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Title:
Ground Vehicle Systems Center (GVSC)
Ground Vehicle Robotics (GVR)
Dismounted Systems
Autonomous Tunnel Exploitation (ATE)
Final Report

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U.S. Army Combat Capabilities Development Command
Ground Vehicle Systems Center
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Warren, Michigan 48397-5000



Ground Vehicle Systems Center (GVSC)
Ground Vehicle Robotics (GVR)
Dismounted Systems
Autonomous Tunnel Exploitation (ATE) Project

Final Report

Prepared for:
Defense Threat Reduction Agency (DTRA)

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Executive Summary

The ATE effort is an Office of the Secretary of Defense (OSD) Coalition Warfare Program (CWP) between the United States and the Republic of Korea Agency for Defense Development (ROK-ADD) executed by GVSC and the Defense Threat Reduction Agency (DTRA) Counter Weapons of Mass Destruction (WMD) Division (CXW). The effort started in 2019 with the objective to develop Robotic and Autonomous System (RAS) capabilities to improve Subterranean (SubT) facility exploitation efforts by combined forces. DTRA CXW served as the Project Agreement (PA) lead and GVSC as the technology lead for the effort.

The primary technical objectives achieved during the ATE effort are:

- a) Localization in Global Positioning System (GPS) and GPS-Denied Environments
- b) Autonomy: Waypoint Navigation, Exploratory
- c) Obstacle Detection and Avoidance
- d) 2D/3D Spatial Mapping and Photogrammetry
- e) Integrating w/Chemical, Biological, Radiological, and Nuclear (CBRN) Sensors to overlay on the map
- f) Mesh Radio Communication
- g) Object Detection with Map Overlay
- h) Automated After Action Reporting

Another key project objective achieved through yearly progress demonstrations showed the ability for the ATE system to produce Real-time 2D mapping with object and localization data that can be dynamically combined with ROK ADD to resolve localization disparities and align facility data into one common operating picture (COP). Additionally a post processed 3D map is produced.

The ATE project was a multi-year effort in which GVSC focused the first year on researching hardware (HW) and software (SW) capabilities suitable for small robotic autonomy. The objective was to design a lightweight, low cost interoperable Modular Mission Payload (MMP) capable of being integrated on multiple robotic platforms to conduct subterranean missions. GVSC conducted multiple Soldier engagements to better understand the SubT mission and responsibilities currently used by units to assist in focusing on realistic capabilities to improve Soldier mission tasks. Year two was focused on development, integration, and testing of the selected HW/SW capabilities. Through the use an agile approach the GVSC team developed SW capabilities for autonomy, navigation, localization and perception in GPS-denied subterranean environments. Other year two objectives included the development of a Web User Interface (WEB-UI) controller that allowed the development team to quickly and efficiently, test and evaluate development progress. Year three was focused on optimizing the MMP design and HW selection to be more efficient and suitable for the Man Transportable Robotic System Increment II (MTRS Inc II) Program of Record (PoR) robotic platform, enhancing the autonomy, navigation, localization, and perception capabilities, performing operational testing and evaluation in relevant SubT

environments, and documentation through a rigorous Systems Modeling Language (SysML) approach. SysML is a general-purpose modeling language for systems engineering applications. It supports the specification, analysis, design, verification and validation of a broad range of systems and systems-of-systems.

The autonomy capability developed by GVSC for this effort established the Robotic Technology Kernel (RTK) Lite product line to provide a software baseline for emerging Science & Technology (S&T) and acquisition programs. GVR established a project agreement with PdM Robotic and Autonomous Systems (RAS) to transition RTK Lite in support of the Enhanced Robotic Payload (ERP) Program of Record. In addition, the RTK Lite is in the process of being integrated onto quadruped UGVs in support of the 10x Dismounted Infantry program and will provide the baseline capability for the Combat Vehicle Robotics (CoVeR) Small Unmanned Ground Vehicle (UGV) as Deployable Sensors effort starting in FY23.

1. Introduction

This document serves as the Final Report for GVSC GVR ATE Project. The major components include:

- Executive Summary
- Introduction
- Hardware Overview
- Software Overview
- Yearly Demonstrations - Overview and Progress
- Testing / Technology Evaluations
- Conclusion

1.1. Purpose

The purpose of the ATE Project was to enhance operational efficiency for underground site exploitation through collaborative engagement between GVSC GVR and ROK ADD on mutually challenging technological areas to increase the capability, compatibility, and interoperability of US and Coalition Partners.

GVR's main purpose was to develop a modular payload for the exploitation of underground facilities (UGFs) that is a transition-able system design and will guide the development of requirements for subterranean and CBRN-E operations.

1.2. Problem Statement

Currently Warfighters lack the capability and capacity to rapidly characterize and exploit UGFs that may contain WMD. The high number of complex adversary UGFs and low numbers of specialized forces to exploit them will significantly slow Coalition forces during combat operations. The Warfighter needs the ability to rapidly exploit, characterize, and assess UGFs in order to isolate adversary WMD and enable ongoing combat operations and follow-on WMD elimination operations.

1.3. Background

The WMD problem is intimately linked to underground facilities on the Korean peninsula. There is a recognized gap in capability, capacity, and interoperability between US/ROK forces conducting site exploitation operations. DTRA has ongoing investment in semi-autonomous site exploitation of underground facilities. The US is ROK's primary Coalition partner. ROK is also a world leader in robotics technology and automation, evident by having led and won the 2015 DARPA Robotics Challenge. DTRA recognized the shared operational need for improved Coalition shared environment capability and capacity, and our respective mutual prowess in the field of advanced robotics as an ideal opportunity for meaningful technical collaboration and demonstration of core advanced robotics technologies to solve a glaring warfighter need. Beyond co-development, future opportunities exist to fold technology demonstrations into multiple, major Coalition exercises at US and/or

ROK facilities to enable warfighter evaluation and input. Importantly, this work has broader application across Global Combatant Commands in which there is a threat of WMD located in UGFs. Ultimately, collaborative improvement in advanced robotics will enable the development of more capable platforms which can increase Coalition capability, capacity and interoperability for site exploitation missions. With more capable autonomous systems, the role of autonomy for supporting site exploitation is expanded, offering to increase Coalition capacity through reductions in manpower, automating complex tasks, decreasing time on target, improving and automating site intelligence reporting, and reducing the risk to ground forces.

1.4. Scope

The US and Republic of Korea will establish a collaborative model and simulation environment through DEVCOM-GVSC GVR and identify areas for co-development and experimentation for advanced robotics. Each year, both countries will demonstrate progressive improvements in robotic, sensor, and subsystem architecture in GPS-denied navigation, 2D/3D mapping and photogrammetry, underground communications, Hazardous Materials (HAZMAT)/WMD sensor integration, and robotic platform collaborative behaviors, in a relevant underground environment. These progressive demonstrations seek to reach a level where collaborative robotic systems share and communicate data between robots, operators, and Coalition force leaders via their COP.

1.5. Objective

GVR's objective was to enhance the SubT Exploitation and Classification mission by introducing RAS capabilities to current Army formations to reduce Warfighter risk as well as physical and cognitive workload through the integration of sensing and autonomy modular mission payloads onto existing PoR unmanned platforms.

1.6. System Description

The ATE Payload system utilizes a modular architecture approach to provide essential autonomous capabilities for exploration and sensing in GPS-enabled and GPS-denied Operational Areas (OAs). Interoperability Profile (IOP) communication facilitates the interconnection between the controller, payload, sensors, and vehicle interface that conforms to the IOP standard, allowing for an adaptive integration between various Unmanned Ground Vehicle (UGV) platforms and requiring minimal configuration. Internally, the payload uses the GVSC developed RTK-Lite software architecture, which is suitable for small dismounted robotic systems and highly scalable using the widely accepted framework known as Robotic Operating System (ROS). The final hardware kit consists of three modular enclosures for computing, localization sensing, and an object of interest detection payload similar to Aided Target Recognition (AiTR) capability used on Unmanned Aerial Systems (UASs). When combined together, the three modules weigh 23 pounds, and measuring 12 inches length, 4.5 inches width, and 14.2 inches height. Require total input voltage of 6-36VDC (24VDC standard input) and nominal power draw of 40-50 Watts.

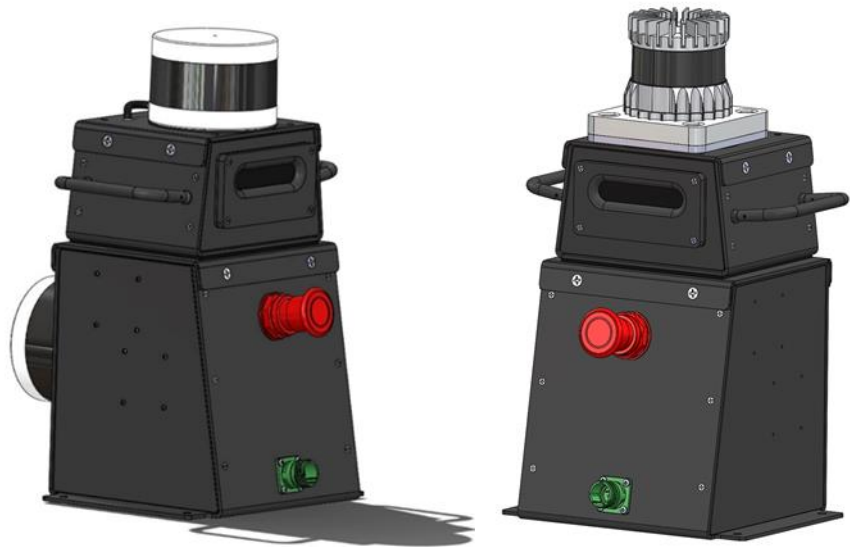


Figure 1: ATE Payload Design One and Two



Figure 2: ATE Payload Design Three

1.7. Participating Organizations

1.7.1. Office of the Secretary of Defense Coalition Warfare Program

1.7.2. Defense Threat Reduction Agency

1.7.3. Ground Vehicle Systems Center Ground Vehicle Robotics

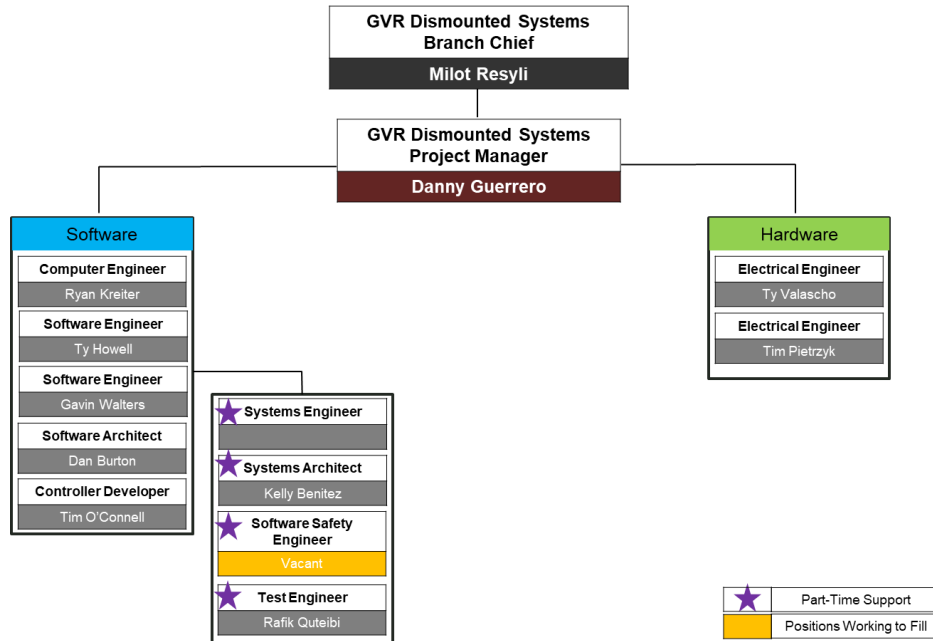


Figure 3: GVR ATE Project Team

1.7.4. Republic of Korea Agency for Defense Development

2. Hardware

2.1. Overview

The ATE payload was designed to be modular and suitable enough for small robotic systems. While developing the ATE payload two configurations utilizing different Light Detection and Ranging (LiDAR) solutions were developed. The first configuration utilized two Velodyne LiDAR's, one placed horizontally for object detection, and the other placed vertically to scan walls and ceilings as the robot moves through an environment. While a final optimized solution was later developed involving a single Ouster LiDAR, with a 90-degree Field of View (FoV) integrated onto the MTRS Inc II robotic platform. The development of the hardware can be captured in yearly improvements in the design, and selection of components for system integration architecture.

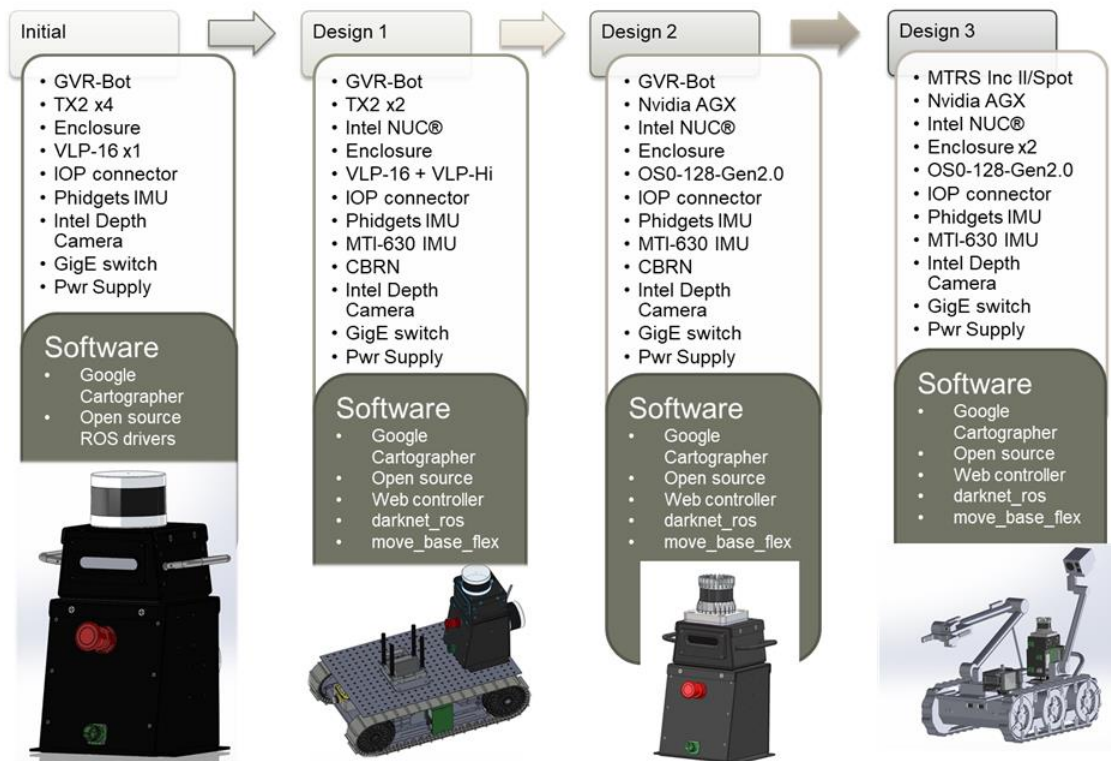


Figure 4: Progression of ATE design and Architecture

The first-year efforts were focused on researching HW solutions that could meet the capability requirements of size, weight, power, processing, and cost. Considerations were made to determine basic prototyped hardware needed to achieve Simultaneous Localization and Mapping (SLAM), using the Google Cartographer algorithm. Initial prototype work was analyzed to target a base design for integration onto GVR's S&T robotic platform, known as the GVR-Bot. The GVR-Bot is an iRobot robotic platform that was re-designed by GVR to serve as an S&T platform for small robotics projects, such as ATE. The GVR-Bot acted as a host prototype mobility platform for the ATE payload

being developed. The GVR-Bot allowed for rapid integration and testing of the ATE Payload capabilities.

The second year was focused on incremental cycled improvements in the hardware and design, optimizing the Commercial off the Shelf (COTS) hardware and working with the software team to further define the requirements. This allowed the system components to perform at the optimal level. Rigorous engineer and operational testing and evaluations were conducted to determine processor, Inertial Measurement Unit (IMU), LiDAR, and computer vision chip selection capable of meeting the new defined requirements.

After testing and evaluation, a design plan was developed for the final year goal of optimizing the ATE payload for integration onto the MTRS Inc II. Having the components and trade off studies conducted from the second-year progression, made for an easier integration of the re-designed ATE payload onto the MTRS Inc II. The re-design focused on minimizing the impact of current capabilities and keeping the payload design modular. Having these requirements of modularity and minimizing current performance impact will allow for the development and transition of the ATE system into future projects, further displaying the capability of small robotics autonomy.

2.2. Analysis & Decisions

2.2.1. Processing

- ❖ Based on extensive processor testing and analysis of four different processors (Nvidia TX2, Nvidia TX2i, Nvidia Xavier AGX, and Intel i7- 8665U Processor), parameters were identified to meet system requirement criteria pertaining to memory, temperature, architecture, and processing speed. Through a detailed analysis, we determined the Google Cartographer algorithm is most efficient with x86 processors paired with 16GB minimum of memory. Considering the cost, power, and size of the processing system we chose an Intel NUC i7 processor to compile the code, which met the system requirement criteria we determined through the testing and analysis. Implementing the processor upgrade improved performance of the Google Cartographer algorithm and allowed the software team to deliver a faster and more complex SLAM capability. Details of the study conclusion can be found in the Software Description Document (SDD) section 3.1 Processing.

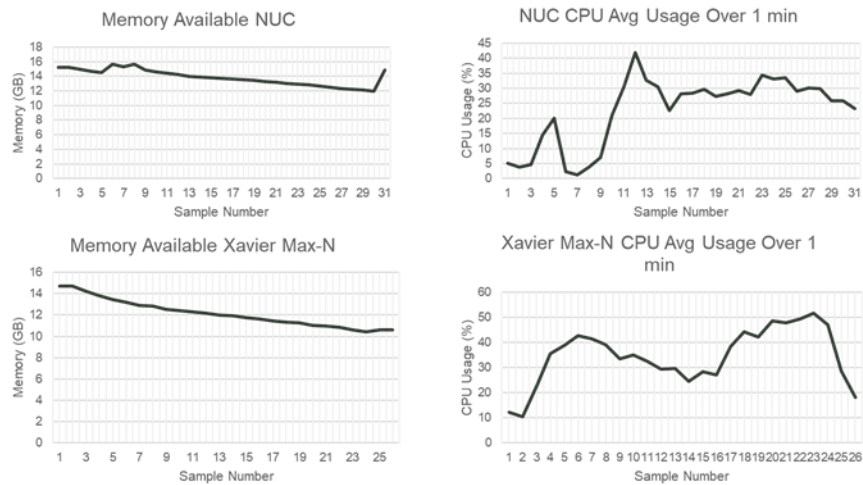


Figure 5: Intel & NVIDIA Performance

2.2.2. LiDAR

- ❖ Initially we used a double LiDAR configuration consisting of two Velodyne's, one vertical and one horizontal. After further testing and analysis, we determined a single fixed LiDAR solution to gather SLAM data would increase reliability and reduce complexity without the need for oscillating LiDAR scanners or a multiple LiDAR configuration. The improved Ouster OS0-128 LiDAR offers a denser/richer point cloud for 3D visualization in post processing. The current ATE payload uses a single Ouster LiDAR laying horizontally across the top of the payload. This allowed the simplification of the payload design and capture the walls and ceiling of an environment.

2.2.3. Depth Camera

- ❖ Stereo depth cameras play a critical role in the software to add features for object detection and teleoperation of a robot. These depth cameras provide the user with teleoperation in standard daylight video for driving while enabling features on object detection overlay and autonomously follow the operator. Currently, the Intel RealSense D435i camera is utilized on the ATE System. The camera meets the performance metrics for size and power required; while other depth cameras exist, many utilize more power or exceed the size of the prototyped ATE payload. Software requirements were also considered for the Intel RealSense camera for, ROS driver and GPU compatibility.

- ❖ **Intel D435i**

- Size: 9 x 2.5 x 2.5 (cm)
- Interfaces: USB
- Input Voltage: 5V
- Power: 3.5W
- FOV: 86 x 57 degrees

- Range: 0.2-10m
- Resolution: 1920x1080
- ROS driver
- Temperature: 0 to 35 C



Figure 6: Intel D435i Camera

2.2.4. Inertial Measurement Unit (IMU)

- ❖ The Intel Real Sense Camera is equipped with an integrated IMU however, through testing we discovered that the accuracy of the IMU over long periods of time was not ideal for cartographer mapping and did not meet the requirements we established for accuracy, resolution, and data output. Therefore, a separate dedicated IMU was selected to provide increased localization accuracy. Through research and analysis, we selected the Xsens MTI-630 IMU due to the high output data rate, resolution, and accuracy it provides. The MTI-630 was also chosen for the compass heading to provide an additional sensor feedback for future localization tasks.
- ❖ IMU MTI-630
 - 400Hz data rate
 - True North heading
 - Gyroscope: $\pm 2000^\circ/\text{s}$
 - Accelerometer: $\pm 10 \text{ g}$ (G-Force)
 - Magnetometer: ± 8 Gaussmeters
 - Bias stability: $8^\circ/\text{hr}$
 - Temp: -40 to 85 C

2.3. Issues/Limitations

2.3.1. Mobility Issues

- ❖ Current limitations of the ATE payload were identified as a result of the host platform mobility issues. During our extensive testing and evaluation, we identified that the harsh terrain and uneven slopes/grades caused problems for the mobility of the GVR-Bot S&T platform. These issues pertained to the robot getting stuck, tipping-over, and sinking in fine silica sand. One of our year three objectives was to address the mobility issues by optimizing the current payload design to be suitable for integration onto the Army's PoR robotic platform MTRS Inc II. Additional testing was performed using both the GVR-Bot and MTRS Inc II platforms to analyze payload performance based on mobility. The testing

concluded that the MTRS Inc II had better mobility performance that caused fewer issues for the payload capabilities.

2.3.2. LiDAR Packet Timing

- ❖ The LiDAR Packet Timing is important for real-time map development and accuracy. During testing and evaluation, we discovered a packet timing issue with the Ouster LiDAR sensor causing degraded SLAM performance. Unlike the initial Velodyne LiDAR sensors utilized in the first prototype, the Ouster LiDAR needs IEEE 1588 PTP standard packet timing so the data from the LiDAR scans can be time synchronized. To get around the issue, data was directed into the Intel NUC processor versus going through the switch increasing the timing of the packet. However, current issues can still arise causing the system to lose packet timing sync, but these are rare events and can be solved after a restart of the system. To properly solve the issue an IEEE 1588 PTP standard needs to be addressed in the network switch.

2.3.3. Radio Network

- ❖ Another limitation of the performance of the ATE payload is radio network communication. With the complexity of underground tunnel systems radio communication is limited even with advanced radio systems. While the main goal of ATE was to create a SLAM payload, the bottleneck of radio communication in subterranean environments still exist. To mitigate this problem, we tasked two GVSC summer students to develop a repeater drop system capable of manually and autonomously deploying radios from the host platform. While the system worked in ideal lab conditions, the drop system was not optimized for rugged environments containing rough terrain, rocks, etc. Further optimization of this feature would need to be addressed to test and evaluate the effectiveness of a robotic deployed radio network used in a relevant operational environment. Establishing a repeater drop system was not a requirement for us to achieve during this effort however, establishing a baseline capability that could be further developed and optimized with future efforts was the objective.

2.4. Lessons Learned

Lessons learned from the hardware perspective that had the greatest impact on the performance of the ATE system was the lack of testing and evaluation in rugged subterranean environments. Conducting more testing and evaluation in rugged subterranean environments would have allowed us to identify both hardware and software issues earlier for the team to conduct more detailed analysis and fixes. However, with COVID travel restrictions and limited testing sites for subterranean environments much of our testing and evaluations were done within the lab, simulation or limited relevant environment.

3. Software

3.1. Overview

The software effort was initiated to provide the warfighter with a capable, modular, and documented software program that supports current and future algorithms for localization, world modeling, and autonomous navigation. Early on we established an initial set of SW requirements to be developed, tested, documented and demonstrated for each of the three project years. These requirements were further defined through user engagements and feedback and in conjunction with existing Maneuver, Maneuver Support and Sustainment requirements.

Year 1 software objectives included teleoperation of the robot from outside the tunnel, manual placement of radio repeaters to form a mesh network, generating a 2D map displayed real-time on a controller, and the manual placement of objects of interest on the 2D map. All objectives were met on time however, due to COVID restrictions the capabilities were demonstrated in a simulation environment that we delivered virtually.

Year 2 software objectives included waypoint navigation between operator placed waypoints with obstacle avoidance, optimizing localization and mapping, automated object recognition, integrated CBRN sensor data onto the 2D map, platform lighting control, and a modeling and simulation environment for testing. All objectives were met on time and the capabilities were demonstrated during our year 2 demonstration event. Due to COVID travel restrictions, DTRA and ROK ADD did not attend however, the demonstration was recorded and shared with all project partners.

Year 3 software objectives included optimizing the autonomy, mesh network formation by robot, automatic 3D model generation, and automated after action reporting. New autonomy navigation behaviors included autonomous exploration and patrolling. These new behaviors were not part of our initial requirements. All objectives were met on time and the capabilities were demonstrated in a relevant operational environment utilizing former Special Operating Forces (SOF) personnel conducting actual reconnaissance, breaching, clearing, and site exploitation missions.

The final software package is contained within one repository as a collection of binaries, open-source code, and government-owned source code that provides all capabilities of the ATE payload.

3.2. Analysis

3.2.1. Simultaneous Localization and Mapping (SLAM)

- ❖ The Simultaneous Localization and Mapping (SLAM) performance improved incrementally throughout the project, refer to Testing (Section 5) and applicable attachments for objective analysis. Several highlights include accurate loop closures over 1km trajectories, localization drift less than 5m over 3mi trajectories at 25mph, and successful exploitation of culverts, drainage tunnels, outdoor and

indoor manufacturing facilities, caves, and office buildings. One area to improve is robustness and fault tolerance during sensor failure – this was seen during the Year 3 demonstration when LiDAR packets were dropped mid-exploitation due to improper setup subsequently causing intermittent and poor SLAM performance. Other areas include improved global loop closure over large loops in rough terrain and addition of other modalities as input to SLAM for robust performance when LiDAR conditions were degraded (e.g. dust, smoke, precipitation). Featureless environments also proved to be a challenge in 2D SLAM versus 3D SLAM configurations as long featureless corridors continually produce similar sub maps that continually overlap during scan matching. 3D SLAM had performed better in these situations as a full 3D point cloud can detect more features during scan matching and localization as opposed to a flat 2D scan with a limited observation space.

3.2.2. Autonomous Navigation

- ❖ The autonomous navigation performance was instantiated in year 2 and improved incrementally between years 2 and 3. This section will cover general performance between waypoints, patrol mode, and return home. The user level autonomy modes (i.e. patrol, exploration, return home, waypoint navigation) all utilize waypoint navigation as the baseline functionality, so any improvements to obstacle avoidance or other areas will immediately trickle down to all autonomy modes. The software is described in detail in the Software Design Document, but in short utilizes a modular architecture for 2D autonomous navigation that allows plugins for planning, control, and world modeling. The initial autonomy demonstration during Year 2 displayed autonomous waypoint navigation and patrol between waypoints generally within sight of each other or around one corner of each other. Performance was excellent in the indoor environment and included dynamic obstacle avoidance and navigation through constrained and narrow doorways. Patrol mode is the autonomous repeating of two or more waypoints continuously, requiring no operator oversight unless an object of interest or CBRN danger condition is identified. Return home offers the operator two methods for autonomous return of the robot to a preset home location. Through retro-traverse (covering the identical path in reverse) or fastest route (robot plans the most efficient path home). One improvement during Year 3 was replacing the point cloud ground filter from a simple z-axis height filter to a fast and accurate ground-place fitting filter (Zermas, 2017). This improved the filtering out of the ground LiDAR returns in environments with terrain rougher than an indoor floor, such as low grass or uneven cave floors and enabled the autonomous exploration shown in Year 3. One limitation of the current system is the sensor blind spots, which have been significantly reduced by switching to the Ouster OS0 LiDAR.

3.2.3. Autonomous Exploration

- ❖ The fully autonomous exploration mode was added during Year 3 development. This section will cover operator input, how it works, performance, and limitations.

The autonomous exploration algorithm works by analyzing the 2D SLAM map for frontiers, or the areas lying between known and unknown map sections. It ranks the frontiers based on their relative size and distance from the robot before sending the highest scoring frontier to the global navigation system as a simple waypoint to navigate to. On successful navigation to the waypoint the frontier algorithm starts again. During this method no operator input is required or desired with the exception of providing an initial boundary box for the robot to explore within (i.e. 100m forward, 200m left/right, and 0m backward). Performance during engineering evaluations and the Year 3 demonstration was excellent, generally requiring no operator oversight until the robot reported exploration completion. One limitation to exploration is the underlying 2D structure of waypoint navigation – the robot struggles in terrain with steep slopes and does not identify negative obstacles.

3.3. System Design Overview

3.3.1. System Capabilities / Use Cases

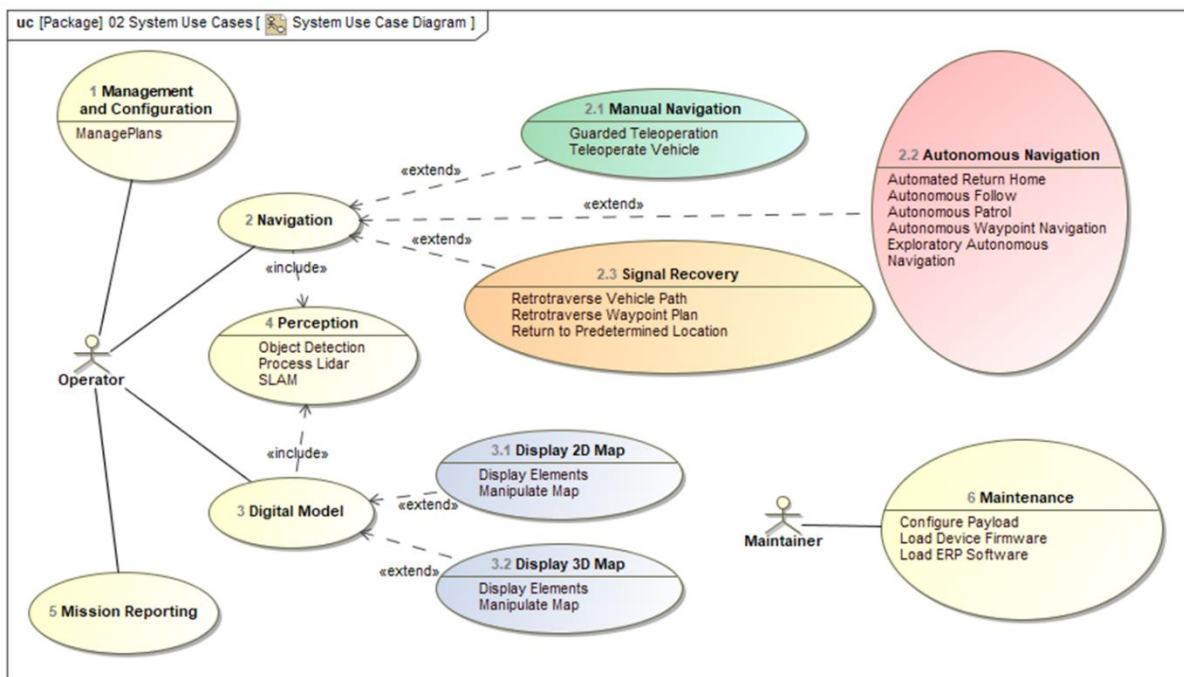
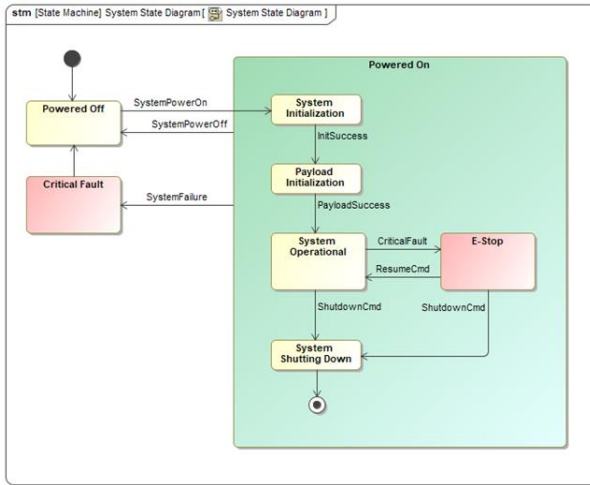


Figure 7: System Capabilities / Use Cases

3.3.2. System States

Vehicle Platform States



ATE Payload States

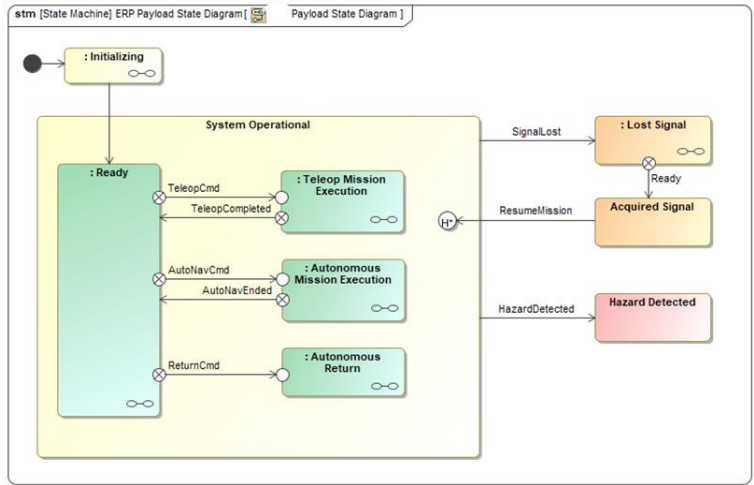


Figure 8: System States

3.3.3. Functional Analysis – Perception

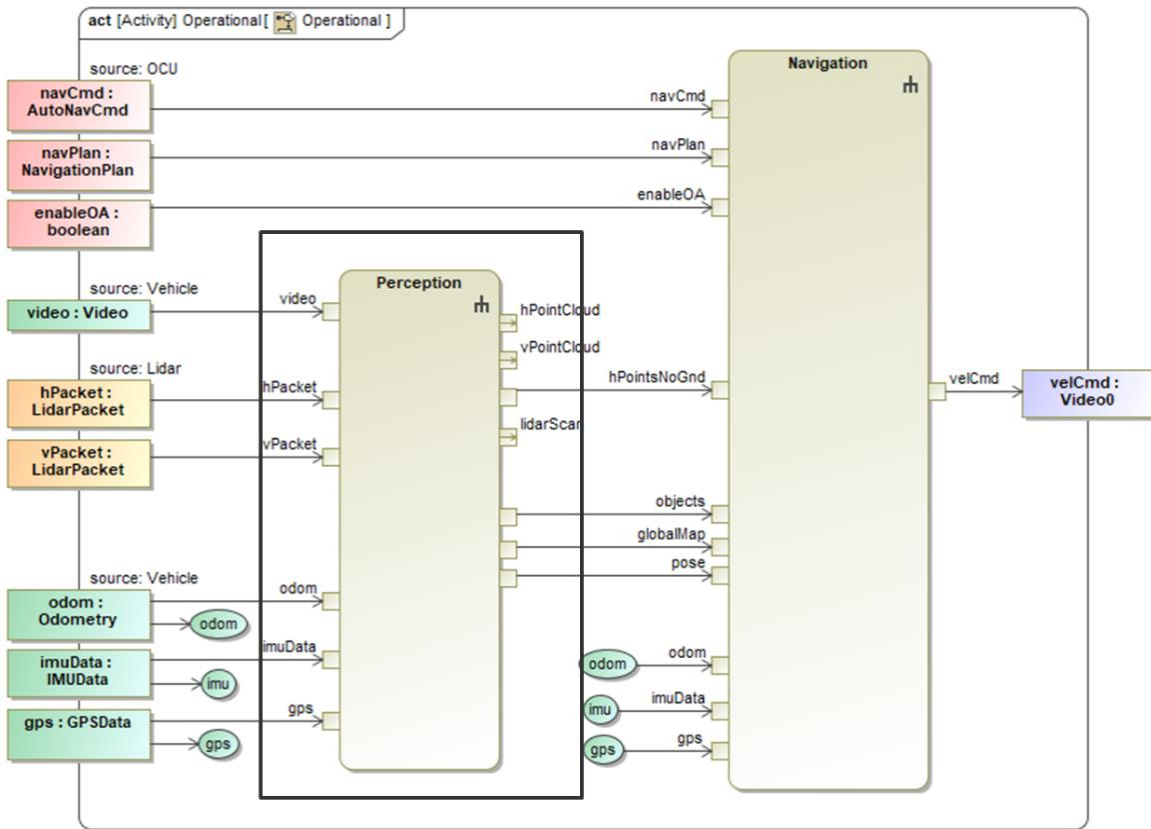


Figure 9: Functional Analysis – Perception

3.3.4. Perception – LIDAR Processing

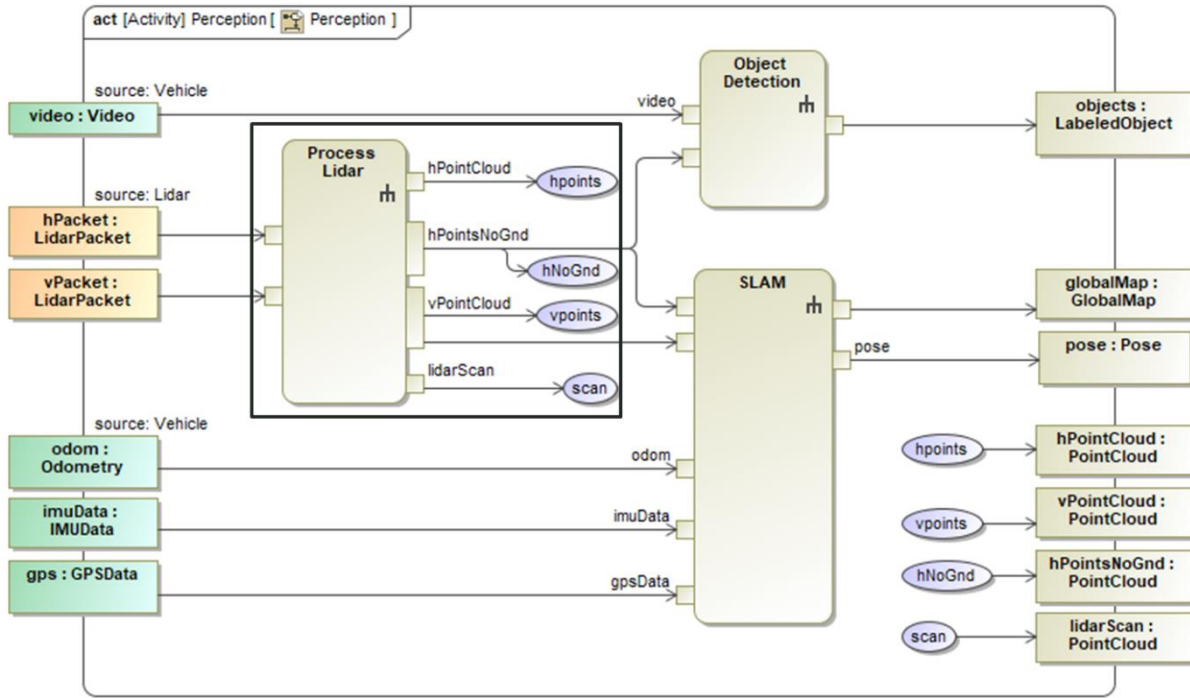


Figure 10: Perception – LIDAR Processing

3.3.5. Obstacle Avoidance / Digital Model LIDAR Functions

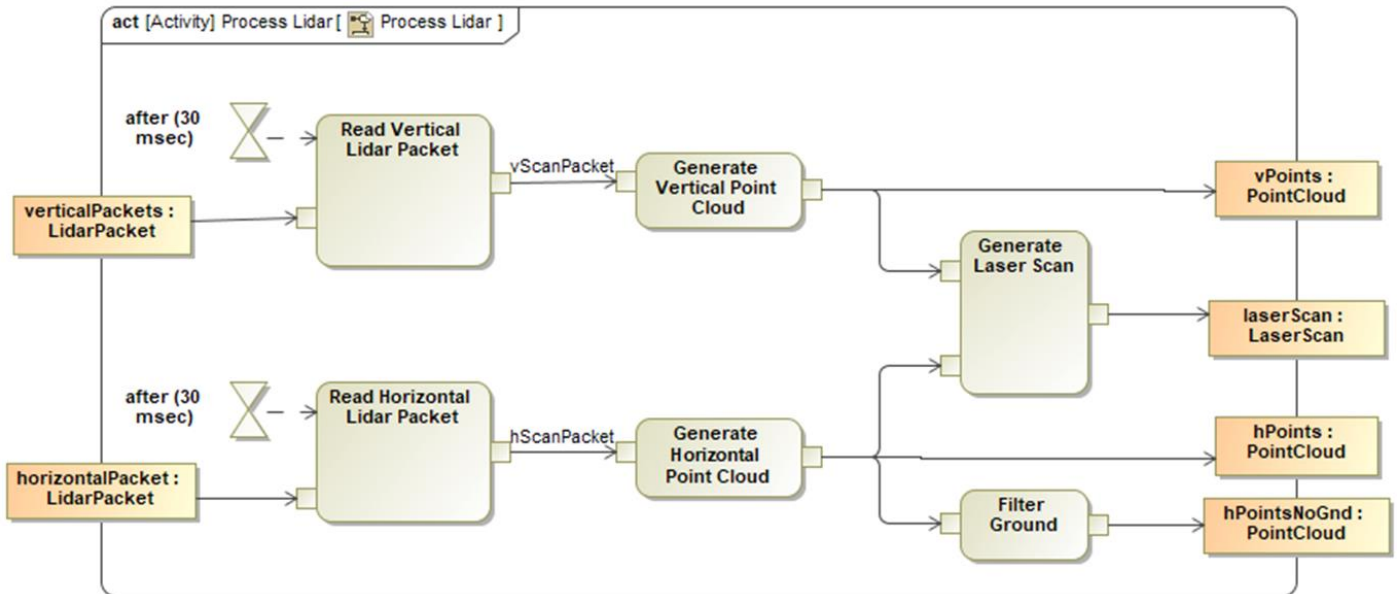


Figure 11: Obstacle Avoidance / Digital Model LIDAR Functions

3.3.6. Perception – Object Detection

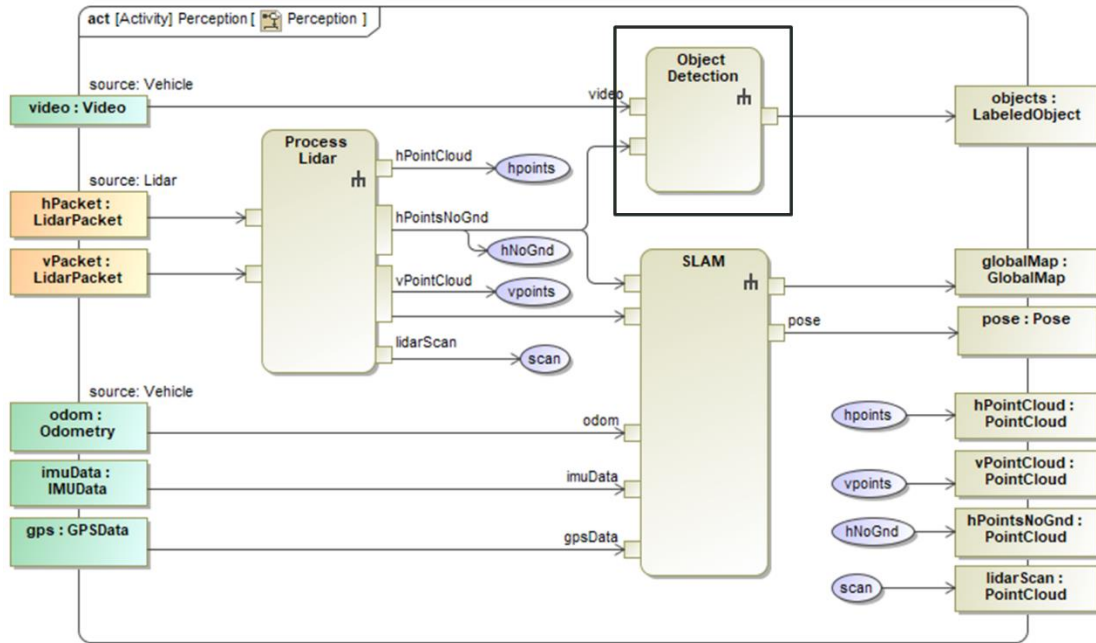


Figure 12: Perception – Object Detection

3.3.7. Detect Objects Functional Analysis

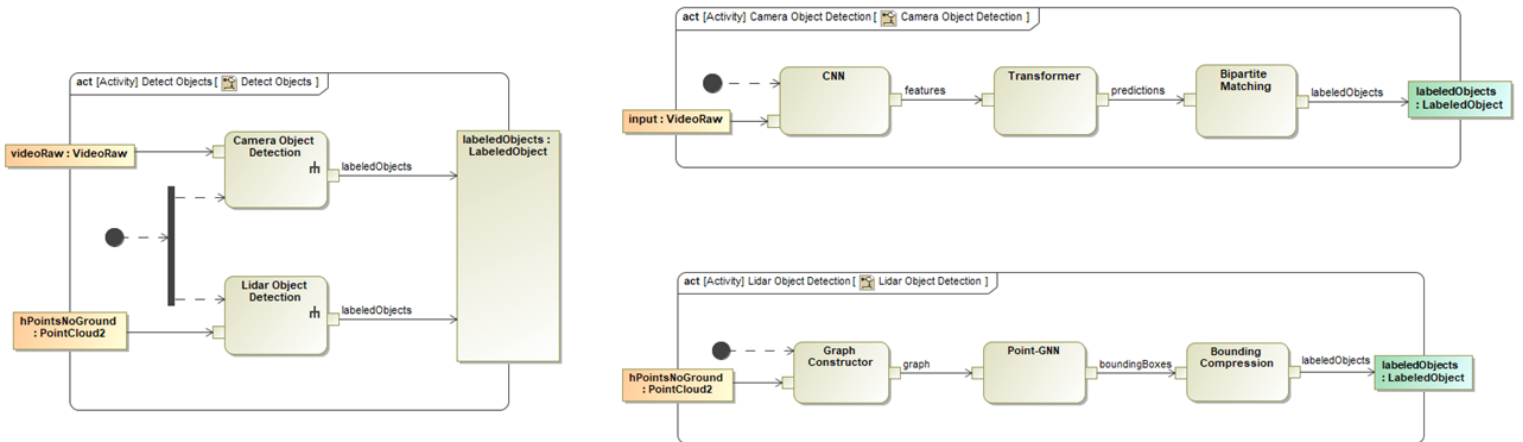


Figure 13: Detect Objects Functional Analysis

3.3.8. Perception – SLAM

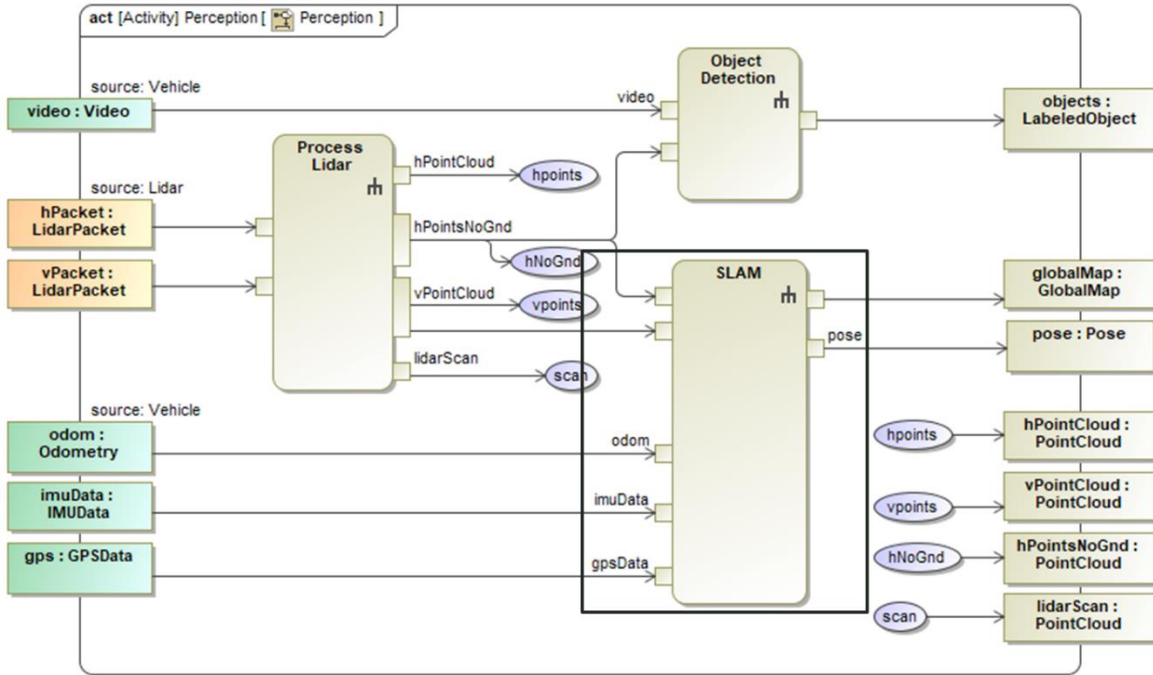


Figure 14: Perception - SLAM

3.3.9. Autonomous Navigation SLAM Functional Analysis

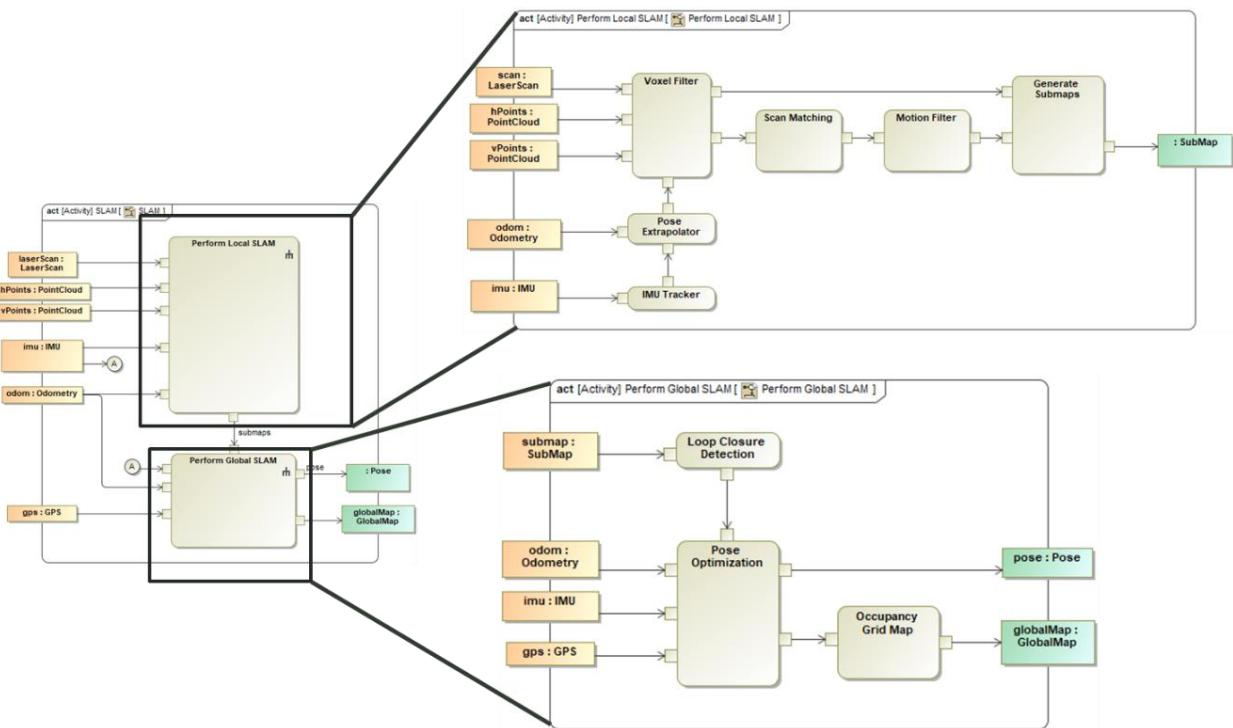


Figure 15: Autonomous Navigation SLAM Functional Analysis

3.3.10. Functional Analysis – Navigation

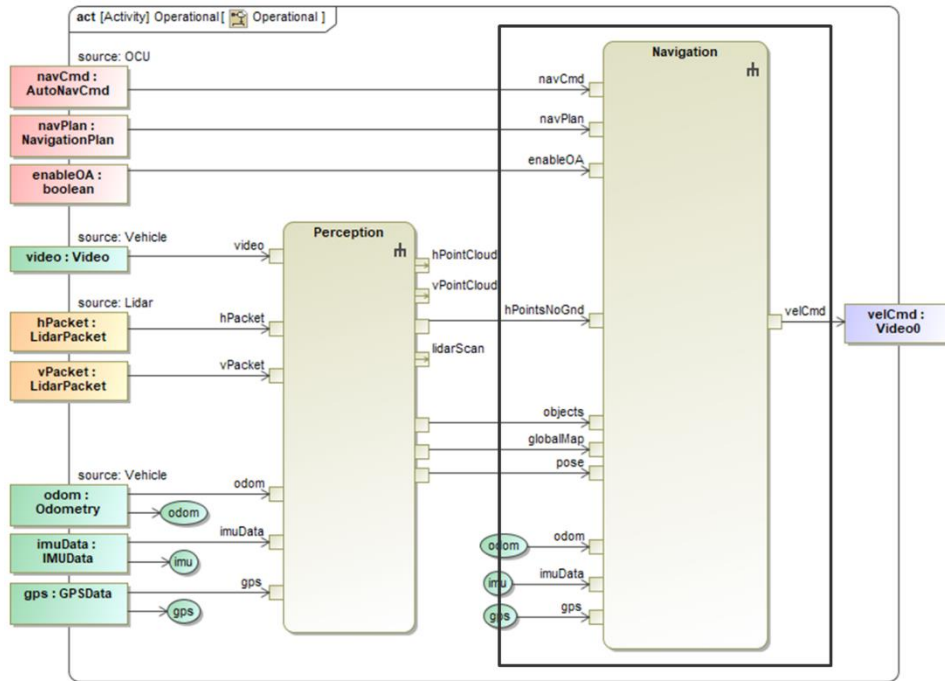


Figure 16: Functional Analysis – Navigation

3.3.11. Autonomous Navigation

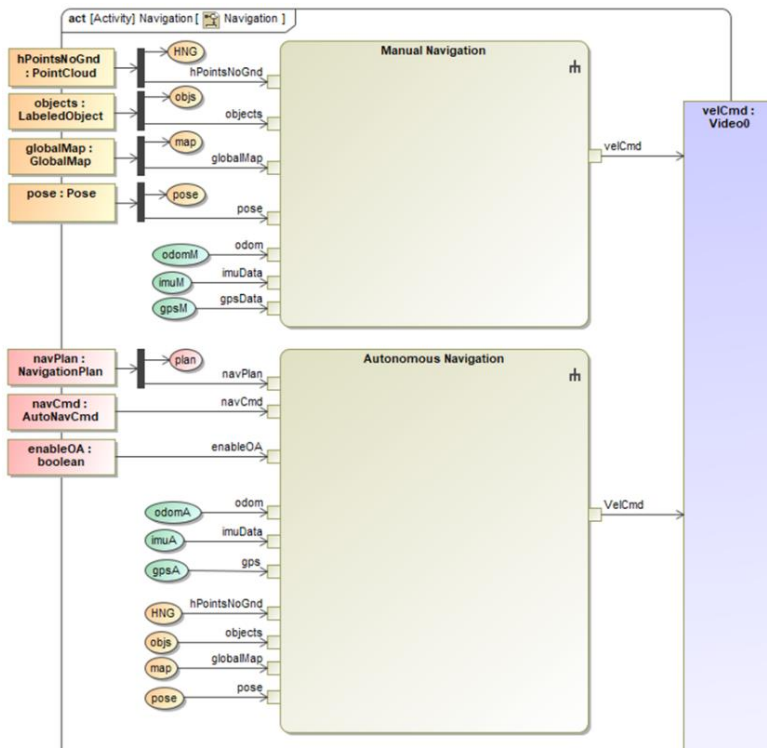


Figure 17: Autonomous Navigation

3.3.12. Autonomous Navigation Functional Analysis

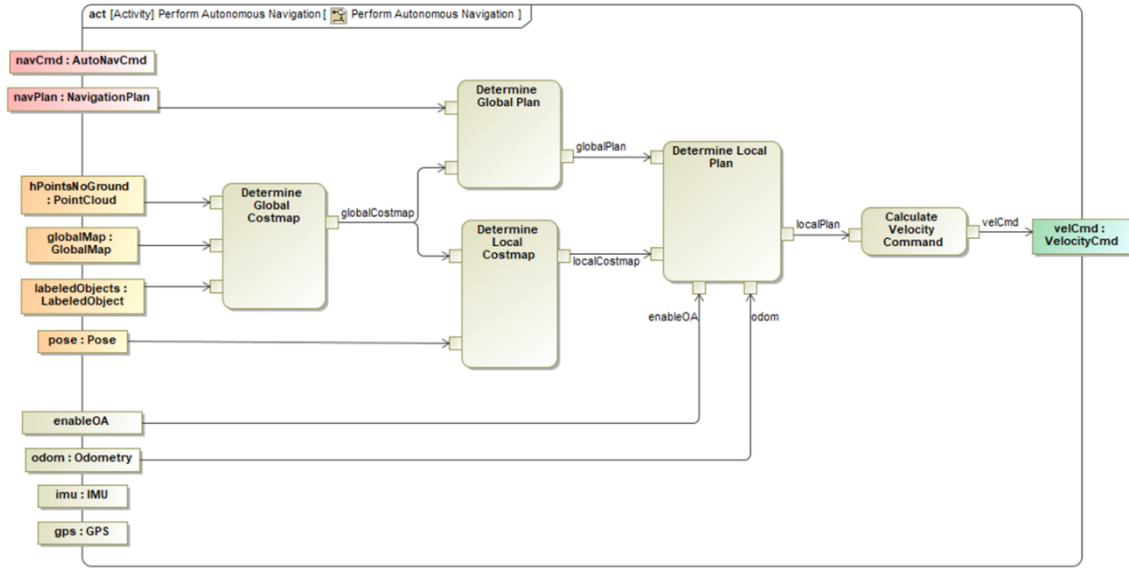


Figure 18: Autonomous Navigation Functional Analysis

3.3.13. Functional Decomposition

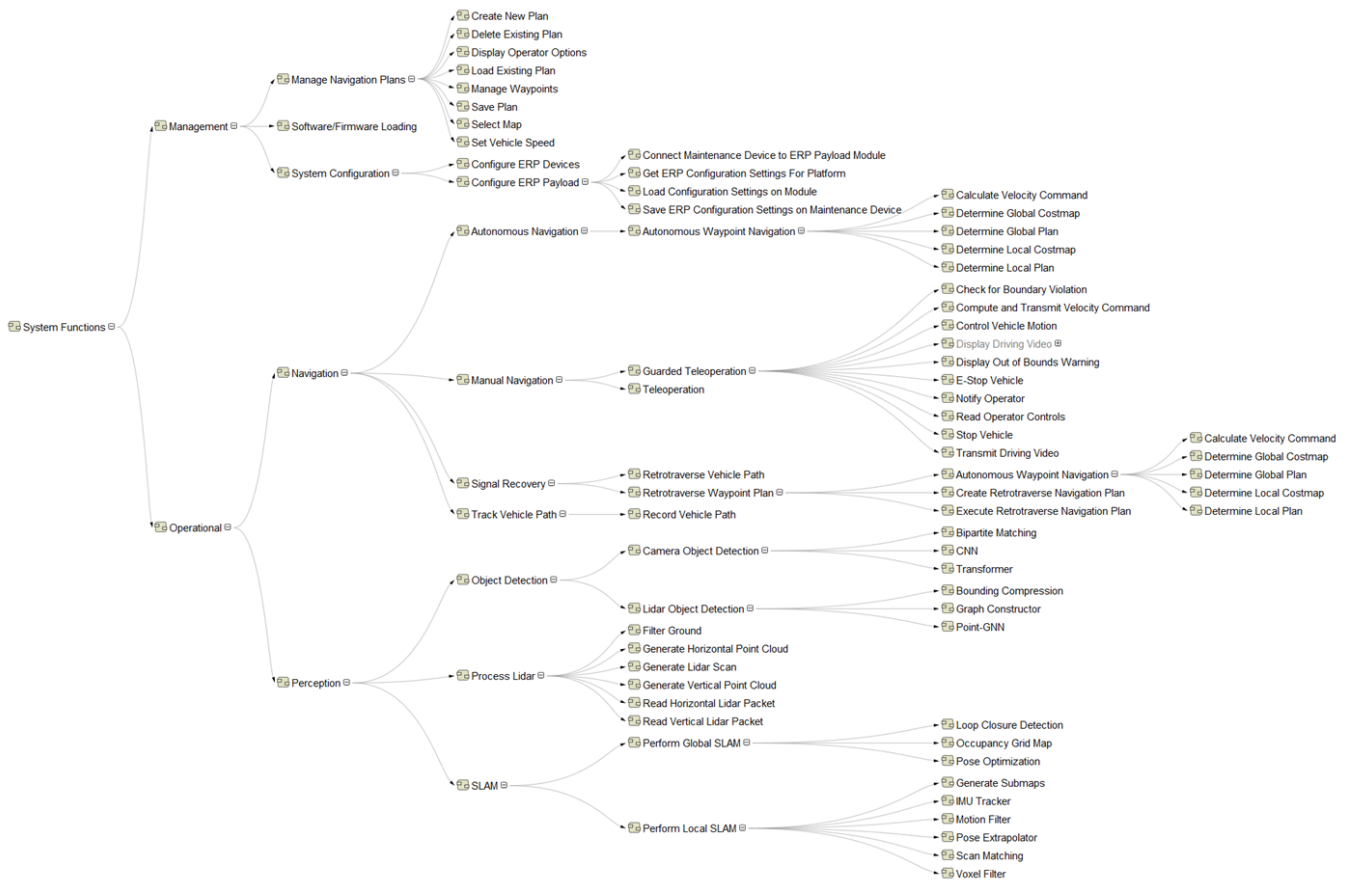


Figure 19: Functional Decomposition

3.4. Lessons Learned

One autonomous navigation software lesson learned was increasing the size of the virtual bumper surrounding the robot. All previous robotic testing prior to the Year 3 demonstration took place in locations with vertical walls, but the caves in Rolla had walls that sloped in the bottom foot. Some LiDAR pointcloud returns of which were filtered out by the ground filter, resulting in the robots navigating too closely to the cave walls around certain turns causing slow-speed collisions, not impacting mission success. By increasing the range autonomy was required to keep from obstacles these collisions were entirely prevented. However, the downside is this change increased the minimum corridor width the robot could autonomously move in. Therefore, increases in the range should be limited.

4. Yearly Demonstrations

4.1. Year 1

4.1.1. Purpose

- ❖ Demonstrate ATE development progress to partners/stakeholders and discuss opportunities to inform integration efforts from a user perspective. Due to the COVID-19 pandemic the in-person demonstration was canceled, and a virtual presentation and video were provided.

4.1.2. Technology Objectives

- ❖ 2D and 3D mapping and localizing GPS denied environments
- ❖ Autonomous Waypoint Navigation (Beta)
- ❖ Integration of Object of Interest Identification on the generated map

4.1.3. Approach

- ❖ GVSC is leveraging local facilities to demonstrate the technology which are intended to represent a GPS-denied “SubT equivalent” environment with some complexity and the size of a football field. While this is not an ideal approach, it allowed us to work around COVID restriction to engage with the customer and user community.

4.2. Year 2

4.2.1. Purpose

- ❖ To evaluate and demonstrate the developmental progress for the ATE technology objectives. The defined concept of operations (CONOPS) is intended to simulate an UGF for exploitation by a CBRN team to determine the layout, CBRN threats, objects of interest (OOI), and provide robotic reconnaissance support during the breaching and clearing of the UGF by a manned CBRN team.

4.2.2. Mission and Execution

- ❖ While conducting a routine patrol in the Detroit Arsenal Area of Operation (DTA AO), 1st Brigade Combat Team (BCT) discovered an industrial facility. Upon initial entry, 1st BCT located an entrance that appears to lead to a suspected underground facility. 1st BCT has cordoned off a 200 meter area, setup security on all suspected entry points, and has requested additional robotic support from GVR team 1 to perform site reconnaissance. As of 0800 on 4 March 2021 an unknown number of hostile personnel are expected to be present. There have been no observations of personnel entering or exiting the objective in the last 24 hours. The presence of ordnances, CBRN and/or WMD are anticipated.
- ❖ On order, GVR Team 1 will remotely deploy the ATE robotic system from the command post and make entry at the breach point. GVR Team 1 will execute a thorough reconnaissance of the UGF identifying any personnel, ordnance, CBRN-E, and WMD threats while producing real-time 2D mapping with object of interest tagging and CBRN readings for the site Commander's situational awareness and improved risk based decision making. Upon completion of the robotic reconnaissance, members from 1st BCT along with the CBRN team will enter the UGV to clear any personnel and/or identified CBRN threats while the ATE robotic system continues to provide real-time sensing and situational awareness.

4.2.3. Demonstration Scenario 1

- ❖ Remote Reconnaissance and Interrogation (1st part of the facility)
 - Area unknown, no intel on facility
 - While at the command post the operator will teleop Robot #1 from the breach point through the facility labeling any areas of interest, objects of interest (OOIs), and CBRN threats.
 - Two radio repeater were manually placed for extended communication.
- ❖ Technologies Demonstrated:
 - Remote reconnaissance and interrogation (real-time video)
 - Extended Communication / Mesh Network
 - OOI identification and tagging
 - Real-time CBRN monitoring
 - Real-time 2D map generation w/OOI and CBRN markings
- ❖ Observations:
 - System maintained effective situational awareness throughout the mission to perform remote recon through teleoperation.
 - Successfully generated a 2D map of the facility in real-time. An issue with loop closing causing a slight map drift was observed when the system remained stagnant for an extended period. The issue was captured and will be addressed in an upcoming development sprint.

- Demonstrated effective OOI's identification for the trained objects (person, backpack, door, etc.). OOIs and areas of interested were properly tagged on the live 2D map by the operator to enhance a commander's situational understanding of the site.
- The integrated MultiRAE displayed readings on the operator interface and the operator was able to mark the map accordingly.

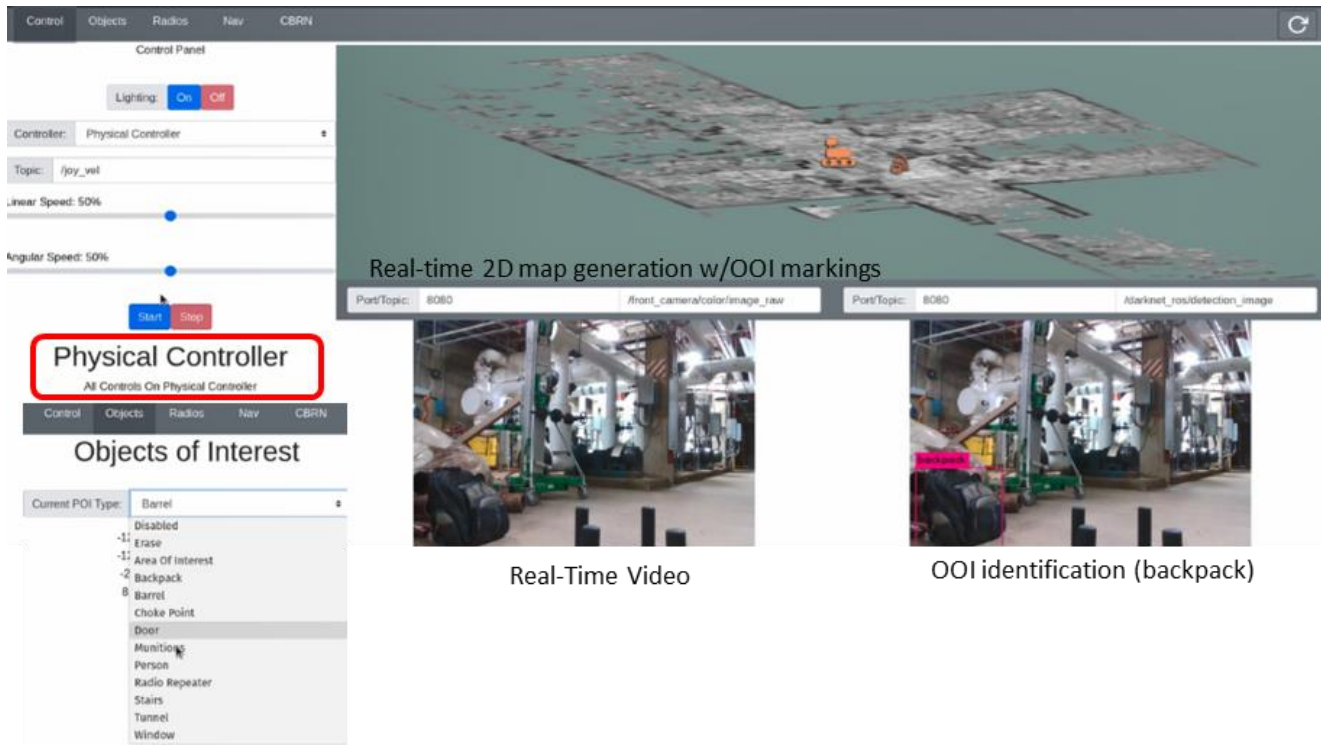


Figure 20: Scenario one OCU screenshot

4.2.4. Demonstration Scenario 2

- ❖ **Autonomy (Return to Home)**
 - After reaching the end of the facility in Scenario 1, the operator will initiate autonomous mode. Robot #1 will autonomously return to the breach point identifying any OOI and CBRN threats to be displayed on the Operator Control Unit (OCU).
- ❖ **Technologies Demonstrated:**
 - Remote reconnaissance and interrogation thru autonomous navigation (real-time video)
 - Extended Communication / Mesh Network
 - OOI tagging
 - Real-time CBRN monitoring
 - Real-time 2D map generation w/OOI and CBRN markings
 - Obstacle detection and avoidance

❖ Observations:

- The system demonstrated a successful return to home without waypoints or operator input. System explored multiple paths to return home initially but corrected its course and successfully returned home.
- Successfully identified OOI while in autonomy mode for the operator to manually place on the OCU.



Figure 21: Scenario two OCU screenshot

4.2.5. Demonstration Scenario 3

❖ Remote Reconnaissance and Interrogation (2nd part of the facility)

- Area unknown, no intel on facility
- While at the command post the operator will teleop Robot #1 from the breach point through the facility labeling any areas of interest, objects of interest (OOIs), and CBRN threats.

❖ Technologies Demonstrated:

- Remote reconnaissance and interrogation (real-time video)
- Extended Communication / Mesh Network
- OOI tagging
- Real-time CBRN monitoring
- Real-time 2D map generation w/OOI and CBRN markings

❖ Observations:

- Successfully demonstrated the ability to switch operating modes between autonomy and teleoperation throughout the mission
- The system continued mapping the new area effectively upon completion of scenario #2.

- Additional OOI's were identified and properly tagged on the live 2D map.
- Map scaled accordingly on the OCU as a larger area of the facility was mapped.

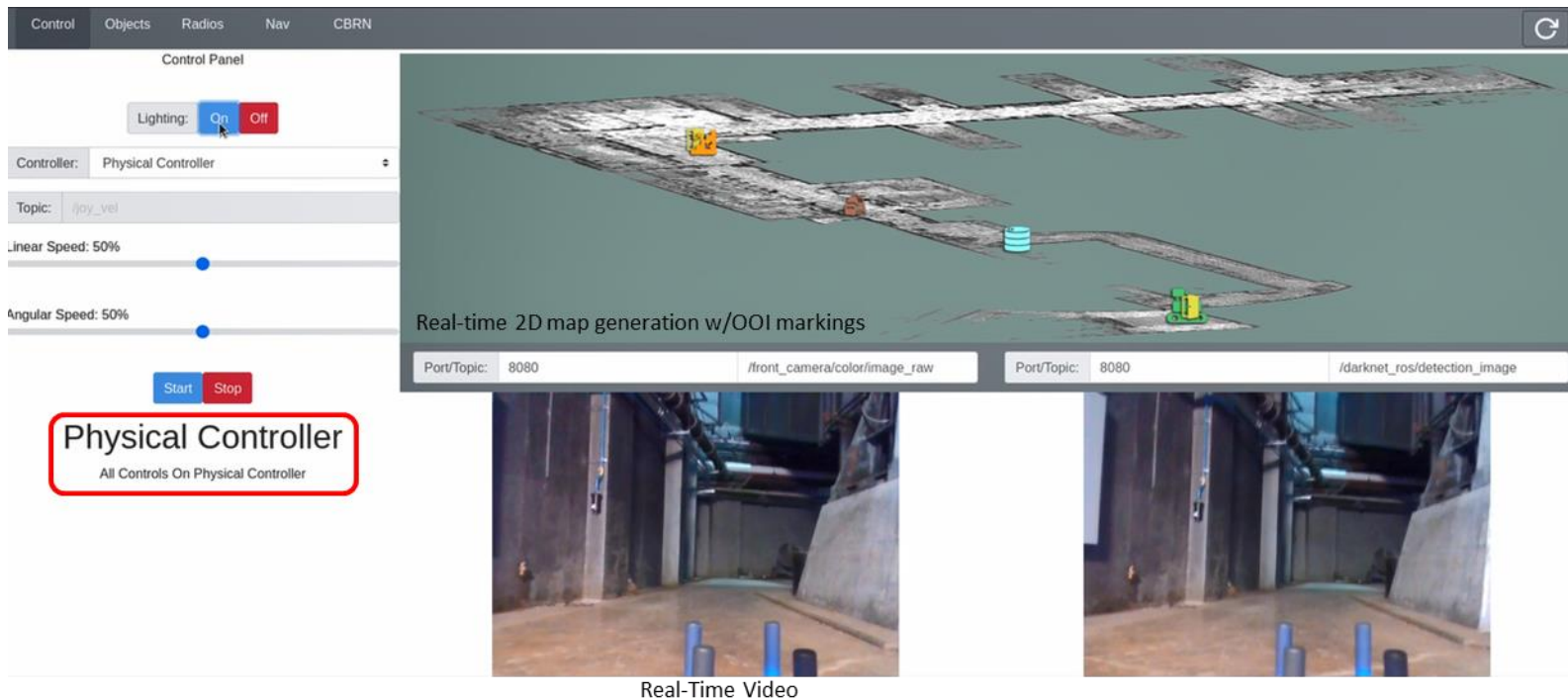


Figure 22: Scenario three OCU screenshot

4.2.6. Demonstration Scenario 4

- ❖ Autonomous Waypoint Navigation
 - Robot #1 has reached the end of the facility in scenario 3, the operator will plot waypoints on the map for Robot #1 to follow until it reaches the breach point, identifying any OOI and CBRN threats to be displayed on the OCU.
- ❖ Technologies Demonstrated:
 - Remote reconnaissance and interrogation thru autonomous navigation (real-time video)
 - Extended Communication / Mesh Network
 - OOI tagging
 - Real-time CBRN monitoring
 - Real-time 2D map generation w/OOI and CBRN markings
 - Obstacle detection and avoidance
- ❖ Observations:
 - Successfully demonstrated waypoint navigation through narrow spaces and complex paths.
 - Initial test run showed that waypoint placement on the map is critical for the system to effectively maneuver through narrow spaces. When commanding

the system to go through doors and complex sections, placing the waypoint beyond the obstacle is ideal. Good data point for operator training.

- Further optimization for detailed waypoint placing and displaying on the map to be considered in year 3.

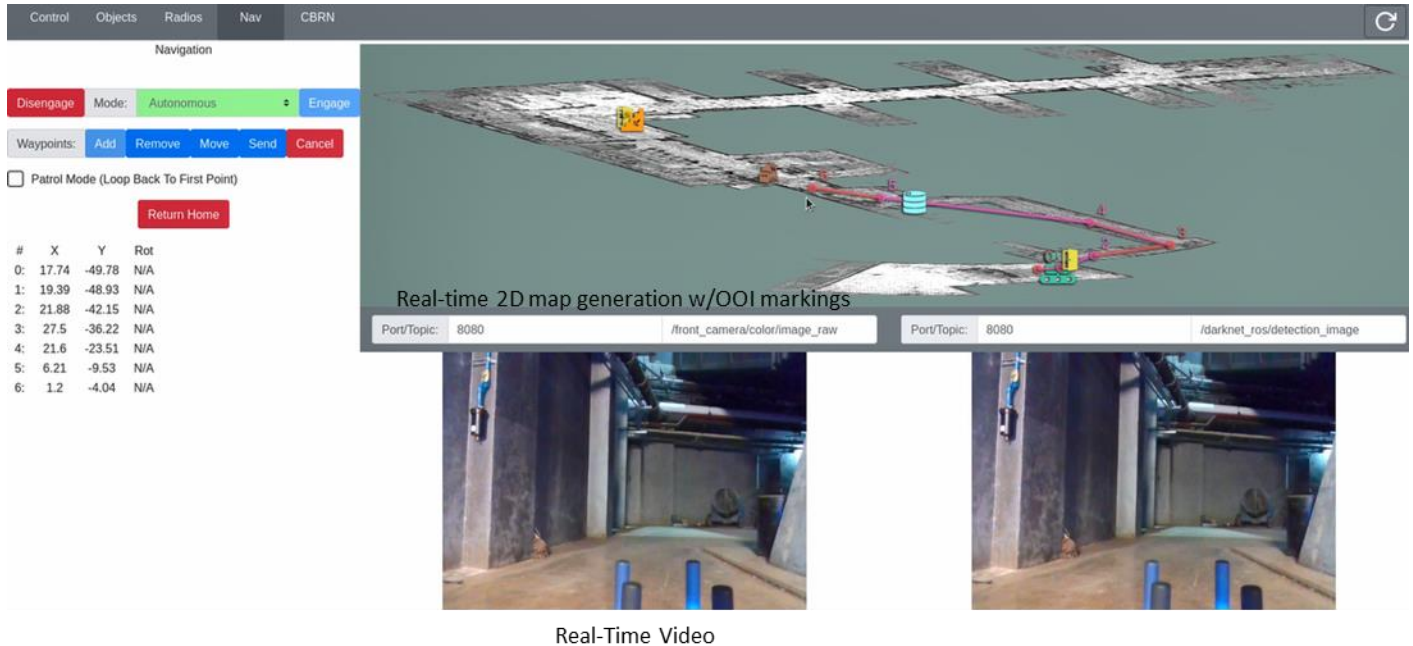


Figure 23: Scenario four OCU screenshot

4.2.7. Demonstration Scenario 5

❖ Autonomous Patrol Mode

- Site Commander has sent in CBRN team to further interrogate and neutralize the identified CBRN threat
- Robot #1 will autonomously patrol a designated route, monitoring air quality for real time alerts to the operator. A new obstacle will be introduced in the robots path to demonstrate obstacle identification and avoidance. Upon completion of patrol mode the operator will initiate teleop mode and return Robot #1 to the Breach Point.

❖ Technologies Demonstrated:

- Continuous remote reconnaissance and interrogation thru autonomous patrol navigation (real-time video)
- Extended Communication / Mesh Network
- OOI tagging
- Real-time CBRN monitoring
- Real-time 2D map generation w/OOI and CBRN markings
- Obstacle detection and avoidance

❖ Observations:

- Successfully demonstrated the patrol mode by designating a section of the map for the system to autonomously patrol back and forth.
- System detected and avoided dynamic obstacles and reported OOI (person) to the operator.
- Further improvements to the operator interface for mission planning and interactive map control identified for year 3.

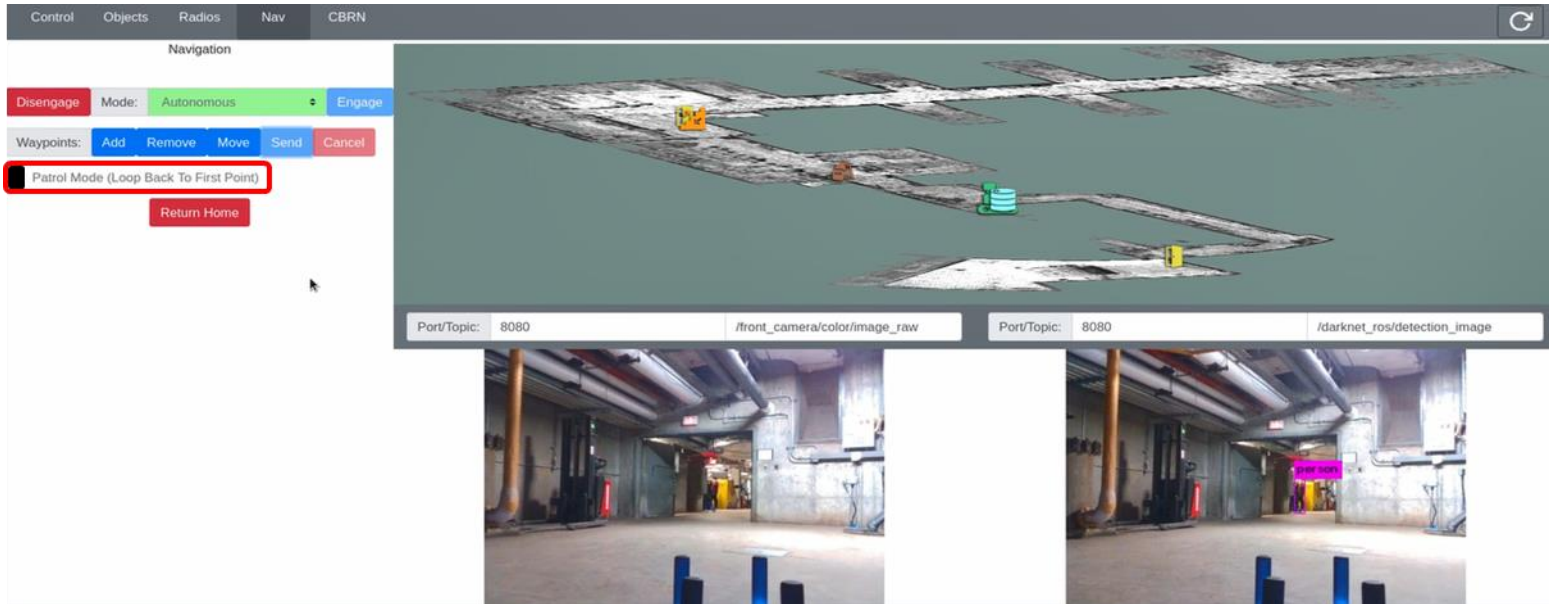


Figure 24: Scenario five OCU screenshot

4.3. Year 3

4.1.4. Purpose

- ❖ To evaluate and demonstrate the developmental progress for the Autonomous Tunnel Exploitation (ATE) technology objectives. The defined concept of operations (CONOPS) is intended to simulate an Underground Facility (UGF) for exploitation by a CBRN team to determine the layout, CBRN threats, objects of interest (OOI), and provide robotic reconnaissance support during the breaching and clearing of the UGF by a manned CBRN team.

4.1.5. Technology

- Autonomous navigation: waypoint, return home, retro-traverse, and exploratory
- Real time GPS-denied 2D / 3D map post processed
- Detect and mark objects of interest
- Deploy radio repeaters
- Detect and monitor air quality/CBRN threat
- Merge 2D maps
- Evaluate ATE effectiveness when integrated with a manned team.

4.1.6. Approach

- ❖ Assess ATE enabled UGVs against current SubT mission tasks to reduce mission risk and enhance team effectiveness. ATE is applicable to the following SubT mission phases:
 - Phase 1 - Reconnaissance of the surface objective
 - Phase 3b - Breach and secure a foothold
 - Phase 3c – Clear the subterranean objective
 - Phase 4 - Site exploitation

4.1.7. Demonstration Scenario 1 – Site Recon

- ❖ Technologies Demonstrated:
 - Real-time 2D map generation w/OOI and CBRN markings
 - Real-time CBRN/environmental monitoring
 - Exploratory autonomy reconnaissance and interrogation
 - Autonomous return to home (fastest route) w/obstacle detection and avoidance
 - Real-time video (team lead and command post)
 - Extended communications (comms) through mesh network
 - OOI tagging
- ❖ Observations:
 - System maintained effective situational awareness throughout the autonomous exploration. Operator input to establish exploratory zone.
 - Experienced a ‘teleportation’ of the bot’s location on the map. This issue would cause the autonomy to fail as there would be two disconnected maps. The planner would have to evaluate its path appropriately. A system restart corrected the issue.
 - Successfully generated a 2D map of the tunnel in real time.
 - Demonstrated effective OOI’s identification on trained objects (person, table, rocket, etc.). OOIs were autonomously tagged on the live 2D map to enhance a commander’s situational understanding of the site.
 - The integrated MultiRAE displayed readings on the operator interface and autonomously marked threat areas on the live 2D map.
 - The system demonstrated a successful return to home without waypoints or operator input. New features include the visual path plan on the 2D map.

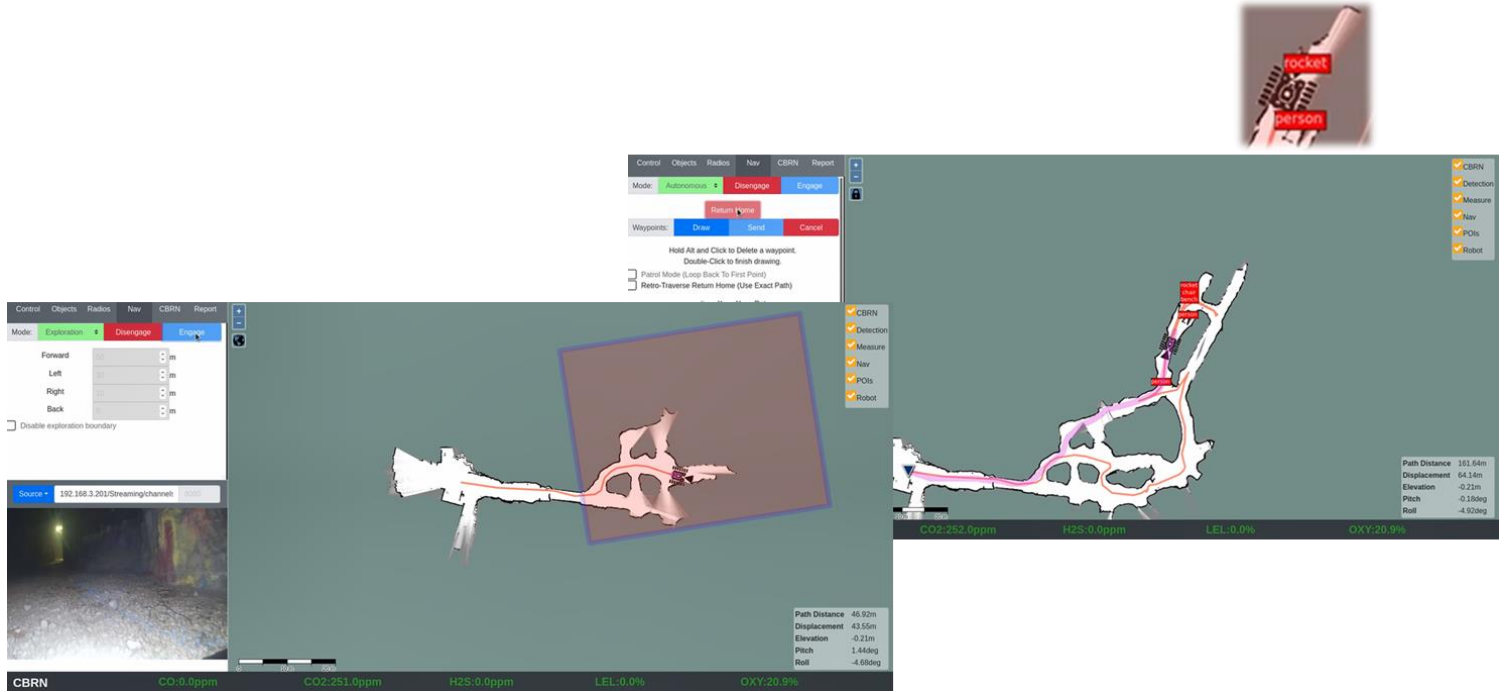


Figure 25: OCU screenshot – Autonomous Exploration and Return Home

4.1.8. Demonstration Scenario 2 – Manned Team Breach and Clear

❖ Technologies Demonstrated:

- Autonomous waypoint navigation w/obstacle detection and avoidance
- Real-time video (team lead and command post)
- Extended comms through mesh network
- OOI tagging
- Real-time CBRN/environmental monitoring
- Real-time 2D map display w/OOI and CBRN markings

❖ Observations:

- Successfully demonstrated waypoint navigation through narrow spaces and complex paths.
- Continuous operational runs showed that number of waypoints and placement on the map is critical for the system to effectively maneuver through narrow spaces and traverse the exact desired path as directed by the team lead.
- The global path plan displayed on the OCU allows the operator and team lead to ensure the system follows the desired path.



Figure 26: OCU screenshot – Autonomous Waypoint Navigation

4.1.9. Demonstration Scenario 3 – Site Exploitation

❖ Technologies Demonstrated:

- Autonomous patrol mode w/obstacle detection and avoidance
- Autonomous return to home (fastest route) w/obstacle detection and avoidance
- Real-time video (team lead and command post)
- Extended comms through mesh network
- OOI tagging
- Real-time CBRN/environmental monitoring
- Real-time 2D map display w/OOI and CBRN markings
- Automated After Action Report (AAR)

❖ Observations:

- Successfully demonstrated the patrol mode by designating a section of the map for the system to autonomously patrol back and forth.
- System detected and avoided dynamic obstacles and reported OOI (person/rocket) to the operator.
- The integrated MultiRAE displayed readings on the operator interface and automatically marked the threat area on the live 2D map.
- The system demonstrated a successful return to home without waypoints or operator input. New features include the visual path plan on the 2D map.

- An automated after action report was generated containing all pertinent mission information.

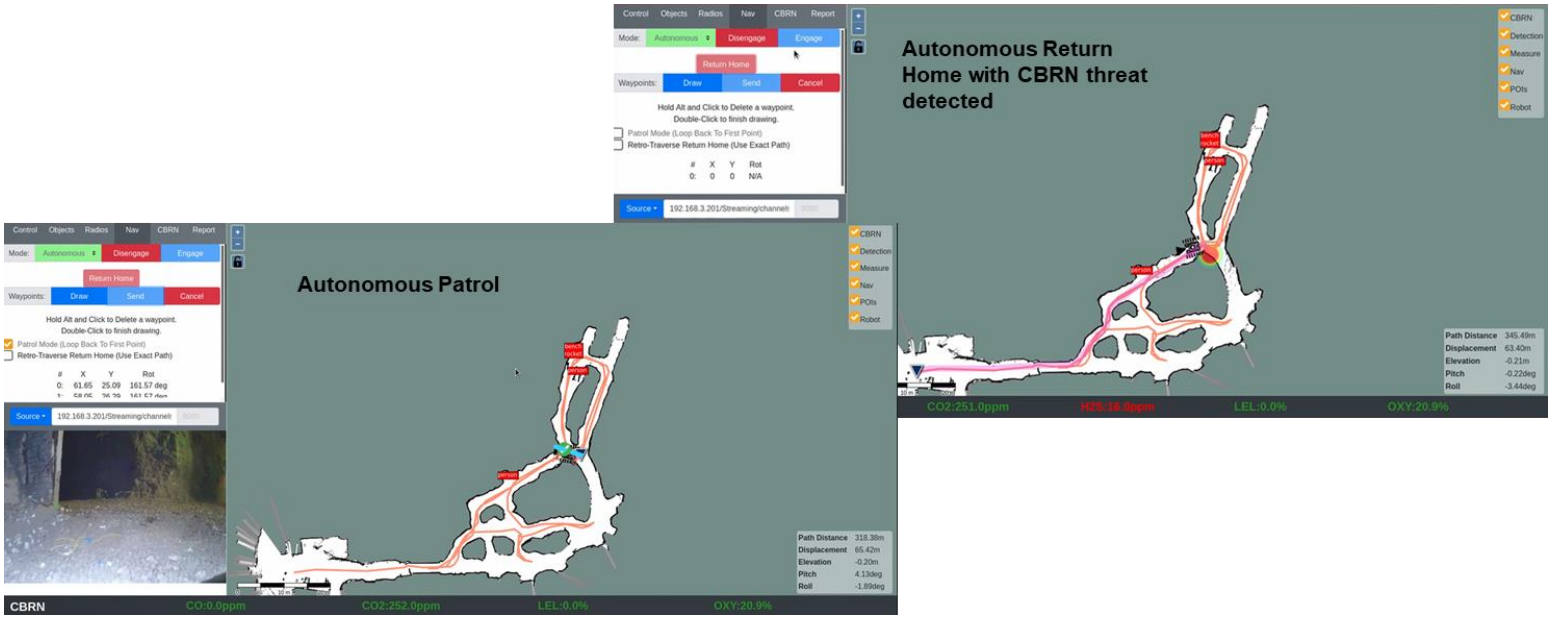


Figure 27: OCU screenshot – Autonomous Patrol and Return Home w/detected CBRN

4.1.10. Post Processed 3D Map

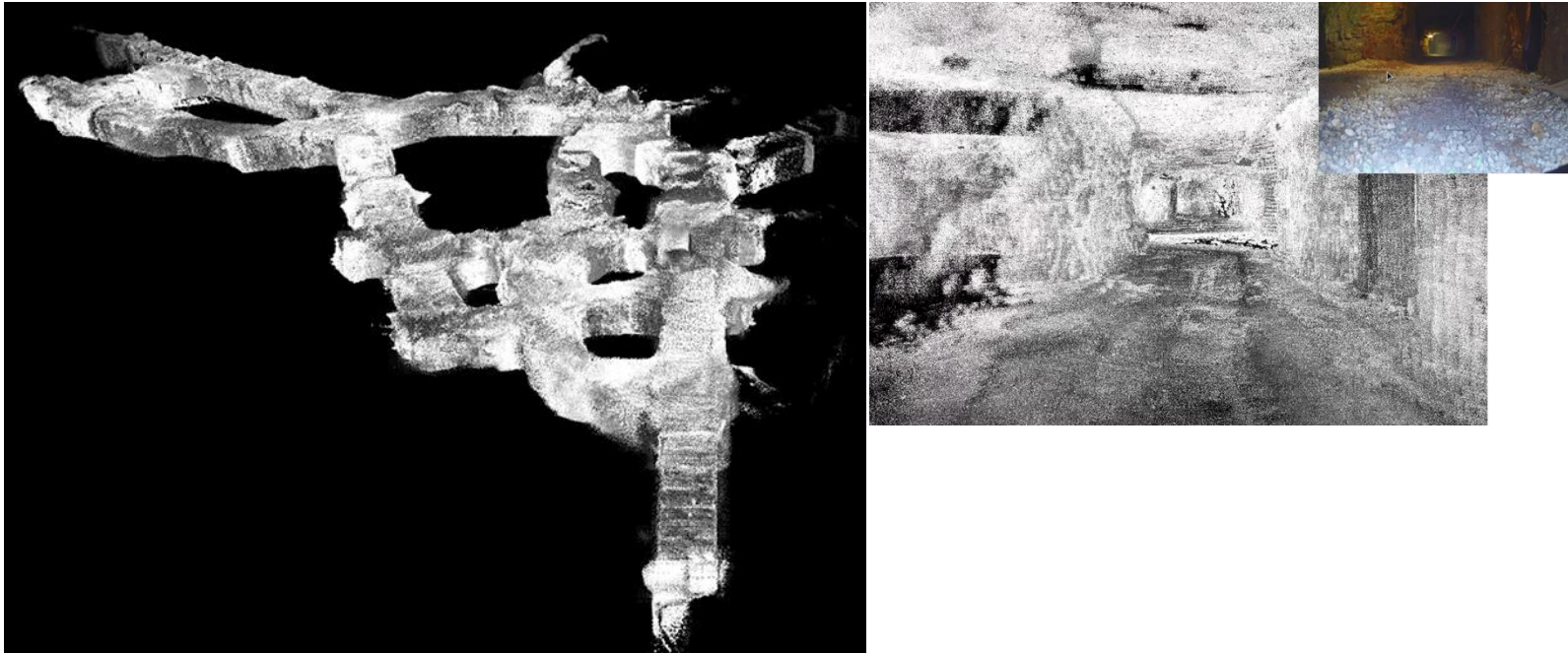


Figure 28: 3D Point Cloud

5. 2D Map Merging

5.1. Overview

Map merging between coalition partners was a primary objective for the Year 3 demonstration. A validation of the map merging approach was conducted in July 2021 using a mutually agreed upon simulation environment from the Defense Advanced Research Projects Agency (DARPA) Subterranean Challenge. An Interface Control Document (ICD) covering the common tunnel map file formats was produced as part of the effort.

5.2. Interface Technique and Formats

- Leverage common and public domain formats for 2D and 3D models compatible with existing DTRA Integrated Munitions Effects Assessment (IMEA) tool and open-source 3D visualization tools
- Use GeoTIFF format for 2D maps, which contain latitude/longitude coordinates of map corners for merging from any reference frame. Both teams independently selected Open Source Software (OSS) Geospatial Data Abstraction Library (GDAL) to produce the GeoTIFF and merge coalition GeoTIFF maps
- Use .ply format for 3D maps, which allow local coordinate frame for simple merging if using the same starting location (simply open both .ply in the same viewer), and two-step merging if GVSC and ADD conduct the exploitation from different starting locations (open both .ply in the same viewer, perform a rough manual alignment and then an automated registration). RoK selected OSS MeshLab and GVSC selected OSS CloudCompare for viewing and merging .ply

5.3. Execution and Results

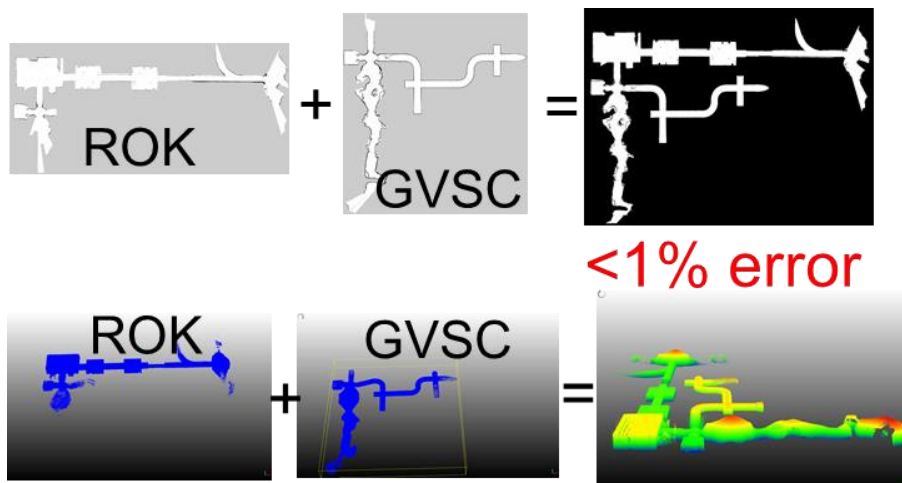


Figure 29: ROK and GVSC merged 2D map results

5.4. Validation

- GVSC and ROK both demonstrated capability to merge two-dimensional and three-dimensional representations of a mapped tunnel facility.
- DARPA SubT simulation world was leveraged due to COVID-19 travel restrictions, facility is greater than 100,000m² and consists of urban, cave, and mining areas with elevation changes and drop offs. Only a portion of the facility was exploited.

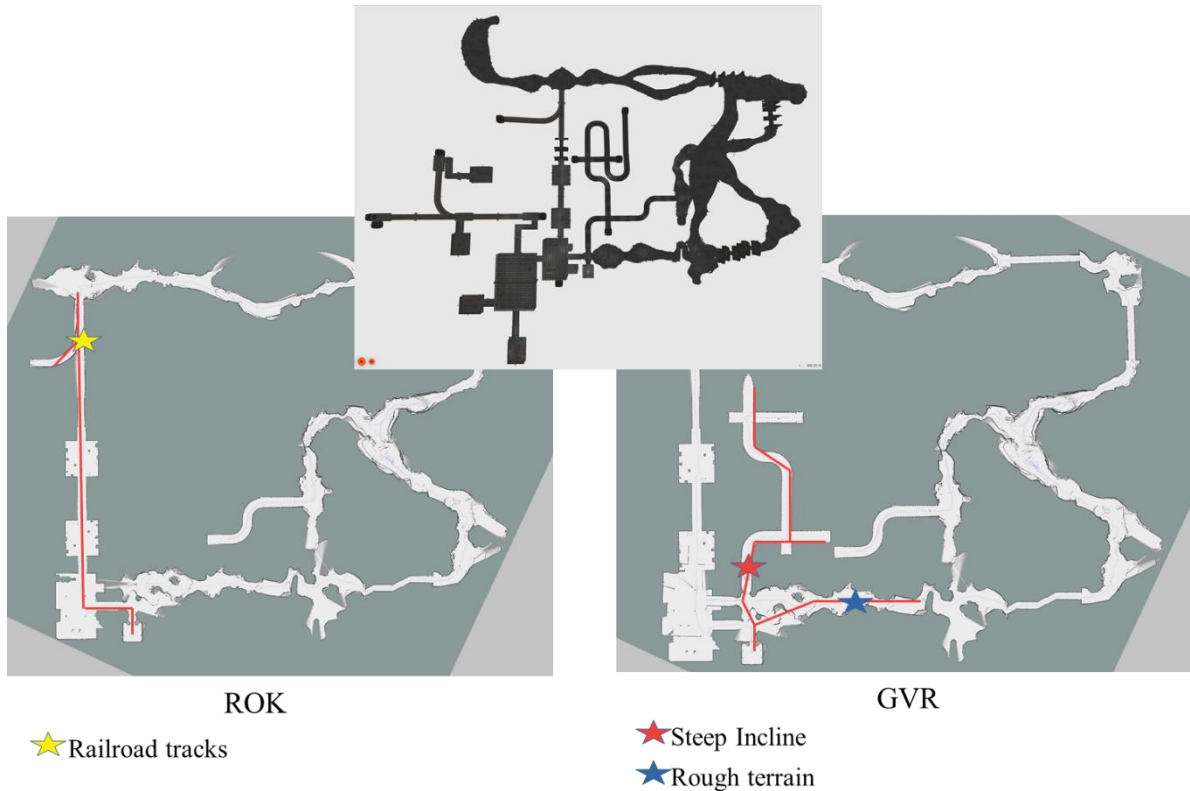


Figure 30: Routes and Merged Maps

5.5. Lessons Learned

During the initial map merging, we inadvertently left the magnetic declination set to Warren, Michigan which resulted in a seven degree offset in map heading and a misaligned map. The map merging was conducted in the simulation environment which requires the declination be set to zero degrees. This error was fixed in follow on map merging efforts that led to a successful and accurate map merge.

6. Testing / Technology Evaluations

6.1. Manual Backpack Mode

6.1.1. Objective

- While not an ATE project objective, we began investigating the utility of the ATE payload used as a backpack for soldiers to map a facility more rapidly. Given the modular design of the payload, the concept would allow a user to decide whether to exploit a facility remotely using an ATE enabled robot or perform a manned mission wearing the ATE payload. The justification for a manned mission would be to have a more rapid and accurate facility map.
- Method: ATE payload was mounted on a backpack and powered by a standard BB2590 battery. The operator turned on the payload and walked the throughout a building at a standard walking pace.
- Evaluate: the effectiveness of the ATE payload to map through other means besides integrated onto a small robot.

6.1.2. Observations

- ATE SLAM tracked optimally even with the tilting and jostling of the backpack rig - no stabilization or isolation method was used.
- Mapping appears to be, at a minimum, as accurate as mapping while robot-mounted - with zero changes in software configuration.
- Live SLAM and navigation are fully responsive, enough to provide an operator with full situational awareness of path traveled, building layout, and the optimal path to any room or exit.
- This mode enables the operator to see a live 2D and 3D map because of the ability for a tethered connection to an OCU. The payload can also map without user input and be viewed by an operator after the mission is completed.
- Seems promising to expand the use of ATE in very complex SubT mission and beyond such as reacting to natural disasters, dense urban environments, etc.

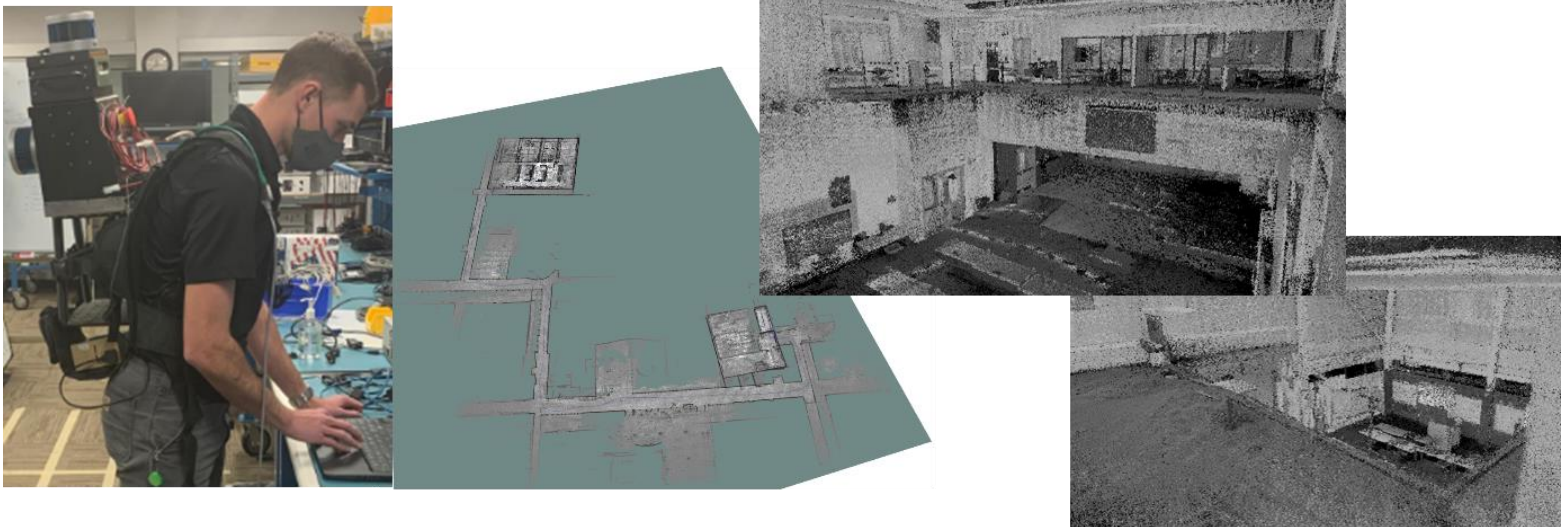


Figure 31: Manual Backpack Mode

6.2. LiDAR Comparison

6.2.1. Objective

- Determine suitability of using a single higher resolution Ouster 3D LiDAR for next-generation sensor payload, vice two lower resolution Velodyne 3D LiDARs.
- Method: Conduct mapping and localization missions in GPS-denied environment using same IMU and similar trajectories with two separate LiDAR payloads.
- Evaluate: point-cloud density, accuracy of 2D map, localization accuracy (e.g. failures to loop close in real-time), ease of use (e.g. start-up time).

6.2.2. Observations

- Ouster produces a higher density point cloud compared to the Velodyne however the ATE payload current configuration utilizing a vertical Velodyne produces a better model when performing in high ceiling areas.
- SLAM performance showed to be comparable between the two.
- The Ouster configuration is more technical to configure and requires additional timing software than the Velodyne.
- A single Ouster is larger than a single Velodyne and each uses the same power consumption.
- Further engineering assessment of overall payload size, one lidar vs two, complexity, cost, and sustainability to be considered before the final configuration decision was made.

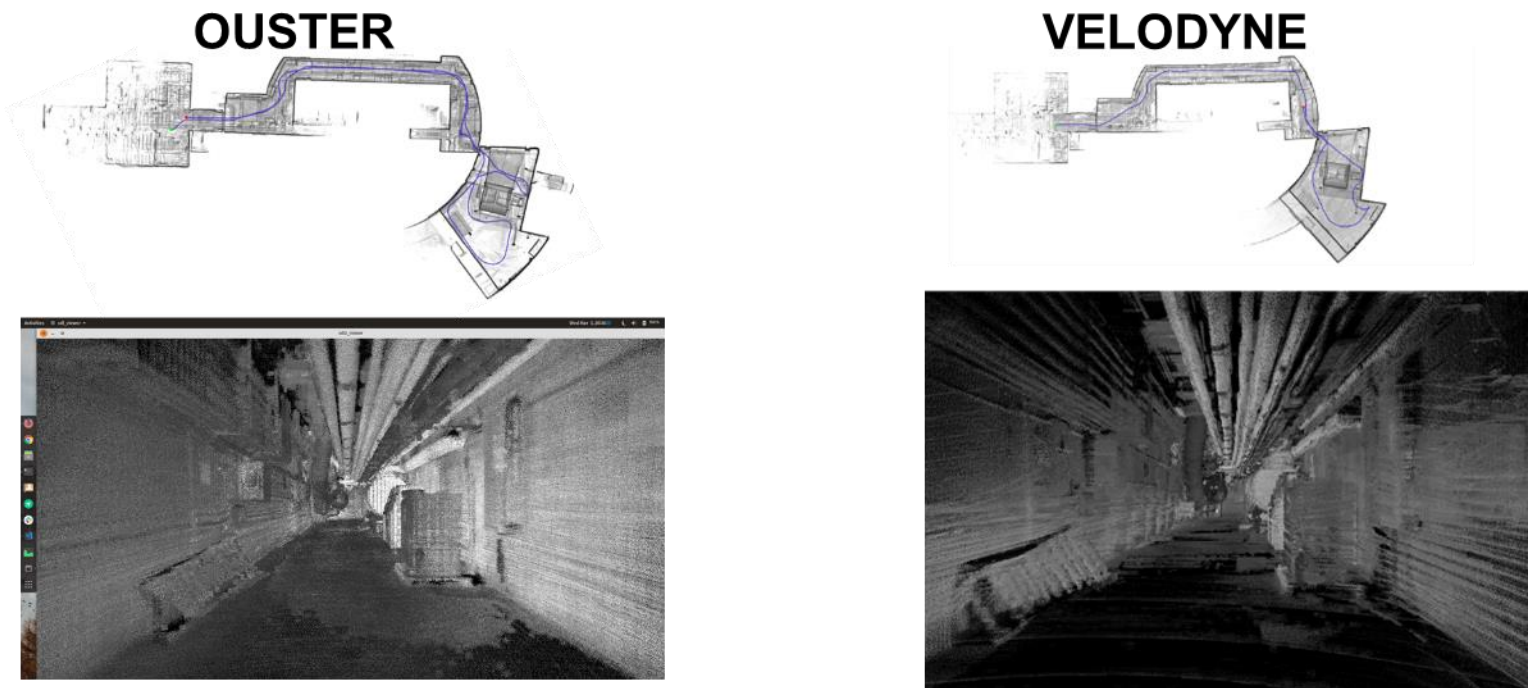


Figure 32: Ouster and Velodyne LiDAR Comparison

6.3. FARO and ATE Payload Comparison

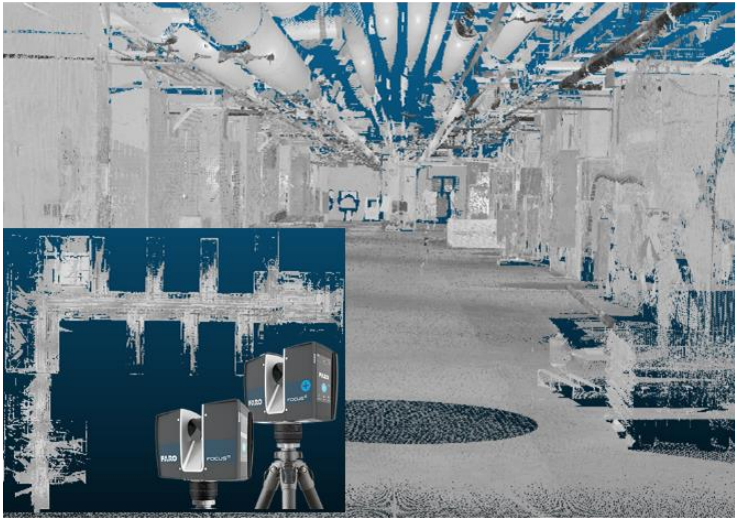
6.3.1. Objective

- Compare accuracy of ATE payload against FARO scanner (industry leader for indoor mapping).
- Method: Conduct scans of the same facility using an architecture grade scanner (FARO) and GVSC developed ATE payload to compute the difference in 3D point clouds between individual scans and compare 3D maps for definition of objects and human perception.
- Evaluate: level of map detail and accuracy between the two systems.

6.3.2. Observations

- ATE showed comparable map accuracy and detail to the FARO scanner.
- The FARO scanner performs 360 degree scans at intervals to generate a full map of a facility. FARO scans were performed 10m apart using the same path as the ATE continuous scanner.
- FARO has a more dense point cloud at each scan point but the map coverage is dependent on the location of the scans.
- ATE continuous mapping approach was able to capture a greater area of the facility at eight times the speed of individual FARO scans.
- Easier to interpret images using the ATE 3D generated map compared to FARO.

FARO



ATE PAYLOAD



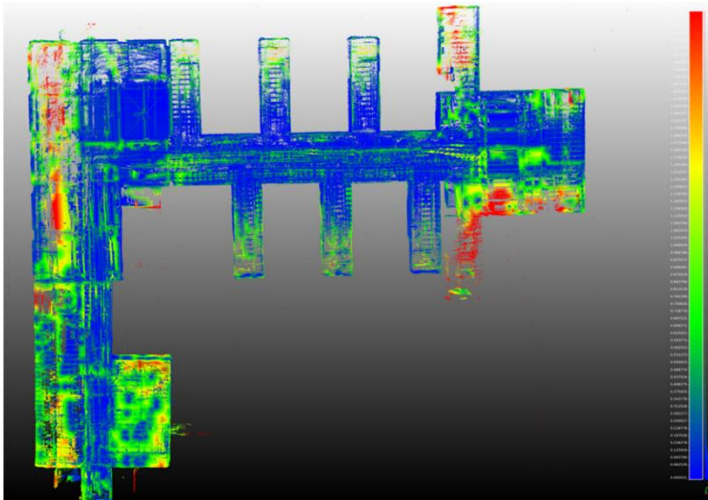
Figure 33: FARO and ATE Payload Comparison

6.4. LIDAR Data

6.4.1. Point Cloud Delta

- Large differences (red) in areas where FARO scans did not cover, but less than 5cm differences (blue) in areas where FARO and ATE payload had similar coverage (central hallway)

POINT CLOUD DELTA



	FARO	ATE
# Points	128M	119M
Size	2.8GB	2.3GB
Mean distance	0.24m	
Std Dev	0.28	
RMS	0.076	

Figure 34: Point Cloud Delta

6.4.2. Comparing Map Data between the three LIDAR Systems

	Long hallway inside to inside corner	Top right to bottom left	3D Point Cloud File Size	# Points (3D Point Cloud)
Ouster	26.745m	56.96m	4.8GB	251.2M
Velodyne	26.66m	57.78m	2.0GB	106.8M
FARO	26.52m	56.48m	3.8GB	173.4M



Figure 35: Ouster, Velodyne and FARO LIDAR Comparison

7. Conclusion

Warfighters lack sufficient capability and capacity to rapidly characterize and exploit Underground Facilities (UGFs) that may contain Weapons of Mass Destruction (WMD). The high number of complex adversary UGFs and low numbers of specialized coalition forces to exploit them, risks significant loss of operational momentum during combat operations. The warfighter needs the ability to rapidly exploit, characterize, and assess UGFs in order to isolate adversary WMD, and enable ongoing combat operations and subsequent WMD elimination operations.

The objective of this project was the collaborative improvement of advanced coalition robotic technologies and interoperability to support the exploitation of UGFs containing WMD. This combined United States (US) and Republic of Korea (ROK) project conducted work in the areas of virtual environment testing and experimentation; Global Positioning System (GPS)/GPS-denied autonomous navigation; two-and three-dimensional (2-D/3-D) mapping and photogrammetry; object recognition; sensor integration; automated reporting; Position, Navigation, and Timing (PNT); autonomous system behavior algorithms; intelligent underground communications; communications and data format element standards and protocols. This effort ultimately improved current robotic subsystem architecture performance capabilities and US/ROK system interoperability to improve the speed and efficiency of underground facility exploitation by US/ROK forces.

Ground Vehicle Systems Center (GVSC) focus for the ATE project was to produce a Modular Mission Payload (MMP) for use on existing Program of Record (PoR) and Science & Technology (S&T) robotic platforms that is designed to help address mapping, air chemical contaminants, and subterranean space monitoring. This MMP will enable the warfighter to conduct a mission safer, more efficient, and more effective.

Through yearly demonstrations, we evaluated the developed capabilities in a variety of realistic and relevant operational environments. The demonstrations allowed GVSC and stakeholders to assess ATE enabled UGVs against current SubT mission tasks aimed to reduce mission risk and enhance team effectiveness. Through rigorous research, planning, development, and testing GVSC was able to meet all project objectives as outlined in FY18-21 Statement of Work (SOW) for Defense Threat Reduction Agency (DTRA) Counter WMD Division (CXW) Autonomous Tunnel Exploitation (ATE) dated 22 May 2018. The on-going COVID-19 global pandemic prevented GVSC and ROK Agency for Defense Development (ADD) to participate in the scheduled joint year three-demonstration assessment. Each organization proceeded with a separate demonstration and provided the results and findings for review.

Early on in this effort, we focused on developing a defined plan by first understanding the ROK mission, Army gaps and requirements through user and acquisition engagements. Having a solid understanding of the mission allowed us to research and identify technology gaps that would meet the specific requirements and increase soldier capabilities. We then established a set of HW and SW requirements through a mission

decomposition to trace operational objectives to functional requirements. Conducting this rigorous planning allowed us to maximize resources for development, verification and validation of the defined capabilities to meet the requirements.

Plan:

- **Understanding the RoK Mission**

Worked with 2nd Infantry Division (2ID) to identify the Hazard Assessment Platoon (HAP) and Chemical, Biological, Radiological, Nuclear, Environmental (CBRNE) Response Team (CRT) as the primary missions for ATE. Identified mapping and autonomy behaviors required to reduce their risk and enhance team effectiveness.

- **Understanding the Army Gaps**

Worked with the user and acquisition communities to identify overlapping gaps such as the Enhanced Robotic Payload (ERP) Program of Record (PoR) in order to shape the capability development with transition in mind.

- **Technology Gaps**

Initial research of existing Army S&T and commercial mapping / autonomy solutions indicated that technology was not suited for small dismounted UGVs and required new development.

- **Defined the Requirements**

Decomposed the requirements to trace operational objectives to functional requirements to specifications for both hardware and software.

- **Project Planning**

Established the development plan for software and hardware, established a modular architecture to comply with Office of the Secretary of Defense (OSD) Modular Open System Architecture (MOSA) requirements, and develop M&S and system level test plans.

Develop:

- **Modular Open System Architecture (MOSA)**

Implemented a ROS based modular open system architecture to enable capability growth and support future acquisition efforts. Performed mission and requirements decomposition to generate system engineering views, reference architectures and core behaviors that support the operational use of the system.

- **Development Rigor**

Adapted agile Software (SW) development with acquisition systems engineering rigor to ensure development tasks are properly planned, documented, configuration managed, and validated at all levels. Implemented Model Based System Engineering (MBSE) to shape and document development.

- **Verification and Validation**

Implemented DARPA's SubT Challenge M&S environments early in the development cycle to enable rapid and recurring testing of new behaviors.

Conducted extensive component and system level testing in relative environments to optimize the technology and validate against the requirements. Assessed Cyber and Intellectual Property rights to ensure transition is feasible.

- **Modular Autonomy/Mapping Payload**

Developed the capability as an Interoperability Profile (IOP) compliant Modular Mission Payload (MMP) that is capable of integrating across multiple PoR and S&T UGVs to provide autonomy and mapping functionality.

Transition:

- **RTK-Lite Product Line**

Proven autonomy and mapping SW, documentation, Systems Modeling Language (SysML), System Engineering (SE) documents, Model & Simulation (M&S) tools, and other artifacts is being transitioned to establish the Robotic Technology Kernel - Lite (RTK-Lite) product line. This provides the Army a capability baseline to support future S&T and PoR efforts.

- **Support S&T Efforts**

ATE developed technology transitioned to support the Dismounted Infantry 10x program. GVSC integrated the autonomy and mapping modular payload onto a Boston Dynamics Spot to support 10x experiments for dismounted autonomous maneuver.

- **Inform PoR**

GVSC established a project agreement with PdM Robotic and Autonomous Systems (RAS) to transition RTK Lite in support of the Enhanced Robotic Payload Program of Record. The capability and supporting systems engineering documents to include System/Subsystem Design Document (SSDD), System Segment Specification (SSS), Software Development Plan (SDP), Cyber Assessment, etc. will transition to inform and shape the PoR execution.

- **Transition to Industry**

Conducting a risk reduction prototype effort with the National Advanced Mobility Consortium (NAMC). Transition matured ATE SW and data knowledge to NAMC members for the industry to become familiar with the product, provide feedback, and leverage as a baseline to compete for future programs.

Appendix

A. Acronyms

ATE	Autonomous Tunnel Exploitation
CBRN	Chemical, Biological, Radiological and Nuclear
COP	Common Operating Picture
CoVeR	Combat Robotic Vehicle
CRSH-H	Common Robotics System – Heavy
CWP	Coalition Warfare Program
DS	Dismounted Systems
DTRA	Defense Threat Reduction Agency
EO	Explosive Ordinance
ERP	Enhanced Robotic Payload
ERP-UGS	Enhanced Robotic Payload – Unmanned Ground System
GUI	Graphical User Interface
GVR	Ground Vehicle Robotics
GVRBOT	Ground Vehicle Robot
GVSC	Ground Vehicles Systems Center
IED	Improvised Explosive Device
IMU	Inertial Measurement Unit
IOP	Interoperability Profile
IRA	Indoor Route A
IRB	Indoor Route B
KPP	Key Performance Parameter
KSA	Key System Attribute
LiDAR	Light Detection and Ranging
MBU	Mobility Base Unit
MMP	Modular Mission Payload
MP	Digital Mapping
MTRS Inc II	Man Transportable Robotic System Increment II
OA	Obstacle Avoidance
OA&DM	Obstacle Avoidance and Digital Modeling
OCU	Operator Control Unit
OS	Operating System
OUT	Outdoor Route
PdM RAS	Product Manager Robotic Autonomous Systems
PoR	Program of Record
RAS-G	Robotics and Autonomous Systems - Ground
RHFR	Return Home - Fastest Route
RHRT	Return Home – Retro-traverse
ROK ADD	Republic of Korea Agency for Defense Development
ROS	Robot Operating System
SLAM	Simultaneous Localization and Mapping
SMACH	State Machine
SDD	Software Design Description
SSDD	System/Subsystem Design Specification
SubT	Subterranean
TEB	Time-Elastic Band
UGS	Unmanned Ground Systems
WMD	Weapons of Mass Destruction
WP	Waypoint Navigation
2D	Two Dimensional
3D	Three Dimensional

B. Test Plans and Procedures

1. Mapping and Return home via fastest route

Objective:

Evaluate the ability of the ERP Obstacle Avoidance & Digital Modeling (OA&DM) payload to digitally map an area of interest and to return home via the fastest route from various distances

Routes:

Indoor Route A

Indoor Route B

Outdoor Route

Test Procedure:

Testing will be performed inside and outside of B200 along three routes. The robot will be positioned at the starting point indicated by a star on the route map. The robot will be powered on and connected to the OCU via Silvus radio. The teleoperation speed will be set to medium. The operator will teleoperate the robot until the robot reaches the ending point indicated by an "X" on the route map.

Indoor Testing

During the teleoperation phase, there will be several 1x2 strips of wood to simulate rough terrain. A CBRN stimulant will be introduced to the MultiRAE mounted on the robot to simulate a CBRN hazard. The robot will stop and not move for a period of five minutes along the route to simulate a pause during a mission.

For Indoor Route A, once the robot reaches the ending point, the operator will stop the robot and engage return home via fastest route.

For Indoor Route B, the operator will continue to teleoperate the robot until it reaches the exploratory area where the operator will explore the area. The operator will then stop the robot and engage return home via fastest route.

Outdoor Testing

The robot will be teleoperated from the outside starting point to the inside ending point. Once the robot reaches the ending point, the operator will stop the robot and engage return home via fastest route.

If the robot is in an area where it does not have enough room to turn around, the operator will take control and teleoperate the robot to face the traveled path and reengage return home via fastest route.

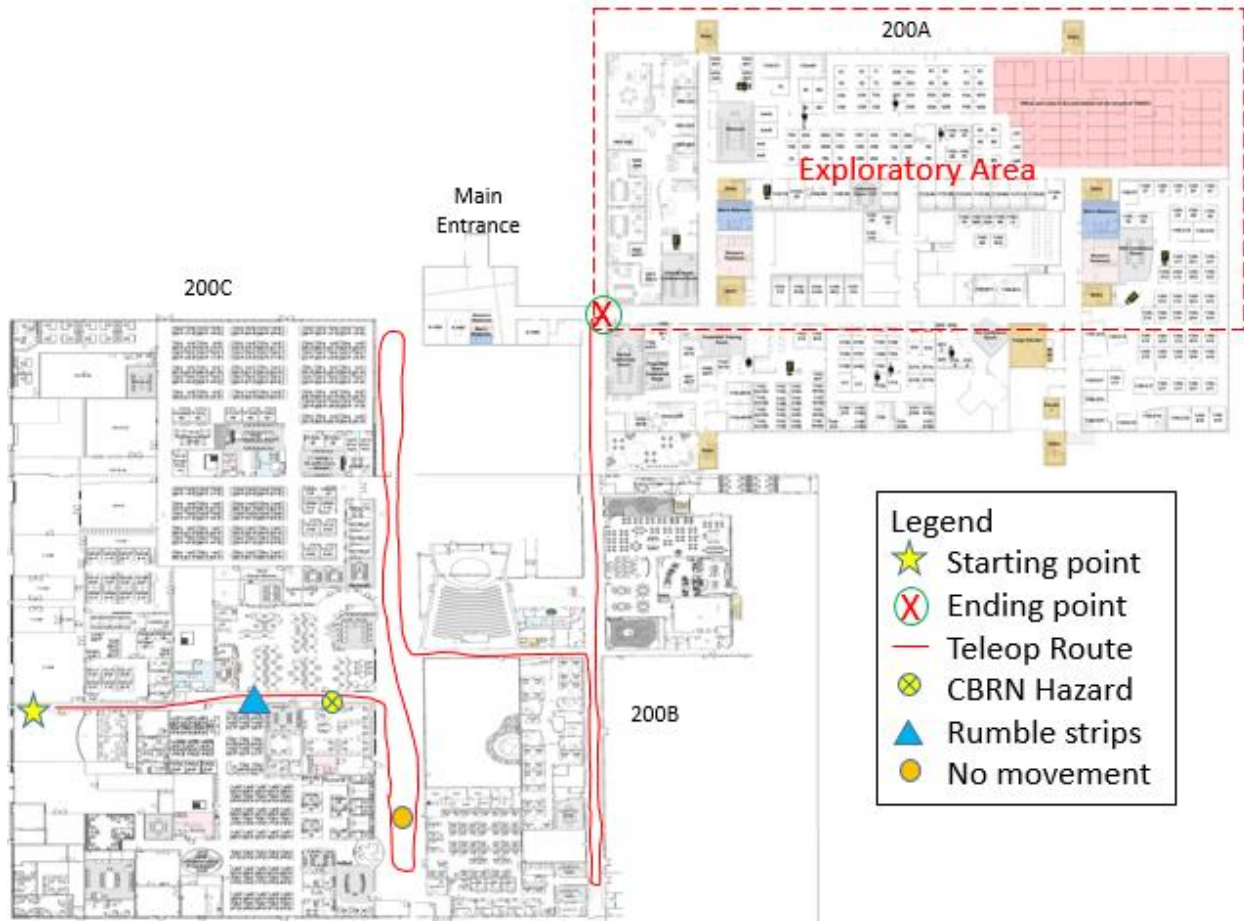
Data Required: The following data will be recorded.

1. Date of test
2. Test item configuration

3. Current time the OCU and MBU were turned on and off
4. Start and end time of each route
5. Distance between starting point and ending point
6. Time to teleop to ending point
7. Map observations to include but not limited to:
 - a. Map drift
 - b. Map drift corrected by loop closing
 - c. Map accuracy
8. Was the CBRN hazard detected
9. Path traveled towards starting point
10. Did the robot return home?
11. Time to return to starting point
12. Observations describing any malfunctions, anomalies, or other issues
13. Any deviation from the test procedure

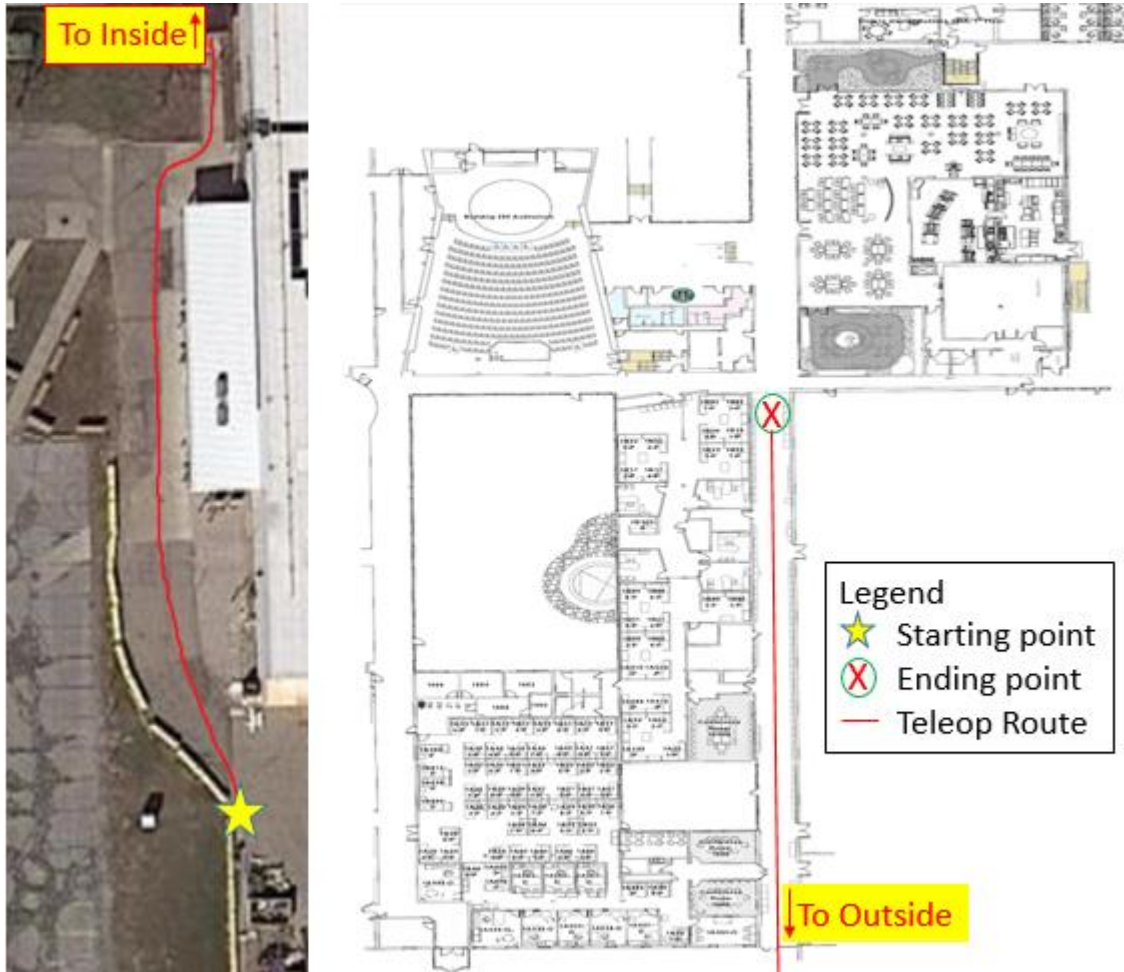
Indoor Route B

Mission 2: The operator will teleoperate the robot from the starting point towards the ending point. The robot will maneuver over rumble strips, analyze a potential CBRN hazard, and will stop for five minutes before continuing along the route. Upon reaching the exploratory area the operator will continue to teleoperate the robot to explore the area. The operator will then stop the robot and engage return home via fastest route.



Outdoor Route

Mission 3: The operator will teleoperate the robot from the outdoor starting point towards the indoor ending point. Once reaching the ending point, the operator will engage the autonomous state, return home via fastest route, for the robot to head back to the starting point.



2. Mapping and Return home via retro-traverse

Objective:

Evaluate the ability of the ERP OA&DM payload to digitally map an area of interest and to return home via the retro-traversed path from various distances.

Routes:

Indoor Route A
Outdoor Route

Test Procedure:

Testing will be performed inside and outside of B200 along two routes. The robot will be positioned at the starting point indicated by a star on the route map. The robot will be powered on and connected to the OCU via Silvus radio. The teleoperation speed will be set to medium. The operator will teleoperate the robot until the robot reaches the ending point indicated by an "X" on the route map.

Indoor testing

During the teleoperation phase, there will be blue tape near the starting point spaced wider than the width of the robot. The robot will be teleoperated between the blue tape. Along the route will be several 1x2 wood piece strips to simulate rough terrain. A CBRN stimulant will be introduced to MultiRAE mounted on the robot to simulate a CBRN hazard. The robot will stop and not move for a period of five minutes along the route to simulate a pause during a mission. Once the robot reaches the ending point, the operator will stop the robot and engage return home via retro-traverse.

If the robot reaches the blue tape, an observation will be made indicating if the robot was able to retro-traverse between the blue tape. A measurement will be taken of the retro-traversed path if the robot traveled beyond the boundary of the two cones.

Outdoor Testing

The robot will be teleoperated from the outside starting point to the inside ending point. Once the robot reaches the ending point, the operator will stop the robot and engage return home via retro-traverse.

If the robot is in an area where it does not have enough room to turn around to start retro-traversing the traveled path, the operator will take control and teleoperate the robot to face the traveled path.

Data Required:

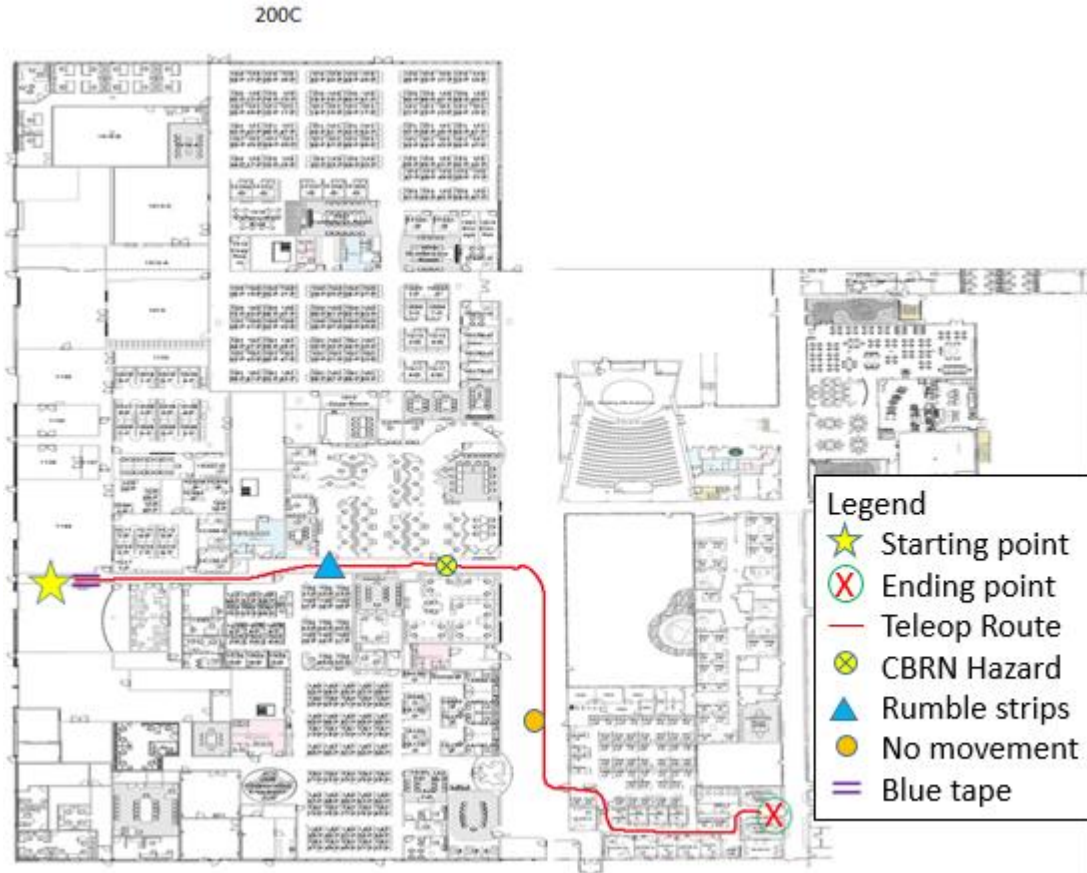
The following data will be recorded.

1. Date of test
2. Test item configuration
3. Current time the OCU and MBU were turned on and off
4. Start and end time of each route
5. Distance between starting point and ending point

6. Time to teleop to ending point
7. Map observations to include but not limited to:
 - a. Map drift
 - b. Map drift corrected by loop closing
 - c. Map accuracy
8. Was the CBRN hazard detected
9. Measure the difference between teleoperated path and retro-traversed path between the blue tape
10. Did the robot return home?
11. Time to retro-traverse to starting point
12. Observations describing any malfunctions, anomalies, or other issues
13. Any deviation from the test procedure

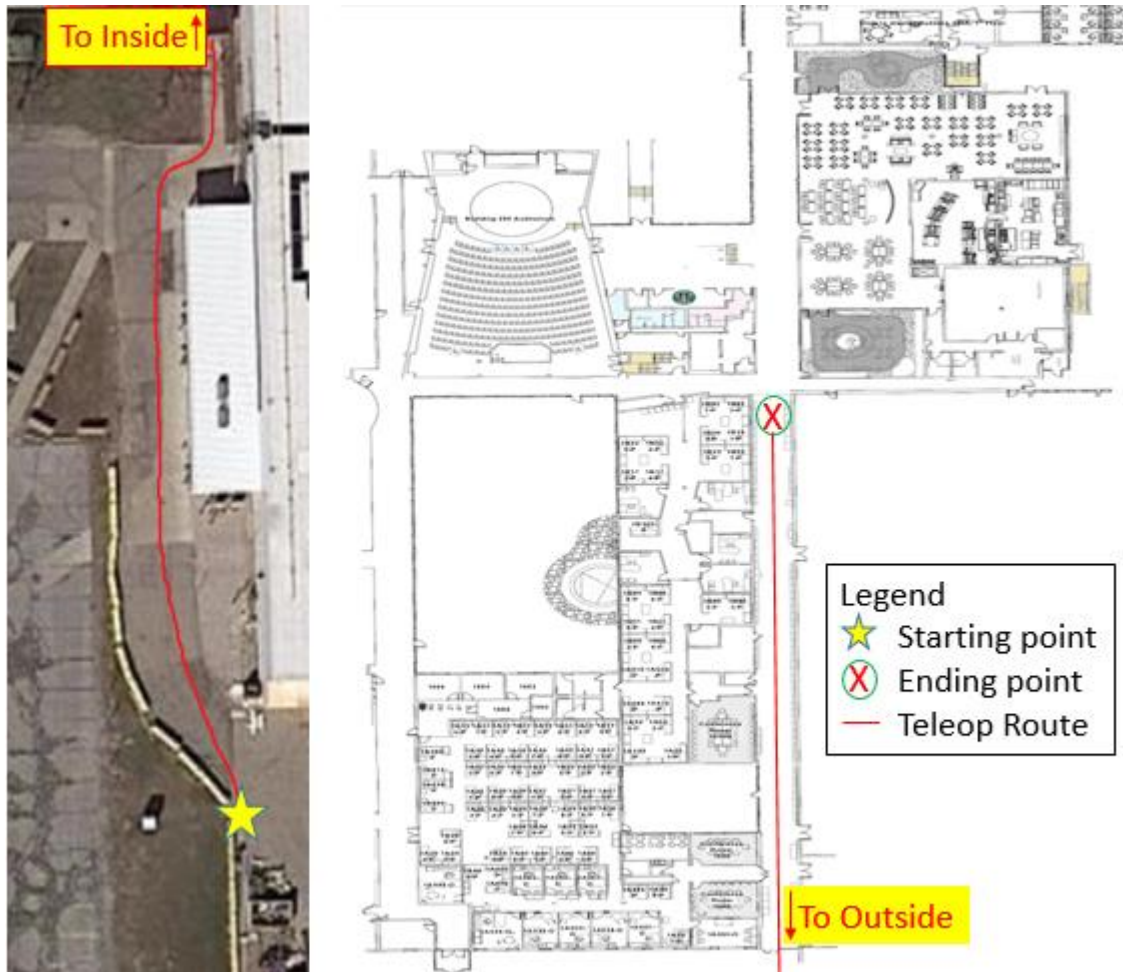
Indoor Route A

Mission 1: The operator will teleoperate the robot from the starting point towards the ending point. The robot will maneuver over rumble strips, analyze a potential CBRN hazard, and will stop for five minutes before entering the GVR office to reach the ending point. Once reaching the ending point, the operator will engage the autonomous state, return home via retro-traverse, for the robot to head back to the starting point.



Outdoor Route

Mission 2: The operator will teleoperate the robot from the outdoor starting point towards the indoor ending point. Once reaching the ending point, the operator will engage the autonomous state, return home via retro-traverse, for the robot to head back to the starting point.



3. Mapping and Waypoint Navigation

Objective:

Evaluate the ability of the ERP OA&DM payload to digitally map an area of interest and to navigate through waypoints.

Routes:

Indoor Route B

Test Procedure:

Testing will be performed inside and outside of B200 along one route. The robot will be positioned at the starting point indicated by a star on the route map. The robot will be powered on and connected to the OCU via Silvus radio. The teleoperation speed will be set to medium.

During the teleoperation phase, there will be several 1x2 strips of wood to simulate rough terrain. A CBRN stimulant will be introduced to the MultiRAE mounted on the robot to simulate a CBRN hazard. The robot will stop and not move for a period of five minutes along the route to simulate a pause during a mission.

The operator will continue to teleoperate the robot until it reaches the exploratory area where the operator will explore the area. The operator will then stop the robot at the ending point and input waypoints towards the direction of the starting point. Waypoint navigation will be engaged. If the robot is in an area where it does not have enough room to turn around after engaging waypoint navigation, the operator will take control and teleoperate the robot to face the traveled path.

Data Required:

The following data will be recorded.

1. Date of test
2. Test item configuration
3. Current time the OCU and MBU were turned on and off
4. Start and end time of each route
5. Distance between starting point and ending point
6. Time to teleop to ending point
7. Map observations to include but not limited to:
 - a. Map drift
 - b. Map drift corrected by loop closing
 - c. Map accuracy
- 8.
9. Was the CBRN hazard detected
10. Observations describing any malfunctions, anomalies, or other issues
11. Any deviation from the test procedure

Indoor Route B

Mission: The operator will teleoperate the robot from the starting point towards the ending point. The robot will maneuver over rumble strips, analyze a potential CBRN hazard, and will stop for five minutes before continuing along the route. Upon reaching the exploratory area the operator will continue to teleoperate the robot to explore the area. The operator will then stop the robot to input waypoints and engage waypoint navigation.

