ARL-TN-1235 ● JAN 2025

Experimentation Plan for the 2024 Combat Vehicle Robotics Evaluation of Applied Research

by Craig Lennon

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REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED START DATE	END DATE
January 2025	Technical Note	22 July 2024	20 October 2024

4. TITLE AND SUBTITLE
Experimentation Plan for the 2024 Combat Vehicle Robotics Evaluation of Applied Research

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER	5e. TASK NUMBER	5f. WORK UNIT NUMBER

6. AUTHOR(S)
Craig Lennon

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
DEVCOM Army Research Laboratory ATTN: FCDD-RLA-JC Aberdeen Proving Ground, MD 21005	ARL-TN-1235

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
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14. ABSTRACT
In August 2024, the ARL's Artificial Intelligence of Maneuver and Mobility (AIMM) research program conducted experiments to provide the DEVCOM Ground Vehicle Systems Center (GVSC) with an opportunity to evaluate AIMM-applied research. This evaluation was held at the ARL Robotics Research Collaboration Campus at Graces Quarters, Maryland, and provided GVSC with data they could analyze to evaluate the research. The experiments demonstrated research in collaborative high-level route and formation planning, low-level path planning, and scene recognition. This technical note describes the experimental plan and documents observer data recorded during the experiment.

15. SUBJECT TERMS
Military Information Sciences, autonomy, scene recognition, multi-robot planning, robotics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UU	38

19a. NAME OF RESPONSIBLE PERSON	19b. PHONE NUMBER *(Include area code)*
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STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

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1. Introduction

In August 2024, representatives of the U.S. Army Combat Capabilities Development Command (DEVCOM) Ground Vehicle Systems Center's (GVSC's) Combat Vehicle Robotics Program (CoVeR) visited the DEVCOM Army Research Laboratory's Robotics Research Collaboration Campus (R2C2) located in Middle River, Maryland, to evaluate ARL-applied research for potential transition into the CoVeR program. The term "engineering evaluation test" (EET) is usually used to describe a test conducted to support a detailed evaluation of a system, and representatives of GVSC conduct EETs to identify technologies that could be merged into the GVSC autonomy library (Smereka and Patel 2020). Although data from the event will be analyzed by the GVSC representatives who conduct EET, the August 2024 evaluation at R2C2 was a demonstration of ARL-applied research projects rather than a test of the platform used to demonstrate the research. Three technologies were evaluated:

- Stratified Topological Autonomy with Learned Contexts (STALC) identified regions of concealment with respect to a hypothesized enemy position and then used these regions to plan low-visibility routes for robots.
- Extraction of scene information identified tree lines that could potentially be used for concealment by a robot.
- A model predictive path integral controller (MPPI) was evaluated as an assessment of progress made in converting the ARL autonomy stack from version 1 of the Robotic Operating System (ROS 1) to version 2 of the Robotic Operating System (ROS 2).

The conversion of the ARL autonomy stack from ROS 1 to ROS 2, which was ongoing at the time of the experiment, affected all the experiments. The ARL autonomy stack module responsible for simultaneous localization and mapping (SLAM) had not been converted to ROS 2, and as a result, the robots needed to rely on GPS receivers to identify their location. Localization via GPS is only precise within a few meters, so several emergency stops of robots wandering off course may have resulted from reliance on GPS instead of the SLAM module that operates without GPS. Aware of this issue going in, we decided that when a robot went too far off course, we would simply stop it, move it back on course, and resume. This allowed us to evaluate research without reliance on SLAM, although with occasional interruptions from the stops.

The experimental runs were divided into scenarios comprising a combination of location and robot parameters. If one set of runs differed from another, either in the region in which they took place or the configuration of the robot (e.g., the setting of parameter values), the sets were considered as two different scenarios. Scenarios were labeled alphabetically in the order in which they took place, and runs are designated by number, so scenario A 1 refers to the first run of scenario A. Each research project, along with the experiment used to demonstrate its value to GVSC and a summary of the results, is briefly explained in its own section. All recorded data from the experiment was handed over to GVSC to use in their assessment. The evaluation criteria described in each section, and the scoring by those criteria recorded in Appendixes A–C, is only the data recorded by human observers during the EET. Section 5 summarizes these results and presents lessons learned during the experiment. The appendixes contain records of observations and scoring of the experiment produced during the experiment.

2. STALC

The STALC research project included algorithms and processes to support cooperative movement of a team of robots from a start position, through regions of low visibility, to a goal region (Dimmig et al. 2023). This process begins with a terrain elevation map and an overhead image, which are analyzed through an algorithmic (but human-supervised) viewshed analysis to identify regions that would be concealed from a hypothesized enemy position and traversable routes between these regions. These low-visibility regions become vertices in a graph, with paths between the low-visibility regions being the edges of the graph. The edges have a weight based on length and how visible the robot would be from the enemy position while traversing the edge (weight being calculated as the integral of visibility over the path). The robots move along edges together in formation or in bounding overwatch, with the mode determined by a preference parameter for overwatch and an estimation of how far on the path the overwatched robot would be visible to the watching robot. A mixed-integer programming solver selects a route and sequence of formations to use while moving along the route. The robots receive this assignment and move along the route. Figure 1 shows an example of a mission conducted in Fort Cavazos, Texas, in June 2024, prior to the August experiments documented here. The green region indicates the hypothesized enemy position while the red regions are regions of low visibility and are enumerated as nodes in the graph, with the mission being to traverse from node 0 (in the lower left), to node 6, and then node 7 (in the upper right). The blue paths are the edges of the graph along which the robot could traverse.

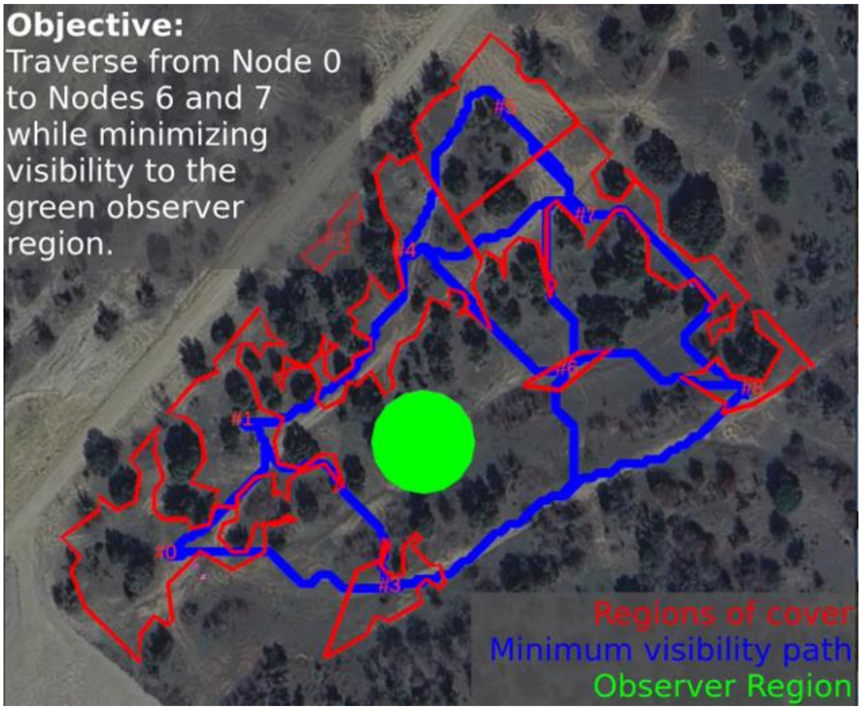

Figure 1. Regions of low visibility connected by traversable paths.

A series of waypoints were laid along the routes by the STALC algorithms and the ARL autonomy stack provided perception, low-level control, and GPS-based localization to guide the robot between these waypoints.

2.1 Experiment Plan

Based on what the STALC process and algorithms were expected to produce, we evaluated each run using the following evaluation criteria:

- A visibility overlay must be produced.
- A graph connecting low-visibility regions (nodes) via paths (edges) must be produced.
- A route and formation must be assigned to the robots.
- The robots should follow the route in the assigned formation.
- The robots should reach the goal.

Each run was evaluated using these criteria and incidents were recorded in which equipment failed or the robot was stopped for safety or other reasons. The evaluations for STALC were conducted over two days: 6 and 8 August 2024. The evaluations on 6 August 2024 were conducted in eight runs split over two different graphs. In scenarios A and C, the default parameter for bounding overwatch preference was used. In scenarios B and D, the preference for overwatch was reduced to ensure there was at least one movement in formation. On 8 August 2024, the 12 runs identified as scenarios H, I, and J took place on the R2C2 military operations on urban terrain (MOUT) site, with scenario J set up the same as scenario I, but with an enhanced preference for overwatch.

Figures 2–9 are pairs of images (one pair per scenario) showing the planned layout of the scenario and the regions of low visibility (and edges between regions) for that scenario. In scenario planning images (e.g., Figure 2), start and end points for the robot are indicated by green and purple dots. If a robot started on a green dot with the purple dot as goal, the next run would start at the purple dot with the green dot as goal. As shown in the legend in Figure 10, light blue lines indicate traversable paths, the dark-blue rectangle is the position of a trailer, and the star is the hypothesized enemy position. Visibility maps produced by the STALC viewshed analysis process (e.g., Figure 3) show contiguous red regions that are low visibility with respect to the enemy position, which is shown in light green. Dark-blue lines are the paths between those regions found by the STALC planning algorithm. Light-green dots are only used for the enemy position in visibility overlays, whereas dark-green dots for start points only appear in the scenario planning images. In Figures 7 and 9, the whole of the MOUT site was traversable, so only start and end positions, and planned enemy positions, are shown.

Figure 2. Plans for scenarios A and C.

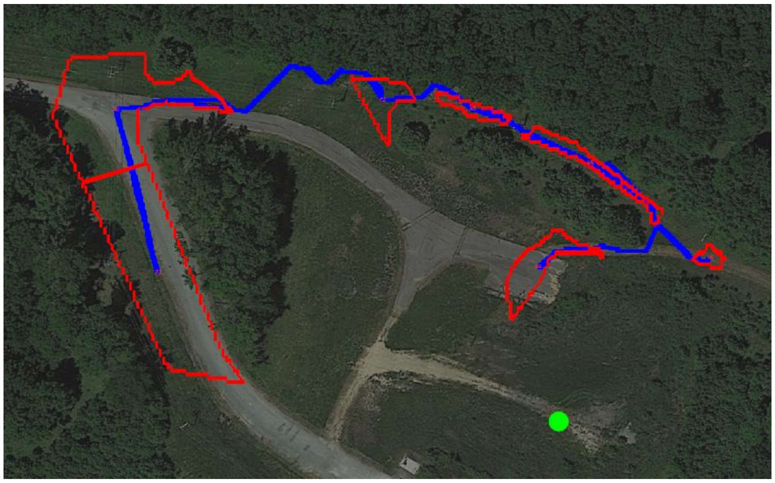

Figure 3. Visibility overlay for scenarios A and C.

Figure 4. Plans for scenarios B and D.

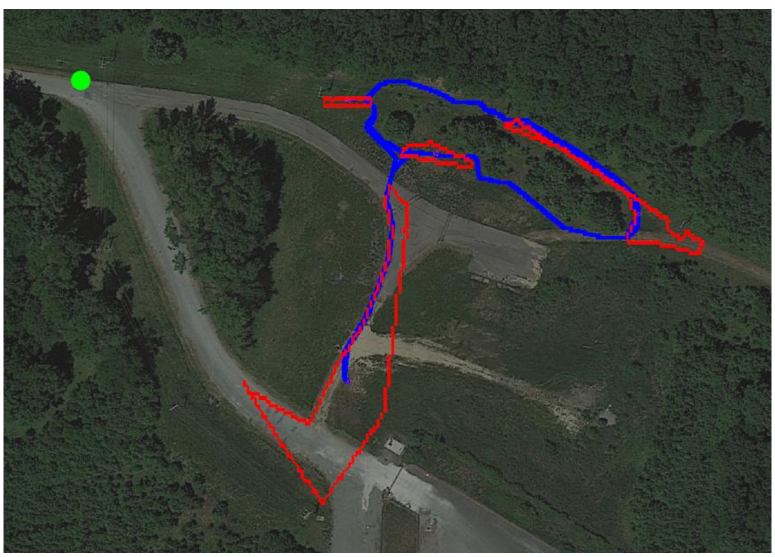

Figure 5. Visibility overlay for scenarios B and D.

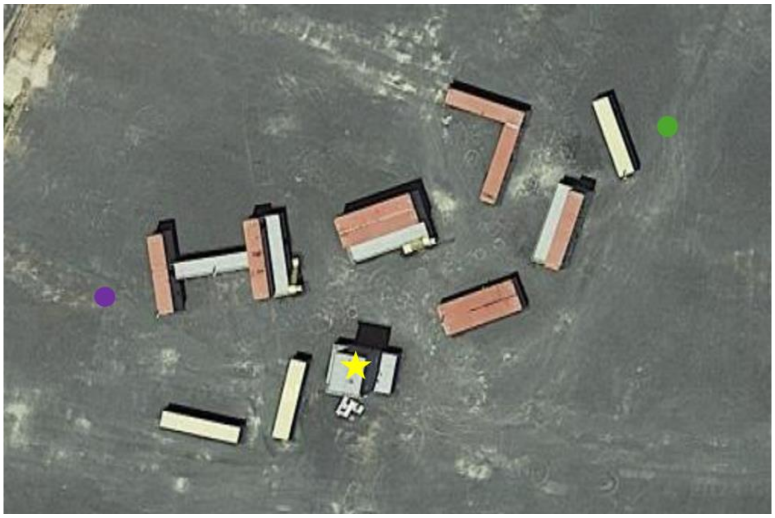

Figure 6. Plan for scenario H.

Figure 7. Visibility overlay for scenario H.

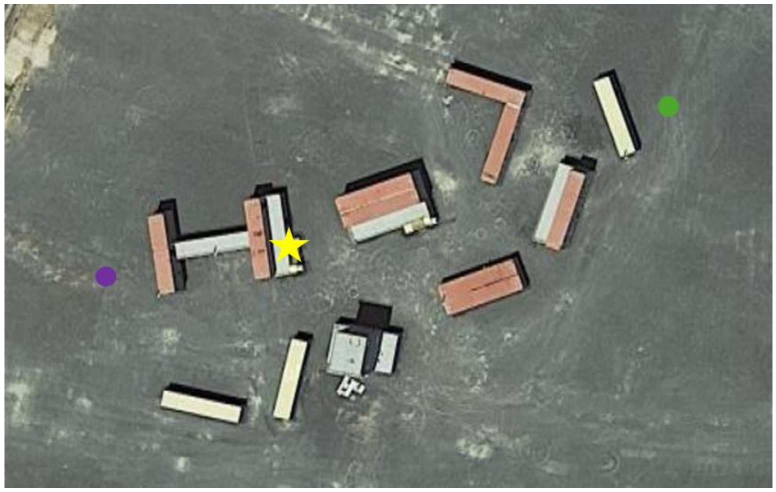

Figure 8. Plan for scenarios I and J.

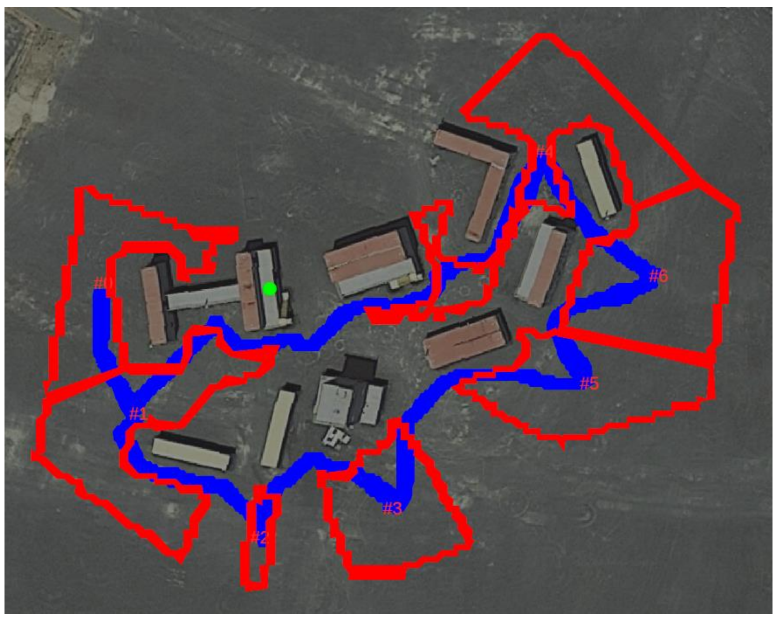

Figure 9. Visibility overlay for scenarios I and J.

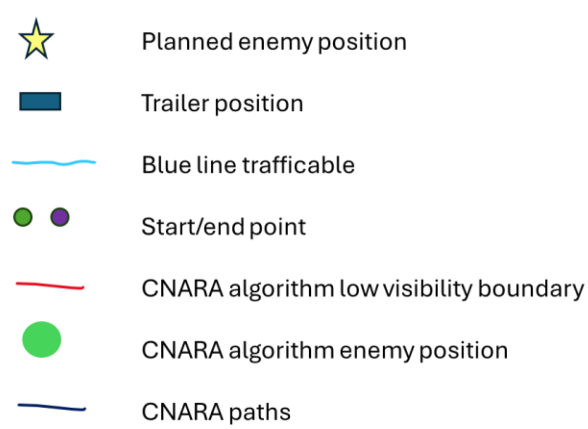

Figure 10. Legend.

For comparison, we also planned a path using an A* planner from the start and end positions used in scenarios H, I, and J based on minimal distance while ignoring visibility considerations. Figure 11 shows this route, which is substantially different from the minimal visibility routes. The enemy position shown in Figure 11 is the position from scenario H, but since being visible to the enemy is ignored, the position does not matter for this visibility overlay.

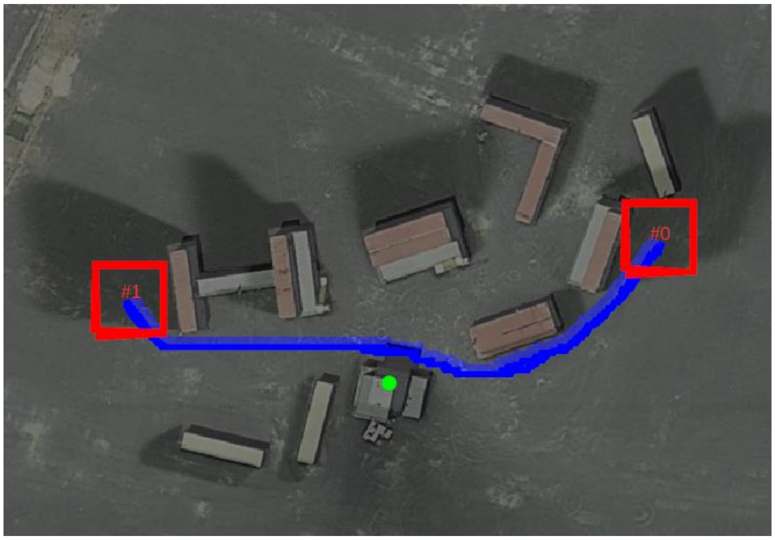

Figure 11. Visibility overlay for baseline with A* planner.

2.2 Results

This section summarizes the evaluation results, for which all tables are included in Appendix A. The process for determining regions of low visibility worked but required human intervention. Objects such trailers or generators are not visible from overhead satellite images and tree lines change over time; thus, a human on the ground needs to assist in identifying regions of low visibility connected by traversable paths. With functioning SLAM, some human intervention in determining visibility and traversability might be replaced by robotic mapping of the area. In all runs, the graph-planning algorithm functioned in selecting routes and formations. Since these runs were testing a high-level planner, we were not concerned about the number of emergency stops, which better measure success of lower-level planning (and perception and localization). There were about 2 stops per run (1.8 on average), with this number including stops of all robots, and there were up to three robots operating on some runs. We cannot determine how many of those stops would have been avoided if SLAM was functional. In summary, the high-level, mixed-integer programming planner performed its function in each run, but there were stops due to failures of either localization or identification of nontraversable regions based on the overhead image.

3. Extracting Scene Information

Research for extracting scene information with military relevance was evaluated by detecting tree lines, which could be used by a robot to find a position from which the robot could conduct surveillance while partially concealed. As input, the tree-line detection algorithm takes a semantic map, upon which regions of the map are labeled as trees, and a density parameter, which specifies what distance between tree regions is acceptable for the trees to be considered a tree line. Regions of the map labeled as trees and within the specified distance from one another are clustered together into a tree line and then bounded by a polygon that can subsequently be referenced as a terrain feature. The expected output looks like Figure 12, in which light-green polygons are the tree lines that bound the tree regions shown in cyan. The semantic map, showing trees (cyan), grass (green), and tree-line polygons (light green), overlays a terrain map in which contour lines are present. The robot was teleoperated down a road (shown in gray) during the runs testing tree-line detection.

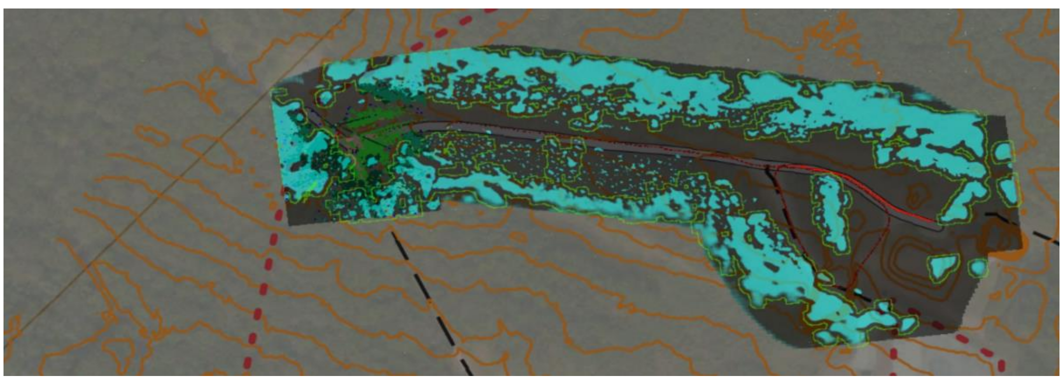

Figure 12. Example showing tree regions bounded by polygons.

The algorithm is intended for use in a cover-seeking behavior, in which a robot maps tree lines which could be used for cover, and upon being told to seek cover, goes to the nearest one that is of sufficient size and between it and a hypothesized enemy position. Based on this intended use, we identified the following evaluation criteria as relevant to the cover seeking behavior:

- A semantic map should be produced as input to the tree-line detection algorithm.
- Tree areas should be bounded by polygons indicating tree-line clusters.
- Polygons should not cover road or open fields.
- Polygons should persist in the map when the trees are out the robot’s view.

- When the robot is in a polygon region, it is less or no more visible than it would be if it were positioned on the road along which it is traveling.

Incidents were recorded in which equipment failed or the robot was stopped for safety or other reasons. The evaluations on 6 August 2024 were conducted in four runs split over two scenarios, each of which drove along a region that had tree line broken up by road, allowing for the appropriate identification of tree line and the possibility of misclassifying road as tree line. The robot was teleoperated during its drive, and the runs were separated into two scenarios because the person driving the robot was given different instructions as to what path to follow in each scenario.

In scenario E (Figure 13), run 1 starts at the green dot and drives on the road (blue line) around the cluster of trees in the direction indicated by the yellow arrow, then drives to the purple dot. Run 2 follows the same route in reverse, starting at the purple dot and ending at the green dot. Tree-line maps for these runs are available in Figures 14 and 15.

Figure 13. Plan for scenario E.

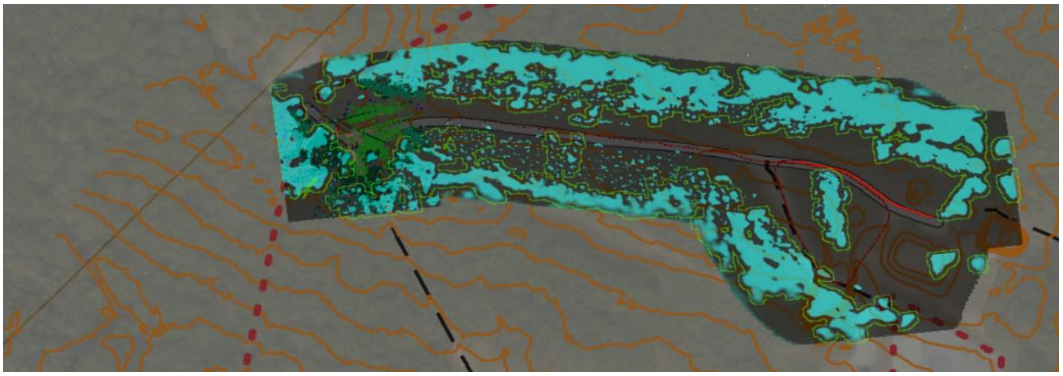

Figure 14. Tree line map for scenario E, run 1.

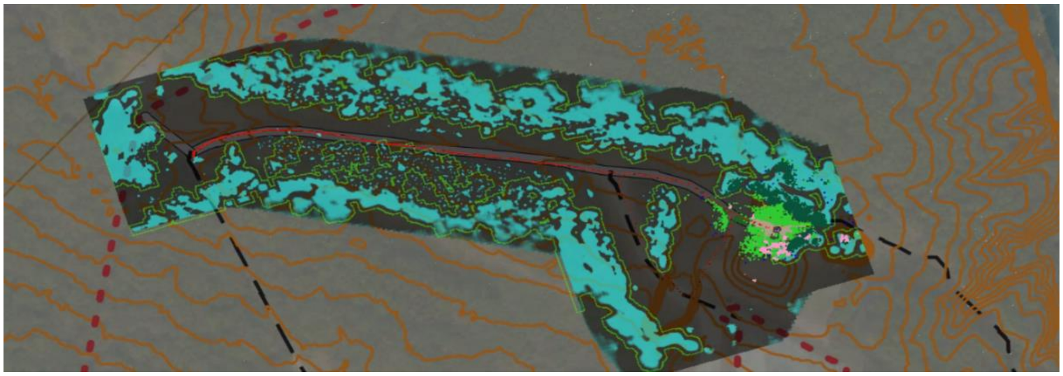

Figure 15. Tree line map for scenario E, run 2.

In scenario F (Figure 16), run 1 starts at the green dot and drives on the road (blue line) around the cluster of trees in the direction indicated by the yellow arrow, then drives to the purple dot. Run 2 follows the same route in reverse, starting at the purple dot and ending at the green dot. Tree-line maps for these runs are available in Figures 17 and 18.

Figure 16. Plan for scenario F.

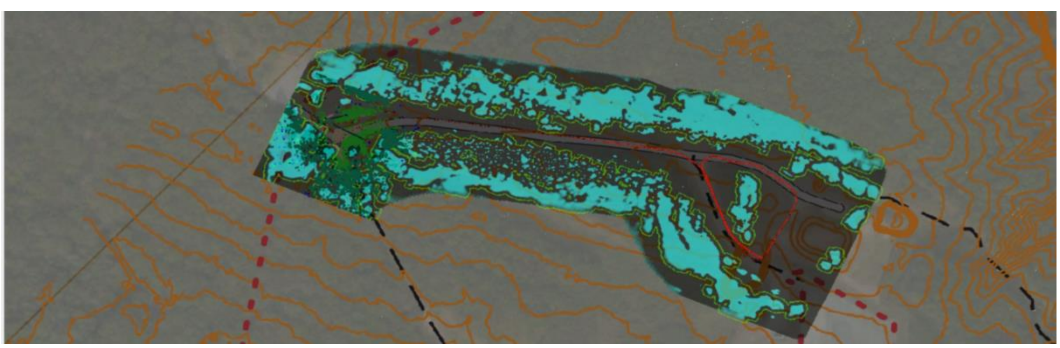

Figure 17. Tree line map for scenario F, run 1.

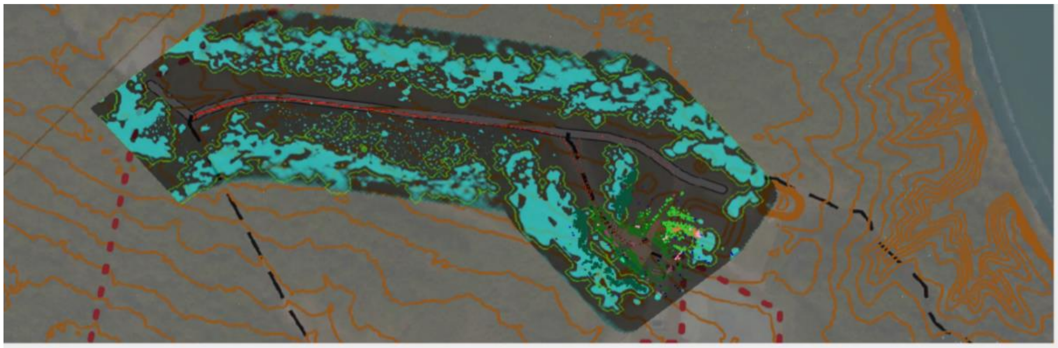

Figure 18. Tree line map for scenario F, run 2.

All evaluation criteria were met for every run. The robot was teleoperated during these runs, so emergency stops did not occur. Tables produced during evaluation are included in Appendix B.

4. MPPI

The MPPI is a planner in the autonomy stack that, when given a waypoint, will plan and continuously replan at high speed to find a low-cost route to the waypoint. The cost map provided to the MPPI planner is based on terrain traversal costs with terrain classification done by terrain-net (Meng 2023), the autonomy stack's default semantic-perception algorithm.

4.1 Experimental Plan

The MPPI planner was used in STALC runs but was also tested over a longer, off-road route. This route started at the green dot in Figure 19, proceeded to the purple dot, the yellow dot, and ended at the brown dot. The blue lines show the general route, not the exact path taken by the robot. The planner was evaluated in each leg of the path for reaching the goal, and the number of emergency stops was recorded.

Figure 19. Routes used for MPPI runs.

The planner was evaluated as a proxy for the conversion of the autonomy stack into ROS 2, and a modification of the planner that allowed it to run on a graphics processing unit (GPU). Consequently, the criteria on which the planner was evaluated were as follows:

- The MPPI planner should run in ROS 2.
- The MPPI planner should use a GPU.
- The MPPI planner should plan and replan as needed to produce a route that reaches the goal point.

Incidents were recorded in which equipment failed or the robot was stopped for safety or other reasons. The implementation of the planner in ROS 2 and its use of a GPU were verified before the experimental runs, which were used to assess the planner's ability to reach the goal point assigned to it. In previous sections, we referred to experimental runs with a letter and number (e.g., scenario K 1). After the first run, we discovered that we were running an out-of-date version of terrain-net and thus had to repeat the run, which we indicate by labeling the runs attempt 1 and attempt 2. We also had one experimental excursion in which an unplanned route was selected as a target of opportunity, which we refer to here by the scenario and the letter X (K X). In total there were five runs as follows:

- K 1, attempt 1 traversed from the green dot through the blue and purple dots to the orange dot.
- K 1, attempt 2 traversed the same route as the first attempt, but with an updated version of terrain net.

- K 2 traversed from the purple dot through the yellow dot to the brown dot.
- K X was a spontaneous attempt to drive off the planned path onto an alternate path and was stopped when the alternate path was not traversable.
- K 3 traversed from the yellow dot through the purple dot to the blue dot.

4.2 Results

The tables for each run summarized here are in Appendix C. In each run except scenario K, run X, the robot navigated to its goal. In run X, the goal point had not been examined prior to the experiment and the path to it was not traversable. The number of stops and whether they were needed to avoid collision or just to check the path are listed in Table 1. If the robot was stopped out of caution and the stop was determined not to be needed, it is listed in the "stop not needed" column; otherwise is in the "stop was needed" column. Worth noting is how much better K 1 was in attempt 2 (once terrain-net was updated), which shows the reliance of planning on the perception module. We cannot determine how many stops there would have been with a functional SLAM module replacing GPS.

Scenario K 1 was on asphalt and a gravel trail and was less challenging for perception than K 2 and K 3, which were on a grassy trail where the distinction between trail and terrain which was not traversable was less clear. The needed stops in runs K 2, K X, and K 3 were all instances in which perception was difficult and may be perception-related rather than planner-related. However, the robot was often swerving into the grass even when trail was clearly visible, which does not seem properly ascribed to perception and would more likely be attributable to control or localization.

Table 1. Stops for each run.

Scenario and run	Stop was needed	Stop not needed
K 1, attempt 1	3	1
K 1, attempt 2	0	0
K 2	1	1
K X	2	0
K 3	2	1

5. Conclusions

Sections 2–4 describe results for an individual research project (STALC, scene extraction, MPPI), so this section will discuss relationships relating to more than one result. When the robot operated autonomously there were frequent stops that forced a reliance on GPS—possibly from the lack of SLAM, and possibly from using an outdated version of terrain-net on 6 August 2024 and the first MPPI run. Scenarios A, B, C, and D from the STALC experiment were conducted in wooded areas with the old version of terrain-net. Considering how many more stops were needed in K 1, attempt 1 versus attempt 2, between which only terrain-net was changed, one is led to believe that some stops in STALC runs A–D likely resulted from perception failures. For the MPPI planner, runs after K 1, attempt 2 were conducted with an updated version of terrain-net, and even with this update there are stops (but fewer), possibly SLAM-related. Finally, on many runs, the GPS receivers failed to get a fix on the robot's position and the robots needed to be moved around to get location and orientation, which was another challenge resulting from lack of SLAM. Despite frequent stops due to some combination of SLAM, perception, or other factors not considered here, all three research projects were successfully demonstrated with data provided to GVSC for more detailed evaluation.

6. References

Dimmig C, Wolfe K, Moore J. Multi-robot planning on dynamic topological graphs using mixed-integer programming. Proceedings of the 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS); 2023 October 1–5; Detroit, MI; c2023. p. 5394–5401.

Meng X et al. TerrainNet: visual modeling of complex terrain for high-speed, off-road navigation. arXiv; 2023 Mar 28. arXiv:2303.15771. https://doi.org/10.48550/arXiv.2303.15771

Smereka JM, Patel S. Combat vehicle robotics (CoVeR): engineering evaluation test concept. DEVCOM Ground Vehicle Systems Center (US); 2020 Sep.

Appendix A. Observations from Scenarios A–D and G–J

Table A-1. Scenario A, run 1, attempt 1.

Scenario/run	Item	Wanda and Warty	Comments
A 1, attempt 1	Start time	1213	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	N	GPS failure -- teleoperated to goal.
	Stops	. . .	2 estops to avoid hitting trees.
	Equipment failures	. . .	Trouble getting GPS fix; rebooted base and restarted stack; due to GPS failure we will teleop to final position and redo the run.
	End time	1224	. . .

Table A-2. Scenario A run 1, attempt 2.

Scenario/run	Item	Wanda and Warty	Comments
A 1, attempt 2	Start time	1424	(redo of run A1, GPS fail first time)
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	4 total estops between robots.
	Equipment failures	. . .	GPS issues on Warty.
	End time	1433	. . .

Table A-3. Scenario A, run 2.

Scenario/run	Item	Wanda and Warty	Comments
A 2	Start time	1440	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	3 total estops between robots.
	Equipment failures	. . .	GPS issues on Wanda.
	End time	1450	. . .

Table A-4. Scenario B, run 1.

Scenario/run	Item	Wanda and Warty	Comments
B 1	Start time	Did not get time	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	. . .
	Equipment failures	. . .	2 estops on Wanda, one estop on Warty because Warty was following Wanda when Wanda stopped.
	End time	1500	. . .

Table A-5. Scenario B, run 2.

Scenario/run	Item	Wanda and Warty	Comments
B 2	Start time	1503	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	. . .
	Equipment failures	. . .	Warty GPS failure.
	End time	Did not get time	. . .

Table A-6. Scenario C, run 1.

Scenario/run	Item	Wanda and Warty	Comments
C 1	Start time	1523	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	3 estops.
	Equipment failures	. . .	GPS trouble on both robots.
	End time	1534	. . .

Table A-7. Scenario C, run 2.

Scenario/run	Item	Wanda and Warty	Comments
C 2	Start time	1536	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	2 estops.
	Equipment failures	. . .	No GPS signal, robots moved forward.
	End time	1545	. . .

Table A-8. Scenario H, run 1.

Scenario/run	Item	Wanda and Warty	Comments
D 1	Start time	1551	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	. . .
	Equipment failures	. . .	. . .
	End time	1555	. . .

Table A-9. Scenario H, run 2.

Scenario/run	Item	Wanda and Warty	Comments
D 2	Start time	1559	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	Estop on Wanda to avoid hitting a tree.
	Equipment failures	. . .	None.
	End time	1602	. . .

Table A-10. Scenario H, run 1.

Scenario/run	Item	Wanda, Warty, Willow	Comments
H 1	Start time	Not recorded	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	3 stops, to avoid collision with a generator, because estop device was low on power, and because too close to building.
	Equipment failures	. . .	None.
	End time	Not recorded	. . .

Table A-11. Scenario H, run 2.

Scenario/run	Item	Wanda, Warty, Willow	Comments
H 2	Start time	1256	Added nontraversable regions for generator into the map.
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	None.
	Equipment failures	. . .	None.
	End time	1302	. . .

Table A-12. Scenario H, run 3.

Scenario/run	Item	Wanda, Warty, Willow	Comments
H 3	Start time	1308	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	None.
	Equipment failures	. . .	None.
	End time	1310	. . .

Table A-13. Scenario H, run 4.

Scenario/run	Item	Wanda, Warty, Willow	Comments
H 4	Start time	1318	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	3 stops to avoid wall collision.
	Equipment failures	. . .	GPS malfunction -- not sure which robot.
	End time	1324	. . .

Table A-14. Scenario H, run 5, attempt 1.

Scenario/run	Item	Wanda, Warty, Willow	Comments
H 5, attempt 1	Start time	1527	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	None.
	Equipment failures	. . .	Lost comms so needed to teleop part of the way.
	End time	1533	. . .

Table A-15. Scenario H, run 5, attempt 2.

Scenario/run	Item	Wanda, Warty, Willow	Comments
H 5, attempt 2	Start time	1541	Repeat of H5 since lost communication on attempt 1.
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	None.
	Equipment failures	. . .	None.
	End time	1544	. . .

Table A-16. Scenario H 1, A* baseline.

Scenario/run	Item	Wanda, Warty, Willow	Comments
A* baseline for H	Start time	1443	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	None.
	Equipment failures	. . .	None.
	End time	1345	. . .

Table A-17. Scenario I, run 1.

Scenario/run	Item	Wanda, Warty, Willow	Comments
I 1	Start time	~1430	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	None.
	Equipment failures	. . .	None.
	End time	1440	. . .

Table A-18. Scenario I, run 2.

Scenario/run	Item	Wanda, Warty, Willow	Comments
I 2	Start time	1423	. . .
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	1 estop on Willow to avoid collision.
	Equipment failures	. . .	None.
	End time	~1449	. . .

Table A-19. Scenario J.

Scenario/run	Item	Wanda, Warty, Willow	Comments
J 1	Start time	1501	Same graph as I2 with different weights.
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	None.
	Equipment failures	. . .	None.
	End time	1505	. . .

Table A-20. Scenario I, run 1, A* baseline.

Scenario/run	Item	Wanda, Warty, Willow	Comments
A* for graph I	Start time	1510	A* baseline.
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	None.
	Equipment failures	. . .	None.
	End time	1512	. . .

Table A-21. Scenario I, run 2, A* baseline.

Scenario/run	Item	Wanda, Warty, Willow	Comments
A* for graph I in reverse	Start time	1513	A* baseline.
	Overlay	Y	. . .
	Graph	Y	. . .
	Route assigned	Y	. . .
	Formation assigned	Y	. . .
	Routed followed	Y	. . .
	Formation followed	Y	. . .
	Goal reached	Y	. . .
	Stops	. . .	None.
	Equipment failures	. . .	None.
	End time	1514	. . .

Appendix B. Scenarios E and F

Table B-1. Scenario E, run 1.

Scenario / run	Run	Item / event	Y/N/time	Warthog(s)	Comments
E 1	1	Start time	Not recorded	Willow	Teleop
		Semantic map	Y	. . .	. . .
		Polygons persist	Y	. . .	. . .
		Polygons bound trees	Y	. . .	. . .
		Open regions not covered	Y	. . .	. . .
		Polygons less visible than road	Y	. . .	. . .
		Stops	None	. . .	. . .
		Failures	None	. . .	. . .
		Stop time	1538	. . .	. . .

Table B-2. Scenario E, run 2.

Scenario / run	Run	Item / event	Y/N/time	Warthog(s)	Comments
E	2	Start time	1542	Willow	Teleop
		Semantic map	Y	. . .	. . .
		Polygons persist	Y	. . .	. . .
		Polygons bound trees	Y	. . .	. . .
		Open regions not covered	Y	. . .	. . .
		Polygons less visible than road	Y	. . .	. . .
		Stops	None	. . .	. . .
		Failures	None	. . .	. . .
		Stop time	1545	. . .	. . .

Table B-3. Scenario F, run 1.

Scenario / run	Run	Item / event	Y/N/time	Warthog(s)	Comments
F	1	Start time	1555	Willow	Teleop
		Semantic map	Y	. . .	. . .
		Polygons persist	Y	. . .	. . .
		Polygons bound trees	Y	. . .	. . .
		Open regions not covered	Y	. . .	. . .
		Polygons less visible than road	Y	. . .	. . .
		Stops	None	. . .	. . .
		Failures	None	. . .	. . .
		Stop time	1558	. . .	. . .

Table B-4. Scenario F, run 2.

Scenario / run	Run	Item / event	Y/N/time	Warthog(s)	Comments
F	2	Start time	1607	Willow	Teleop
		Semantic map	Y	. . .	. . .
		Polygons persist	Y	. . .	. . .
		Polygons bound trees	Y	. . .	. . .
		Open regions not covered	Y	. . .	. . .
		Polygons less visible than road	Y	. . .	. . .
		Stops	None	. . .	. . .
		Failures	None	. . .	. . .
		Stop time	1611	. . .	. . .

Appendix C. Observations from Scenario K

Table C-1. Scenario K, run 1, attempt 1.

Scenario/run	Time	Event	Comment
K 1, attempt 1	1229	Start	Robot was "Willow."
	1231	. . .	Swerved into grass.
	1232	Stop	Car blocked the route – manual stop until the car was gone.
	1234	Resume	. . .
	1236	Stop	Robot drove into ditch which was not visible in tall grass.
	1239	Teleop	Robot moved back onto the road.
	1242	Start	. . .
	1243	Stop	Robot too close to ditch, stopped and resumed without moving vehicle, just checked depth of ditch.
	1244	Stop	Robot too deep into vegetation, stopped to teleop it out.
	1250	Start	. . .
	1253	End	. . .
	. . .	. . .	After this run, a new version of terrain-net specific to R2C2 was put on the robot and K1 was run again.

Table C-2. Scenario K, run 1, attempt 2.

Scenario/run	Time	Event	Comment
K 1, attempt 2	. . .	. . .	Updated terrain net.
	1500	Start	Robot was "Willow."
	. . .	. . .	Robot has several swerves into tall grass, but no estops needed.
	1509	End	Run complete.
	. . .	. . .	Robot sometimes swerves across the road, unclear why, but no estops required.

Table C-3. Scenario K, run 2.

Scenario/run	Time	Event	Comment
K 2	. . .	. . .	Driving on grassy trail.
	1522	Start	Robot was "Willow."
	1524	Stop	Stopped because too close to fence, teleop back on trail and start.
	1525	Resume	. . .
	1528	Stop	Stopped to check trail ahead of robot for caution. Stop was not needed.
	1533	Resume	. . .
	1535	End	Run complete.

Table C-4. Scenario K, run X.

Scenario/run	Time	Event	Comment
K x	. . .	. . .	Route was not a preplanned trail I listed ahead of time. Doomed to failure.
	1545	Start	Robot was "Willow."
	1547	Stop	Driving into bush so stopped.
	1548	Resume	. . .
	1548	Stop	Stopped for another bush.
	1552	Resume	. . .
	1552	Stop	No viable terrain to drive on – end run.

Table C-5. Scenario K, run 3.

Scenario/run	Time	Event	Comment
K 3	. . .	. . .	Still "Willow."
	1607	Start	. . .
	1609	Stop	Drove into bush, stopped to teleop back on trail.
	1612	Resume	. . .
	1615	Stop	Stopped to avoid hitting fence.
	1616	Resume	Estimated stop time, time not recorded.
	1621	Stop	While driving through tall grass, robot was stopped for caution, estimated, time not recorded.
	1623	Resume	. . .
	1625	End	Mission complete.

List of Symbols, Abbreviations, and Acronyms

ARL	Army Research Laboratory
CoVeR	Combat Vehicle Robotics Program
DEVCOM	U.S. Army Combat Capabilities Development Command
EET	engineering evaluation test
estop	emergency stop
GPS	global positioning system
GPU	graphics processing unit
GVSC	Ground Vehicle Systems Center
MOUT	military operations on urban terrain
MPPI	model predictive path integral controller
R2C2	Robotics Research Collaboration Campus
ROS 1	version 1 of the Robotic Operating System
ROS 2	version 2 of the Robotic Operating System
SLAM	simultaneous localization and mapping
STALC	Stratified Topological Autonomy with Learned Contexts
teleop	teleoperate

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