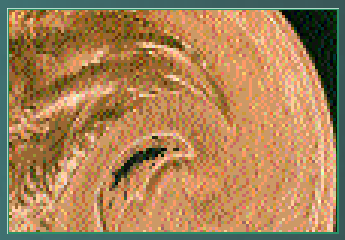
SENSORS AND RELATED TECHNOLOGY



Sensors are becoming essential for today's commercial products, which must have increasingly sophisticated capabilities. Automobiles need crash sensors to detect a car's deceleration and deploy the air bag long before the driver and passenger move toward the dashboard. Videocameras rely on motion sensors to help reduce jitter and stabilize picturetaking. And in security cameras, infrared sensors allow the detection of heat patterns given off by the human body in nighttime conditions. Advanced sensor technology has allowed U.S. companies to develop new commercial products that can make a significant contribution to our Nation's economy.

Today's Market

The 1993 U.S. sensor market reached $4 billion, and it is expected to grow significantly by the year 2000. The worldwide sensor market was $7 billion in 1993 and, like the U.S. sensor market, will grow substantially by the year 2000, possibly reaching $12.7 billion. One of the largest segments of the worldwide sensor market is passenger car sensors, whose share has grown from $2.63 billion in 1991 to $4.7 billion in 1996. In 1997, 47 million sensors are expected to be installed worldwide, with a large portion in the United States.[1]

Tomorrow's Opportunity

BMDO has funded some of the most innovative sensor research and development for its ballistic missile defense systems. As one of the first programs to be implemented by BMDO, sensor activities have focused on improving sensor materials and developing innovative approaches to track multiple targets with multiple sensors in a noisy environment. Developers, in turn, have converted their BMDO sensor products to such commercial uses as astronomic, automotive, and environmental applications. The following section describes a few examples of the commercialization activities of BMDO-funded companies.

---

[1]All marketing figures cited from the staff of *Sensors*.

Can You Imagine . . .

. . . a low-cost, digital accelerometer that improves the performance of triggering devices for automobile air bags.

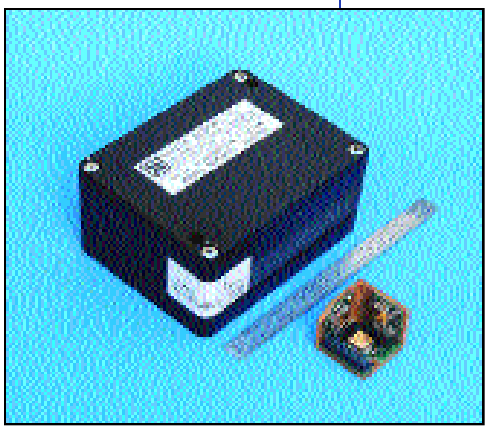
ACCELEROMETERS FIND A HOME IN AUTO AIR BAGS

CHRYSLER USES THESE ACCELEROMETERS FOR AIR BAG TRIGGERS IN FIVE CAR MODELS.

Although the seat belt is the first line of defense in a car accident, air bag systems offer additional protection during frontal impacts of sufficient force. As an integral part of car safety, air bags continually undergo improvements to provide state-of-the-art protection for drivers and passengers.

Until about two years ago, "ball-and-tube" devices triggered most air bags. A collision jolted a ball that traveled down a tube to activate an electrical signal, triggering the air bag. However, a light-impact collision sometimes caused the device's mechanics to inflate unnecessarily or prevented the air bag from working later in a high-impact collision.

A low-cost digital accelerometer from Silicon Designs, Inc. (Issaquah, WA), overcomes these problems. This miniature accelerometer forms the basis of a crash sensor that is superior to the mechanical devices found in previous air bag designs. It rejects certain patterns of vibration, reducing the chance of unnecessary inflation or system malfunction. Silicon Designs has signed a licensing agreement with TRW, Inc., which sells the accelerometers to a large percentage of the automotive industry. Today, Chrysler uses these accelerometers in five car models.



■ Silicon Designs' data acquisition system, pictured above, uses several miniature accelerometers, and has been used in automotive suspension testing.

The accelerometer's other uses include motion detection, active suspension, and aircraft flight control. For example, some racing cars use it to monitor acceleration and cornering, and General Motors Corporation used it in an automotive suspension monitoring system at its proving ground. It may also prove useful in aircraft flight control, because an autopilot system needs an accelerometer to sense changes in the direction (right and left movement) and altitude (up and down movement) of the aircraft.

The radiation-hardened accelerometer was developed with BMDO funding for research in kinetic energy vehicles. Because of its ability to measure changes in velocity, it is well suited to navigate and guide these vehicles, as well as act as the fuzing. In addition, the accelerometer is being put to work in the safe-and-aim device for the BMDO-funded PAC-3, an extension of the Patriot missile family. It costs half as much as current designs for contact fuzes used in the high-speed missiles.

ABOUT THE TECHNOLOGY

The digital accelerometer consists of two chips assembled in a single integrated circuit package: a sensory chip and an integrated electronics chip. The sensory chip contains two micromachined, capacitive sense elements that change their capacitance in response to acceleration. The integrated electronics chip measures the change in capacitance and converts it to a digital pulse output stream. Overall, the accelerometer is low-power (1.0 milliamps at five volts direct current) and operates over a wide temperature range (–55 to +125˚C). It has been designed for high-volume production at low cost.

INFRARED CAMERA SURVEYS FIRE SCENE

Can You Imagine . . .

. . . a highly sensitive, hand-held camera that could help firefighters pinpoint hot spots after forest fires.

Even after a forest fire subsides, firefighters remain alert for hot spots, areas where wood still smolders. These spots can ignite almost instantly if a gust of wind fans them, even slightly. Because they burn with little smoke and no flame, hot spots are difficult to locate.

The Jet Propulsion Laboratory (JPL; Pasadena, CA), in partnership with Amber, developed a highly sensitive, handheld camera that could help firefighters pinpoint hot spots after forest fires. The camera features quantum-well infrared photodetectors (QWIPs) that cover an essential long-wavelength portion of the infrared spectrum. This capability allows the camera to see through smoke and detect lingering hot spots that appear innocuous to the eye. It works effectively in both daytime and nighttime conditions.

Built on gallium arsenide (GaAs) substrates, QWIPs are tiny structures that are extremely sensitive to heat radiation. GaAs-based QWIPs are easier to manufacture than conventional mercury long-wavelength infrared detectors, which can have low yields and high costs. The QWIP cameras' cost should drop below that of competing infrared cameras as the technology matures.

In its debut as a fire-observing device, JPL's camera helped a news crew from KCAL-TV in Los Angeles cover the dramatic Malibu fires in October 1996. The camera hopped a flight on the station's news helicopter, allowing the crew and television audience to get a unique perspective on the fires. It enabled the station to transmit live images of the hot spots by detecting their infrared heat patterns.

JPL'S CAMERA HELPED A LOS ANGELES TELEVISION NEWS CREW GET A UNIQUE PERSPECTIVE ON FIRES THAT RACED THROUGH MALIBU, CALIFORNIA.

Other potential applications of the technology range from the prosaic to the provocative. In the medical arena, by sensing a change in the heat pattern of the patient's blood, the camera could enable doctors to detect tumors close to a patient's skin. By providing a visual image of airport runways in bad weather conditions, it could help pilots to make more precise landings. Pollution monitoring, weather detection, law enforcement, and search-and-rescue operations may also benefit from JPL's technology.

■ Pictured above is the first portable QWIP camera, which uses a 256 x 256 focal plane array tuned to detect infrared radiation in the 8- to 9-micron wavelength range.

NASA- and BMDO-sponsored programs funded JPL's QWIP research. NASA may use the technology for observation satellites, while BMDO will use it to study the phenomenology of missile plumes. In a recent proposal to BMDO, Amber has proposed to build and sell 15 QWIP-based infrared cameras to explore potential research opportunities. In addition, a QWIP-based camera is being considered for use on a second Clementine satellite mission.

ABOUT THE TECHNOLOGY

A quantum well is a microscopic "trap" for an electron inside a transparent solid medium. When exposed to radiation of the appropriate wavelength, the electron can be liberated, producing an electric current. Many quantum wells in a pixel can be used to detect infrared light with a total current proportional to the amount of light hitting the pixel.

The QWIP camera uses a 256 x 256 focal plane array tuned to detect infrared radiation in the 8- to 9-micron wavelength range. It contains a Stirling cooler, a closed-cycle refrigerator about the size of a fist. The small motor circulates a gas to cool the array from room temperature to very low temperatures, about –343˚F, in 10 minutes. The camera weighs just 10 pounds, and it measures about 4.5 inches wide, 10.5 inches deep, and 7 inches high. The camera's current prototype plugs into a 110-volt wall socket for power, although battery power can make it portable.

Can You Imagine . . .

. . . a calibration-free thermometer that may help fossil-fuel power plants protect boiler tubes and other costly equipment from overheating.

NEW SENSOR TAKES THE HEAT IN UTILITY APPLICATIONS

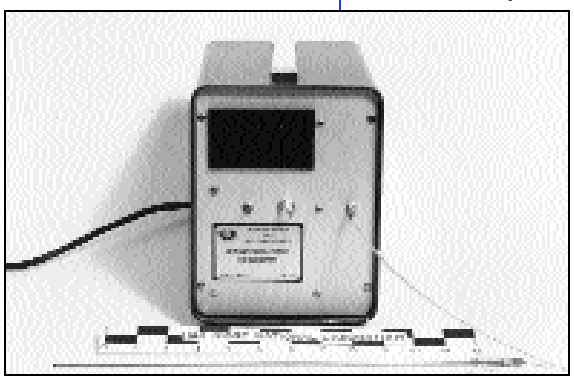
THE COMMERCIALIZATION OF THE JOHNSON NOISE THERMOMETER IS CURRENTLY IN NEGOTIATIONS.

Sensors are perhaps some of the oldest equipment in today's fossil-fuel power plants. As a result, they do not accurately provide the data required for either efficient plant operation or early detection of equipment failure. In power plant boiler tubes, for example, the reliability of resistance temperature detectors (RTDs) decreases when steam temperatures rise above 500˚C. At these temperatures, boiler tubes may explode, requiring costly repairs and plant downtime.

To prevent boiler tubes from overheating, plant personnel need a better way to verify RTD temperature readings. In cooperation with the Electric Power Research Institute (EPRI; Palo Alto, CA), researchers at Oak Ridge National Laboratory (ORNL; Oak Ridge, TN) developed a simple device called the Johnson Noise Thermometer (JNT). Originally developed to monitor coolant temperatures up to 1,100˚C, the JNT was intended for use on a space-based nuclear reactor jointly funded by BMDO, NASA, and the U.S. Department of Energy.

The JNT can measure temperatures up to 1,100˚C over long periods with an accuracy of about 1 percent. Because the JNT can maintain this level of accuracy indefinitely, it eliminates the need for expensive recalibration or replacement of conventional thermometers. Other thermometers, susceptible to drift, provide less accurate temperature measurements at high temperatures.

The JNT's accuracy over long periods at high temperatures makes it attractive for verifying the accuracy of RTDs in fossil-fuel and nuclear power plants. To demonstrate this technology, ORNL tested several JNT prototypes at the Tennessee Valley Authority's Kingston steam plant. In these tests, the devices successfully identified when existing RTDs drifted.



■ Pictured above is an industrial prototype of the JNT. In a demonstration at a fossil-fuel utility plant, this device monitored furnace temperature.

EPRI, which funded the tests, is negotiating the commercialization of JNT technology, but must still address shielding material and packaging requirements, among other issues. It has already found one utility to support this research and continues to look for others.

Power plants could also use the JNT to generate power more cost-effectively. Higher temperatures and pressures increase the efficiency of a plant's turbines, and the JNT can help plant personnel monitor such temperatures. Other uses for the technology may include unattended temperature recording and monitoring, as well as controlling chemical, ceramic, metallurgy, and petroleum processes.

ABOUT THE TECHNOLOGY

The JNT operates on the principle that any electrical conductor (metal, semiconductor, or resistor) produces random electrical signal oscillations because of thermal vibrations in the material structure. For alternating current signals in the 10 kHz range and higher, Johnson noise predominates as the internally generated noise component, varying proportionally with the total resistance of the circuit element and its temperature. Therefore, temperature measurement is possible as long as the resistance is known. Unlike other RTDs, however, the JNT does not require the relationship between temperature and resistance, because it works regardless of the material. It is particularly attractive for applications where long-term stability and calibration-free operation are critical.

VIBRATION SENSOR CROSSES THE BRIDGE TO STRUCTURAL APPLICATIONS

Can You Imagine . . .

. . . a vibration sensor that can help transportation authorities determine when highway bridges need maintenance.

Along with heavy traffic and bad weather conditions, infrequent maintenance takes its toll on America's highway bridges. According to the Federal Highway Administration, one-third of the Nation's bridges are structurally unsound or otherwise deficient, and the monetary backlog for repairs—from deck replacements to complete reconstruction—hovers at about $78 billion.[1]

Squeezed by decreasing Federal funds for bridge maintenance, states and localities sorely need innovative technology that lowers costs and streamlines maintenance and repair of structural problems. With BMDO funding, ERG Systems, Inc. (St. James, NY), has developed a rugged, reliable, low-cost vibration sensor that may advance the technology for monitoring the safety of bridges, a time-consuming and costly job.

The sensor, a fiber-optic light-emitting diode (FO/LED), can measure the vibration of a free-standing structure or of a structure in which it is embedded. Detecting movement photoelectrically through light reflected from a curved or flat surface would allow the sensor to detect problems before severe hazards develop. Continuous monitoring using the sensor and a system to alert transportation officials to schedule preventive maintenance could reduce future repair costs. The extremely compact, lightweight FO/LED can withstand harsh environments—such as the one found on New York City's heavily traveled George Washington Bridge—better than other laser-based vibrometers.

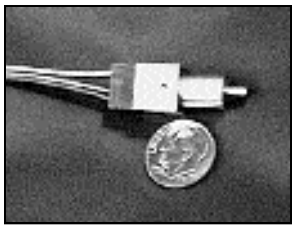
The FO/LED can monitor the structural integrity of aircraft, commercial machinery, building construction, and other types of heavy industry. It also can measure microdisplacements such as those found in engine camshafts of automobiles. In this automotive application, the device could help reduce component wear and improve fuel efficiency.

ERG Systems actually reduced the BMDO SBIR funding it originally requested, thanks to private sector capital and New York State funds. The company's cost-effective sensor, if manufactured in volume, could sell for $40 per unit. Optical Research Associates, a leading distributor for optical equipment and accessories, now provides marketing and sales support for the FO/LED.

OPTICAL RESEARCH ASSOCIATES, A LEADING DISTRIBUTOR FOR OPTICAL EQUIPMENT AND ACCESSORIES, PROVIDES MARKETING AND SALES SUPPORT FOR THE FO/LED TECHNOLOGY.

ABOUT THE TECHNOLOGY

The FO/LED's sealed monolithic housing, with a dual fiber-optic probe, measures less than 3 cm long and less than 2 cm^2. The LED fiber-optic channel produces a constant light output that the external (vibrating) surface reflects into a photodiode input channel. The amount of light the photodiode receives depends on the relative displacement of the external surface. The device senses vibrations through oscillation of the photodiode's output signal voltage.



■ ERG's fiber-optic light-emitting diode, pictured above, can measure the vibration of a free-standing structure or of a structure in which it is embedded.

[1]American Public Works Association. Transportation is America's way of life. World Wide Web at http://www.pubworks.org/roads.html.

Can You Imagine . . .

. . . a family of low-cost, high-volume, production-rate inertial sensors for the automotive industry.

NEW SENSORS TO ENHANCE VEHICLE OPERATION

ROCKWELL AND DRAPER LABORATORY EXPECT THE MINIATURE SENSORS TO PLAY MAJOR ROLES IN AUTOMOTIVE PASSENGER SAFETY AND INTELLIGENT NAVIGATION.

Previously ancillary, but now essential, sensors are involved in nearly every aspect of vehicle operation. Today's sensors keep a close watch on exhaust gas to minimize emissions, on deceleration to deploy air bags quickly in accidents, and on wheel motion to improve the reliability of antilock braking systems. In recent years, the number of sensors per automobile has quadrupled: In 1980, automobiles incorporated 10 to 30 sensors; in 1990, they contained 50 to 100 sensors.[1]

Car makers need new sensor technologies for future vehicle designs. Inertial sensors, for example, play major roles in passenger safety, vehicle dynamic control, and intelligent navigation systems. However, their cost—even when produced in large batches—limits their widespread use in the automotive industry.

Rockwell International (Anaheim, CA) joined forces with researchers at The Charles Stark Draper Laboratory, Inc. (Cambridge, MA), to develop a family of low-cost, high-volume, production-rate inertial sensors for the automotive industry. These sensors will owe much of their existence to Draper Laboratory's work for BMDO, which involved building miniature inertial sensor units to guide ballistic missile interceptors.

Inertial sensors measure rotation and linear acceleration and, in large systems, help guide moving objects or detect unwanted motion. Rockwell and Draper Laboratory see many uses for smaller, low-cost versions of these sensors in the automotive industry. A lateral skid detector, for example, requires sensing uncontrolled sideways movement to trigger a system to re-establish control. Such a device does not exist today, simply because no low-cost instrument accurately measures the kind of angular rate triggered by a skidding or sliding car.

The Silicon Micromachined Angular Rate Sensor, the first product being developed, provides single-axis angular rate data such as yaw, pitch, and roll. It can be used in sensing dynamic vehicle motion to help make antilock brakes safer, increase steering responsiveness, and improve driving comfort. The Rockwell/Draper Laboratory team plans to develop several other products, including gyroscopes and accelerometers for four-wheel steering, automatic braking, skid detection, and collision avoidance. Ultimately, the companies expect to develop a product that provides intelligent control, diagnostic, and navigation functions in a single package.

■ The Silicon Micromachined Angular Rate Sensor, pictured above, provides single-axis angular rate data, such as yaw, pitch, and roll.

ABOUT THE TECHNOLOGY

Rockwell and Draper Laboratory are developing low-cost, miniaturized inertial systems that contain accelerometers, gyroscopes, and information processors in dedicated units. These systems will measure 2 x 2 x 0.05 cm, require less than one milliwatt of power, and be accurate up to 100 degrees per hour. Further development could lead to devices with accuracies as high as 10 degrees per hour, while still keeping costs under $100 per unit. In general, inertial systems tend to drift. For inertial sensing applications, lower drift rates increase unit precision.

Draper will fabricate the sensors using an innovative micromachining process that employs a controlled isotropic chemical etch of silicon to form up to 10,000 devices on a single silicon wafer. This mass production keeps the device portion of the inertial sensor's total cost minimal.

[1]Abachi, Raida. 1996. An overview of automotive sensors. *Sensors*. April, 82–85.

BMDO-FUNDED ALGORITHM ENHANCES ENVIRONMENTAL FORECASTS

Can You Imagine . . .

. . . an algorithm that simplifies data from computers and sensors so the paths of groundwater contaminants can be predicted.

Predicting environmental contamination is important today because groundwater contaminants can leach into the earth's aquifers and then appear in drinking water. At weapons facilities, highly toxic materials for weapons manufacturing and chlorinated hydrocarbons for equipment cleaning pose costly cleanup questions for environmental engineers: Where will contaminants end up next? To what extent is the environment at risk? The answers to such questions can help engineers determine the extent of contamination and the best strategy for effective remediation.

Coleman Research Corporation (Columbia, MD) developed a technology that can predict the paths of groundwater contaminants. The company's technology, Data Fusion Modeling (DFM), helps scientists assess the environmental impact in at-risk sites. Like modern weather-prediction techniques, DFM analyzes vast amounts of computer and sensor inputs, information that normally requires a supercomputer to process. But an algorithm developed for BMDO simplifies the data so that a Unix-based system or high-end personal computer can process them.

CRC'S TECHNOLOGY HAS ALREADY HELPED SCIENTISTS ASSESS THE ENVIRONMENTAL IMPACT IN AT-RISK SITES.

CRC successfully applied its DFM software and services to several hydrogeological projects, such as site characterization and remediation at the Hanford and Savannah River weapons facilities. At the Savannah River weapons site, the software accurately predicted the movement of tritium leaching from a hazardous materials burial ground into the groundwater.

Fossil-fuel power plants can also use aspects of this technology for nonlinear model predictive control (NMPC), a system that predicts the plant's response to control actuators. Simulation results at two of Southern California Edison's El Segundo units demonstrated many of its benefits. For example, the system changed the power output of the simulated plant about six times faster than conventional means, and it produced higher performance and better fuel efficiency. In particular, thermal efficiency improved almost 1 percent, saving the plant roughly $480,000 each year.

■ In addition to its environmental uses, CRC's technology can be used to control plant processes.

In addition to environmental applications, DFM can be used with medical imaging to track electrical activity in the brain. This application of the technology could lead to better treatments for patients with epilepsy. DFM also could apply to spacecraft guidance and control. CRC originally developed the algorithm for a BMDO missile defense system to help computers and sensors track targets and decoys.

ABOUT THE TECHNOLOGY

The CRC algorithm optimizes computer and sensor resources, combining redundant data and reducing the number of calculations that a processing system must handle. Most automated prediction and control systems receive information from many sensors and compare the data from each sensor. This process eliminates faulty data that result from sensor misalignment and random signal variations; however, it produces redundant data that tie up a computer. The CRC algorithm eliminates these redundant data, thus lowering the computational demands on the predictive control system. As a result, a system that previously required supercomputer monitoring can now use a Unix-based workstation or high-end personal computer.