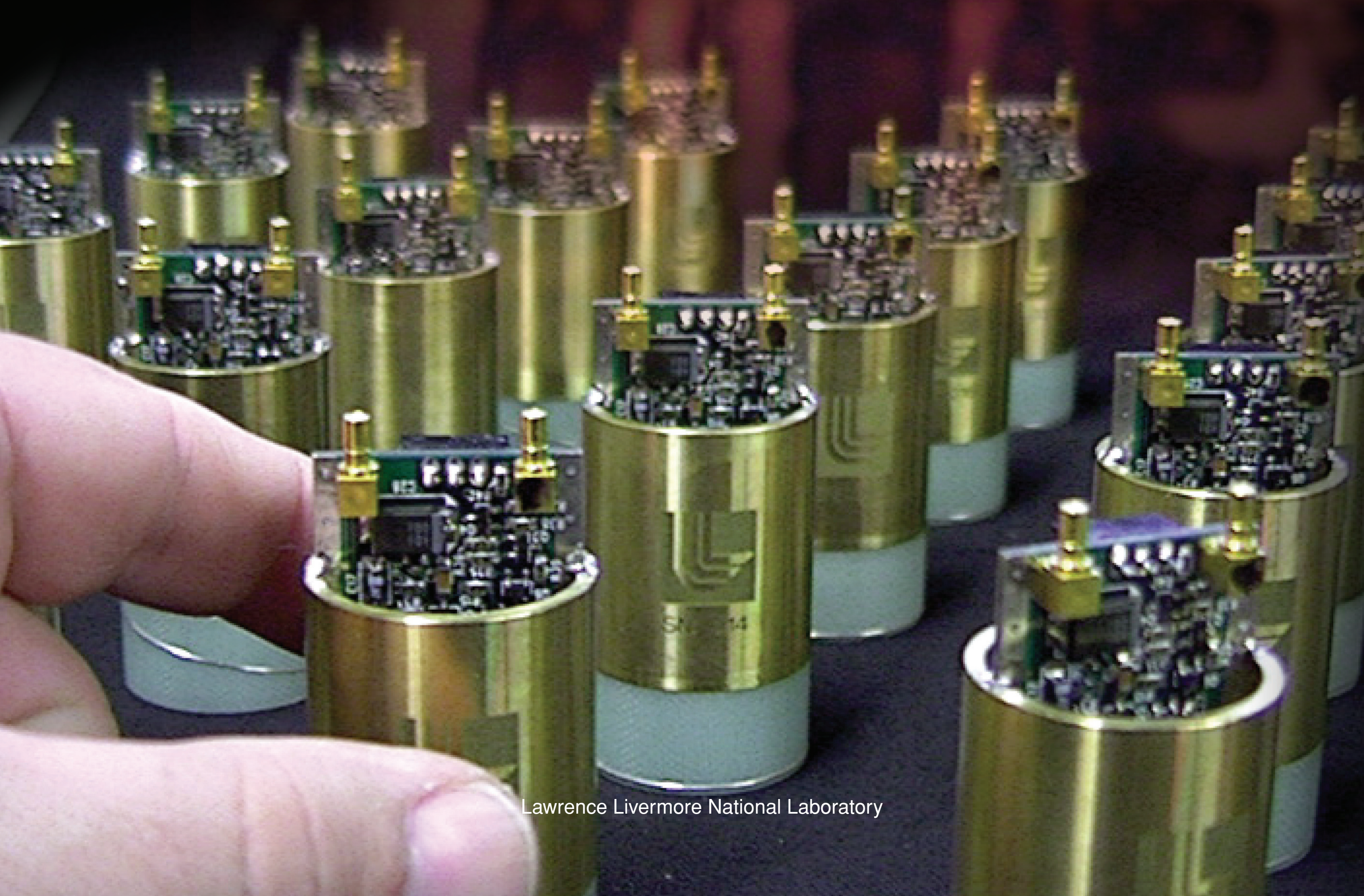
Exploring the Ultrawideband

Compact, low-cost radar and communication systems using ultrawideband frequencies are strengthening national security while changing commercial markets.



LAWRENCE Livermore research efforts and inventions quietly advance many fields. In one instance, however, a Livermore invention that stemmed from laser research has spawned a variety of new commercial products, including some that support national and homeland security.

The invention is called micropower impulse radar (MIR), a fundamentally different type of radar that is compact, low power, inexpensive, and unusually versatile. MIR sends out extremely short electromagnetic pulses in ultrawideband (UWB), an extremely wide range of frequencies. (See the box at right.)

Instead of the continuous energy waves used in conventional radar or radio, MIR transmits UWB pulses that are as fleeting as a few trillionths of a second. The pulses reflect off nearby objects and are detected by a high-speed sampling receiver. MIR is unique because of its ability to efficiently send and detect these very low-power pulses without interfering with nearby electronic equipment.

For the past decade, Livermore has transferred the MIR technology to numerous companies for various applications. (See the box on p. 14.) More recently, Livermore researchers have been applying their experience with MIR to develop new types of UWB-based sensing, imaging, and communication devices that are portable, rugged, energy-efficient, and resistant to detection and interception.

Millions of Pulses Per Second

The Livermore radar and communication devices have a transmitter that emits many millions of pulses per second, with each pulse lasting as short as 50 picoseconds (50-trillionths of a second). A simple, single-wire antenna 4 centimeters long can be used,

Micropower impulse radar sensors used in proximity fuses have been successfully tested. The fuses trigger small bombs to detonate at about 1 meter from the ground.

The Ultrawideband Revolution

Livermore's micropower impulse radar and radio communication systems are part of the ultrawideband (UWB) revolution. Scientists and engineers have known about UWB signals since Guglielmo Marconi experimented with spark-gap devices in the late 1800s, but the signals are more difficult to control or detect than narrowband (single-frequency) signals. The UWB is a wireless communication technology that transmits data in extremely short (50- to 1,000-picosecond) pulses spread out over a wide range of the electromagnetic spectrum. Large data bursts (hundreds of gigabits per second) are possible because data are carried simultaneously at a wide range of frequencies across the electromagnetic spectrum.

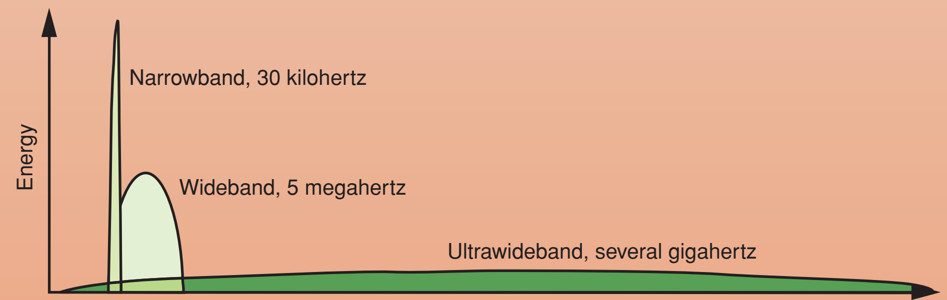
The combination of broad spectrum, low power, and extremely short pulses causes much less interference with other devices than do conventional narrowband wireless systems. In turn, UWB is much more resistant to electrical interference from other devices than competing wireless technologies.

UWB's data capacity, speed, low power requirements, and resistance to interference have attracted the attention of major electronic corporations who recognize the technology's commercial potential. Because UWB can penetrate walls, it could become the center of all communications within homes and small offices. UWB signals could carry voice, data, and video. Products could speed downloading images from a digital camera to a computer, connecting printers to computers, and routing high-definition signals to televisions.

The Federal Communications Commission (FCC) currently restricts commercial UWB applications to between 3.1 and 10.6 gigahertz because of a concern they could interfere with existing transmissions, especially flight radios, beacons, and the Global Positioning System. FCC rules also limit UWB commercial devices to less than 1 watt, which prevents them from working beyond a relatively short distance (about 10 meters).

Using an experimental license, Livermore has developed numerous UWB systems in frequency bands ranging from 200 megahertz to 100 gigahertz. Tests at Livermore have shown that the devices do not cause undue interference with other electronic devices operating in this broad frequency range. Livermore efforts are directed at developing UWB devices for the government that operate both above and below the 3.1- to 10.6-gigahertz band designated for commercial devices.

A task force convened by the Institute of Electrical and Electronics Engineers (IEEE) is developing a new standard for UWB products, called IEEE 802.15.3a. Livermore engineers have been involved with determining this international standard for UWB use.



Ultrawideband (UWB) pulses spread energy over many frequencies, as opposed to traditional narrowband, which covers a limited band of about 30 kilohertz. Cellular phones operate in the wideband, which covers 5 megahertz. Compared to conventional radios and phones, UWB pulses generate a tiny fraction of energy and appear like random noise signals.

but larger antennas provide greater range, directionality, and penetration of materials.

Radar units use an extremely sensitive receiver that is set to detect UWB echoes over a preset distance, ranging from a few centimeters to many tens of meters. When recorded data are combined with special algorithms, MIR imaging applications are possible. For example, to find buried objects, researchers apply image reconstruction software to visualize one "slice" of the object at a certain depth. Many slices stacked together form a three-dimensional view.

The electromagnetic pulses penetrate most low-conductivity materials, such as rubber, plastic, wood, concrete, glass, and dry soil. MIR-based tools can locate wooden or steel studs in a wall and steel within concrete. The signals can also penetrate substances with moderate electrical conductivity, such as the human body. Because penetration of MIR signals decreases as a material's electrical conductivity increases, MIR devices cannot penetrate metal or seawater.

Another advantage of MIR devices is that electromagnetic emissions are typically less than 1 milliwatt; thus, they are safe to use around people and do not interfere with computers, digital watches, cellular phones, or radio and television signals. What's more, these devices are small and relatively inexpensive to manufacture. In most cases, they use commercial components. Typical MIR circuit boards measure less than 10 square centimeters.

Since developing the first MIR devices, Livermore researchers have decreased power requirements, extended the range, enhanced penetration capability, devised new processing algorithms, and found many new applications. About 20 engineers and technicians, led by Steve Azevedo, are working on radar and radio projects, which fall into three general areas: sensors, imagers, and communications.

MIR technology makes possible extremely accurate systems for motion detection and localization. At least one MIR licensee is using the technology for alerting drivers to obstacles in blind spots. Livermore engineers are using modified

Micropower Impulse Radar Reaps Rewards and Royalties

Micropower impulse radar (MIR) was invented in 1993 by Livermore electronics engineer Tom McEwan. The original device stemmed from the single-shot transient digitizer and won an R&D 100 Award for 1993. (See *E&TR*, April 1994, pp. 1–6, and *S&TR*, January/February 1996, pp. 12–18.) McEwan adapted the transient digitizer into a remarkably small, low-power radar system that uses ultrawideband (UWB) pulses and works well at short distances. The first commercial license for MIR technology was issued in 1994; Livermore currently has 16 active licenses to use the radar in various applications.

Since then, MIR has been applied to numerous uses, including an electronic dipstick that won an R&D 100 Award (see *S&TR*, October 1996, pp. 16–17); a land-mine detection system (see *S&TR*, November 1997, pp. 18–20); and a bridge inspection system that also won an R&D 100 Award (see *S&TR*, October 1998, pp. 8–9).

Livermore holds 30 MIR patents, with extensive patent coverage in many foreign countries. Royalty income for the past five years exceeds $5 million. MIR has been one of the most commercially successful licensed inventions both at Livermore and throughout the Department of Energy. Livermore researchers continue to use the technology to support Laboratory research programs.

Livermore engineering technologist Mike Newman used a micropower impulse radar sensor attached to an extender to search through rubble at ground zero of the World Trade Center following the September 11, 2001, terrorist attacks.

versions of MIR motion sensors for such applications as search and rescue under rubble, measurement of explosive velocities up to 3,800 meters per second in Livermore's High Explosives Applications Facility, proximity fuses for rockets and cluster bombs, helicopter blade tracking, demilitarization of rocket motors, medical diagnostics, cargo container intrusion sensing, inspection of bridge decks, and perimeter security.

MIR to the Rescue

Livermore engineers have developed portable MIR motion detectors to assist search and rescue operations. The units use directional, high-gain antennas to detect motion caused by breathing and heartbeats up to 100 meters away. Tests at federal facilities have demonstrated the devices' ability to detect subjects through deep piles of rubble. At a test in May 2004 conducted at the National Aeronautics and Space Administration's Ames Research Center and attended by representatives of the Defense Advanced Research Projects Agency and Department of Homeland Security, the MIR team located five out of five hidden "incapacitated" survivors.

"We want to locate survivors even through thick barriers of concrete," says engineer John Chang. He notes that MIR would complement standard techniques, such as search dogs and listening devices.

Prototypes were unexpectedly put to the test when a nine-member Livermore team was deployed by the Department of Energy (DOE) for 2 weeks following the September 11, 2001, attacks on the World Trade Center. The team used several different MIR devices, which were rapidly configured and tested for breathing detection through several meters of rubble. The team found no survivors (no survivors were found by any of the ground zero search teams) but discovered some previously unknown voids in the rubble, according to team member Doug Poland.

New Kinds of Medical Devices

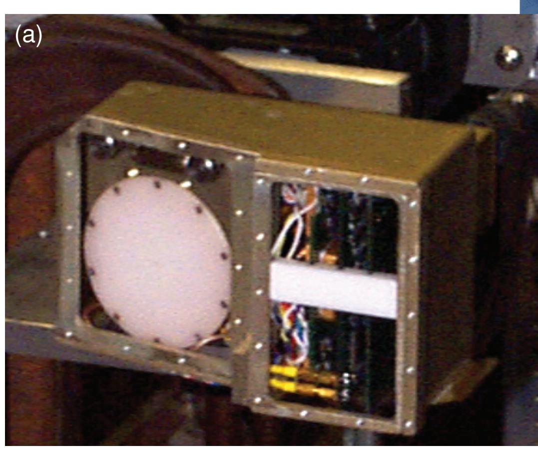
Livermore engineers are also working on MIR sensors for portable, low-cost devices for use in emergency medical care. The instruments are medically safe—electromagnetic emission levels average less than one-thousandth the emissions of a cellular telephone. "Our sensors are noninvasive, portable, cost effective, and generate no ionizing radiation," says Chang.

The U.S. Army is interested in using MIR technology to improve combat casualty care. One idea is a wearable device that monitors a soldier's vital signs and relays that information to a medical command post. Medics could carry MIR devices to locate injured soldiers by their breathing. Researchers are developing devices to detect life-threatening injuries to the head and lungs. Lightweight, handheld prototypes are powered by a single 9-volt battery, and connect to a laptop computer.

Rocket Motors and Helicopter Blades

MIR has been the focus of two projects for the Department of Defense (DoD). The first demonstrates the feasibility of using MIR for controlling a water-jet cutter to remove propellant from rocket motors so the propellant can be recycled. Tests of a prototype sensor showed that the powerful water spray did not interfere with the radar pulses. This year, Livermore engineers are building a sensor with three MIR radars; tests of the sensor are scheduled to occur in 2005.

The second effort uses MIR to significantly reduce maintenance costs for U.S. Marine and Navy V-22 Osprey helicopters. The MIR device, called a radar blade tracker, received a DoD Life Cycle Cost Reduction Award. The device is placed



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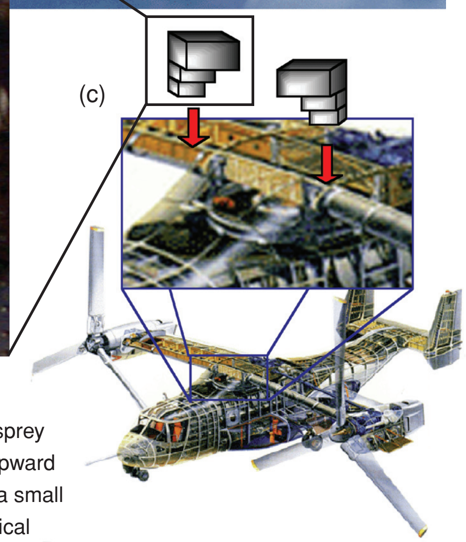


(a) A 96-gigahertz radar sensor significantly reduces maintenance costs for (b) U.S. Marine and Navy V-22 Osprey helicopters. (c) The device emits ultrawideband pulses upward to the overhead rotating blades. Pulses are reflected by a small section of the blade as it passes over the radar. The vertical distance can be precisely calculated from the transit time of pulses to and from the moving blades.

beneath a helicopter rotor and emits UWB pulses upward to the overhead rotating blades. Pulses are reflected by a small section of the blade as it passes over the radar. The transit time of pulses to and from the moving blades is measured, allowing the vertical distance to be calculated precisely. If the rotor blades are outside the required range, rebalancing may be necessary to prevent damage to the rotor or excessive transmission vibration.

Sensors for Troops and Containers

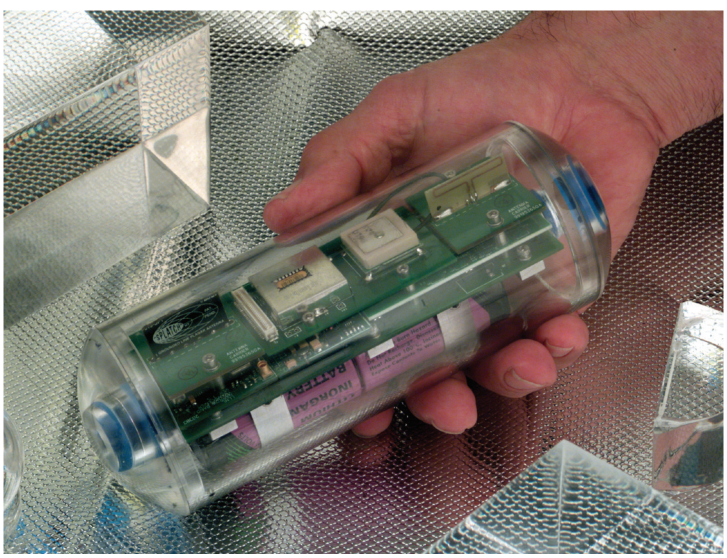
Livermore engineers have developed sensors in response to the military's need for portable, rugged, low-power motion sensors that avoid detection and interception. One device looks like a flashlight and detects motion from up to 15 meters away through nonmetallic barriers, such as wooden doors, drywall, and concrete. A similar device equipped with an omnidirectional antenna can generate a protective "bubble." All motion outside the bubble and limited motion inside the bubble can be ignored, while any penetration of the bubble triggers a data recorder, camera, or audible alarm.

Guardian is a group of individual motion detectors that form a wireless system to monitor environments for both military and civilian applications. The system consists of individual nodes that contain a transmitter, receiver, global positioning satellite module, and processor. The nodes form a network with each other and communicate with a "mother" node that sends information to a remote monitoring station.

The sensors continuously measure reflected signals from a designated distance and issue an alarm when a change occurs. Richard Leach, principal investigator for Guardian, says, "Guardian can form a protective electronic fence around facilities; any penetration of the fence triggers an alarm."

Livermore engineers are also developing a system that monitors the status of shipping containers before they arrive at U.S. docks. The effort is part of a "smart container" program funded by several federal agencies. More than 18 million cargo containers enter U.S. ports every year, and any one of them could contain clandestine material.

The inexpensive system would be installed in every cargo container and would last at least 10 years. Each device would detect any intrusion, monitor radiation levels of that container using an attached radiation sensor, and then transmit the results to a computer on the ship. Engineers are researching how to network thousands of these devices into an efficient system that uses UWB communications.



This prototype Guardian system is equipped with an antenna, Global Positioning System (GPS), ultrawideband radar, micropower impulse radar (MIR) antenna and motion sensor, processor, and batteries.

Imaging Bridges

MIR sensors' small size makes them suitable for assembling into arrays that generate images. One imaging effort is the HERMES (High-Performance Electromagnetic Roadway Mapping and Evaluation System) Bridge Inspector for imaging bridge decks and pinpointing needed repairs. Many U.S. bridge decks, the weakest component of bridges, are deteriorating, often because of corroding steel reinforcing bars (rebar) hidden by concrete and asphalt. The Federal Highway Administration and 24 state highway departments have funded HERMES development.

HERMES uses 64 MIR modules mounted underneath a trailer pulled by a vehicle at traffic speeds. The sensors, assembled into an array about 2 meters wide, are spaced about 3 centimeters apart. They send out UWB pulses with frequencies ranging from 1 to 5 gigahertz, penetrating concrete to a depth of up to 30 centimeters. As the pulses propagate through the bridge deck, the echoes are recorded by a computer inside the trailer and compiled into a three-dimensional map of the deck.

A Livermore team, led by Jose Hernandez, is planning extensive field-testing of HERMES, including the comparison of images with the actual state of a bridge deck following bridge demolition. A major goal is to create a national HERMES image database. Azevedo compares the current stage of HERMES development to early computerized axial tomography (CAT) scans in the 1970s, when physicians were unsure what the images signified. "We need more 'bridge cadavers' so when we see a particular image of a bridge deck, we can correlate it to real pathology."

Radar Camera Sees through Walls

A simple imaging system, called Urban Eyes, uses two MIR sensors to provide a real-time view of motion behind walls. Two radar sensors are placed against a wall 1 meter apart; the computer triangulates the location of moving figures on the other side of the wall. The system provides an image as though looking overhead, while an icon follows the motion of the principal object on a nearby computer screen.

Livermore engineers are using an array of up to 16 or more sensors to develop a handheld MIR radar camera capable of producing real-time video (30 frames per second), which would show much greater detail than Urban Eyes. The camera could aid first responders, such as police units responding to a hostage situation. In such a case, the officer holding the camera against a wall would see a moving picture of people located inside. Special beam-forming hardware and signal processing would show the first real-time images of people through smoke, haze, or walls and could potentially locate concealed weapons.

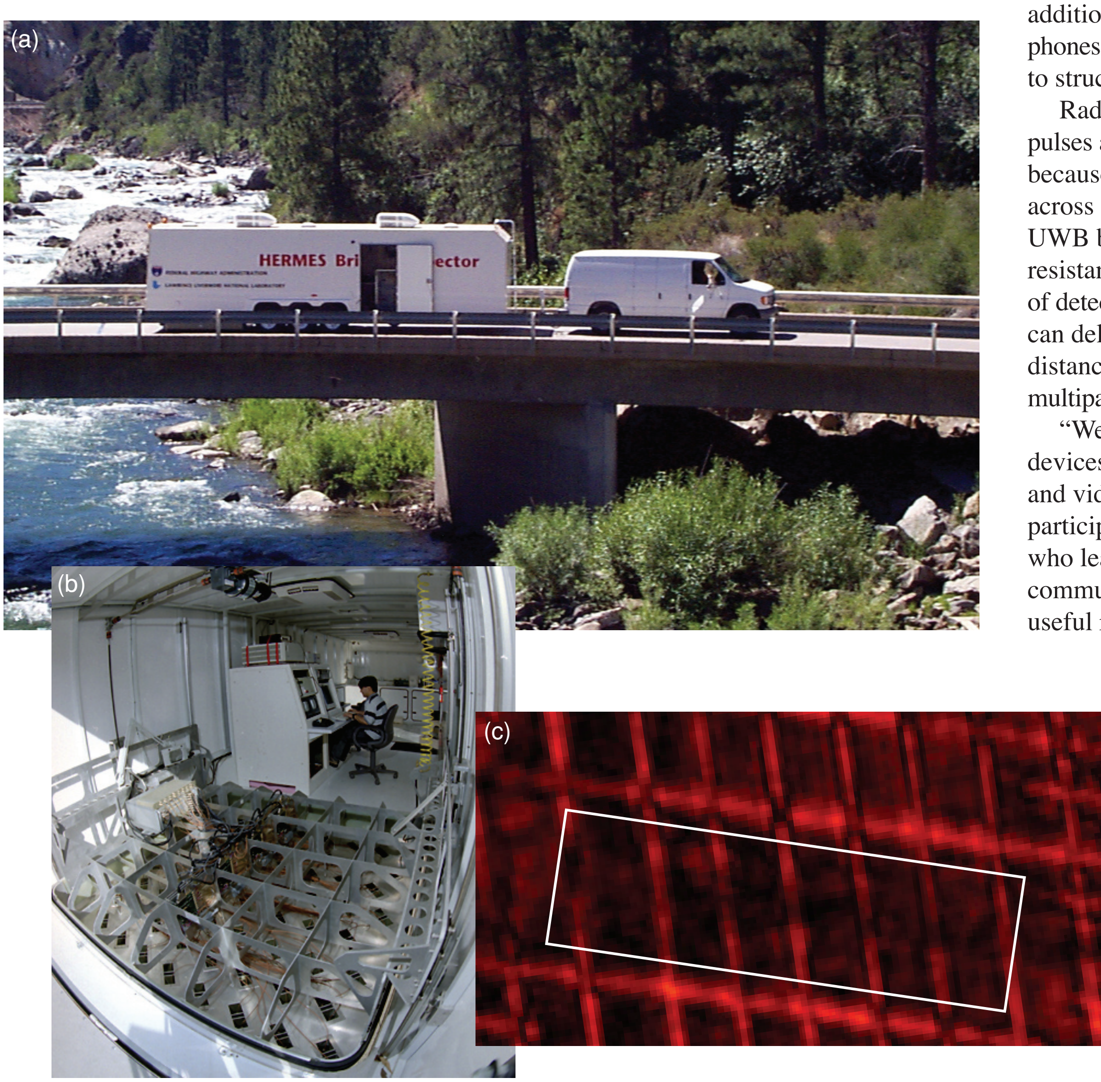
Engineer Carlos Romero says the unit would offer important advantages over current tools, some of which can signal that a threat exists but cannot pinpoint its location. Other tools provide the location of the threat but are slow, complex and bulky and require large computers. The research team is collaborating with the University of California at Davis to study how best to display radar-based images for first responders.

New World of Communications

The MIR research group is extending its expertise in UWB to new types of communication devices, such as radios used in police, military, and intelligence operations. Standard radios are susceptible to detection and jamming because they operate on fixed frequency bands. In addition, in urban areas, radios and cellular phones fade as signals bounce from structure to structure.

Radio communications based on UWB pulses are ideal for combat and surveillance because the signals spread their energy across a wide range of frequencies. The UWB bandwidth provides high capacity, resistance to jamming, and low probability of detection. Furthermore, UWB technology can deliver large amounts of data over distances less than 1 kilometer in extreme multipath and electronic noise environments.

"We want to supply our troops with devices that can rapidly send voice, data, and video information among sensors and participants," says engineer Farid Dowla, who leads Livermore's UWB radio communications development effort. "A useful radio communication system should



(a) The HERMES (High-Performance Electromagnetic Roadway Mapping and Evaluation System) Bridge Inspector is a radar-based sensing system mounted in a trailer. (b) The array of 64 radar modules located beneath the trailer produces images of the insides of bridge decks. (c) This image shows a suspect area where a delamination in the concrete may have occurred.

be able to handle all these sensors with identical radios." Sensors may include everything from temperature probes to microphones to video cameras.

Livermore engineers are designing small and lightweight radios that function for days on batteries and send signals that penetrate walls. Because the radios have a simple physical architecture, they are low in cost and power consumption. Dowla notes that one strength of UWB communications devices is the small number of parts they require.

The team is focusing first on sensor and voice communications between ground-to-ground and ground-to-unmanned aircraft. In 2003, the team demonstrated UWB communications for low-power transmitters and receivers. Data were delivered at 2 megabits per second over a distance of about 20 meters. The team also demonstrated longer-range communications at lower data rates.

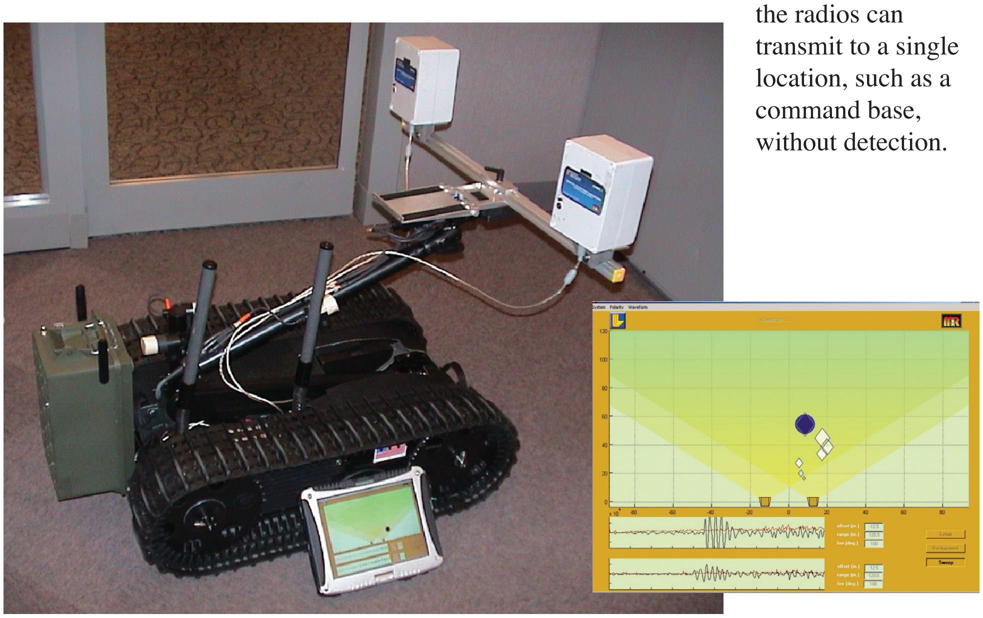
A major challenge is ensuring that signals are not distorted by the harsh electronic environment of battle and urban areas, where signals can be reflected and scattered many times. Just as a cellular telephone fades and drops out when signals interfere at certain locations, pulses in UWB get distorted as they pass from transmitter to receiver in harsh environments.

Livermore engineers developed and advanced a method to detect pulses of data that eliminates distortion yet retains the advantages of UWB. Called transmit-reference signaling, the technique sends a pair of closely spaced pulses, the first serving as a reference to the second. The second pulse is modulated with respect to the first to incorporate data bits. This type of communication could be secure (for military and homeland security applications), reliable (for buildings and tunnels), and noninterfering with existing radios.

In the same way that arrays of radar are used for imaging, arrays of UWB radios will provide more complete information and security. If the precise location of several communicators (for example, soldiers in the field) is known, the radios can transmit to a single location, such as a command base, without detection.

UWB signal processing also permits communicating with a specific point in the distance. For example, transmitters can communicate with a particular spot in a room from the outside of a building, in cases where it is essential to talk to a specific "good guy" in the midst of "bad guys."

The Livermore team members are developing for DOE a network of UWB walkie-talkies that would serve as a backup to typical narrowband radios. They are also exploring video communication over short distances. Video requirements are high—6 megabits per second—but UWB can deliver between tens and hundreds of megabits of data per second.



Urban Eyes uses two micropower impulse radar sensors to provide a real-time view of motion behind walls. In this example, Urban Eyes is attached to a robot, which places the sensors against a wall. A laptop computer displays (inset) an overhead view of rudimentary moving figures on the other side of the wall.

A Lawrence Livermore protective force officer holds a riot shield that has been modified to include antennas for the radar camera array. When the shield is fully functional, the officer will be able to see through the shield and view a display of real-time radar images of objects or humans concealed by walls or smoke.

Cooperative ultrawideband radios can perform long-range communications without being intercepted, a drawback of current military radios. In this artist's conception, communications from all soldiers and air assets can be coordinated so that the transmitted signals are detected and received at only one location—the command station at upper left.

MIR to the Ball Game

The MIR research team continues to develop prototypes that will contribute to national defense and homeland security. There seems to be no end to new applications, especially those in the commercial sector. For example, Northeastern University professor Carey Rappaport recently asked his class for their ideas. One suggestion from a baseball fan was a handheld device that umpires could use to quickly check for corked bats.

It's safe to say we're seeing just the beginning of micropower impulse radar and radio products and the dawn of the age of ultrawideband. In particular, says Azevedo, the future looks bright for powerful arrays of MIR sensors and radios.

—Arnie Heller

Key Words: High-Performance Electromagnetic Roadway Mapping and Evaluation System (HERMES) Bridge Inspector, micropower impulse radar (MIR), narrowband, ultrawideband (UWB).

For further information contact Steve Azevedo (925) 422-8538 (azevedo3@llnl.gov).