Digitally Optimized Autonomous Robotic Systems for Hanford Waste Tank Handling, Year 1 Summary

[Revision 1]

DOE EM-TDO

Automated Pit Exploration System (APES) Year 1 Report

Hanford Tank Waste R&D Award 278709

MAY 2025

Anthony D'Andrea
Kaleb Houck
Pengcheng Cao
Kris Egan

Idaho National Laboratory

Leonel Lagos
Anthony Abrahao

Florida International University

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

[Revision 1]

Digitally Optimized Autonomous Robotic Systems for Hanford Waste Tank Handling, Year 1 Summary

Automated Pit Exploration System (APES) Year 1 Report

Hanford Tank Waste R&D Award 278709

Anthony D'Andrea
Kaleb Houck
Pengcheng Cao
Kris Egan
Idaho National Laboratory
Leonel Lagos
Anthony Abrahao
Florida International University

May 2025

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of EMTDO
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

ABSTRACT

The Hanford Site is responsible for managing approximately 56 million gallons of radioactive and chemically hazardous waste stored in 177 underground tanks. A critical aspect of this task involves preparing and maintaining tank pits, which house retrieval equipment such as pumps, valves, and support equipment. These pits are heavily contaminated and require thorough inspection, cleaning, characterization, decontamination, and refurbishment before initiating waste transfer processes. The tank pits, situated above the tanks, provide access to the tanks, pumps, waste transfer lines, and various other components, and often contain miscellaneous debris. Many pits have not been accessed for decades, necessitating the removal of old concrete covers, video inspections, and radiation-level measurements to ensure safe cleanout activities.

Historically, operations in these high-radiation environments, where radiation levels can reach up to 50 rem/hour, have involved manual labor performed from behind shielded panels with long-handled tools, which is slow, tedious, and costly. The pits are covered with a 2-ft-thick concrete cover block that must be removed before traditional inspections can take place. Limited records on tank operational history further complicate accessing these pits, making the process both time-consuming and expensive.

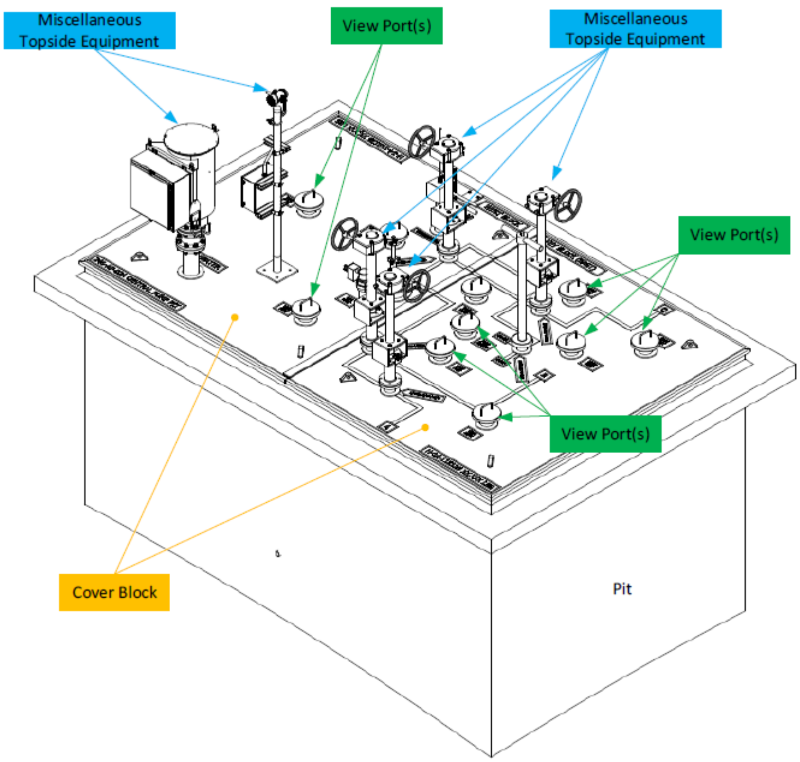

Figure A-1. Non-representative reference pit (WRPS, RPP-RPT-6488, 2024).

Current efforts by Washington River Protection Solutions (WRPS), the Tank Operations Contractor for Hanford, focus on deploying unique robotic tools to minimize human exposure in high-hazard areas. The WRPS Modular Robotic Tooling System, first deployed in May 2022, represents a significant advancement in robotic capabilities for pit work, allowing for tasks such as coating repair and maintenance. However, there remains a capability gap for a technology that can perform visual inspections and light-duty tasks without the removal of heavy concrete covers. Such a robotics capability would need to navigate complex obstacles, access hard-to-reach locations, and be adaptable for various tasks, thereby enhancing the efficiency and safety of pit operations by reducing the need for labor-intensive and costly removal of concrete covers.

The Idaho National Laboratory (INL) is working to significantly enhance the pit inspection process at the Hanford Site by deploying the Automated Pit Exploration System (APES), utilizing the laboratory's experience with robotic systems, digital engineering, and data visualization. This advanced system is designed to perform automated, noninvasive pit inspections, radiation mapping, and simple tool manipulations without the need to remove heavy concrete cover blocks. The APES system allows for remote operation, thereby reducing operator fatigue and error while enhancing safety by minimizing direct human intervention in high-radiation areas. It features a robotic manipulator arm, developed by Florida International University (FIU), equipped with various sensors for monitoring, mapping, and inspecting. In addition to the robotic arm, a crawler robot is used that can be deployed to the bottom of the tanks for close-up visual inspections. These systems and sensors provide real-time data to a digital twin system for artificial intelligence/machine learning predictions. Data visualization techniques are used to enhance operator experience, enabling better environmental understanding and decision-making.

CONTENTS

FIGURES

TABLES

Page intentionally left blank

ACRONYMS

AI	artificial intelligence
APES	Automated Pit Exploration System
CAD	computer-aided design
CMU	Carnegie Mellon University
GPU	graphics processing unit
DOE	U.S. Department of Energy
DT	digital twin
IMU	Inertial Measurement Unit
INL	Idaho National Laboratory
FIU	Florida International University
R&D	research and development
LiDAR	Light Detection and Ranging
ML	machine learning
MR	mixed reality
PDU	Process Development Unit
ROS2	Robot Operating System 2
SLAM	Simultaneous Localization and Mapping
WRPS	Washington River Protection Services (contract now under H2C)

Page intentionally left blank

Digitally Optimized Autonomous Robotic Systems for Hanford Waste Tank Handling, Year 1 Summary

Automated Pit Exploration System (APES) Year 1 Report

Hanford Tank Waste R&D Award 278709

1. SYSTEM AND OPERATIONAL REQUIREMENTS

Operating systems within the Hanford waste tank farms require strict adherence to safety and operational regulations. While the Automated Pit Exploration System (APES) developed and built during this project is meant to be a demonstration unit, adhering to these standards is pivotal for developing new technologies that can later be adopted by the Hanford Site. Requirements are determined by working with the Prime contract for the Hanford Site H2C, and the Idaho National Laboratory (INL) engineering and project management. Table 1 documents these functional requirements as well as INL's expected measurement of compliance.

Table 1. Requirements compliance table.

ID	Requirement	Compliance level (0-10)	Notes
1	The system will operate within environmental conditions described in Section 1.1.	10	All conditions can be met.
2	The system will adhere to design requirements within Section 1.2.	9	The project scope is to build and test a prototype system. Durability and drop tests will be limited as necessary to complete a demonstration system.
3	The system will adhere to visual inspection requirements within Section 1.3.	9	Video streaming capabilities are limited by cameras that can fit down the viewport. Frame rate and resolution are trade-offs that need to be made. Greater resolution is not always preferred over reasonable frame rates.
4	The system will adhere to data collection requirements within Section 1.4.	8	Research into radiation sensors is ongoing. Sensors identified to fit within the system may fall short of detecting up to 1,000.
5	The system will adhere to software and controls system requirements within Section 1.5.	10	All conditions can be met.

ID	Requirement	Compliance level (0-10)	Notes
6	Section 1.6 contains optional system functionality (outside the original scope of the proposal) that the Hanford Site has expressed interest in a pit inspection system doing.	Optional	INL will investigate and implement additional functionality as time and budget allow. Other material considerations for a final build would be evaluated and refined at a later date for a full deployment system.

1.1. Environmental Conditions

The pits are an underground radiological environment. As such, remote operation requirements within a closed-off, low-light, radioactive space are set forth here.

1. Beta radiation range 5–1,000 mrem/hour (strontium).
2. Gamma radiation range 1–60 rem/hour Gamma (Cesium).
3. Operating temperatures range: +14°F to +104°F.
4. Storage temperatures range: +0°F to +120°F.
5. There is no lighting within the pits; the system will provide its own light source.
6. Humidity conditions: up to 90%, non-condensing.
7. The system will be exposed to liquids. The robotic manipulator will have an Ingress Protection (IP) rating of 65 or greater, and the sensors will have an IP rating of 67 or greater.
8. The 2-ft-thick concrete covers likely block communications and Wi-Fi signals. The robots and sensors will have hardline tethers for data transmission.

1.2. Standard Design Requirements

Standard design requirements include functional, performance, and other operational requirements. These guide the overall design of the system and how it handles inspection-related and deployment activities.

1. The system will be deployed through a 4-inch view port. The overall diameter of the system with sensors will fall within 3.8 inches to accommodate variations in view port sizes.
2. The system should be capable of scanning a 10 ft^3 pit mock-up environment.
3. A pit representative mock-up will be made to test the system.
4. Any supporting structure will be limited to 2 feet below the cover block.
5. Supporting structure above the cover block will be limited to 100 lb/ft^2.
6. The system will have the ability to collect small contamination samples.
7. The system will have the ability to survive a drop test.
8. The system will include visual, radiation, light detection and ranging (LiDAR), temperature, pressure, and humidity capabilities that can be viewed in real-time.
9. The system will minimize entries into the port, ideally less than three.

10. The system will be able to complete a pit scan within one hour.
11. The structure of the system above the pit will automatically introduce and retract the robots from the pits.
12. The structure of the above ground components will be capable of being built in place with two operators.
13. The system will be constructed and deployable without the use of a crane.
14. The system will be housed and powered from a single ground vehicle platform.
15. The system will provide lighting sources.
16. The robotic arm will have a carrying capacity greater than 10 lb.
17. The system should use commercial off-the-shelf components where practical.
18. The system will have a minimum of these:
    a. A robotic arm configuration for overhead inspections
    b. A robotic crawler configuration for bottom-of-pit deployments
    c. An overhead pan-tilt-zoom camera for third-person view of the system.

1.3. Visual Inspection Requirements

Multiple visualizations are going into the production of the APES, for example, a standard camera capable of taking still photos and videos, a depth camera capable of measuring distances based on visual data to build area maps, and a LiDAR for point cloud visualizations. In addition to these, options are being explored to include an infrared (IR) camera. The IR camera can be used in tandem with machine learning (ML) techniques to process data invisible to the naked eye. This data can be used to detect cracks or the wearing of enamel coatings. The robotic arm configuration is planned to house all visual sensor variations while the crawler robot will house a standard 2D camera.

1. The camera systems will be able to live stream and record video.
2. The camera systems will be able to have a full 360-degree field of view and be able to access all areas of interest within the pit.
3. The system will have high-resolution cameras capable of 9-megapixel photograph resolution and 4k peripheral output.
4. The system will output point cloud data.
5. The standard camera will have zoom and focus capabilities.
6. Lighting will be sufficient to produce a clear image.

1.4. Data Collection Requirements

APES will house various data collection sensors, including, radiation, Temperature, vapor, dewpoint/humidity, and pressure sensors. Data collected with these sensors will be viewable in real-time, in stored data, overlayed with generated maps and within the digital twin of the system.

1. All sensors will be deployed by robots.
2. Data will be recorded and available to view in real-time.
3. Data will be overlayed with generated maps of the pits.
4. Data collection will take place within and outside the pits.

5. Radiation sensors will have scan angular resolution less than or equal to 5 degrees.
6. Radiation sensor will be able to detect 5–1,000 rem/ hour.

1.5. Software/ Control Systems Requirements

The APES is an intricate system of various components and subsystems, all brought together to complete a singular purpose of autonomously inspecting pit environments. Multiple programs and systems need to communicate with one another to complete these tasks. Different software platforms are needed for component controls, robotic simulations and ML, digital twinning, operator interface, and systems visualizations. These systems will ideally operate seamlessly in one operator interface. It has been repeatedly observed that if a system is not easy to use, operators will simply opt not to use it. Success in providing an intuitive, easy-to-use operator interface is essential to crossing technology over the valley of death.

1. The system will utilize Robot Operating System (ROS) 2 as its main communications framework.
2. The system will use Unity for visualizations.
3. The system will use Deep Lynx for a digital twin (DT) and metadata storage platform.
4. The system will use NVIDIA Omniverse and Isaac ROS for robotics simulations and ML.
5. A DT of the system and the pit environment will be created.
6. The DT will be used for predictive modeling to inform operators how the system is changing overtime and where additional wear may be forming and maintenance may need to occur.
7. The system will use mixed reality (MR) headsets for real-time visualizations.
8. Controls of the various pieces of equipment will be performed with a standard mouse and keyboard or game controller.
9. The system will have the ability to be accurately positioned and avoid collisions within the pit.
10. All communications will take place with tethered connections. Wireless controls will not be permitted.
11. The system will have path planning and collision avoidance with operator feedback.

1.6. Additional Interest Areas

Through conversations and documentation from the operators at the Hanford Site, additional desired functionality has been discovered. As these features were not initially identified during the proposal they are outside the scope and budget of the initial project. Some features could be implemented later and will be explored as time and budget allows. APES uses an open end-of-arm tool design platform; this feature allows for expansion of tools and functionalities after initial installation. In addition to functionality additions, some of the options below are material requirements that will apply to a deployed system on the site; no comment can be made on material determinations at this time.

1. Explore the ability to interface with and manipulate various valves, hoses, tubing, and debris.
2. Explore the ability to install test plugs suck as “Griptight Test Plugs” 2-inch or 3-inch sizes.
3. Explore the ability to deploy a spray cleaning end-of-arm tool apparatus.
4. Deployment system materials should adhere to TFC-ENG-STD-34, which is the standard for nonmetallic materials selection.
5. Deployment systems construction should use stainless steel where possible.

6. Deployment systems should have the ability to survive a 3-foot drop test. Drop tests will not be performed on the demonstration system, additional durability testing and refinement will need to take place after the scope of this research project.
7. The deployment system should use Quintolubric 888-46 as a fluid for required fluid-controlled components.

2. DESIGN CONCEPTING AND RESEARCH

2.1. Research/Design Areas

Under collaborative effort to support the Hanford Site goals, several methods have been researched to match the features that were discussed in the previous sections. Table 2 through Table 10indicate areas of research that were used to match features and expectations as the project has been defined and refined to meet the adaptive and evolving project milestones.

Table 2. Crawlers.

Design Element Crawlers			
Concept/Equipment	Research Support	In Development	Implemented
Troglotrek is partnered with the Sigma HD 100 camera system	X		
Tracer X5 with a LiDAR camera system	X		
Nexxis Hellcat & Panther systems with Juicebox controller	X		
Nexxis custom robotic crawler systems with Juicebox controller		X	
Minicam PLS250S with pulley system	X		
Minicam CRP90 with pulley system	X		
High-bred custom designed system		X	

Table 3. Cameras.

Design Element Camera Systems			
Concept/Equipment	Research Support	In Development	Implemented
1080p Cyclopz HD pole camera	X		
Voyager C68 HD videoscope	X		
XTC videoscope	X		
Proteus	X		
Minicam CAMO28L	X		
Minicam CAMO26	X		
PhaseONE band solution camera integrated RGB, achromatic, NIR cameras	X		
IXM-RS280F RGB/NIR combination	X		
Nexxis Scope 89 drop camera		X	
D3 Engineering AR0234 camera			X
Emergent Vision Tec CMV 5000	X		
Axis communications FA1105	X		
RPC A4NX Jetson control box			X

Table 4. Imagery software.

Design Element 3-D RGB/NIR Software			
Concept/Equipment	Research Support	In Development	Implemented
PhaseONE PAS	X		
Video generators	X		
OAK-D Pro W – LUXONIS	X		
ZED-X MINI Stereo camera			X

Table 5. LiDAR.

Design Element LiDAR			
Concept/Equipment	Research Support	In Development	Implemented
Keyence laser proximity sensors	X		
Velodyne puck	X		
Ouster OS0 ultra-wide LiDAR	X		
Livox Mid 360			X
DataSensing LGS-A10 2D LiDAR	X		

Table 6. Mobile Tank access design.

Design Element Mobile Tank Platform Support Equipment			
Concept/Equipment	Research Support	In Development	Implemented
Black Bruin hydraulic motors/on-demand wheel drive system	X		
Mobile crane supported system deployment	X		
Above pit wheeled steel weldment frame structure	X		

Table 7. Infrastructure.

Design Element High-Bay Infrastructure			
Concept/Equipment	Research Support	In Development	Implemented
30 × 30 × 18 temporary building design	X		
High-bay rental locations across Idaho Falls, Idaho	X		
Power requirements and design	X		
Porta floor design	X		
Outside contract support	X		
Custom space inside INL PDU Lab			X

Table 8. Workstation.

Design Element Workstation Design for Ford Lighting			
Concept/Equipment	Research Support	In Development	Implemented
Mobile workstation and mounting system		X	

Table 9. Cranes.

Design Element Portable/Fixed Crane System			
Concept/Equipment	Research Support	In Development	Implemented
Ford Lighting bed drawings/crane mounting support		X	
PH150 portable crane system	X		
Steller EC3200 portable crane system	X		
IMT 3203I portable crane system	X		
Intur 3515E/3516E portable crane system	X		
Aluminum bed plate mounting equipment		X	
Powertwin II stabilization jacks		X	

Table 10. Deployment vehicle.

Design Element Deployment Vehicle/ Power Delivery System			
Concept/Equipment	Research Support	In Development	Implemented
Ford Lighting		X	
Chevy van	X		
Electric service truck	X		
Electric service van	X		

2.2. System Deployment Structure Concepting and Design

Various functional systems or subsystems have been identified to build a complete system. In addition to the robots, systems are needed to complete the tasks of bringing the robotic systems into position, fixturing them in the correct locations, lowering the robotics into the pits, and extracting the robotics in a controlled manner. The following is a breakdown of these system components:

1. System support structure/ platform and housing
2. Introduction/Extraction mechanism
3. Mechanism for removing the plug caps from the viewports
4. Custom robotic manipulator arm
5. Crawler configuration robot.

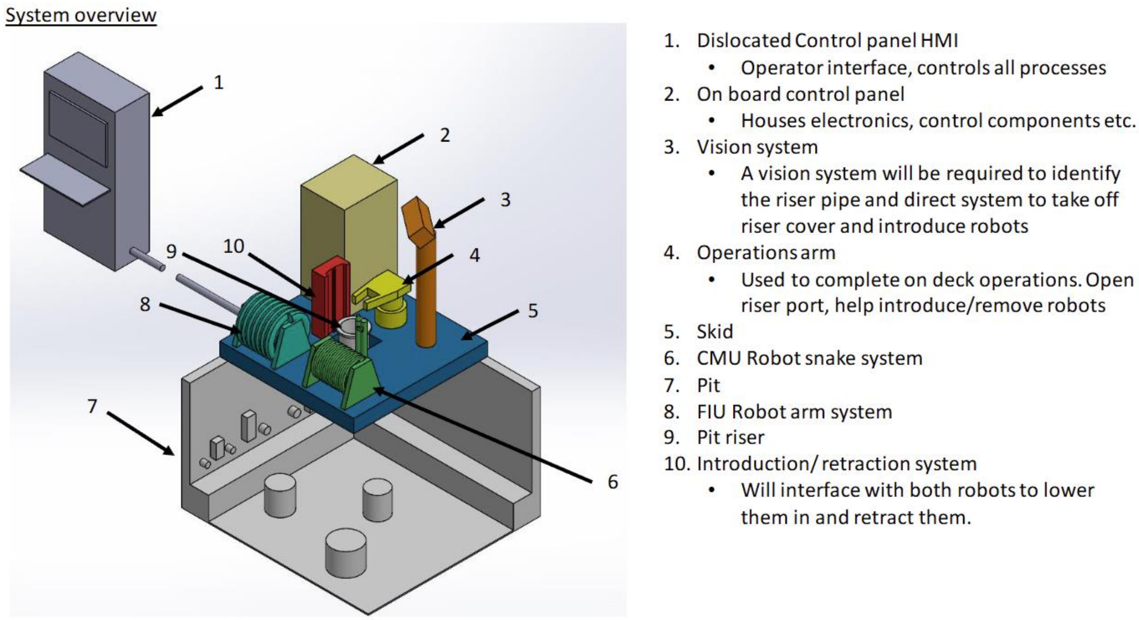

Figure 1. Initial system overview concept.

2.2.1. System Support Structure/Platform and Housing

It has been identified that a single platform or structure is needed to organize and house the various pieces of robotic equipment and position the robots on the pit. Multiple designs have been considered for this subsystem. The INL team first explored using an adjustable, fabricated steel-frame structure that can adjust to span the width of each different pit. The idea would be that the entire system and structure would be built into a single component that could be driven into place or assembled on site. While offering greater configurability, long-term component housing, and support structure, the concept is very expensive, cumbersome, complex to deploy and may have trouble fitting into each pit area.

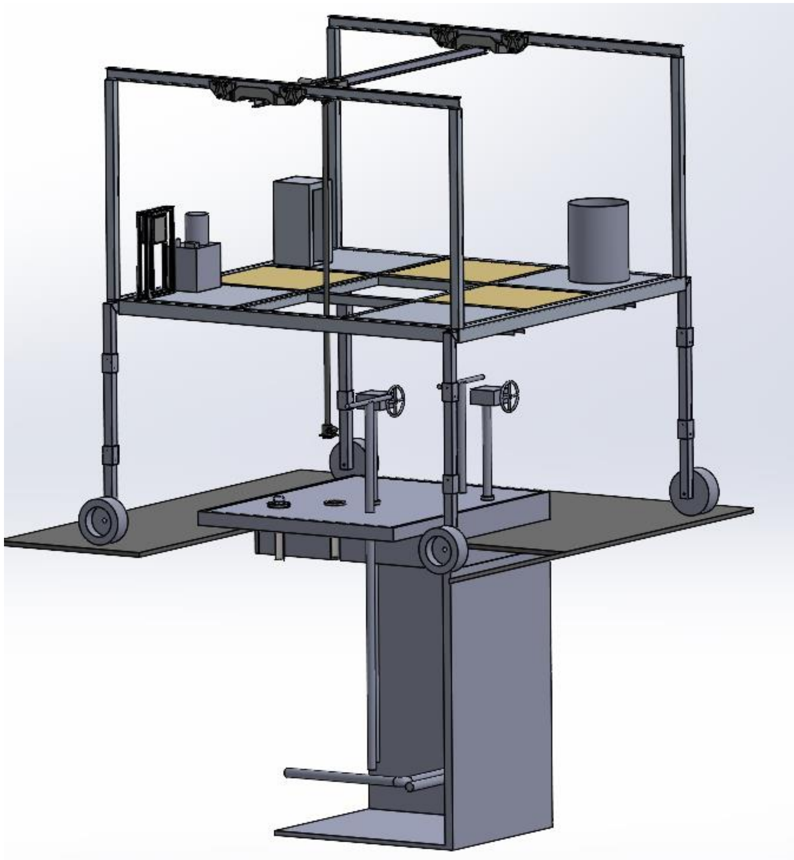

Figure 2. Adjustable full system support frame concept.

To solve some of the issues identified while exploring structural framed and overhead skid designs, the team explored vehicle-based delivery systems. These platforms offer multiple advantages, the first being operator familiarity. Pickup trucks are a commonplace vehicle, and the interface is used by everyone with a driver's license on a near-daily basis. The relatively small vehicle compared to other material handling equipment can be driven into place on site, and the robotics can be deployed from the bed of the truck. Newer trucks with electric power delivery systems offer the added capability to directly power the APES without bringing in external power from a generator. In addition to this, the truck cab can be used as an operator suite, providing a more comfortable, climate-controlled environment from which the controls can be operated and viewed. The mobile truck deployment platform was ultimately chosen as a final design solution for these reasons. The design choice comes with the tradeoff of needing to design smaller, more configurable robots and introduction mechanisms that can fit in the bed of the truck. While offering a challenge, this design conforms with H2Cs request that mechanisms can be assembled in place and by hand with two operators.

2.2.2. Powering Solutions

Figure 3. Ground vehicle based delivery system concept.

Figure 4 displays a simplified schematic representation of the experimental circuit. The experimental setup connects various components to the outlets on a Ford F150 Lightning, turning them on and off and adjusting the load values. Apart from the pickup truck circuit, this rest of the test circuit consisted of the following components:

- Dell™ Precision 5690 Workstation (referred to as "Laptop" in Figure 1 with input voltage 120 V)
- Box fan (nominal voltage 115 V and current 14.4 A)
- Syslogic™ RPC RSL A4AGX AI Rugged Computer (input 120 V)
- Adjustable 240 V resistive load bank.

This experimental setup included all the system components, as illustrated in Figure 4. Both Dell and Syslogic computers as well as a box fan were connected to the 120 V outlets located in the vehicle's front trunk (frunk), while their power consumption was measured using a clamp meter and then displayed and logged using a Hioki Power Analyzer PW6001. An adjustable load bank was connected to the 240 V outlet at the rear of the vehicle. A graphics processing unit (GPU) for stress tests was initiated on the Dell workstation, and one Robot Operating System 2 (ROS2) program incorporating a rosbag replay with intense GPU usage was executed on the Syslogic computer to simulate the real-world APES operation. Initially, the box fan and load bank remained powered off. The vehicle's heater and lights were kept on throughout all the tests to simulate typical operating conditions. The conceptual design of the pickup truck-based delivery and power system pickup truck powering robot operation is depicted in Figure 33.

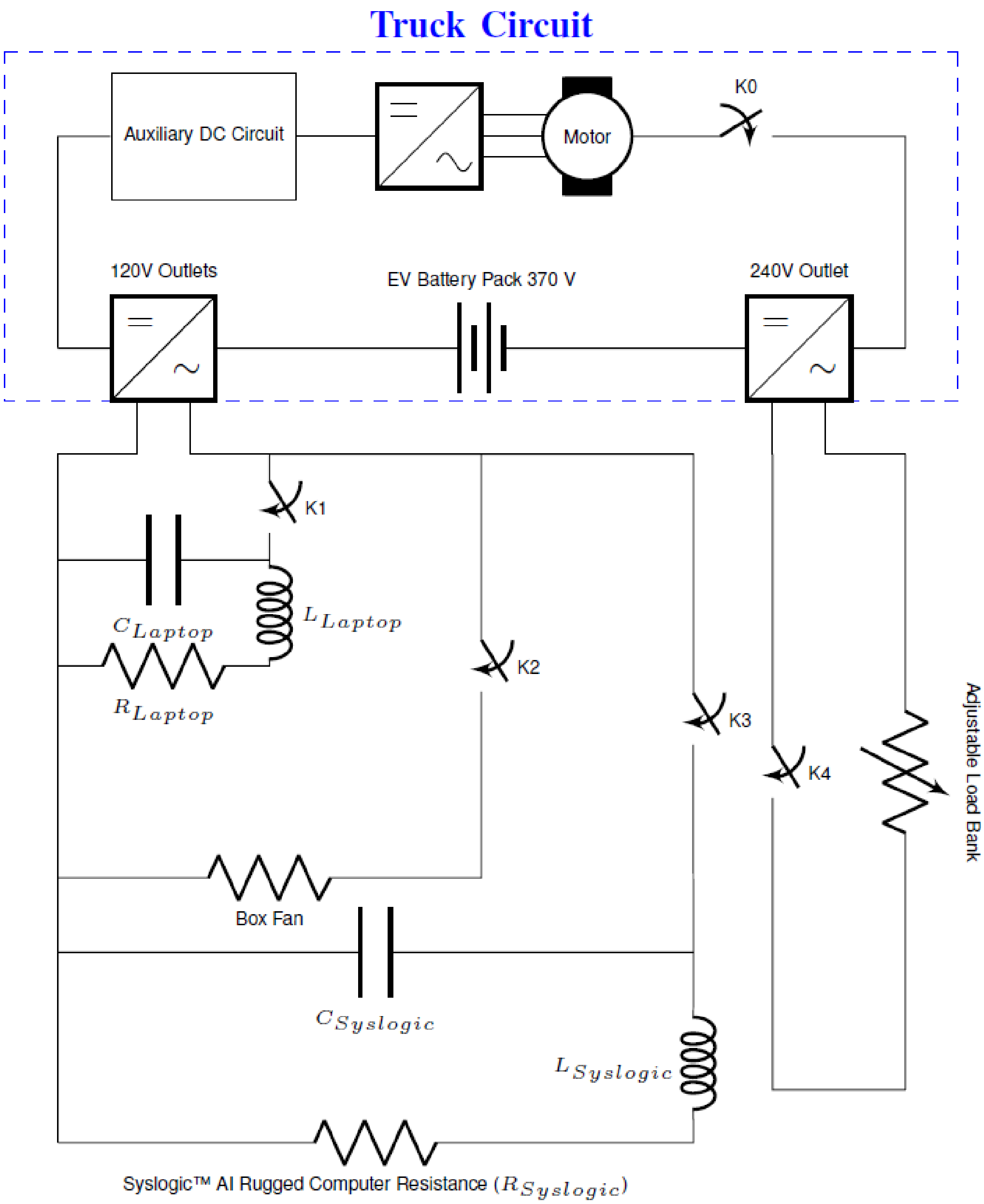

Figure 4. Simulated APES multi-robot system electric circuit powered by F-150 lightning.

Three tests were conducted. The first was a load performance test, during which various loads were applied to evaluate the onboard power delivery system's response. The second test assessed the 240 V outlet's power limit by increasing the load on the load bank until the outlet's maximum capacity was reached while all other components were running. The third test, a battery drawdown assessment, involved operating the components in a steady-state condition for one hour. Battery life and vehicle mileage were recorded at the start and end of this test.

The results of the tests confirm a pickup truck's ability to deliver consistent power with minimal distortion and without unexpected cutouts demonstrate its suitability for supporting complex multi-robotic systems like APES. Notably, the onboard battery exhibited only a modest level of charge depletion under the expected operational load, indicating sufficient reserve capacity for both operational and transportation needs. The more detailed presentation of the results can be found in previous publications by Cao et al. (2025).

2.2.3. Introduction and Extraction Mechanisms

Concepts have been created for how the robots will be lowered into place through 4-inch view ports and will be positioned within the pit and then extracted back out. These positioning mechanisms should be highly controllable and offer variable depth positioning. Considerations were also taken as to how the robots could be extracted with containment or allowing the components that went inside the pit to be bagged out.

2.2.3.1. Robotic Pipe Puller

A design and prototype have been developed for an internal pipe pulling device. The idea behind this device is that it could be placed inside an enclosed pipe with the robot pre-mounted to it, and then that pipe could be mounted directly on the riser. The entire pipe pulling mechanism would be lowered and raised internal to the pipe. The tested prototype is a miniaturized length design that was used for pulling force testing. The results from these tests are scaled up to determine the design viability.

The prototype test results yielded valuable insight into how such a design would perform in a real-world scenario as well as how pit conditions could affect the functionality of equipment. Frictional coefficients between the wheels and the sides of the pipes varied more than expected. Given the need for precise positioning for the robots, it was determined that while functional, the design could not be relied on if the pipe's interior had greasy, dusty, or wet sections that could cause the wheels to slip. Lower-than-calculated potential pull forces or payload capacity was also observed for the testing but could be remedied with slight adjustments to tensioning mechanisms, higher torque motors, and additional contact wheels. Tests yielded an average maximum payload capacity of 4.8 kg, which would translate to a full-scale model capacity of 17 kg. Successful tests proved the ability to accurately position a payload within a completely enclosed pipe environment with a lightweight device. While not chosen to be used for the robotic components, the design could still be implemented for auxiliary camera and lighting systems that could be deployed through an additional view port to give a third-person view of the system in operation.

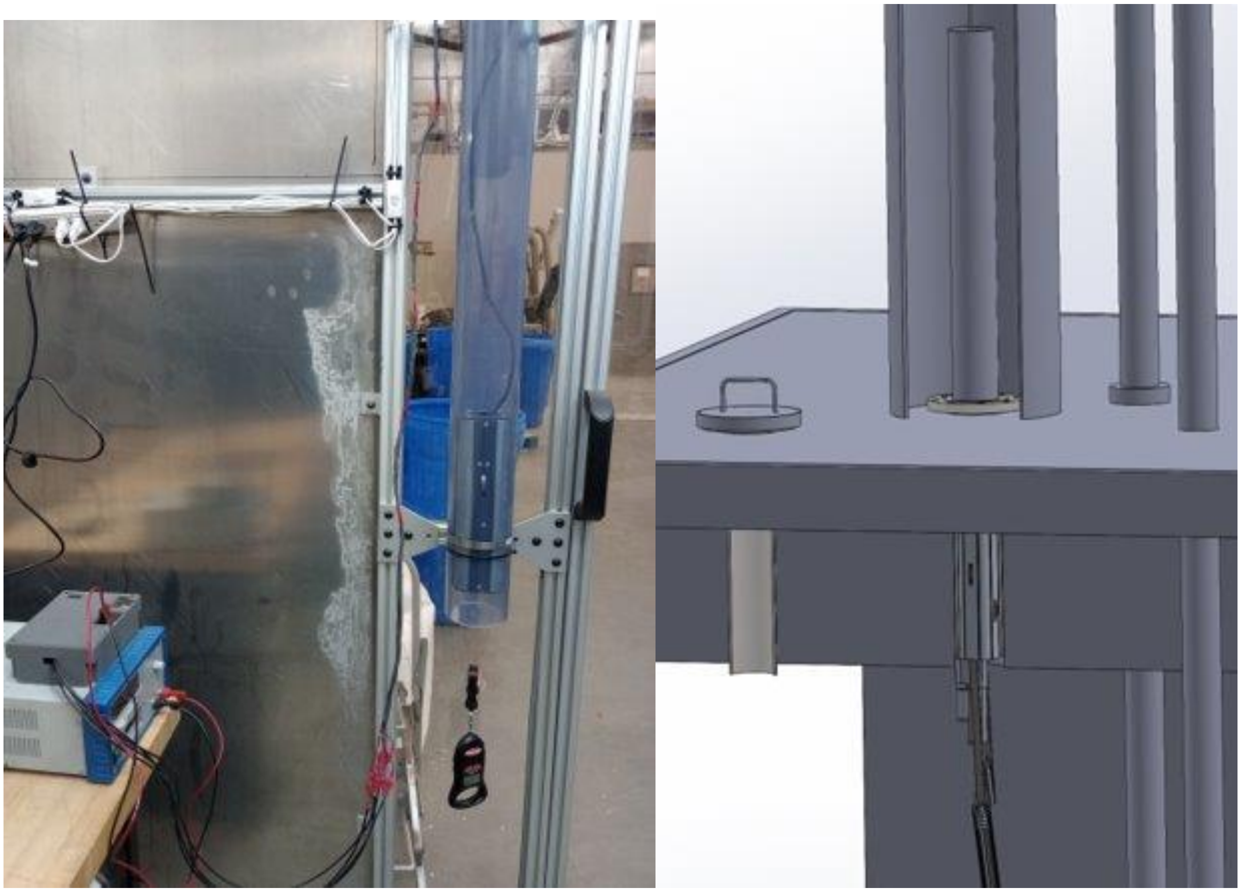

Figure 5. Robot pipe puller prototype and CAD concept.

2.2.3.2. Geared Bearing Rail Slide

Additional designs have been explored and modeled for the introduction and extraction of robotic components into the pits. These designs offer a more robust positioning method, but are larger, heavier, and more complex to set up. It has been determined that the reliable positioning of the robot is the critical determining factor in design decision. The trade-offs can be mitigated, and additional setup time is an acceptable trade-off for the system to function in a more reliable manner. These designs include various types of geared drive systems for vertical motion, turntables for rotation, and actuated internal mechanisms to deploy additional supporting/stabilizing arms.

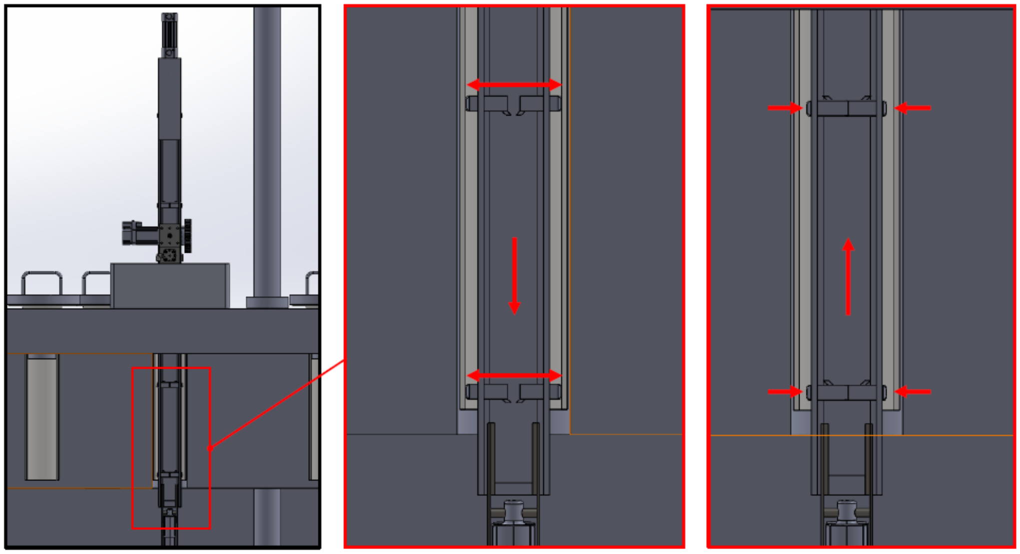

Figure 6. Geared rack introduction/extraction CAD concept with extension supports.

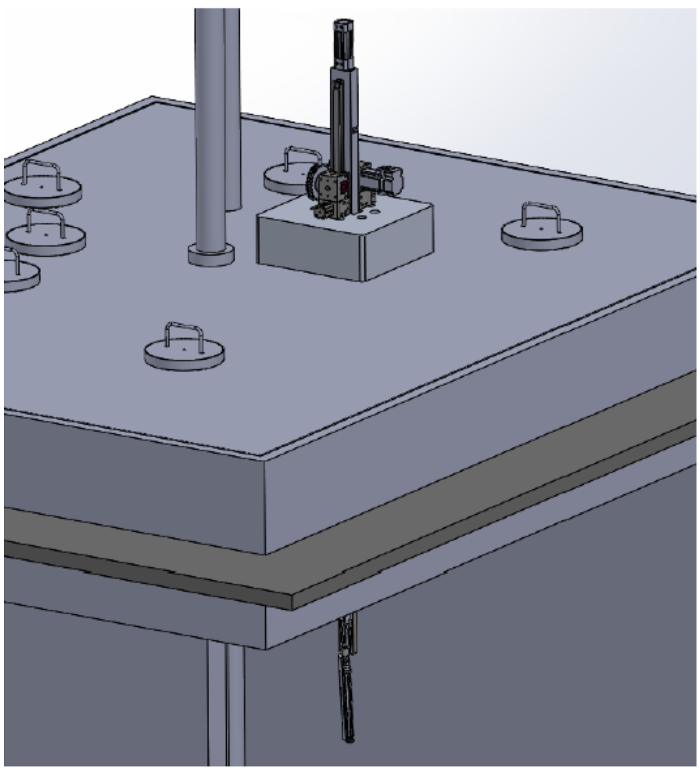

Figure 7. Geared rack introduction/extraction CAD concept.

2.2.4. Florida International University Robotic Arm

Florida International University (FIU) is collaborating with INL on the project to develop a robotic arm. Multiple design concepts have been worked up and discussed. Each design has its own unique strengths and weaknesses. The telescoping arm would have a long reach and move through certain obstacles. The scissor design could be good for manipulating equipment or plugs along the sides of the pits, and the cable-driven arm could offer more flexibility. The designs have kept open considerations for the various sensors and end-of-arm tooling attachments and will allow for swapable end effectors. The final design was the cable driven arm. Its increased flexibility and payload capacity should offer superior performance for inspecting the entire pit environment.

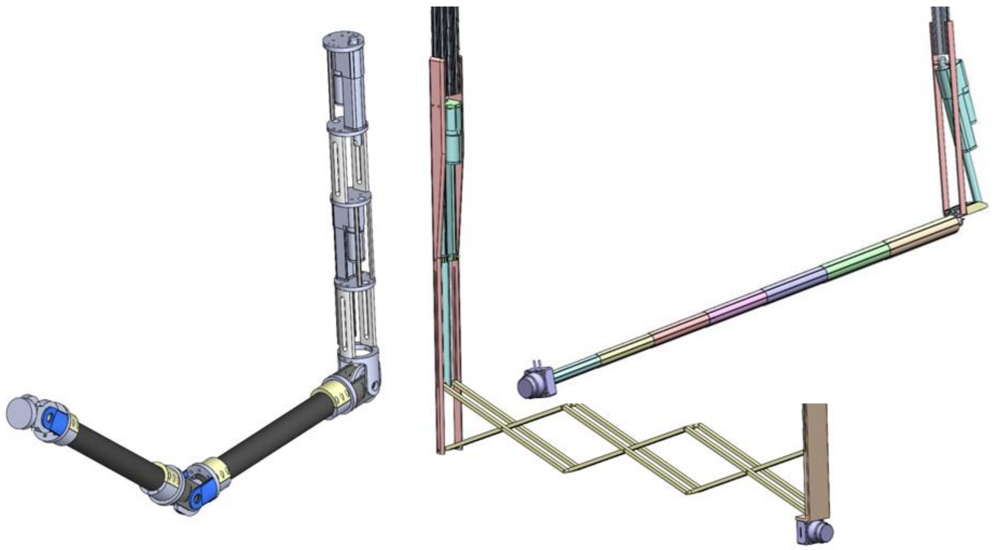

Figure 8. FIU robotic arm concept designs. Cable driven, scissor, telescoping (from left to right).

In addition to using computer-aided design (CAD) modeling, the team at FIU built function prototypes of their designs. These prototypes are invaluable for providing data on refining designs, identifying wear or weak points, and proving the concept is functional. The cable-driven arm prototype has exceeded the payload weight capacity requirement and can supply a degree of controllability that is superior to other designs. For these reasons, it was chosen as the final design path. Further design changes are already underway to make the arm stronger and more rigid, to include more axes of rotation, and to find more durable fabrication materials.

Figure 9. Cable driven arm prototype.

2.2.5. Robotic Crawler Configuration

In addition to the robotic arm configuration, the system has a robotic crawler that will be deployed through the same 4-inch view ports. The crawler will be lowered to the bottom of the pits via a tethered cable. This crawler robot will enable close-up views of the concrete at the bottom of the pits as well as offer a bottom-up view. The initial intention is to mount the camera to the crawler, but the team is exploring options for the other sensors to be attached to it as well.

Initially, INL had planned on collaborating with Carnegie Mellon University (CMU) to develop a version of their snake robot that could perform this task. After the project started, negotiations began between subcontracting and legal departments. Unfortunately, contractual agreements could not be made between the two parties. Eight months into the negotiations, project management did not believe a solution could be found nor that target milestones could be completed. With U.S. Department of Energy (DOE) approval, the decision was made to no longer pursue the subcontract with CMU, and instead buy a robotic crawler from the company Nexxis. This custom crawler will be able to complete the same inspection tasks as the other robot. The budget that was reserved for the subcontract is going to the purchase of the crawler as well as the extra software, controls, and integration development that INL will need to do. The order for the system was submitted, and delivery of the system is expected in the second quarter of Year 2 of the project.

2.3. Digital Twin, Artificial Intelligence, and Automation Platforms

The core components of the software architecture have been identified to build a complete system. Data from robotics platforms will be collected and stored on a computer system located on the truck powering and hosting the robotic systems. This computer system will be a standard laptop computer that hosts a high-end GPU for the purposes of training and executing artificial intelligence (AI) models. Additionally, the truck will host a ruggedized NVIDIA Jetson AGX Orin that is designed to perform robotic automation. The computer storage will additionally host the software platforms that will perform data acquisition, the robotic operating systems, process orchestration, robotic automation, DT, and visualization.

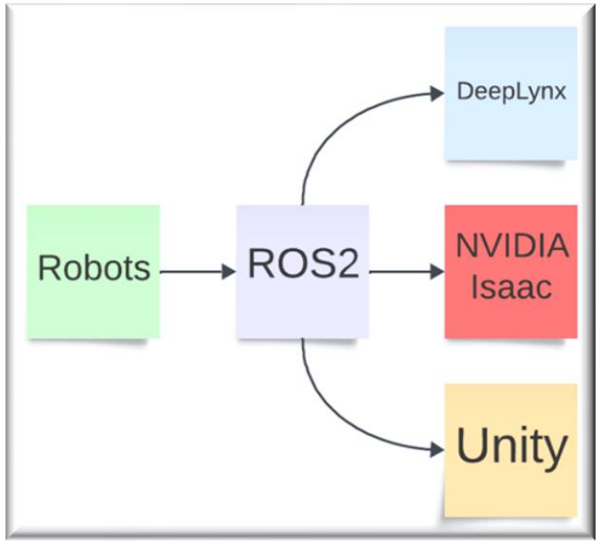

Figure 10. Software data flow.

2.3.1. DeepLynx Digital Thread Platform

DeepLynx is an open-source data warehouse developed by INL to facilitate digital thread and DT activities. DeepLynx stores both time-series data that will come from the sensors and other data formats in a graph database specified by an ontology. The APES project has started configuration of the data sources and ontology that will be used for the pit inspection system. The DeepLynx system is a mature system used across multiple DT efforts, so the work performed by the team is configuration and integration into the other systems in the software architecture. Discussions are ongoing on how to best ingest data from ROS2 into DeepLynx due to its publisher-subscriber architecture. The Jester software used previously on DT efforts may be modified to support this effort, or alternatively AirFlow, an open-source orchestration system can be used to facilitate this requirement. Additional information is on DeepLynx Digital thread platform through INL's software webpage (Ritter, Darrington, and Browning).

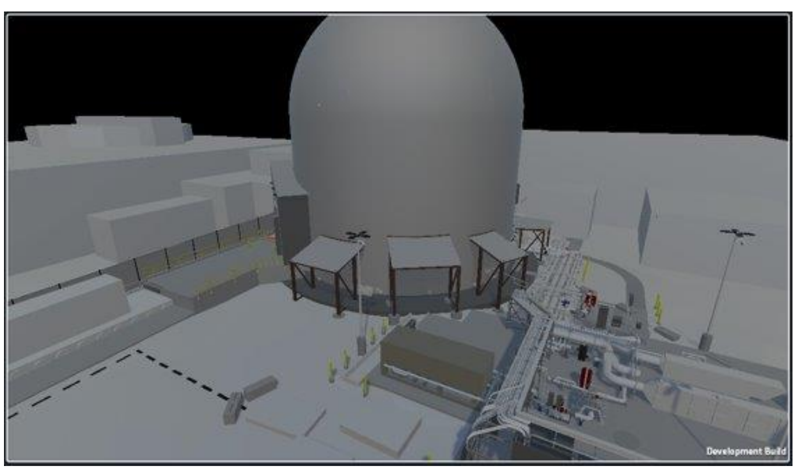

Figure 11. DeepLynx DT viewer example.

2.3.2. NVIDIA Isaac

NVIDIA Isaac is robotics simulation software that incorporates a high-fidelity physics engine to enable developers to train autonomous machines in virtual environments. This system can interact with physical robots as well as virtual robots through ROS2. Through this connection, a virtual environment meant to represent the intended environment can be used to train robotic AI to perform autonomous operations. This software can also integrate virtual or physical sensors as well to simulate readings that are gathered during operations with robotic systems. This capability will allow the team to prepare autonomous operations with the robots under design both before they exist and before they enter the intended environment—the pits at Hanford. Current efforts are focused on integrating with ROS2 operating on robotic systems, including feeds from a Boston Dynamics SPOT robot and a Yahboom robotic rover. These two platforms, while they do not do what will be deployed in the pits, will allow for validation of the simulation strategy. Two interns have started since the end of Year 1 who will be focused entirely on this part of the project.

2.3.3. Unity

Unity is a game engine used for creating 2D and 3D interactive experiences. The purpose of using Unity will be to provide a user interface to the data collected by robotic systems and results from AI. Current efforts on Unity are focused on integrating the game engine into ROS2 for the purpose of visualizing real-time data feeds from robots being used in development. The ROSSharp package, which is being developed by Siemens, as well as a ROS2 bridge are key components that will be implemented to facilitate integration. This work will be useful for visualizing real-time operations. Additionally, efforts have begun to visualize the historical data from performing pit operations by integrating with DeepLynx. The team has created a CAD mock-up representing a nominal pit to be used for initial visualization efforts and for the use of robotic simulation. Additionally, the team has received LiDAR scans in the form of point clouds and are working toward incorporating those into both the visualization and simulation platforms.

3. CONTROL SYSTEM SOFTWARE

Efficient control system software for APES, which incorporates various components and subsystems that must communicate efficiently, is to be built for the project. It requires different software platforms for component controls, digital twinning, operator interface, and system visualizations—all ideally operating seamlessly within one operator interface for ease of use. This control system has the complex task of taking multiple systems that were developed to be standalone systems with a variety of different sensors and configurations and integrate them to function as a single, seamless system. To facilitate this work, the ROS2 software framework is being used. This architecture will offer a simplified method of communication between various components, enabling the equipment to be controlled and data to be transferred back and forth.

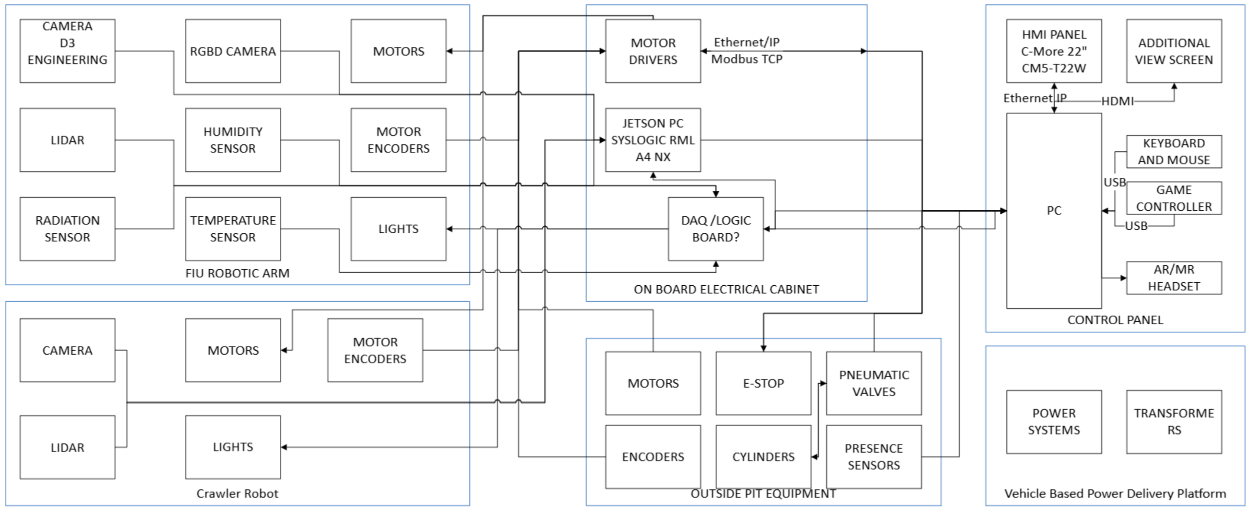

Figure 12. Equipment communications plan.

3.1. ROS2 Software with Distributed Computing

To design the software to navigate the crawler robot inside the tank pits to collect sensor data, the team needs to take the limitation of the onboard computational resources into consideration. Fortunately, the overall design plan uses tethered communication, which includes Ethernet cable connections. Additionally, it is possible to use ROS2 in-domain communication to split computations between multiple computers. Therefore, the team proposes distributing computational tasks between an edge robot computer and a more powerful cloud-based computer using ROS2 in-domain communication over an Ethernet connection.

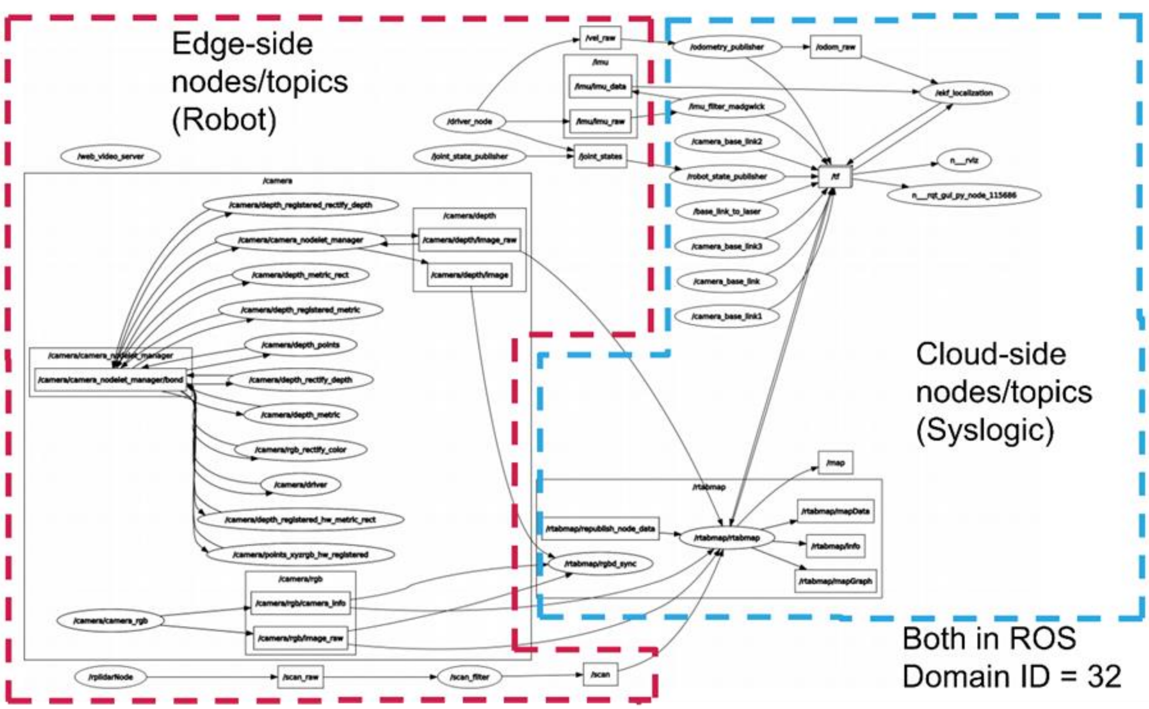

Figure 13. Edge-cloud computation task allocation for ROS2.

3.1.1. Edge-Side Software

The robot is interfaces with the RGB-D camera and LiDAR sensors. These nodes publish essential data streaming topics, including `/camera/rgb/image_raw` and `/scan`. The robot processes these streams locally and publishes them into the shared ROS2 domain, making them available to subscribers running on the cloud-based system.

3.1.2. Cloud-Side Software

The Syslogic computer subscribes to these raw sensor topics for higher level processing such as mapping, localization, and visualization. Key nodes on the cloud computer include `/rtabmap/rtabmap` and `/ekf_localization`, which are responsible for SLAM (Simultaneous Localization and Mapping), sensor fusion, and broadcasting transforms for RViz. RTAB-Map modules like `/map`, `/mapGraph` and `/mapData` are also hosted on the cloud, significantly reducing the computational load on the edge device. This separation of responsibilities ensures real-time responsiveness at the edge while leveraging the cloud's computational power for intensive processing through efficient ROS2 in-domain communication.

The resulting ROS2 rqt graph is shown in Figure 5. This diagram illustrates how computational responsibilities and topic communications are distributed between the edge and cloud computers via Ethernet connection, both of which operating under ROS_Domain ID = 32. The edge-side (highlighted with the magenta dashed box) is responsible for low-level hardware interfacing and real-time sensor data publishing, while the cloud-side (blue dashed box) manages higher level perception, localization, and visualization tasks.

3.1.3. Test Results

During the test, the team also runs the system performance monitor software on both cloud and edge computers five minutes after the ROS2 software is started on both sides to prevent observing significant fluctuations or surges in CPU usage. Both computers are running on Ubuntu 22.04.5 LTS Linux-based operating systems, and their truncated 60-second CPU usages are shown in Figure 14 and Figure 15. As can be observed from these plots, both computers are keeping their CPU usages mostly under 50% when running all the tasks in Figure 5. This validates the project's approach and showcases great potential for distributing more available resources for other robotic tasks without exhausting the robot onboard computer's resources or compromising performances.

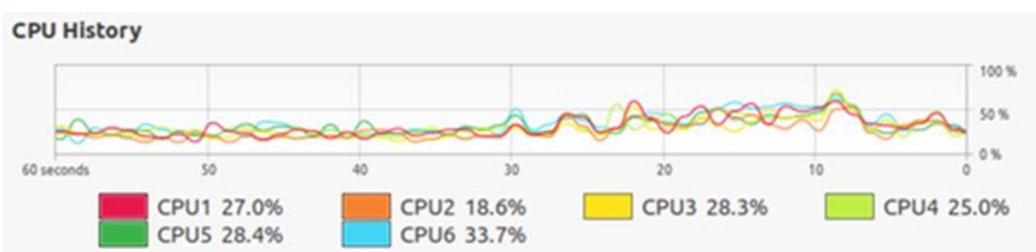

Figure 14. Edge computer CPU usage.

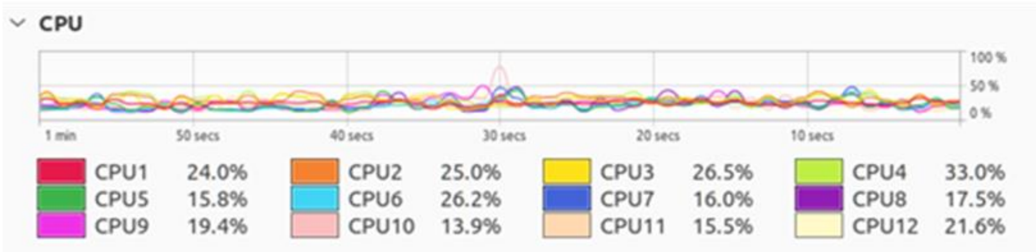

Figure 15. Cloud computer CPU usage.

3.2. Robot Navigation Systems

Immediately after performing distributed computing tests, the team conducts mapping and navigation simulations and then tests the software kit in the real-world scenario. The reason for running this simulation and the subsequent real-world deployment is that the team will need to deploy the crawler robot to traverse inside the pits to build 3D point cloud maps and to perform structural health and radiation-level monitoring. This simulation is fully run on the cloud computer. However, the subsequent in-lab SLAM testing is completed using the distributed computing in the same ROS domain as discussed in Section 3.1.

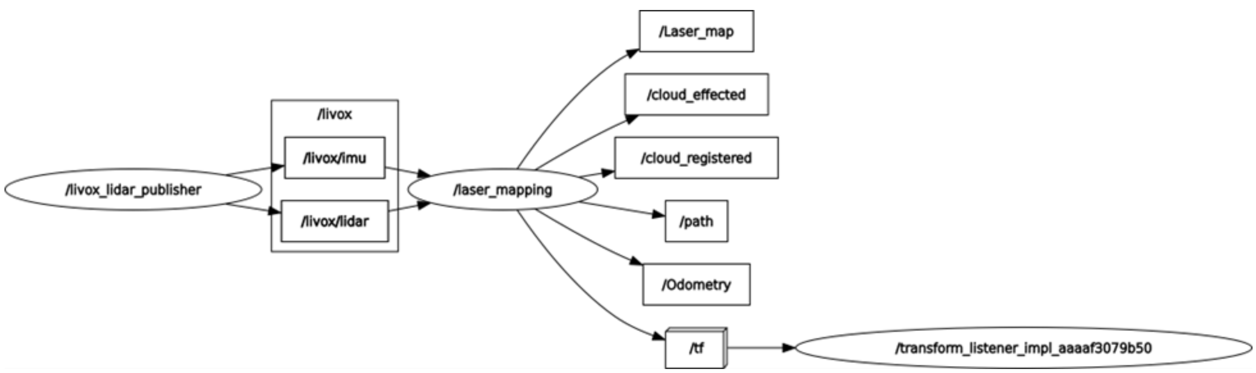

Figure 16. ROS2 diagram for LiDAR-based navigation package.

3.2.1. Hardware Setup

First, the hardware setup includes the SPOT robot dog, developed by Boston Dynamics, which is known for its agility and ability to navigate challenging environments. The sensor-computer kit includes a Livox MID-360 LiDAR sensor, a ZED-X Mini RGB-D camera for visual output, and a Syslogic rugged edge AI computer capable of processing the sensor data in real-time. This computer may be equipped with a powerful CPU and GPU to handle computationally intensive tasks like SLAM.

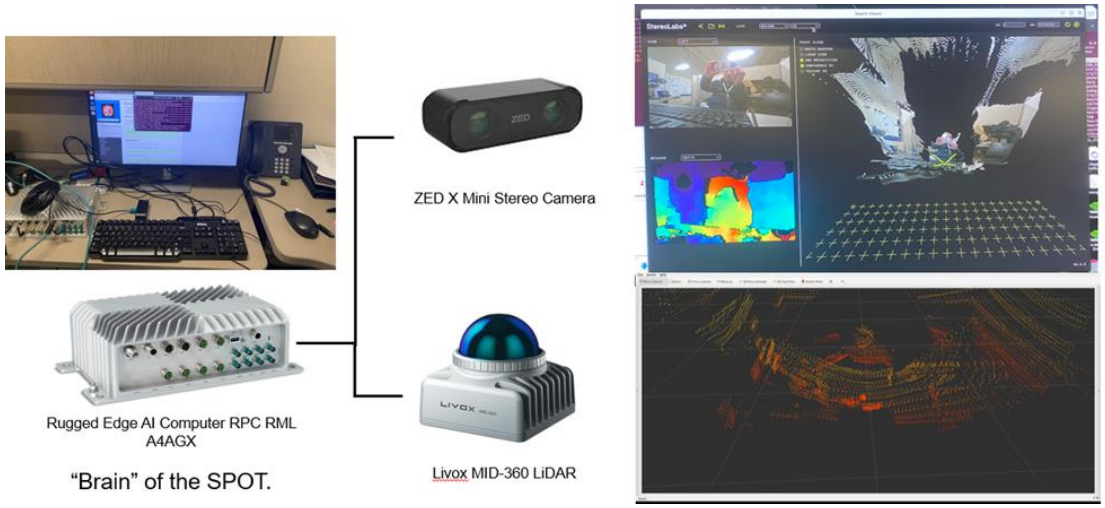

Figure 17. Hardware setup for robot navigation.

3.2.2. Software Packages

The FAST-LIO package (Xu and Fu 2021) is used. FAST-LIO is designed for real-time processing and combines LiDAR data with inertial measurements to provide accurate and fast odometry estimates and point cloud mapping. The ROS is commonly used to facilitate communication between different software components and hardware sensors. The FAST-LIO package is typically integrated into a ROS environment to make use of its tools and libraries.

The integration process involves mounting the LiDAR sensor and IMU (Inertial Measurement Unit) on the SPOT robot. These sensors are calibrated and configured to ensure accurate data capture. Data stream setup includes establishing topics for LiDAR point clouds and IMU data in ROS, which are published in real-time as the SPOT robot moves. The FAST-LIO package is then configured to subscribe to these LiDAR and IMU data topics. Parameters, such as sensor offset, noise characteristics, and processing rates, are fine-tuned for the specific hardware setup. The resulting ROS2 diagram is shown in Figure 8.

3.2.3. Real-World Navigation Tests

During the mapping process, as SPOT navigates the Process Development Unit (PDU) high bay, the LiDAR sensor continuously scans the environment, producing point cloud data. FAST-LIO processes the incoming LiDAR and IMU data to perform odometry estimation. This includes feature extraction, where key features in the point clouds are identified, motion estimation using IMU data to estimate the robot's motion between scans, and point cloud registration, where successive point clouds are aligned to build a coherent map. The processed data is then used to generate a 3D map of the environment in real-time, which can be visualized using tools like RViz in ROS2.

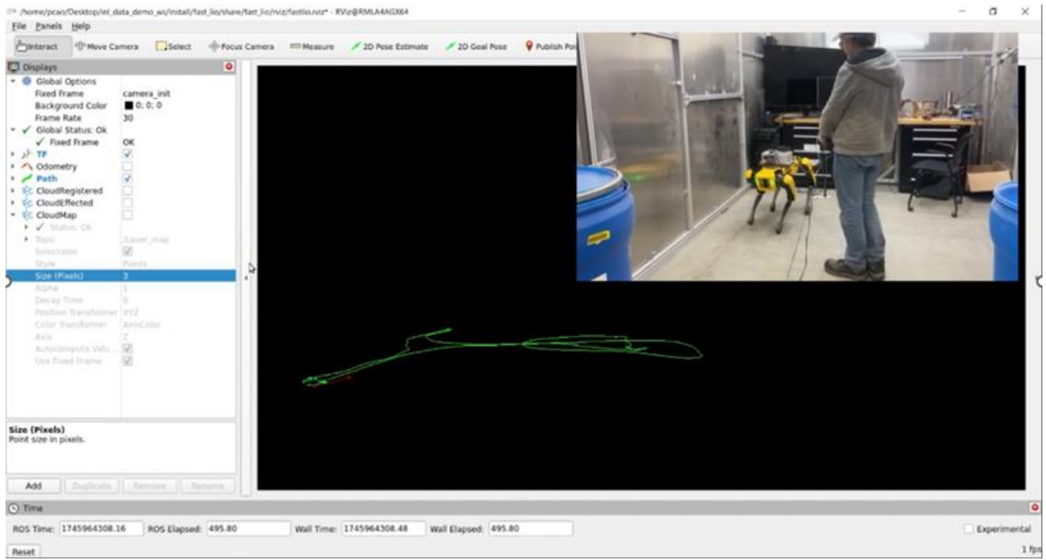

Figure 18. SPOT localization with loop closure detection.

The application in the PDU high bay involves environment mapping, where the generated 3D map captures the layout and features of the high bay. This includes walls, equipment, and other structural elements. The map can be used for autonomous navigation, enabling SPOT to plan paths and avoid obstacles. It also aids in inspection tasks, providing a detailed spatial representation of the environment.

There are several benefits and challenges associated with this implementation. The benefits include high accuracy by combining LiDAR with IMU data for precise mapping, real-time processing that enables immediate feedback and decision-making as well as adaptability to various environments and conditions. However, there are challenges, such as ensuring accurate sensor calibration, the requirement for a robust onboard computer for real-time processing, and environmental factors like lighting, reflective surfaces, and dynamic obstacles, that can affect LiDAR performance. The resulting point cloud map of covered area inside PDU high bays is shown in Figure 19.

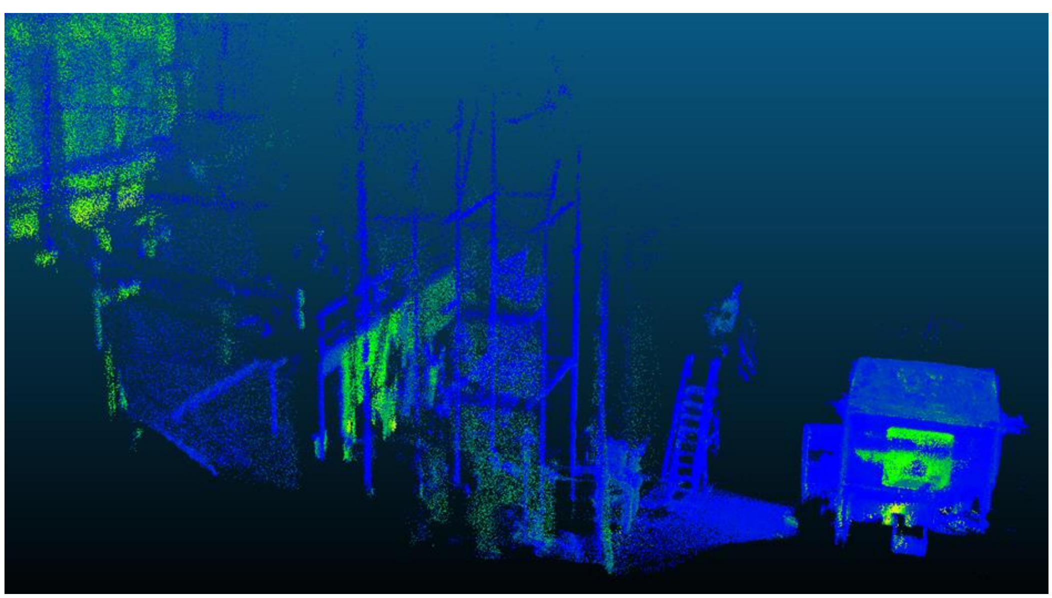

Figure 19. PDU high-bay point cloud reconstruction.

4. YEAR 1 GO/NO GO DETERMINATIONS

The following are the Go/No Go criteria for Year 1. These determinations will help ensure that all critical aspects of the project are addressed before proceeding to the next phase. Determinations were informed by project timelines and by operational requirements, as outlined in Section 1. Refer to Figure 20 for the proposal project timeline used for Go/ No Go tasks.

1. **Functional Requirements for a Robotic System Gathered**
   a. Go: All functional requirements have been thoroughly gathered, documented, and approved by stakeholders.
   b. No Go: Functional requirements are incomplete, not documented, or lack stakeholder approval.

   Determination:
   GO. Criteria for the first determination has been met. The team worked with Washington River Protection Services (now H2C) as well as other experts in the field to gather and record functional requirements. See Section 1 for summarized version.
2. **Concepting for a Robotic Arm Completed and Design Path Chosen**
   a. Go: Concepting for the robotic arm is complete and has resulted in a feasible design that can meet functional requirements. A definitive design path has been chosen, documented, and approved.
   b. No Go**:** Concepting for the robotic arm is incomplete; there is no clear, documented, and approved design path; or the design timeline cannot be completed due to delays or budget restrictions.

   Determination:
   GO: Concepting and initial prototyping has been completed, and a final design path has been chosen. See Section 2.2.4
3. **Concepting for System Equipment Completed and Design Path Chosen**
   a. Go: Concepting for all required system equipment is complete and has resulted in a feasible design that can meet functional requirements. A definitive design path has been chosen, documented, and approved.
   b. No Go: Concepting for system equipment is incomplete; there is no clear, documented, and approved design path; or the design timeline cannot be completed due to delays or budget restrictions.

   Determination:
   GO: Concepting and initial prototyping has been completed, and a final design path has been chosen. See Sections 2.2.1–2.2.3.
4. **Concepting for a Snake Robot/ Crawler Completed and Design Path Chosen**
   a. Go: Concepting for the snake robot/ crawler is complete, and a definitive design path has been chosen, documented, and approved.
   b. No Go: Concepting for the snake robot is incomplete; there is no clear, documented, and approved design path; or the design timeline cannot be completed due to delays or budget restrictions.

   Determination:
   Project Wide Determination: GO. Project scope was changed with DOE approval from CMU snake robot subcontract to a replacement crawler robot. A crawler is placed on order, and project management has determined that overall project goals and milestones can still be met with adjusted project scope. See Section 2.2.5.
   Specific Snake Robot Determination: NO GO. The subcontract could not be enacted to save the project. Portions of the project scope and milestones were changed to an off-the-shelf robotic crawler.

5. Sensors and Components Identified

a. Go: All necessary sensors and components have been identified, sourced, and documented.

b. No Go**:** Sensors and components are not fully identified, or documentation and sourcing are incomplete.

Determination:
GO: All necessary sensors have been identified and purchased. Testing with sensors has begun. See Section 2.1.

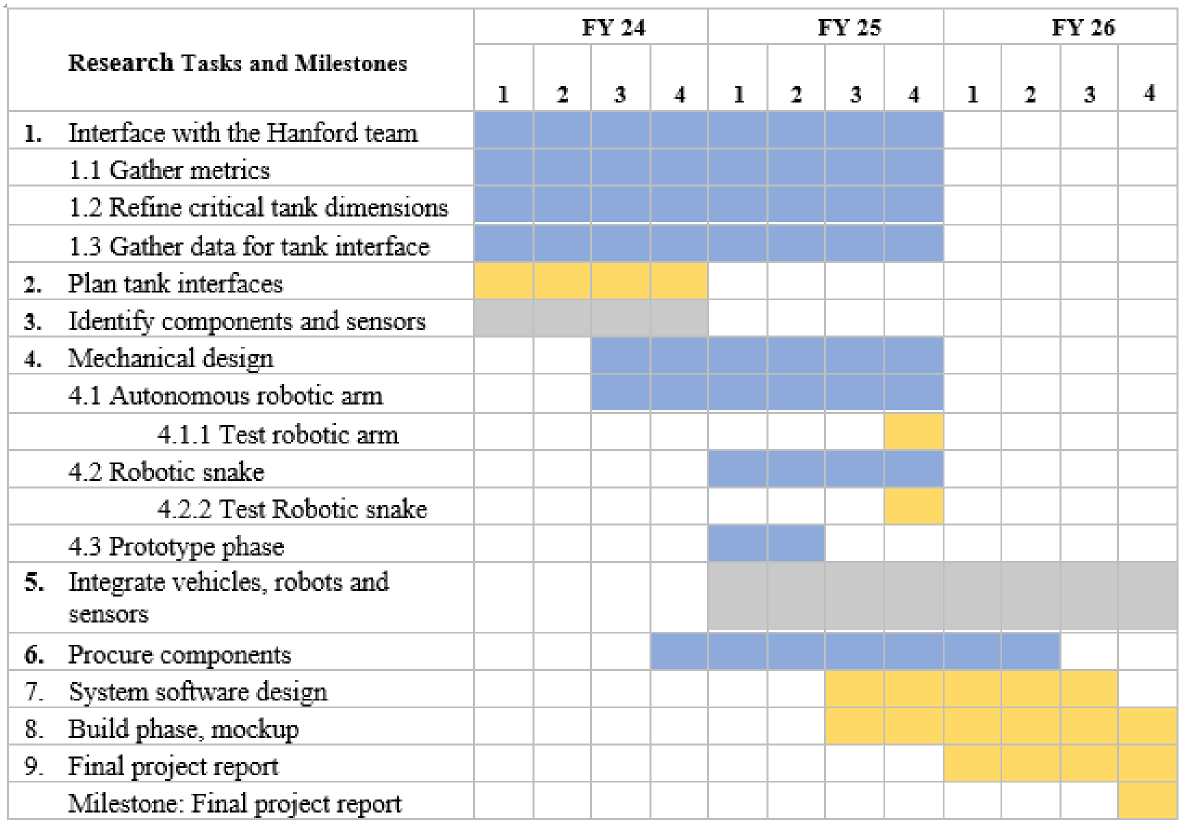

Figure 20. Proposal timetable of activities.

5. REFERENCES

Cao, P., et al. 2025. "Power Quality and Load Capacity Evaluations of an Electric Vehicle for Multi-Robot System Applications." In Proceedings of 2025 IEEE SusTech Conference, Santa Ana, CA, USA. https://edas.info/showManuscript.php?m=1571110797&ext=pdf&type=stamped (Accessed: 28 May 2025).

INL Software. Ritter, C., J. Darrington, and J. Browning. 2020. DEEP LYNX: Digital Engineering Data Warehouse. Software https://inlsoftware.inl.gov/product/deep-lynx.