organics on Mars

Two decades of research on terrestrial life, plus largely discredited bio-signatures in the Martian meteorite ALH84001, have shown that a single, easily measured definition for life is elusive. However, there is consensus that organic compounds are the building blocks of living organisms. If found in a sample from the surface of another planet they would represent a high-priority target for return and additional analysis.

Unfortunately, the solar system is filled with abiotic sources of organic materials, including meteorites that rain down on Mars and other planets. A key question is how to distinguish potential native Martian organics from the abundant abiotic organics found in meteorites throughout the solar system. Despite the prediction of abundant



A first-generation bench-top version of the laser desorption resonance ionization mass spectrometer (LDRIMS) was developed in an SwRI laboratory in Boulder, Colo. It comprises a desorption laser (1), resonance ionization lasers (2) and a mass spectrometer (3).

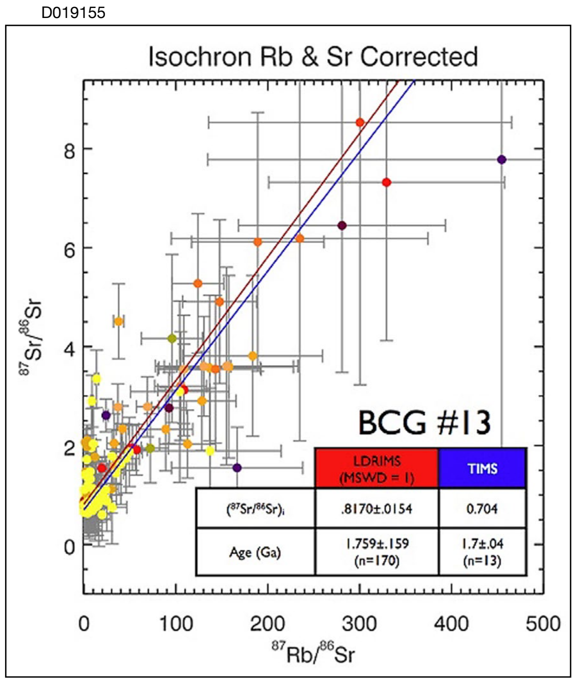
organic infall from meteors and the observed presence of meteorites on the surface of Mars by the Mars rovers, no native organic signatures have yet been found, despite the presence of instruments like the gas chromatography mass spectrometers aboard the Viking and Mars Science Laboratory spacecraft. One hypothesized explanation is that organic compounds are rapidly broken down on the surface of Mars by the highly oxidizing surface environment. Nonetheless, given that organic signatures on Mars are hard to find, thus hindering *in-situ* analysis and identification, it is very likely that the mere detection of an organic compound in a Mars sample would justify its inclusion in a sample-return cache.

Surface dating on the Moon and Mars

In-situ geochronology measurements are important because current estimates of surface age, and hence surface history, are derived from crater counting, in which one assumes that older surfaces have both bigger and more craters while younger surfaces have relatively smaller and fewer craters. For the Moon, these estimates have been calibrated by the radiometric dating of rocks brought back to Earth by the Apollo astronauts. No samples have yet been returned from a known region of Mars that can be used to directly calibrate the ages derived from crater counts, so we are forced to extrapolate estimates of the impact rate for the Moon to Mars. However, even for the Moon there are uncertainties in the duration and timing of the period of heaviest bombardment of asteroids and comets, while no timing constraints exist for the period from 1 billion to 3.5 billion years ago. Worse yet, cratering rate estimates from the most recent era are non-unique. Improving our knowledge of the age of the lunar surfaces has proven to be so pressing a goal that the Decadal Survey lists missions to return lunar samples as a top priority.

For Mars studies, the ratio of impact rates between the Red Planet and the Moon is uncertain, leading to wide variances in determining the age of surface features. This is complicated further by the Moon's own impact modeling uncertainties, leading the Decadal Survey to support the development of future instruments with a focus on the most important *in-situ* measurements, including *in-situ* geochronology experiments [National Research Council, 2012].

Rocky bodies throughout the solar system, including Mars, the Moon, Venus, Mercury and Earth itself, would similarly benefit from new measurements. These constraints could dramatically improve our understanding of solar-system-wide bombardment history, and thus of the relationship between the end of the heaviest bombardment and the rise of life.



This isochron of a granite sample measured with LDRIMS-1 compares aging data derived by LDRIMS (red line) with traditional aging methods (blue line).

Radiometric dating of rocks

Radiometric dating is based on the observation that radioactive isotopes decay into a different isotope over fixed periods of time, so that the age of a rock sample can be measured by comparing the abundance of each isotope. For example, half of the ^{87}Rb in a mineral will decay into ^{87}Sr over 48.8 billion years. Since the solar system itself is only about 4.5 billion years old, one can calculate that only about 6 percent of ^{87}Rb will have decayed to ^{87}Sr in even the oldest rocks. Modern mass spectrometers are very sensitive and can easily measure the abundance of Rb and Sr to better than 0.002 percent, producing dates as young as about 1 million years. The LDRIMS measurement focuses on the Rb-Sr system because it has been used for reliably dating a wide range of terrestrial and lunar samples, as well as Martian meteorites, and Rb and Sr are present in relatively high abundances in most rocks, making them easy to measure [Faure, 1986].

What makes Rb-Sr dating difficult is that ^{87}Rb and ^{87}Sr have very nearly the same mass, so a mass spectrometer alone cannot tell them apart. The traditional technique is to crush the sample, separate the minerals by hand under a microscope, leach the Rb and Sr from each mineral powder in acid, and use liquid chromatography to separate the Rb and Sr. The separates are then plated onto filaments for each element and mineral, and only then are they measured in a mass spectrometer. Obviously, chemical separation techniques for ^{87}Rb-^{87}Sr are unsuitable for *in-situ* planetary exploration due to this complexity, as well as its need for large mass, volume and power to perform the analysis.

Technology of tomorrow, today

The SwRI geochronometer uses a technique for dating called resonance ionization, which eliminates the need for chemical separation of ^{87}Rb from ^{87}Sr. In this method, a laser vaporizes a small sample of the target rock, generating greater than 99.9 percent neutral atoms; then wavelength-tuned lasers are used to resonantly excite electronic states of neutral strontium, and the resulting excited atoms are photoionized. The strontium is then extracted into the mass spectrometer. This process is followed a couple of microseconds later by a similar process for rubidium, which, although it has isotopes of the same mass, is separated from the strontium in time. The mass spectrometer thus measures the rubidium independently, which eliminates mass interferences and ensures that the measured atoms came from the same ablation event and hence the same mineral. This method enables good estimates of Rb and Sr, and hence of the time that has passed since the rock's formation.

For organics, the SwRI instrument employs a subset of the lasers used for dating to ablate neutral atoms from the sample and then ionizes them with a deep-ultraviolet laser.

Results

The first-generation, bench-top LDRIMS-1 system has demonstrated a sensitivity to 300 parts per trillion, which is more than sufficient for dating. It typically obtains isotope ratio precisions of ±0.3 to ±0.1 percent in 3,000 ablations of one spot on a sample in about three minutes. It measures 100 to 300 spots in a raster pattern, sampling a range of different minerals, and thus their rubidium-strontium ratios. The LDRIMS-1 has been tested on samples of Boulder Creek Granite from Elephant Butte, Colo. Traditional measurements, and the SwRI team's own preliminary micro-drill thermal ionization mass spectrometry (TIMS) measurements of individual minerals, are consistent with an age of 1.7 billion years ±40 million years.

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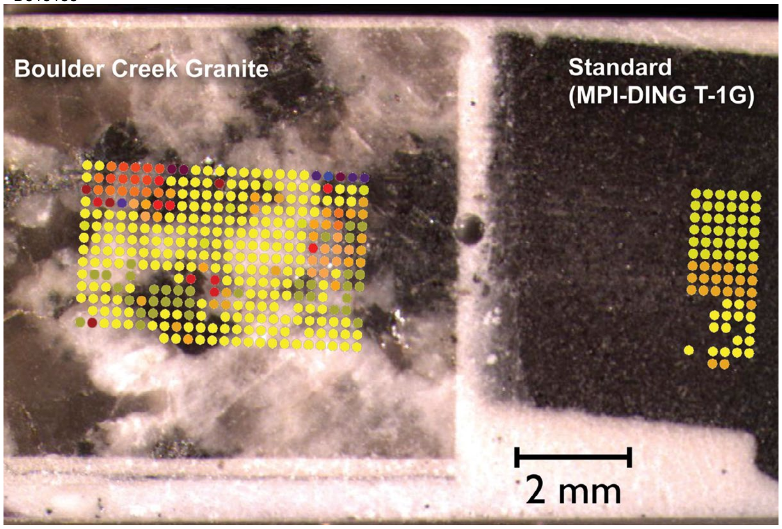

The LDRIMS-1 measured hundreds of spots on a granite sample, shown here by a group of colored dots, spaced 300 microns apart and producing microscopic pits about 75 microns wide and 0.5 micron deep.

To obtain an LDRIMS-1 date of the sample, the team measured hundreds of spots with approximately 300 micron (μm) spacing, producing microscopic pits about 75 μm wide and 0.5 μm deep. Traditional analyses can take one to six months to measure enough spots to generate an age estimate, compared to the LDRIMS-1 data for which hundreds of points were collected in less than 4.5 hours with no sample preparation. Assuming 300 spot measurements and 3,000 shots, approximately 1 million shots are required per date; the LDRIMS diode laser design typically produces billions of shots, allowing for 1,000 or more dating measurements.

Repeat measurement runs were carried out over six months to address subtle issues in software automation and laser reliability. The results were well within the age measured using TIMS techniques and had a precision and accuracy exceeding that called for by NASA (±200 Ma).

The second-generation LDRIMS-2 system is under development. The control electronics, mass spectrometer, miniature desorption laser and software are functioning, while the miniature strontium resonance laser system is undergoing final tuning and the rubidium laser system has been selected for rapid development by NASA.

The SwRI team has already been able to demonstrate laser ablation mass spectrometry (LAMS) and laser desorption secondary ionization mass spectrometry (L2MS) using LDRIMS-2. LAMS uses high-power laser ablation to directly create ions to characterize a sample, while L2MS uses a second, high-intensity laser beam to ionize neutral atoms removed from the sample by laser desorption. Both techniques are subsets of the full LDRIMS capability, requiring software timing control similar to LDRIMS. Advantages of LAMS include the measurement of a wide array of elements, while L2MS is one of the most sensitive organic detection methods available. Demonstrating these techniques is an important part of the LDRIMS science strategy, as measurements of geochemistry and organics can provide insight into habitability and identify potential biomarkers.

The future

The SwRI team is working to prepare the instrument and techniques described here for a Mars 2020 Rover proposal. To that end, they are dating more samples, expanding the suite of organics measurements, preparing to take data in the field, and working with development partners to miniaturize the instrument to a 1 cubic-foot box. The team seeks to enhance the characterization of landing sites on Mars by providing *in-situ* triage of potential samples for Earth return, improving the odds of returning relevant samples, and enhancing near-term science return.

Questions about this article? Contact Anderson at (303) 546-9670 or anderson@boulder.swri.org.

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A New Use for an

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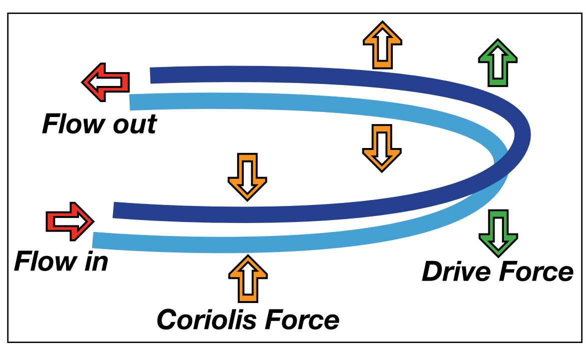
SwRI researchers are testing Coriolis flow meters for natural gas industry applications

By Terry Grimley

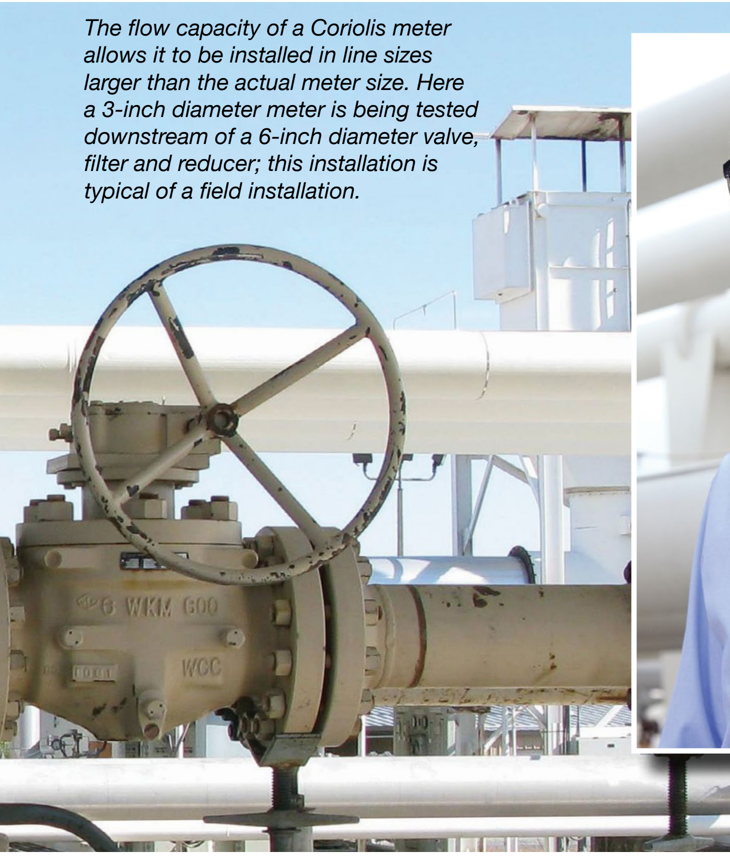
Accurate measurement of any fluid commodity is important because at some point money will change hands based on the quantity measured. In the oil and gas industry, the value and quantity of the products exchanged are enormous. According to the Energy Information Agency, natural gas production in the United States alone is more than 80 billion cubic feet per day.

Although fluid quantity measurement can be as simple as determining the height of a liquid in a cylindrical tank, gas measurements typically involve measuring flowing fluid quantity as a function of time to compute a total quantity. For decades, the most common flow meter in industrial operations was the orifice meter, which uses a plate with a hole smaller than the pipe diameter to create a differential pressure that is measured and used to compute the flow rate. Numerous other types of flow meters rely on measuring differential pressure or the rotation speed of a turbine wheel, or more recently, the measure of the transit time of ultrasonic energy as it crosses the flow stream. These meters do not directly measure the mass flow rate of the fluid, but must rely on additional physical measurements and fluid property correlations to determine the total mass (or “standard” volume) of fluid that is used for monetary transactions. This limitation has led the natural gas industry to show new interest in Coriolis flow meters because of their ability to determine more directly the mass flow rate of a fluid.



As the drive system vibrates the flow tube, the U-tube configuration creates a difference in the direction of the Coriolis forces from the tube inlet to the tube outlet, creating a twist in the flow tube that is measured as a phase difference. By using two tubes in parallel, the meter can be balanced.

Old Standby



The flow capacity of a Coriolis meter allows it to be installed in line sizes larger than the actual meter size. Here a 3-inch diameter meter is being tested downstream of a 6-inch diameter valve, filter and reducer; this installation is typical of a field installation.

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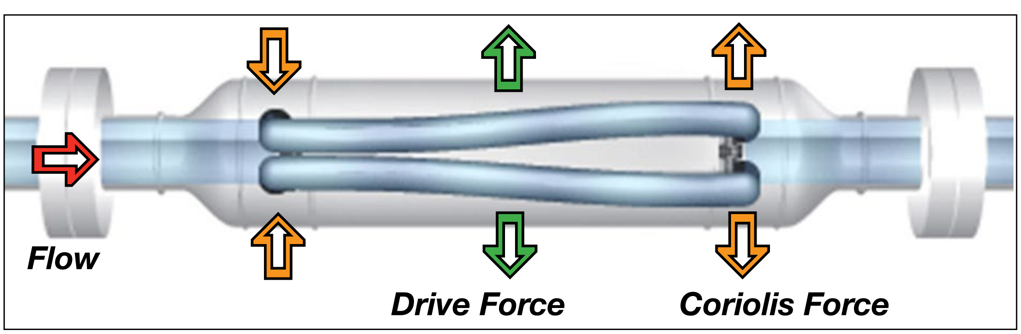
Terry Grimley is manager of the Flow Measurement Section in the Fluids Engineering Department of SwRI's Mechanical Engineering Division. Grimley, whose specialties include heat transfer, fluid mechanics and two-phase flow, oversees operation of SwRI's Metering Research Facility.

The conceptual basis for Coriolis meters is not new. A paper published in 1835 by French engineer Gaspard-Gustave de Coriolis discussed forces that exist in a rotating frame of reference. One component of these forces eventually became known as the Coriolis force.

The first patents for the concept of a Coriolis flow meter were filed in the 1950s, and by the 1970s they were commercially introduced for use with liquids and other fluids. However, it wasn't until the 1990s that developments in digital electronics made it possible for Coriolis meters to function properly in natural gas applications. Digital electronics provide the increased sensitivity needed to measure the signals produced as a result of gas mass flow rates which are a fraction of that for liquid flowing through the same size flow tube. Today, partially based on research by Southwest Research Institute (SwRI) engineers at the Institute's Metering Research Facility (MRF), Coriolis meters are gaining wide acceptance within the natural gas industry.

How they work

Coriolis flow meters rely on the inertial force imparted on a flow tube that results from electromechanically oscillating the flow tube at its natural frequency. Using a U-shaped tube for the flow path, the Coriolis forces act in opposite directions at the inlet and outlet of the flow tube, causing the tube to twist slightly. Sensors located near each end of the tube measure the twist via a change in the phase relationship of the tube motion. The measured time shift is proportional to the mass flow through the sensor. That measurement is independent of the type of fluid flowing through the meter tubes. In addition, the change in the natural frequency of the tube/fluid combination can be used to measure the fluid density. For natural gas measurements, the resulting frequency shift typically is not sufficient to provide accurate gas density measurement. Instead, the tube frequency becomes a diagnostic



A top view of a dual-tube Coriolis meter shows an exaggerated twist in the flow tubes resulting from the Coriolis force generated by flow through the tubes in combination with the electromechanically driven tube vibration. When there is no flow, the tubes vibrate without being twisted.

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The Metering Research Facility at SwRI consists of two separate closed-loop natural gas flow loops used for flow measurement research projects as well as flow meter calibration. The flow loops allow the simulation of end-use operating conditions because of the ability to set and control the pressure, temperature and flow rate. The reference flow rate uncertainty is roughly 0.25 percent, and the repeatability is considerably lower, making the facility well-suited for performing meter calibrations and for studying the subtle changes in meter performance resulting from changes in the meter installation configuration, operating conditions and other parameters. The MRF was originally built in the early 1990s through an industry project sponsored by the Gas Research Institute (now the Gas Technology Institute) and was later purchased by SwRI. The facility has been providing flow measurement research and flow meter calibrations for more than 20 years.

measurement for the operational condition of the meter.

Early testing of Coriolis flow meters at SwRI identified stability issues related to flow noise (turbulence and other velocity perturbations), which is inherent in any fluid flow but can be more significant in Coriolis flow meters because the flow noise can cause a meter response of a magnitude similar to the induced Coriolis force. Meter manufacturers overcame these problems by using the increased signal processing power in the meters' electronics. Additional research to characterize the performance of meters from multiple manufacturers in a variety of piping configurations and over a wide range of operating conditions provided some of the base performance data that the industry needed to develop a generally accepted recommended practice for Coriolis meters. The American Gas Association (AGA) first published Report Number 11, "Measurement of Natural Gas by Coriolis Meters," in 2003. It was revised earlier this year to reflect the evolution of Coriolis technology for natural gas applications.

Advantages of Coriolis meters

Most non-Coriolis flow meters require that a significant length of straight pipe be installed upstream and downstream from the meter to assure non-turbulent flow. Costs associated with installing this piping, or to install flow conditioners — devices placed in the flow path upstream of the meter that reduce the minimum length of straight pipe required — can be a large percentage of the overall cost of a meter station. Most Coriolis flow meters do not

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This high-pressure 8-inch-diameter Coriolis meter has capacity sufficient to allow it to be used in many gas transmission pipeline applications. The elimination of secondary instrumentation and surrounding piping requirements can make the installation cost-competitive with other measurement technologies.

require this, making them an attractive cost-saving option.

Coriolis meters also do not require high-accuracy auxiliary pressure, temperature and flow stream composition measurements. While they must compensate for changes in tube stiffness resulting from changes in flow stream temperature and pressure, the accuracy requirements of those measurements are significantly lower than for volumetric-type flow measurement devices. Coriolis meters have internal temperature sensors that assess the tube temperature for the purpose of compensation. Depending on the meter size, the effect of flow-stream pressure can range from insignificant for small meters (2-inch diameter) to 0.1 percent per 100 psi change in line pressure for larger meters (8-inch diameter). Eliminating auxiliary measurements not only reduces the initial facility cost, but more importantly it also eliminates the number of auxiliary devices requiring periodic maintenance and calibration.

The main limitation of Coriolis flow meters is the pressure drop required to reach the manufacturer-specified flow capacity, so the meters must be installed where this is not an issue. Even with multiple flow tubes, the total flow area of a Coriolis meter is normally much smaller than the flow area of the surrounding pipe. Reducing the flow area provides increased velocity in the meter's flow tubes that improves measurement sensitivity, but this also creates a pressure drop greater than other flow measurement methods because of the combination of increased velocity and the bent-tube geometry.

For a commercial client, SwRI researchers used the MRF to assess the performance of a meter installed downstream of some common field elements, such as filters, valves and elbows. The results allowed the company to develop standard installation practices, determine practical capacity limits and generate calibration requirements for installing Coriolis meter technology.

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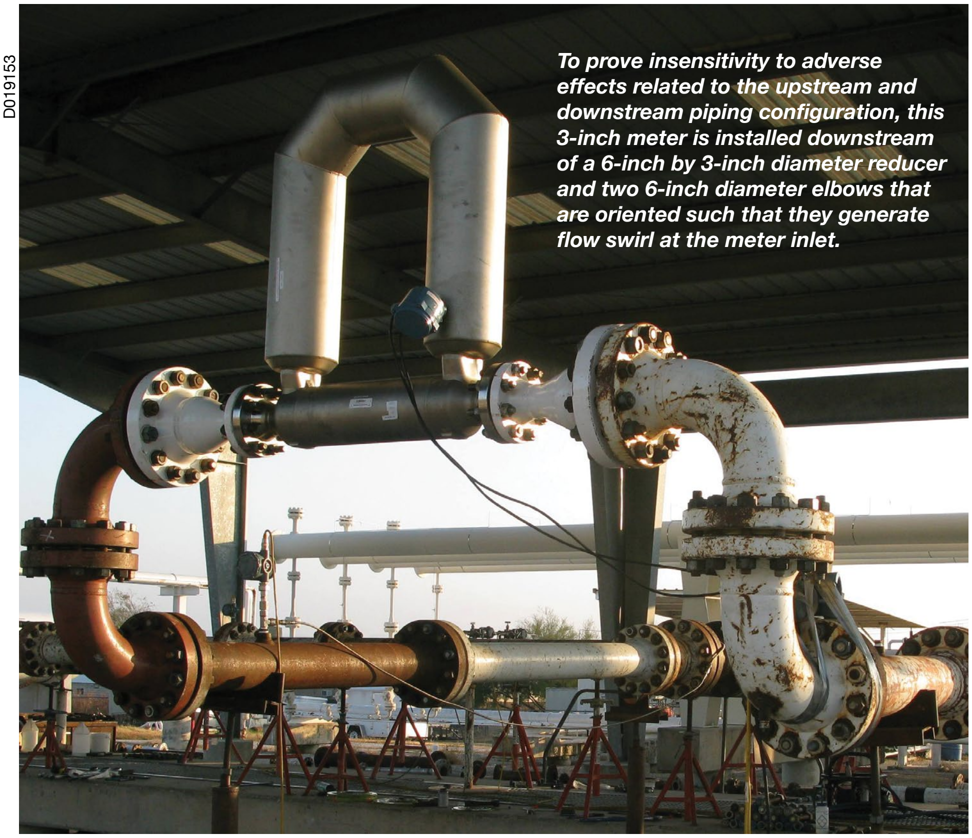


To prove insensitivity to adverse effects related to the upstream and downstream piping configuration, this 3-inch meter is installed downstream of a 6-inch by 3-inch diameter reducer and two 6-inch diameter elbows that are oriented such that they generate flow swirl at the meter inlet.

Evaluating the dynamics of larger meters

Until a few years ago, Coriolis meters for natural gas applications typically were limited to relatively small line diameters, generally less than 4 inches. Recently, however, the industry has introduced meters with flange diameters of 8 inches and larger based on better understanding of the fluid dynamics associated with Coriolis flow meters and the availability of the high-energy magnets used in the meters. As larger meters were being developed, the MRF served as a test bed for both manufacturers and end-users of Coriolis meters.

Verifying the accuracy performance of larger Coriolis flow meters is of particular interest to end-users, because even a small margin of error can translate into large amounts of money. For example, a 0.1-percent error in an 8-inch diameter Coriolis meter operating at 50-percent capacity with natural gas at a line pressure of 1,000 psia equals about $200,000 per year (assuming gas costs of $4 per thousand standard cubic feet).

Other applications

Besides natural gas, Coriolis flow meters are also commonly used to measure supercritical ethylene, which has a significantly higher monetary value than natural gas. Ethylene, one of the highest-volume chemicals produced, is primarily used for producing plastics. It is commonly stored at a pressure and temperature beyond the boundary where a fluid behaves as strictly a gas or a liquid. While orifice meters are commonly used for this application, Coriolis flow meters provide a less expensive system with more accurate measurement. Flow testing with natural gas can be used to verify the flow meter's performance at pressures similar to those common in supercritical ethylene applications.

Whether for the natural gas industry or other markets, SwRI will continue to help its clients further this important metering technology.

Questions about this article? Contact Grimley at (210) 522-2353 or terry.grimley@swri.org.

Robots at Work

SwRI-developed technologies are guiding the future of automation in industry

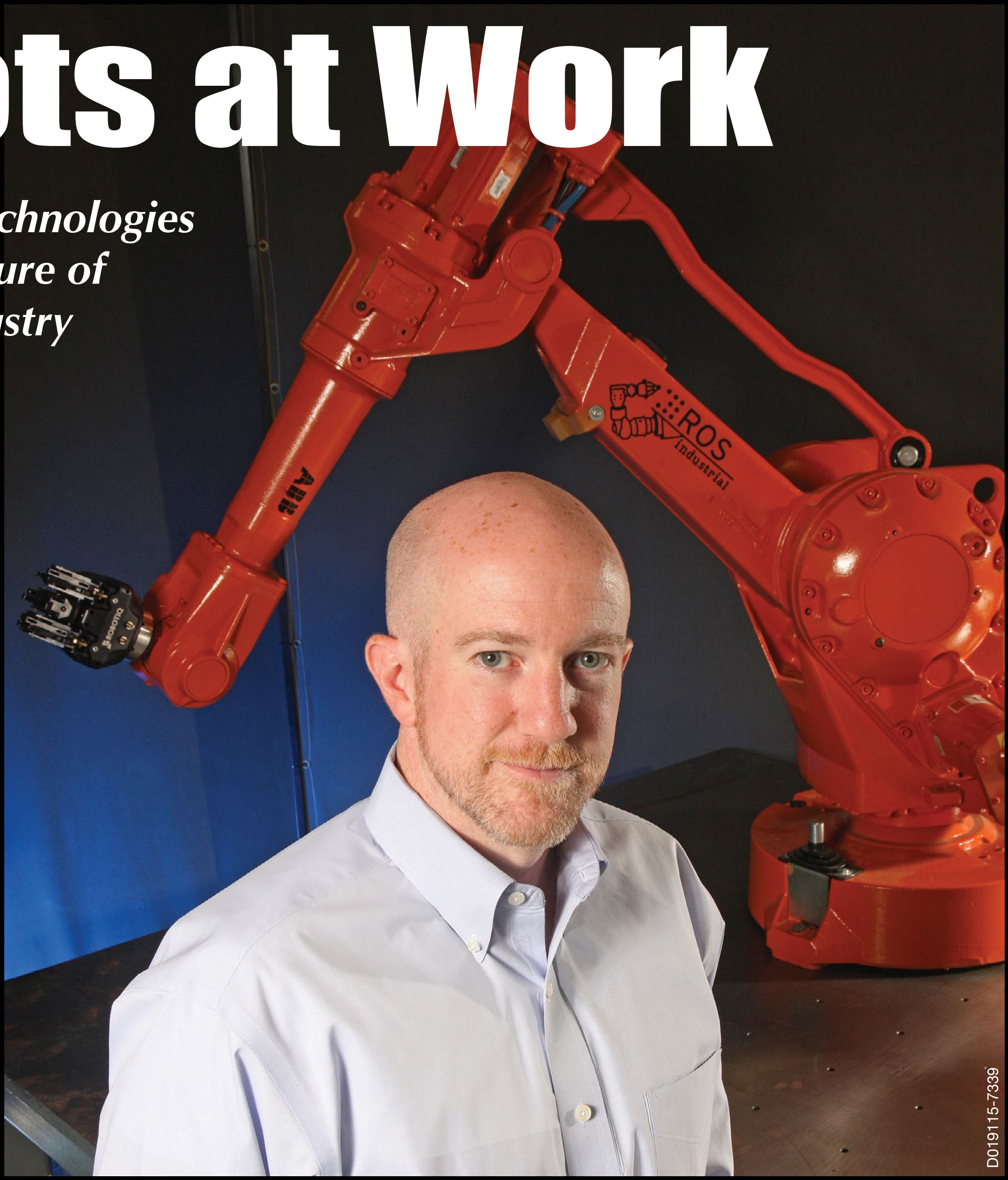
By Clay Flannigan

One of the earliest robotic manipulators was developed in the late 1950s and deployed on a General Motors automotive assembly line in 1961. The robot, called Unimate, handled hot, die-cast parts that were potentially dangerous to workers. Although robots like Unimate did not fulfill the human-like depictions of mid-20th Century science-fiction robots, they were steadily adopted by manufacturers for jobs such as spot welding or painting automobile bodies.

Industrial robot capabilities have continued to advance in areas such as payload, accuracy and speed. Today's robotic arms can pick up complete truck bodies or emplace minute electronic components, and they can package goods much faster than a human. Despite all these advancements, however, robots have barely ventured beyond the repetitive tasks of the factory floor.

Unlike the futuristic expectations of the 1950s, people still have limited exposure to robots in their daily lives, and even the robots in manufacturing environments typically are relegated to simple, repetitive and highly structured tasks. Why is this? Shouldn't there be a market for a robot that is able to fold our laundry or perform our mundane daily work tasks?

Engineers at Southwest Research Institute (SwRI) are developing technologies to overcome some of the historical limitations in the use of automation for complex industrial tasks. Through internal research and client-funded projects, SwRI teams are giving robots greater intelligence, more flexibility and greater ability to work collaboratively with humans.

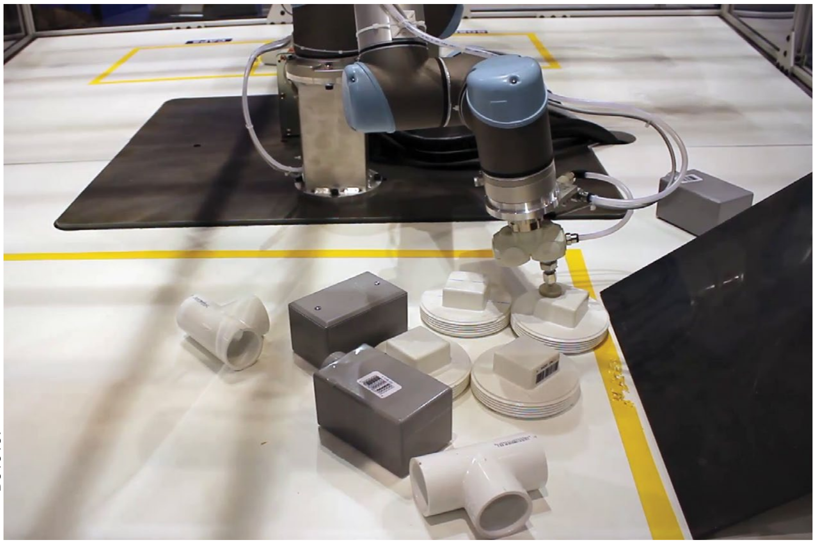


Clay Flannigan is manager of the Robotics and Automation Engineering Section within the Automation and Data Systems Division. His areas of expertise include machine design, robotics, control software and sensing systems. His section specializes in robotics, controls, computer perception and general automation hardware for a variety of industries.

Perception and planning

Traditionally, industrial robots have been deployed in jobs that require little decision-making. They typically perform the same task repetitively and have little ability to adapt to new situations. Providing robots with more human-like flexibility to adapt to dynamic or uncertain environments is a classic problem for robotics researchers. Many cognitive models exist to describe this problem, but they all share common elements of perceiving the environment and using this data, combined with prior knowledge, to plan an action.

Recently, there has been a dramatic shift in the use of 3-D sensing techniques to provide better context for robotic decision-making. Computing power has progressed to make real-time stereo imaging practical, and the console gaming industry has provided a revolutionary 3-D sensing capability with



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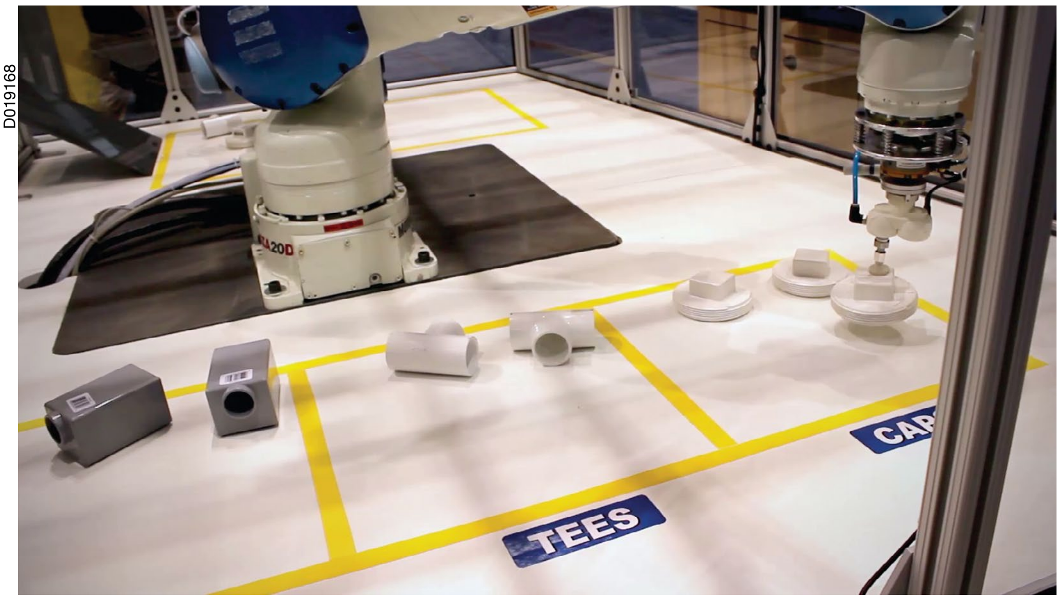
SwRI has developed methods that permit robots to pick objects from cluttered piles or bins (left), recognize those objects based on their shape, and sort them (below).



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the Microsoft Kinect® sensor. These sensing solutions combine high resolution, color and 3-D views of the robot's workspace, permitting the development of new algorithms to locate and identify objects within that space.

Using novel 3-D data analysis algorithms, the SwRI team recently developed techniques for object recognition in cluttered scenes. This enables robots to perform material handling tasks without need for dedicated tooling or fixtures. Such techniques enable robots to pick randomly oriented parts from bins or boxes and then insert them into a subassembly. In addition, sortation of highly varied parts is a common need for applications like mail handling or waste recycling facilities.

The SwRI-developed techniques combine digital models, built using prior knowledge of the parts, and various matching algorithms to identify the parts in the robot's field of view. In some cases, machine-learning algorithms are employed to "teach" the robot what a particular object looks like. Once a hypothesis for an object is generated from the sensor data, a pose estimate is created. This pose information is then provided to the planning algorithms to create robot arm trajectories and grasp strategies.

Giving robots mobility

Most industrial robot installations are permanently bolted in place with cages surrounding them, excluding human interaction with the robot. In such a paradigm, the parts must be brought to the tool, rather than the tool to the parts. For many industries, such as those that use assembly lines, this is the preferred approach. However, there are situations where it is preferable to bring the tool to the workpiece.

In aerospace manufacturing, for example, it is often easier to move the manufacturing process rather than the part due to the size of most commercial aircraft. SwRI has a long history of developing large robots for use in aerospace coating removal processes, but to date, the robots have been limited to relatively small aircraft such as fighter jets. For larger aircraft, such as commercial airliners, mobile robotic systems may be more cost-effective and flexible than the traditional fixed or tracked systems.

SwRI engineers recently demonstrated the ability to integrate a commercially available off-the-shelf (COTS) robotic manipulator onto a COTS mobile base to increase the effective workspace of the robot by a factor of 10 or more. This system, called MR ROAM (Metrology Referenced Roving Accurate Manipulator) uses a high-accuracy metrology system to locate the mobile system to sub-millimeter accuracy in work volumes of more than 500 square meters. The SwRI team developed specialized control strategies to permit coordinated motion of the mobile base with the manipulator, thereby providing the capabilities of a much larger robot. In addition to larger scales, MR ROAM technologies can be more flexible because the mobile base does not require significant facility modifications for tracks or dedicated work cells.

Human factors in robot interaction

Robot mobility and the manipulation of objects in unstructured environments are two capabilities that set the stage for robotic

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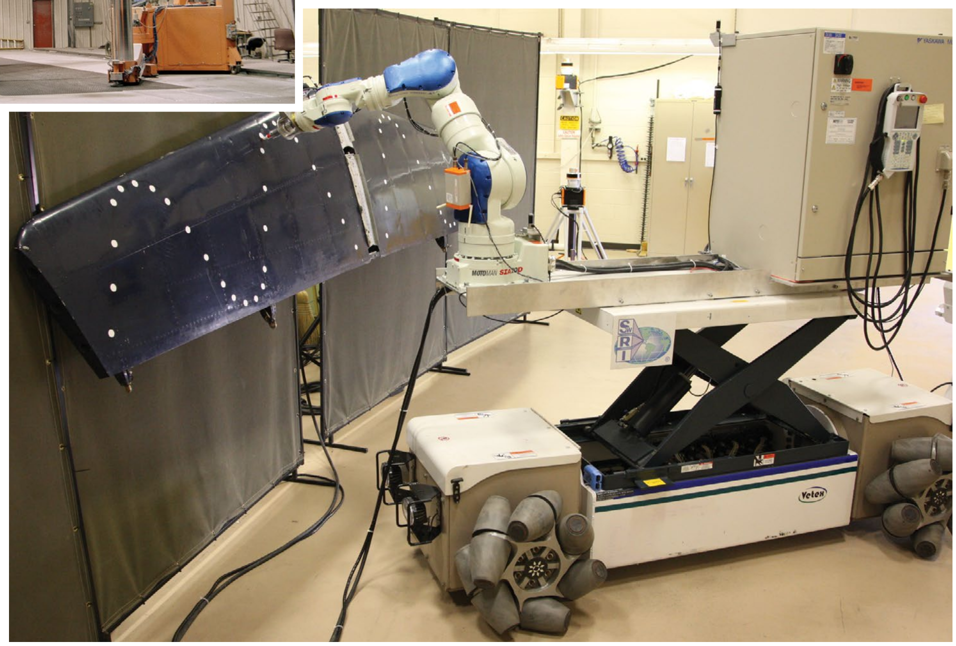
For more than 20 years, SwRI has been developing large robotic systems for aerospace coatings applications such as the robotic depaint system designed to maintain the U.S. Air Force's fleet of F-15 fighter jets. Current research has demonstrated that for some applications, a mobile solution can be less costly and more flexible.



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systems to operate openly in the "human" environments found in most factories. However, such a future vision is only possible if it can be done safely. There is significant activity in the robotics community and at SwRI to address these issues. Recently, the Robotics Industries Association (RIA), which is responsible for robotics safety standards in the U.S., ratified an updated ANSI/RIA R15.06-2012 standard. For the first time, this standard outlines situations where people may work collaboratively with industrial robots.

SwRI engineers also have been performing enabling research in the area of human tracking and behavior monitoring. Effective collaboration between machines and people requires that the machines be able to detect human presence and actions. For the former, SwRI collaborated with the National Institute of Standards and Technology (NIST) to develop a 3-D sensor-based capability to detect humans and track them in typical manufacturing environments. NIST is using this system to develop measurement methods and standards for incorporating human tracking systems onto machines like automated guided vehicles (AGV), forklifts and mobile manipulators.

In addition to knowing the location and velocity of a person in a robotic workspace, often one would like to recognize specific actions so the machines can respond appropriately. For example, if a person holds up a tool in a certain posture, the robot might respond by grasping the tool and taking it from the person. SwRI engineers are working on machine learning methods that enable robots to visually detect such classes of actions. These methods extract a kinematic "skeleton" model of the person from a 3-D image. By tracking this skeleton over time, SwRI's methods are able to classify certain repeated motion sequences as specific actions to which the robot can then react in a more meaningful, or safer, manner.

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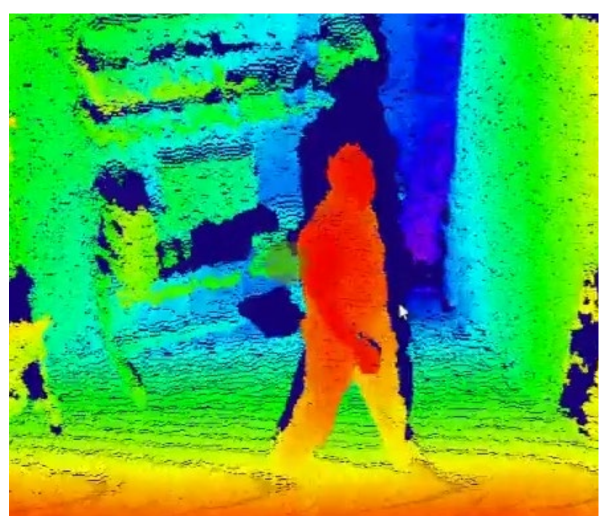

SwRI engineers developed a system to detect and track humans in manufacturing environments, even in the presence of occlusions or variations in the human pose. The system uses color and 3-D images like those shown at right and learns the "signature," or visible characteristics, of individuals in real time so that they can be uniquely tracked through the field of view.

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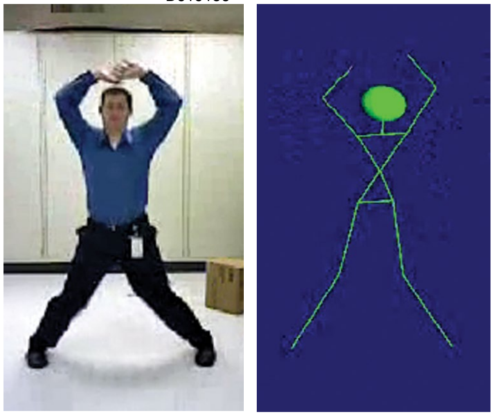

To recognize human actions, the SwRI-developed system tracks gross motions using skeleton models. A machine learning system, which has prior knowledge about different types of actions, can then classify the motion by type.

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SwRI started the ROS-Industrial open source project to build an international community around the use of the advanced, open-source Robot Operating System (ROS) for industrial applications.

An open software framework

In 2010, version 1.0 of the Robot Operating System (ROS) was made publically available. ROS is an open-source software framework for developing robotic systems. Since then, it has become the predominant platform for robotics research used by many academic research labs, especially for mobile and service robotics. Stewardship of ROS was initially provided by Willow Garage, a private technology startup, but has recently transitioned to the Open Source Robotics Foundation (OSRF).

ROS provides a flexible architecture with advanced capabilities not found in most industrial robot controller solutions. In addition, it has a large community of developers who use it for a huge range of applications. Because of the potential value of integrating the capabilities of ROS more closely with industrial robots, SwRI invested internal research funding for a visiting researcher position at Willow Garage. Over the next four months SwRI created the foundation of ROS-Industrial, an open-source extension of ROS that focuses on the needs of manufacturers and industrial robot users. It includes software packages for things such as low-level drivers for various robots and their ancillary equipment. It also has high-level functionality for capabilities, such as path planning, that are unique to industrial problems.

In its first year the ROS-Industrial project has attracted dozens of developers worldwide and gained support from several major robot vendors. End users are beginning to develop production systems using the software, and the ROS-Industrial consortium has formed to provide a roadmap to continue to foster the project. ROS-Industrial provides an important link between the robotics research community and end users, and SwRI is contributing many of the technologies it has developed back to the project. In doing so, there is a clear path to commercial adoption for these advanced capabilities.

Future vision

The combination of technologies for advanced perception, planning, mobility and human interaction within an open software framework is poised to accelerate the adoption of robotics in new manufacturing areas. Industries that traditionally have been difficult to automate are seeing rapid advances, and the ability for workers to interact with machines could improve productivity dramatically. Just as the early robotic systems were rapidly adopted for repetitive tasks in automated manufacturing, the next decade will witness a similar revolution in robots used for repetitive tasks where more flexibility and better decision-making are required.

Questions about this article? Contact Flannigan at (210) 522-6805 or clay.flannigan@swri.org.

TECHNICS

Brief notes about the world of science and technology at Southwest Research Institute

SwRI receives $1.5 million for thin-film deposition technology development

Work is under way at Southwest Research Institute (SwRI) on a $1.5 million, three-year project awarded by the Defense Advanced Research Projects Agency to develop novel technologies for depositing thin films.

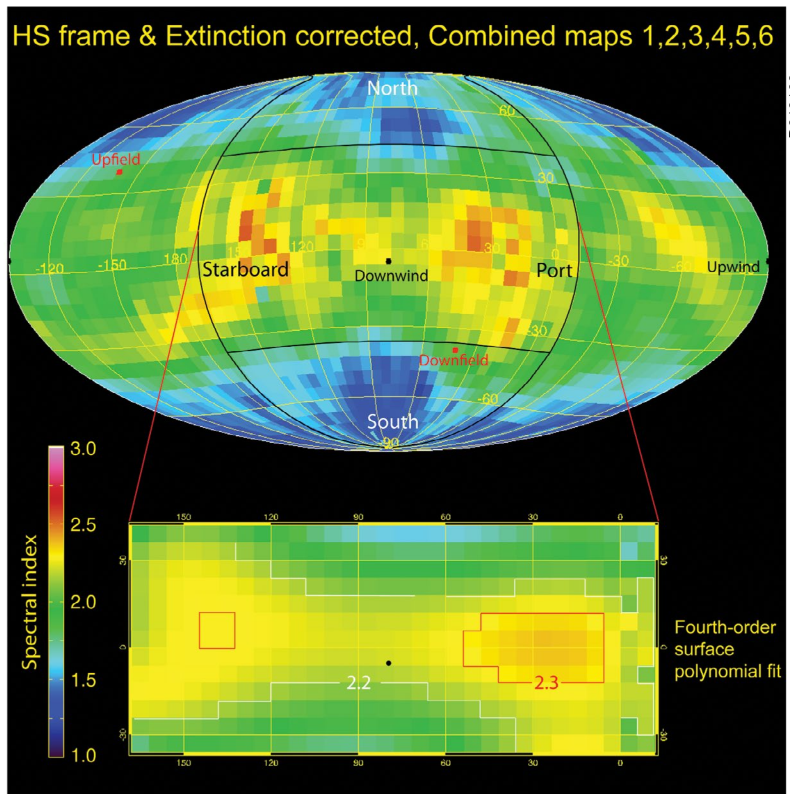
The contract award is under DARPA's Local Control (LoCo) of Materials Synthesis program, which is investigating non-thermal approaches for depositing thin-film coatings onto the surfaces of a variety of materials. The objective of the program is to overcome the reliance on high-thermal energy input by examining the process of thin-film deposition at the molecular component level in areas such as reactant flux, surface mobility and reaction energy, among others.

Many current high-temperature deposition processes cannot be used on military vehicles and other equipment because they exceed the temperature limit of the material. The LoCo program will attempt to create new, low-temperature deposition processes and a new range of coating-substrate pairings to improve the surface properties of materials used in a wide range of defense technologies including rotor blades, infrared missile domes and photovoltaics, among others.

"Drawing from our experience in developing novel plasma technologies and thin-film deposition processes, we are focusing on the thin-film deposition process component of reactant flux," said Dr. Vicky Poenitzsch, a senior research scientist in SwRI's Materials Engineering Department and manager of the DARPA project.

Contact Poenitzsch at (210) 522-3755 or vicky.poenitzsch@swri.org.

IBEX spacecraft images reveal unexpected heliotail structure



NASA's Interstellar Boundary Explorer (IBEX) spacecraft recently provided the first complete pictures of the solar system's downwind region, revealing a unique and unexpected structure.

Researchers have long theorized that, like a comet, a "tail" trails the heliosphere, the giant bubble in which our solar system resides, as the heliosphere moves through interstellar space. The first IBEX images released in 2009 showed an unexpected ribbon of surprisingly high energetic neutral atom (ENA) emissions circling the upwind side of the solar system. With the collection of additional ENAs over the first year of observations, a structure dominated by lower energy ENAs emerged, which was preliminarily identified as the heliotail. However, it was quite small and appeared to be offset from the downwind direction, possibly because of interactions from the galaxy's external magnetic field.

As the next two years of IBEX data filled in the observational hole in the downwind direction, researchers found a second tail region to the side of the previously identified one. The IBEX team reoriented the IBEX maps and two similar, low-energy ENA structures became clearly visible straddling the downwind direction of the heliosphere, indicating structures that better resemble "lobes" than a single unified tail.

"It may well be that these are separate structures bent back toward the downwind direction. However, we can't say that for certain with the data we have today," said Dr. Dave McComas, IBEX principal investigator and assistant vice president of the Space Science and Engineering Division at Southwest Research Institute.

The paper, "The Heliotail Revealed by IBEX," by D.J. McComas, M.A. Dayeh, H.O. Funsten, G. Livadiotis, and N.A. Schwadron, was published July 10, 2013 in the *Astrophysical Journal*.

IBEX is part of NASA's series of low-cost, rapidly developed Small Explorer space missions. Southwest Research Institute in San Antonio leads the IBEX mission with teams of national and international partners. NASA's Goddard Space Flight Center in Greenbelt, Md., manages the Explorers Program for NASA's Science Mission Directorate in Washington.

Contact McComas at (210) 522-5983 or david.mccomas@swri.org.

Moon radiation findings may reduce health risks to astronauts

Space scientists from the University of New Hampshire (UNH) and Southwest Research Institute (SwRI) report that data gathered by NASA's Lunar Reconnaissance Orbiter (LRO) show that lighter materials like plastics provide effective shielding against the radiation hazards faced by astronauts during extended space travel. The finding could help reduce health risks to humans on future missions into deep space.

Aluminum has always been the primary material in spacecraft construction, but it provides relatively little protection against high-energy cosmic rays and can add so much mass to spacecraft that they become cost-prohibitive to launch.

The scientists have published their findings online in the American Geophysical Union journal *Space Weather*. Titled "Measurements of Galactic Cosmic Ray Shielding with the CRaTER Instrument," the work is based on observations made by the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on board the LRO spacecraft. Lead author of the paper is Cary Zeitlin of the SwRI Earth, Oceans, and Space Department at UNH. Co-author Nathan Schwadron of the UNH Institute for the Study of Earth, Oceans, and Space is the principal investigator for CRaTER.

Says Zeitlin, "This is the first study using observations from space to confirm what has been thought for some time — that plastics and other lightweight materials are pound-for-pound more effective for shielding against cosmic radiation than aluminum. Shielding can't entirely solve the radiation exposure problem in deep space, but there are clear differences in effectiveness of different materials."

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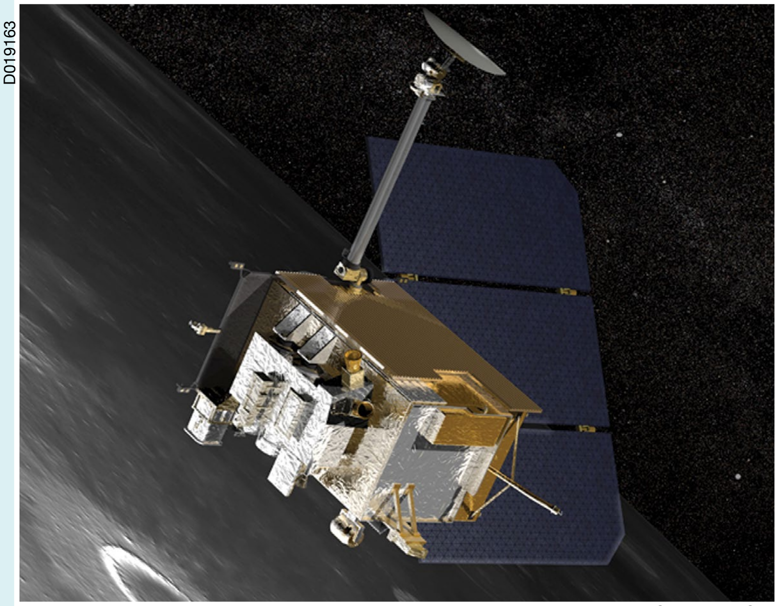

Courtesy NASA

The NASA Goddard Space Flight Center in Greenbelt, Md., developed and manages the LRO mission. LRO's current science mission is implemented for NASA's Science Mission Directorate. NASA's Exploration Systems Mission Directorate sponsored LRO's initial one-year exploration mission that concluded in September 2010.

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SwRI recognized for developing connected commercial vehicle technology

Southwest Research Institute (SwRI) played a key role in a project recognized by the Intelligent Transportation Society of New York (ITS-NY) to advance national connected vehicle policy.

The Commercial Vehicle Infrastructure Integration Project (CVII) was the first significant national effort to integrate connected vehicle technology into large trucks and maintenance vehicles and to develop applications and functionalities specifically for commercial vehicle operations. ITS-NY recognized it as the Project of the Year at its 20th Annual Meeting and Technology Exhibition June 13–14 in Saratoga Springs, N.Y. Led by the New York State Department of Transportation, the project team included the I-95 Corridor Coalition, Volvo Group, SwRI, Kapsch and the Federal Highway Administration.

The project represents a milestone effort to advance national connected vehicle concepts by including the heavy vehicle industry as key stakeholders and users of the new technology. SwRI led the team's efforts in software application development for on-board equipment. These applications utilize 5.9 GHz Dedicated Short Range Communications (DSRC) to exchange data between the commercial vehicle, infrastructure and other commercial, passenger and maintenance vehicles to enable a cooperative system of intelligent vehicles.

"This project is the first of its kind to develop and test connected vehicle technology in commercial vehicles," said Michael Brown, a staff engineer in SwRI's Automation and Data Systems Division. "SwRI developed the capability for maintenance vehicles to alert commercial vehicles," said Brown. "We also developed vehicle-to-vehicle applications, including blind-spot warnings, hard-braking events, tailgate warnings, and unsafe-to-merge/pass scenarios, as well as a railroad crossing warning system."

Contact Brown at (210) 522-3104 or michael.brown@swri.org.

Technical Staff Activities

Publications

Antebi, B., X.G. Cheng, J.N. Harris, L.B. Gower, X.D. Chen and J. Ling. “Biomimetic Collagen-hydroxyapatite Composite Fabricated via a Novel Perfusion-flow Mineralization Technique.” *Tissue Engineering*: Part C, Vol. 19, No. 7, (2013): 487–496, doi:10.1089/ten.TEC.2012.0452.

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Allegrini, F. "Strofio Calibration." Paper presented at the 4th Search for Exospheric Refilling and Emitted Natural Abundances (SERENA) – Hermean Environment Working Group (HEWG) Meeting, Key Largo, Fla., May 2013.

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Breslof, M., S. Endy and M. Slocum. "Giving Money Away: Subagreements." Paper presented at the Society of Research Administrators International (SRA) Managing the Legal and Regulatory Research Landscape Meeting, Washington, February 2013.

Breslof, M., S. Endy and M. Slocum. "Stimulating the Public Good Through Research: Contracting for Grants." Paper presented at the Society of Research Administrators International (SRA) Managing the Legal and Regulatory Research Landscape Meeting, Washington, February 2013.

Technical Staff Activities

Breslof, M., S. Endy and M. Slocum. “Working for Others: Federal and Non-Federal Contracting.” Paper presented at the Society of Research Administrators International (SRA) Managing the Legal and Regulatory Research Landscape Meeting, Washington, February 2013.

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