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AUTONOMOUS GROUND RESUPPLY AUTONOMY KIT

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ABSTRACT

In this paper, we will present the results of our efforts developing the Autonomy Kit for the Tank Automotive Research Development and Engineering Center's (TARDEC) Autonomous Ground Resupply (AGR) Sustainment Operations (SO) program. Robotic Research, LLC was responsible for the design, build, and implementation of the "Autonomy Kit" for the AGR SO. The Autonomy Kit is designed to be a fault-tolerant, vehicle-agnostic applique kit that provides the hardware and software needed to perform higher-level autonomous driving and planning functions. In the first Increment, the main focus was developing a "Leader/Follower" capability, where a manned "Leader" vehicle could perform a mission with a number of unmanned "Followers" reproducing its trajectory, maintaining convoy constraints, and avoiding obstacles in the path.

INTRODUCTION

Tank Automotive Research Development and Engineering Center's (TARDEC) Autonomous Ground Resupply (AGR) program is focused on the automation and optimization of moving, storing, tracking, modeling and managing supplies in an efficient and effective way to optimize battle field logistics. One of the major programs underneath the AGR umbrella is Sustainment Operations (SO), which is focused on the automation of multi-vehicle convoys to support Brigade and above operations. The primary purpose for using an autonomous system as part of convoy operations is to improve Force Protection; reducing the amount of personnel operating Tactical Wheeled Vehicles in a convoy will limit exposure time to potential attack and will allow personnel to partake in other important parts of the mission, such as convoy protection.

Sustainment Operations is focused on designing and building a new open system architecture that will enable robotic capability for both the Leader/Follower and Automated Convoy Operations Programs of Record (PoR). One of the main goals is to develop a fault-tolerant, modular architecture to provide optionally-manned capabilities to a desired vehicle. In SO, the target platform is the Palletized Load System (PLS) vehicle (Figure 1), although the Autonomy Kit could be installed onto any tactical wheeled vehicle with minor modifications.

Figure 1: AGR SO system integrated onto PLS M1075A1

The SO system is divided into three modular kits (Figure 2) – the Autonomy Kit (responsible for the higher level autonomous functionalities), the By-Wire Active Safety Kit (BWASK) (responsible for the lower level vehicle control, along with Advanced Driver Assistant Systems (ADAS), such as lane keeping, collision mitigation braking, etc.) and the Warfighter Machine Interface/Radio Network Interface (WMI/RNI) Kit (responsible for providing the human interface to the autonomous vehicle, along with the inter- and intra-vehicle communications backbone).

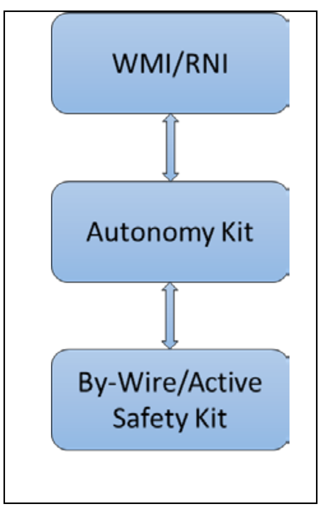

Figure 2: Tier I Modular Architecture

The AGR program is organized into three two-year Increments. In each Increment the design is refined, new features are developed, and the system is evaluated in both Technical and Operational Demonstrations. The first Increment of the AGR SO program culminated in an Operation Evaluation, where soldiers with the Army's 1st Armored Division conducted manned and optionally unmanned resupply missions.

Robotic Research, LLC is the prime contractor for the design, build, implementation, and test of the Autonomy Kit for the AGR SO. Therefore, the thrust of this paper will be on the architecture, design, and results of the Autonomy Kit.

AUTONOMY KIT MODES

During the first Increment, two primary robotic modalities were demonstrated:

Leader/Follower (LF): Leader/Follower mode allows an optionally manned vehicle to autonomously follow the path set out by the "ultimate leader" (i.e., the first vehicle in the March Unit). In the first Increment, the ultimate leader is a manually driven vehicle. Further extensions to this work could include other leader modalities, including teleoperation and/or waypoint navigation.

Teleoperation: In Teleoperation mode, the commander can remotely control the motion of the vehicle via the WMI. Video streams are displayed to the commander for feedback and situational awareness.

AUTONOMY KIT HARDWARE

The Autonomy Kit hardware consists of the sensing and computing resources necessary for perception, world modeling, planning and execution of the Leader/Follower and teleoperation tasks. It also contains all power conditioning, signal switching and routing to ensure that the computers can access all appropriate sensor data and communicate internally and with the WMI/RNI and BWASK Kits. The hardware is identical on Leader and

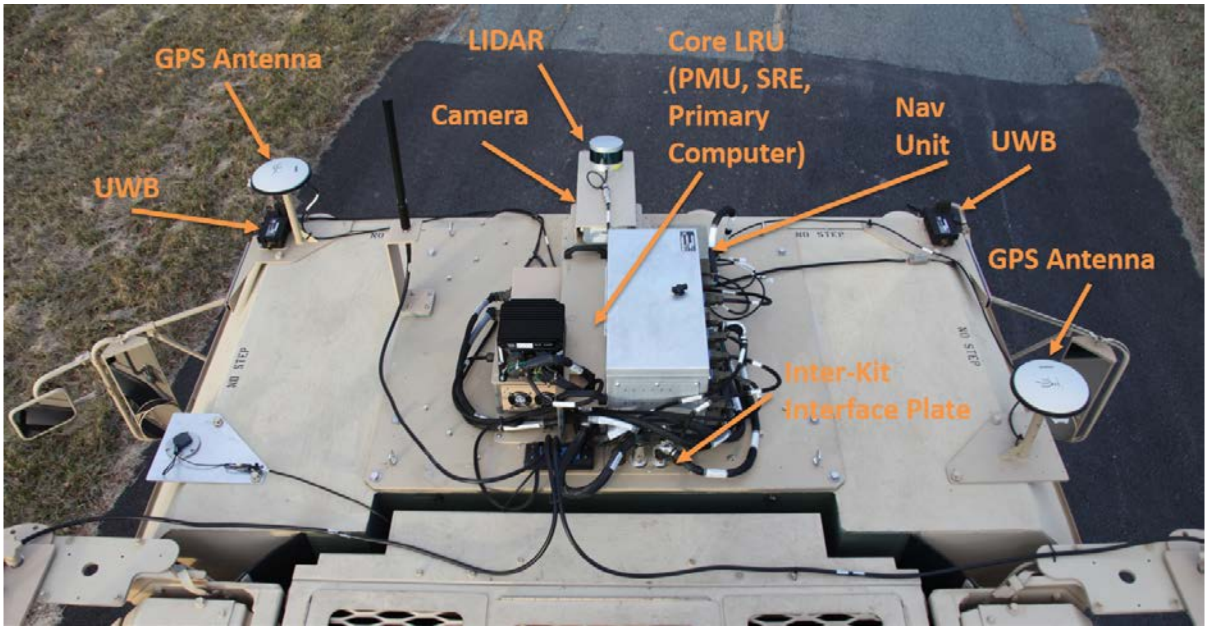

Figure 3: Autonomy Kit mounted to the rooftop of a PLS. Cosmetic cover not shown.

Follower vehicles, and in fact, any AGR vehicle can be used as a Leader or Follower.

The sensor suite for the Autonomy Kit includes Commercial of the Shelf (COTS) LIDAR sensors, Automotive RADAR, and color cameras. Additionally, the suite includes a Robotic-Research designed RR-N-140 Navigation System and Ultra-wideband (UWB) Ranging Nodes. The LIDAR sensors are used for obstacle detection and avoidance (OD/OA), as well as map registration and localization. The RADAR is used for OD/OA and tracking the Leader. The UWB Nodes are used for relative vehicle positioning information. The camera is used for teleoperation and visual feedback to the system operator. The non-sensing components of the Autonomy Kit include primary and secondary system computers, a power conditioning unit, and a Signal routing enclosure, which includes power, CAN Bus, and ethernet routing. The system has been designed with far more power and ethernet than is needed for expandability, to support addition of other sensing and computing resources in future increments.

The majority of the Autonomy Kit is installed on the roof of the PLS vehicle (Figure 3), and is attached to the turret ring mount. This serves the dual purposes of reducing interference with components installed in the cab and making a common mount with many tactical vehicles.

SOFTWARE ARCHITECTURE

The Tier I architecture (Figure 2) is the highest-level breakdown of functionality into separate, modular “kits”. The interfaces between these kits are defined via PM Force Projection’s Interoperability Profiles (IOP). The purpose of IOP is to provide standard interfaces (hardware and software) to allow the option of substituting major subsystems (if desired). Because of this goal, the decision was made to utilize IOP interfaces at the Tier I level.

At the Tier II+ level (internal to the Autonomy Kit), the decision was made to utilize the Robot Operating System (ROS) for inter-process communication. There were a few reasons for this decision. Firstly, ROS has gained traction in both the academic and, more recently, commercial markets. With this large user base, there are many open-source tools, software modules, etc. that can be leveraged for use on this program. ROS provides an adaptable messaging backbone which allows us to combine our custom software seamlessly with these open source tools. Additionally, since there are many corporations/institutions utilizing ROS, future integration efforts will be easier, as one will not have to bridge between different messaging and communications paradigms. Additionally, TARDEC has an on-going effort called “ROS-M”, a militarized version of ROS. As ROS-M becomes available, the goal will be to transition the AGR system into its framework.

The Tier II+ software architecture (Figure 4) is generally organized into a few categories, modeled after the 4D-RCS Reference Model Architecture (Figure 5) [1]. These categories are Sensor Processing, World Model, and Behavior Generation, which each contain several coordinating modules.

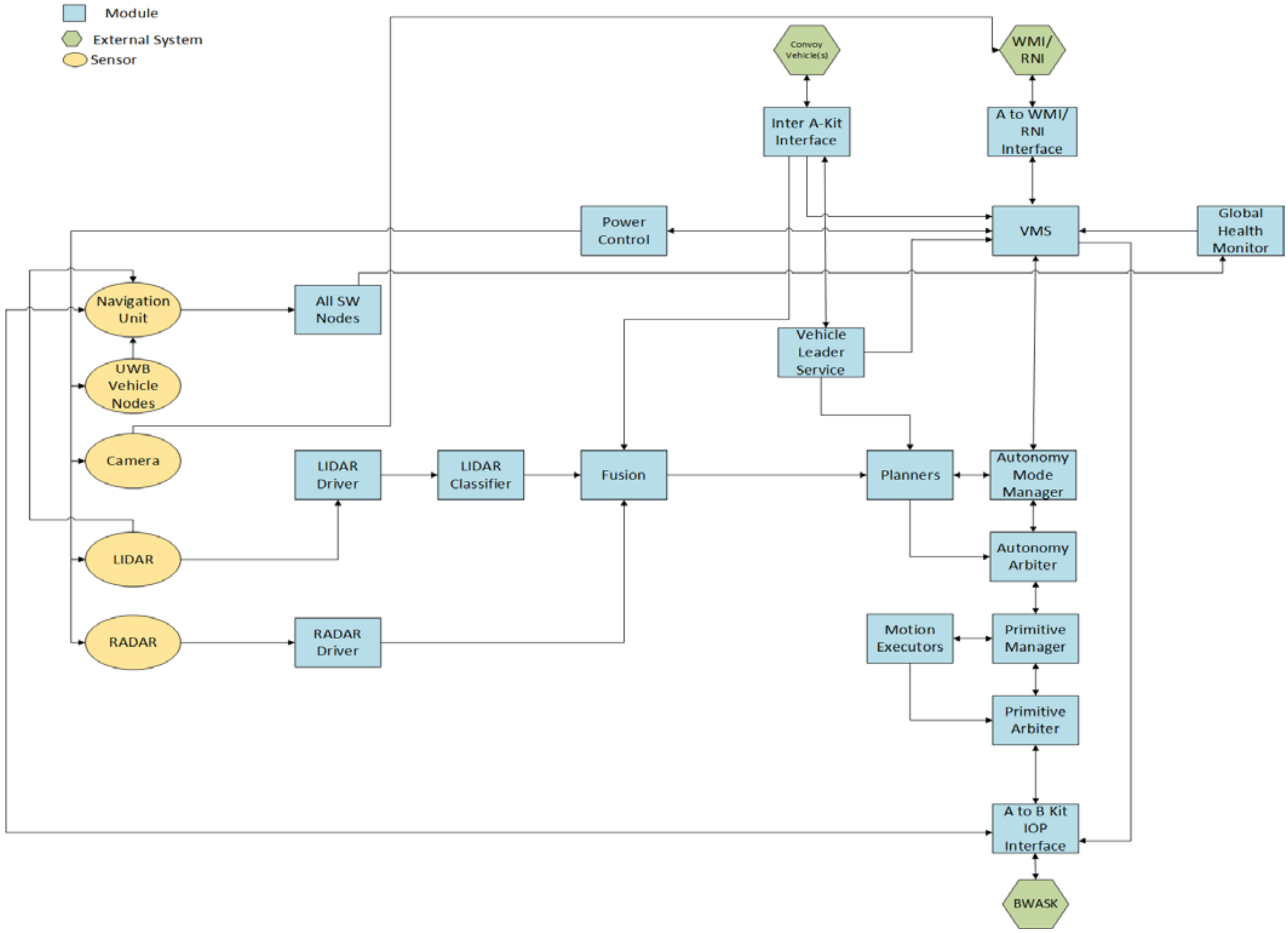

Figure : Tier II+ Autonomy Kit Software Architecture

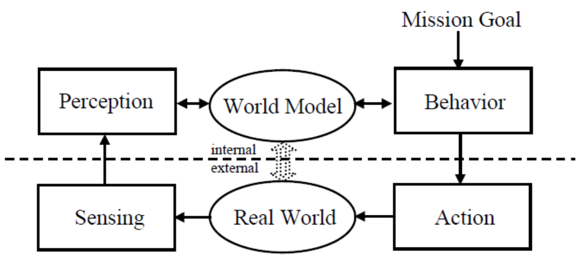

Figure 5: The fundamental structure of a 4D/RCS control loop. An internal world model of the external world provides support to both perception and behavior. Sensors measure properties of the external world. Perception extracts the information necessary to keep the world model current and accurate from the sensory data stream. Behavior uses the world model to decompose goals into appropriate action.

Sensor Processing modules operate on sensor data to detect and classify entities in the environment. In AGR, the Sensor Processing modules include:

LIDAR Driver: The LIDAR Driver is responsible for reading raw UDP data from the LIDAR sensor and converting this data into a ROS PointCloud.

RADAR Driver: The RADAR Driver is responsible for reading raw CAN data, collating the information, and outputting a series of track messages in ROS format.

LIDAR Classifier: The LIDAR Classifier is responsible for labeling each point in the raw point cloud with a "classification". The possible classifications include:

- Ground
  - Points that make up the ground plane. These points are assumed to be traversable by the platform.
- Steep But Short
  - Points that have a high angle compared to the ground place, but are short in height (e.g., curb). These points may or may not be traversable depending on the capabilities of the platform.
- Obstacle
  - Points that are considered non-traversable.
- Cover
  - Points that are above the height of the platform, and, hence, can be traveled under.

The **World Model** modules are responsible for building and maintaining an internal representation of the state of the world. The World Module modules include:

Fusion: The Fusion module reads information from multiple sources, including pose information for the vehicles in the March Unit, LIDAR point clouds, and RADAR tracks. This sensor data is transformed into a consistent frame and overlaid into a fused point cloud.

Vehicle Leader Service**:** The Vehicle Leader Service (VLS) is responsible for collecting localization information of the Leader vehicle, which is subsequently sent to the Follower Vehicle(s). The VLS maintains a historical list of lead vehicle poses. This method allows for improved following performance in a convoy, and prevents issues with error stack-up as more vehicles are added to the convoy (see Software Design Decisions section).

The **Behavior Generation** modules plan and control the actions of the vehicle in order to reach the desired goal state.

Vehicle Management Service: The Vehicle Management Service (VMS) is the overall system state machine for the Autonomy Kit. It tracks and reports the current state of the Autonomy Kit and performs state transitions if interlocks are met.
The VMS is responsible for the vehicle state, including the autonomy state and the control of

separate elements of the Autonomy Kit. Due to the complexities of interactions between modalities, sensors, hardware actuators, and other Autonomy Kit modules, the VMS must have a sematic understanding of these subsystems. As such, the VMS will gate all controls coming into the Autonomy Kit from external sources, such as the external control station or the WMI.

The VMS will expose available behaviors to the outside world through a set of messages which will allow requesting and reporting of autonomy modes. When an autonomy mode (e.g. Teleoperation) is selected, the VMS will use its diagnostics module to determine if the autonomy software is healthy enough to enter that modality by checking against a set of interlocks. The VMS is not directly responsible for picking the specific planning modules required to execute an action. Rather, it ensures that the surrounding system is capable.

Global Health Monitor: The Global Health Monitor is responsible for monitoring the health of the system, including but not limited to sensor states, software module performance and status, and communications. This module is responsible for parsing data flowing around the system, aggregating this data, testing it against set conditions, and reporting the results up to VMS. The VMS uses these results to determine if an autonomy mode can be entered and maintained.

Autonomy Mode Manager: The Autonomy Mode Manager is responsible for selecting an appropriate Planner module based on the outputs of the VMS. Each Planner running on the system publishes its capabilities to the Autonomy Mode Manager, and the Manager selects the correct planner to execute based on the desired autonomy mode. The capabilities include the ability to handle specific autonomy modes and the type of output trajectory from each planner.

Planner: The Planner is responsible for generating desired trajectories for the vehicle. For Increment 1 of AGR, the planning task is fairly simple – the X,Y trajectory to follow is sent back from the Leader vehicle. The Planner is mostly responsible for determining the speed to traverse the Leader’s trajectory. The speed controller attempts to maintain the commanded gap distance within a tight tolerance (10%), while also applying other, system level constraints. For example, the vehicle is not allowed to deviate by more than a certain percent from the leaders’ speed for safety reasons. The Planner is also responsible for generating a deceleration in the event that an obstacle is in the path of the Follower. All trajectories published by the planner are kinematically correct, meaning that they are achievable by the vehicle and obey dynamic constraints on speed, acceleration, and curvature. Lastly, the Planner also generates a “Safe Harbor” trajectory. The Safe Harbor trajectory is always a stop plan that could be followed in the case of a fault/error. The intention of Safe Harbor is for the By-Wire Kit to follow this plan in that case that it loses communication with the Autonomy Kit.

Primitive Manager: The Primitive Manager is responsible for selecting an appropriate Motion Executor module. It has equivalent functionality/purpose to the Autonomy Mode Manager, but at a lower level of control. Each Motion Executor module has a set of capabilities including which type(s) of plan it can handle. The Primitive Manager is responsible for selecting an available module which can process trajectories coming from the planner.

Motion Executor: The Motion Executor Module is responsible for interpreting high-level plans and sending down motion control commands that can be executed by the By-Wire Kit. These messages consist of instantaneous speed and curvature (steering) commands.

SOFTWARE DESIGN DECISIONS

One of the early design decisions made on AGR was to utilize the path of the March Unit Leader vehicle as the desired trajectory to follow. In previous systems, the primary method for vehicle following has been to track and follow the immediate leader (which may or not be the ultimate leader). However, when following the immediate leader, errors can accumulate. This can cause lateral instability and general path following inaccuracies.

An additional constraint placed on the system was the lack of apriori mapping information. In many commercial autonomous vehicle applications, the road network can be quantified and mapped (potentially many times, and with multiple sensor modalities) to sub-meter accuracy before an autonomous vehicle is expected to operate on that terrain. That data can be used to improve performance in many areas, including location (using Simultaneous Localization and Mapping or registration techniques). For the convoy application, that same expectation does not hold, as the vehicles need to be able to complete the missions even if the area has never been traversed. Therefore, the system had to be designed to operate without any access to apriori information. However, because of the nature of a convoy, the lead vehicle can be used to generate similar information – data about the state of the environment at a time fairly close to when the autonomous followers will need to traverse the area. The information can be transmitted between the leader and the followers to improve performance [2]. Utilizing the leader data to improve the follower's localization solution also enables the March Unit Leader following mentioned previously; no line of sight is needed to the March Unit Leader in order to follow its path. Another benefit of this technique is that using features in the environment to register can enable GPS-denied operations. In fact, the testing in Camp Grayling included driving through heavy tree canopy, which severely degraded GPS signals (and posed line of sight challenges because of winding terrain). Without utilizing this sharing of information, it is unlikely that the vehicles would have been able to accurately traverse through that course.

In addition to utilizing the March Unit Leader's path, the decision was also made to use the March Unit Leader's speed as a control input to the Follower vehicles. The human in the lead vehicle can make determinations about the environment and terrain and use this information to intelligently select a speed. The robotic system is only allowed to exceed the leader's speed at any given point by 5mph, the logic being that if the leader traversed an area slowly, there is likely a good reason for it (e.g., pedestrians in the environment, harsh terrain, etc.).

SYSTEM VERIFICATION TESTING

During the first year of the AGR program, system level requirements were developed to ensure that the design of the system would meet the needs and desires of the government customer and the future Program of Records. 49 requirements were flowed down to the Autonomy Kit for the initial Increment I testing. These requirements covered a wide range of topics, including environmental, functional, and performance. Some of the requirements were verified by inspection or analysis, while the test and demonstration requirements were analyzed in a week long System Verification Test (SVT). This event occurred in Camp Grayling Michigan from July 24 through July 29 2017.

To verify that the Autonomy Kit was meeting all of the allocated requirements, verification data was collected and analyzed. This verification data is stored the form of rosbags, which is a time-indexed open data file format defined as part of ROS. These rosbags are automatically collected and captured for all ROS messages in the

Autonomy Kit system. Automated scripts were developed to analyze many of the performance requirements, including gap distance maintenance and cross-track accuracy.

The Autonomy Kit passed ≈80% of the Tier 0 and Tier 1 (Program Needs and Must Meet, respectively) requirements that were tested during SVTs.

Highlights:

- There was a 100% Pass rate for static and dynamic obstacle detection and avoidance.
- No failures were observed during nominal gap following.

Needs Further Improvement:

- While cross-track accuracy would, on average, meet or exceed the requirements (8-16in, depending on terrain), the requirement was not met 100% of the time. An example plot showing cross-track accuracy can be seen in Figure 6. The cross-track error from navigation error is below the AGR requirement of 0.4m for unimproved roads >75% of the time.

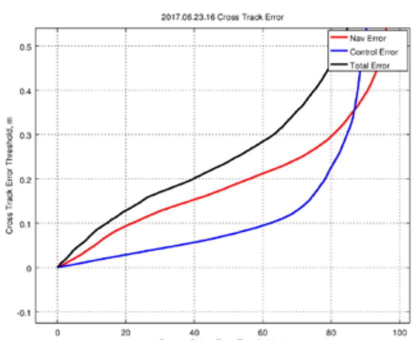

Figure 6: Cross-track accuracy plot shows errors of 0.4m or less >75% of the time

OPERATIONAL EVALUATION AND NEXT STEPS

The Increment I Operational Evaluation with Soldiers occurred at Camp Grayling, MI during September 11-22, 2017. This event was supported by seven Soldiers from Army's 1st Armored Division out of Ft. Bliss, TX. During this evaluation, the Soldiers were able to evaluate both the teleoperation and Leader/Follower modalities on a variety of different terrains. Additionally, the soldiers were able to test using a completely unmanned follower vehicle.

Environments tested include (Figure 7):

- Primary (asphalt) roads, secondary (dirt) roads, and trails
- Tree canopy course with undulating, curvy terrain
- Military Operations on Urban Terrain (MOUT) site operations
- Various other areas, including a single lane bridge

The overall Soldier feedback coming out of this event was extremely positive. The soldiers provided both written and oral statements as to the efficacy of the system, stating that they believed the system should be utilized by today's forces while praising the ease of use and following accuracy. Suggested improvements included user interface design modifications, additional requested features (e.g, reverse capabilities, capacity for larger march units), and general information to improve the effectiveness for in-theatre operations.

The first Increment of the AGR SO demonstrated the effectiveness of the new architecture and implementation for both Leader/Follower and Teleoperation. As this program continues into Increment II and beyond, the goals are to continue improving the system, adding new functionality, expanding to more followers, and increasing robustness, reliability, and fault-tolerance.

Additionally, as a part of the Expedient Leader/Follower (ExLF) program, the results of the AGR program will be used to rapidly deliver and issue 70 Leader/Follower enabled PLS vehicles to Soldiers for a one-year Operational Technical Demonstration (OTD) starting 4QFY19. The goal of ExLF is to get LF technology in the hands of the Soldier quickly and inexpensively by building off of the AGR SO technology. Over time, as more and more functionality comes online and matures in AGR, these enhancements can be migrated to ExLF and put into use in the OTD.

Figure 7: At Camp Grayling, the vehicles were tested in a variety of different terrains, including an Urban MOUT site, gravel roads, and through tree canopy.

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[2] Wilhelm, R., Schneider, A., Klarquist, W., Lacaze , A., Murphy, K., Balas, C. Cooperative Localization To Improve Convoy Stability (CLICS). 2017 NDIA Ground Vehicle Systems Engineering And Technology Symposium. August 8-10, 2017.