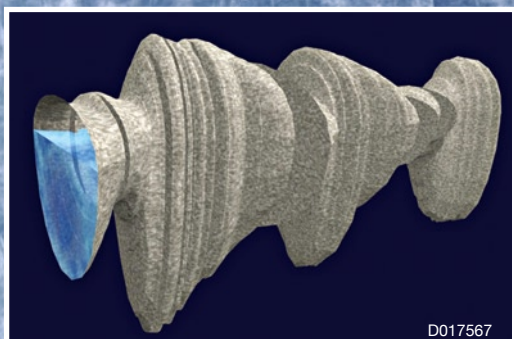


# Groundwater Voyager

An SwRI-developed miniature robot sensor creates a map of submerged caves and channels



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*Neutrally buoyant sensors are designed to ride the current within a flooded underground channel or cave and, using miniature transmitters and receivers, gather information about the shape and morphology of the chamber through which they travel.*

By Ronald T. Green, Ph.D., and Ben Abbott, Ph.D.

**W**hile spelunking and cave diving make for good, if somewhat dangerous, recreational activities, geologists and hydrologists frequently rely on instruments carried

by human divers to generate reliable maps of underwater caverns through which groundwater enters, moves about and then exits from karst limestone aquifers. Information gathered from these dives is collected and analyzed, then generalized to create a reasonable estimate of the size of the cave network, water-bearing capacity, ease of recharge and sensitivity to pollution or contamination.

Aside from the hazard to human safety, exploring aquifers and underwater caverns in this manner is limited in some cases by sheer distance and in others by channel segments that are too narrow to accommodate a human diver.

Some limited information about groundwater behavior can be gained indirectly by means of tracers, such as dyes introduced at a recharge feature and

**R&D Magazine has recognized SwRI's neutrally buoyant sensor technology with its R&D 100 Award, presented annually to the 100 most significant advances in technology. In all, SwRI has won 35 of the awards dating back to 1971.**

then tracked to the place where they emerge at a spring or well. However, to map the actual limestone corridors through which groundwater flows requires a mechanical system that can gather, store and transmit dimensional data as it travels with the groundwater's flow. This requires a system that is small, inexpensive, non-polluting, safe, autonomous, self-powered and able to communicate electronically with receiving equipment once it has emerged.

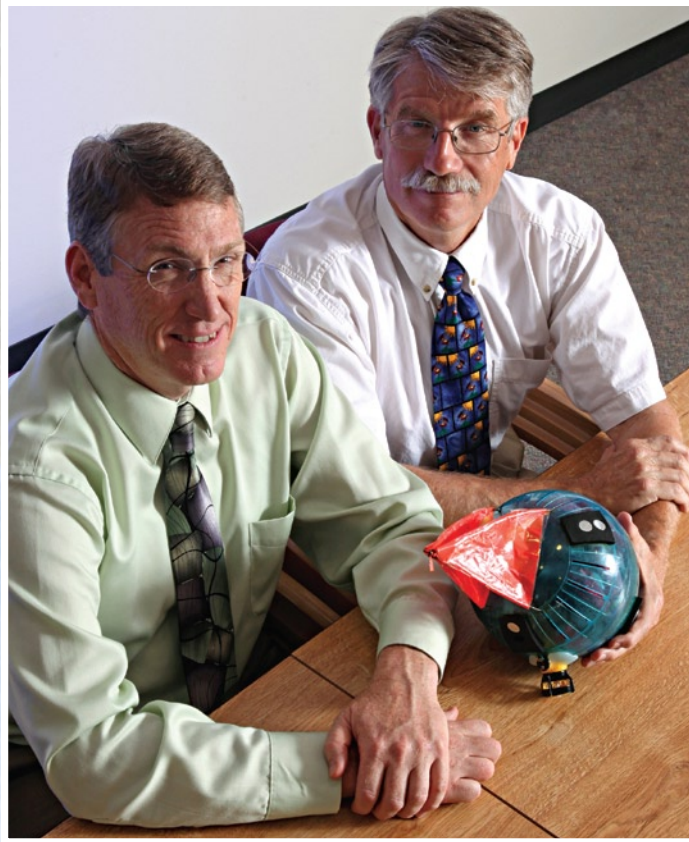
A team of hydrologists and electrical engineers at Southwest Research Institute (SwRI) has developed a neutrally buoyant sensor to remotely characterize the path, dimension and morphology of caves and other underground conduits and cavities. The

patent-pending system was developed under internal funding, and the units were constructed using off-the-shelf components whenever possible to minimize the cost.

Neutrally buoyant sensors, so-called

because they are designed to neither ride on the surface nor sink to the bottom, gather dimensional and directional data via an array of ultrasound sensors relative to a compass, or, in this case, a three-axis magnetometer.

The sensor also is equipped with a propulsion system to move it through the cave and avoid becoming hung on an obstacle or trapped in an eddy. Information gathered during travel is collected at the conclusion of the voyage, either by retrieving the sensor and physically transferring the data or by remotely transferring the data to a static sensor tethered to the ground surface close enough to allow remote communication. Spatial scale is determined by comparing ultrasound measurements taken of a stationary object



*Dr. Ben Abbott, left, is an Institute engineer in the Communications and Embedded Systems Department of the Automation and Data Systems Division. He has extensive expertise in wireless sensor network technologies and has participated in development of several network-centric data acquisition, recording and telemetry systems. Dr. Ronald T. Green, right, is a hydrogeologist with additional expertise in geology and geophysics. He is an Institute scientist in the Department of Earth, Material and Planetary Sciences within SwRI's Geosciences and Engineering Division.*

located near dams or beneath roads and buildings. In 2004, SwRI scientists and engineers began an initiative to develop tools for enhanced characterization and representation of flow through karst aquifers. A new MODFLOW computer code variant, MODFLOW-DCM V2.0, was created as part of this project. MODFLOW-DCM models groundwa-

ter flow through conduits within porous media. Three karst aquifers have been modeled using MODFLOW-DCM: the Barton Springs segment of the Edwards Aquifer in South Central Texas, the Santa Fe River Sink/Rise system of the Floridan Aquifer in North Central Florida, and the Blue Spring system of the Floridan Aquifer in Volusia County in Northeast Florida.

regime (that is, whether it is laminar or turbulent) provide additional meaningful model calibration targets to augment the conventional targets of hydraulic head and spring discharge. Methods such as tracer tests or mapping by cave divers are of limited applicability, and attempts to infer conduit locations using geologic features such as fracture lineaments and sinkholes have not been encouraging. Scientists needed new tools to characterize conduits to improve the chances of success using karst aquifer flow modeling tools.

#### **Developing a new sensor**

The SwRI team's initial objective was to develop and demonstrate an inexpensive sensor designed for placement in conduits up-gradient from spring orifices, with deployment either through sinkholes or wells that intersect karst conduits. The sensors were instrumented to record velocity, path traveled and conduit dimensions as they flow along. Data would be extracted manually from the sensors, so they had to be retrieved at the spring orifices.

Prototypes were tested under various laboratory and field settings to demonstrate and assess their capabilities. Field

by multiple sensors at multiple times. A sufficient number of measurements can uniquely determine the spatial scale and morphology of the cave interior.

Existing systems can perform some of the functions of the SwRI-developed sensor using a profiling sonar unit or a laser-based range measurement tool, but they are constrained by relatively high cost, excessive size or a need to be deployed through a borehole. The SwRI-developed remote sensors are unique in their ability to access small caves and conduit passageways. Their low cost also makes them relatively expendable. Many can be deployed, yet a survey is a success if information is retrieved from only one sensor. Finally, the resolution of mapping is superior to that typically provided by cave divers because of the richness of data collected by multiple ultrasound sensors.

#### **The science of cave water flow**

Besides its importance to water-resource managers, knowledge of water flow through caves and conduits, and the size and shape of the voids, is also important when karst features are

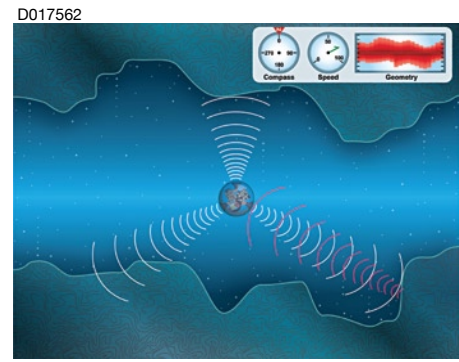
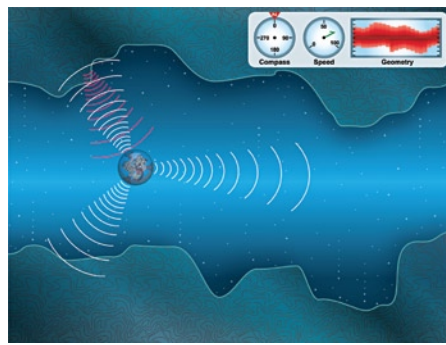
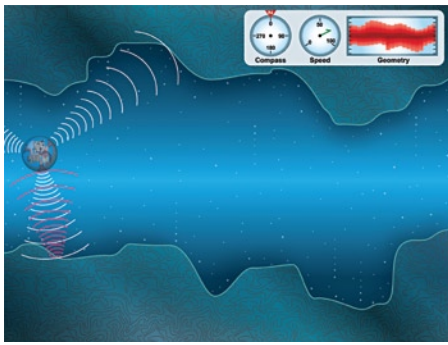
ter flow through conduits within porous media. Three karst aquifers have been modeled using MODFLOW-DCM: the Barton Springs segment of the Edwards Aquifer in South Central Texas, the Santa Fe River Sink/Rise system of the Floridan Aquifer in North Central Florida, and the Blue Spring system of the Floridan Aquifer in Volusia County in Northeast Florida.

Efficient and effective application of MODFLOW-DCM to karst aquifers hinges on identifying conduit location and morphology characterization. In particular, reducing uncertainty in conduit location and properties such as geometry and size will improve the prospect that the MODFLOW-DCM model will successfully simulate karst aquifer flow regimes. Measurements of groundwater flow velocity and flow

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*Different sizes of prototype sensors were evaluated, and a number of modifications, such as fins and propellers, were added to improve performance or address deficiencies.*



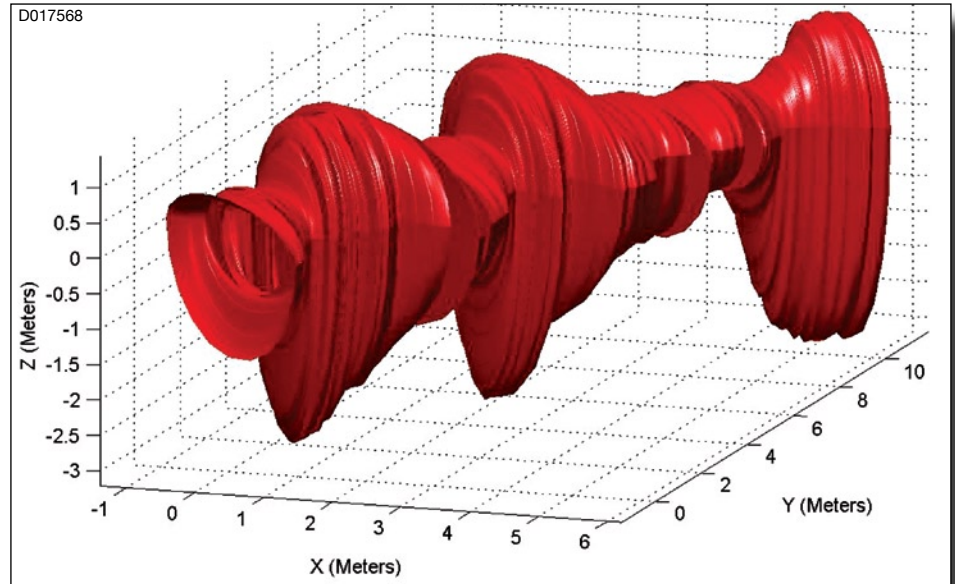
Signals transmitted from a sensor drifting through the flooded cave are transmitted in three directions, and the return signals are processed and stored for analysis following recovery of the sensor after it emerges from the cave (right). The resulting three-dimensional graphic (inset) represents the size and morphology of the cave segment's interior walls as determined by processing the sensor's stored data.

testing was performed at the Spring Creek Cave and Honey Creek Cave near San Antonio. Several sizes and versions of sensors were employed to address various technological challenges encountered during development and deployment. Sensor sizes varied from 4 centimeters in diameter (golf ball size) to 8 cm (softball size) and 22 cm (small soccer ball size). For proof-of-concept, there was no effort to miniaturize the sensor components.

Development efforts focused on two functionalities: an instrumentation package capable of measuring key attributes of a conduit in a karst aquifer; and the ability to negotiate through the flow regime of a fully saturated conduit under natural conditions. The first functionality was straightforward. Meeting the second functionality, however, presented more challenges than initially anticipated. The prototype design evolved during the project as the SwRI team addressed unanticipated challenges, such as how to keep the sensor in the main flow channel of a semi-saturated conduit.

### Instrumentation functionality

The prototype sensors were assembled with commercially available components. The need to characterize conduit geometry, flow path and flow rate led to a design that included ultrasound sensors, dual-axis magnetometers and accelerometers. The magnetometers enable the sensor to gauge its pointing direction relative to magnetic North, and the accelerometer enables the determination of



motion dynamics as the sensor travels through a conduit. The most important aspect of the design, however, was related to the use of ultrasonic transducers to characterize conduit geometry and, ultimately, velocity.

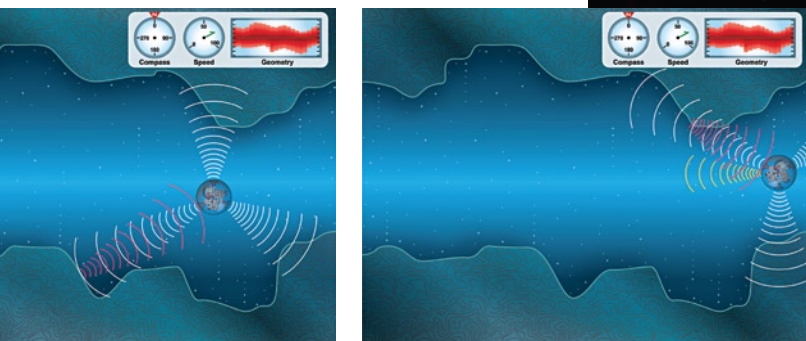
The SwRI team decided to use six pairs of ultrasonic transducers, equally positioned around the sensor enclosure, to transmit sonar "pings" outward to the conduit walls. Each pair consisted of a transmitter that sent out ultrasound pulses normal to the sensor node, and a receiver that recorded the reflected ultrasound pulse. Accurate distances to the surrounding conduit features would be determined using the time of arrival of the reflected pulses. This sonar ranging would not only accurately characterize the conduit geometry but also detect wall features that can be used for velocity calculations. Post-processing of data from all components enables calculation of real-time velocity along the conduit path as well as the shape and size of the conduit.

An initial, non-submersible version of a sensor prototype was evaluated in a building hallway to demonstrate that the

application was functional in an open-air environment. After successful hallway tests, a submersible prototype was constructed using off-the-shelf electronic components and a printed circuit board for the main circuitry. Six pairs of waterproof ultrasonic sensors were connected to the board via coaxial cabling. For ease of access, the SwRI team mounted the assembly inside a 22-cm, clear-plastic ball. For later deployments, a motorized propeller and control circuitry were fitted to the ball for navigating conduit terrain.

### Flow dynamic functionality

Developing the sensor's flow functionality was an iterative process in which new features were added to succeeding generations of prototypes deployed into Spring Creek Cave. First-generation spherical prototypes tended to float out of the main flow channel and stall at the cave walls due to a flow vector pattern called Poiseuille's flow. This pattern, normally observed in pipelines, exhibits the greatest flow stream in the center and no flow at the walls. This initial batch of



sensors traveled no more than 30 meters in two days after being deployed.

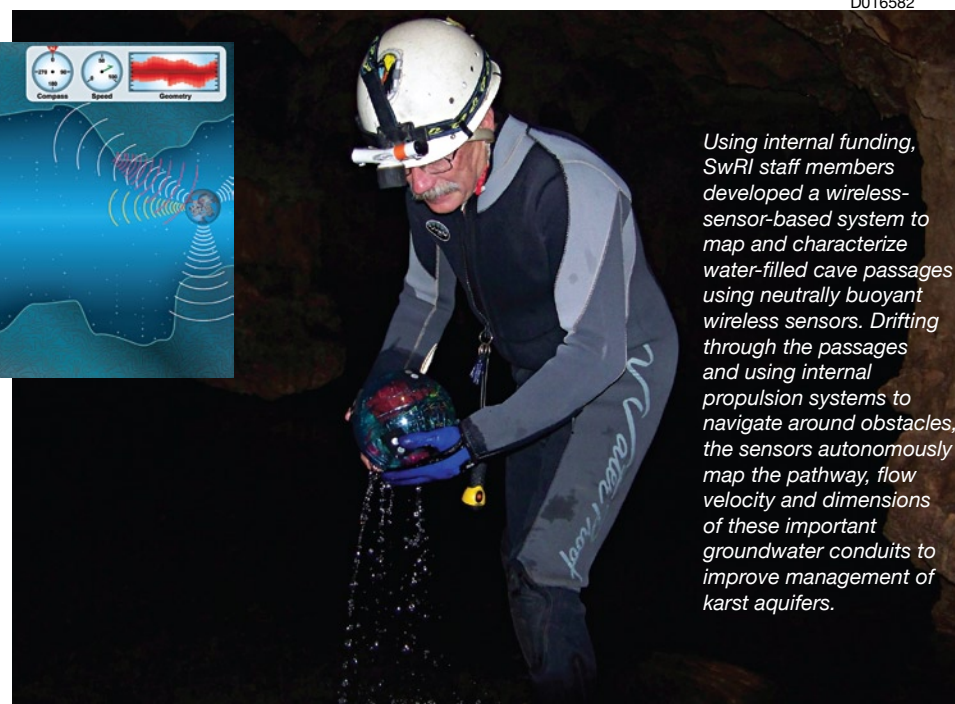
The SwRI team attached fins to the sensors to avoid this stalling tendency and added bottom weights to maintain a constant attitude and prevent rotation. These proved effective in reducing the tendency to rotate out of the flow field.

Meanwhile, the importance of neutral buoyancy became apparent as sensors that floated on the surface tended to snag on stalactites and other cave features and those that sank to the cave floor departed from the flow channel and stopped moving. In response, the SwRI team attached the propeller mechanism. Set at an angle near the bottom of each sensor shell, the propeller was programmed to engage at preset intervals to first provide forward rotation to drive the sensor downward, then reverse rotation to drive the sensor upward to avoid becoming embedded in mud or silt on the cave floor.

Three of the propeller-equipped sensors were deployed at various locations near the cave mouth to observe whether the new functionality would enable them to navigate past restrictions in the flow regime. They performed well enough to collect ultrasound, magnetometer and accelerometer data for a segment of the cave.

### Data analysis

Data from these prototypes were collected to ascertain the ability to remotely characterize a wet cave. Sonar and magnetometer data proved more useful than accelerometer data. The first step in reducing sonar data was to calculate the sensor velocity along the conduit flow path. This consisted of cross-correlating the front and rear sonar signals on both sides of the sensor to determine the relative sample delays between detected features. A correlation was made for each sample over time windows. Centering



*Using internal funding, SwRI staff members developed a wireless-sensor-based system to map and characterize water-filled cave passages using neutrally buoyant wireless sensors. Drifting through the passages and using internal propulsion systems to navigate around obstacles, the sensors autonomously map the pathway, flow velocity and dimensions of these important groundwater conduits to improve management of karst aquifers.*

the delay window around each sample, the distance window was calculated using the front sonar reading for the first sample of the window and the rear sonar reading for the last sample of the window.

Dividing the distance by the delay, the velocity at each sample was determined. The first and last windows of the sample were smoothed to the average velocity of the nearest known sample. For each sample, the front and rear sonar readings were used to calculate the normal distances to each side of the conduit. The top and bottom samples provided the distances to the ceiling and floor of the conduit, respectively. Preliminary distances were converted to final distances using calibrated values derived as multiplication factors to correlate water travel times to distance. Assuming a smooth transition arch around the conduit, additional distances were interpolated around the conduit geometry.

### Future applications

Future generations of sensors might be equipped with additional instrumentation to collect environmental data, such as temperature, gas composition and water chemistry. They also could be miniaturized to a diameter as small as 2 cm to 5 cm. Meanwhile, the propulsion system might be replaced with a more sophisti-

cated buoyancy system that would activate only as needed.

Neutrally buoyant sensors could be used in applications other than caves, such as pipes that are limited in diameter or whose interior size has been reduced due to sediment deposition or corrosion; sanitary sewers in older cities where accurate maps and records are not available and whose condition precludes safe human access; or geotechnical settings, such as mines or conduits that are not safe for manned entry. ♦

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