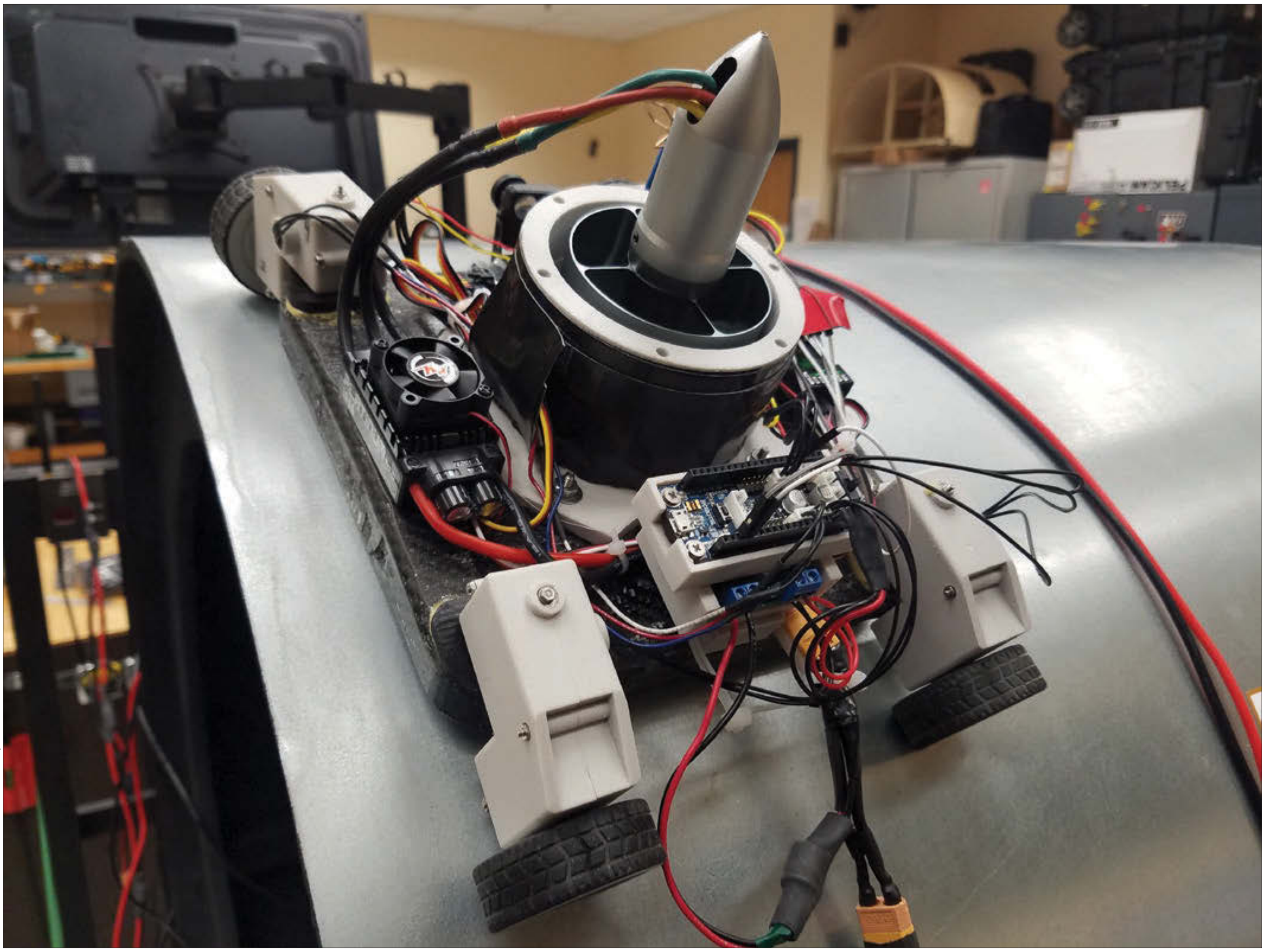

Photo: Florida International University

Fig. 1: Bench-scale testing of the external pipe crawler.

Robotics R&D for legacy nuclear waste

University researchers and STEM students are developing robotics systems for the DOE's nuclear complex.

By Leonel E. Lagos and Dwayne E. McDaniel

The mission of the U.S. Department of Energy's Office of Environmental Management (EM) is to address the environmental legacy of five decades of Cold War–era nuclear weapons production and government-sponsored nuclear energy research. This legacy includes some of the world's most dangerous radioactive sites, with large amounts of radioactive wastes, spent nuclear fuel, excess plutonium and uranium, thousands of contaminated facilities, and contaminated soil and groundwater. Created in 1989, EM has the responsibility for completing the cleanup of this Cold War legacy and managing the remaining nuclear materials. As the largest environmental cleanup program in the world, EM has been charged with cleaning up 107 sites across the country, the total square mileage of which is equal to that of Rhode Island and Delaware combined. EM has made substantial progress in nearly every area of nuclear waste cleanup and has completed cleanup at 91 of these sites[1].

Since 1995, Florida International University's (FIU) Applied Research Center has contributed to the EM mission by conducting applied research in the

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areas of high-level waste management; deactivation and decommissioning; soil and groundwater; robotics; information technology; and science, technology, engineering, and math (STEM) education and training. The descriptions and motivations for the development of the various robotic mechanisms being developed at FIU in support of EM environmental remediation efforts follow.

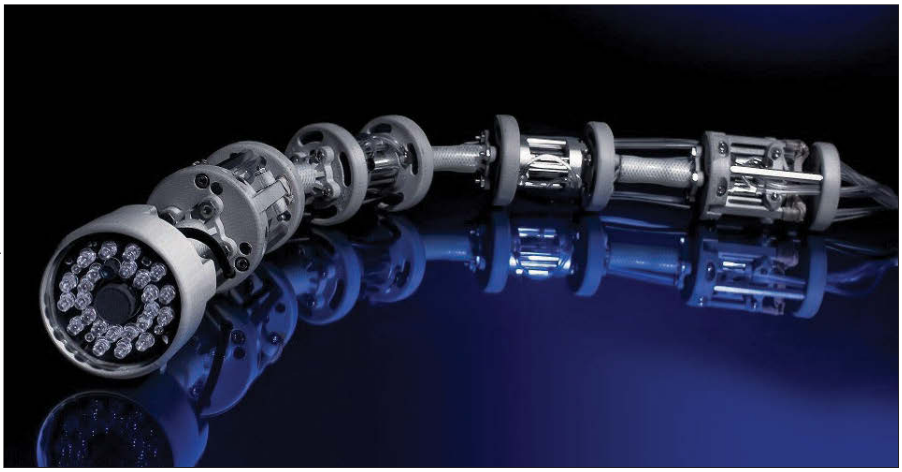

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Fig. 2: 3- and 4-inch internal pipe crawler.

External pipe crawler

FIU is developing a robotic crawler that can aid in assessing the structural integrity of the H Canyon exhaust tunnel at the Savannah River Site. The concrete walls of the tunnel have degraded due to radioactive and acidic fumes exhausted through the tunnel for over 60 years. This research is being conducted in conjunction with the University of Florida and the University of Texas at Austin, which through the DOE's Nuclear Energy University Program are developing the robotic platform that will house and deploy the robotic crawler and provide a means to inspect the tunnel.

The crawler utilizes an electronic ducted fan to create forces that allow the system to navigate around the entire circumference of a 3-foot-diameter aluminum duct housed inside the exhaust tunnel. The crawler must be able to navigate around the duct and view the concrete walls, which otherwise can't be inspected, using the mobile platform being developed by our collaborators.

The chassis of the crawler is designed to match the geometry of the duct in order to maintain a consistent separation distance between the underside of the crawler chassis and the surface of the duct (Fig. 1). Since the duct is cylindrical in shape, the crawler is designed to make use of a two-DOF (degrees of freedom) motor mount setup at each of the four wheels. This allows the crawler to move to any point on the surface of the duct by moving laterally and then radially, or vice versa, until the desired location is reached.

The crawler can be equipped with a suite of sensors to assist in the characterization of the conditions inside the tunnel, including radiation, thermal, and humidity sensors. Utilizing an onboard camera, engineers will be able to visually assess the damage to the walls behind the duct. The final prototype of the crawler will be able to perform either semiautonomous or autonomous tasks, with the goal of being a multifunctional system that can be used to aid in the structural assessment of the tunnel and provide information on the conditions inside the tunnel.

Internal pipe crawlers

FIU is also developing multiple internal pipe crawlers for the DOE with applications for the inspection of pipes and infrastructure (Fig. 2). A number of pipe crawlers have been developed for various applications in industry, but very few are focused on small-diameter pipes. One of FIU's first pipe crawlers, funded through EM, was designed to traverse through 3- and 4-inch-diameter pipes with lengths of up to 150 feet and to navigate through a number of 45 degree and 90 degree angles[2]. The objective was to navigate through the air supply line of Hanford's double-shell tanks to provide information regarding the integrity of the inner liner of the tanks. The crawler consists of two grippers that grip the pipe walls and two extenders that can extend and retract, providing the motion. These four modules use pneumatic actuators and are activated sequentially to provide forward and backward motion. The unit includes a camera on the front of the unit for real-time video feedback and a tether that provides air to the actuators and a power and data line for the camera. Because the system is modular, additional grippers or extenders can be added as needed. FIU is also developing sensor modules that can be integrated into the system and can provide a suite of sensors, including light detection and ranging (LiDAR) systems, ultrasonic sensors, and environmental sensors. The crawler's construction is very simple and cost-effective, using 3-D printed components and commercial off-the-shelf actuators, cameras, and sensors.

In addition to the 3- and 4-inch pipe crawler, FIU is developing a 6-inch crawler that operates in a similar manner as its sister crawler but is being developed to traverse through a 6-inch drain line (Fig. 3). The drain lines of the Hanford double-shell tanks mate with drain slots underneath the secondary liner and provide an avenue to inspect the secondary liner. The intended purpose of the 6-inch version is to navigate through approximately 50 feet of pipe with 90 degree elbows and

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Fig. 3: Advanced prototype of FIU's 6-inch internal pipe crawler.

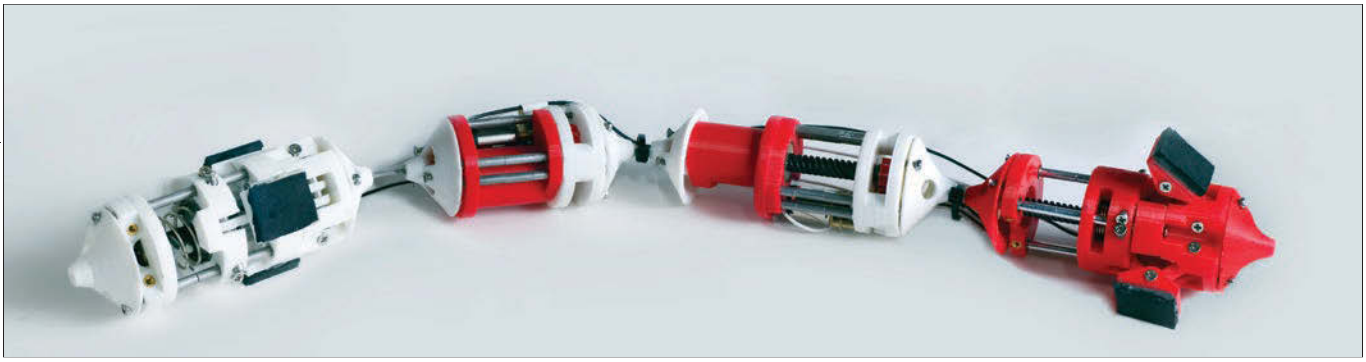

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Fig. 4: Prototype of FIU's 2-inch crawler.

deploy a child rover—a smaller robotic device mounted on a larger one—that can travel through the drain slots and provide information on the integrity of the secondary liner. Unlike the smaller crawler, this version is expected to find significant scaling, water, and mud within the pipe. The final design has been modified to address these constraints with guides that will assist in moving past the scaling and pneumatic actuators that are aligned perpendicular to the motion in the grippers to maximize the gripping force. Figure 3 shows a prototype of the initial design and a more rugged prototype with a sturdier frame and stronger pull force. This system can also be augmented with a sensor module to provide additional information about the inside of the pipe.

FIU is also developing a crawler that navigates through 2-inch-diameter pipe (Fig. 4). This system is being funded through the DOE's National Energy Technology Laboratory and is intended to inspect super heater lines in fossil energy power plants. With the constraint of the smaller diameter of pipe, pneumatic actuators are not possible, so a nut/lead screw design was employed. In addition, the super heater lines have 180 degree bends with varying radii of curvature. This requires a significantly smaller module geometry, with motors that supply only a fraction of the pull force generated by the larger crawlers. It is anticipated that this unit will need to be coupled with multiple crawlers to traverse through the entire length of the super heater lines. Similar to the other crawlers, the frame is constructed with 3-D printed material, and the system components are commercially available. This system will also have additional modules that will house small ultrasonic sensors that provide information on the integrity of the pipes.

Miniature rover

FIU has been developing a miniature rover to navigate through refractory slots underneath the primary liner of the double-shell tanks at Hanford[3]. The slots distribute air to cool the primary liner of the tanks and offer the best approach for obtaining information regarding tank health. For most of the tanks at Hanford, the slots are approximately 1-inch wide and are structured like tree branches emanating from the center of the tank. The tank liner is constructed using carbon steel, which allows for the use of magnets to adhere the rover to the underside of the tank liner. The rover (Fig. 5) can be deployed through the annulus of the tank and can enter any of the refractory slots from the annulus. It will then need to travel approximately 35 feet to reach the center of the tank. The rover is powered with four independently driven wheels and includes a camera and a magnetic mechanical arm that allows the unit to navigate over weld seams. In the near future, an additional module will be attached to the rear of the rover and will include an ultrasonic sensor that is able to measure the thickness of the liner and identify areas of concern.

Exoskeletons and more

The application of robotics in the form of robotic manipulators/hands and operator-assisting aids such as wearable robotic devices (exoskeletons and sensors) is a great avenue to minimize fatigue and reduce injuries to the workforce. Exoskeletons can be used to minimize muscle fatigue and reduce injuries among glovebox operators, while robotic manipulators can be substituted to automate repeated and predefined routine tasks.

FIU, in collaboration with Florida Atlantic University and Idaho National Laboratory, is conducting a robotics research project funded by EM under its Minority Serving Institution Partnering Program. The objective of the project is to quantify human fatigue during glovebox operations and to evaluate the feasibility of a dexterous robotic manipulator for

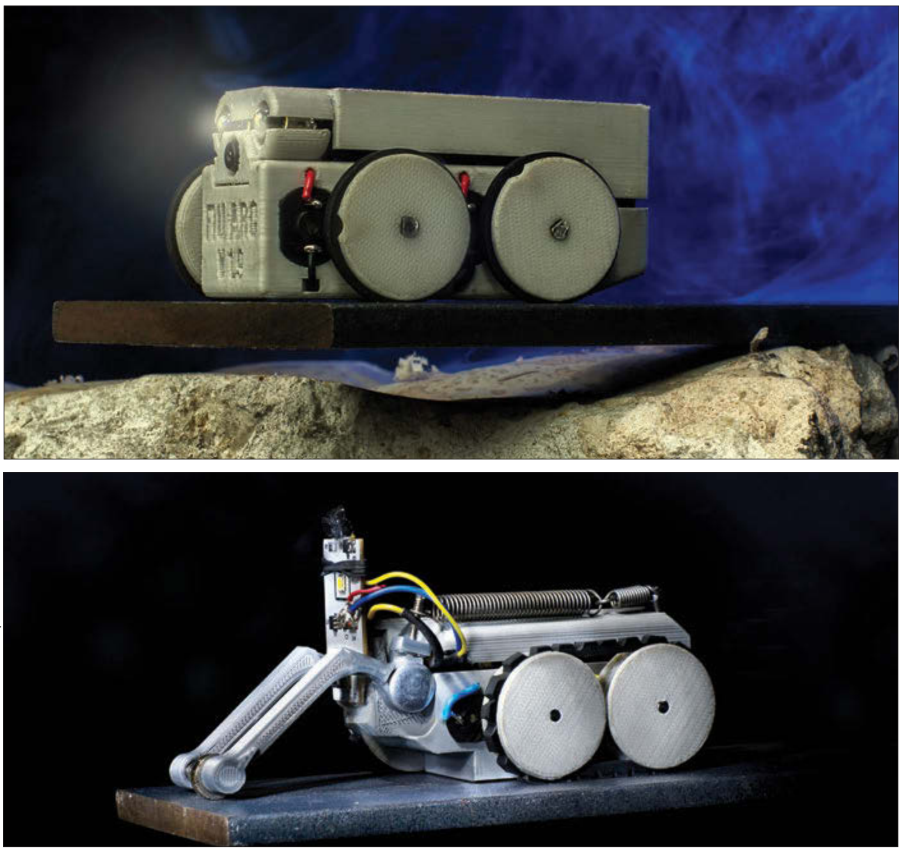

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Fig. 5: Initial prototype (top) and final prototype (bottom) of the miniature rover.

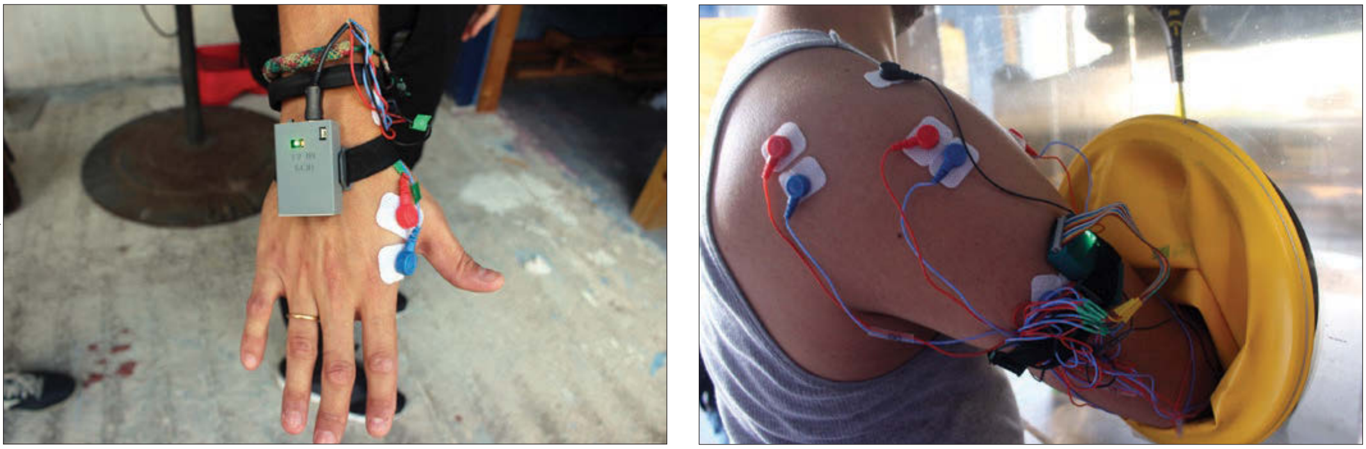

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Fig. 6: Electromyography sensor for human testing, placed on the hand and arm.

use in those tasks[4]. Research included investigation of various glovebox tasks, detection of human muscle fatigue using electromyography sensors while conducting the tasks, customization of a robotic hand-and-arm combination to conduct the same tasks, and statistical analysis for performance comparison between the two methods of testing: using humans to perform tasks and using a robotic arm/hand to perform the same tasks. In addition, during phase two of this project, the FIU team has expanded the research to include the development of a novel design and the prototyping and testing of an exoskeleton mechanism.

As a first step, the FIU team concentrated on the development of a high-precision electromyography device, the industry's first Wi-Fi–certified, single-chip microcontroller unit with built-in Wi-Fi connectivity. The purpose of the sensor is to quantify human fatigue during glovebox operations. The sensor (Fig. 6) was used for human testing and data acquisition. The advantages of the sensor include its low-profile nature and sensor placement range, which allow the devices to record accurately while leaving the hand and arm unencumbered and with full dexterity. In order to quantify human fatigue using the electromyography device, approval for the human test subjects was obtained from the Institutional Review Board.

The i-Limb Quantum robotic hand was used for the duration of the experiment. The hand comes with a user-controlled interface with two inputs to open and close the hand. An application called BioSim can be used to toggle between the grasp type chosen, such as finger tapping, power grasp, lateral card pinch, or precision grasp between thumb and index finger. To operate the hand using the controller designed for this project, a Teensy 3.6 microcontroller was chosen. This microcontroller was able to output two analog signals for hand control that were specified by human operators through a joystick to open and close the hand. Also, a UR5 robot arm was programmed to run autonomously while the user controlled the robot hand. This allowed preprogrammed paths that accounted for the sand-scooping and brick-brushing tasks independent of the control for the arm.

Once the arm and hand were initialized, the hand was inserted into the glove. This was done by configuring the hand into a preprogrammed posture and inserting the fingertips into the glove (Fig. 7a). The arm program started to move the hand through the glove opening while the user rolled the glove further onto the hand (Fig. 7b). This continued until the hand was completely in the glovebox in the starting position for running the tasks (Fig. 7c). This same procedure, in reverse order, was conducted to remove the hand from the glovebox, running a preprogrammed trajectory for removal.

The brick-brushing task set up during human testing was used for the robotic testing as well. Four bricks were placed in the glovebox in an arced configuration so that the robot could reach each brick. For the task, the robot was programmed to brush each brick 10 times and then progress to the next brick, as shown in Fig. 8. This was cycled until the last brick and was repeated for the duration of the experiment. The us-

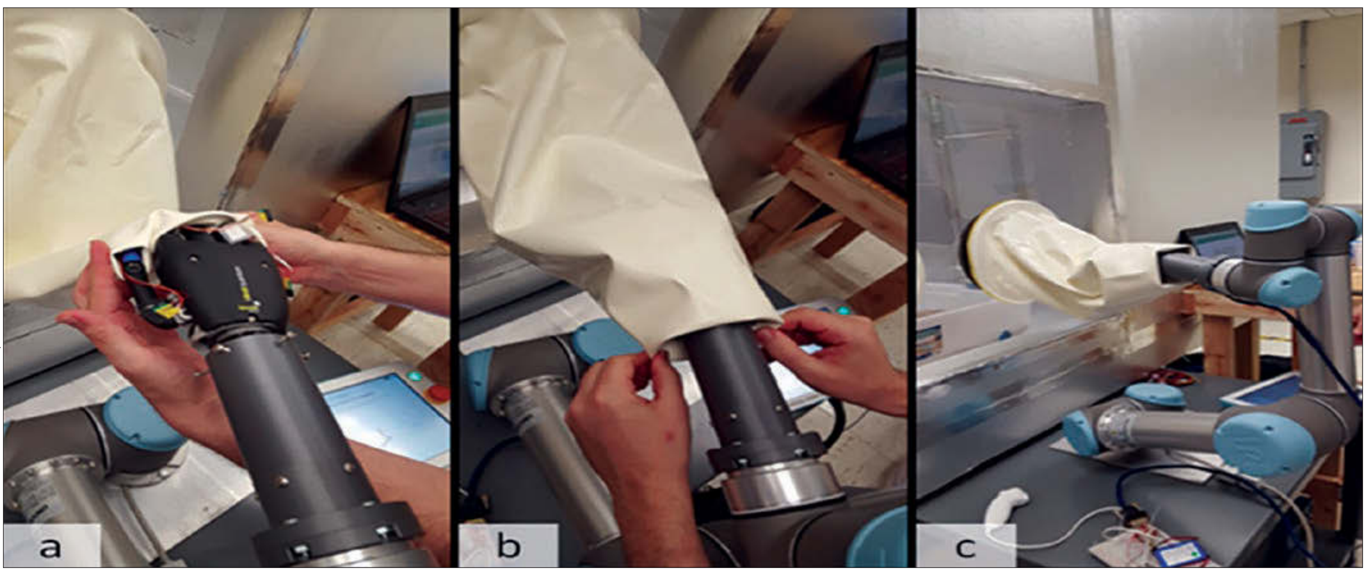

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Fig. 7: Procedure for inserting the hand into the glovebox for testing: (a) initial hand posture to insert fingertips into the glove, (b) hand fully inserted into the glove, and (c) the arm inserting the hand into the glovebox.

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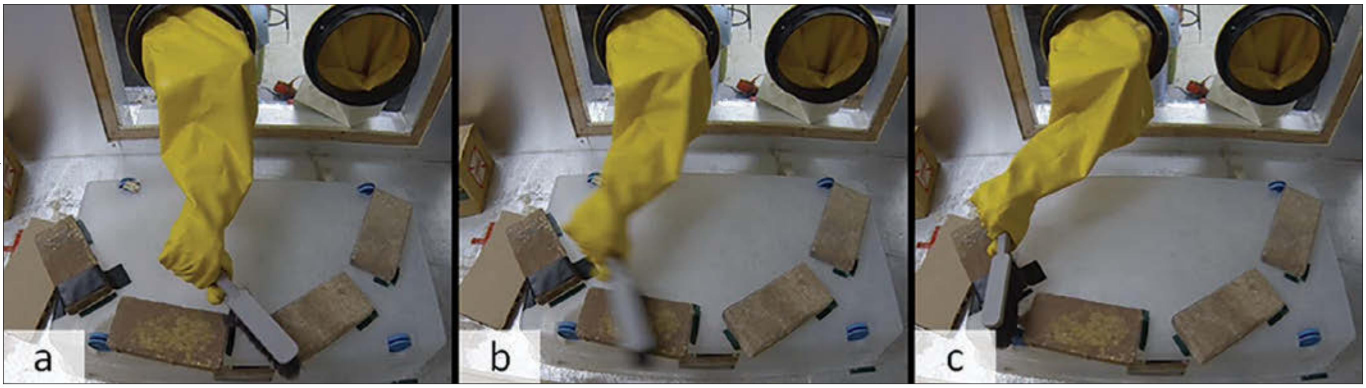

Fig. 8: Photo sequence of the brick-brushing task during the motion of one brushing stroke.

er interface allowed the participant to control the hand grasping the brush throughout the duration of the experiment, while the arm moved autonomously, based on a preprogrammed path plan[5].

Radiation mapping

Accurate facility characterization information is a critical element in successfully understanding radiological hazards, planning cleanup efforts, and meeting quality assurance objectives established by DOE standards and guidelines. When characterizing facilities, advanced autonomous systems are safe, efficient, and cost-effective tools that can safely deploy state-of-the-art instrumentation without exposing workers to radiation risks.

Given the large size of many facilities, coupled with the high cost of radiation sensors and the nature of radiological sources, mobile systems provide a cost-effective alternative to current on-site sensor networks or manual measurements performed by site personnel. Autonomous systems can also be used for continuous radiation measurements needed to assess the condition of the facility during operation, decommissioning, and/or end state assessments.

The aim of this research is to support deactivation and decommissioning activities by providing nondestructive gamma measurements, laser and visual mapping, and possibly hyperspectral imaging data of radiological infrastructures and facilities.

As illustrated in Fig. 9, the Jaguar V6 tracked robotic platform is equipped with a manipulator arm that carries an end effector coupled with a compact high-performance gamma-ray spectrometer and a depth camera. Several surrounding cameras and a multichannel 3-D LiDAR have been mounted on the platform to facilitate autonomous navigation and mapping. The five-DOF manipulator arm increases the capability of the system to perform radiation sensing and mapping, as the sensor and the depth camera can be positioned in tight and hard-to-reach locations.

The FIU team has been testing several state-of-the-art Simultaneous Localization and Mapping (SLAM) packages available in the Robot Operating System community. Figure 10 shows preliminary mapping results using Real-Time Appearance-Based Mapping (RTAB-Map)[6]. The point cloud—a set of data points in space, generally produced by 3-D scanners, which measure many points on the external surfaces of objects around them—was generated using the 3-D LiDAR data and stereo-camera images employing a Visual-SLAM algorithm. Successive camera frames were used to track set points and triangulate their 3-D position, while simultaneously using this information to approximate the camera position.

For the radiation modeling strategy, the radiation levels present in the environment will be measured by a high-performance radiation sensor located at the end effector of the unmanned ground vehicle. The data gathered by the sensor will be assimilated into a continuous stochastic distribution model to enable statistically consistent prediction at unobserved locations, to estimate the radiation distribution.

The team is also working toward developing an adaptive sampling strategy to guide the robot's movements. Similar to the modeling strategy, we are utilizing the Gaussian Process Regression[7] to model the expected radiation distribution to select sampling locations. Regression is done using a Matérn kernel method previously used in similar applications[8].

Looking ahead

EM has made enormous progress over the last 30 years, but very difficult environmental remediation challenges will be faced in the next few decades, and the use of robotics will play a significant role in EM's future efforts. The research efforts outlined here offer numerous benefits on both the research and the educational fronts. In addition to providing engineering and research solutions for the EM environmental remediation mission, the

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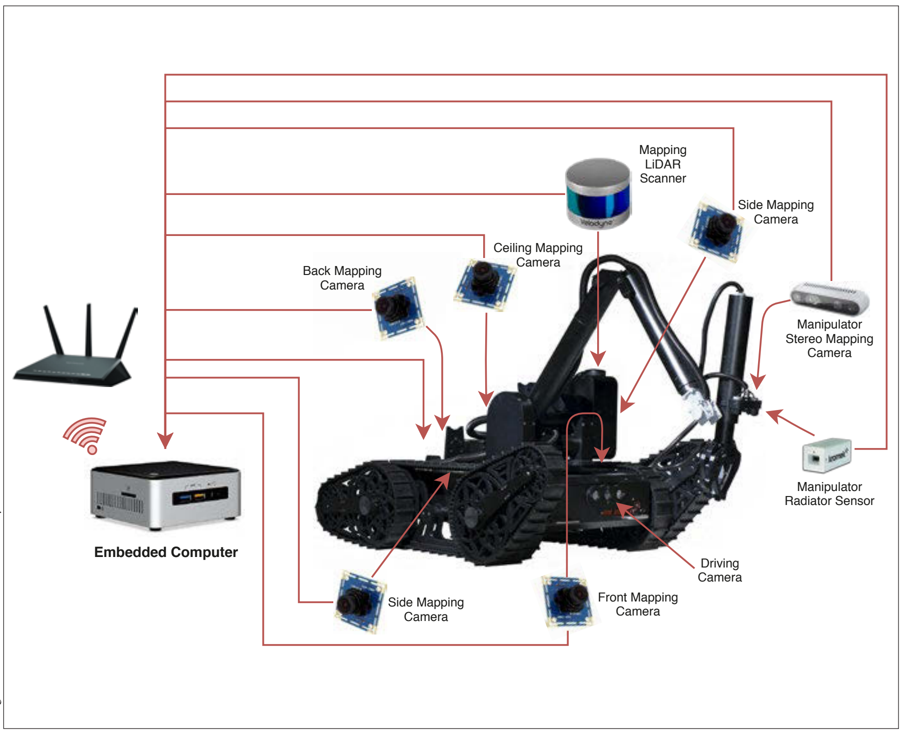

Fig. 9: The Jaguar V6 tracked robotic platform with arm manipulator and instrumentation.

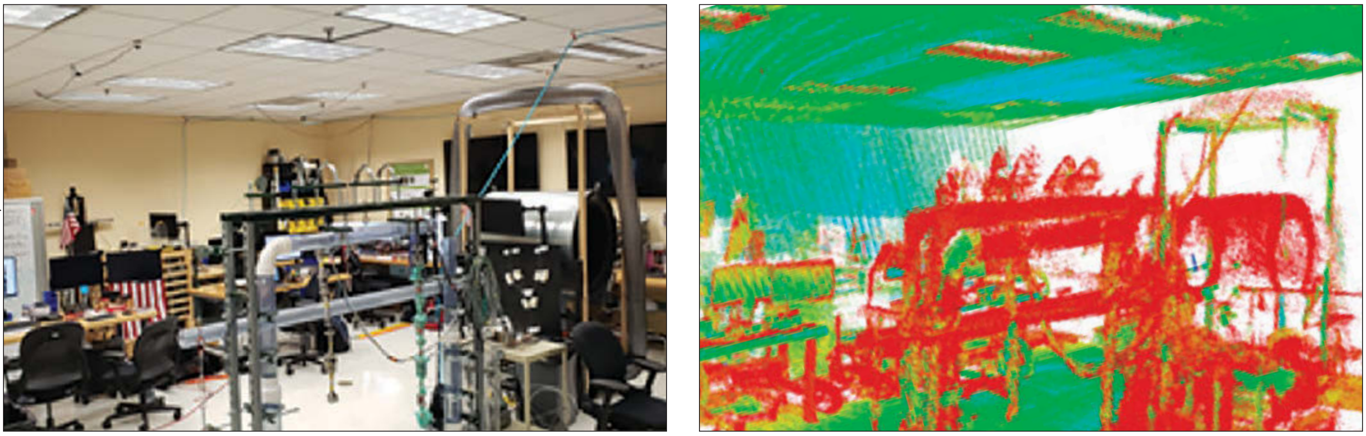

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Fig. 10: At left, a photograph of the FIU Applied Research Center's Robotics Lab. At right, the same lab, after implementing Real-Time Appearance-Based Mapping.

projects also offer STEM minority students from FIU opportunities to enhance their knowledge and skill sets and to potentially prepare them to embrace the future EM workforce.

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