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# SANDIA TECHNOLOGY

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# COUNTERING EMERGING THREATS

**ALSO:**

**New Systems for Countering Terrorism**

**Meeting the Logistics and Demilitarization Challenges**

Sandia National Laboratories

A Department of Energy National Laboratory

# FROM THE *Editor*

Dear Readers:

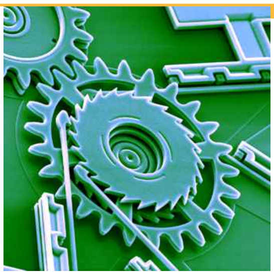
Developing technologies that help protect our nation from threats at home and abroad is no small task. Whether on a foreign battlefield or in a high-traffic government building in America, we must have the means to thwart or minimize harm, and that typically means maintaining technological superiority over our potential enemies. Sandia National Laboratories, a national security laboratory, is developing a broad range of technologies to address that need.

This issue of Sandia Technology outlines some of those technologies, which encompass Sandia's work in robotics, computing, integrated microsystems, and biotechnology. Integrating disparate technologies into practical, effective systems that bolster America's national security is Sandia's strength.

Today's advanced technologies—chemical, biological, nuclear, and information warfare—pose threats of greater harm than ever to the nation. As this issue shows, superior technologies, developed for the purposes of defense, can detect, locate, characterize, defend against and, if necessary, destroy these threats.

Sandia remains ready to provide our nation with the technical capability to respond to threats against our armed forces, our citizens, or our survival as a free nation.

Chris Miller
*Editor*



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***by Dr. Mark L. Swinson***
***Acting Director, DARPA***
***Information Technology Office***

# Countering Emerging Threats

## *Technologies for Asymmetrical Warfare, Protection of our Homeland and Future Warfighting*

In an age with only one international superpower, the quest for a peaceful and free world faces one great leveler: technology. Sandia National Laboratories has been working to achieve and maintain national technological superiority in weapons systems since its founding in 1949. Sandia applies advanced science and engineering to give our National Command Authorities (the President and the Secretary of Defense or their duly deputized alternates or successors) the capability to detect, repel and defeat threats to our national security, whether on the battlefield, against our homeland, or arising from abroad.

Historians have argued for a second leveler: the passage of time. Today, news from the battlefield is instantaneous and diplomacy moves swiftly. Satellite television crews were on the beach at Grenada and Panama, on the rooftops of Baghdad, and on the streets of Mogadishu and Kosovo.

The 20$^{th}$ century showed that regional powers could become international powers (or threats) virtually overnight, many times by using superior or at least disruptive technology, at other times with ideological or abject terrorism. The threat of superior technology shaped policies of regional and global dominance. Achieving and sustaining technological superiority is a critical national mission—technological parity among nations has led to massive regional and global conflicts.

With the widespread availability of advanced technology, waging peace is more difficult than ever. National preparedness depends in part upon increasing both the depth and scope of our technology-based defenses. While today's advanced technologies—particularly in the areas of chemical, biological, nuclear, and information warfare—pose threats of greater harm than ever to the nation, the same technologies can detect, locate, characterize, defend against, and if necessary, destroy these threats.

This image shows a ratcheting system fabricated in the five-level technology. Twenty of these gears fit on a period in a newspaper sentence.

*Today, microsystems and the next-generation development of nanosystems are providing tiny sensors, actuators, and microlocks for robots not much bigger than a large insect.*

## Technological Superiority in a New Era

Sandia is now applying the vast storehouse of weaponization and systems integration knowledge to emerging threats. This work applies not only to the transformation of our armed forces into a mobile, technologically superior warfighting force, but also to solving new problems of asymmetrical warfare and homeland defense against the possibility of increasingly sophisticated terrorist attacks.

Sandia's work is helping America secure a more peaceful and freer world through technology. Our scientists and engineers conduct basic research that supports our nuclear weapons mission with technologies immediately applicable to emerging threats. At the strategic level, our experts on nuclear safeguards and global intelligence support our nuclear mission, provide guidance and support to many agencies to combat proliferation, and supress attempts at regional supremacy, terrorism, and threats against our armed forces and homeland.

## An Integrated Effort

Past issues of *Sandia Technology* have focused on our world-leading role in developing and fielding microsystems and on our nonproliferation programs. All of these efforts contribute technologies and expertise used to counter emerging threats.

Today, microsystems and the next-generation development of nanosystems are providing tiny sensors, actuators and microlocks for robots not much bigger than a large insect. Micro- and nanosystems play a large role in most of the systems Sandia is developing and fielding for countering emerging threats. Sandia incorporates state-of-the-art integrated microsystems into flexible systems as small as a grain of rice for both national security and commercial applications. These tiny systems, used as accelerometers, actuators, chemical and biological sensors, strain gauges and for other electromechanical tasks, replace older systems that were the size of suitcases. They are seamlessly integrated into flexible systems large enough to apply coatings to aircraft or, in our Hexapod, to manufacture complex parts about the size of a compact car—with precision down to nanometers.

Likewise, the emerging threats programs can use or easily adapt sensors and systems integration technologies from nonproliferation programs for the purposes of future warfighting and homeland defense. Activities such as intelligence gathering and analysis share common technologies whether their purpose is international treaty verification or battlefield superiority. Sandia's ability to develop and integrate technologies into delivered systems is the focus of the following articles.

Many of the technologies in this issue were invented and developed through Sandia's Laboratory Directed Research and Development (LDRD) program, most in support of the Department of Energy's Defense, Nonproliferation and Basic Energy Research Programs.

# Developing Technologies

## *for Asymmetrical Warfare and Homeland Defense*

**In the nation's entire defense complex, Sandia has played a unique role by taking complete responsibility to make concepts, such as advanced nuclear designs, into deliverable systems. As awesome as modern nuclear explosives are, it was Sandia that made the concepts into deliverable weapons, designing and integrating about 6,500 of a modern weapon's 6,800 components. Today, that intense development and systems integration work continues in ways beyond stockpile stewardship. It is concentrated on the transformation of today's national defense forces.**

## Directed Energy Weapons

Without question, directed energy systems will be the weapons for dominance on future battlefields and in less-than-battle situations. Imagine a bullet that travels at the speed of light, has a range of several hundred miles or more, and still packs enough wallop to disintegrate a half-ton, hardened warhead traveling at 18,000 miles per hour. That is the goal of the U.S. Air Force Airborne Laser project. Sandia is contributing key concepts, materials and expertise to this and other directed energy projects. Hitting a target about the size of a large trash can from hundreds or even thousands of miles away requires extraordinary precision. Adaptive optics that correct for atmospheric distortions are just one part of Sandia's contributions. Sandia lasers with pulses in the femtosecond range (light travels .003 millimeters in a femtosecond) are another. A third is Sandia's capability to fuse and manage, in real time, the vast amounts of targeting and guidance data.

Beyond high-energy bullets, Sandia is developing a wide range of systems for electromagnetic warfare and defense. Sandia also is developing strategic wide-band technologies that will disrupt an adversary's total communications system, and narrow-band technologies to disrupt specific data channels. Tactical systems to cut specific infrastructure links have already been demonstrated. Coupled with Sandia technologies for spoofing and anti-spoofing—deceiving an adversary's systems and defeating attempts to deceive our own—these systems will give a theater or battlefield commander new weapons and defenses for future warfare.

Directed energy systems will play an increasing role in military operations other than war and in defending our homeland against terrorism. Non-lethal systems based on microwaves or lasers will replace tear gas for dispersing riotous crowds or delaying attacks on sensitive facilities. A microwave system that produces the sensation, and only the sensation, of intense burning at a range of several hundred yards has already been demonstrated. While causing no permanent damage, the sensation, according to one volunteer, "is something that you only want to experience once in your lifetime."

## Difficult Targets

Difficult targets include hardened, deeply buried underground facilities used to manufacture and store weapons of mass destruction, relocatable targets such as Scud missile launchers, and small incoming warheads from theater or strategic missile systems. In every case, authorities responsible for defeating difficult targets need technologies that enable fast, often real-time, and overwhelmingly effective responses to complex and diverse early indications of potentially catastrophic threats. Sandia is developing a variety of technologies and capabilities that meet the challenges of these threats. These capabilities include:

- automatic target recognition
- data fusion
- decision aids and predictive tools
- detection of underground facility construction
- global situational awareness
- instrumentation
- novel warheads, including penetrators
- robotics
- sensor technology, including synthetic aperture radars and unattended ground sensors
- signal processing
- system integration

In support of the Strategic Defense Initiative in the late 1980s, Sandia used modified Polaris missiles to deliver targets from the Kauai Test Facility.

## Ballistic Missile Defense System

Because Sandia designed most of the components of the nation's nuclear stockpile, it possesses a vast storehouse of knowledge about warhead flight characteristics, various signatures and behaviors. Further, its five-decade role in national security assessments gives it even more knowledge of adversaries' designs and potential capabilities. Today, Sandia uses this knowledge to design and build realistic targets for National Missile Defense tests. This work includes smart, instrumented targets, modeling and simulation of lethality effects, and technologies associated with countermeasures. Sandia also prepares and launches target missiles from its Kauai Test Facility.

Sandia's "Snowbots" were able to locate avalanche victims four times faster than humans with trained dogs.

## Swarm Behavior—or Collective Intelligence

By observing swarms of insects, schools of fish, and flocks of birds, Sandia researchers have developed revolutionary new approaches to robotics and solutions to systems problems. One hardly considers an ant or a bee to be capable of a logical, systematic approach, yet these insects have developed highly sophisticated communications and tasking capabilities to find and transport food and to defend their nests.

At Sandia, this swarm behavior is being successfully applied to robotic vehicles equipped with a wide array of sensors, manipulators, and even weapons. To work collaboratively requires Sandia's highly refined systems integration capabilities. Not only must the sensors and instruments collect and process data while operating in an unstructured environment, the swarm must be able to communicate and then make decisions about how best to accomplish its mission—and sometimes that decision is to call in a person to make a judgment.

Sandia has demonstrated swarm behavior—actually swarm intelligence—in unstructured environments such as guarding a perimeter, intercepting an intruder, searching a building or a warehouse for intruders or harmful substances, or finding skiers buried in an avalanche. Sandia's "Snowbots" were able to locate avalanche victims four times faster than humans with trained dogs.

The key to Sandia's success is world-leading expertise in robotics and the information disciplines required to distribute decision making across a virtually unlimited array of platforms, sensors and instruments, all the while providing the systems environment that holds the swarm together.

The “hopper” is a small device with a unique combustion engine that lets it hop into position. It has intelligence, communications, and a self-awareness of its position and orientation. If a number of these were deployed as a defensive perimeter system and some of them were destroyed, others could re-deploy themselves to keep the perimeter fully covered. For planetary exploration, they can replace vehicles because they can travel great distances and surmount obstacles much more efficiently.

## Information Security and Warfare

Exactly when is a system secure against credible threats? Deciding that requires dedicated expertise on both the attacking and defending side. Call it cyber-war games.

When it comes to a nuclear weapon system, Sandia has developed the systems and measurements needed to say, with certainty, “There is less than a one in a billion chance that this undesired effect will happen over this period of time.”

Can we apply the same techniques to our burgeoning information systems? The technological wave of computing and telecommunications enables new science and engineering capabilities, but it also harbors threats. Desktop computers linked in both structured

## Surround and Diversion by a Squad of Mobile Robotic Vehicles

Cooperating squads of robotic vehicles may some day be employed for tasks such as fighting forest fires, cleaning up oil spills, delivering and distributing supplies to remote field operations, and conducting a variety of military missions. In a Tactical Mobile Robotics program for the Defense Advanced Research Projects Agency, Sandia demonstrated the capability to remotely surround a facility with a squad of mobile robotic vehicles. This proof-of-concept scenario involved a squad of six RATLER™ mobile robotic vehicles. These carbon composite electric all-wheel drive vehicles are about the size of two bread boxes. A passive central pivot connecting the two halves provides a simple but effective suspension. Software on the vehicles accepts and processes path, obstacle, and goal perimeter information and executes the mission autonomously.

The RATLERs and their remote base-station began the scenario two hundred meters from the target facility. To complete the mission, the vehicles had to autonomously navigate terrain typical of the desert Southwest, including crossing a deep ravine, negotiating tumbleweeds and other thick brush, and following man-made tracks. Several of the vehicles then surrounded the perimeter near the rear exit of the facility while other vehicles entered the main entrance to create a diversion.

A single operator was able to plan and execute the entire six-vehicle mission using the remote command station.

Swarms of microsystems-equipped robots use collective intelligence to perform tasks thought impossible only four years ago. Nearly indestructible, they sense, think, and communicate with each other and act in concert to accomplish a mission. Recent developments that replaced batteries with small fuel cells have tripled their range.

Sandia's Information Design Assurance Red Team seeks out weaknesses in computing systems.

networks and in near-chaotic networks (a.k.a., the Internet) have replaced the isolated computer room.

Most of the nation's defense systems were built without the infamous "back doors" of some commercial systems, and tested against then-known threats. But that doesn't mean that a determined adversary can't find a little crack in a foundation and, like a termite, find a way to undermine a core system.

## The Red Team and Software Immunology™

Over the past two years, a group known informally as the Red Team (formally, the Information Design Assurance Red Team, or IDART) has either successfully invaded or devised successful mock attacks on 35 out of 35 information systems.

The Red Team's successes show how hard it is to protect our information systems against a determined attack. The team surmounted traditional defenses such as passwords, firewalls, filters, activity monitoring, and traps, and eventually found some avenue and method to compromise a system.

*Using the cross-disciplinary approach that is the mark of many Sandia discoveries, Sandia scientists theorized a computer defense system that acted like the human immunological system.*

The Red Team's most formidable foe also came from Sandia. Suppose the system, like the human body and other living beings, had built-in defenses that could detect and destroy intruders?

Using the cross-disciplinary approach that is the mark of many Sandia discoveries, Sandia scientists theorized a computer defense system that acted like the human immunological system. These software agents, much like white blood cells patrolling our vascular network, were native to the system, so they knew when events were normal and passing entities were doing their gainful work. But once an agent detected an intruder, or something going wrong, not only would the agent attack, it would immediately sound the alarm for other agents. These other agents could be like it or tailored for other defensive purposes, but the end is the same—the intruder or unexpected event is immediately isolated and flagged, and its links to any computer process cut off.

While still under development, Software Immunology and its underlying development principles have been recognized by the National Academy of Sciences as a topic worthy of the designation Formal Methodology—the first software technique ever accorded that scientific designation.

*Fielding New Systems for*

# Countering Terrorism

Sandia not only develops new technologies for national security but plays a leading role in working with industry and government agencies to field tools and systems in use today. From simple but effective decontamination foams to worldwide systems for locating hard to find threats, Sandia technologies are playing a role as the nation defines its future warfighting and homeland defense strategies.

## A Basic Defense: Decontamination Foam

Biological and chemical agents, whether engineered as weapons, or accidentally released as in Bhopal, India, in 1984, are the worst nightmares for emergency planners. In addition to thousands of naturally toxic compounds are others specifically engineered as nerve gasses and blister agents.

Maintaining a stockpile of thousands of individual neutralizers and antidotes and then deploying the correct ones quickly and without causing more harm is seemingly impossible. But Sandia has developed a single decontamination foam that has rendered all typical chemical and biological agents harmless. Even more remarkable, the foam's basic ingredients come from household ingredients such as bleach, hair conditioner, and toothpaste. The foam is harmless to humans, and can be sprayed quickly over wide areas. Sandia engineered the foam so that it will cling to vertical surfaces and maintain its bulk until washed away.

In tests at Dugway Proving ground, Sandia's decontamination foam scored first among twenty others against chemical agents, and tied for first among eight others against biological agents. And Sandia's foam had two distinct advantages—it was the only foam used against both types of agents and, unlike all others, it required no environmental assessment whatsoever prior to use.

**While it seems impossible, Sandia has developed a single decontamination foam that has rendered all typical chemical and biological agents harmless.**

Sandia has licensed the foam technology to a number of commercial firms, which are developing it for uses such as mass decontamination, spills, and hospitals. It has been deployed as a preventive measure at presidential debates and a political convention. Small systems that look like a twin canister fire extinguisher are already on the market for $29.95, and could well become standard issue for police, fire, and emergency vehicles.

## Stand-off Chemical and Biological Detection

The intentional release of a deadly chemical agent occurred most recently in a Tokyo subway when in 1995 a terrorist group released sarin nerve gas. Over the past 80 years, chemical and biological agents have been released many times in warfare, on the battlefield and among civilian populations, despite all conventions of warfare. Far outnumbering incidents of barbaric terrorism, industrial accidents range from a single slightly sickened worker to blasts of volcanic gasses that have annihilated cities. There is little doubt that many of these will happen again.

Sandia's µChemLab™ has successfully passed tests for a number of chem/bio agents and against common interferrants, or substances that block detection of the harmful agents.

The ability to rapidly identify a dangerous compound from a distance has benefits, whether on the battlefield or responding to a terrorist act. Too often, first responders lack the proper instruments and training, and can become victims themselves.

One of the "Grand challenges" posed to DOE national laboratories is fielding a handheld system equivalent to a fully staffed analytical laboratory. Sandia's µChemLab™ has successfully passed tests for a number of chem/bio agents and against common interferrants, or substances that block detection of the harmful agents. The µChemLab™ uses an array of microtechnologies such as filters, piping, and detectors that are molecularly sized or engineered. In the hands of a first responder, it will identify which of thousands of substances might be present in the air or water.

Sandia realizes that even µChemLab™ has limitations. Suppose an environment is too hazardous for humans, or it would take too long to deploy on-site instruments? Suppose you were a soldier on a battlefield and saw a cloud of gas through your binoculars? Sandia has demonstrated standoff detection, or detection from a distance, with a number of technologies.

The microsystems-based Polychromator could be built into that soldier's binoculars. Through an innovative series of incredibly fast micromechanical and physics-based steps, the Polychromator sorts through millions of possibilities and identifies the compounds in the gas. That information could be displayed in the binoculars and transmitted to command stations. A dream? Every step of the system has been demonstrated except for movable microsystems-based spectral gratings —but that is a Sandia microtechnology used in a different way than is being adapted for the Polychromator.

The Polychromator is only one of a number of technological developments in standoff detection. LIDAR (LIght Detection And Ranging) systems use scanning methods to sweep a landscape and characterize the substances in atmospheric plumes. Nonscanning systems provide near real-time ranging and other information—NASA used a Sandia nonscanning system to verify that the solar panels of the International Space Station had been perfectly deployed.

*[ The Polychromator is only one of a number of exciting technological developments in standoff detection. ]*

Other new sensors are based on technologies such as surface acoustic waves and fiber optics for chemicals, quartz resonators for fluids and electrical or gravity field differences—all based on microsystems.

TECHNICAL CONTACT:
Bill Guyton
505-844-9170
wguyton@sandia.gov


This computer image simulates a soldier on a battlefield looking remotely at a gas cloud through a pair of binoculars containing the Polychromator chip.

## Bomb Detection and Disablement

Until just a few years ago, bomb squads disposed of most explosive devices by removing them to a safe place and setting them off. But just moving a device, if possible, was incalculably dangerous. Now bomb squad personnel have a host of new tools—and extensive training to handle bombs in new ways—developed from Sandia technologies.

In many situations, Sandia's bomb disablement systems, such as the PAN Disrupter, are used to disable an explosive device by defeating the physics of an explosion.

Sandia has developed techniques and systems to identify and characterize bombs from a distance in a wide variety of situations, including technologies that can disrupt explosive devices on trucks or other vehicles.

Phil Bennett, left, discusses potential enhancements to the Albuquerque Police Department's bomb squad robot.

## Turning Robotics Outside In—The SMART Approach to Handling Explosive Devices

In a demonstration area at Sandia, a small robotic vehicle approaches a simulated pipe bomb. An operator looking through video cameras mounted on the vehicle and its arms surveys the situation and considers his options. Can the bomb be disabled in place? Does it have to be moved? What's the best sequence to perform either task? What tools do I need?

Since the first automated machines, the progression of robotics has taken manual tasks and gradually added automation. In a structured environment, this led to successful automated machines. For example, numerically controlled lathes, directed by metal punch tapes, turned out extremely sophisticated and precise parts—but could do nothing more. At

# Bomb Squad Training

Back in 1994 Sandian Chris Cherry never would have guessed his experimental training workshop for bomb squad members, called Operation Albuquerque, would one day attract the international pedigree of bomb disabler it does today.

That first year 24 bomb technicians, many from New Mexico, participated in a week of classroom instruction, hands-on demonstrations, and lifelike training scenarios focusing on emerging bomb-disablement techniques and technologies.

In 1995 the invitation-only crowd grew to 30, then to 64 in 1997, and by 1999, the year the City of Riverside, Calif., hosted the fourth conference, the list of 100 attendees had to be pared down from more than 250 applicants.

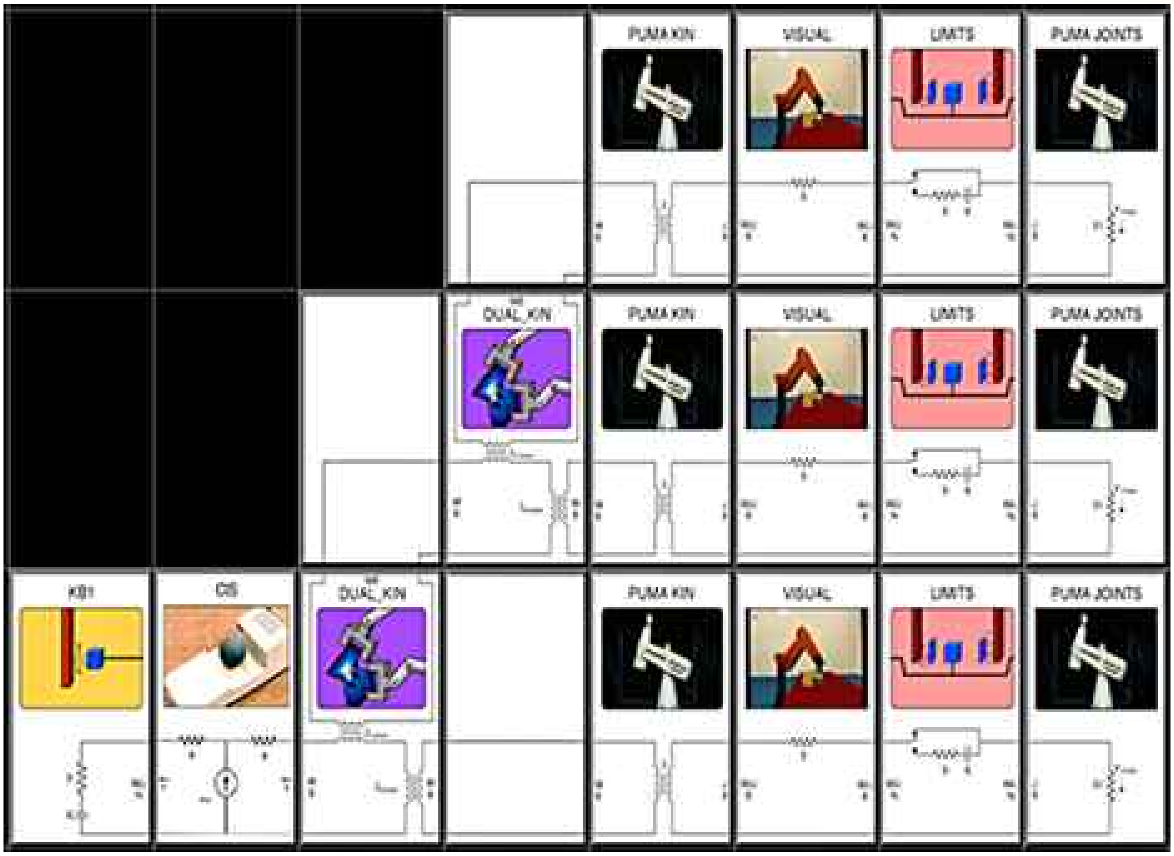
Many of the world's top disablers were there—representing bomb squads from several large U.S. cities, federal law enforcement agencies, and antiterrorism organizations from some of the world's terrorism hot spots.

The PAN Disupter disables explosive devices by defeating the physics of an explosion.

As more bomb techs heard about the training, more had to be turned away from the chance to learn how new technology could help them stay out of harm's way. As the workshop's organizer, Chris was in a position he didn't enjoy.

"This is technology that saves lives," he says. "It should be made available to anyone who needs it."

So he took the show on the road. With funding support from the National Institute of Justice, Chris is now teaching a series of smaller-scale, regional workshops called "Operation America."




SMART now consists of modules for more than 300 robotic instruments and controls, all of which can be put together on a computer screen like assembling LEGO building pieces. The system then generates the computer programs to operate the custom assembly. Working throughout the modules are robotic functions such as coordinated motion, collision avoidance, video targeting, and automatic orientation, as well as basic robotics rules for movement.

some point between manual and fully automated, the progress failed, typically very early in the real life, unstructured environments faced by bomb squad personnel.

In the early '90s, Sandia started on a radically different path. Sandia analyzed how fully automated systems and components could operate together and where a human may have to intervene.

Out of these analyses came two related software packages: SMART, the Sandia Modular Architecture for Robotics and Teleoperation; and Umbra, a simulation environment with capabilities for describing and controlling multiple robots, and incorporating weather, terrain, and RF interference modules (see page 17). "Back then our goal was to offload detail from the operator of teleoperated robotic systems, and to fully exploit robotics systems, but always under the control of the operator," said Phil Bennett, manager of the SMART program. "We were so far ahead of the robotics industry that nobody understood our approach. As threats like improvised explosive devices grew, we're getting inquiries from all over the world."

SMART now consists of modules for more than 300 robotic instruments and controls, all of which can be put together on a computer screen like assembling LEGO building pieces. The system then generates the computer programs to operate the custom assembly. Working throughout the modules are robotic functions such as coordinated motion, collision avoidance, video targeting, and automatic orientation, as well as basic robotics rules for movement. For robotics developers, adding modules is a matter of interfacing existing device drivers into the SMART shell.

For operators, SMART reduces time and effort and provides opportunity for intervention. With current robotic systems, a simple teleoperation, such as picking up a pipe bomb, takes from three to six minutes. Adding only SMART robotics functions cuts the time in half and reduces operator anxiety. Adding more of SMART, such as visual targeting and automatic path planning, cuts the time again, up to the limits of the robot's speed of movement.

TECHNICAL CONTACT:
Phil Bennett
505-845-8777
pcbenne@sandia.gov

Sandia's Accident Response Mobile Manipulator (ARMMS).

# Rugged Mobile Robotic System for Surveillance and Reconnaissance

At a 226-acre test range at Sandia, robotic vehicles encounter terrain and obstacles meant to drive their computerized brains crazy and wear out their mechanized hearts. The vehicles range in size from hobbyshop racers to 10-wheeled heavy trucks and carry anything from miniaturized sensor packages to mechanical arms capable of extracting large bombs from the wreckage of an aircraft.

The largest vehicle is Sandia's Accident Response Mobile Manipulator System (ARMMS). There was a time when an accident involving nuclear weapons or other hazardous materials forced people to risk their lives in recovery and remediation efforts. ARMMS changes that potentially deadly scenario.

Using a military Humvee for its platform, ARMMS provides a full range of capabilities for comprehensive accident response. It can be teleoperated via a single fiber optic cable or a radio frequency communication link. An on-board mapping and sensor suite detects and locates radioactive debris and hazardous gases.

Among the smaller vehicles is Marvin, an extremely rugged mobile robotic system that withstands violent deployment. It can be dropped from an aircraft or a speeding truck, be forcefully ejected from a window, or be launched on a missile into extremely rugged terrain.

Sandia previously had delivered rugged field-ready systems with SARGE, the Surveillance And Reconnaissance Ground Equipment robot. SARGE was the first mobile robotic vehicle to undergo extensive proof-of-concept testing with a U.S. Army scout battalion at the Ft. Benning, Ga., U.S. Army Infantry School, and with the U.S. Marines in an "urban warrior" mock battle exercise in the San Francisco Bay Area.

Customized technology was used to enable the teleoperated Marvin to survive impact velocities exceeding 75 feet per second, tumble to a stop, and drive away completely intact and operational. Marvin's technologies include:

- wheels that absorb the shock of landing and spring back to their original shape
- a symmetrical vehicle that can operate either side up, without complicated self-righting mechanisms
- a spin-turn capability so that mission-specific sensor packages can perform surveillance
- a built-in global positioning system (GPS) that shows an overlay of a Marvin icon on a high-resolution aerial photograph or topographic map to allow the operator to determine vehicle location and direct the vehicle to the desired destination

TECHNICAL CONTACT:
Keith Miller
505-845-8812
akmille@sandia.gov

Marvin, an extremely rugged mobile robotic system, can withstand violent deployment.

Sandia researcher Bill Hensley checks the Lynx synthetic-aperture radar (SAR) installed on a General Atomics I-GNAT unmanned aerial vehicle.

*Locate, Identify and Target the Threat*

## Synthetic Aperture Radar

***Clouds, haze, smoke, and even smog can blind many airborne surveillance systems.*** The nighttime poses its own problems, requiring the use of systems with less resolution. Sandia's small, high-resolution synthetic aperture radars (SAR) now provide all-weather, round-the-clock surveillance, with 3-D capabilities. A synthetic aperture means that the effective size of a receiver (the "camera lens") can be greatly expanded by intensive, real-time information processing, which also yields 3-D information.

Sandia has reduced the size of SARs so that small unmanned aerial vehicles (UAVs) can easily carry them. Current UAVs are about halfway between the size of a large model airplane and a small private plane, and can fly at altitudes of about 60,000 feet for durations of about three days. Future generations of the aircraft will be smaller, harder to detect, and have even greater performance.

Hovering over a battlefield, Sandia SARs can provide 3-D field terrain maps in minutes. Instead of trying to interpret terrain lines on a flat map, these maps, produced on a rubber-like material, give field commanders an immediate visual representation of obstacles.

## Sensors and Systems for the 21st Century

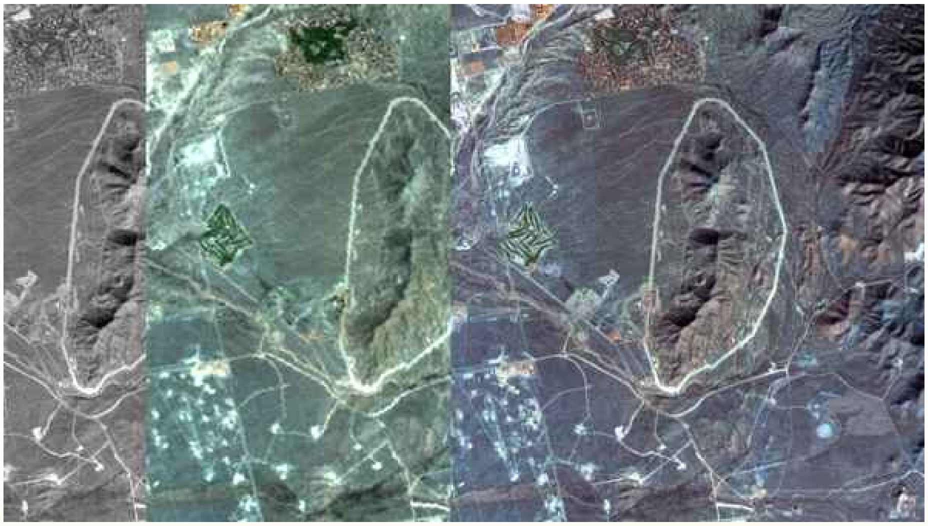
Starting in the 1940s with instruments to measure the effects of nuclear blasts, Sandia has developed sensors that see, hear, and feel events and substances thousands of times more sensitive than humans could detect.

Today's sensors range from miniature radio tags that serve as transponders for both friend and foe, to the instruments on board the now-orbiting Multispectral Thermal Imager satellite, which takes images on 15 spectral bands.

In between is a vast array of sensors that detect such things as changes in gravity or a surface's response to electromagnetic energy or the presence of anti-neutrinos. Sandia's material sciences and microelectronics expertise combine to produce sensors and complete systems that are startlingly small, are capable of detecting parts per trillion, and can simultaneously analyze thousands of compounds.

One of the most promising technologies under development at Sandia is ion mobility spectrometry. It is used in the explosives-detection portal now being deployed at airports and sensitive facilities. It quickly detects and characterizes minute quantities of explosives molecules.

Singly, these sensors give the nation unprecedented capabilities for surveillance and intelligence. But Sandia goes many steps beyond sensor technology. By fusing the data from many different types of sensors, Sandia develops information unobtainable from single sources.



Sensor-fusion technology—which can identify obscured objects and track, for example, military vehicles to show a history of activity at a site—can support nonproliferation and treaty verification. The technology combines independent information collected from multiple sensors to provide a clear understanding of one object.

# MEETING *the Logistics and Demilitarization* CHALLENGES

The Department of Defense has set an ambitious goal of reducing logistics costs by about $20 billion per year, or 25 percent of current expenditures on logistics. Achieving this goal will require revolutionary new technologies and systems for how we build, supply, maintain, repair, and eventually retire our defense assets.

## Robotics at Work

The noblest aim of robots has been to keep people out of harm's way—to perform tasks that are too dangerous, too difficult, or too monotonous for humans to do safely every time.

Early this year at the Mason & Hanger Pantex plant near Amarillo, a Sandia-developed robotic system performed such a task—it grabbed and moved a W80 pit across a room. It was the first time a nuclear weapons pit had ever been lifted by a robot.

Sandia robotic systems also help national security by autonomously watching for proliferation activities and guard nuclear facilities, surveilling and remediating hazardous sites, and disassembling old munitions. Other systems—developed at a fraction of the cost of a commercial supplier if one had had the capability—apply special coatings for the F-117 Stealth and F-22 Raptor and improve the quality of the Space Shuttle's main engines.

For industry and medicine, Sandia has delivered flexible systems that are now at work performing everything from single, repetitive manufacturing tasks to assisting a surgeon's precision and steadiness during delicate operations.

Sandian Walter Wapman with a robot that disassembles old 40mm munition clips.

*The noblest aim of robots has been to keep people out of harm's way—to perform tasks that are too dangerous, too difficult, or too monotonous for humans to do safely every time.*

## Demilitarization

The legacy of past conflicts is staggering—vast stockpiles of decaying munitions, millions of land mines, and as discovered early this year during the clean up of the old Rocky Mountain Arsenal near Denver, Colo., munitions where they were never expected to be. Workers at the arsenal found forgotten "bomblets" of sarin nerve gas.

Sandia's Explosive Destruction System (EDS), already at work in England destroying leftover World War I munitions, was airlifted to the site. Using technologies that explosively slice a bomb open and then quickly neutralize the contents, the EDS safely destroyed all six bomblets.

A second Sandia system uses supercritical water oxidation—essentially superheated, super-pressurized water—to destroy munitions that would damage the environment too much if simply detonated. The wastes are destroyed within seconds, producing such commonplace, and nonthreatening, end products as carbon dioxide, water, and salts.

The U.S. Army is responsible for coordinating munitions demilitarization for all the military services.

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From atop a 25-foot ladder, Sandian Larry Shipers examines a pair of cameras that provide feedback to a computer system that controls Sandia's automated painting system for the F-117 Nighthawk, also known as Stealth. The system sprays a thin radar-absorbent coating on the surfaces of the fighters. To test the system, this cardboard mockup of some of the aircraft's more hard-to-reach surfaces was constructed in a high bay.

# PAINTING THE STEALTH AIRCRAFT

U.S. F-117A Nighthawks, also known as Stealth fighters, swoop largely undetected through radar because their "radar-invisible" paint and angular exterior minimize reflected signals. Over the next few years, the fleet of Nighthawks will be refurbished, which includes removing the aging thin films and coatings and replacing them with a radar-absorbent paint that is easier and less expensive to apply and maintain. Any deviation from the Nighthawk's exacting surface specifications—even an air bubble or a screw not tightened exactly to specifications—could result in a blip on an enemy's radar screen.

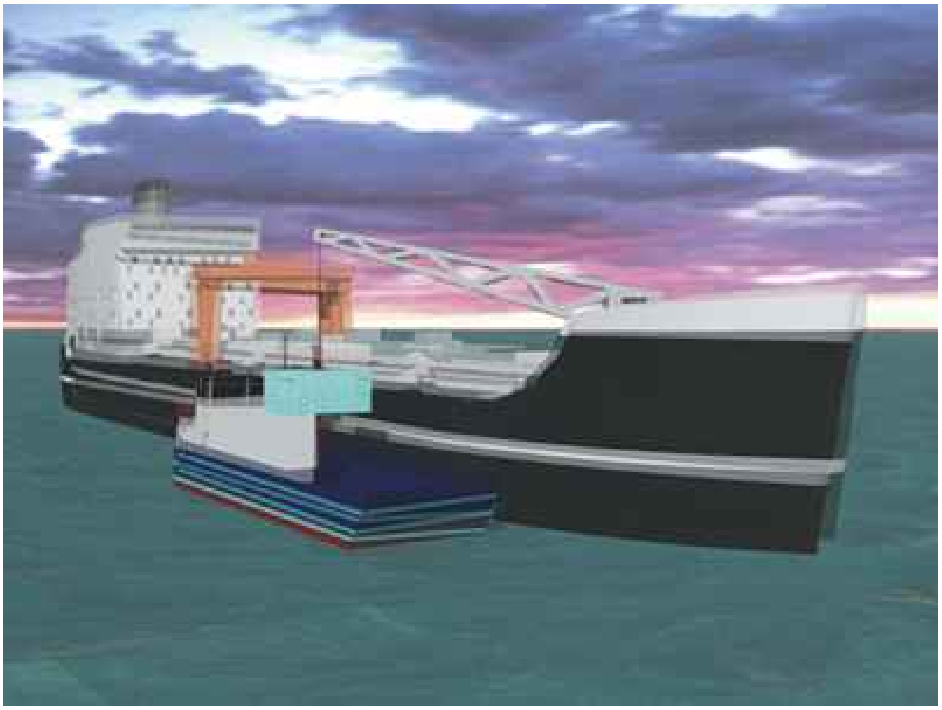
It took five painters and a masking crew 4 1/2 days to paint the first Nighthawk. Could this process be automated?

Nighthawks are large aircraft—65 feet long with a 43-foot wing span—and each one is slightly different from the others. The Nighthawk's angularity and the need to keep the paint spray nozzles at precise distances from the aircraft's surface at all times require both accuracy and adaptability.

Using commercially available robotics, Sandia developed a unique path-planning system that adjusts for differences from aircraft to aircraft. Path planning is one result of Sandia's years of research in "geometric reasoning," developed with DOE Defense Programs and lab-directed research funding. Geometric reasoning gives robots the capability to automatically determine the movements needed to carry out a task, even if the work varies from piece to piece.

The first robotically painted aircraft took only three days with a smaller crew. Now in production mode, the system saves the Air Force money and time and improves the final finish quality. Signature testing on the robot-sprayed aircraft was significantly better than expected. According to Col. Samuel Ryals, director of the Air Force's F-117A System Program Office, the system is expected to yield a net cost savings measured in millions of dollars over the next four years.

TECHNICAL CONTACT:
Pablo Garcia
505-844-5799
pgarcia@sandia.gov



Logistics at Sea: Transferring cargoes at sea, in rough waters in harbors, or at offshore platforms has always been a difficult and perilous endeavor. Sandia's swing-free crane technology lessens the hazards by compensating for pitch, yaw, and roll simultaneously in real time. This not only reduces the dangers but also greatly speeds up operations such as re-supplying ships at sea.

*[ Sandia has joined the demilitarization effort to rid the world of land mines. Worldwide, there are an estimated 100 million land mines in 68 countries. ]*

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More than 300,000 tones of munitions are currently waiting to be demilled, some dating back to World War II. This amount is increasing by about 70,000 to 100,000 tons per year. Currently, personnel undertake the hazardous task of disassembling these munitions.

When Jim Wheeler, director of the Defense Ammunition Center, decided to insert flexible automation systems into their conventional demil operations, he turned to Sandia's robotic expertise for guidance. Having already successfully solved a similar problem for DOE with an automated gas generator disassembly system, Sandia was able to quickly adapt its technology and system integration capability to create a prototype system for the Army that would disassemble 40mm fixed-round munitions. Within nine months, Sandia designed, developed, delivered, and demonstrated a complex prototype system at the McAlester Army Ammunition Plant in Oklahoma.

Sandia has joined the demilitarization effort to rid the world of land mines. Worldwide, there are an estimated 100 million land mines in 68 countries. Those with the worst problems are Angola, Afghanistan, Cambodia, Iraq, Laos, and the Balkans.

Sandia's work in land-mine detection and demining ranges from chemical sensing to laying down a quick-hardening foam to clear a path for military vehicles. Sandia also is developing robotic vehicles and backscattered X-ray technologies that can be used to support the demining effort.

The Sandia team focuses its efforts on three types, or levels, of demining activities. The first is standard military demining used for clearing a path for soldiers and vehicles during war. The second level, also connected with military operations, deals with an army's need to clear greater numbers of mines in an occupied country. The third level is humanitarian demining and tries to remove all mines and restore an area to productive use.

TECHNICAL CONTACT:
Walt Wapman
505-844-9761
wwapman@sandia.gov

Aircraft inspection Sandia technologies, such as resonant ultrasound inspections and composite doubler repairs, improve the quality and save time for aircraft maintenance. Sandia is working with the FAA on a number of new initiatives. We are studying the entire inspection and certification process so that inspectors will have a better understanding of the aging process, and also of the impact of new technologies as they are incorporated into existing and new aircraft. Sandia also is studying the nonstructural parts of aircraft, beginning with wiring degradation, an area of particular concern in nuclear environments that directly applies to wiring in aircraft.

# Modeling and Simulation

## Who knows what evils lurk in the paths of robots? Umbra knows

When one robotic vehicle encounters a tree and decides to go left, will a whole battalion of tanks on the other side of the mountain go haywire?

Unless other robotic vehicles can adjust their paths and capabilities while coping with their own obstacles, that battalion of tanks could suddenly "go blind," or lose critical battle information and become the hunted rather than the hunters.

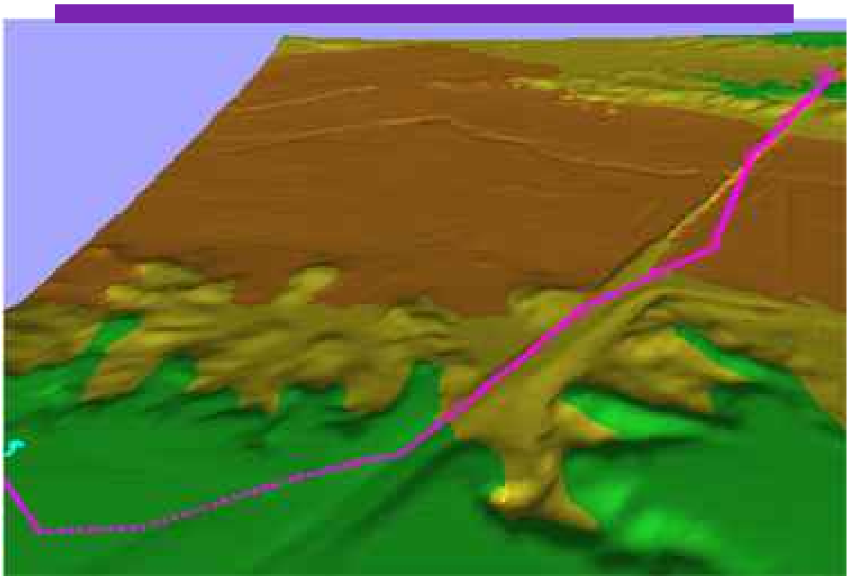
That's the type of scenario facing mission planners in exercises for future warfighting. The answer, and the planners' confidence in it, depends on the type of modeling and simulation (or mod/sim) system. A traditional mod/sim system is often scripted: *Robot meets tree. Robot spends 30 seconds to go left around tree. Robot is out of communication from seconds 15 through 27. Robot increases speed to catch up to others…*

In the real world, the robot may decide to go right, may never lose communication, may get stuck in an endless loop trying to avoid a circle of obstacles, or may tip over and simply stop functioning. And that's where Sandia's Umbra (Latin for "shadow") provides answers. Umbra takes real-world data, such as terrain information from SARs, satellites or the USGS, and presents the robot with a "reality-based" obstacle—without the script.

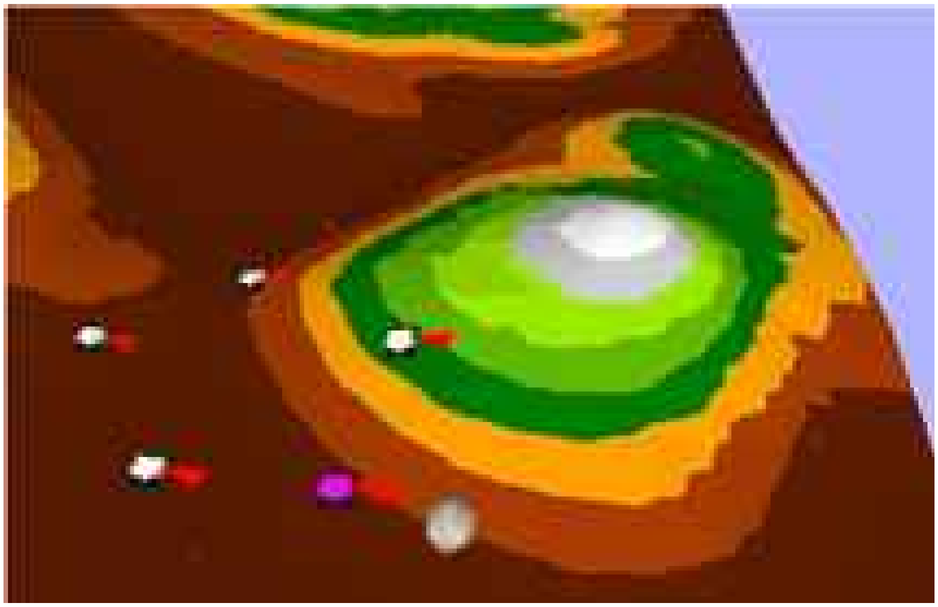
Umbra's ability to use real-world data in assessing robotic behavior is just the first level of mod/sim (see previous article on SMART). Once the behaviors of each component of a system are modeled, how will the entire system work, especially when confronted, individually and collectively, with a bewildering variety of real-world obstacles? Again, Umbra provides answers, based on models that analysts and planners can trust.

Simulating an entire system of operations requires modeling and simulation capabilities well beyond those now deployed in centers for training, analysis, and mission planning. The use of unmanned vehicles and unattended sensors requires a network-centric style of communications, control, and intelligence. This results in large, very complex systems that are difficult to simulate confidently with traditional script-based methods.

"The performance of robots in the real world is greatly affected by even small obstacles," said Ray Harrigan, senior manager of the Intelligent Systems Principles department. "A small hill can disrupt communications



A radical robotics philosophy that's proven effective in unstructured environments has led to international demand for Sandia robotics. "We are exploring how little—not how much— we have to tell autonomous robots for them to accomplish a mission," says Ray Harrigan, senior manager of the Intelligent Systems Principles department. "In path-planning missions, for example, it's usually better to tell the robotic vehicle only what you want to achieve and let it figure out the best solution, and how to handle problems. We used to try to figure out the best solution beforehand and load our solution into the vehicle, along with every conceivable problem it might encounter on the way. We found out we weren't very good at envisioning the obstacles, and that it was better to give the robots basic skills for maneuvering, and let them cope with unanticipated problems."



Umbra allows planners to simulate swarm behavior with real-world factors such as terrain, communications loads and vehicle limits.

or slow a vehicle by 70 percent or more. What happens in one small part of a system affects other parts, but the relationship is non-linear."

Warfighting mod/sim systems initially focused on coordinating the behavior of swarms of robots. Umbra contains these behaviors but adds real-world factors such as terrain, obstacles, network communications loads, and vehicle limits—all based on computational models rather than simulation scripts.

Umbra began as laboratory-directed research by Sandia computer scientists. Their goal was an abstraction of how large, complex systems work. They developed the concept of "embodied agents," software models that could incorporate real-world geometry, physics for mobility, sensor inputs, robotic instrument capabilities and limitations, and controller actions. Within the Umbra framework, they built a library of modules for terrain, communications, kinematics and motions, obstacle detection and distance measurement, vehicle control laws, and automated planning for vehicle routes and collision-free robotic actions.

Umbra's framework will link with other mod/sim systems, such as JCATS (Joint Conflict and Tactical Simulation) developed at Lawrence Livermore lab and used at the Joint Warfighting Center. "This expands the capabilities of both systems," said Harrigan. "Umbra is a bridge across many technologies, so there is a matrix of organizations interested in using it to expand their mod/sim capabilities."

TECHNICAL CONTACT:
Ray Harrigan
505-844-3004
rwharri@sandia.gov.

## Mod/sim, a Sandiawide Effort

Sandia's prowess in modeling and simulation began with two fundamental advances in computer sciences. The first was the ability to make thousands of processors work together efficiently when most computer companies believed that a dozen or so processors were the limit. This advance resulted in the first teraflops-class computer of the Accelerated Computing Strategic Initiative (ACSI). The second, perhaps even more fundamental advance was Sandia's proof that the solutions to large computation problems could be reduced from exponential to linear methods. Where computer scientists once believed that doubling the size of a problem required four times the computer resources to solve, Sandia proved that the solution required only an increment in resources. Without that proof, even teraflops computers would be vastly limited in the problems they could solve. Both advances won Sandia a Gordon Bell award. Sandia is the only institution to win two of these awards for solving "Grand Challenges" in computer sciences.

ACSI's goal is to model and simulate the entire life cycle of a nuclear weapon. Using many of the same computer science tools, other Sandia research efforts in large, very complex, nonlinear systems are drawing interest for battlefield planning, predictive and prognostic maintenance, emergency response, and critical infrastructure analyses.

Sandia's work with massively-parallel computer architectures and algorithms have boosted the nation's ability to solve very large problems.

# INSIGHTS

*by Dr. Mark L. Swinson*

*Acting Director, DARPA Information Technology Office*

## Robotic beasts and machines

Many of our robots will have forms dictated by their tasks, environments or even our imaginations. We can expect to see robotic insects, dogs, and birds as well as robotic cars, boats, and perhaps washing machines. Robotics may represent the greatest unmet technological expectation of the 20th century, but many of those expectations will likely begin to be realized early in this century.

Advances in artificial intelligence technologies are critical to this progress. One example is situated machine learning. Reinforcement learning can be used for an unsupervised, learning-with-critic approach where mappings from precepts to actions are learned inductively through trial and error. Other approaches may include evolutionary methods that begin with an initial pool of program elements, and then use genetic operators such as recombination and mutation to produce successive generations of increasingly successful controllers.

These approaches (as well as others) will teach robots to adjust parameters, exploit patterns, evolve rule sets, generate behaviors (and aggregations of behaviors), devise new strategies, predict changes in the environment, and even exchange this knowledge with other robots. Such robots can acquire new knowledge, as well as adapt existing knowledge to new circumstances, and thereby solve problems in ways we humans may not understand. Indeed, emergent behavior, rather than being suppressed by careful design, may instead be encouraged by equally careful design.

As robots become more pervasive, then like automobiles they are likely to become increasingly complex. Indeed, some robots may be comprised of millions of parts. If fast, cheap, rapid manufacture of these robots is to occur, it may be necessary to remove humans from the process altogether. Jordan Pollack and his colleagues at Brandeis University are using commercial CADCAM simulators together with a genetic algorithm to evolve the body and brains of simple robots. They have succeeded in automatically designing, improving, and creating a real robot with only trivial human intervention. So far, the work has focused solely on creating a robot for locomotion, but eventually this approach may allow cheap, near-perfect solutions to be evolved and deployed, even for complex tasks requiring unintuitive solutions.

## Humanoid Robots

Humanoid robotics include a rich diversity of projects where perception, processing, and action are embodied in a recognizably anthropomorphic form in order to emulate some subset of the physical, cognitive, and social dimensions of the human body and experience, with the goal of creating a new kind of tool. Such a tool would be intended to work not just for humans but also with them. Humanoids will be able to work safely along side humans in typical, everyday environments, as well as the more daunting environments of space and underseas, and thereby extend our capabilities in ways we cannot at present imagine.

Indeed, humanoids may prove to be the ideal robot design to interact with people. After all, humans tend to naturally interact with other human-like entities; the interface may well be hardwired in

Continued on next page

our brains. Their human-like, robot bodies will allow them to seamlessly blend into environments already designed for humans. While we humans have historically adapted to the limitations of our machines, here the machines will be designed to adapt to us.

Humanoids will not only provide a new way for us to interact with machines, but may also serve as an intuitive filter for humans to interact with an increasingly ubiquitous and pervasive information environment.

Humanoid robots that can incrementally acquire new knowledge from autonomous interactions with the environment will accomplish tasks by means their designers did not explicitly implement (or perhaps even conceive of), and will perhaps thereby be capable of adapting to the unanticipated circumstances of an unstructured, dynamic environment. Already, humanoid robots have demonstrated basic task decomposition necessary to carry out complex commands given through gesture and speech. Humanoids have also demonstrated the ability to adapt, to orchestrate existing capabilities, and to create new behaviors using a variety of machine learning techniques.

Humanoid robots may well rekindle a new inspiration for artificial intelligence as they motivate research toward intelligent, autonomous systems. Already, a growing number of robotics researchers have found that the human form provides an excellent platform upon which to enable real-world learning. A 'similar' body facilitates learning based upon imitation, by making it easier to map the human's action onto the robot. In fact, it may be that human-like intelligence actually requires a human-like body.

As a minimum, the anthropomorphic form factor of these robots enables them to easily interface with existing technology and infrastructure with minimal disruption. Hence, humanoids appear to be a uniquely appropriate form factor by which to gradually introduce "intelligent" robots into new application domains.

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*The Defense Advanced Research Projects Agency (DARPA) is the central research and development organization for the Department of Defense.*

A butterfly rests next to a precision microcomponent made with LIGA (an acronym from German words for lithography, electroplating, and molding) micromachining technology. LIGA is a technique to create a mold on a micron scale. It uses the mold to mass-produce tiny, three-dimensional structures in a variety of materials including metals, polymers, and ceramics. Sandia has licensed proprietary LIGA expertise to AXSUN Technologies, a telecommunications firm based in the Boston area.

*ON THE COVER:*
*The Mini Intrusion Detection System (MIDS) uses a passive infrared sensor that detects an intruder without his or her knowledge. The detector components are designed to be buried in the ground and can operate for several months using 9-volt batteries. The detector transmits its particular digital burst to a remote receiving location, allowing for quick identification of where the intrusion has occurred.*

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To request additional copies or to subscribe, contact:
Michelle Fleming
Marketing Communications Dept.
MS 0129
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0129
Voice: (505) 844-4902
Fax: (505) 844-1392
*e-mail: meflemi@sandia.gov*

*Sandia Technology* Staff:
Laboratory Directed Research & Development Program
Manager: Chuck Meyers, Sandia National Laboratories
Editor: Chris Miller, Sandia National Laboratories
Writing: Peter Nolan
Design: Douglas Prout, Technically Write
Photography: Randy J. Montoya and
Lynda Hadley, Sandia National Laboratories

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Marketing Communications Dept.
MS 0129
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0129