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Sent: Monday, November 20, 2023 3:08 PM
To: Reid, Douglas J <douglas_j_reid@rl.gov>
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To: Nelson, Erik N <Erik.Nelson@rl.doe.gov>
Subject: RE: FIU Lateral Gamma Scanner Crawler Paper Edits

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Doug,

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Erik N. Nelson
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Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
Office of River Protection under Contract DE-AC27-08RV14800

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Revision 0

Development of Control Software for Autonomous and User-monitored Operation of Lateral Gamma Scanner System

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APPROVED
By Julia Raymer at 2:18 pm, Dec 18, 2023

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STUDENT SUMMER INTERNSHIP TECHNICAL REPORT

Development of Control Software for Autonomous and User-monitored Operation of Lateral Gamma Scanner System.

DOE-FIU SCIENCE & TECHNOLOGY WORKFORCE DEVELOPMENT PROGRAM

Date submitted:

September 27, 2023

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Submitted to:

U.S. Department of Energy
Office of Environmental Management
Under Cooperative Agreement # DE-EM0005213

Applied Research Center
FLORIDA INTERNATIONAL UNIVERSITY

EXECUTIVE SUMMARY

The CTO, in collaboration with Florida International University, continues to develop the Lateral Gamma Scanner (LGS), a tool capable of autonomously monitoring for leaks in the area underneath single shell tanks at the Hanford Site by means of transporting gamma radiation sensors through the tanks' laterals. The LGS uses the Robot Operating System to synchronize and autonomously operate a peristaltic motion pipe-crawler and a mechanical deployment-and-retrieval reel. The latest stage of the LGS's development has focused on improving the system's maintainability and operator-friendliness by streamlining the crawler's design and by making user-focused additions to its software. The improvements described in this report continue to gear the system towards a deployment readiness by ensuring that inspection routines can be performed consistently and autonomously while being monitored from a station external to the tank farms.

ACKNOWLEDGEMENTS

This research work has been supported by the DOE-FIU Science & Technology Workforce Development Initiative, an innovative program developed by the U.S. Department of Energy's Office of Environmental Management (DOE-EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2023, a DOE Fellow intern, Josue Estrada, spent 8 weeks doing a summer internship at Washington River Protection Solutions at the Hanford Site under the supervision and guidance of Dr. Douglas Reid. The intern's project was initiated on May 1, 2023, and continued through July 29, 2023, with the objective of furthering the development of an automated inspection tool for detecting gamma radiation leaks underneath the tanks at the SX tank farm.

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GLOSSARY

BT	Behavior Tree
CTF	Cold Test Facility
CTO	Chief Technology Office
DOE	Department of Energy
EKF	Extended Kalman Filter
FIU	Florida International University
FSM	Finite State Machine
GUI	Graphical User Interface
IMU	Inertial Measurement Unit
IP	Internet Protocol
LGS	Lateral Gamma Scanner
LiDAR	Light Detection and Ranging
ROS2	Robot Operating System 2
PVC	Poly Vinyl Chloride

1. INTRODUCTION

This report documents the progress achieved during a 2023 summer internship focused on advancing the development of a robotic inspection tool that can routinely and autonomously scan for an increase in radiation under the tank farms at the Hanford Site. The source of this radiation would be a potential leak of waste from a tank during operations to retrieve waste from the tank. These tanks have multiple riser penetrations for internal access, however external access is challenging. One method of external access is a system of lateral pipes that run beneath some of the tanks. These 3-inch-diameter horizontal pipes are shown in Figure 1 in plan and Figure 2 in elevation.

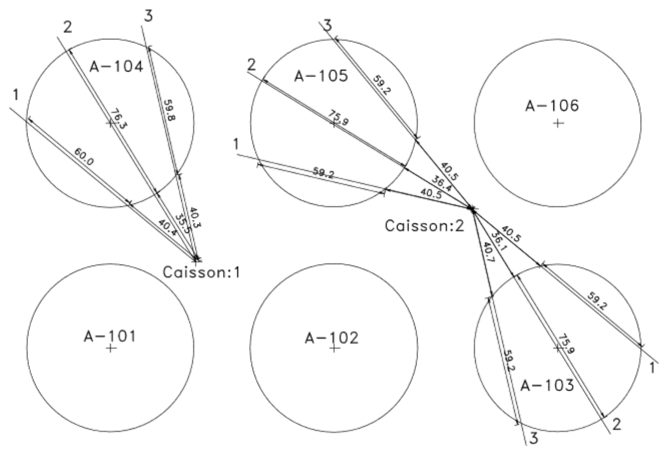

Figure 1. Tank farm diagram showing lateral channels.

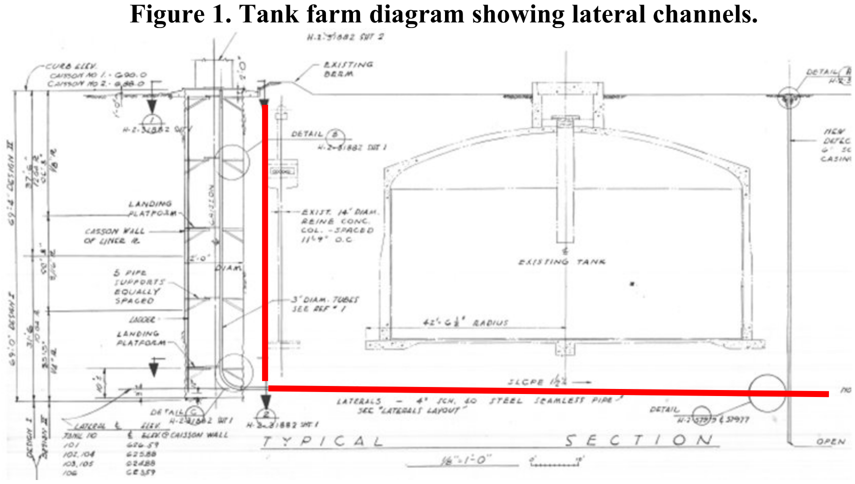

Figure 2. Individual Tank Schematic

The lateral pipes located 10 feet beneath the tanks (as shown in Figure 2), run parallel to the tank's bottom surface, extending to the opposing tank wall. They are accessed from the surface by going through a caisson installed during the farm's construction. While radiation measurements through these laterals were attempted in the past, it involved a costly deployment process with a large team of operators. The Robotics Laboratory at FIU's Applied Research Center has collaborated with Washington River Protection Solutions to develop an inspection tool that utilizes these lateral pipes. This tool can transport gamma radiation sensors along the lateral pipe using a robotic system that combines a peristaltic-motion pneumatic pipe crawler and a mechanized reel into an integrated automated delivery system.

An autonomous system would enable multiple daily scans without requiring continuous and expensive operator involvement. The team’s objective is to create a robust inspection system capable of automatically conducting multiple inspections daily, logging the results of scans along the tank diameter, and retrieving itself in the event of failure.

Before the FY23 internship, the system included hardware components such as the pipe crawler and mechanical reel, along with software components that synchronize their movement and that perform a prototype form of autonomous behavior. The scope of the 2023 summer internship focused on developing a more robust autonomous model, incorporating a user-friendly control interface for tank farm operators, and testing the latest mechanical enhancements in the pipe crawler's design. This report will detail the methods involved in the development of these features which focus on accelerating the deployment of the Lateral Gamma Scanner system (LGS).

2. SYSTEM DESCRIPTION

2.1 Hardware Components

The LGS system (Figure 3) is required to perform two primary mechanical functions: deploying and retrieving the sensors through the vertical pipe, and transporting them through the lateral pipes. Given the unique geometry and inherent constraints of this mission, the LGS development team allocated these functions tasks to two main actuated components, a pipe crawler designed to propel the sensors through the lateral sections, and an actuated reel responsible for both, lowering them through the vertical sections, and finally extracting the system to the surface.

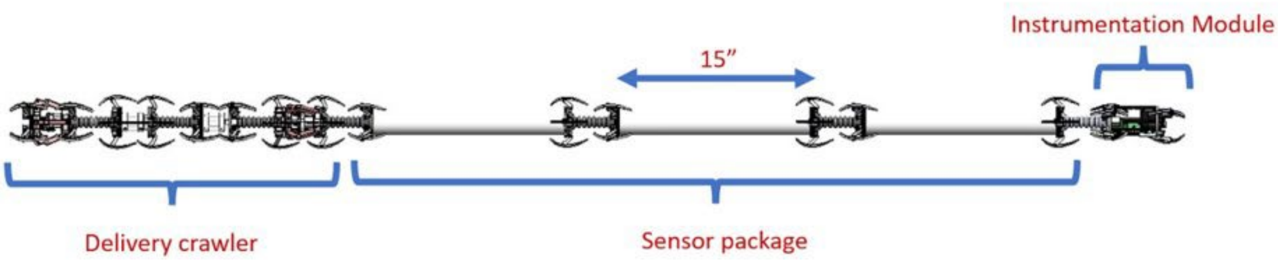

Figure 3. Pipe crawler sections (the rightmost module is the crawler's front)

The task of advancing sensors through the lateral sections is a particularly challenging function that has not been successfully achieved by systems relying solely on gravity. To accomplish this, the LGS employs a pipe crawler that utilizes peristaltic motion for propulsion and for pushing along the sensor payload. Peristaltic motion involves a combination of gripper modules, which grip or release the inner pipe wall, along with extender modules that elongate the crawler. These modules are organized with gripper modules positioned at both the front and rear of the crawler and with extender modules in between. Peristaltic motion is performed by first engaging the back gripper to fix the position of the crawler's back in the pipe. The extenders then activate to elongate the crawler, pushing the frontal sections. The front gripper is then engaged while the back gripper is disengaged, fixing the front position of the crawler's front before compressing the extenders and finalizing one forward crawling cycle.

The second actuated component is a motorized reel, which handles the deployment and retrieval of the crawler and sensors by unwinding or winding the tether that connects the system's electronics and pneumatics. The reel's spinning body has been segmented into halves. One half performs the regular function of spooling the tether, while the other half accommodates the solenoid valves that actuate the pistons, the relays to control these, the crawler control computer, the voltage regulators to power the system, and ethernet switches that connect the network. These devices are assembled on this rotating body since they are need to spin along with the connected tether, as shown on Figure 4. Adjacent to the main reel body, there is a control panel housing the motor driver, power supplies, and the reel's control computer. This panel is ventilated for heat management and includes an emergency power-cutoff safety button.

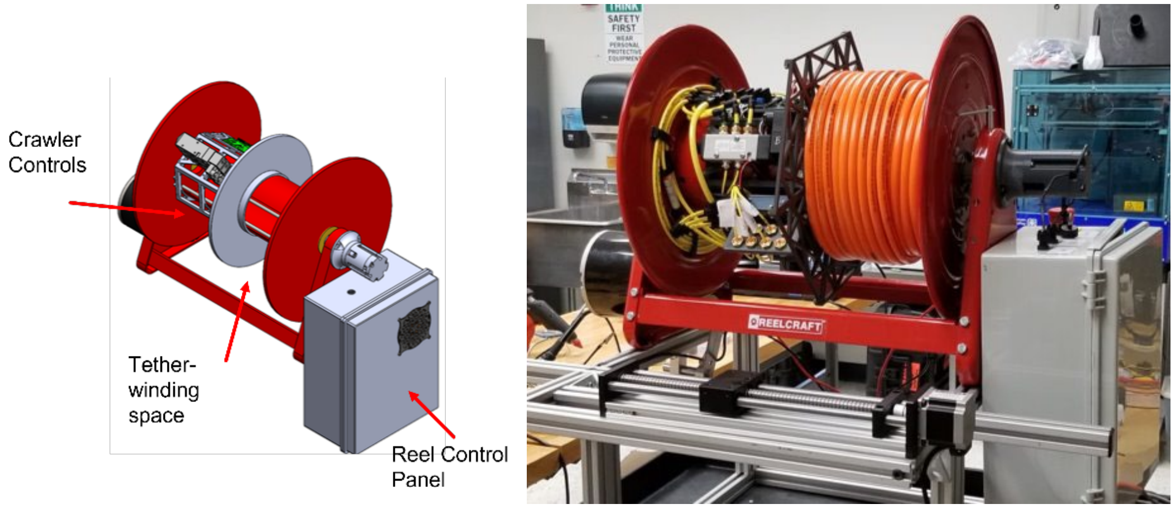

Figure 4. Mechanized Reel, labeled CAD model to the left and prototype to the right.

To enhance the mechanized reel's performance, the system includes tether-spooling assister carriage, an auxiliary actuated device which ensures minimal crossover in the cable's winding for safety, as highlighted in Figure 5. Communication between separate computers and microcontrollers controlling these three actuated hardware components, as well as sensors collecting data from their environment, is established using the Robot Operating System (ROS2). This framework facilitates communication channels between concurrently running computer programs across devices in an Internet Protocol (IP) network. This allows us to create robotic tools whose functions are distributed among programs running on several computers in distinct physical locations. Such distribution is necessary in the LGS, where sensors, actuators, and central processors must be located underground, at the tank farm surface, and outside the tank farm in a control computer, all securely connected through a locally wired IP network.

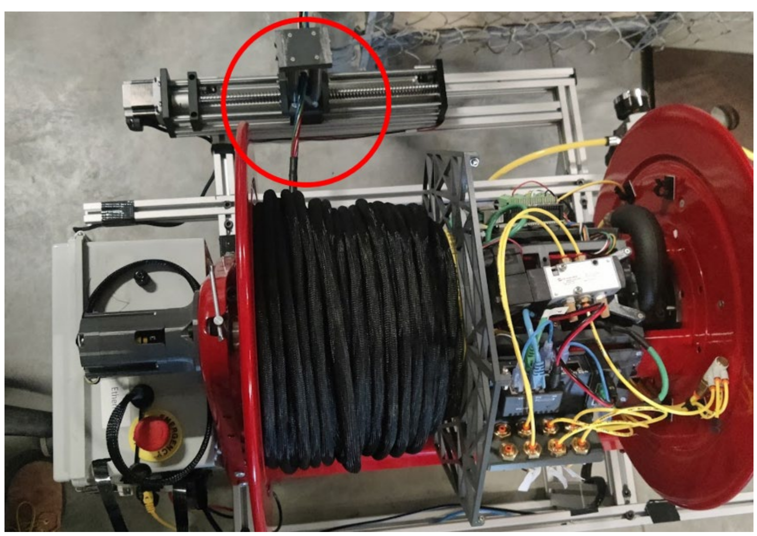

Figure 5. Tether-spooling assister highlighted

2.2 **Hardware Updates**

Mechanical tests conducted during the 2022 summer internship revealed design issues which could potentially impact the pipe crawler's performance and its maintainability. Consequently, one of the primary objectives for 2023 was to address these issues. As described below, a new design was developed to improve these aspects of the system.

The first of these issues pertains to the peristaltic motion crawl and its ability to overcome imperfections in the inner pipe wall. Accumulations of sediment or debris could hinder crawler's progress by blocking its path or reducing the effective inner diameter of the pipe to a point where motion is impeded by friction. These issues were encountered at different points during the testing phase, with the back grippers failing to provide sufficient grip to fix the crawler's back in place, and the front module being unable to advance through irregular pipe fittings.

The second of these issues relates to the potential need for maintenance of the crawler's electronics in the future. In the 2022 design, the ethernet cable that runs from the rear of the crawler to its head had to be cut, wound around the modules through restrictive channels, and then re-soldered on the other side. This reattachment process required specialized soldering techniques that would not be feasible for site operators.

The crawler's 2023 update dealt with both of these shortcomings simultaneously by modifying the design of the gripper and crawler modules. The modules' piston configuration transitioned from a single central piston to four smaller pistons distributed around a central hole as shown in Figure 6.

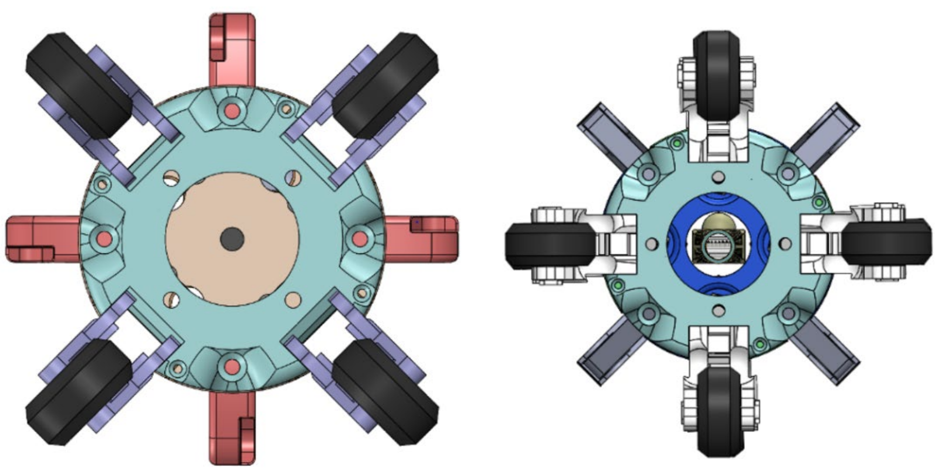

Figure 6. Solid core modules (left) and new hollow core modules (right)

This modification addressed the blockages encountered when the crawler attempted to push through moderate imperfections in the pipe inner wall, including irregular fittings between the pipes and pipe diameter reductions caused by deformation or debris deposits. The four pistons that create the hollow core, although individually not as strong as the 60lb single piston, combine to provide a total 100lb of push force. This force is transferred through the gripping arms shown in Figure 7, into a friction force normal to the inner wall. The translated force, aided by a high-friction rubber coated was tested (as pictured in Figure 8) to produce over 45lb of static strength, which is more suitable for pushing the crawler's front through pipe imperfections.

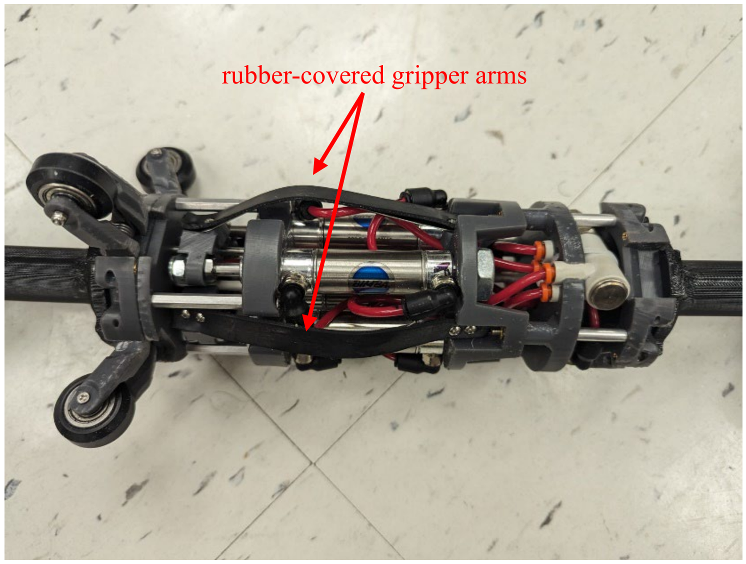

Figure 7. Four-piston gripper module

Figure 8. Static Friction Tests for Gripper Module Strength

Additionally, change proactively addressed concerns of the tool's maintainability. The new design's piston arrangement created a hollow center that allows for the seamless insertion or removal of the cables that run through the individual modules (the Ethernet cable and the pneumatic lines that distribute the air to the frontal cylinders). This not only removes the need for a complete disassembly of the crawler during cable-related maintenance, but also eliminates the need for custom-soldered cables. In case of cable failure, the old cable can be easily removed and a generic 10ft RJ45 ethernet can be inserted as a replacement, making the 2023 version of the crawler more easily maintainable than its predecessor.

2.3 **Software Updates**

2.3.1 Automation Models

The iteration tested in the summer of 2022 was controlled with a preliminary behavior model based on a Finite State machine (FSM), a mathematical model used to describe a system or process that can be in one of several states at any given time. The system's behavior is defined by the transitions between these states in response to the input events it receives. In the LGS, the control FSM was defined by states that mirrored distinct sections of the inspection, including the vertical section, the end of the pipe, and the crawler retrieval, among others. Transitions between states reflected real-life transitions between physical sections of the pipe based on the input read by sensors such as the IMU’s gyroscope or the LiDAR's time-of-flight readings.

An FSM can be visually represented by a directed graph, where each node corresponds to a state and each edge represents a transition from one state to another in response to a specific input event. Figure 9 depicts such graphical representation of the original LGS's prototype FSM, with the boxes in the diagram representing the states and their associated actions, and the arrows between these representing the possible transitions between them.

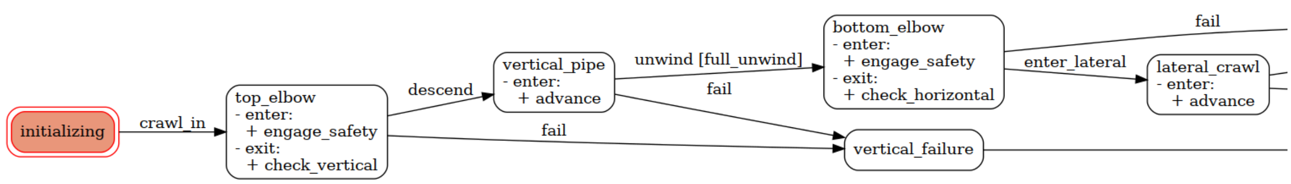

Figure 9. Finite State Machine Diagram

Although FSMs are simple to conceptually straightforward, their simplicity comes with certain limitations. Each state defines not only internal actions but also all the possible transitions out of itself. This inter-relation means that adding new steps to the inspection process would require creating corresponding states, modifying all adjacent states, and redefining the transitions between them. Moreover, FSM states must mirror real-world scenarios as specifically as possible, which makes each state too unique to be re-used in a different context. These insights, along with considerations for future iterations with varied requirements and processes, prompted the development to adopt a more modular and flexible behavior model found in the literature.

2.3.2 Behavior Tree

The 2023 iteration of the autonomous control model operates under a behavior tree (BT) model, a decision-making framework that offers greater modularity and scalability. A BT has a hierarchical structure, composed of a root node representing the overall behavior and multiple child nodes defining sub-behaviors, such as the one illustrated in Figure 10. Each child node can be another BT or a simpler control structure, such as a sequence or a selector. This hierarchy is "ticked" node by node starting at the root, until a tick reaches a node at the bottom of the tree. At this point, the node executes its role and returns one of three statuses (SUCCESS, FAILURE, or RUNNING) as a signal to its parent node. This branching structure results in more complex decision-making by allowing the system to consider multiple options simultaneously. In contrast, FSMs tend to be flatter structures with a fixed number of states that limit their complexity.

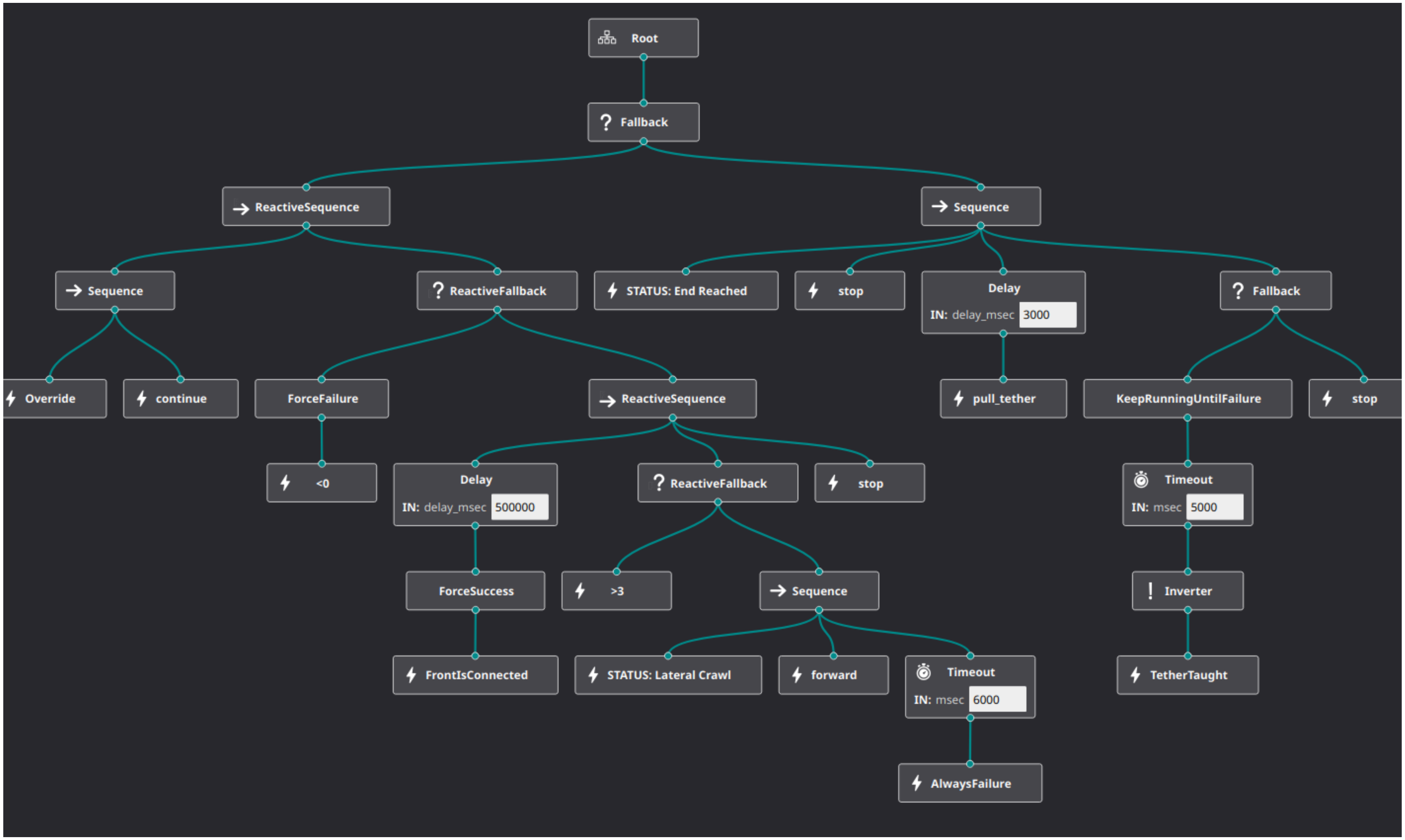

Figure 10. Behavior Tree Node Diagram

Another advantage of BTs is their ability to handle concurrent behaviors, which can be challenging for FSMs. In a BT, multiple branches can run concurrently, each representing a different behavior. This allows the system to handle multiple goals or tasks at the same time without having to switch between different states. FSMs on the other hand, typically allow a single active state at any given time, which can make it difficult to manage concurrent behaviors or to prioritize different goals. While FSMs are still a useful tool for modeling certain types of systems, BTs offer greater flexibility and versatility for complex behaviors and decision-making.

The LGS's decision making is controlled by a behavior tree node implemented using the BehaviorTreeCPP library. Each node carries out a specific action or checks for a specific condition such as probing a sensor, actuating a piston, or reading the reel's encoder. These more granular nodes are composed and re-used as needed in the tree. This is where modularity comes into play since actions such as activating the crawler's grippers are employed in different points in the inspection and under different conditions. While the action remains the same each time, it can be used for different purposes depending on how it is structured in the tree and with which other conditions it is sequenced.

Figure 11 shows one of the LGS's sub-trees, a section of the behavior tree which is meant to be re-used. This works since at the end of the sub-tree's execution, the parent node will output any of the three possible states and thus, a sub-tree's root can be treated as a regular node. One example of a sub-tree used at many points in the inspection is the one used for position estimation, which is composed by a smaller tree of nodes performing a sequence that involves stopping the crawler, tightening the tether, reading the IMU sensor, and calculating position values.

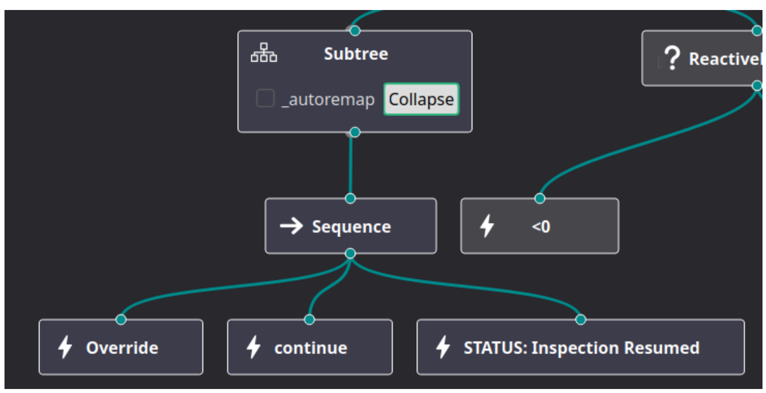

Figure 11. Behavior Tree Sub-Tree

These estimation sources can be combined using an Extended Kalman Filter (EKF) operating as a separate ROS2 node. This filter type allows for placing greater weight on the more accurate estimation sources and accounts for system noise for measurements like the IMU and the pump count. Finally, the node outputs a calculated position value which is used by the behavior tree to make its decisions.

2.3.3 Graphical User Interface

The final stage of development of the Lateral Gamma Scanner system involves adapting the system to be employed by operators at the tank farms. During their developmental stages, the programs that comprise the LGS's software network were individually activated and accessed through a command line. This command line was also the for retrieving information about the inspection's status. However, the proposed field-ready tool would be operational without requiring any specialized programming, networking, or command line knowledge. This section details the addition of a means for operators at the site to monitor and control the inspection process in a more intuitive manner.

For this purpose, the specialized software components that manage networking and automation have been wrapped in an operator-friendly, graphical user interface (GUI) program. This program was built using QT, a C++ library used to create custom graphical applications, and is designed to serve the functions of monitoring the inspection's status and manually overriding the autonomous process when necessary. Crucially, the GUI integrates ROS2 to have access to the system's sensor and actuator data and to send requests through actions and services. Additionally, this ROS2 integration allows the GUI program to be run on an external computer outside of the tank farm, connecting to the system's network via a single Ethernet cable.

Figure 12 presents the GUI's layout, which features the interface's main monitoring functions on its primary screen. This layout prominently displays sensor data and video feeds from the crawler's front camera and the reel's top camera. The default view shows both video feeds simultaneously but can be adjusted to maximize either one. Next to these video frames, the GUI includes buttons for recording the video feed and for capturing frames during an ongoing inspection. These videos and images are saved and logged with file names reflecting the date and time of capture.

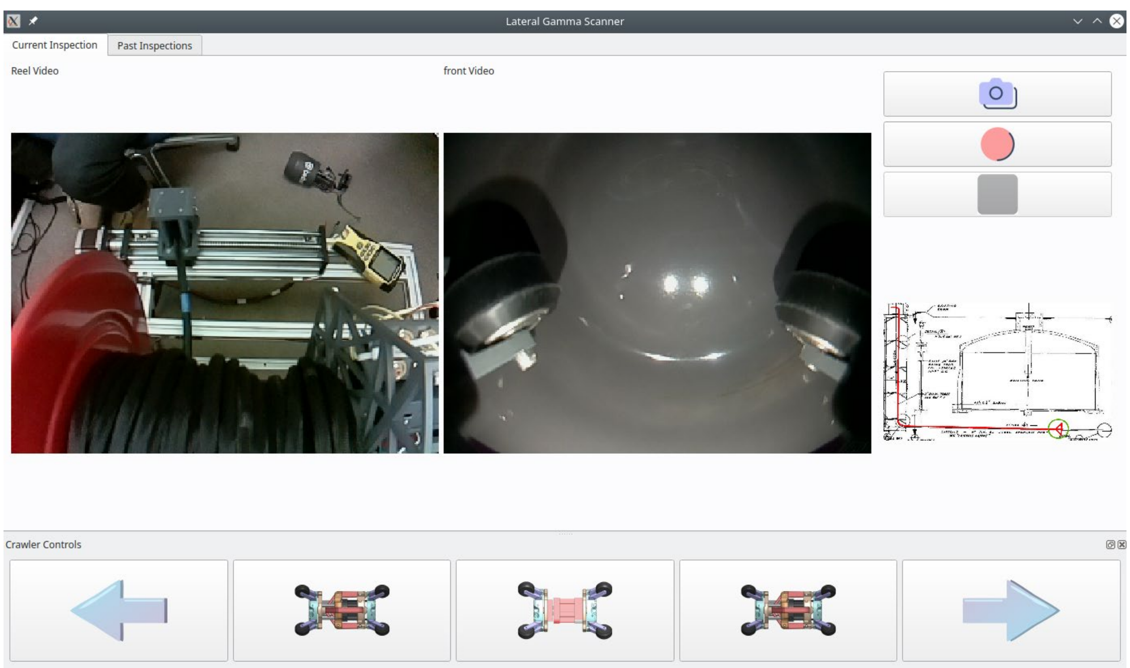

Figure 12. Custom Graphical User Interface

The same user interface program can be used to view the saved videos and images. As shown in Figure 13, a separate tab on the GUI switches the main display into a playback mode, presenting a list of previously recorded videos organized by the capture date and time. Operators can choose to view videos recorded by the front camera, the reel camera, or both.

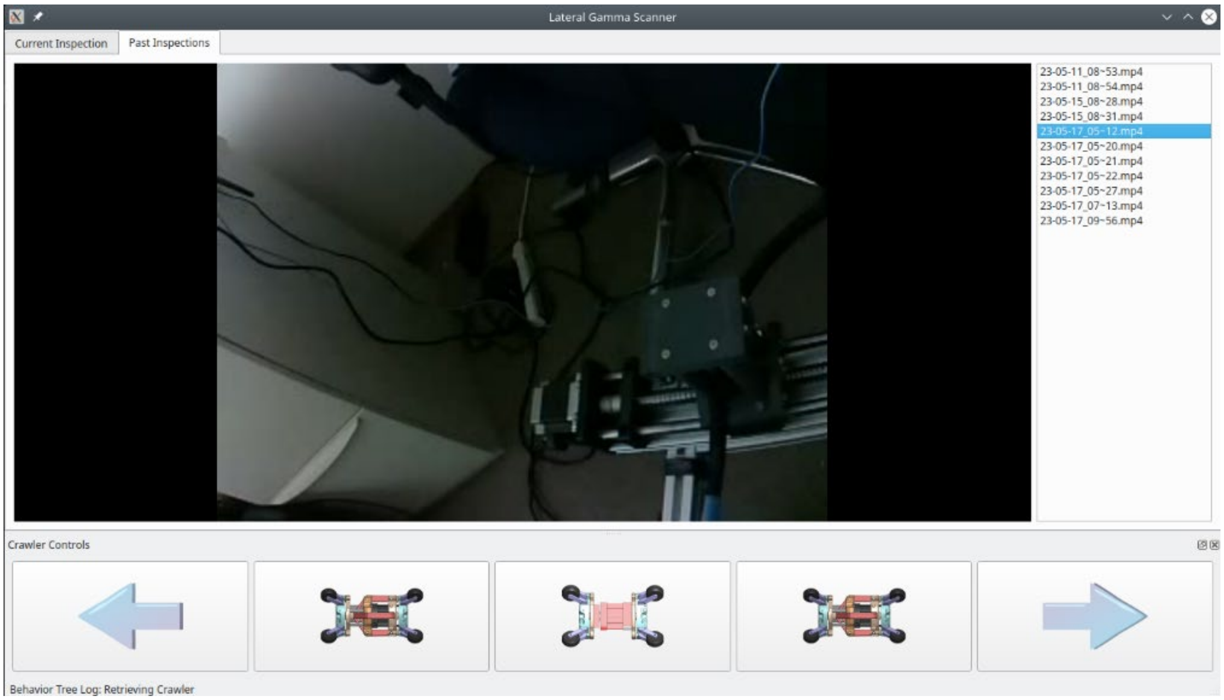

Figure 13. Custom User Interface's playback tab

While the continuous video feeds are useful for monitoring irregularities in the pipe and the reel's performance, they alone are insufficient for determining the crawler's position or the inspection's status. To address this, the GUI includes additional methods of status monitoring. These methods utilize the GUI's embedded ROS2 node, which connects to most nodes in the network, notably to the behavior tree's node, from which it receives live information of the inspection. These two methods are a persistent status message bar at the bottom of the program, and a side-view diagram of the tank highlighting what section of the pipe the crawler is currently traversing. Both status monitoring sources, shown in Figure 12, can display any of the inspection sections. As part of hierarchical structure, the Behavior tree model starts all its behavior sequences with nodes that publish the name of the upcoming sequence into the ROS2 network through a dedicated "topic". The node in the GUI subscribes to this topic and displays the communicated behavior tree status in the bottom status bar and presents a corresponding tank diagram image.

In addition to providing a broad inspection status reflecting the crawler's position during the inspection, the interface offers more granular information about the system's actuators and its environment. Specific sensor data such as the angle read by the IMU, the time of flight read by the front LiDAR can be displayed in the status bar. Finally, at every point of the peristaltic motion cycle, the current engaged/disengaged position of the crawler's pneumatic cylinders is reflected live as part of the interactive crawler buttons in the GUI's control panel.

The GUI's control panel, located at its bottom as shown in Figure 12, gives the interface its manual-control capabilities. This panel not only serves as a monitoring point for autonomous operation but also allows for manual overrides at any point in the process. Figure 14 illustrates this panel, which consists of an array of buttons for individually engaging or disengaging the crawler's modules corresponding to button's picture. The panel also includes forward and backward arrow buttons, located in front of and behind the module buttons. These arrows can be clicked to make the crawler perform peristaltic motion forward or backward. Finally, the panel includes buttons to wind and unwind the tether by activating the reel. These buttons combine to provide access to the system's all possible actuator functions.

Finally, the GUI includes a main "GO"/ "STOP" button that acts as the central control point to start and interrupt of the behavior tree, also shown in Figure. The GUI's ability to reflect, interrupt, or resume the operation was added both as a safety feature to retrieve the crawler in case of failure in the behavior tree, and as an additional measure to anticipate future additions to the inspection process.

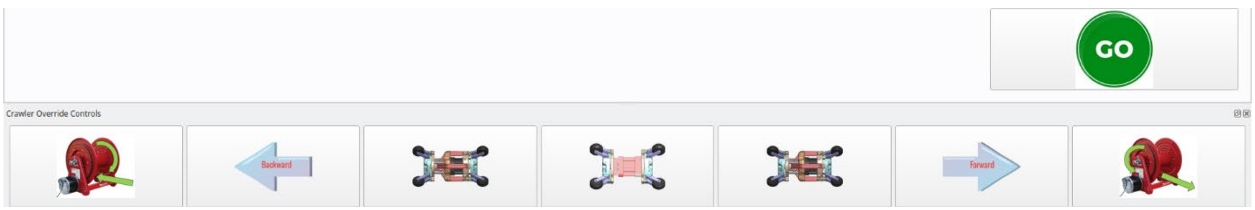

Figure 14. User Interface's Manual Override Panel

TESTING AND RESULTS

The initial testing priority during the 2023 internship was assessing the mechanical performance of the re-designed modules described in section 2.1. The newly updated crawler had undergone preliminary tests in a smaller mockup and had demonstrated its crawling capabilities adequately. However, the testbeds at the Hanford Site's Cold Test Facility (CTF), shown in Figure 15, presented an unforeseen source of resistance against the crawl. The high temperatures at the CTF caused several of the PVC pipes used in the mockup to contract in diameter at their fitting points due to pressure from the pipe-coupler pieces. Despite these reduced diameter conditions, the stronger gripper modules of the 2023 design exhibited their strength by effectively propelling the crawler's head through the pipe fittings.

These mechanical tests, similar to those realized in 2022, confirmed that the re-designed crawler is just as capable as the previous single-piston version. The system performed the inspection by crawling to the end of the pipe was passively retrieved by the reel. The success of these tests marked the transition of the focus towards the development and testing of the Behavior Tree controller, the User Interface, and the updated ROS2 network created to support them.

Figure 15. Cold Test Facility mockup structure

The Behavior Tree’s hierarchical structure of subtrees proved to be ideal for conducting modular tests that correspond to the individual sections of the crawler’s run. The most complex sections of the BT correspond to the top and bottom elbows, where transitions occur between vertical and horizontal sections and which involve probing the imu sensors as well as estimating the crawler’s position. The subtrees for these sections were successfully tested to autonomously transition the crawler through the elbows.

Furthermore, the extended straight section of pipe was utilized to assess the crawler's odometry, which involved estimating its position along the lateral run. Clear PVC sections were installed in the middle and at the end of the pipe run to assess the consistency and accuracy of the position estimation. Throughout the majority of the pipe run, the crawler’s location precision was measured to be within 10cm. This result was obtained by repeatedly attempting to stop the crawler at a specific point and measuring variances from this mark. Precision improved to a sub-centimeter level when the crawler reaches the last 15 feet of the pipe run. At this point, the front module’s LiDAR is activated and used to correct the estimation and increase its precision.

Final tests validated the User Interface’s ability to command the system’s crawler and reel to execute any of the possible actions, thus pausing the autonomous routine. The User Interface consistently displayed the inspection’s state in its status bar and indicator diagram. These features were demonstrated at a closing live demonstration as shown in Figure 16, where the autonomous routine from the behavior tree was being performed by the crawler and reflected on the user interface. The interface program was displayed on a touch screen, allowing participants to intervene at any point by touching the relevant buttons to halt or resume the crawl, activate its modules individually, and deploy or retrieve the tether.

Figure 16. Graphical User Interface presented at the 2023 demonstration

FUTURE WORK

The tests conducted in the Summer of 2023 revealed issues with the crawler’s cable management. The pneumatic and Ethernet lines that run through the crawler's body must be long enough to allow the extender modules to fully elongate the crawler. Yet, every time these modules are compressed, the entire length of cable slack accumulates at the same point. For this reason, future work involves the design of a passive mechanism to guide extra slack neatly through the extenders.

Currently the crawler’s front module is powered by a Raspberry Pi Zero 2. This computer was selected for its capability of running ROS2 and for its compact footprint. However, it lacks a native Ethernet Port, leading to the use of two adapters for connectivity: one that adapts from Ethernet to USB-A and a second one that adapts from USB-A to the Raspberry Pi's micro-USB port. These extra adapters have been found to be a point of unreliable connection and will be bypassed by switching from the current computer to a custom-designed one with an integrated Ethernet Port.

Additionally future work requires the design of a system for anchoring the reel to the tank farm floor. In the test setup at the CTF, the steel grating provided by the structure's floor was used to anchor the mechanized reel as a precautionary measure as shown in Figure 17. This precaution was proven necessary during the crawler's retrieval, as the tension in the tether also pulled the reel strongly, which would have toppled over if it were not fastened to the grating. However, the tank farm surface lacks such grating, which will warrant the development of an alternative way secure the reel in place. This could be achieved by either adding enough weight to the reel's base, or by anchoring the reel to the ground by other means.

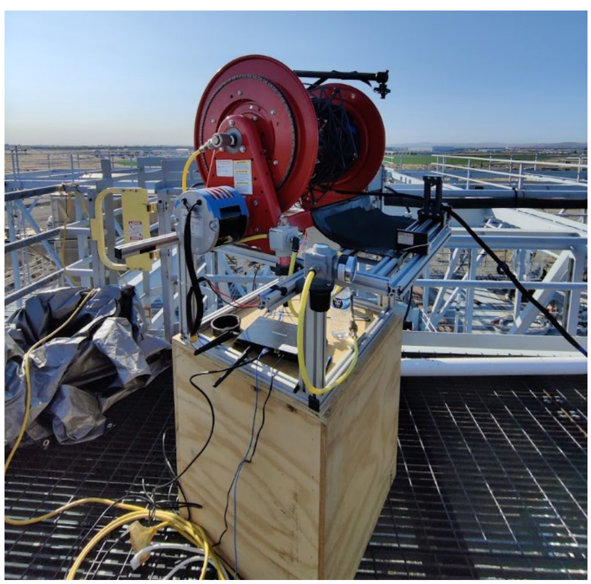

Figure 17. Mechanized Reel fastened to the mockup's grating.

The final stage of the LGS's development centers around the selection and integration of appropriate gamma sensors for the inspection. Thus far, mock sensors have been utilized as placeholders for real operational sensors. The selection of these sensors will be based on their calibration to radiation parameters relevant for leak detection. After their selection, these sensors must be integrated both, into the hardware by interfacing them with the computer in the crawler's front module, and into the software by writing a ROS node that obtains the measurement values and shares them to the external computer and the graphical user interface. Additionally, it will be essential to formulate an appropriate Behavior Tree which aligns with the operational requirements of the selected sensors.

CONCLUSION

The tests and demonstration conducted in 2023 marked a significant milestone in advancing the development of the Lateral Gamma Scanner (LGS) inspection tool, paving the way for its operation by a broader workforce with the introduction of an autonomous model that also allows for semi-autonomous monitoring. Lessons learned in the 2022 tests helped streamline the crawler's design and accelerate the tests in this internship period. Notably, the crawler's re-designed modules were successful in consistently performing the peristaltic motion, even under challenging pipe conditions, such as pipe shrinkage and reduced compressor pressure.

The newly integrated graphical user interface was proved to be an effective means of monitoring and intuitively controlling autonomous operation. Additionally, process of designing the operation itself was made more operator-friendly through the transition to a graphical Behavior Tree editor and removing the need to change this routine through coding. Finally this improved architecture of custom ROS2 nodes was shown to effectively communicate the Behavior Tree and the Graphical User Interface bilaterally, as to allow the GUI to reflect the inspection process but is also able to control it, stop it, and resume it.

The CTO will continue its collaboration with FIU's Applied Robotics Laboratory to bring the LGS to its final stages of development. The upcoming focus will revolve around the careful selection and integration of suitable gamma sensors, as well as the execution of relevant tests that will determine the system's readiness for deployment at the Tank Farms. This collaborative effort represents a significant step toward enhancing safety and efficiency in nuclear facility inspection and maintenance.

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