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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



About the cover

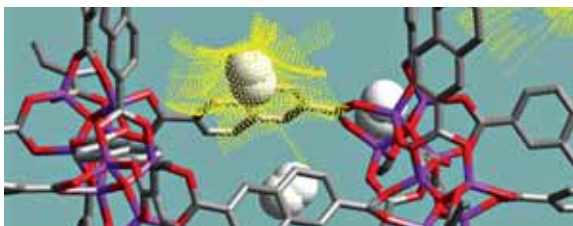
Highly magnified grains of cornstarch-based blast media are used to remove aircraft coatings without liquids and with minimal risk of damage to the underlying structure.

ARTICLES



2 Depainting By Numbers

An SwRI-developed robotic system removes coatings from off-airframe components of military aircraft.



6 New Materials, New Methods

SwRI researchers are using advanced computational tools to develop and analyze nanomaterials.



12 Enhancing Our World's Energy Supply

SwRI engineers are developing new technology for subsea natural gas production.



16 Digging Into Simulation

An SwRI-developed simulator helps train excavator operators safely and effectively.



20 Street Smart

SwRI plays a significant role in the 15th World Congress on ITS.

Departments

Technics....22

Technical Staff Activities....24

Recent Features....29

Depainting By Numbers

An SwRI-developed robotic system removes coatings from off-airframe components of military aircraft

By Dan H. Weissling

Applying and removing coatings on military aircraft has become increasingly complicated by the widespread adoption of airframes with lightweight, fragile composite materials alongside traditional aluminum alloys, as well as the use of complex curves to maximize performance and minimize radar reflection.

At the same time, military maintenance centers have sought to take advantage of the greater precision and lower costs offered by automated, robotic systems.

The challenge has been to create robotic depaint systems that apply blast media in a way that removes the coating quickly and efficiently, yet does not damage the structure beneath.

History

Over time, Southwest Research Institute (SwRI) has become a world leader in automated paint removal, beginning with a project completed in 1992 to remove paint from F-16 fighter aircraft at Hill AFB, Utah. The Robotic Paint Stripping Cell (RPSC) at Hill remains in steady use today. A concurrent system, called the Robotic Depaint System (RDS), remains in use at Robins AFB, Georgia, for the stripping of F-15 fighter aircraft. Although there have been attempts by others to develop automated, full-aircraft depainting systems, none has approached the success achieved with both the RPSC and the RDS.

Over the years, robots have moved from the laboratory to commercial applications in a variety of industries. At



Airframe components, such as this section of a horizontal stabilizer, are removed and placed in jigs for depainting using the ACRES system. The robot can be programmed to handle different structures from several types of aircraft.

the same time, aircraft materials have moved toward thinner metal skins and lighter-weight composite materials. Environmental, safety and ergonomic requirements have gained importance. However, much of the depainting of aircraft and aircraft components is still being performed either through labor-intensive manual blasting or chemical stripping. The U.S. Air Force is working proactively to

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implement processes that are more cost-effective and that reduce the hazardous waste stream and prevent occupational injuries.

In 2007, SwRI was contracted by the URS Corporation, prime contractor for the project, to develop a system for depainting off-airframe components at Hill AFB. Many of the C-130, A-10 and F-16 aircraft are typically disassembled and reworked as part of the overhaul process. The resulting off-airframe components, consisting primarily of flight control surfaces such as wings and flaps, are stripped using conventional, manual means with either plastic media blasting or chemical stripping. Leveraging the experience gained from a similar system developed for Robins AFB, known as ADSOC, a team of SwRI engineers began a new system that was dubbed ACRES (Automated Coating Removal System).

The overall system includes four major subsystems: media blast, robotic automation, component support and fixturing, and component preparation and handling.

Blast system

The blast subsystem includes a self-contained blast booth that uses a negative-pressure ventilation system and an operator control room. As is typical with many blast systems, the used media is recirculated through a floor recovery system and routed through a series of separators that remove broken-down media as well as ferrous and non-ferrous contaminants, including paint residue. Approximately 5 percent to 10 percent of the media is broken down per cycle, requiring a small amount of replenishment. Both new and cleaned media are transported to pressurized blast pots and metered through blast hoses to the nozzles at the robot's end-effector.

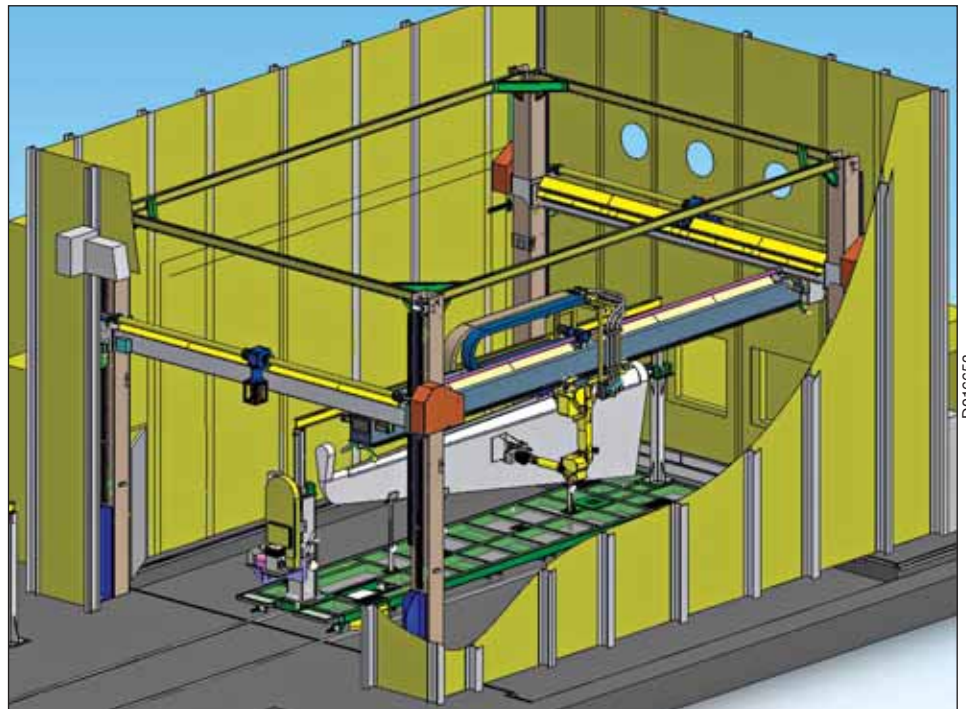
ACRES robot

One major difference between the off-airframe ACRES and its full-aircraft predecessors is the robot type.

The full-aircraft system's robots are free-standing and supported by a track in the floor, and the robot essentially "walks" around the aircraft. By comparison, the ACRES robot is supported by an overhead gantry structure which allows its manipulator to move around the aircraft components from above. Also, in contrast to previous systems, the ACRES robot is a combination of custom and commercial off-the-shelf (COTS) technologies.

A FANUC Robotics manipulator with five degrees of freedom is the primary workhorse. To gain full access to the wide variety of aircraft components ACRES would depaint, SwRI engineers designed an additional three degrees of freedom to move the entire FANUC manipulator in three-dimensional space. Overall, the ACRES structure is 36 feet long, 22 feet wide and 20 feet tall, creating a work envelope approximately 25.5 feet long, 16.5 feet wide and 12.5 feet tall. ACRES can accommodate any component that fits within that space.

The total weight of the movable portion of the robot is approximately 14,300 pounds. To reduce the motor size required to move such a large mass, steel counterweights weighing approximately



This computer diagram shows how blast media is confined within an enclosed booth while the ACRES robot manipulates the media blast nozzle alongside an airframe component.

3,500 pounds each hang inside the four support legs of the gantry.

The gantry's up-and-down motion is referred to as the Z-axis. Side-to-side movement in a direction normal to the aircraft component's surface is the X-axis. The manipulator moves side-to-side along the Y-axis that is parallel with the long axis of the component being stripped. These motions are accomplished by means of a large rack-and-pinion drive system on each axis.

The robot end-effector comprises an array of three flat, or "fan," nozzles that project the media at high velocity onto the aircraft substrate, stripping about a 9-inch swath. The end-effector also has a built-in camera that allows the operator in the control room to see the strip zone from the perspective of the end-effector.

ACRES also features a carefully designed user interface that comprises three elements. The first is an operator console with easy-to-use functionality, which serves as the primary user interface during paint-stripping operations. The operator can start, stop, jog, back up and control the speed of the robot's motion program. The second interface consists of PC-supported video monitors that allow the operator to select the component to be stripped, troubleshoot and view error logs, and monitor the status of the blast system. The third interface

is a "teach" pendant that allows the advanced operator to manually jog the robot and create path files for new components.

A major consideration in the ACRES design was safety. Multiple safety features were implemented to protect aircraft components and the operator from any potential harm resulting from hardware or software failures of the robot. In addition to non-backdriveable drive components, the design includes other safety features such as large disk brakes located on each of the four Z-axes, tilt sensors, proximity and through-beam sensors, hardware and software interlocks, a "whisker switch" hoop surrounding the robot end-effector, and permanently mounted over-travel hard stops on each of the X, Y and Z-axes.

Fixturing

Although ACRES can be programmed to depaint any component that fits within its large work envelope, the system will initially be pre-configured to depaint 27 off-airframe components, including the A-10's rudders, elevators, inboard flaps, outboard flaps, de-

celerons, outer wings and inner wing. F-16 components include horizontal stabilizers, flaperon, leading edge and wings; C-130 components include ailerons, elevators, rudder and floor panels. Unlike previous systems that required the operator to "teach" reference points to locate each component in three-dimensional space, ACRES takes advantage of absolute positioning by using a universal component support chassis that will affix each component in a repeatable position.

The component support chassis is a large steel frame, approximately 27 feet long and weighing over 5,000 pounds, that shuttles the aircraft components into and out of the blast booth. It is pneumatically driven on steel rails that are embedded in the floor. The chassis is designed for utmost flexibility; components can be base-mounted, hung and even rotated. A rotation mechanism mounted on one end of the chassis is designed to support and rotate the large A-10 wing.

Preparation and handling

ACRES includes a staging area outside the blast booth where components are prepared for blasting. This work includes masking areas that are not to be stripped and sealing all critical seams against media ingress. Support stands, similar to those used on the chassis, are replicated in the prep area. Due to very limiting space constraints and the need to protect aircraft components from damage, SwRI engineers developed effective

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U.S. Air Force photo by Sue Sapp

The ACRES system eliminates worker exposure to hazardous environments, such as the chemical stripping process shown above.



The ACRES operator's station uses standard PC-supported video monitors that allow the operator to select the component to be stripped, troubleshoot and view error logs, and monitor the status of the blast system.

procedures and handling tools to transfer parts into and out of the staging area.

Applications, present and future

ACRES will enable the Air Force to depaint off-airframe components more efficiently and effectively. The system will provide better consistency of the depaint process, reduce manpower and cost, and remove the operator from a potentially unsafe work environment.

The system is designed to use a new blast media, known as GPX, which has several advantages over the commonly used acrylic plastic media. With its cornstarch-based chemical matrix, it is not only less aggressive for sensitive substrates such as composites and thin-skinned aluminum, but it is also biodegradable. This more environmentally friendly media will result in additional savings to the government due to a smaller hazardous waste stream.

The ACRES design team at SwRI recognized that

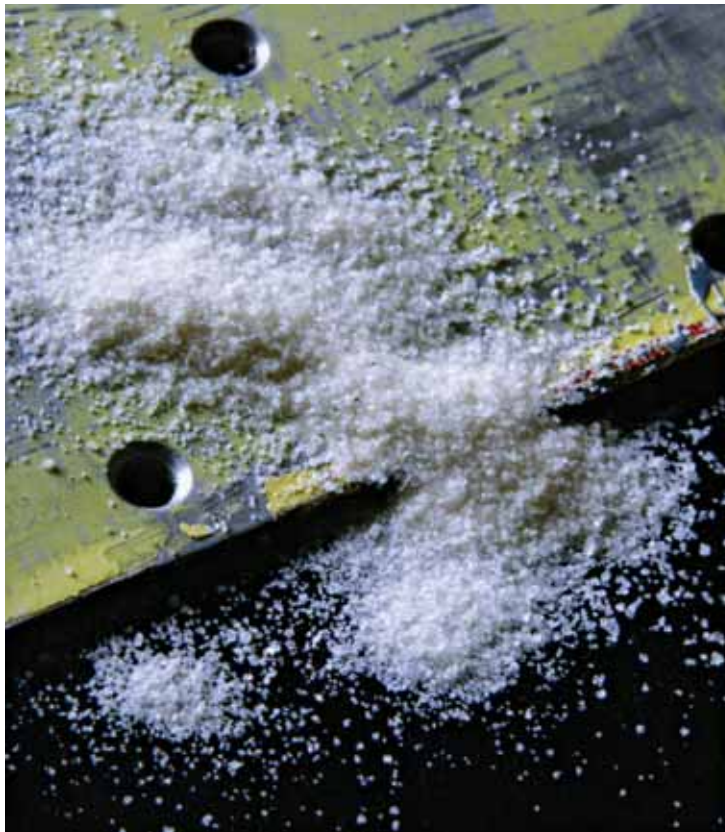
new processes may be introduced in the future for stripping paint. A major effort is under way to apply laser technology for this application. The ACRES robot has

sufficient accuracy and repeatability to be retrofitted with a laser end-effector

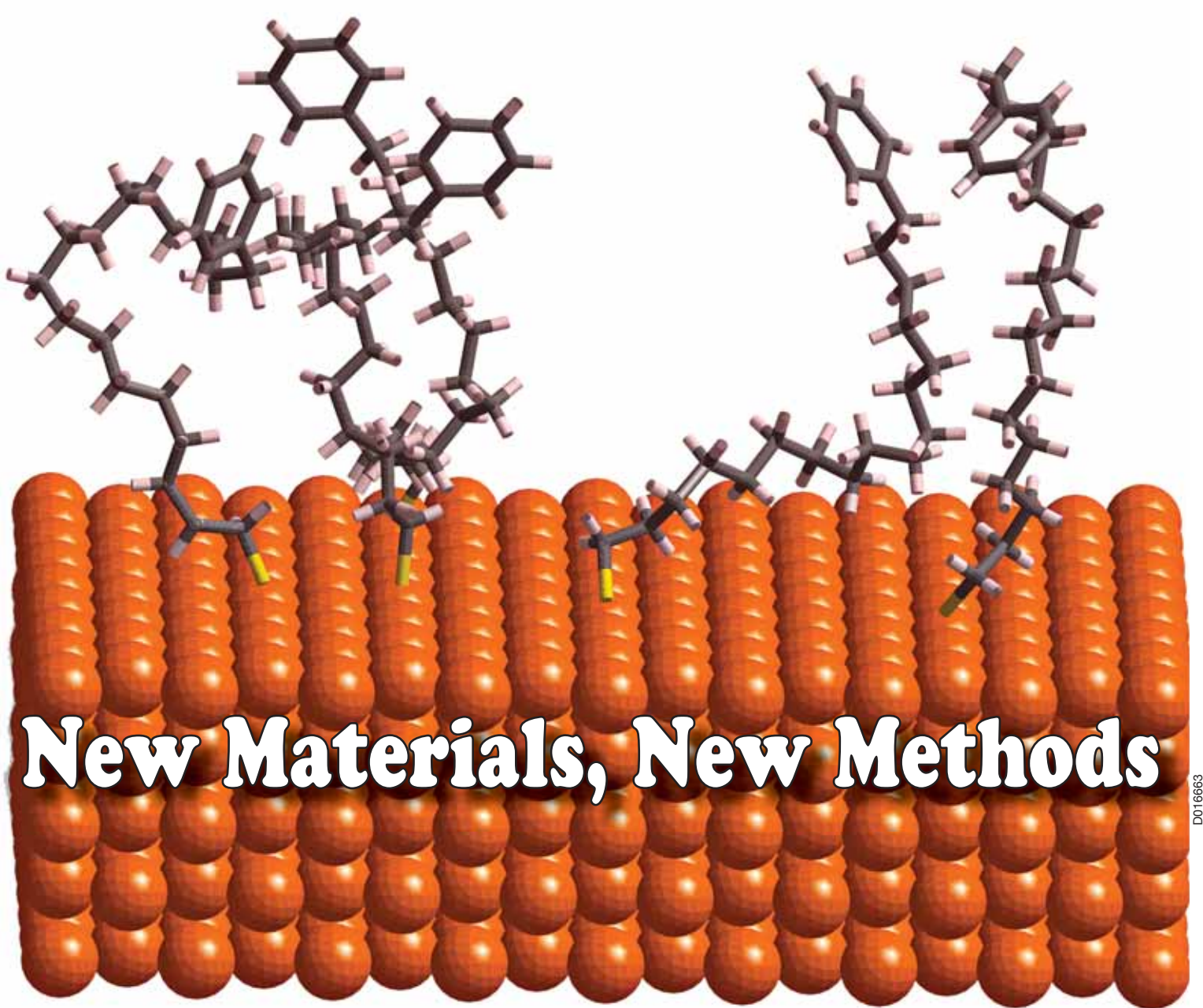
should the process be validated. Other paint removal processes could be incorporated as well.

Installation of ACRES at Hill AFB occurred during the autumn of 2008. SwRI plans to continue providing operational, training and maintenance support for the system under contract to Hill AFB. v

Questions about this article? Contact Weissling at (210) 522-3535 or dan.weissling@swri.org.



A new, cornstarch-based blast media can remove aircraft coatings without liquids and with minimal risk of damage to the underlying structure. About 90 percent to 95 percent of used media can be recovered, cleaned and reused in the next depaint cycle.



New Materials, New Methods

DOT6663

SwRI researchers are using advanced computational tools to develop and analyze nanomaterials

Using molecular dynamics theory, researchers can simulate the adsorption and surface structuring of boundary layer molecules (lubricant additive) on an ideal metal surface.

By Kwai S. Chan, Ph.D., Michael A. Miller, Ph.D. and Wuwei Liang, Ph.D.

Southwest Research Institute (SwRI) has strong technical programs in materials integrity and characterization, probabilistic mechanics, biomechanics, surface engineering, materials chemistry, environmental effects and failure analysis. These program areas all employ some combination of experimental and numerical investigations to understand and predict material behavior and performance. In situations where fundamental material behavior is

needed but cannot be measured in the laboratory because conditions are too severe — or the material does not yet even exist — SwRI researchers turn to the emerging field of computational material science, where underlying material properties and behavior can be predicted using computer simulations.

Computational material science uses theoretical calculations to develop the scientific basis for exploring, selecting and designing materials as well as for

optimizing and predicting material properties at various length scales ranging from atomic, molecular and microscopic to macroscopic scales. The key idea behind computational material science is to accelerate the discovery process, shorten the time, and reduce the cost of developing and inserting advanced materials into the design of new products. Using computational methods departs from the traditional empirical approach, which relies on experimental observations and

trial-and-error for material development and is more costly and time-consuming.

One area where computational material science is increasingly being applied is the field of nanomaterials. The emergence of nanotechnology has created a new class of materials with unique structures and properties that are not adequately addressed by existing theories. Because of the small size, *ab initio* methods— also known as first-principles methods because they rely on basic and established laws of nature — and molecular dynamics codes are required to predict or simulate the properties of nano-scaled materials. In first-principles methods, material structures and properties are predicted on the basis of electronic bonding and quantum mechanics computations with limited use of empirical data. In molecular dynamics, materials are presented as a system of atoms with interactions that are treated classically and governed by interatomic potentials that may be either obtained semi-empirically or computed directly from first-principles methods. In many instances, the experimental difficulties associated with measuring the properties of nano-scaled or small-volume materials are overwhelming, and it becomes more advantageous to compute the relevant material properties on the basis of first-principles or molecular dynamics methods or both. In other instances, theoretical computations can predict, verify or optimize experimental measurements. Similarly, there are situations where the properties to be measured are beyond the detection limits of current technologies. They can only be computed using theoretical means, thus providing the impetus for the emergence of computational material science as a scientific discipline. A recent National Research Council study identified “the integration of materials information, captured in computational tools, with engineering product performance analysis and manufacturing-process simulation” as an emerging engineering discipline and a national need.

SwRI researchers are involved in a wide range of activities concerned with computational material science and engineering. Because the problems being ad-



Dr. Michael Miller (left) is a staff scientist in the Materials Engineering Department in SwRI's Mechanical and Materials Engineering Division. Miller, a physical chemist, specializes in experimental and theoretical methods of analyzing organic, inorganic and polymeric compounds in complex systems. Dr. Kwai Chan (center) is an Institute scientist in the Materials Engineering Department. Chan, recognized internationally for his work in materials science, has more than 25 years experience in materials research including modeling the mechanical behavior of materials and developing life-prediction methods. Dr. Wuwei Liang is a research engineer in the Materials Engineering Department. Liang's research focuses on computational mechanics and materials science, with an emphasis on fracture, fatigue, nanomaterials and probabilistic analysis and design. Background: 76-node parallel computer cluster dedicated to computational materials science.

of one or more intermetallic phases embedded in a metallic matrix or an intermetallic matrix containing ductile metallic particles. In many instances, the alloys exhibit low fracture resistance because substantial amounts of intermetallic phases in the microstructure cause the Nb matrix to behave in a brittle manner.

Depending on the alloy composition, as many as six intermetallic phases in alloyed forms can exist in the microstructure of Nb-based alloys and *in-situ* composites, which often contain six or more elements such as Nb, chromium (Cr), titanium (Ti), silicon (Si), aluminum (Al), hafnium (Hf) and others. These intermetallic phases provide high-temperature creep strength and oxidation resistance, while the Nb solid solution improves the ambient-temperature fracture resistance.

The large number of potential combinations of alloying elements, however, makes the discovery of beneficial alloy additions a daunting task if undertaken by empirical means alone.

In a project funded by the U.S.

ressed are diverse, a variety of computational methods are being used including *ab initio*, molecular dynamic, thermodynamic and diffusion codes. In a number of research projects, SwRI scientists and engineers have applied computational material science and engineering to solve practical problems for government and industry clients.

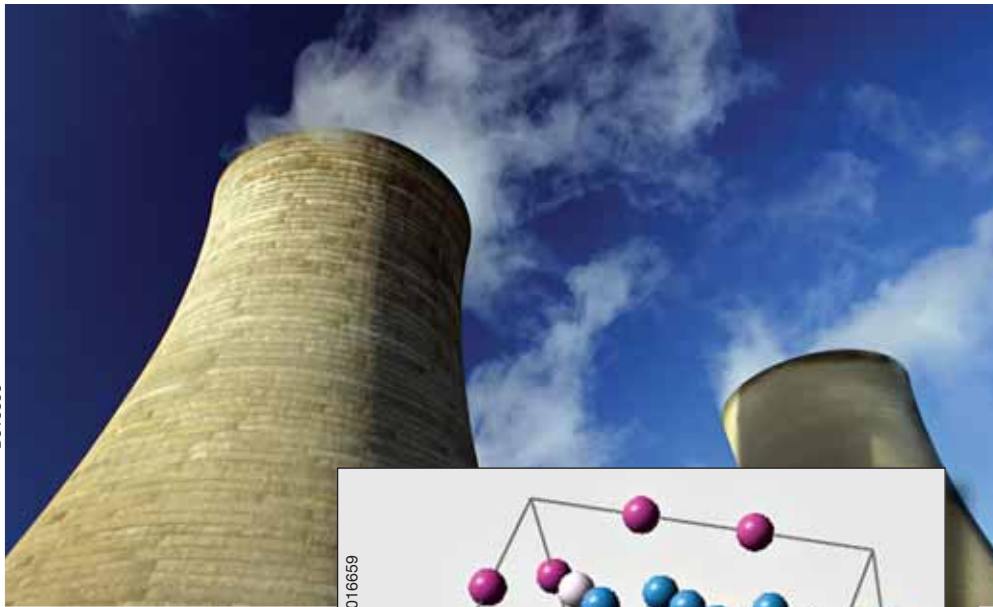
Designing fracture-resistant composites

Considerable efforts have been made to develop new niobium (Nb)-based alloys and composites for potential application as turbine blade materials in military engines. These efforts have been motivated by the desire to increase the thrust-to-weight ratio by increasing the operating temperature of the engine. The Nb-based multiphase alloys are seen as possible high-temperature materials of the future because their melting point is greater than that of current blade materials made of nickel-based alloys. These Nb-based alloys are processed to exhibit a multiphase microstructure containing a significant amount



New alloys are being evaluated for high-temperature applications such as aircraft turbine blades.

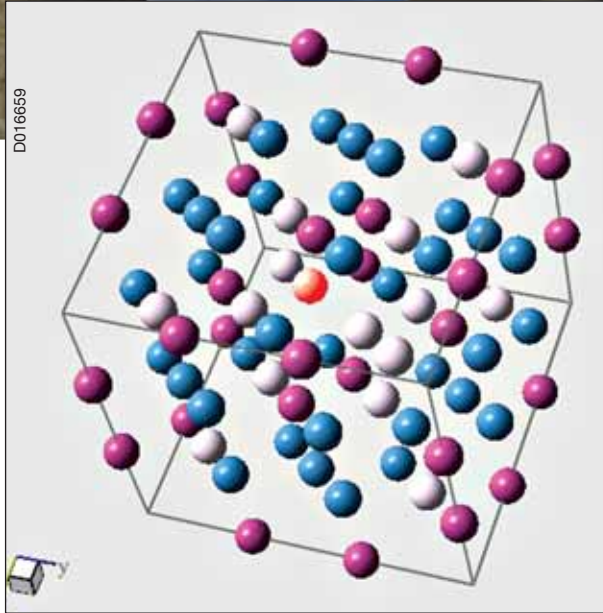
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Air Force Office of Scientific Research, SwRI materials scientists developed a set of computational tools and extended an internally developed *ab initio* code for designing Nb-based alloys and composites with desired composition, microstructure and performance. The SwRI team used the computational results to identify beneficial alloying additions that would increase crack-tip plastic deformation and therefore fracture toughness. The SwRI approach allowed a systematic evaluation of the alloying effects on fracture resistance of individual elements. Adding titanium enhanced fracture toughness and reduced the barrier against crack-tip plastic deformation, while adding Cr and Al reduced fracture resistance by decreasing plastic deformation. These computational tools provided an effective means for optimizing alloy composition, microstructure, and fracture properties for Nb-based alloys and composites.

Nuclear waste disposal and management

Nickel-based alloys such as Alloy 22 are candidate materials for applications such as the outer containers of waste packages for the disposal of high-level nuclear waste. During fabrication processes and long-term storage, Ni-based alloy outer containers can undergo microstructural changes caused by the formation of ordered Ni_2 (chromium, molybdenum) and brittle intermetallic phases.



A supercell is used to compute the migration energy of a Cr atom (single atom shown in red, at center) toward a vacancy in a Ni-Mo-Cr alloy (Ni: purple; Mo: blue; Cr: white).

The precipitation temperature of these brittle intermetallic phases and the ordering temperature of $\text{Ni}_2(\text{Cr}, \text{Mo})$ are in the range of 773 to 1,073 degrees Kelvin, and both reactions are sluggish. Because of slow reaction kinetics, the formation, morphological evolution, and properties of the $\text{Ni}_2(\text{Cr}, \text{Mo})$ and brittle intermetallic phases cannot be measured confidently using short-term tests over a reasonable time frame. Similarly, the mechanical properties of $\text{Ni}_2(\text{Cr}, \text{Mo})$ and brittle intermetallic phases are largely unknown because they have not been measured due to the fact that specimens are difficult to prepare and heat-treat.

To circumvent these experimental limitations, SwRI researchers used a first-principles, quantum-mechanical compu-

tational code (WIEN2K) based on the full potential linearized augmented plane wave (FLAPW) method to compute the energy of formation of potentially brittle intermetallic phases in a Ni-base alloy. The thermodynamic data were incorporated into an existing database for Ni alloys and used in conjunction with Thermo-Calc[®] software to compute the binary Ni-Cr phase diagram and to predict the formation of ordered phases in Alloy 22 (Ni-21.2Cr-15.5Mo-4Fe-3W, in weight percent) at various temperatures. In addition, they used WIEN2K to compute the elastic constant, theoretical stress-strain curve, tensile ductility and fracture toughness of Ni_2Cr and Ni_2Mo . With these results, researchers were able to assess the long-term stability and potential degradation of Ni-base alloys in a nuclear waste repository environment.

SwRI researchers used computational methods in an internal research project to compute the mobility database for Ni-Mo-Cr-Fe-W alloys. Again using the WIEN2K code, they computed the electronic structure and total energy of an n-atom supercell, which comprises multiple unit cells of the crystal lattice, with atom positions designed to simulate the desired diffusion processes. The computational procedure involved calculating the energy for vacancy formation, the energy barrier for solute migration and the correlation factor of individual diffusive species in the host metal. Using first-principles computational results of the energy of vacancy formation, they computed migration energy for solute self-diffusion and activation energy for diffusion of Mo, Cr, Fe, W, and Ni in Ni-Mo-Cr-Fe-W alloys such as Alloy 22, to expand the existing mobility database required for long-term diffusion kinetics computations for these alloys.

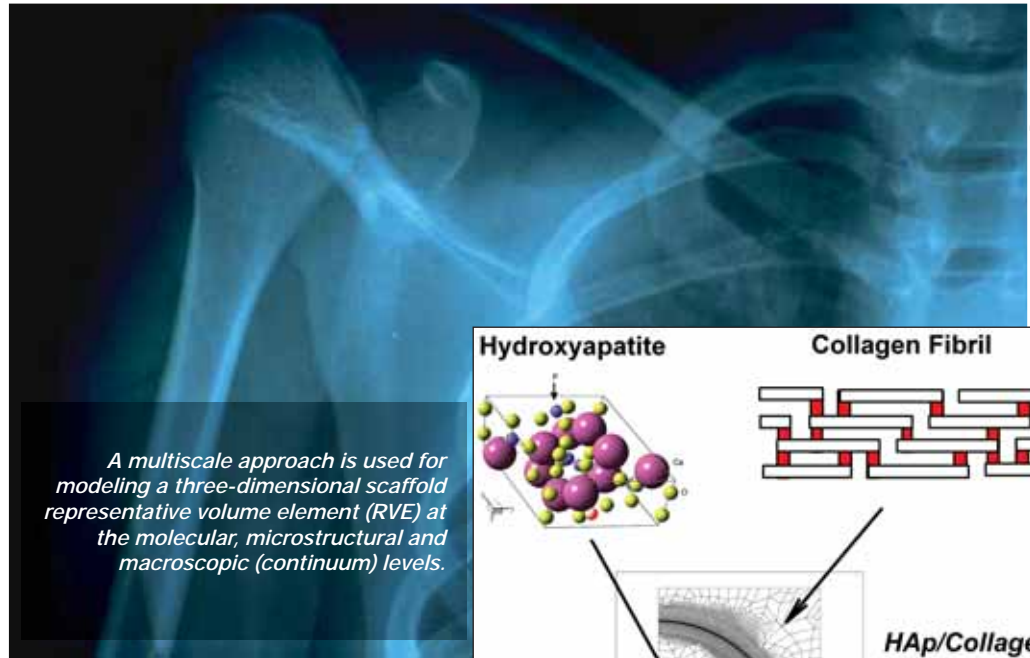
Developing nanocoatings for power generation applications

The U.S. Department of Energy (DOE) and power generation companies are interested in achieving greater power plant efficiency by increasing steam temperature to 760 degrees Centigrade and steam pressure to 35 Mega Pascals. This combination of high steam temperature and pressure, referred to as the ultra super-critical (USC) condition, has been shown to promote coal ash corrosion and increase corrosion rates. To improve

reliability and availability of fossil-fired USC boilers, it is essential to develop advanced nanostructured coatings that provide excellent corrosion and erosion resistance without adversely affecting other properties of the component materials, such as toughness and thermal fatigue strength.

For a project funded by DOE through EPRI, SwRI scientists applied computational methods to design and assess potential Fe-Cr-Ni-Al systems to produce stable nanostructured coatings that form a protective, continuous scale of alumina or chromia. They used the Thermo-Calc® software to generate phase diagrams for the design of Fe-Cr-Ni-Al nanocoatings and performed computational modeling of the grain growth process and sintering of voids to assess microstructural stability. Researchers used the DICTRA® diffusion code for interdiffusion of Al, Cr and Ni to maximize the long-term stability of the nanocoatings.

The computational results identified a new series of nanocoatings that maintain long-term stability and corrosion resistance by forming a diffusion barrier layer at the coating/substrate interface that prevents Cr or Al loss from inward diffusion. Fabrication and characterization of these new nanocoatings are currently in progress.

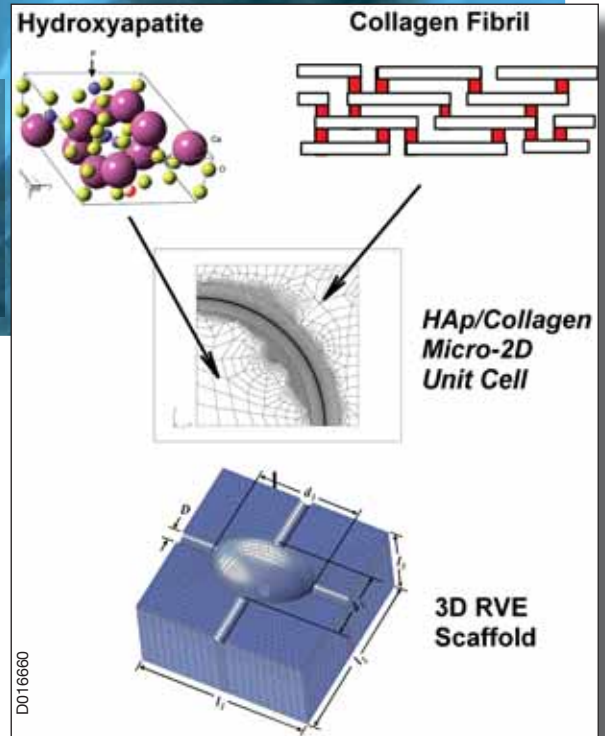


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A multiscale approach is used for modeling a three-dimensional scaffold representative volume element (RVE) at the molecular, microstructural and macroscopic (continuum) levels.

Designing tissue engineering scaffolds

Bone-tissue engineering scaffolds are used to heal large defects caused by trauma or disease, or by therapies directed toward mitigating disease. To promote bone formation, vasculature-inducing pore geometry is critical in scaffold design, because bone tissue regeneration does not proceed without vascular invasion. The optimum scaffold architecture for bone tissue regeneration is a porous structure with a narrow range of pore sizes and density, and a high degree of interconnectivity among pores. To achieve such a design, the microstructure of the scaffold material must be optimized to satisfy both

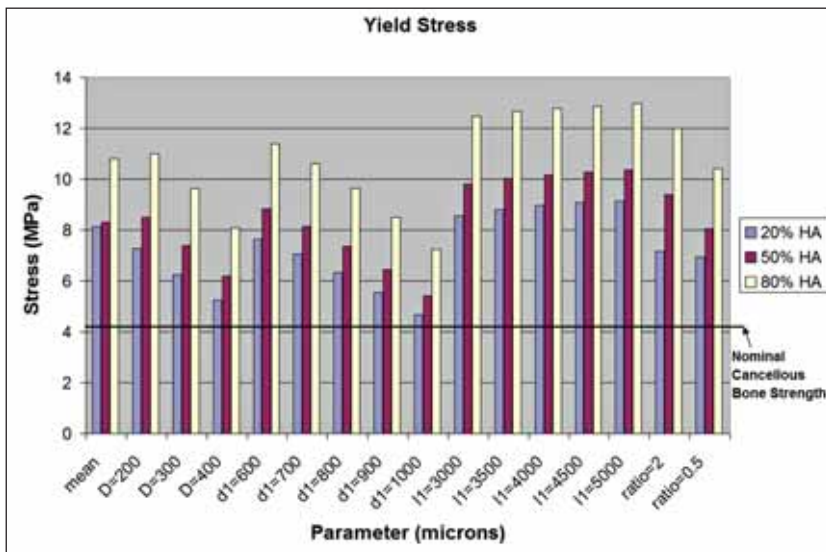


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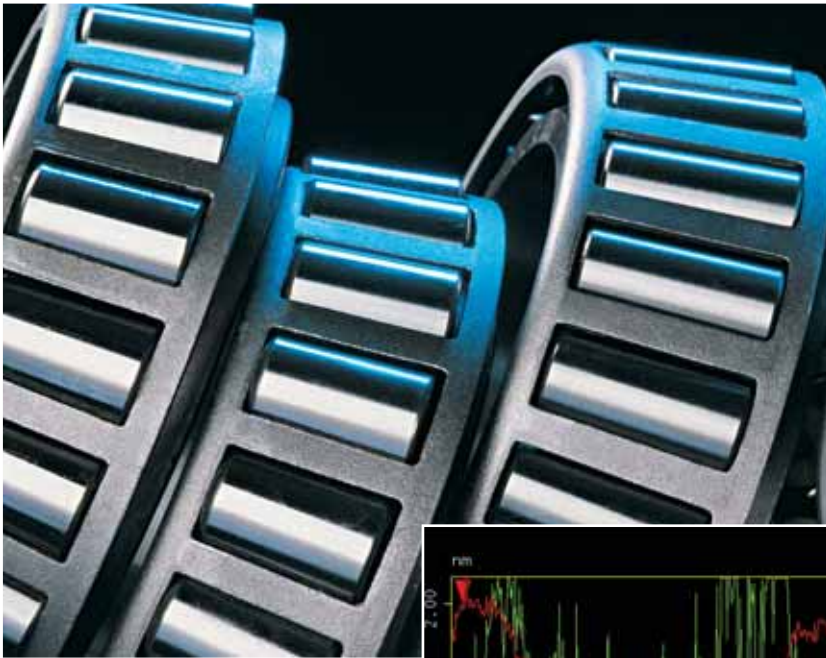
biological and mechanical function requirements. The limitations of many existing scaffold fabrication methods have required biology to adapt to the scaffold geometry, rather than designing the scaffold geometry to accommodate the biological imperatives of bone-wound healing.

As part of an internally funded program, SwRI researchers applied computational material science to develop a multiscale modeling approach for designing a scaffold made from a two-phase composite of brittle hydroxyapatite (HAp) particles embedded in a ductile collagen matrix. Property optimization is essential because a highly porous structure that promotes cell growth may lack the strength and toughness required as a load-bearing scaffold. SwRI researchers calculated the elastic properties and theoretical strengths of nanoscaled HAp particles from first principles. They then used the finite element method to predict the constitutive properties of the HAp/collagen composites for several HAp contents. These constitutive relations of the composite were

This bar chart shows parametric results for scaffold property optimization.



D016661



Two-dimensional friction maps and the structural ordering (e.g., island formation) that occurs for a lubricant additive on an ideal surface are measured using atomic force microscopy (AFM). Molecular dynamics simulations are performed in parallel to explain or verify the AFM-measured friction at the scale of molecular distances. This tactic enables one to engineer and evaluate novel lubricant additives by making appropriate modifications to the chemical structure of the additive depending on the specific application.

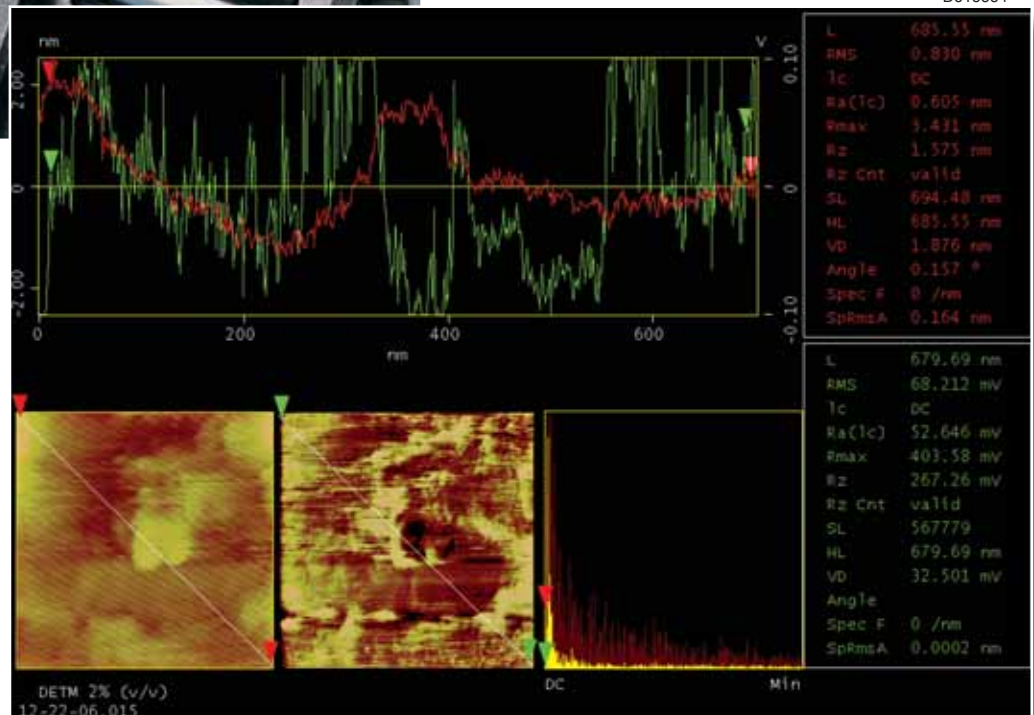
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used to optimize the mechanical properties of a three-dimensional scaffold with respect to pore size, pore density and volume fractions of HAp in the composite so that the scaffold properties exceed or match those of bone tissue.

Nanotribology and surface structure of lubricant additives

Tribology is the science and technology of interacting surfaces in relative motion. Molecules such as detergents or lipids, which generally constitute various classes of lubricant additive packages, have remarkable tribological properties when used as interfacial boundary layers between two contacting metal surfaces under dynamic loads. The current understanding of the tribological behavior of such boundary-layer additive molecules is incomplete at the fundamental level because the mechanisms of adsorption or chemisorption, surface structure and phase state, and tribology over molecular-distance scales remain poorly understood. This lack of fundamental understanding has hindered the development of new additives, or improvements in existing ones.

In a project funded by a commercial client, SwRI researchers used molecular dynamics theory to predict the surface structure and tribological properties of boundary-layer molecules (lubricant additives) between two metal surfaces. They then correlated the molecular dynamics



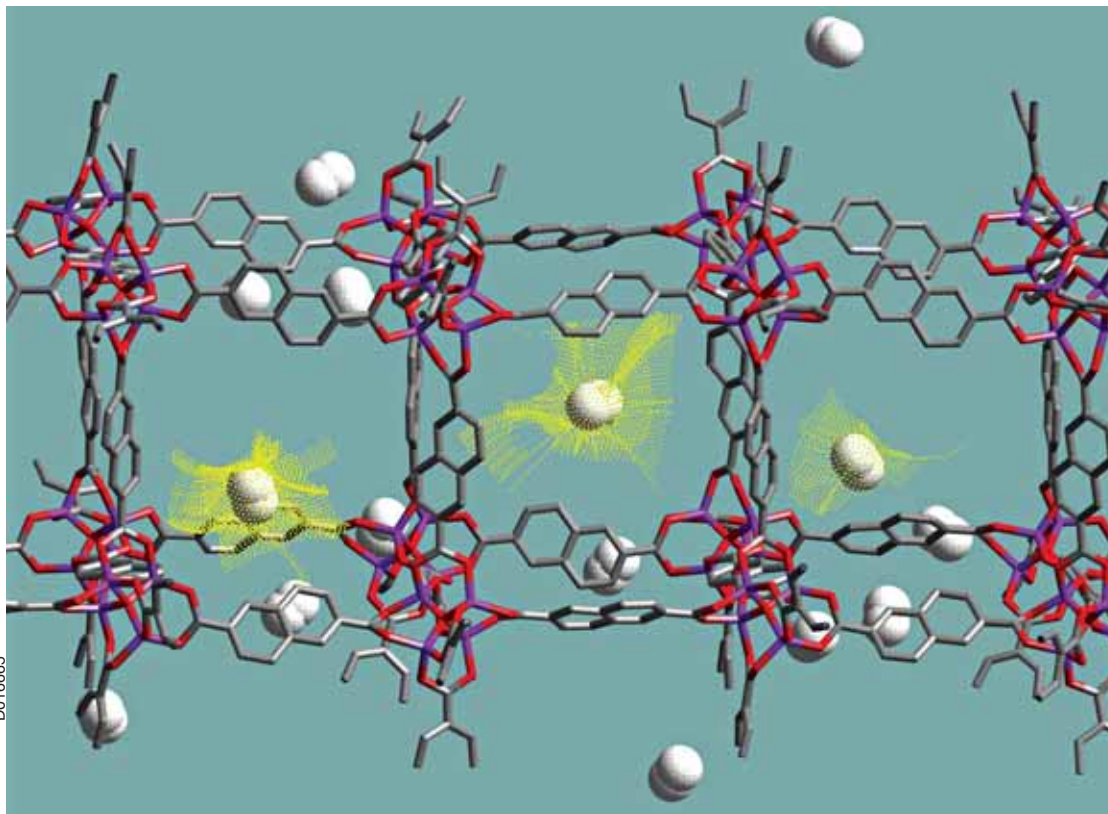
predictions with the surface structure and friction maps derived using atomic force microscopy techniques. The results established a tactic for assessing the relationship among molecular adsorption, surface structure and tribological properties, leading to a better understanding of existing lubricant additives and to developing strategies for synthesizing new ones with improved properties.

Hydrogen storage materials

The principal obstacle to implementing a hydrogen-based economy remains storage under ambient conditions of temperature and pressure.

While most approaches to this problem have focused on physical adsorption, wherein useful uptake is realized only at low temperatures (77 degrees Kelvin, for example), recent experiments have suggested the possibility of chemically adsorptive strategies based on nanostructures consisting of catalyst particles on, or caged within, a highly porous structure.

Under funding from DOE and SwRI's internal research program, researchers are currently applying *ab initio* and molecular dynamics theories to design novel nanoscale architectures for solid-state hydrogen storage, providing important insights into the underlying mechanism for hydrogen uptake in new structural



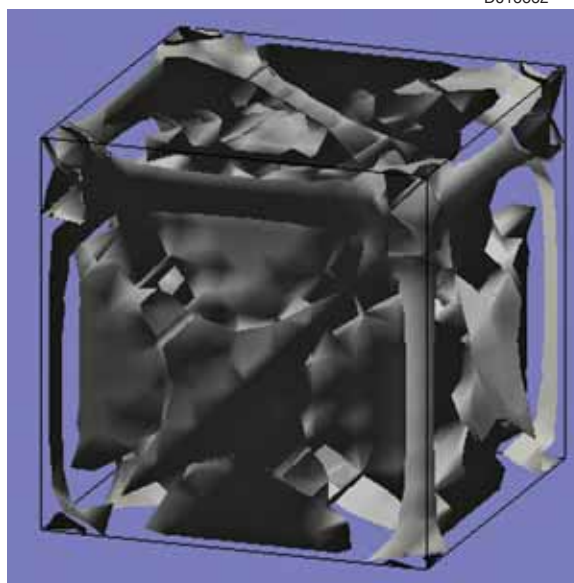
Molecular dynamics simulations combined with *ab initio* calculations are being used to study the hydrogen adsorption (known as physisorption) and hydrogen addition reactions involved in an isoreticular metal-organic-framework (IRMOF-8) for hydrogen storage applications. This image shows the surface field for non-bonded interactions of select hydrogen molecules trapped in the small, though highly ordered, voids of the framework. IRMOFs of similar structure have been measured by SwRI scientists to adsorb up to 68 percent of the equivalent liquid density of hydrogen, requiring only 60 bars of pressure and 77 degrees Kelvin.

D016665

motifs. Using *ab initio* computations, SwRI scientists are exploring the electronic and catalytic properties of nanometer-sized metallic compounds of unique elemental combinations useful in facilitating the binding and dissociation of hydrogen molecules in highly porous substrates. Some of these are isoreticular metal-organic-frameworks, single-wall carbon nanotubes and new forms of carbon materials. They are further combining these levels of theory with molecular dynamics simulations to critically assess the thermodynamic and kinetic viability of hydrogen storage materials predicted on catalytically doped porous structures.

Future applications

Computational material science provides an important avenue for accelerating the development of advanced materials and for turning them into new products. By validating theories with critical experiments, computational material science can speed up the discovery process, develop scientific understanding at the atomic or molecular levels, and solve engineering problems in a wide range of disciplines where conventional approaches have proved inadequate. There



D016662

This image shows an *ab initio* calculation of the electronic Fermi surface of an AuAl₂ unit cell. Clusters of this metal compound are being explored as dissociation catalyst for hydrogen storage applications.

are continuing efforts by SwRI researchers to apply the computational material science approach to designing new nano-coatings for power generation. Efforts are also continuing to develop unique nanostructured materials for tissue engineering scaffold applications. There is also a plan to apply this emerging technology to novel cathode and anode materials for lithium batteries and other devices for energy conversion.

In the future, the proliferation of computation-based material design may evolve into an integral part of the component and structure design process as scientists and engineers face increasingly more complex problems that require fundamental solutions in shorter times. v

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Enhancing Our World's Energy Supply

SwRI engineers are developing new technology for subsea natural gas production



Magnetic bearings provide bearing support to the vertical rotor, eliminating the need for lubricants.

By J. Jeffrey Moore, Ph.D. and David L. Ransom, P.E.

With rising energy prices, new technologies are needed to produce natural gas from increasingly extreme environments. Many gas fields have remained untapped because of poor economic returns considering the construction costs of offshore platforms. However, developing a subsea natural gas compressor would permit harvesting these marginal gas fields without expensive platforms. Centrifugal compressors are most commonly used for this application. They must be designed to operate in a high-pressure, high-power environment (more than 1,000 psi and greater than 10,000 horsepower). Traditionally these compressors are driven by gas turbines or large electric motors. To minimize the subsea footprint, the compressor would be directly driven by a high-speed electric motor in a hermetically sealed casing suitable for the subsea environment.

In many applications, magnetic bearings support the rotor, eliminating the need for lubricants. They use powerful electromagnets coupled to a feedback control system and are well suited for a subsea application because they can operate in the pressurized hydrocar-

bon environment. The proposed design, developed by an SwRI client, uses a vertically oriented rotor that has several advantages in packaging and by minimizing contamination of the motor. If an upset of the magnetic bearing system occurs, the rotor will drop, or delevitate, onto auxiliary bearings, allowing the unit to be shut down without damaging the rotor or stator components. However, this transient delevitation has never been tested for a vertical rotor with three or more bearings.

A research program was jointly set up between the commercial client and Southwest Research Institute (SwRI) to investigate the rotordynamic behavior of a vertical rotor supported on magnetic bearings when the rotor is dropped onto auxiliary rolling element bearings. SwRI engineers designed and built a sub-scale test rig capable of delevitating the rotor from a speed of 30,000 rpm and performed experimental tests for a variety of operating conditions. As part of this study, SwRI researchers also developed a numerical tool to model the flexible rotor and stator dynamics as well as the auxiliary bearing characteristics.

Auxiliary bearings are critical components because they must endure mul-

iple impacts and frictional contact forces associated with rapid acceleration, high rotational speed and radial load. They must operate in harsh temperature conditions with no lubrication. The lateral motion of the rotor is controlled by the auxiliary bearings, but a radial clearance, or deadband, exists between the rotor and the auxiliary bearings and complicates the dynamics. During the drop phase, the rotor may experience a lateral, self-excited vibration regime (backward or forward whirl), which can produce high dynamic loads on the bearings. In the case of a vertical-axis machine, the backward or forward whirl regime is even more likely to occur, because gravity loads will not contribute to stabilizing rotor position and prevent rotor whirl.

When the program started, auxiliary bearing design and overall machine behavior during the drop phase were identified as critical issues for robust machine operation, even in the case of active magnetic bearing failure. A second goal was to restart the machine after multiple delevitations without retrieving the entire unit from the seabed. Most delevitation technical knowledge has been developed for horizontal turbo-



Dr. J. Jeffrey Moore (left) is a program manager in SwRI's Fluids Engineering Department in the Mechanical and Materials Engineering Division. Moore's areas of expertise include turbomachinery rotordynamics research for the natural gas, power generation and wind power industries. David L. Ransom, P.E., is a principal engineer in the Fluids Engineering Department. Ransom specializes in rotordynamics and structural dynamics for both energy and space exploration applications.

control of seven axes (six radial and one axial) at three bearing locations. The auxiliary bearings, also from a commercial supplier, are pre-loaded pairs of angular contact bearings and are supported in the radial direction by a damper ribbon, a wavy strip of spring material. To minimize cost, the test rig was built to reduced scale, but the rig exhibits behavior according to rotordynamic similitude, offering similar vibration modes and natural frequencies compared to the running speed. However, to

define rotor orbits in these planes. Four velocity transducers, located on the casing at the upper and middle bearing planes, are used to detect housing vibration. The transient data is captured using a 24-bit data acquisition system that acquires all 16 channels in a continuous waveform at 12,000 samples per second. The test rig was placed in a concrete pit located in an SwRI laboratory and securely attached to the floor in the event of a catastrophic bearing failure. The motor, AMB and data acquisition system are controlled from a separate room, with two concrete walls providing additional protection.

Numerical modeling

Several key characteristics determine the nature of this simulation. First, the landing event is time-transient because both speed and vibration are changing in time. The model must include nonlinear bearing supports because of the com-

machinery. Only a few comparisons between predictions and measurements were performed for vertical units because they are less commonly used.

The SwRI team put in place a complete numerical and experimental approach to yield a predictive tool capable of analyzing prototype performance and drive-suitable design solutions. The numerical part of the task consisted of a MatLab® based code developed to predict rotor drop behavior through a nonlinear transient simulation, taking into account both rotor and housing flexibility and the auxiliary bearing's nonlinear dynamics. SwRI engineers validated this predictive tool by comparing its performance with experimental data obtained from the dedicated test rig at SwRI.

Experimental activity

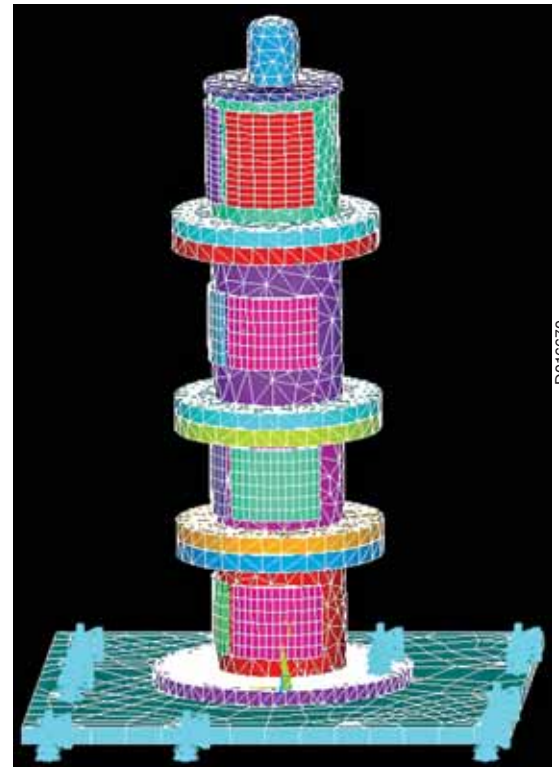
SwRI engineers designed and built a test rig that represents a one-third scale motor/compressor. The rig consists of a three-bearing rotor suspended within a vertical casing. The primary bearings, which are commercially available active magnetic bearings (AMB), provide

accomplish this the test rig rotor must spin at up to three times the speed of the full-scale rotor, or about 30,000 rpm.

Because the scale model is designed for rotordynamic study, several of the full-scale components must be simulated by additional rotor mass. The actual motor core is simulated by a large dummy mass between the top and middle bearings. The compressor impellers are simulated with integral steel disks that have the appropriate scaled inertia properties.

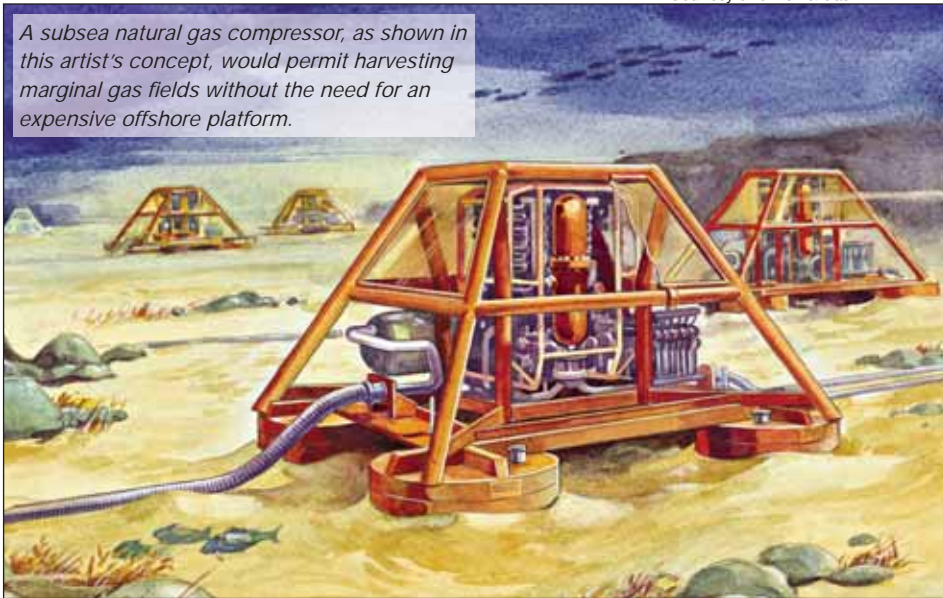
The test rotor is driven by a 5.5-kilowatt induction electric motor using a variable-frequency drive connected via a flexible coupling to the top end of the motor-compressor assembly. This drive motor accelerates and decelerates the rotor in a controlled fashion, matching as closely as possible the anticipated rate of deceleration of the full-scale unit.

Instrumentation includes the AMB sensors at all three bearing locations (radial and axial), as well as two additional pairs of probes placed at rotor mid-span planes



This fully meshed finite element model of the test rig casing includes all non-rotating components, with more than 500,000 degrees of freedom.

A subsea natural gas compressor, as shown in this artist's concept, would permit harvesting marginal gas fields without the need for an expensive offshore platform.



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combination of the dead-band clearance in the auxiliary bearings and the nonlinear stiffness of the combined angular contact bearing pair and the damper ribbon. Second, the geometry includes a flexible rotor and a casing with structural modes in the operating speed range. Typically, rotating machinery is designed to avoid structural modes within the operating speed range, but the vertical orientation makes this impractical. These features combine to require a fully flexible dynamic model of both the rotor and casing.

The finite element models are quite large, especially for the solution of a fully transient problem. This model includes all of the non-rotating components of the test rig, with more than 500,000 degrees of freedom (DOF). Although the finite element model of the rotating components is much smaller, less than 400 DOF, it is still much larger than those typically used in similar transient simulations. Most models have only 10 or 20 degrees of freedom, often without flexible rotor or structure models.

Using the process of component mode synthesis, which is an order reduction technique used for large finite element models, the rotor and casing models are reduced to only a few modes, while critical dynamic information, such as casing vibration modes, are maintained. These reduced models are then coupled by interface force equations instead of the traditional direct stiffness approach. The reduced-order model is simulated using an integration method in Matlab.

Central to the success of the simulation is the calculation of the interface forces between the various simulation components. The pair of preloaded angular contact bearings comes in direct contact with the rotating shaft. This bearing pair is mounted within a preloaded ribbon damper, mounted in a bearing housing that is bolted to the machine case.

Three interface force locations are considered in this simulation. At position one there is direct contact between the rotor and the bearing inner race. This contact can result in both radial and tangential force transmission, and is represented with a Hertzian contact model. The contact results in the sudden acceleration of bearing inner race.

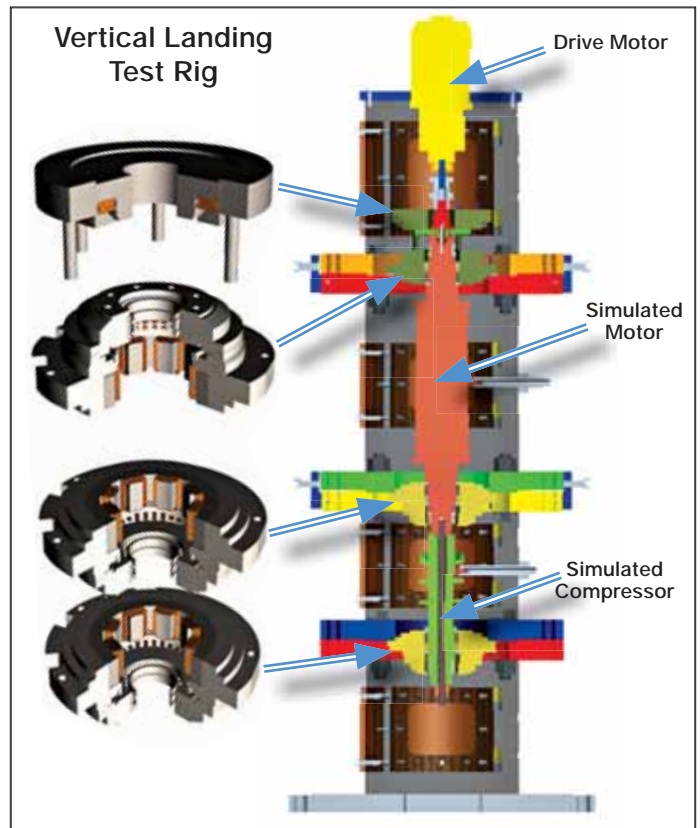
The interface forces at position two are determined from the angular contact bearing load/deflection curve. This curve includes the compliance of the angular contact bearing as well as additional compliance caused by the kinematics of the bearing preload technique. The third interface, position

three, involves a somewhat bilinear stiffness, with radial and tangential components.

For the range of damper ribbon radial motion, the radial and tangential forces are calculated from a complex stiffness developed by the bearing manufacturer. A separate test program is being pursued to validate this critical model.

Significant findings

At the beginning of the program, the greatest unknowns revolved around the characteristics of rotor whirl in the vertical orientation. Prior to this work, the engineering community generally considered the whirl frequency, which is the rate at which the rotor precesses (not its rotational speed), to be determined by the mass of the rotor and the stiffness of the catcher-bearing support system. This is a fairly common approach in rotordynamics and has been verified repeatedly in more typical industrial machines such as high-power compressors supported on oil film bearings. For this test rig, the predicted whirl frequency using this simplified linear model is around 150 Hz. However, the rotor very clearly whirled at no more than 90 Hz and in most cases has shown whirl at around 68 Hz.



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The SwRI-designed test rig represents a one-third scale of the compressor, and consists of a three-bearing rotor suspended within a vertical casing.

Measured and predicted vibration orbits showing forward whirling of the rotor during delevitation.

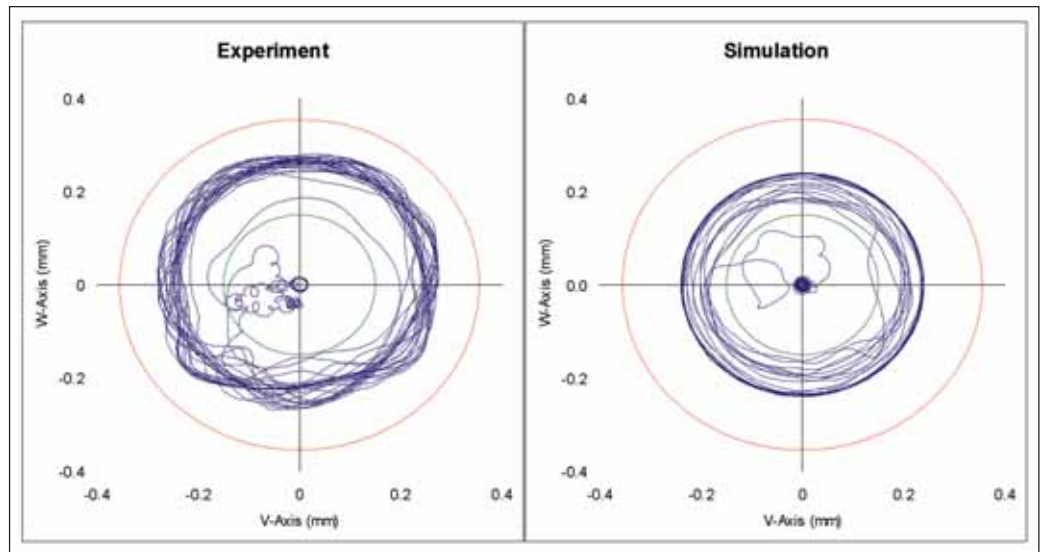
The synchronous response to residual shaft unbalance is shown as starting at 333 Hz (20,000 rpm). At about 300 Hz, the rotor passes through its own natural bending frequency, resulting in peak vibrations for this drop test.

From a machine-design perspective, the lower than predicted whirl frequency is good news as bearing loads decrease proportional to whirl frequency squared, and angular contact bearing life is strongly dependent on load. From a design-analysis perspective, the question then became whether the team could predict the real whirl frequency.

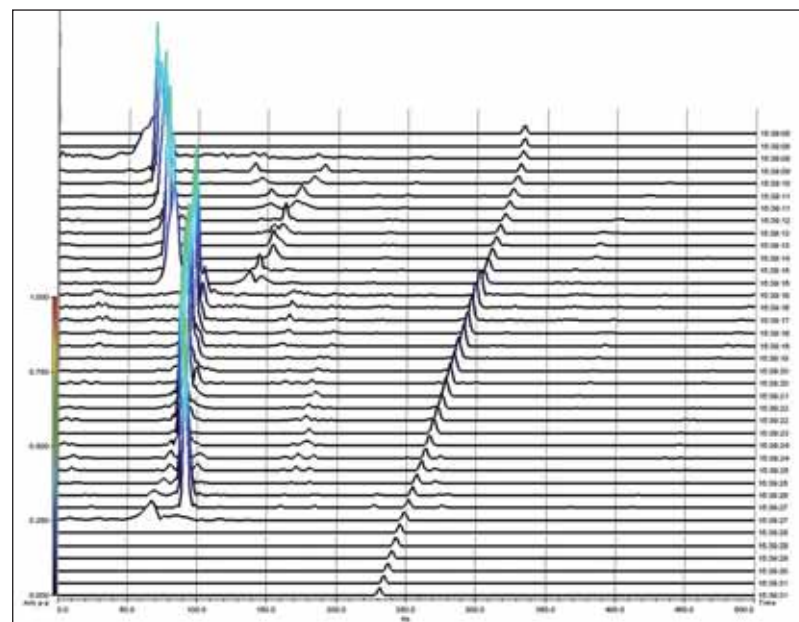
Another important experimental finding involves the direction of the whirl. Initial simulation results indicated the possibility of backward whirl. In such an event, the rotor would tend to roll inside the inner race, in a direction opposite the direction of spin. Typically, this is an undesirable condition that can lead to catastrophic damage if contact occurs between the rotor and stator outside the catcher bearings. However, in the complete series of drop tests performed (18 in all, most above 20,000 rpm), the rotor has proceeded directly into forward whirl. This finding led the team to search for the mysterious force that drives the rotor into forward whirl. This phenomenon has been observed by other researchers but has yet to be satisfactorily explained.

Future work

This forward whirl phenomenon is now a focal point of the research program, and researchers are investigating several explanations. These include correctly modeling the influence of residual unbalance, internal friction of the rotating components, and asymmetric contact at the axial bearing, driving the rotor into forward whirl. Understanding the source of this forward whirling force is important to the successful design and analysis of a full-scale machine.



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Waterfall vibration plot showing whirl frequency measured during delevitation of the rotor onto auxiliary bearings.

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In addition, the experimental program is continuing, with emphasis on establishing endurance limits for the angular contact bearings, thereby determining how many delevitations the bearings can accommodate. This program includes two series of identical drop tests in which the health of the angular contact bearings is monitored by a combination of vibration, sound and drag measurements. This information will be important in validating the design tools the bearing manufacturer used in predicting bearing life.

This research program is enabling SwRI engineers to use skills in mechanical design, rotordynamics, solid mechanics, linear control theory, nonlinear transient simulation and fabrication of a high-speed test rig. Its results closed

many technology gaps, enabling the client to accelerate its product development while minimizing risk, all without consuming the client's in-house resources. The success of this program highlights the value that SwRI brings to clients to streamline their product development process. v

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Acknowledgments

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Digging Into Simulation

An SwRI-developed simulator helps train excavator operators safely and effectively

Simulated operations of excavation machinery include positioning of loaded dirt into the bed of a truck.



DOT166-49

By J. Brian Fisher

Southwest Research Institute (SwRI) engineers have developed an effective and affordable alternative for training heavy-construction equipment operators through modeling and simulation.

In large part, construction equipment operators are trained using actual machinery. The cost-effectiveness of this practice is undermined by direct and indirect costs, such as rental fees, fuel, wear and tear, instructor salary and opportunity costs incurred while the equipment is pulled away from profitable work on the jobsite to support training. In addition, using actual equipment for training increases risks of personal injury or property damage and limits the opportunity for instructional feedback.

To address these issues, a team of engineers from Southwest Research Institute (SwRI) developed the Excavator Operator Training Simulator (EOTS) in cooperation with a major manufacturer

of construction equipment. This system, which operates on a personal computer, provides several advantages over traditional training approaches.

Instructors can use it to teach skills ranging from simple tasks to complex procedures. Trainees practice in a risk-free environment, without the potential for equipment damage or personal injury. This portable system provides highly accessible training that is not restricted by real-world limitations such as inclement weather and equipment availability. Finally, the system provides detailed performance measurement, with immediate and meaningful instructional feedback to students.

While simulation-based training has been used for many years in high-end military and commercial applications, the costs associated with such training limited its use to applications such as flight simulators. Only recently has this approach become cost-effective for training on a

broader range of equipment. However, affordability is not the most important quality associated with simulator applications. Without a sound instructional approach, using a simulator to teach heavy-equipment operator skills would be ineffective. By combining the Institute's extensive experience in modeling and simulation with the manufacturer's expertise in construction equipment and associated training methods, the SwRI team developed a system that provides a meaningful training experience, motivates the trainee and supports learning by accurately simulating the working environment.

Providing meaningful training

Some training simulators simply model system behavior and allow the trainee to perform fairly arbitrary or mundane activities. In contrast, the EOTS focuses on training in the context of

real-world tasks. It provides numerous lessons centered on key situations the trainee will face day after day on the job, such as maneuvering and positioning the excavator, digging trenches straight and level, loading trucks efficiently, moving and placing loads such as trench boxes and pipe, and loading the excavator onto a trailer for transport.

Each lesson is designed to familiarize trainees with the controls and associated equipment responses so they learn the proper skills and techniques before they use a piece of equipment for the first time.

While proper technique is important, safe operation is even more so. It must be learned and practiced before an operator can work effectively on a real jobsite. Each EOTS training lesson includes potential safety hazards that trainees must recognize, and situations to which they must respond properly in order to complete the lesson. Simulated safety hazards include operations near power lines, open trenches, other equipment, facilities and personnel. In addition, trainees must learn to maintain proper load limits to avoid tipping. To build safety habits, the EOTS provides a practice mode in which trainees receive real-time warnings as they encounter potential safety hazards during a lesson. This trains the operator to recognize potential dangers and correct his or her behavior in time to avoid unsafe conditions. The trainee is later tested, operating the simulator in an assessment mode where no warnings are given. This forces the student to recognize hazards, just as on a real jobsite.

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J. Brian Fisher is manager of the Immersive Technologies Section in the Training, Simulation and Performance Improvement Division. He manages a team that specializes in developing software programs for real-time 3-D graphics, modeling and computer systems.

Motivating the trainee

Truly effective training requires that the trainee be motivated to complete the learning objectives. The SwRI team implemented a unique scoring approach that provides a competitive environment where performance is measured in terms of financial success and ranked against other trainees. In each lesson, profits are calculated based on a comparison of the trainee's productivity against the labor and equipment costs incurred. In addition to being productive, the trainee must complete the lesson while avoiding actions that would damage the equipment or the jobsite. Careless behavior, such as slamming the bucket or hitting other equipment, reduces a trainee's profits by deducting costs associated with equipment damage.

Safety also plays a key role in the scoring. The same zero-tolerance approach to unsafe actions on the jobsite applies in the EOTS simulator.

A trainee's action that leads to a safety violation results in a no-score, and the student must repeat the lesson. This scoring approach not only motivates the trainee by encouraging competition, but also provides a constant reminder that performance affects the bottom line and that safety is the top priority.

Imagery generated as part of the SwRI-developed training software is designed to be as faithful as possible to actual excavating equipment, shown here, in order to aid operators' transition following completion of their training.



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Trenching activity is simulated using SwRI-developed software that can train operators to excavate a trench, hoist and position a retaining structure inside it, and then operate the shovel within the workspace of the retaining structure, all without risk to personal safety.

Simulating the jobsite environment

Providing realistic training in a virtual construction environment presents numerous technical challenges. Sophisticated techniques must be applied to model the physical and visual characteristics of the excavator and its interaction with the jobsite to support the broad range of activities included in the EOTS lessons. The coupled motion of the excavator and its various articulated parts must be modeled accurately and efficiently to support effective training. Operator control actions must produce accurate movements of the articulated parts and maneuver the excavator in a manner consistent with actual equipment performance. In addition, the dynamics model must accurately simulate the equipment response associated with stalling the bucket while digging, moving heavy loads such as pipe or trench boxes, tipping the excavator when load limits are exceeded, and detecting collisions to determine when equipment has been damaged. While these types of models have been developed for many types of simulators in the past, implementing them for a complex construction environment in a manner that supports real-time performance on widely available, consumer-level PCs requires careful implementation and optimization.

Dirt modeling

The most challenging aspect of building a virtual construction environment was to develop realistic physical and visual models of the interaction of the excavator bucket with dirt. By combining kinematic models with surface and volume modeling and rendering techniques, the SwRI team developed a sophisticated dirt simulation to support numerous training features, including loading of the bucket; dirt flow, piling and retention; and an accurate generation and realistic depiction of trenches.

Bucket loading algorithms are based on the volume swept by the bucket, and they compensate for stalling conditions associated with dirt properties as well as the bucket's attitude and the speed and direction of motion. Methods for determining how dirt is retained in the bucket, and how it flows from the bucket and accumulates on the ground or in other vehicles, are based on the angle of repose, the bucket's motion and the dirt's properties. Additional techniques were implemented to generate and display realistic trenches, including a combination of cut surfaces and loose dirt to provide visual cues that help the trainee ascertain depth.

The visual depiction of bucket/dirt interactions is generated using a pre-tessellated surface with configurable grid spacing that divides the training area into a number of polygonal faces. This grid is deformed in real time as necessary to display the movement of dirt in response to trainees' actions. By allowing the grid to be configurable, users are able to maximize the display fidelity based on the capabilities of their PC graphics card.



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Military application of the excavator operation simulator allows trainees at multiple stations to work independently on different phases of excavation while being supervised by a single trainer.

Various textures are applied to the dirt to allow trainees to easily distinguish between various static and dynamic states of the dirt, such as undisturbed surfaces, nearly vertical cut surfaces, and/or loose surfaces. Small amounts of dirt falling from the bucket or passing around the edges of the blade are modeled with particle effects subject to gravity and minimal collision detection. Larger volumes of dirt moving out of the bucket and onto the ground, or into another piece of equipment, or larger volumes of soil being forced around or over a blade are modeled as a procedural solid with animated, dynamic or procedural textures to enhance the appearance of motion.

Auditory and visual cues

To provide a cost-effective solution, motion is not included in the EOTS. Without motion, appropriate visual and sound cues assume greater importance in providing primary feedback to the trainee. Visual cues that allow the trainee to sense motion and depth are critical to operating equipment in this type of environment. The addition of detailed visual models, real-time simulated shadows, texturing, and shading help to provide these cues. Sounds also provide valuable cues to the trainee to help assess the

performance of the equipment. The EOTS includes numerous sounds to reinforce visual cues. These sounds provide feedback that helps a trainee determine how quickly the excavator and its parts are moving, or when the hydraulic system is laboring to indicate an impending blade-stalling condition.

The use of realistic controls that respond like those in the equipment also plays a key role in providing an effective training environment. While the EOTS is capable of supporting gaming joysticks, most customers prefer the optional "replica" controls that provide a more accurate feel. These controls, which include a set of joysticks and foot pedals, were constructed from actual excavator components and provide a range of motion, feel and equipment response which closely matches that of the actual equipment.

Conclusion

SwRI and its collaborators have applied advanced simulation techniques and a sound instructional approach to create a cost-effective method for training excavator operators. Numerous systems have been delivered to various clients in the United States and abroad, including commercial construction companies, equipment dealers, operator unions and train-

ing organizations. These systems have proven themselves as a valued resource not only for training, but also for supporting business development, recruiting activities and the screening of potential new employees as a tool to determine skill level.

SwRI also has produced a customized version for the U.S. Army training school at Fort Leonard Wood, Missouri. Customized hardware and software were delivered for 30 complete simulators as a precursor to training on actual equipment and to supplement training during inclement weather.

The EOTS is the first in a line of heavy equipment training simulators planned for release. SwRI and its collaborators are developing additional training simulators for a four-wheel loader and a motor-grader, and others are in the planning stages. Each subsequent simulator will leverage and extend the capabilities of the architecture and approach developed for the EOTS. This proven approach will allow these systems to continue to reduce training costs and risks while providing a highly accessible, cost-effective training basis for years to come. v

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Street Smart

SwRI Plays Significant Role in 15th World Congress on ITS

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As a leader in intelligent transportation systems (ITS), Southwest Research Institute (SwRI) played multiple roles in the 15th World Congress on ITS, Nov 17-20 in New York. SwRI participated in fully integrated demonstrations showcasing “IntelliDrive” vehicle infrastructure integration, vehicle-to-roadside and vehicle-to-vehicle communications applications, and innovative mobility solutions operating on the streets and highways of New York City.

“The next generation of ITS technology is focusing on saving time, resources and, most importantly, lives,” said Dr. Steven W. Dellenback, director of SwRI’s ITS Department. “We’re solving today’s problems with tomorrow’s technology. In the near term, we are focusing on how to prevent vehicles from getting into accidents. In the long term, our vision of a vehicle that drives itself is well within our technology grasp.”

The SwRI staff coordinated and participated in an autonomous vehicle demonstration on 11th Avenue that brought together leaders in the field of vehicle autonomy to highlight what the future of

surface transportation might look like. SwRI demonstrated its fully autonomous, driverless ground vehicle negotiating a course in Manhattan, along with a DARPA Urban Challenge autonomous vehicle. A five-block section of 11th Avenue was closed to traffic to allow the teams to demonstrate applications such as vehicle-to-vehicle based collision avoidance, traffic signal violation warnings and autonomous vehicle operations.

Among the scenarios the autonomous vehicles sensed and navigated were a U-turn, closed lanes, avoiding a stalled vehicle and passing a slow-moving vehicle. The two driverless vehicles also interacted at a number of intersections with human-driven vehicles.

As a leader in ITS technologies, SwRI developed its autonomous vehicle and related technologies through a \$5 million internal research and development program called the Southwest Safe Transport Initiative. SSTI is charged with developing enabling technologies to provide cars, trucks and tractors with active safety and autonomous capabilities to improve safety and mobility in urban

An autonomous vehicle, which SwRI engineers modified from an SUV, participated in a live demonstration on the streets of New York City during the 15th World Congress on ITS in November 2008.

traffic environments. The other team in the demonstration was a successful participant in the 2007 DARPA challenges aimed at accelerating the development of autonomous vehicle technologies for military applications.

In collaboration with French national laboratory INRIA, the Institute also demonstrated how an autonomous vehicle can cooperate with a human-driven vehicle using dedicated short range communications (DSRC) to share sensor data in a pedestrian warning and avoidance system. The demonstration showed how cooperative vehicle systems can compensate for blind spots or occluded visibility at a pedestrian crosswalk.

The demonstration involved a pedestrian stepping into a crosswalk in front of a stopped vehicle, such as a



Traffic signal timing can be controlled to provide priority to mass transit or emergency vehicles operating in traffic by using vehicle-to-infrastructure software applications.

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bus or van. As the SwRI autonomous vehicle approached the intersection, the pedestrian could not be detected by the vehicle's onboard sensors or by the driver. Traveling in the opposite direction, another vehicle, equipped with sensors and DSRC radio, detected the pedestrian in the crosswalk and transmitted information about the crosswalk and pedestrian to the SwRI vehicle. This enhanced perception allowed the SwRI vehicle to automatically stop at the crosswalk to allow the pedestrian to safely cross.

"The cooperative sensor sharing system was first developed by SwRI and INRIA engineers on CyCabs and tested at INRIA facilities in Versailles, France," said Paul Avery, a senior research engineer in SwRI's ITS Department. "Next, the algorithms were ported onto the SwRI autonomous vehicle platform, and we developed additional interfaces for the system to utilize DSRC."

Additionally, SwRI worked with other ITS World Congress demonstrators to implement the Vehicle Infrastructure Integration test bed in Manhattan and

along the Long Island Expressway, demonstrating how the next-generation ITS technology can improve vehicle safety and efficiency. The IntelliDrive initiative is working to deploy advanced vehicle-to-vehicle and vehicle-to-infrastructure communications technologies to improve roadway safety and mobility. SwRI provided overall system integration and coordination for the tour buses and developed the probe data and mass transit/emergency vehicle signal preempt priority applications. SwRI also provided a probe data map viewer on the buses as well as a roadside probe data collection application. Congress participants were

able to ride six demonstration buses on Manhattan and Long Island test routes.

"Over the past several decades, improvements to surface infrastructure and vehicle safety systems have reduced the number of fatalities around the world. However, a significant number of vehicle accidents are still attributable to driver error," said Ryan Lamm, SwRI intelligent vehicle systems manager. "Removing the driver from the scenario could provide a safer, more environmentally friendly and more convenient way for people to commute."

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TECHNICS

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

Ulysses' observations reveal Sun is blowing surprisingly weaker solar wind

Surprising data from the Ulysses spacecraft show that the solar wind, or the continuous outflow of plasma and magnetic fields from the Sun's atmosphere (corona) into interplanetary space, is only about three-fourths as strong as it was a decade ago, during the last interval of low solar activity. Since its launch in 1990, Ulysses has completed nearly three polar orbits around the Sun, enabling researchers to observe the three-dimensional structure of the solar wind and heliosphere, or region of space dominated by our Sun, for the first time.

"This pioneering spacecraft has allowed us to discover new and fascinating things about the Sun's million-mile-per-hour solar wind and how it changes over time," said Dr. David J. McComas, principal investigator of the Solar Wind Observations Over the Poles of the Sun (SWOOPS) experiment onboard Ulysses and senior executive director of SwRI's Space Science and Engineering Division. "To see such a significant and consistent long-term reduction in the solar wind output is really remarkable."

Over its 18 years in orbit about the Sun, Ulysses has observed the solar wind at

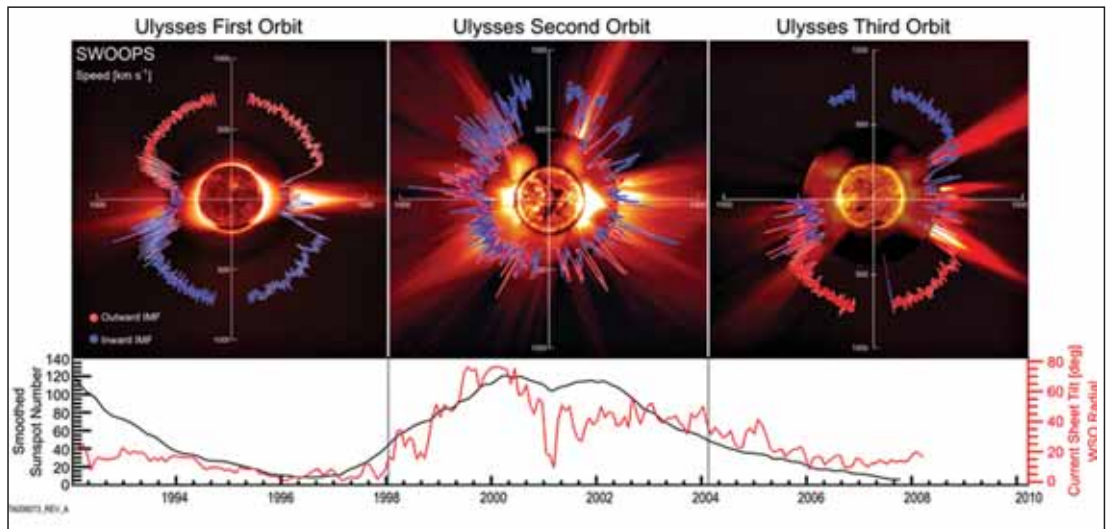
both the minimum and maximum phases of the solar activity (or sunspot) cycle. During solar minimum, the wind is well ordered, with a fast, steady wind over the poles and a slow variable wind at lower latitudes; at solar maximum, the solar wind is highly chaotic, with fast and slow wind streams and more frequent coronal mass ejections at all solar latitudes.

"During the third orbit, we weren't surprised to see a return to a

solar minimum configuration," said McComas, "but we were surprised to find that the solar wind is much less powerful than it had been in the previous solar minimum. The wind speed is almost the same, but the density and pressure are significantly lower, and the wind is blowing out about a quarter less hard."

Ulysses is a joint venture of NASA and the European Space Agency. ESA provided the spacecraft and NASA provided the launch vehicle and upper stage boosters. An international team of investigators designed and built the science payload. For more information about Ulysses, visit: <http://ulysses.jpl.nasa.gov/> or <http://sci.esa.int/ulysses>.

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Holt elected ASME president for 2009

Dr. Amos Holt, vice president of Environmental, Safety and Quality Systems at Southwest Research Institute (SwRI), has been elected president of the American Society of Mechanical Engineers. He will begin serving a one-year term as president in June 2009. ASME announced the selection at its 2008 International Mechanical Engineering Congress and Exposition, held Oct. 31 in Boston.

Holt joined SwRI in 1985 as vice president of its Nondestructive Evaluation Science and Technology Division. His previous employers were Bell Helicopter and Babcock & Wilcox. He became vice president of Institute Quality Systems in 2000, a role later expanded to include oversight of SwRI's Environmental and Safety Systems program.

Holt, who has been a member of ASME for 26 years, has served in a number of positions for the organization including secretary and treasurer. He was named a Fellow in 1993, and was elected an Honorary Member in 2002 for "developing quality procedures for nondestructive evaluation and advancing NDE applications in the aerospace, petroleum, electric power and other industries." He is also a 2000 recipient of ASME's Dedicated Service Award.

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SwRI-led Center for Lunar Origin and Evolution selected to be part of NASA Lunar Science Institute

A team led by Southwest Research Institute (SwRI) has been selected by NASA to be a founding member of the agency's new Lunar Science Institute. The new Center for Lunar Origin and Evolution (CLOE) will help build fundamental knowledge of the history of the Moon and, by inference, the Earth and the rest of the Solar System.

CLOE is one of seven teams selected by NASA as the first members of the Lunar Science Institute (NLSI), which is dedicated to advancing the field of lunar science. The \$6 million, four-year, SwRI-led effort focuses on expanding knowledge on the formation and bombardment history of the Moon.

"Unlike the Earth, which has been heavily processed, the Moon still bears the scars from the era when the planets formed," said CLOE Principal Investigator Dr. William Bottke, assistant director of the Space Studies Department of the SwRI Planetary Science Directorate in Boulder, Colo. "CLOE will bring a multi-disciplinary approach to unraveling the origin of the Earth-Moon system and the early evolution of the solar system."

Dr. Robin Canup, executive director of the Planetary Science Directorate, added, "Our participation in NLSI moves our group in an exciting new direction, and we look forward to contributing to NASA's new lunar science initiative."

CLOE research focuses on three scientific themes, including the formation of the Moon through a giant collision with the early Earth, the early bombardment history of the Moon, and changes in the comet and asteroid impact rate over time. The research brings together expertise in a wide range of fields, including the study of planet and satellite formation (in collaboration with the University of Arizona and the Carnegie Institution for Science); analysis of the oldest minerals on Earth, the Moon and meteorites (in partnership with the University of Colorado Department of Geological Sciences); and modeling of the evolution of comets and asteroids that have hit the Moon. Team members, in collaboration with educators at the Denver School for Science and Technology, the Summer Science Program and the Lunar and Planetary Institute, will work to encourage and excite future lunar scientists, educators and the public.

Contact Bottke at (303) 546-9670 or bottke@boulder.swri.edu.

Khair named an SAE Fellow



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Magdi K. Khair, an Institute engineer in the Engine, Emissions and Vehicle Research Division at Southwest Research Institute (SwRI), was named a Fellow of the Society of Automotive Engineers (SAE).

The honor of Fellow recognizes long-term members who have made a significant impact on the Society. A grade member for more than 20 years, Khair was honored for his leadership, research and innovation on diesel engine technology, specifically exhaust gas recirculation.

Khair has been employed at SwRI since 1991. A specialist in the areas of engine testing and exhaust emissions control, Khair provides technical support and leadership in various aspects of engine exhaust emissions measurement, characterization and control technology development.

Khair is the recipient of the Forest R. McFarland Award by SAE for significant contributions to a number of diesel-related technical and educational activities. He also received three SwRI Office of Automotive Engineering Mentor Awards, nominated by his peers for the dedication of his time and skills to help educate fellow staff members.

Contact Khair at (210) 522-5311 or magdi.khair@swri.org.

IBEX building first all-sky map of the edge of the solar system

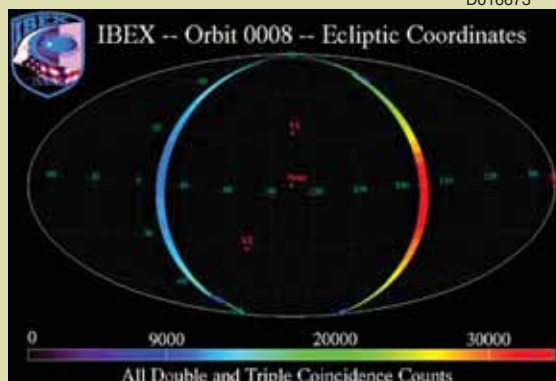
Following two months of commissioning, during which the spacecraft and sensors were tuned for optimum mission performance, the Interstellar Boundary Explorer (IBEX) spacecraft began gathering data to build the first maps of the edge of the heliosphere, the region of space influenced by the Sun.

IBEX is using energetic neutral atom (ENA) imaging to create the first global maps of interactions between the million-mile-per-hour solar wind blown out in all directions by the Sun and the low-density material between the stars, known as the interstellar medium.

"We are seeing fabulous initial results from IBEX, but just as artisans use looms to build up colorful textiles by weaving one thread at a time, the IBEX sensors also need time – six months – to build up a complete map of the sky," said Dr. David McComas, IBEX principal investigator and senior executive director of the Space Science and Engineering Division at Southwest Research Institute.

IBEX will enable researchers to examine the structures and dynamics of the outer heliosphere and to investigate the acceleration and propagation of charged particles in this complex and important region. IBEX is the latest in NASA's series of low-cost, rapidly developed Small Explorers spacecraft. The IBEX mission was developed by Southwest Research Institute with a national and international team of partners. NASA's Goddard Space Flight Center manages the Explorers Program for NASA's Science Mission Directorate.

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Bertrand, A.R., B.A. Abbott, K.J. Saylor and T.B. Grace. "Technology Trades for Management of Telemetry Network Systems." Paper presented at the International Telemetering Conference, San Diego, October 2008.

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Bresloff, M.J. "Contract Changes." Paper presented at the Society of Research Administrators (SRA) International Meeting, Nashville, Tenn., October 2007.

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Kenney, J.D., M.L. Moodie, G.L. Ragsdale and T.B. Grace. "Technology Trades in IP-Based Telemetry Networks." Paper presented at the International Telemetering Conference, San Diego, October 2008.

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Moebius, E., H. Kucharek, L. Saul, P. Wurz, S. Fuselier, M. Bzowski, V. Izmodenov, D.J. McComas, H.R. Mueller and D. Alexashov.

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"Diagnosing the Local Interstellar Gas Flow with IBEX." Paper presented at the 37th COSPAR Scientific Assembly, Montreal, July 2008.

Moodie, M.L., T.B. Grace and J.R. Roach. "Telemetric Networks." Paper presented at the International Telemetering Conference, San Diego, October 2008.

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Pan, J.C. "An Improved GC/MS Method for the Determination of PAHs in Extender Oils." Paper presented at the International Rubber Conference and Exhibition 2008 (IRC 2008), Kuala Lumpur, Malaysia, October 2008.

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Price, J.C. "Ensuring System Security Using Data Flow Analysis." Paper presented to the San Antonio Chapter of the Open Web Application Security Project, San Antonio, October 2008.

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Vickers, D.W. "Research Topics for IT in Healthcare." Paper presented at the Veterans Affairs Information Technology Connection (VAITC) Conference, National Harbor, Md., July 2008.

TECHNICAL STAFF ACTIVITIES

Internal Research

Funded July 1, 2008

Ballew, M. "Advanced Statistical Methods for Improved and Automated Engine Trending and Diagnostics."

Cope, D. "Integration of Technologies for Structural Integrity Assessment of Critical Safety-of-Flight Components."

Drabik, S. "Development of Calcium Phosphate Nanoparticles and Their Use as Vaccine Adjuvants."

Furman, B. "Surface Treatment of Commercially Produced Zirconia Nanoparticle Dispersions."

Grantz, M. "Radio Signal Classification Minimizing a Cost Function."

Hamilton, V. "Mid-Infrared Spectroscopy of Meteorites and the Identification of Meteorite Parent Bodies."

Holladay, K. "Characterizing the Parallel Speedup of the Genetic Programming Environment for FIFTH on a High Performance Computing Cluster."

Lysiak, K. "Innovative DF (Direction Finding) Antenna Design."

Miller, B. "The Titan Submersible Explorer: A First-Order Evaluation of Concept."

Mullin, S., E. Sagebiel, J. Mathis, C. Weiss and P. Cox. "Fundamental Measurements of Landmine Blast Loading."

Olkin, C. "Concept Study for a Discovery Mission to Investigate the Atmosphere and Subsurface of Venus."

Phillips, M. "Design of a Spacecraft Solar Power System."

Polendo, J., B. Nance and K. Lysiak. "Dynamic Platform Direction Finding and Target Tracking."

Reed, P. "Model-based Algorithm Design."

Retherford, K., F. Crary, C. Paty, R. Gladstone, M. Davis, M. Tapley, T. Finley and J. Redfern. "Ganymede Orbiter Mission to Search for an Internal Ocean."

Rittimann, R., R. King and P. Siemsen. "Investigation of the Feasibility of Using Conductive Composite Materials for Low Radar Cross Section Very Large MF/HF Transmit/Receive Antennas."

Van Rheeden, D. "A Spatial Correlation Approach to Geolocation."

Walter, G., R. Pabalan, S. Painter, K. Smart and R. Green. "Evaluation of Geologic Carbon Sequestration Impacts on Drinking-water Aquifers."

Zoss, J., S. Edwards and G. Regner. "Hardware Abstraction for General-purpose Robot Control."

Morrow, T.B., E. Kelner and T.E. Owen. "Gas Energy Meter for Inferential Determination of Thermophysical Properties of a Gas Mixture at Multiple States of the Gas." U.S. Patent No. 7,398,160. July 2008.

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Mathis, R.J., M.C. Marshall, N.K. Reinhardt, E.M. Brigance, G.I. Elias Jr. and K.R. Collins. "Anti-Traction, Mobility Denial Methods and Products." U.S. Patent No. 7,405,184. July 2008.

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- **Underwater Intervention**, New Orleans; Mar. 3-5, 2009
- **Gulf South Rotating Machinery Symposium**, Baton Rouge, La.; Mar. 16-18, 2009
- **Society of Toxicology**, Baltimore; Mar. 16-18, 2009
- **INTERPHEX**, New York; Mar. 17-19, 2009
- **CIPPE (China International Petroleum and Petrochemical Technology and Equipment Exhibit)**, Beijing; Mar. 19-21, 2009
- **NACE Corrosion 2009**, Atlanta; Mar. 22-25, 2009
- **Dixie Crow**, Warner Robins, Ga.; Mar. 22-26, 2009
- **Ground Robotics Capabilities Conference**, Dallas; March 24-27, 2009
- **Digital Energy Conference**, Houston; April 7-8, 2009
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