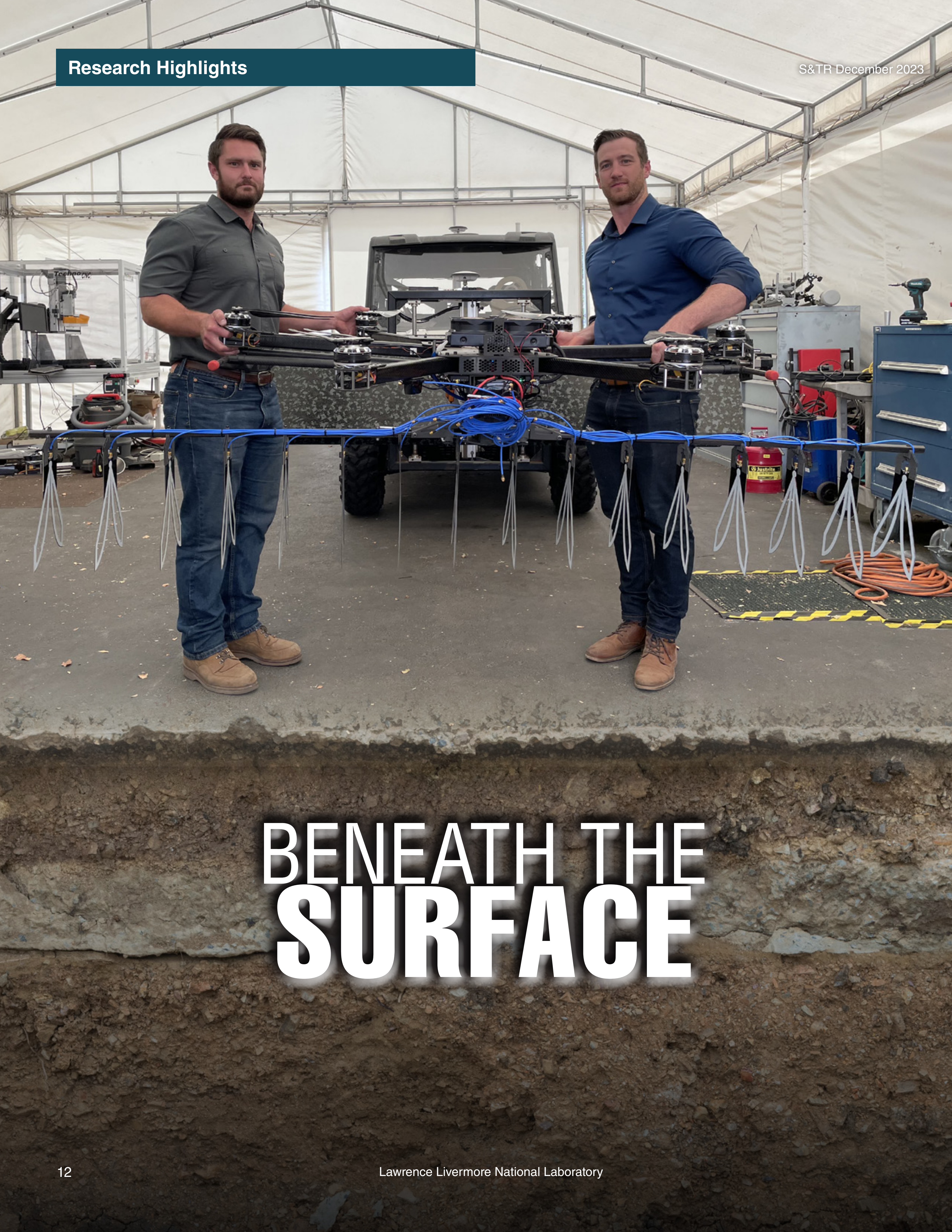


BENEATH THE SURFACE

HISTORICALLY, few field-ready methods have existed for detecting landmines or explosives that lay concealed underground, leaving military personnel to face potentially treacherous terrain. Today, Multistatic Imaging Radar (MiRadar), a ground-penetrating radar (GPR) technology developed at Lawrence Livermore, can search large areas for buried threats before military personnel are deployed. Designed for the U.S. military, MiRadar promises to significantly impact defense, transportation, emergency response, and mine clearance efforts, leading to a paradigm shift in the way subsurface and buried explosives are found.

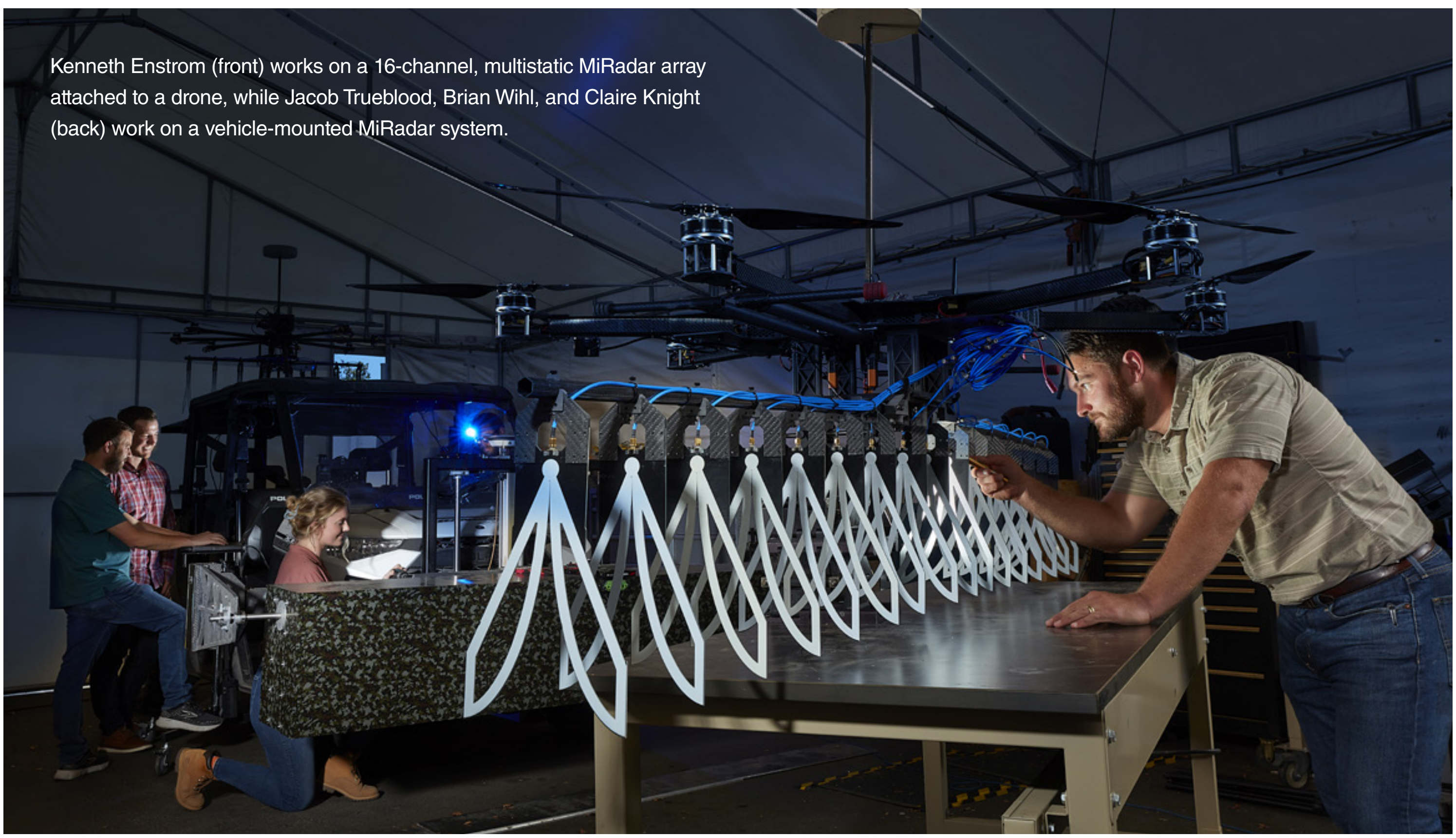
During operation, the MiRadar system transmits instantaneous wideband radio waves to penetrate substrates such as sand, soil, and concrete and then processes returned waves to detect buried objects and potential dangers in real time using 3D imaging. Lawrence Livermore's Defense Systems program leader Reg Beer says, "When we first started developing MiRadar, an American soldier using vehicle-mounted GPR had to hope that a sensor didn't trigger the very explosives that the GPR was trying to detect. We have since redesigned this technology and downsized it to fit on a small drone, helping to identify hazards ahead of time and keeping civilians and military personnel safe."

Building On the Past

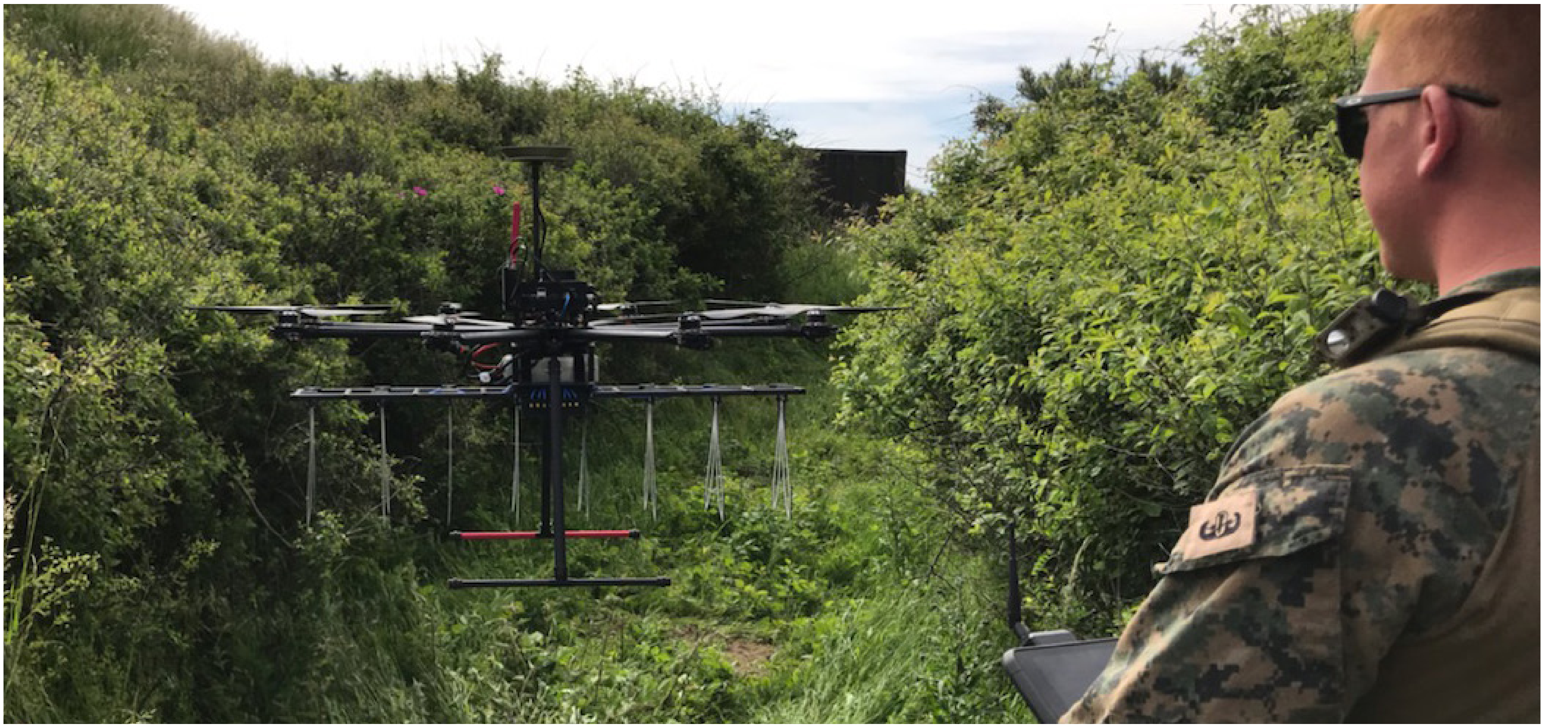
MiRadar follows the theoretical principles used earlier in GPR technologies, such as micropower impulse radar (MIR), a patented Lawrence Livermore invention developed in 1993. The Federal Highway Administration applied MIR to bridge inspection in the 1990s. At that time, the technology used a two-dimensional array to collect data for subsequent processing, resulting in 2D images that required significant post-processing and made real-time results impossible.

Today, MiRadar uses a linear, one-dimensional array of transceiver antennas, aiding in faster and safer explosive detection. MiRadar combines advanced imaging techniques such as multistatic radar imaging to enable any combination of antennas to act as receivers or transmitters. In recent years, the team has extended MiRadar's array from 8 to 16 transceiver channels. Mechanical engineering generalist Kenneth Enstrom explains, "The 8 channel was a fixed design, but actuating the array made it possible to incorporate 16 channels. This way, when the drone is grounded the arrays collapse under it, and when the drone takes off, the arrays expand and swing out like butterfly wings."

As the transceiver antennas work together searching for buried threats, they rapidly emit wideband impulses that radiate and



Kenneth Enstrom (front) works on a 16-channel, multistatic MiRadar array attached to a drone, while Jacob Trueblood, Brian Wihl, and Claire Knight (back) work on a vehicle-mounted MiRadar system.



penetrate the ground. The antennas in receive mode then feed their returns, or findings, into reconstruction algorithms that apply machine-learning technology to the data to convert and interpret the raw data into high-resolution, 3D images of the subsurface area. Instead of producing raw data that require expert interpretation, as MIR did, MiRadar produces a colored image with spatial shape—displaying everything in its respective place, in real time. For this reason, MiRadar requires minimal user training as it automatically reconstructs acquired data into easy-to-interpret images.

The resulting images are similar to medical computerized tomography scans and ultrasound images used to generate a planar image of the body's interior. MiRadar project lead Brian Wihl explains, "We have taken an imaging approach, transforming raw data into real-time, easy-to-read 3D images that allow for automated detection of buried hazards with minimal false alarms or reports." The team's approach has aided in MiRadar's ability to quickly deploy and locate buried hazards, making it the first camera-style system to provide a 3D projection of underground objects—reporting their size, depth, and in some cases material composition.

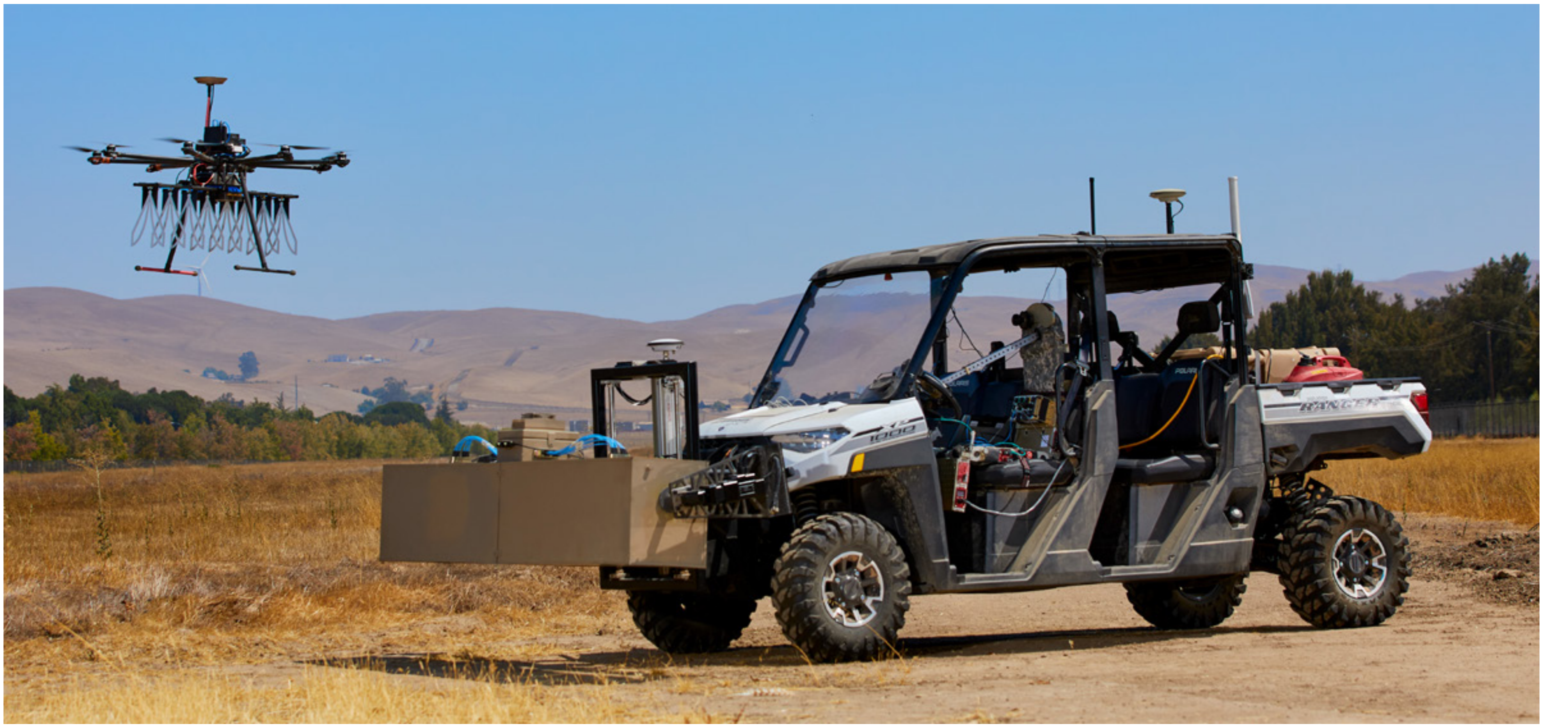
From Design to Prototype

In addition to improving the imaging capabilities, MiRadar has been significantly reduced in size, weight, and power, enabling operation on compact drones. MiRadar currently weighs in at less than two kilograms, nearly 100 times less than earlier array systems. The process of shrinking GPR technology is comparable to that of cameras and cell phones—which have been made smaller over the years by combining functionality into ever more integrated packages—until the required components fit into a space small enough to, in this case, be attached to a small, uncrewed aircraft system.

Warfighters who have tested MiRadar firsthand report that it is an intuitive and powerful tool for military route clearance as well as humanitarian efforts underway to detect hidden or long-forgotten landmines and explosives in war-torn areas.

Prior to being redesigned, the original, vehicle-mounted MiRadar had to be manually moved up and down, allowing the system to be close to the ground during operation. The team automated this process so that MiRadar can move with the click of a button. Machine learning also plays a large role, taking in real-time information and automatically adjusting the drone's flight path without delay or the need for a human operator. Another part of the redesign included testing and integrating a new GPS solution into the system to more accurately track the radar's and other sensors' proximity to the ground. "One of the questions we had to answer was, 'How will we integrate the different sensors and tell each of them where they are and how far they are from the GPS?'" says electrical engineer Jacob Trueblood. "Ultimately, this work is about solving problems and building something that has never been done before."

The MiRadar team has been dedicated to building the whole system from scratch at Livermore, from the radar to the individual drone components, such as the propellers, to the imaging software code. The Laboratory's 3D printing capabilities and on-site machine shops have helped streamline



An eight-channel multistatic array MiRadar system mounted on a drone flies ahead of a traditional vehicle-mounted ground penetrating radar at Livermore's outdoor testing field.

the manufacturing process and rapidly prototype and test new designs. To date, the team has developed and tested a hybrid-electric drone that can run on battery power and gasoline, and they have confirmed the possibility to create a fully 3D-printed platform with the same flight time and payload capability as more costly off-the-shelf components.

"What makes this project unique is our ability to design, print, and test a part in the same day, make modifications, and repeat as needed," says mechanical engineer Claire Knight. "Everything must be designed with 'lightweight' in mind—finding a happy medium between making components robust but still light enough for a drone to carry."

Testing Makes Perfect

When evaluating new designs, the team uses Livermore's Robotics Integration Laboratory, an outdoor, 743-square-meter enclosure that serves as a testing field for autonomous drones, vehicles, and robots. "Teamwork is a huge part of this project," says Knight. "Having the opportunity to bring our cross-disciplinary team together on test days and interact with users is really important and motivating and makes the work we are doing more tangible."

A big piece of this project is doing field work and interacting with military personnel, who are the end-users of this technology, gaining their user insights and perspectives. In fact, warfighters who have tested MiRadar firsthand report that it is an intuitive and powerful tool for military route clearance as well as humanitarian efforts currently underway to detect hidden or long-forgotten landmines and explosives in war-torn areas.

Wihl says, "Most of our field-testing requests come from military bases and other government agencies. We see an amazing number of use cases and scenarios from beaches to deserts, flat to hilly terrain, and dry to humid conditions." Beer adds, "Testing in different regions shows us what works and what doesn't. This process is especially important since GPR radiates waves through the soil, and dielectric properties vary around the world."

Such a technology offers opportunities for commercial use in applications to understand subsurface structures, locate conduits and gas lines under concrete, and assist construction companies in mapping areas before digging, preventing workers from hitting buried pipelines or other objects. In some cases, multiple MiRadar systems can run at once to find objects even faster. "We try to consider every request to use MiRadar," says Beer. "Every test and every new application help us fine tune and assess the performance of this system."

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Key Words: 3D imaging, drone, ground-penetrating radar (GPR), machine learning, micropower impulse radar (MIR), Multistatic Imaging Radar (MiRadar).

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