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# Unmanned Ground Vehicle Two-Level Planning Technology Assessment

**by Barry A. Bodt, Marshal A. Childers, Susan G. Hill, Richard S. Camden, Juan Pablo Gonzalez, Robert M. Dean, William F. Dodson, Greg Kreafle, Alberto LaCaze, and Leonard Sapronov**

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**Army Research Laboratory**
Aberdeen Proving Ground, MD 21005-5067

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**14. ABSTRACT**
The recently concluded 8-year Robotics Collaborative Technology Alliance (RCTA) pursued technologies to support tactical behaviors of unmanned ground systems as a way to illustrate advances in the research program thrust areas of perception, intelligent control, and Soldier-machine interface. In April 2009, the U.S. Army Research Laboratory conducted an experiment at Fort Indiantown Gap, PA, to measure the capability of current autonomous navigation planning algorithms to solve complex terrain challenges previously not achievable under the local planning approach used in Demo III, the forerunner program and baseline for the RCTA. The principal focus was to evaluate the relative performance of three planning algorithms representing the span of research from Demo III to the closing months of the RCTA.

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# 1. Introduction

The recently concluded 8-year Robotics Collaborative Technology Alliance (RCTA) pursued technologies to support tactical behaviors of unmanned ground systems as a way to illustrate advances in the research program thrust areas of perception, intelligent control, and Soldier-machine interface. In April 2009, the U.S. Army Research Laboratory (ARL) conducted an experiment at Fort Indiantown Gap (FTIG), PA, to measure the capability of current autonomous navigation planning algorithms to solve complex terrain challenges previously not achievable under the local planning approach used in Demo III, the forerunner program and baseline for the RCTA. The principal focus was to evaluate the relative performance of three planning algorithms representing the span of research from Demo III to the closing months of the RCTA.

The approaches evaluated were the (1) Demo III Autonomous Mobility (AM) Planner with local planning only, (2) Dynamic Replanner (DR) with shared sensed data and a continuous update of the global plan, and (3) Field Cost Interface (FCI) Planner, which continuously generated a combined cost (local + global) by combining the kinematic constraints of the vehicle and the recommendations of the global planner. The Dynamic and FCI planners involve two-level autonomous mobility planning to solve route challenges, adding to the local planner established in Demo III the ability to update the global map with sensed data and to revise the route with both local and global information considered. An additional High-Maneuverability Planner (HMP) was available to DR for local repositioning to make feasible the execution of dynamically determined routes, hence calling for a change in direction outside the kinematic constraints of the platform.

Prior to the field experiment, the experimental conditions were modeled in robotic interactive visualization and exploitation technology (RIVET), a high-fidelity hardware-in-the-loop simulator, and the experimental design was executed in simulation. Simulating the experiment served to (1) confirm the feasibility and level of challenge for the proposed route, and (2) establish a reference set for the expected performance of the planners evaluated. The design included seven route scenarios of varying difficulty and three planners. Three replications of a full factorial design (63 runs) were run in RIVET. Each scenario had an achievable goal point (based on natural terrain alone), but each route was physically blocked to create a cul-de-sac impassable by the experimental unmanned vehicle (XUV) under the initial plan. Thus, in order for a planner to successfully navigate the XUV to the goal, an alternative route had to be found, first out of the cul-de-sac and then to the goal.

In the field experimentation at FTIG, at least two replications of each scenario were attempted for each planner. The AM planner reached the goal on 33% of the runs, FCI achieved 48% of the goal points, and DR achieved 64% of the goal points. A distinction in performance was

made between achieving the goal point and solving the intermediate cul-de-sac challenge. The AM planner solved 40% of the cul-de-sacs, FCI solved 52%, and DR solved 79%. This is a major improvement in maneuvering in complex terrain and is a technology enabler for more complex tactical behaviors and reduced operator workload.

RIVET was successful in predicting about half (48%) of the field run performance, but the lack of run-to-run variability in RIVET hindered its usefulness in building a reference distribution of performance. Its use as a planning tool, however, was invaluable. The feasibility and level of challenge confirmed in simulation translated to the field extremely well, so that differences in performance anticipated among the three planners were observed in the field. Setting an appropriate level of challenge for an experiment had been elusive in earlier studies without RIVET, resulting in some inefficient testing.

# 2. Background

## 2.1 History

In 2000, the ARL Demo III unmanned ground vehicle (UGV) technology program demonstrated integrated UGV perception and planning for autonomous navigation in unstructured environments. The purpose of Demo III was to develop UGV technology that enabled robust autonomous mobility in relevant environments. The focus for UGV performance measurement was twofold: (1) to determine the level of maturity of autonomous mobility technology and (2) to measure the impact on Soldier workload when operator intervention is required to continue UGV operation. In 2002 and 2003, the Demo III program conducted a series of experiments at three sites that ascertained the technology readiness level (TRL) of autonomous navigation for UGVs.[1] The UGV platform was the XUV. With regard to mobility, the accomplishment in Demo III was the enhanced local navigation around obstacles as the XUV followed a predetermined waypoint route up to 2 km long. Successful performance in a relevant environment earned a TRL-6 designation for the autonomous navigation system at that time. Since 2003, technology developments under the ARL RCTA have been measured in terms of their contribution to notional mission profiles envisioned by the Future Combat Systems Program.[1] Generally, two tracks of experimentation have been followed: (1) tactical behaviors, especially as to conducting reconnaissance and (2) safe operations when the UGV is operating in close proximity to humans.[1]

[1]Camden, R.; Bodt, B.; Schipani, S.; Bornstein, J.; Runyon, T.; French, F.; Shoemaker, C.; Jacoff, A.; Lytle, A. *Autonomous Mobility Technology Assessment Final Report*; ARL-TR-3471; U. S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2005.

## 2.2 Purpose of the Experiment

The purpose of this experiment is to measure the advances in autonomous navigation under extremely challenging scenarios. In the TRL-6 study, navigation was stressed primarily by vegetation and natural obstacle challenges, impacting the way toward the next waypoint of a predetermined route. In this study, the challenge was more austere. Planning algorithms were used to guide the XUV between waypoints and around natural obstacles and, to be more flexible in completing a mission, to untether the robot from a predetermined waypoint route to move tactically to a goal point. This autonomous tactical movement required the planner to resolve incomplete or erroneous terrain information or unexpected terrain situations, making the original planned path impossible to traverse.

To accomplish tactical movement, the methods for resolving local challenges had to evolve. Since the time of Demo III and the TRL-6 experiment, when faced with a situation where no traversable local path could be found by the XUV, the method to finding an alternate path has been to successively back up (5, 10, and 15 m) and search for an acceptable local path to the next waypoint through the terrain ahead using a sensor-based near-field (~40 m) representation of the environment. This approach emphasizes the view in front of the XUV and assumes that the planned path is achievable if a small tolerance is given to the XUV to deviate from that planned path around any local obstacle. This approach (local planning only) had a limited capability because it required frequent operator assistance in order to continue to the goal point. Locally sensed data remained at the local level. Higher-level planning relied upon static, a priori data from an external source and resulted in a predetermined waypoint route.

Research on two-level (local and global) planning was a major initiative in the RCTA. Sensed terrain data would be shared from the local to the global level, and routes would potentially be adjusted in light of the new information. It was believed that new methods for finding alternative paths in consideration of a goal point would result. The autonomy of the vehicle would be enhanced, and the operator's workload would be reduced.

No operator interventions (teleop, manual backup, etc.) were permitted in this experiment to keep the focus on the technologies designed to improve autonomous mobility.

## 2.3 Three Autonomous Navigation Approaches

In recent years, researchers from the RCTA have developed several new approaches to combining local and global planning into a hierarchical approach to autonomous navigation.[2,3] These approaches have the potential to enable the XUV to overcome complex terrain challenges and significantly reduce the need for operator assistance in successfully completing a tactical

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[2]Childers, M.; Bodt, B.; Hill, S.; Camden, R. The Impact of Multi-Level Path Planning on Unmanned Ground Vehicle Tactical Behavior; 26th Army Science Conference, Orlando, FL, December 2008.

[3]Childers, M.; Bodt, B.; Hill, S.; Camden, R.; Dean, R.; Dodson, W.; Sutton, L.; Sapronov, L. *Unmanned Ground Vehicle Tactical Behaviors Technology Assessment*; ARL-TR-4698: U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2009.

movement. The ultimate goal for the development of such planning algorithms is to achieve adaptive control in dynamic, unfamiliar situations. The experiment focused on measuring the performance differences among three planning approaches and assessing the benefit they provide to the UGV when faced with challenging situations.

### 2.3.1 Autonomous Mobility

In this mode, the XUV receives an initial global route generated by the Command and Control global planner from a priori data. The XUV then uses the perception system and the local AM planner to follow this route and avoid obstacles along the way. The local planner considers the kinematic constraints of the XUV but has no knowledge of conditions beyond the sensor range (~40 m). In this mode, there are no updates to the global route, and the XUV will most likely fail to find an alternative if there are blockages that invalidate the original route and that cannot be avoided with local maneuvers.

Figure 1 shows the initial plan generated from a priori data from the start point (SP) to the goal. The AM planner would attempt to follow this route and would normally do so successfully if the a priori data is reasonably accurate.

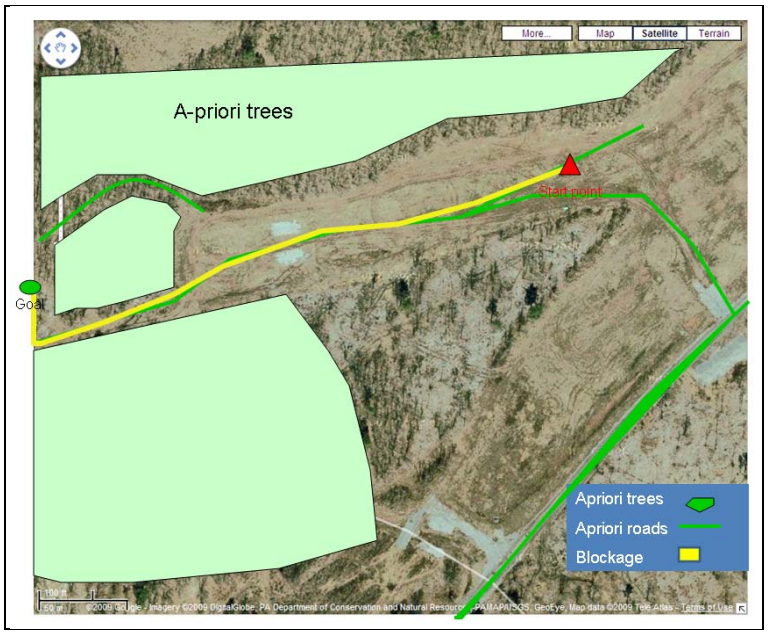


Figure 1. An initial route planned by the global planner.

### 2.3.2 Dynamic Replanner

The DR makes use of sensed terrain data passed from local to global maps (called best information planning). The global map is now continuously improved with current, locally sensed terrain information. In this mode, the global planner generates an initial optimal route based on the a priori feature data. As the global map is updated, a new global route is

continuously generated and compared to the current route. When a sufficient difference in the routes occurs, the new global route is sent to the XUV. The global plan always ignores the kinematic constraints of the XUV, so if the route has an initial heading that differs from the vehicle's current heading by more than 45°, the HMP is called to reposition the vehicle before following the intended route.

Figure 2 illustrates a new global plan generated by the DR after sensing the blockage on the original planned route, and figure 3 illustrates a new global plan at the point where it sensed that the first alternative route was also blocked.

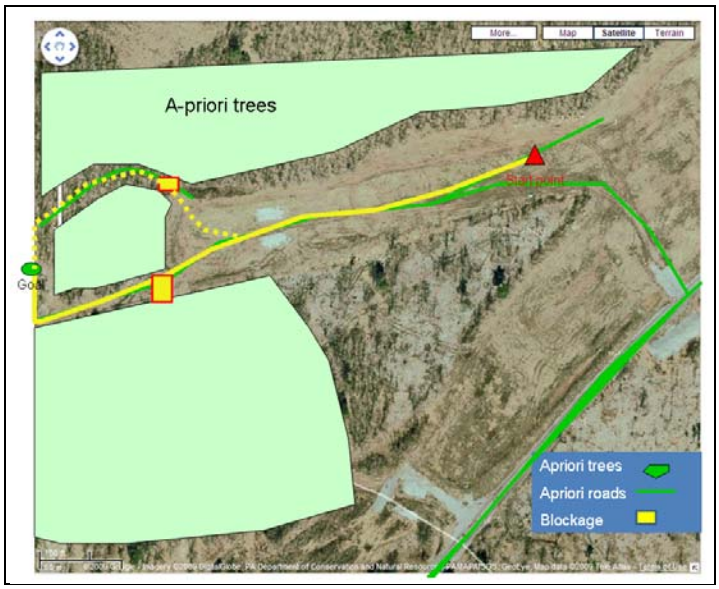


Figure 2. An alternate route generated by the DR.

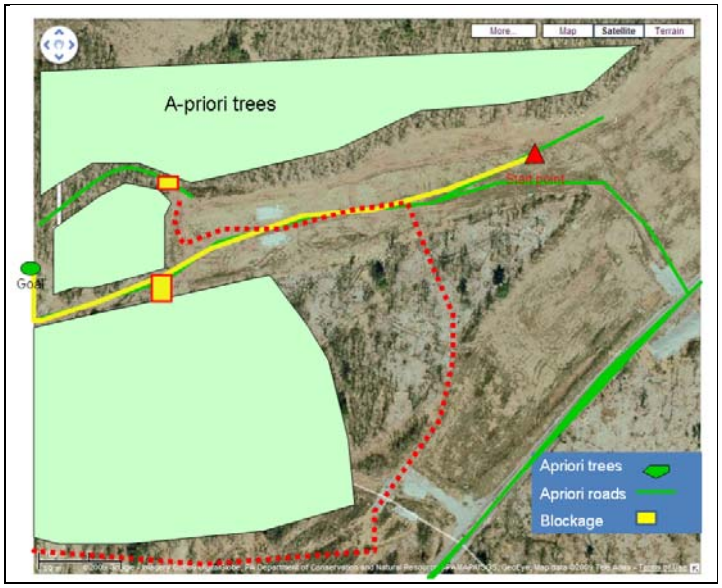


Figure 3. Second alternative route generated by the DR.

The HMP is a search-based, nonholonomic planner that models not only the position ($x$,$y$) of the XUV, but also its heading and its limited turning radius. As such, it is able to provide paths that are kinematically correct and that are not limited to a predetermined set of egographs. The planner has a small set of primitive motions that are repeated over the search space, generating complex trajectories that adapt to the constraints of the environment. This planner is able to automatically generate maneuvers, such as three-point turns and "k" turns. However, because of the complexity of its planning space, in a few seconds HMP can only plan trajectories within a small region near the vehicle (~20 m). Figure 4 illustrates an HMP-planned maneuver when the dynamic replanner sends a new plan that begins more than 45° from the current trajectory.

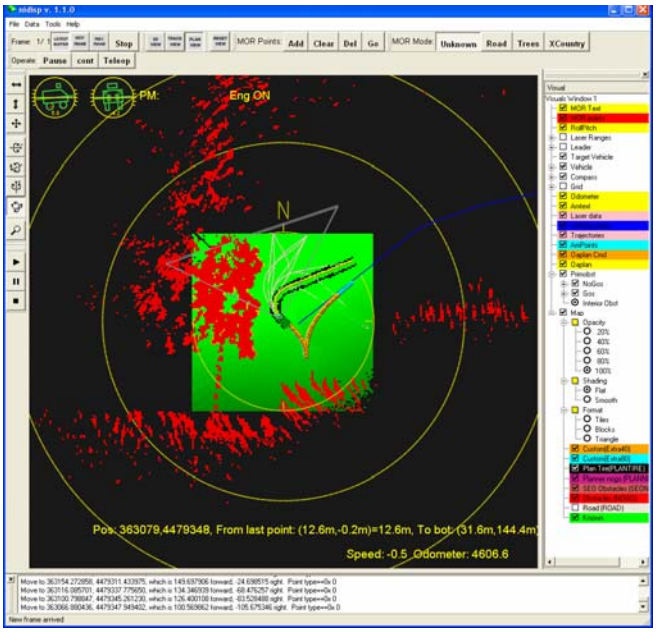


Figure 4. HMP-generated maneuver.

### 2.3.3 Field Cost Interface

The FCI planner continuously generates a cost field at a radius R from the vehicle, using both prior data and sensed data. FCI then generates a combined cost (local + global) at each point in the circle defined by the radius R, thereby combining the kinematic constraints of the vehicle and the recommendations of the global planner. The lowest combined cost becomes the new local plan. Figure 5 illustrates the field costs at the "donut" surrounding the XUV as it moves toward the first blockage in scenario 5.

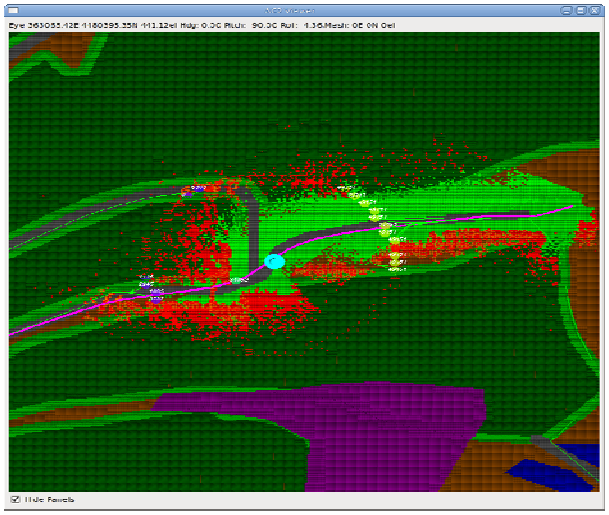

Figure 5. Field costs at cul-de-sac in scenario 5.

The FCI's performance depends on the weight that global costs are given when combined with local costs:

$$C_{total} = C'_{local} + CellScale*C'_{global}\,, \tag{1}$$

where $C'_{local}$ and $C'_{global}$ are scaled local and global path costs. Prior to this assessment, the value of CellScale was tuned using RIVET simulations and field experiments in the fall of 2008. Based on a limited number of runs, a value of 0.2 was determined to perform best and was the value chosen for this assessment. Unlike with the DR, the HMP has not been integrated with the FCI planner, putting FCI at a disadvantage where the ability to maneuver in a tight space is required.

## 3. Robotic Interactive Visualization and Exploitation Technology (RIVET)

RIVET is a high-fidelity hardware-in-the-loop simulator that not only generates a rich world representation in real time, but also simulates sensors and the interactions of the vehicle with the terrain and other moving entities, while having the same low-level interface as the actual hardware in the robotic vehicle.

Developed under the RCTA, RIVET features a game-based, interactive, multiuser modeling and simulation platform specifically suited to developing perception, planning, and other robotic technologies faster and more affordably. RIVET's feature-rich environment and scalability allow users to configure the system to include pedestrians as well as air-, ground-, and sea-based robotic assets so that realistic small-team tasks can be played out safely and repetitively in the virtual world.

By leveraging the latest developments in game technology and graphics hardware, RIVET is able to provide stunning graphics, special effects, high-fidelity physics simulation, terrain rendering, sensor simulation, and weather effects, such as fog and rain.

### 3.1 Representing Mobility Features

The current representation used in RIVET allows limited modeling of local terrain characteristics that excludes ruts, shoulders, gravel, etc. As a result, subsystems that detect and use these features are not well simulated. In the assessment, this was evident in some of the more rugged runs in which the behavior of the vehicle in the field exceeded behaviors in RIVET.

### 3.2 Path Blockages

In the synthetic environment of RIVET, XUV routes were blocked by inserting barrel entities into the simulation environment at the desired location across the width of the trail. This provided an effective path blockage, as illustrated in figure 6.

Figure 6. Scenario 5 cul-de-sac with blocked trails, as seen in RIVET.

In the field, creating a blocked path for the XUV was considerably more difficult. Vehicles, barrels, and cones were needed to fully block the path along the trails. Any area of sparse shrubs/trees was also augmented with man-made obstacles to achieve the intended blockage through an area.

Figure 7 is a panoramic photo of the actual area simulated in RIVET, where the trail on the left is blocked with barrels and cones, the low brush in the middle is blocked with cones, and the trail on the right is blocked with a high-mobility multipurpose wheeled vehicle (HMMWV). One can easily see the difference (compare to figure 6) between RIVET and the actual area in the representation of the trees and shrubs.

Figure 7. Scenario 5 cul-de-sac with blocked trails.

## 4. Scenario Background

Fielded UGVs will operate in an almost infinite variety of terrain conditions. With the terrain available in Tactical Vehicle Maneuver Area-Bravo (TMVA-B) at FTIG, seven scenarios were devised on four separate areas of terrain. The objective in defining scenarios was to construct diverse situations that would defeat the AM capability (cause the XUV to back three times and call for operator assistance) but still allow the potential for the DR and the FCI planner to find, without operator intervention, an alternate route to the goal.

Scenarios were constructed using the following approach. In each scenario, an SP and goal were selected such that given the a priori data, the global planner could generate a straightforward and easily achievable initial plan over the given terrain. Hundreds of XUV field runs previously conducted in this program had shown that unobstructed paths were normally completed with the AM planner. Then, to challenge all three mobility planners, each route was physically blocked to make XUV passage impossible along the intended route. The blockage was not available to

the global map and hence the initial plan, but rather had to be locally sensed by the XUV. The blocked passage was expected to force the planners to search for an alternate route to the goal. Each scenario and terrain area had unique challenges that are described in the following section. A limited use of a priori terrain information was provided to help shape each situation. In one scenario, false a priori data was introduced to suggest a likely alternate path that, if visited, would also be found impassible by the XUV.

# 5. Experimental Approach

## 5.1 Experimental Design

An experimental design was constructed that could be executed both in simulations and in field runs at FTIG. This design included seven scenarios and three planners. A single replication of a full factorial design, crossing each scenario with each planner, would require 21 runs. The intent of the experimental design was to provide a span of cul-de-sac challenges for the planners that would fairly stress the new technology. Absolute measurement of performance in operational or field testing environments is elusive. Often, there is no single quantitative measure, such as time or distance, that adequately represents performance. Did the planner allow the XUV to overcome the specific blockage challenge and was navigation to the goal point achieved? These questions are answered with an affirmative or negative.

To gain additional insight, expectations remained subjective on the performance of the XUV in the field. Subject matter experts (SMEs) evaluated the XUV behavior at various points along a course according to a relatively common expectation of performance. These expectations were forged in discussion prior to the experiment and helped determine the seven routes chosen. The expectations, prior to the field testing, were further solidified through a simulation study working toward a reference distribution of behavior for the XUV under the three planners and seven courses. Performance expectation is where the analysis starts for each scenario.

## 5.2 Parametric Study in Simulation

All seven scenarios were modeled in the RIVET environment, and a parametric study consisting of 63 runs was conducted in RIVET. Variables were scenario (seven levels) and planners (AM, DR, FCI) with three repetitions of each configuration. Tree/shrub density and distribution were not varied as additional conditions because of time constraints; although, it was conjectured that doing so may have introduced more realistic variation in the simulated outcomes. The RIVET runs were used to verify the performance of the planning algorithms as well as validate the experimenter's expectations of the planners' performance in each scenario. All 63 runs were executed in RIVET. The results of the RIVET runs are included in the following discussion.

## 5.3 Field Experiment

The field experiment was designed to replicate the RIVET parametric study but with additional replications because of expected variations in the XUV performance in the field environment. More replications would be required for trends in performance to become evident. The variables were scenario (seven levels), planner (three levels), and repetitions (five reps in the field). To save time and accomplish as many useful runs as possible, not all replications in each cell were executed. For the AM runs, when it became apparent that repeated runs using AM would produce identical failed results, fewer replications were done with that planner (see table 1).

Table 1. The number of runs executed in RIVET and in the field.

| Scenario | No. of Runs | | | | | |
|---|---|---|---|---|---|---|
| | RIVET | | | Field | | |
| | AM | DR | FCI | AM | DR | FCI |
| 1 | 3 | 3 | 3 | 1 | 5 | 3 |
| 2 | 3 | 3 | 3 | 4 | 4 | 4 |
| 3 | 3 | 3 | 3 | 2 | 4 | 3 |
| 4 | 3 | 3 | 3 | — | — | — |
| 5 | 3 | 3 | 3 | 2 | 5 | 5 |
| 6 | 3 | 3 | 3 | 1 | 5 | 5 |
| 7 | 3 | 3 | 3 | 5 | 5 | 5 |

Scenario 4, a variant of scenario 3 with additional a priori data, was not run in the field because it was believed that the slight difference in a priori data between scenarios 3 and 4 would not appreciably affect XUV performance for any planner.

In scenarios 5 and 6, a successful solution of the cul-de-sac and subsequent travel to the goal resulted in a run of ~1800 m. To conserve experimental time, the runs were truncated after the XUV completely exited the cul-de-sac area in the “finger” and moved to the tank trail and a clear path to the goal.

Several runs were rerun because of events unrelated to the performance of the planners. For example, a steering component was broken on one run, and in another run, unmapped water from a recent rain (not near the cul-de-sac) created a mobility barrier that caused an emergency stop (e-stop) for safety.

## 5.4 Data Collected

The data collected included configuration files, XUV text logs (csv and bin formats), observer comments, and bufMor (internal AM logs) files for each run. Vehicle logs from the XUV included time, easting, northing, status messages from XUV movement, and planned paths (easting and northing) from the global planner. The XUV logs are the basic data analyzed for this report.

## 5.5 Data Reduction

XUV logs were converted to Excel files, and duplicate plan entries were eliminated. For DR runs, the global planner generated and passed to the XUV more plans than the XUV could execute. Newly generated consecutive plans were compared, and if the new plan was within 5 s and 5 m in distance of the current plan, it was removed. This more accurately described the actual XUV performance.

Following the completion of the experiment, notes from five observers were compared to establish which runs would be included in the analysis.

## 5.6 Graphics for Each Run

Graphics illustrating the XUV path and narratives describing each run are located in appendix A. Experimenters' observations are located in appendix B. Figure 8 is an example of the run graphics.

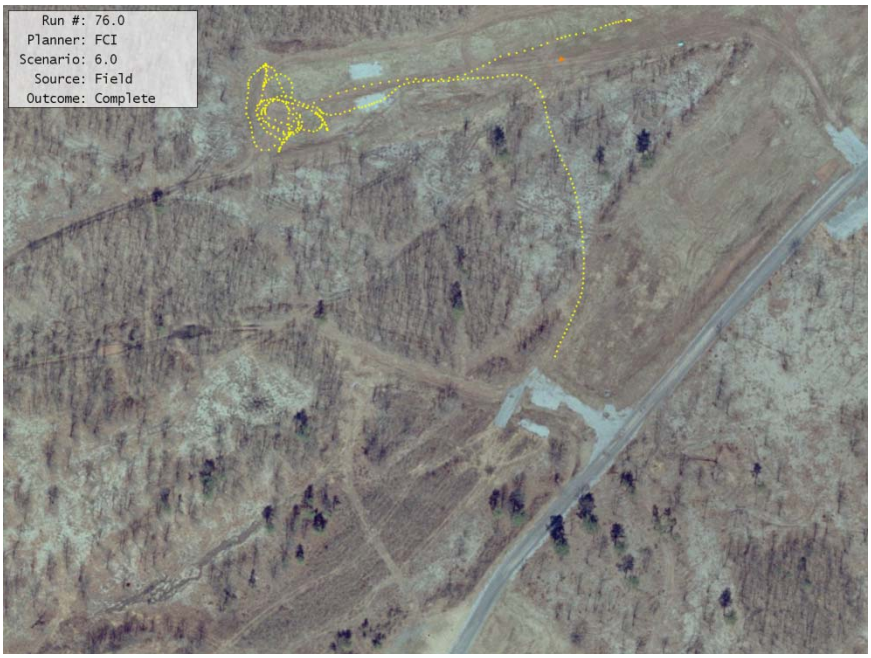


Figure 8. Sample graphic from run 76.

# 6. Scenario 1

## 6.1 Situation

In scenario 1, the SP was on the trail next to the tree line on Dan Grove Highway (figure 9). The goal was ~300 m northeast of the start. A priori data included a trail from the SP to the goal, trees to the west of the trail, an a priori trail to the goal beyond the blockage, and a nuclear, biological, and chemical (NBC) area (XUV no go) along the main tank trail to the east. The NBC area was to prevent the XUV from taking the low-cost route along a main trail, encouraging it to consider another alternative route instead. The trail was blocked ~60 m from the SP in an area surrounded by trees and high brush. There was not room for the XUV to turn around at the point of blockage. Backing up was the only possible maneuver.

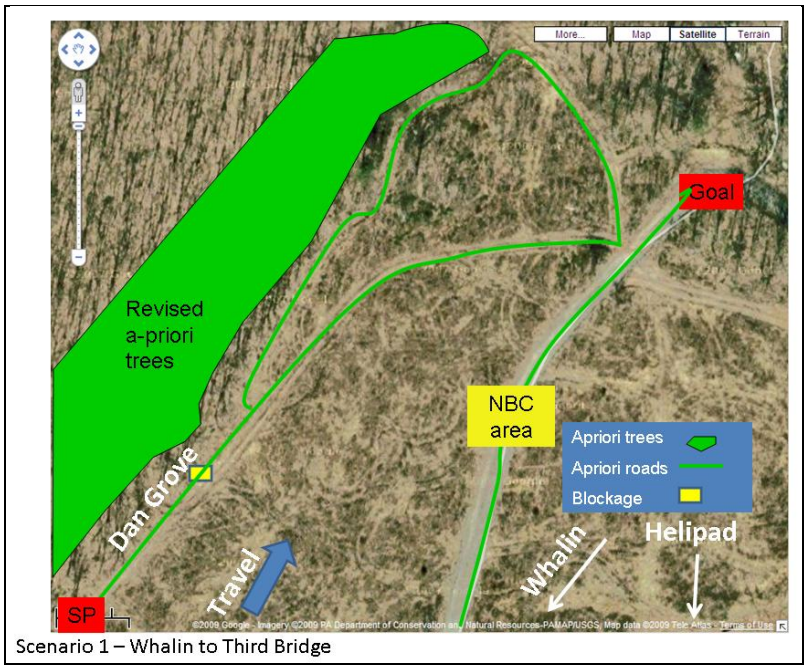


Figure 9. Scenario 1 description.

## 6.2 Expectations

The expectations were that (1) AM would back up three times and need operator assistance, and (2) upon seeing the blockage, the DR and FCI would replan back up the trail and look for an opening to the east where an unmarked trail paralleled the original route and was open to the goal; potentially, on the DR runs, HMP would enable the XUV to turn around in this confined space. FCI would need to back up to the new planned path because of the lack of HMP interface.

## 6.3 Results

The following list describes the column headings in the results tables:

- Scenario: 1–7.
- Planner: AM, DR, FCI.
- Source: RIVET or field.
- Run: run number.
- Plans: number of unique global plans found in the XUV log file.
- Distance: distance XUV traveled in meters.
- Total time: time from start to stop in minutes.
- Time eng. off: time the engine was off (primarily from stalls).
- Time HMP: time spent with HMP as the local planner.
- Av spd kph: average speed entire run (dist/[total time – time eng. off]).
- ET: elapse time (total time – time eng off).
- Outcome: completed or DNF (did not finish).
- Backups: number of times XUV backed up.

Table 2. Scenario 1 results.

| Scenario # | Planner | Source | Run | Plans | Dist (m) | Total time (min) | eng_off (min) | Time HMP (min) | ET (min) | avg spd kph | Backups | Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | AM only | Field | 33 | | 156.19 | 3.17 | | | 3.17 | 2.96 | 3 | Stuck |
| 1 | AM only | RIVET | 238 | | 151.54 | 2.40 | 0.00 | | 2.40 | 3.79 | 3 | Backups |
| 1 | AM only | RIVET | 239 | | 152.71 | 2.59 | 0.00 | | 2.59 | 3.53 | 3 | Backups |
| 1 | AM only | RIVET | 240 | | 155.13 | 2.39 | 0.00 | | 2.39 | 3.90 | 3 | Backups |
| 1 | DR | Field | 31.3 | 20 | 311.68 | 8.18 | | 4.06 | 8.18 | 2.29 | | Complete |
| 1 | DR | Field | 35 | 15 | 369.98 | 17.56 | | 5.53 | 17.56 | 1.26 | 4 | Complete |
| 1 | DR | Field | 38 | 2 | 178.86 | 6.83 | | 3.33 | 6.83 | 1.57 | 6 | Stuck |
| 1 | DR | Field | 42 | 13 | 520.49 | 10.22 | 0.50 | 6.69 | 9.73 | 3.21 | 5 | Complete |
| 1 | DR | Field | 43 | 5 | 134.06 | 5.63 | | 1.91 | 5.63 | 1.43 | 1 | HMP |
| 1 | DR | RIVET | 231 | 10 | 257.82 | 3.90 | 0.00 | 3.90 | 3.90 | 3.97 | | Complete |
| 1 | DR | RIVET | 232 | 13 | 261.07 | 3.19 | 0.00 | 3.16 | 3.19 | 4.91 | 1 | Complete |
| 1 | DR | RIVET | 233 | 10 | 236.94 | 2.92 | 0.00 | 2.92 | 2.92 | 4.87 | | Complete |
| 1 | FCI | Field | 32 | 1 | 317.28 | 4.12 | | | 4.12 | 4.63 | 3 | Complete |
| 1 | FCI | Field | 34 | 1 | 169.87 | 2.85 | | | 2.85 | 3.57 | 3 | Backups |
| 1 | FCI | Field | 39 | 1 | 168.56 | 2.66 | 0.37 | | 2.30 | 4.40 | 3 | Backups |
| 1 | FCI | RIVET | 226 | 1 | 155.77 | 2.27 | 0.00 | | 2.27 | 4.12 | 3 | Backups |
| 1 | FCI | RIVET | 227 | 1 | 141.00 | 2.15 | 0.00 | | 2.15 | 3.93 | 3 | Backups |
| 1 | FCI | RIVET | 228 | 1 | 156.28 | 2.24 | 0.00 | | 2.24 | 4.18 | 3 | Backups |

### 6.4 Autonomous Mobility

The three RIVET runs with AM planner resulted in identical behaviors. The XUV moved down the trail, saw the blockage, backed up three times, and the run was halted.

One field run (run 33) with AM was conducted and similarly ended after max backups. AM was unable to find an alternate route.

### 6.5 Dynamic Replanner

The three RIVET runs with the DR resulted in identical behaviors. The XUV moved down the trail and saw the blockage. HMP maneuvered the XUV back to the point where an opening existed to the southeast. The XUV then drove through the opening and discovered an unmarked trail to its left and parallel to the original plan. It followed that trail to the goal. In the RIVET runs, HMP was invoked 99.7% of the time on all three runs. All three RIVET runs achieved the goal. The orange triangles appearing in the figures of DR runs (figures A-3–A-8) represent the location of the XUV when a new global plan to the goal is accepted by the XUV. Hence, many new plans are observed in cul-de-sac situations, and fewer new plans are observed in less congested environments where the XUV is moving easily toward the goal.

Three of the five field runs achieved the goal. Two of the three successful field runs, runs 31.3 and 42, closely resembled the RIVET runs. For each, the XUV saw the blockage, returned to the opening on the southeast, discovered the unmarked trail to its left, and proceeded slowly down the unmarked trail under HMP control. The DR continuously generated plans that directed the XUV back to the original trail, beyond the blockage. However, the XUV was unable to find a clear path through the brush and trees, and eventually the DR gave a plan that followed the unmarked trail to the goal. On run 35, the XUV followed a similar path but this time found a clear path back to the original trail and completed the run on the original trail past the blockage. Runs 38 and 43 ended in e-stops when the HMP planner backed the XUV into an unknown area of dense brush.

### 6.6 Field Cost Interface

Under RIVET, all three FCI runs went as expected. None achieved the goal point. All FCI runs in RIVET saw the blockage, backed up three times, and the runs were halted.

Field runs 34 and 39 were very similar to RIVET runs, stopping after three backups. On run 32, the XUV backed up three consecutive times without moving forward. (More typical of the backup behavior is for the XUV to move forward and probe the local terrain after changing the perspective via the backup.) This combined 60-m backup enabled it to discover the opening to the southeast and the unmarked trail paralleling the original path to the goal. The XUV proceeded down the unmarked trail to the goal.

# 7. Scenario 2

## 7.1 Situation

Scenario 2 is a derivation of scenario 1 with the same SP and goal (figure 10). The blockage was placed further north along the trail, after an opening to an alternate trail to the left that had a path to the goal. A priori data for scenario 2 is the same as scenario 1. There was not room for the XUV to turn around at the point of blockage. Backing up was the only possible maneuver.

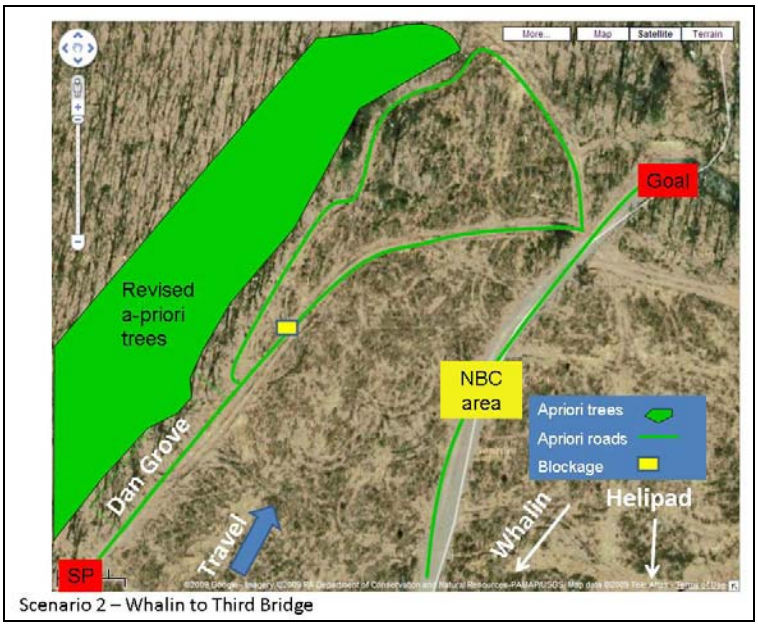


Figure 10. Scenario 2 description.

## 7.2 Expectations

The expectations were that (1) AM would back up three times and need operator assistance, ending the run for this experiment, and (2) upon seeing the blockage, the DR and FCI would replan back the trail and look for an opening to the west where a trail branched north from the original planned route and was open to the goal. Potentially, HMP would enable the XUV to turn around in this confined space, while FCI would need to back up to the new planned path because of the lack of HMP interface.

## 7.3 Results

Table 3. Scenario 2 results.

| Scenario # | Planner | Source | Run | Plans | Dist (m) | Total time (min) | eng_off (min) | Time HMP (min) | ET (min) | avg spd kph | Backups | Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | AM only | Field | 47 | | 257.15 | 3.11 | 0.27 | | 2.84 | 5.42 | 3 | Complete |
| 2 | AM only | Field | 51 | | 251.04 | 7.27 | | 0.02 | 7.27 | 2.07 | 4 | Complete |
| 2 | AM only | Field | 52 | | 146.00 | 1.71 | | | 1.71 | 5.12 | | Complete |
| 2 | AM only | Field | 57 | | 91.19 | 2.21 | | | 2.21 | 2.47 | 2 | E-stop |
| 2 | AM only | RIVET | 241 | | 189.70 | 2.80 | 0.00 | | 2.80 | 4.07 | 3 | Backups |
| 2 | AM only | RIVET | 242 | | 182.28 | 2.54 | 0.00 | | 2.54 | 4.31 | 3 | Backups |
| 2 | AM only | RIVET | 243 | | 185.03 | 2.55 | 0.00 | | 2.55 | 4.36 | 3 | Backups |
| 2 | DR | Field | 48 | 7 | 273.20 | 4.97 | 0.38 | 2.26 | 4.59 | 3.57 | 2 | Complete |
| 2 | DR | Field | 49 | 7 | 368.24 | 8.47 | | 5.80 | 8.47 | 2.61 | 2 | Complete |
| 2 | DR | Field | 53 | 4 | 201.70 | 2.53 | 0.36 | 0.94 | 2.17 | 5.57 | 1 | Complete |
| 2 | DR | Field | 56 | 5 | 91.32 | 3.01 | 0.20 | 0.91 | 2.81 | 1.95 | | E-Stop HMP |
| 2 | DR | RIVET | 206 | 5 | 326.57 | 4.15 | 0.00 | 3.16 | 4.15 | 4.73 | | Complete |
| 2 | DR | RIVET | 207 | 6 | 328.16 | 4.94 | 0.00 | 3.93 | 4.94 | 3.98 | | Complete |
| 2 | DR | RIVET | 208 | 6 | 345.55 | 5.90 | 0.00 | 5.05 | 5.90 | 3.51 | | Complete |
| 2 | FCI | Field | 46 | 1 | 189.29 | 5.52 | | | 5.52 | 2.06 | 4 | Backups |
| 2 | FCI | Field | 50 | 1 | 394.78 | 8.37 | | | 8.37 | 2.83 | 6 | Complete |
| 2 | FCI | Field | 54 | 1 | 132.78 | 1.61 | | | 1.61 | 4.95 | | Complete |
| 2 | FCI | Field | 55 | 1 | 174.75 | 4.69 | | | 4.69 | 2.24 | 4 | E-stop |
| 2 | FCI | RIVET | 220 | 1 | 180.26 | 2.27 | 0.00 | | 2.27 | 4.77 | 2 | Backups |
| 2 | FCI | RIVET | 221 | 1 | 181.82 | 2.46 | 0.00 | | 2.46 | 4.44 | 3 | Backups |
| 2 | FCI | RIVET | 222 | 1 | 243.02 | 3.43 | 0.00 | | 3.43 | 4.25 | 5 | Backups |

## 7.4 Autonomous Mobility

The three RIVET runs with AM planner resulted in identical behaviors. The XUV moved down the trail, saw the blockage, and backed up three times. The runs were ended after three consecutive backups. AM was unable to find an alternate route.

Three of the four AM field runs (47, 51, and 52) were able to successfully, but unexpectedly, find an alternate route to the east of the blockage. This was probably the result of sparse enough brush in the area for AM to find a local path and move the XUV through to the goal. With each successful run through the brush, the next run became easier for the planner to find a path through the brush. Run 57 ended in an e-stop when the XUV backed too close to a HMMWV used for blockage.

None of the field runs for AM were similar to the RIVET runs.

## 7.5 Dynamic Replanner

The three RIVET runs with the DR resulted in identical behaviors. The XUV moved down the trail and saw the blockage. HMP maneuvered the XUV back to the point where an opening existed to a trail to the east. The XUV then followed the trail to the goal. In the RIVET runs, HMP was invoked 76%–86% of the time.

Three of the four field runs achieved the goal. On runs 48, 49, and 53, the XUV saw the blockage, generated new plans to the east of the blockage, and found its way to the goal. No plans were generated on these runs that would have utilized the trail to the west, leading to speculation that the alternate trail was not in the a priori data as it was in RIVET. As with AM, the more trips through the shrubs, the wider and easier the path became. It is unclear whether the NBC area intended as part of the a priori data was set for all runs. These three successful runs, upon taking the alternative path to the east, continued east to a main tank trail that should have been avoided due to an NBC presence. In run 56, the XUV was e-stopped after two backups because it backed into dense shrubs.

None of the field runs for DR resembled the RIVET runs.

### 7.6 Field Cost Interface

None of the three RIVET runs achieved the goal point; all RIVET runs ended after three backups shortly after encountering the blockage. Again, this was unexpected as there should have been a path to the west in the a priori data.

Runs 50 and 54 achieved the goal. These runs were similar to the successful DR and AM runs because the XUV saw the blockage, moved off the trail to the east of the blockage through high shrubs, and found its way to the goal. As with previous runs, the more trips through the shrubs, the wider and easier the path became. Run 46.2 was e-stopped because of max backups. Run 55.1 was e-stopped because it backed too close to the HMMWV used in the blockage.

One field run for FCI was similar to the three unsuccessful RIVET runs.

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## 8. Scenario 3

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### 8.1 Situation

In scenario 3, the SP was on the trail at the base of a hill to the north of the helicopter pad (figure 11). The goal was on the helicopter pad, and there was an open trail from the SP up the hill directly to the goal. The trail was deeply rutted, steep, and surrounded by high shrubs on each side, and was included in the a priori data. An alternate, unmarked trail existed to the west of the original path and a “false” trail to the east of the original plan was included in the a priori data. This false a priori trail was not passable by the XUV. The planned path was blocked ~80 m from the SP on the steepest part of the deeply rutted trail with high shrubs on both sides. There was not room for the XUV to turn around at the point of blockage. Backing up was the only possible maneuver. The only possible path to the goal was an unmarked trail to the west of the original plan.

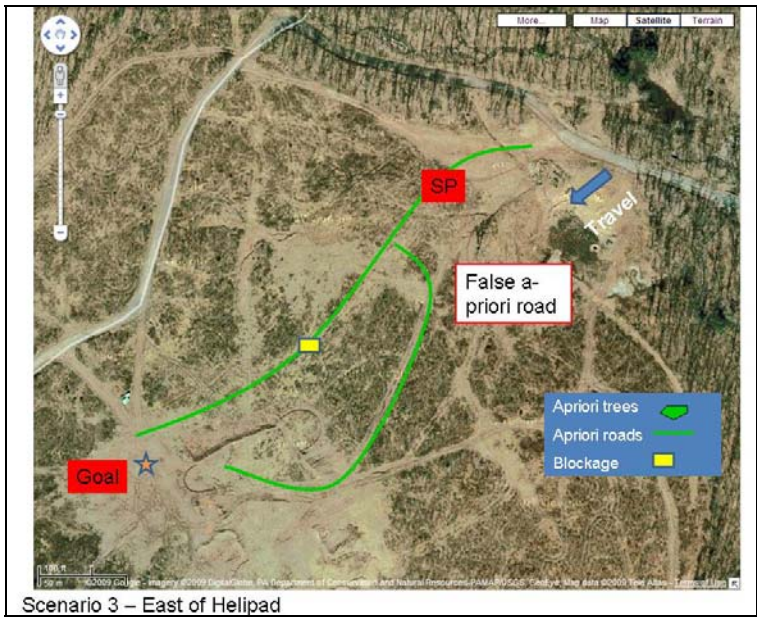



Figure 11. Scenario 3 description.

## 8.2 Expectations

The expectations were that (1) AM would back up three times and need operator assistance, and (2) upon seeing the blockage, the DR and FCI would replan back the trail and look for an opening to the east where an a priori trail gave a path to the goal, discover that this way was impassible, and then search for a path to the west of the original plan, hopefully finding the unmarked trail to the goal.

## 8.3 Results

Table 4. Scenario 3 results.

| Scenario # | Planner | Source | Run | Plans | Dist (m) | Total time (min) | eng_off (min) | Time HMP (min) | ET (min) | avg spd kph | Backups | Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | AM only | Field | 63 | | 210.30 | 2.89 | 0.25 | | 2.65 | 4.77 | 3 | Backups |
| 3 | AM only | Field | 64 | | 293.85 | 3.67 | 0.23 | | 3.44 | 5.13 | 3 | Backups |
| 3 | AM only | RIVET | 293 | 1 | 142.57 | 1.87 | 0.00 | | 1.87 | 4.57 | 3 | Backups |
| 3 | AM only | RIVET | 294 | 1 | 144.37 | 1.97 | 0.00 | | 1.97 | 4.39 | 3 | Backups |
| 3 | AM only | RIVET | 295 | 1 | 142.29 | 2.01 | 0.00 | | 2.01 | 4.25 | 3 | Backups |
| 3 | DR | Field | 62 | 8 | 139.31 | 18.35 | | 10.52 | 18.35 | 0.46 | 1 | HMP |
| 3 | DR | Field | 65 | 19 | 446.51 | 12.97 | | 9.51 | 12.97 | 2.07 | 3 | E-stop |
| 3 | DR | Field | 68 | 21 | 187.07 | 6.54 | 0.26 | 5.57 | 6.28 | 1.79 | | HMP |
| 3 | DR | Field | 72 | 3 | 95.02 | 0.67 | 0.02 | 0.17 | 0.65 | 8.73 | | E-stop |
| 3 | DR | RIVET | 290 | 6 | 253.34 | 2.60 | 0.00 | 1.95 | 2.60 | 5.85 | | Complete |
| 3 | DR | RIVET | 291 | 8 | 241.73 | 2.65 | 0.00 | 2.05 | 2.65 | 5.48 | | Complete |
| 3 | DR | RIVET | 292 | 8 | 282.77 | 3.64 | 0.00 | 2.06 | 3.64 | 4.67 | 2 | Complete |
| 3 | FCI | Field | 61 | 1 | 310.97 | 4.65 | | | 4.65 | 4.02 | 3 | Complete |
| 3 | FCI | Field | 66 | 1 | 268.25 | 4.30 | 0.47 | | 3.83 | 4.21 | 6 | Backups |
| 3 | FCI | Field | 69 | 1 | 339.58 | 4.94 | 0.25 | | 4.69 | 4.35 | 4 | Complete |
| 3 | FCI | RIVET | 286 | 1 | 959.97 | 15.01 | 0.00 | | 15.01 | 3.84 | 27 | Backups |
| 3 | FCI | RIVET | 287 | 1 | 201.96 | 2.35 | 0.00 | | 2.35 | 5.15 | 3 | Backups |
| 3 | FCI | RIVET | 288 | 1 | 519.61 | 8.07 | 0.00 | | 8.07 | 3.86 | 13 | Backups |

## 8.4 Autonomous Mobility

The three RIVET runs with AM planner resulted in identical behaviors. The XUV moved up the trail, saw the blockage, and backed up three times. The runs were ended after three consecutive backups. AM was unable to find an alternate route.

The two field runs with AM planner (63 and 64) resulted in behavior identical to the RIVET runs. The XUV moved up the trail, saw the blockage, and backed up three times. The trail at the point of the blockage was steep and deeply rutted, making any maneuver difficult. The runs were ended after three consecutive backups. AM was unable to find an alternate route.

## 8.5 Dynamic Replanner

The three RIVET runs with the DR resulted in identical behaviors (figure 12). The XUV moved up the trail and saw the blockage. HMP maneuvered the XUV back to the point where an opening existed to the west. DR then generated successive plans to move the XUV to the goal through an unmarked trail. The a priori road to the east was not explored. In the RIVET runs, HMP was invoked 57% to 77% of the time.

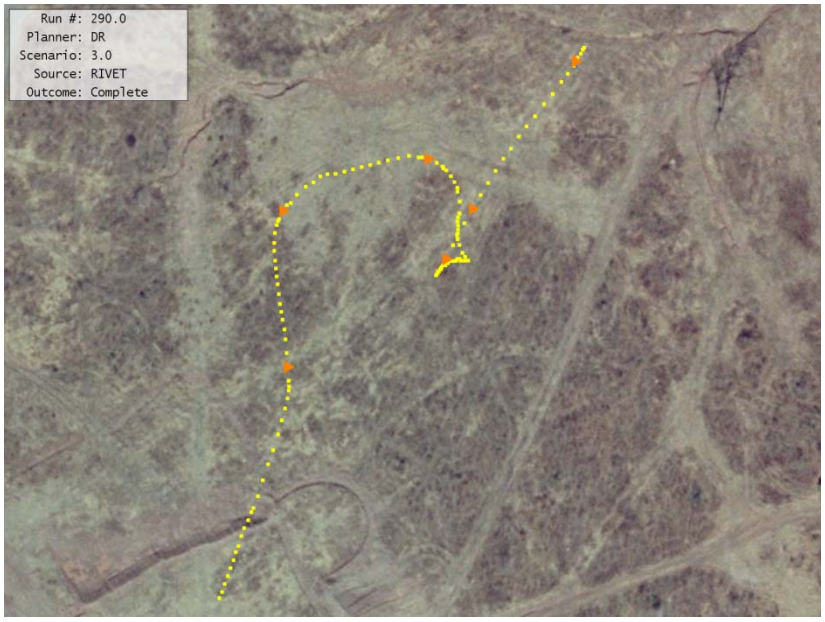



Figure 12. RIVET run 290.

None of the four field runs achieved the goal. On runs 62 and 68, the XUV saw the blockage and generated new plans back to the point where an opening existed to the west. However, HMP was unable to maneuver the XUV back down the steep trail, and both runs were e-stopped when HMP backed into high brush. During run 72, the XUV went through the barrels at the blockage and was e-stopped. On run 65, the XUV maneuvered back to the base of the hill and explored the false

a priori trail to the east, finding it impassable. It then generated plans to the west of the original plan toward the unmarked trail to the goal. However, the XUV failed to find the small opening in the brush for the unmarked trail and was e-stopped short of the goal. In the field runs, HMP was invoked 25% to 85% of the time.

None of the field runs resembled the RIVET runs.

### 8.6 Field Cost Interface

The three RIVET runs with the FCI planner resulted in identical behaviors. The XUV moved up the trail, saw the blockage, and backed up three times until the run was halted for max backups.

Two of the three FCI field runs achieved the goal. On runs 61 and 69, the XUV saw the blockage, backed to the base of the hill, and immediately explored the area to the west of the original plan, discovering the unmarked trail to the goal. In run 66, the XUV moved up the trail, saw the blockage, and backed up six times until the run was halted for max backups.

## 9. Scenario 4

### 9.1 Situation

Scenario 4 was exactly like scenario 3, with the exception of additional a priori data on trees and shrubs near the alternate unmarked trail that existed to the west of the original path (figure 13). It was thought that additional a priori data may increase the probability of finding the unmarked trail to the goal.

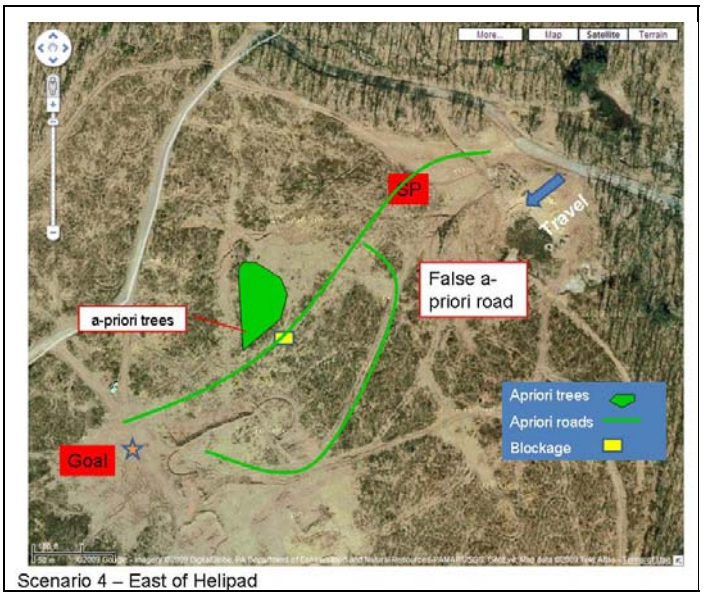



Figure 13. Scenario 4 description.

## 9.2 Expectations

The expectations were that (1) AM would back up three times and need operator assistance, and (2) upon seeing the blockage, the DR and FCI would replan back the trail and look for an opening to the east where an a priori trail gave a path to the goal, discover that this way was impassible, and then search for a path to the west of the original plan, hopefully finding the unmarked trail to the goal with the assistance of additional a priori tree data.

## 9.3 Results

Table 5. Scenario 4 results.

| Scenario # | Planner | Source | Run | Plans | Dist (m) | Total time (min) | eng_off (min) | Time HMP (min) | ET (min) | avg spd kph | Backups | Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | AM only | RIVET | 283 | 1 | 143.09 | 1.94 | 0.00 | | 1.94 | 4.43 | 3 | Backups |
| 4 | AM only | RIVET | 284 | 1 | 145.30 | 1.92 | 0.00 | | 1.92 | 4.54 | 3 | Backups |
| 4 | AM only | RIVET | 285 | 1 | 136.00 | 2.00 | 0.00 | | 2.00 | 4.08 | 3 | Backups |
| 4 | DR | RIVET | 280 | 9 | 241.34 | 2.39 | 0.00 | 1.69 | 2.39 | 6.05 | | Complete |
| 4 | DR | RIVET | 281 | 6 | 247.78 | 2.41 | 0.00 | 1.88 | 2.41 | 6.16 | | Complete |
| 4 | DR | RIVET | 282 | 9 | 238.60 | 2.28 | 0.00 | 1.50 | 2.28 | 6.29 | | Complete |
| 4 | FCI | RIVET | 275 | 1 | 393.16 | 5.52 | 0.00 | | 5.52 | 4.27 | 9 | Backups |
| 4 | FCI | RIVET | 276 | 1 | 201.17 | 2.41 | 0.00 | | 2.41 | 5.01 | 3 | Backups |
| 4 | FCI | RIVET | 277 | 1 | 202.55 | 2.34 | 0.00 | | 2.34 | 5.20 | 3 | Backups |

## 9.4 Autonomous Mobility

Scenario 4 was run only in RIVET. The three RIVET runs with AM planner resulted in identical behaviors. The XUV moved up the trail, saw the blockage, and backed up three times. The runs were ended after three consecutive backups. AM was unable to find an alternate route

## 9.5 Dynamic Replanner

The three RIVET runs with the DR resulted in identical behaviors. The XUV moved up the trail and saw the blockage. HMP maneuvered the XUV back to the point where an opening existed to the west. DR then generated successive plans to move the XUV to the goal through an unmarked trail.

## 9.6 Field Cost Interface

The three RIVET runs with the FCI planner resulted in identical behaviors. The XUV moved up the trail, saw the blockage, and backed up three times until the run was halted for max backups.

# 10. Scenario 5

## 10.1 Situation

In scenario 5, the SP was at the opening of the terrain area known as the “finger” in the “football field” (figure 14). The goal was on the main tank trail to the west of the cul-de-sac, ~400 m west of the SP. The initial plan was along the a priori trail toward the goal, which narrowed into a one-lane trail for ~200 m, then ended on the main tank trail where the goal was about 50 m north. A priori data included trails from the SP to the goal, trees to the north and south of the trail, an alternate a priori trail at the base of the “finger” north of the original path, and trees between the two a priori trails. The planned trail was blocked where the trail narrowed, and the alternate a priori trail was also blocked where it entered the trees. This situation constituted a very large, open cul-de-sac with plenty of maneuver room for the XUV.

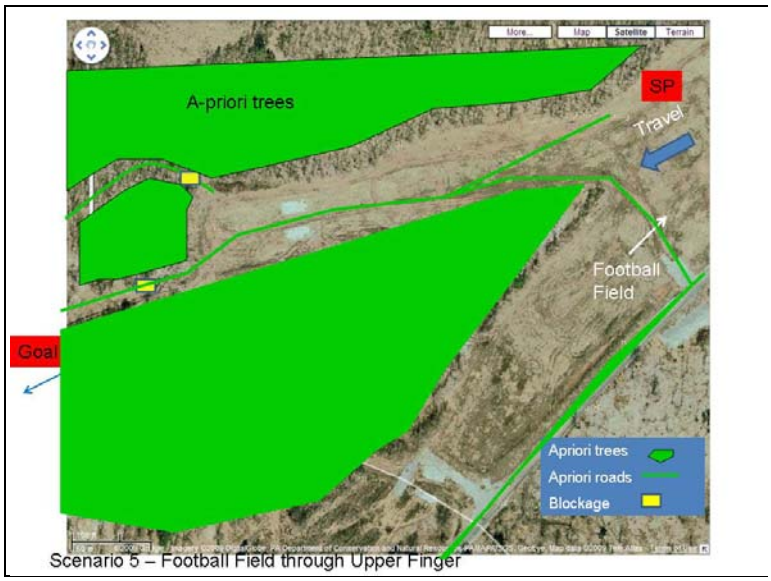



Figure 14. Scenario 5 description.

## 10.2 Expectations

One expectation was that AM would see the blockage and repeatedly circle, trying to find a path through the original plan. For this reason, a “three circle” rule was instituted to end a run if the XUV did not appear to be finding a solution after circling three times and/or backing up three times and calling for operator assistance. Another expectation was that upon seeing the initial blockage, the DR and FCI would replan to the nearby alternate trail. Upon finding it blocked, DR and FCI were expected to plan for the XUV to return the way it came and discover an alternative way on the trail around the trees and shrubs to the east.

## 10.3 Results

Table 6. Scenario 5 results.

| Scenario # | Planner | Source | Run | Plans | Dist (m) | Total time (min) | eng_off (min) | Time HMP (min) | ET (min) | avg spd kph | Backups | Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | AM only | Field | 16 | | 265.76 | 9.53 | 0.32 | | 9.21 | 1.73 | 1 | circles |
| 5 | AM only | Field | 20 | | 451.59 | 4.93 | | | 4.93 | 5.50 | 2 | circles |
| 5 | AM only | RIVET | 234 | 1 | 248.93 | 2.53 | 0.00 | | 2.53 | 5.91 | 2 | Backups |
| 5 | AM only | RIVET | 235 | | 248.49 | 2.47 | 0.00 | | 2.47 | 6.03 | 3 | Backups |
| 5 | AM only | RIVET | 236 | | 293.74 | 3.31 | 0.00 | | 3.31 | 5.33 | 3 | Backups |
| 5 | DR | Field | 18 | 14 | 653.39 | 4.63 | | 2.15 | 4.63 | 8.47 | 1 | Complete |
| 5 | DR | Field | 19 | 17 | 824.49 | 11.94 | | 4.92 | 11.94 | 4.14 | | Complete |
| 5 | DR | Field | 22 | 8 | 682.36 | 4.92 | | 2.14 | 4.92 | 8.32 | | Complete |
| 5 | DR | Field | 27 | 20 | 727.25 | 6.94 | 0.32 | 3.70 | 6.62 | 6.59 | | Complete |
| 5 | DR | Field | 30 | 13 | 757.55 | 7.16 | | 2.02 | 7.16 | 6.35 | 5 | Complete |
| 5 | DR | RIVET | 23 | 16 | 635.43 | 5.78 | 0.00 | 3.10 | 5.78 | 6.59 | | Complete |
| 5 | DR | RIVET | 24 | 10 | 689.19 | 5.19 | 0.00 | 2.54 | 5.19 | 7.97 | | Complete |
| 5 | DR | RIVET | 201 | 10 | 627.00 | 5.01 | 0.00 | 2.69 | 5.01 | 7.51 | 1 | Complete |
| 5 | FCI | Field | 17 | 1 | 336.93 | 3.51 | 0.07 | | 3.44 | 5.87 | | E-stop |
| 5 | FCI | Field | 21 | 1 | 494.46 | 9.79 | | | 9.79 | 3.03 | | E-stop |
| 5 | FCI | Field | 23 | 1 | 923.50 | 12.36 | | | 12.36 | 4.48 | 1 | Complete |
| 5 | FCI | Field | 25 | 2 | 1248.00 | 15.56 | | | 15.56 | 4.81 | 10 | circles |
| 5 | FCI | Field | 28 | 1 | 801.98 | 5.53 | | | 5.53 | 8.71 | 1 | Complete |
| 5 | FCI | RIVET | 12 | 1 | 735.67 | 5.73 | 0.00 | | 5.73 | 7.70 | 2 | Complete |
| 5 | FCI | RIVET | 13 | 1 | 725.60 | 5.19 | 0.00 | | 5.19 | 8.38 | 1 | Complete |
| 5 | FCI | RIVET | 215 | 1 | 664.26 | 4.87 | 0.00 | | 4.87 | 8.18 | 1 | Complete |

## 10.4 Autonomous Mobility

All three RIVET runs were ended on max backups immediately upon encountering the blockage on the initial planned path. AM would see the blockage of the original path, back up, and be unable to find a plan through the blockage.

In the two field runs (16.1 and 20) with the AM planner, the XUV repeatedly circled in the cul-de-sac, trying to find an acceptable way along the planned path. After circling three or more times, the runs were e-stopped.

## 10.5 Dynamic Replanner

In the three RIVET runs, the XUV proceeded along the planned route, saw the path blocked, and attempted to go through the alternate route nearby to the north but saw that it also was blocked. The XUV then replanned back east past the starting point, around the a priori trees, and south toward the tank trail and a clear path to the goal. These runs spent 49%–54% of the time in HMP at the cul-de-sac while generating and trying alternate plans.

The five field runs resembled very closely the RIVET runs. The field runs tended to spend additional time and distance exploring alternate routes in the cul-de-sac, probably because of the highly varied vegetation on/around the alternate paths out of the cul-de-sac. These runs spent 28%–53% of the time in HMP at the cul-de-sac while generating and trying alternate plans.

### 10.6 Field Cost Interface

In the three RIVET runs, the XUV preceded along the planned route, saw the path blocked, and circled several times while attempting to find a way through the original and alternate trails. The XUV eventually replanned back past the starting point, around the a priori trees, and south toward the tank trail and a clear path to the goal.

Two of the five field runs were successful in finding an alternate route. Runs 23 and 28 were successful in achieving the goal but were 100–200 m longer than the corresponding RIVET runs because these runs spent additional time and distance circling in the cul-de-sac and building up local terrain data before deciding to replan back past the starting point, around the a priori trees and south toward the tank trail and a clear path to the goal. Three of the runs (21.1, 25.2, and 17) saw the blockage and spent additional time and distance circling in the cul-de-sac, but FCI never generated a plan back toward the SP. The runs were ended after three or more circles.

Two of the five field runs resembled very closely the RIVET runs.

## 11. Scenario 6

### 11.1 Situation

Scenario 6 was exactly the same as scenario 5 with one exception. The a priori tree data was shortened by ~100 m in the southerly direction (figure 15). This was done to allow the XUV to explore for alternate paths through this wooded area, which had several unmarked trails through to the tank trail on the southern side. Plans and blockages remained, as in scenario 5.

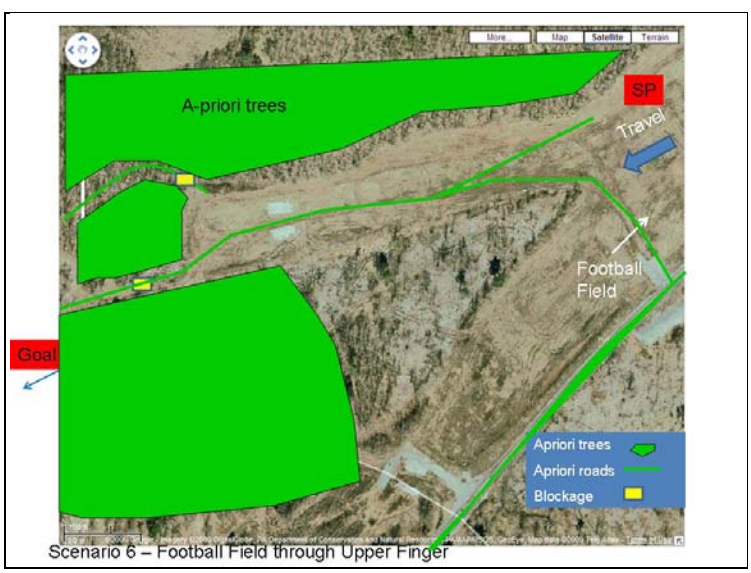



Figure 15. Scenario 6 description.

## 11.2 Expectations

The expectations were that (1) AM would see the blockage and repeatedly circle, trying to find a path through the original plan, and (2) upon seeing the initial blockage, the DR and FCI would replan to the nearby alternate trail. Upon finding it blocked, DR and FCI were expected to plan for the XUV to return the way it came and discover an alternative way through the trees and shrubs to the south.

## 11.3 Results

Table 7. Scenario 6 results.

| Scenario # | Planner | Source | Run | Plans | Dist (m) | Total time (min) | eng_off (min) | Time HMP (min) | ET (min) | avg spd kph | Backups | Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | AM only | Field | 78 | | 480.19 | 3.70 | | | 3.70 | 7.78 | 1 | circles |
| 6 | AM only | RIVET | 261 | | 410.04 | 4.92 | 0.00 | | 4.92 | 5.00 | 5 | Backups |
| 6 | AM only | RIVET | 262 | | 452.09 | 5.07 | 0.00 | | 5.07 | 5.35 | 6 | Backups |
| 6 | AM only | RIVET | 263 | | 679.10 | 9.40 | 0.00 | | 9.40 | 4.34 | 12 | Backups |
| 6 | DR | Field | 77.1 | 20 | 722.00 | 19.69 | | 7.98 | 19.69 | 2.20 | 4 | Complete |
| 6 | DR | Field | 80 | 18 | 605.20 | 7.15 | | 5.51 | 7.15 | 5.08 | | Complete |
| 6 | DR | Field | 84 | 25 | 719.32 | 18.73 | | 5.79 | 18.73 | 2.30 | 4 | Complete |
| 6 | DR | Field | 86 | 19 | 557.95 | 6.01 | | 3.07 | 6.01 | 5.57 | 1 | Complete |
| 6 | DR | Field | 89 | 17 | 560.73 | 5.23 | | 3.10 | 5.23 | 6.43 | | Complete |
| 6 | DR | RIVET | 258 | 15 | 409.07 | 3.20 | 0.00 | 1.36 | 3.20 | 7.67 | | Complete |
| 6 | DR | RIVET | 259 | 14 | 422.67 | 3.10 | 0.00 | 1.25 | 3.10 | 8.18 | | Complete |
| 6 | DR | RIVET | 260 | 15 | 448.44 | 3.82 | 0.00 | 1.52 | 3.82 | 7.05 | | Complete |
| 6 | FCI | Field | 76 | 1 | 896.50 | 7.89 | | | 7.89 | 6.82 | | Complete |
| 6 | FCI | Field | 79.1 | 1 | 674.38 | 5.27 | | | 5.27 | 7.68 | 1 | Complete |
| 6 | FCI | Field | 82 | 1 | 684.42 | 4.66 | | | 4.66 | 8.81 | | Complete |
| 6 | FCI | Field | 85 | 1 | 1103.38 | 9.69 | | | 9.69 | 6.83 | 1 | Complete |
| 6 | FCI | Field | 88 | 1 | 592.16 | 3.90 | | | 3.90 | 9.11 | | Complete |
| 6 | FCI | RIVET | 251 | 1 | 511.35 | 3.95 | 0.00 | | 3.95 | 7.76 | | Complete |
| 6 | FCI | RIVET | 254 | 1 | 589.00 | 4.84 | 0.00 | | 4.84 | 7.30 | 3 | Complete |
| 6 | FCI | RIVET | 255 | 1 | 526.46 | 3.87 | 0.00 | | 3.87 | 8.16 | 1 | Complete |

## 11.4 Autonomous Mobility

All three RIVET runs ended on max backups after circling and repeatedly trying to go through the blocked area.

In the one field run with AM, the XUV repeatedly circled in the cul-de-sac, trying to find an acceptable way along the initial planned path. After circling three or more times, the run was stopped.

## 11.5 Dynamic Replanner

In the three RIVET runs, the XUV proceeded along the planned route, saw the path blocked, and attempted to go through the alternate route nearby to the north but saw that it also was blocked. The XUV then replanned back past the starting point and discovered a path through the trees south toward the tank trail and a clear path to the goal. These runs spent 40%–42% of the time in HMP at the cul-de-sac while generating and trying alternate plans.

The five field runs resembled very closely the RIVET runs. The field runs tended to spend additional time and distance exploring alternate routes in the cul-de-sac, probably because of the highly varied vegetation on/around the alternate paths out of the cul-de-sac. These runs spent 31%–77% of the time in HMP at the cul-de-sac while generating and trying alternate plans

### 11.6 Field Cost Interface

In the three RIVET runs, the XUV proceeded along the planned route, saw that the path was blocked, and circled several times while attempting to find a way through the original and alternate trails. The XUV eventually replanned back past the starting point and discovered a route through the trees south toward the tank trail and a clear path to the goal.

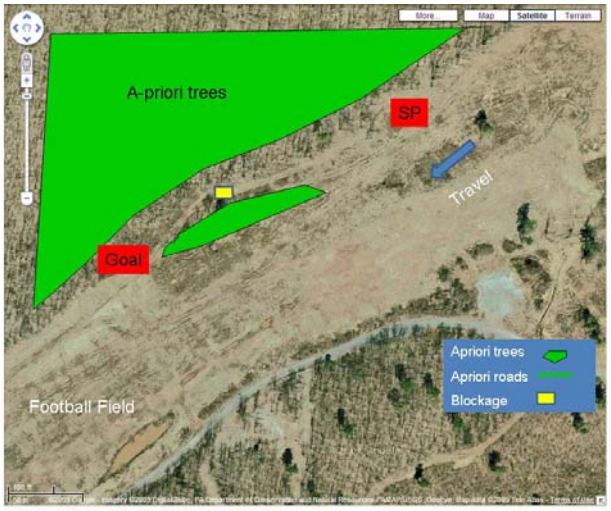
All five field runs were successful in finding an alternate route similar to the runs in RIVET. These runs spent additional time and distance circling in the cul-de-sac, building up local terrain data before replanning back past the starting point and discovering a path through the trees south toward the tank trail and a clear path to the goal.

All five of the field runs resembled very closely the RIVET runs.

## 12. Scenario 7

### 12.1 Situation

Scenario 7 was the simplest scenario (figure 16). The SP and goal were along a tree line in the football field. The trail to the goal went between a solid tree line to the north and a small set of trees and shrubs to the south. Both sets of trees were in the a priori data. The path between the trees was blocked ~50 m into the tree line.




Scenario 7 – East of Football Field

Figure 16. Scenario 7 description.

## 12.2 Expectations

The expectations were that (1) AM would see the blockage and repeatedly back up because of the heavy foliage on both sides of the trail (it was expected that max backups would end these runs) and (2) upon seeing the initial blockage, the DR and FCI would replan back to the split in the terrain and find the alternate route to the goal.

## 12.3 Results

Table 8. Scenario 7 results.

| Scenario # | Planner | Source | Run | Plans | Dist (m) | Total time (min) | eng_off (min) | Time HMP (min) | ET (min) | avg spd kph | Backups | Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | AM only | Field | 2 | | 253.83 | 3.34 | 0.30 | | 3.05 | 5.00 | 2 | E-stop |
| 7 | AM only | Field | 4 | 1 | 341.02 | 5.28 | | | 5.28 | 3.87 | 3 | Complete |
| 7 | AM only | Field | 8 | | 206.87 | 0.99 | | | 0.99 | 12.48 | | Complete |
| 7 | AM only | Field | 10 | | 175.14 | 2.71 | | | 2.71 | 3.88 | 3 | E-stop |
| 7 | AM only | Field | 13 | 1 | 211.05 | 2.91 | 0.46 | | 2.44 | 5.19 | 3 | Max Backups |
| 7 | AM only | RIVET | 248 | | 495.66 | 3.45 | 0.00 | | 3.45 | 8.61 | | Complete |
| 7 | AM only | RIVET | 249 | | 530.77 | 3.79 | 0.00 | | 3.79 | 8.40 | | Complete |
| 7 | AM only | RIVET | 250 | | 921.04 | 8.01 | 0.00 | | 8.01 | 6.90 | 2 | Complete |
| 7 | DR | Field | 1 | 11 | 432.62 | 7.37 | | 4.42 | 7.37 | 3.52 | 5 | Complete |
| 7 | DR | Field | 6 | 8 | 331.99 | 6.11 | | 4.18 | 6.11 | 3.26 | | Complete |
| 7 | DR | Field | 7 | 16 | 368.12 | 12.73 | | 5.73 | 12.73 | 1.73 | 1 | E-stop |
| 7 | DR | Field | 11 | 13 | 260.12 | 19.40 | | 16.52 | 19.40 | 0.80 | 3 | E-Stop HMP |
| 7 | DR | Field | 15 | 19 | 365.36 | 9.62 | | 4.65 | 9.62 | 2.28 | 6 | Max Backups |
| 7 | DR | RIVET | 212 | 11 | 282.32 | 3.07 | 0.00 | 2.21 | 3.07 | 5.53 | | Complete |
| 7 | DR | RIVET | 213 | 10 | 296.26 | 2.46 | 0.00 | 1.50 | 2.46 | 7.24 | | Complete |
| 7 | DR | RIVET | 214 | 14 | 281.37 | 3.34 | 0.00 | 2.68 | 3.34 | 5.06 | | Complete |
| 7 | FCI | Field | 3 | 1 | 212.12 | 2.85 | 0.24 | | 2.62 | 4.86 | 3 | Max Backups |
| 7 | FCI | Field | 5 | 1 | 193.94 | 2.52 | | | 2.52 | 4.62 | 3 | Max Backups |
| 7 | FCI | Field | 9 | 1 | 193.41 | 3.38 | 0.24 | | 3.14 | 3.69 | 3 | Max Backups |
| 7 | FCI | Field | 12 | 2 | 186.52 | 2.74 | 0.24 | | 2.51 | 4.47 | 3 | Max Backups |
| 7 | FCI | Field | 14 | 1 | 213.63 | 3.16 | | | 3.16 | 4.05 | 3 | Max Backups |
| 7 | FCI | RIVET | 17 | 1 | 266.89 | 1.49 | 0.00 | | 1.49 | 10.74 | | Complete |
| 7 | FCI | RIVET | 224 | 1 | 286.07 | 2.00 | 0.00 | | 2.00 | 8.57 | | Complete |
| 7 | FCI | RIVET | 225 | 1 | 291.51 | 2.06 | 0.00 | | 2.06 | 8.49 | | Complete |

## 12.4 Autonomous Mobility

All three RIVET runs were successfully completed as the XUV sensed the blockage and turned around 180° to return to the place in the trail where an alternative trail existed to the goal. The RIVET-modeled foliage around the blockage allowed this maneuvering. This was not expected.

The field runs varied considerably. Run 8 completely ignored the original path and skirted to the south of the cul-de-sac directly to the goal. Run 4 found the cul-de-sac but backed up three times and was then positioned in a location where it was able to find an open path along the trail to the west. From that point, it went directly to the goal. Run 2 was e-stopped at the blockage site, run 10 was e-stopped when the XUV backed into a rock, and run 13 was ended for max backups. Although two field runs achieved the goal, none did so in the manner of RIVET, where the XUV was able to turn in the simulated environment.

### 12.5 Dynamic Replanner

In the three RIVET runs, the XUV proceeded along the planned route, saw that the path was blocked, and planned a way out. To achieve the plan, HMP directed a 180° turn, and the XUV followed a new plan back the trail and around the southern side of the trees to the goal.

In the field runs, after the blockage was encountered, HMP backed the XUV the entire distance out of the cul-de-sac on four of the five runs. Two of those runs ended in completions. All of the remaining three runs were able to escape the cul-de-sac but were unable to complete the run. A suspected navigation problem ended run 7 after HMP executed a k-turn and retreated from the blockage, and an HMP problem ended run 11. Run 15 ended for max backups.

### 12.6 Field Cost Interface

In the three RIVET runs, the XUV proceeded along the planned route, saw that the path was blocked, circled for a 180° turn out of the cul-de-sac, and followed a new plan back the trail and around the southern side of the trees to the goal. As with the AM RIVET runs, the modeled terrain allowed room for the turn.

In the five field runs, the XUV encountered the blockage and backed up three times but not far enough to enable the XUV to see the unobstructed path to the goal below the tree line. All five runs ended with max backups.

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## 13. Discussion and Analysis

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### 13.1 Analytical Approach

Analysis of UGV planner performance is extremely challenging for several reasons, such as the nature of a field test, limited control over a key explanatory variable, the lack of a definitive performance measure, and the overall complexity of the system. Field experimentation always introduces greater variability due to noise variables not present in the sterile surroundings in most development testing. This problem is magnified when testing UGV planners because variables one might think of as noise (e.g., nuances in the foliage, ground undulations) can influence perception/planning in ways unanticipated by experimenters, sending the UGV along a route not previously considered.

Beyond local nuances in the terrain, there is the challenge of finding the exact set of macro terrain conditions necessary to build a meaningful scenario. Even at FTIG, a relatively large and rich area for terrain variation, finding conditions that will stress planner reasoning (different for each planner) so that successes are earned and failures can be learned from is difficult. When such a scenario is seen in the existing terrain, it usually requires dressing up in some manner with other obstacles or a priori data to force the planner to solve an intended problem rather than work

around the new challenge by employing an already proven planning capability. Previous to this study, the validity of the planned scenario to provide the intended challenge was only in the eyes of an SME.

A definitive performance measure remains elusive. The goal should be to assess the decision making of the planner as it progresses toward the goal. However, evaluation at markers over the length of a course according to some scoring rubric is infeasible because, due to unanticipated branching by the UGV, there is no way for the evaluation plan to consider all paths, unless in a post hoc manner. The UGV might avoid a number of those markers. Time and distance measures would be of little value. The objective measure remaining is only whether or not the UGV overcame the intended challenge and reached the goal. A subjective measure might be possible to score the degree to which the UGV behavior on a scenario was consistent with SME expectation, but that was not attempted here.

Finally, the complexity of the technology heightens the significance of the three reasons just discussed. To begin, there are a number of settings related to perception and planning that can be tuned to a specific environment (e.g., the previously mentioned CellScale in FCI). Even in AM, numerous local planning costs considered make finding suitable scenarios difficult. When costs are expanded to the global decision space by FCI and DR, the SME must rely on a notional understanding of the planners' intent.

With that in mind, the focus of the analysis was on the expected behavior of the UGV in well-considered scenarios and whether or not the planner overcame the principal challenge and reached the goal. A collective SME notional understanding of expected behavior influenced the scenario choices and the planned dressing up of those routes in the global map or in the field. RIVET was used to reinforce and augment the notional understanding and was valuable in confirming the scenarios, but fell short of providing the definitive reference distribution for behavior. While actual performance is measured and compared to RIVET results, analysis looked beyond RIVET for explanations of observed UGV behavior when appropriate.

### 13.2 Expectations in RIVET

An initial question to consider is, Did the planners perform in RIVET as expected in each scenario? All three RIVET runs in each configuration gave identical results, so RIVET provided no variation in performance within a set of experimental conditions. Table 9 shows the percentage of runs in RIVET that matched the experimenter's expectations, which were that AM would fail to reach the goal and that DR and FCI runs would solve the cul-de-sac and reach the goal. In 15 of 18 experimental conditions (scenario 4 is not considered), the planners performed as expected, except for FCI in scenarios 1–3. In each exception, the trail where the blockage was placed was very constrained, leaving the XUV with only the choice of backing up when the block was encountered. The scenarios were constructed so that backing up three times would not

Table 9. RIVET runs achieving goal point.

| | | Scenario | | | | | |
|---|---|---|---|---|---|---|---|
| Planner | Result | 1 | 2 | 3 | 5 | 6 | 7 |
| AM | RIVET | 0/1 (0%) | 0/1 (0%) | 0/1 (0%) | 0/1 (0%) | 0/1 (0%) | 0/1 (0%) |
| DR | RIVET | 3/3 (100%) | 3/3 (100%) | 3/3 (100%) | 3/3 (100%) | 3/3 (100%) | 3/3 (100%) |
| FCI | RIVET | 0/3 (0%) | 0/3 (0%) | 0/3 (0%) | 3/3 (100%) | 3/3 (100%) | 3/3 (100%) |

Note: Red indicates 0%–24% completed.

ordinarily enable the XUV to observe an alternative route; hence, each FCI run in these scenarios ended in a stop for max backups. The lack of an HMP interface to FCI probably contributed to this failure to maneuver to a location where an alternate route could be observed. These results, obtained before the field portion of the experiment, confirmed the validity of the scenarios to the extent possible in simulation.

### 13.3 Expectations in the Field

A second question to consider is, Did the planners perform in the field runs as expected in each scenario? There was considerable variation in the routes taken and the outcomes of the field runs.

#### 13.3.1 Reaching the Goal Point

Table 10 shows the outcomes of the runs in the field. "Complete" means that the XUV reached the intended goal after overcoming the obstacles placed in the original planned path. Color codes are used to illustrate the percentage of runs achieving the goal point.

Table 10. Field runs reaching the goal point.

| | | Scenario | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Planner | Result | 1 | 2 | 3 | 5 | 6 | 7 | Subtotal | |
| AM | | Complete | Complete | Complete | Complete | Complete | Complete | 5/15 | |
| | Field | 0/1 (0%) | 3/4 (75%) | 0/2 (0%) | 0/2 (0%) | 0/1 (0%) | 2/5 (40%) | (33%) | |
| | | | | | | | | | Total |
| DR | | Complete | Complete | Complete | Complete | Complete | Complete | 18/28 | 35/68 |
| | Field | 3/5 (60%) | 3/4 (75%) | 0/4 (0%) | 5/5 (100%) | 5/5 (100%) | 2/5 (40%) | (64%) | (51%) |
| | | | | | | | | | |
| FCI | | Complete | Complete | Complete | Complete | Complete | Complete | 12/25 | |
| | Field | 1/3 (33%) | 2/4 (50%) | 2/3 (67%) | 2/5 (40%) | 5/5 (100%) | 0/5 (0%) | (48%) | |

Note: Green indicates 75%–100% match, yellow is 25%–74% match, and red is 0%–24% completed.

AM runs went about as expected. Four of the scenario cul-de-sacs stumped the XUV totally. Scenario 2 was solved by AM because the trail prior to the block was not so dense with brush that AM could not find an alternate route around the block through the brush and trees. DR and FCI also benefitted from this location; each planner, when successful, chose the identical bypass of the cul-de-sac. DR reached the goal point on 64% of its runs but completely failed scenario 3, where it was expected to retreat from a cul-del-sac on a narrow trail on a steep hill. Two runs were e-stopped when HMP backed the XUV into trees, and the third run was e-stopped when the XUV went through the barrels blocking the trail. FCI was less effective (48%) than DR and completely failed in scenario 7, where it could never see a clear path after three backups.

Six runs did not achieve the goal point but did overcome the blockage and solve the cul-de-sac problem. After getting past the blockage, runs 2, 7, 11, 38, 46.2, and 65 experienced other mobility problems that caused an e-stop before reaching the goal. Figure 17 illustrates this point with run 7 of scenario 7. In this run, the DR solved the cul-de-sac (upper right) and moved toward the goal point, generating several new plans along the way until it lost the NAV solution and the run was e-stopped. At the point of the e-stop, the XUV had a viable plan to the goal.

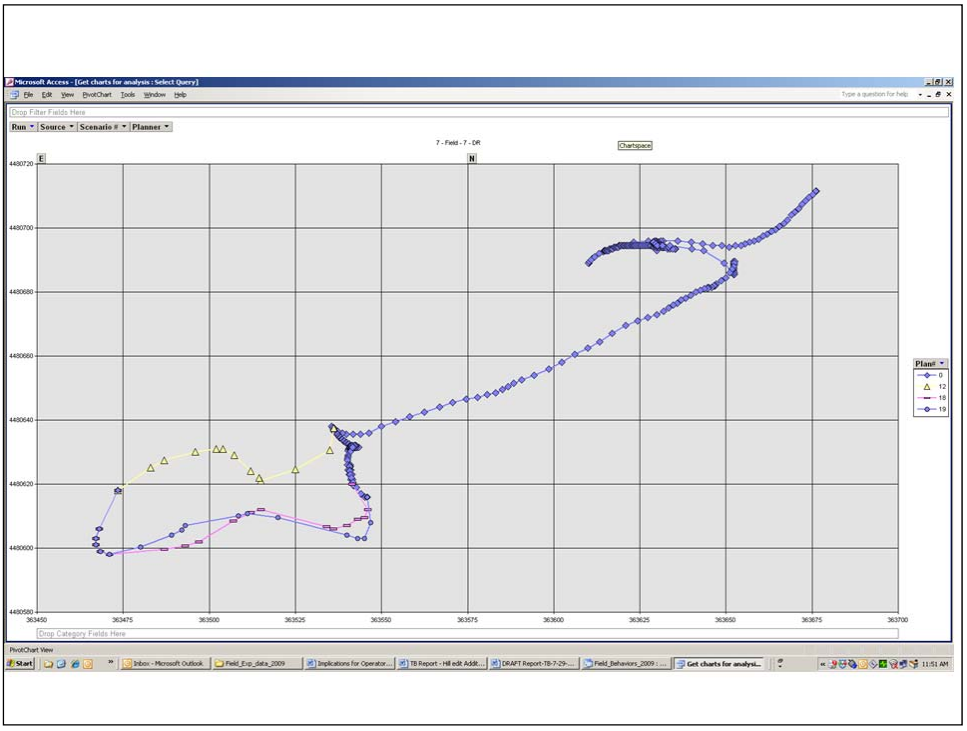


Figure 17. Run 7 where XUV solves cul-de-sac but does not achieve the goal point.

Table 11 shows the percentage of runs that solved the cul-de-sac regardless of whether or not the XUV reached the goal point.

Table 11. Field runs solving the cul-de-sac.

| | | Scenario | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Planner | | 1 | 2 | 3 | 5 | 6 | 7 | Subtotal | |
| AM | Result | Solved | Solved | Solved | Solved | Solved | Solved | 6/15 | |
| | Field | 0/1 (0%) | 3/4 (75%) | 0/2 (0%) | 0/2 (0%) | 0/1 (0%) | 3/5 (60%) | (40%) | |
| | | | | | | | | | Total |
| DR | Result | Solved | Solved | Solved | Solved | Solved | Solved | 22/28 | 41/68 |
| | Field | 4/5 (80%) | 3/4 (75%) | 1/4 (25%) | 5/5 (100%) | 5/5 (100%) | 4/5 (80%) | (79%) | (60%) |
| | | | | | | | | | |
| FCI | Result | Solved | Solved | Solved | Solved | Solved | Solved | 13/25 | |
| | Field | 1/3 (33%) | 3/4 (75%) | 2/3 (67%) | 2/5 (40%) | 5/5 (100%) | 0/5 (0%) | (52%) | |
| | | | | | | | | | |

Note: Green indicates 75%–100% match, yellow is 25%–74% match, and red is 0%–24% completed.

Results suggest DR and FCI were very effective at solving the cul-de-sacs, DR at 79% and FCI at 52%. The percentage of completed runs and the percentage of runs that "solved" the cul-de-sac are shown in figure 18.

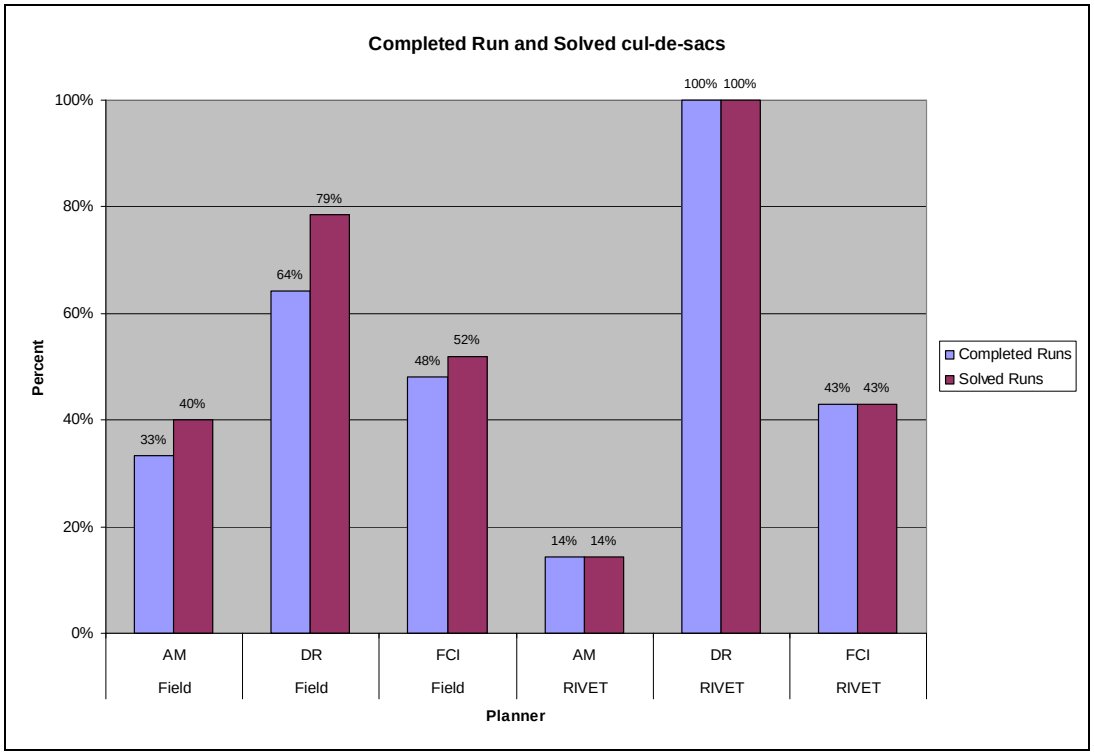


Figure 18. Comparison of completed runs vs. solved runs.

### 13.3.2 AM Observations

Despite attempts to design them otherwise, scenarios 2 and 7 turned out to be solvable by AM. AM runs were successful in scenario 2 because the shrubs and trees along the trail near the blockage were not sufficiently dense to keep the XUV from finding an opening after it backed away from the block. In scenario 7, AM never entered the cul-de-sac on one run and was able to back completely out of the cul-de-sac on a second run. Except for these instances, the AM runs could not solve the scenarios.

### 13.3.3 DR Observations

With the exception of scenario 3, DR runs achieved the goal on 18/24 (75%) of the runs and solved 21/24 (88%) of the cul-de-sacs. This is very good performance given the difficulty of the scenarios. The steep terrain and rutted trail on scenario 3 prohibited the HMP from maneuvering the XUV well at the point of the blockage. On the one run when the XUV was able to maneuver and generate new plans, it failed to find the small opening leading to an unmarked trail up the hill to the goal. In scenario 7, the failed run had navigation and HMP issues discussed in appendix A. It could be argued that success in scenario 2 might have been, as with AM, more a local planning achievement, but as new global routes pulled it in that direction DR is credited.

### 13.3.4 FCI Observations

FCI runs were successful about half the time (48%). Scenario 7 was singularly difficult for FCI. In all five scenario 7 runs, the XUV backed up three times but was not able to observe an alternative route; hence, each of the FCI runs in this scenario ended in a stop for max backups. The lack of an HMP interface probably contributed to this failure to maneuver to a location where an alternate route could be observed. The same factors applied to failed runs in scenarios 1–3. The same caveat for successful scenario 2 performance for DR could be made for FCI, but FCI is credited for the three successes.

## 13.4 Scenario Difficulty

Each scenario had its own particular level of difficulty attributable to the size of the cul-de-sac, the maneuver room available, the density of the trees and shrubs, etc. When data was used from only the DR and FCI runs, and based on the percentage of runs completed, scenarios 3 and 7 were the most difficult for the planners to solve (see figure 19). The blockage in scenario 3 was on a narrow trail on a steep hill—a very difficult mobility problem for the XUV. Scenario 7 difficulty was caused by the depth of the cul-de-sac and the lack of maneuver room near the blockage. The XUV was often not able to turn around or back up far enough to exit the cul-de-sac.

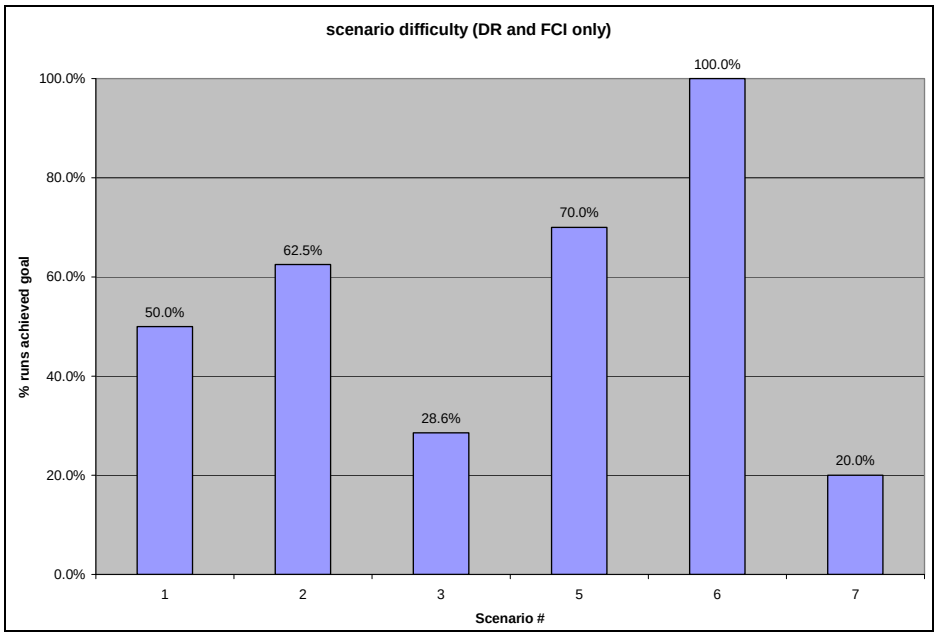


Figure 19. Scenario difficulty (percent goal achieved DR and FCI only).

# 14. Excursion Scenario 1.1

## 14.1 Situation

Scenario 1.1 was the same as scenario 1 except that the NBC area was removed in order to see if the DR would plan to use the low-cost main tank trail to the east as an alternate route (figure 20). Added as an excursion during the field experiment, scenario 1.1 was not run in RIVET.

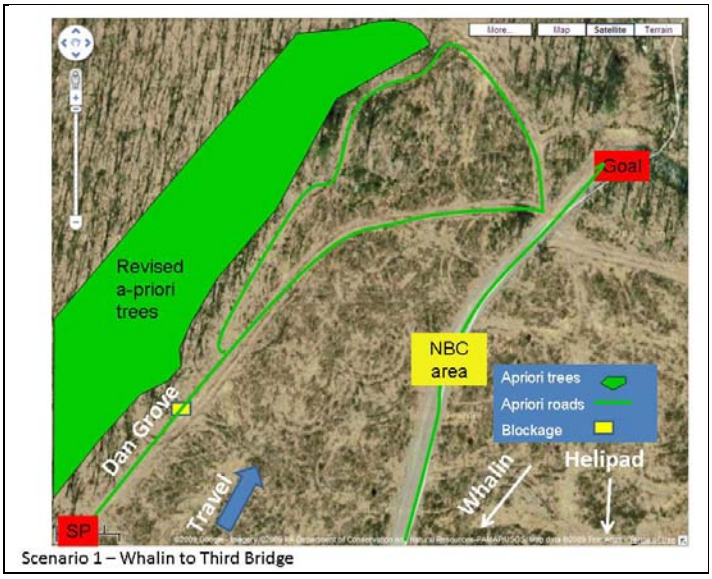


Figure 20. Scenario 1.1 description.

### 14.2 Dynamic Replanner

On neither run did the DR plan a path that utilized the main tank trail to the east. Run 116 (figure 21) was typical of the DR runs 31.3 and 42, where the XUV saw the blockage, returned to the opening on the right, discovered the unmarked trail to the left, and proceeded slowly down the unmarked trail under HMP control. The DR generated plans that directed the XUV back to the original trail, beyond the blockage. However, the XUV was unable to find a clear path through the brush and trees, and eventually the DR gave a plan that followed the unmarked trail to the goal. On run 114 (figure 21), the XUV was e-stopped when the HMP backed it into an unknown area of high brush near the blockage.

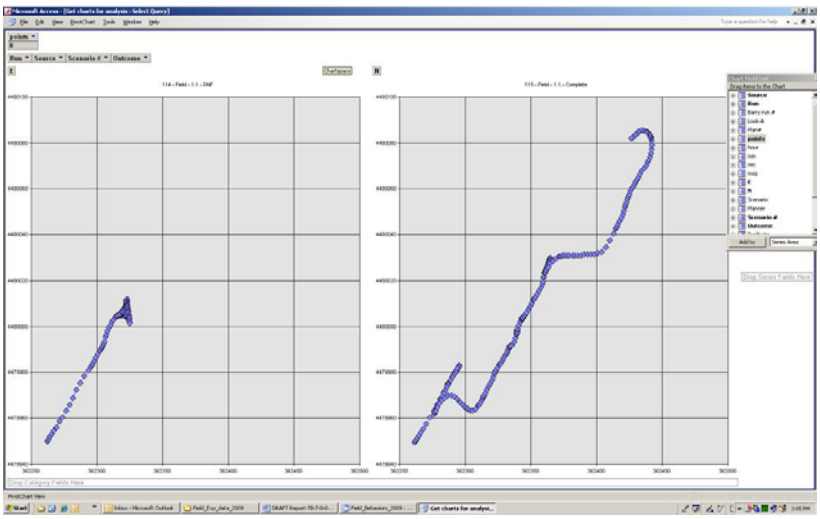

Figure 21. Scenario 1.1 runs with no NBC blockage.

## 15. Excursion Scenario 6.1

### 15.1 Situation

Scenario 6.1 was exactly the same as scenario 6 with one exception (figure 22). The first alternative path, the trail out of the finger area north of the original path, was not blocked. This constituted a scenario not quite as challenging as scenario 6. This scenario was an ad hoc addition to the experiment and was not run in RIVET.

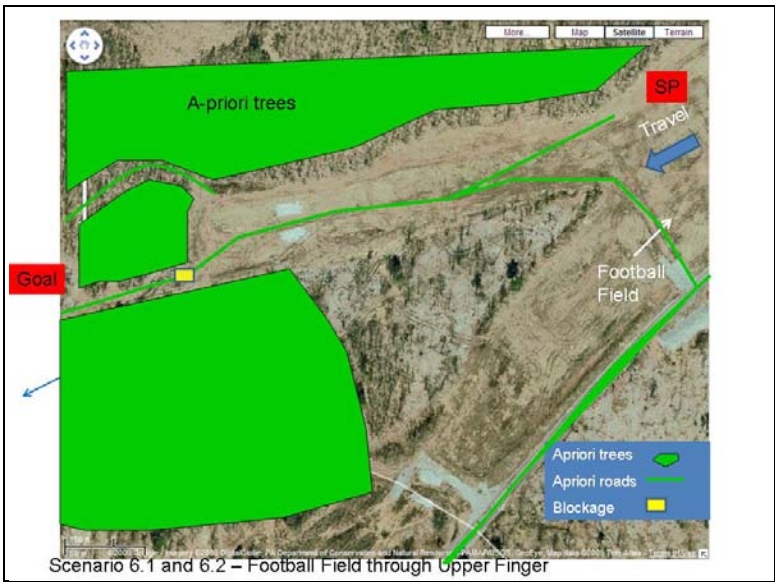


Figure 22. Scenario 6.1 description.

## 15.2 Expectations

The expectations were that (1) AM would encounter the blockage on the original path and possibly find the opening to the trail to the north, and (2) upon encountering the initial blockage, the DR and FCI would generate new plans to the nearby alternate trail to the north.

## 15.3 Results

Table 12. Scenario 6.1 results.

| Scenario # | Planner | Source | Run | Plans | Dist (m) | Total time (min) | eng_off (min) | Time HMP (min) | ET (min) | avg spd kph | Backups | Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6.1 | AM only | Field | 109 | 1 | 742.09 | 6.57 | | | 6.57 | 6.78 | 1 | circles |
| 6.1 | AM only | Field | 114 | | 483.67 | 5.09 | | | 5.09 | 5.71 | 4 | circles |
| 6.1 | DR | Field | 107 | 8 | 232.81 | 1.58 | 0.12 | 1.45 | 1.46 | 9.60 | | Complete |
| 6.1 | DR | Field | 112 | 7 | 247.39 | 1.66 | 0.03 | 0.61 | 1.62 | 9.15 | | Complete |
| 6.1 | FCI | Field | 108 | 1 | 254.90 | 2.04 | 0.29 | | 1.75 | 8.74 | | Complete |
| 6.1 | FCI | Field | 113 | 1 | 233.31 | 1.34 | 0.02 | | 1.32 | 10.60 | | Complete |

## 15.4 Autonomous Mobility

In the two field runs, the XUV repeatedly circled in the cul-de-sac and never came close enough to the unblocked trail in the north to see the opening. After circling three or more times, the run was e-stopped.

## 15.5 Dynamic Replanner

In the two field runs, the XUV sensed the blockage in the original path and quickly generated and executed a new global path through the alternate trail to the north. These runs spent 37% and 92% of the time in HMP at the cul-de-sac before generating the new global plan that worked.

### 15.6 Field Cost Interface

In the two field runs, the XUV sensed the blockage in the original path and quickly generated and executed a new path through the alternate trail to the north. This occurred quickly and seamlessly on both runs.

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## 16. Excursion Scenario 6.2

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### 16.1 Situation

Scenario 6.2 was exactly the same as scenario 6. This scenario was an ad hoc addition to the experiment and was not run in RIVET. The weight for local/global costs in the FCI planner calculations was varied in two runs using the FCI planner only.

### 16.2 Expectations

Observing the performance of FCI in scenario 6 and noting the number of times the XUV circled the cul-de-sac before generating a path out of the cul-de-sac, the experimenters decided to run the same scenario but with a different ratio of between the local and global planner weights for FCI. The variable CellScale was reduced from 0.2 to 0.1 for the excursion, giving more weight to the local planner, which was less forgiving of the obvious brush in the immediate path and caused the XUV to more quickly generate a path out of the cul-de-sac.

### 16.3 Results

Table 13. Scenario 6.2 results.

| Scenario # | Planner | Source | Run | Plans | Dist (m) | Total time (min) | eng_off (min) | Time HMP (min) | ET (min) | avg spd kph | Backups | Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6.2 | FCI | Field | 110 | 1 | 860.47 | 7.90 | | | 7.90 | 6.53 | 1 | Complete |
| 6.2 | FCI | Field | 111 | 1 | 446.21 | 4.31 | 0.47 | | 3.84 | 6.97 | 2 | E-stop |

### 16.4 Field Cost Interface

As expected, on both runs, the XUV exited the cul-de-sac area after circling twice near the blockages. One run was completed, and the second run was e-stopped when the XUV ran into undetected and unmarked water after exiting the cul-de-sac.

## 17. Effects of Varying CellScale

FCI runs in scenarios 5 and 6 successfully solved the cul-de-sac after several "circles" of the cul-de-sac area. Several looks at the terrain were required in order to cause the perception system to recognize the local blockages and increase the local cost, enabling the FCI planner to then select a plan that took the XUV out of the cul-de-sac area. FCI runs circled the area an average of 4.2 times when the CellScale was set to 0.2. Data from these runs are found in table 14.

Table 14. Number of circles for FCI runs in scenarios 5 and 6.

| Run No. | No. of Circles | CellScale | Source |
|---|---|---|---|
| 21.1 | 3 | 0.2 | Field |
| 23 | 3 | 0.2 | Field |
| 25.2 | 8 | 0.2 | Field |
| 28 | 3 | 0.2 | Field |
| 76 | 5 | 0.2 | Field |
| 79.1 | 2 | 0.2 | Field |
| 82 | 4 | 0.2 | Field |
| 85 | 8 | 0.2 | Field |
| 88 | 2 | 0.2 | Field |
| **Average No. of Circles = 4.2** | | | |

While not conclusive, this is evidence that CellScale is influential in the performance of the FCI planner and should be investigated using different levels and various terrain situations.

## 18. Similarities and Differences Between RIVET and Field Runs

### 18.1 RIVET

RIVET was an invaluable tool in preparing for the assessment. It provided a test bed for the integrated planners, which would not have been available otherwise. It has been used to replicate and test bugs and other issues that are only present when running all the processes and sensors present in the XUV. It also provides a more controlled environment with generous display options in which multiple people can work together when trying to troubleshoot the integrated system. Lastly, it proved to be a valuable training tool that reduces the learning curve for operating the XUV and the different planners. In many of the scenarios, RIVET's

representation was so good that the behavior of the XUV in the field matched the simulation even in small nuances and exercised some bugs that were hard to reproduce. Still, there are a number of areas in which there is room for improvement.

### 18.2 Matched Runs

As illustrated in figure 23, in some instances, RIVET and field runs matched very closely.

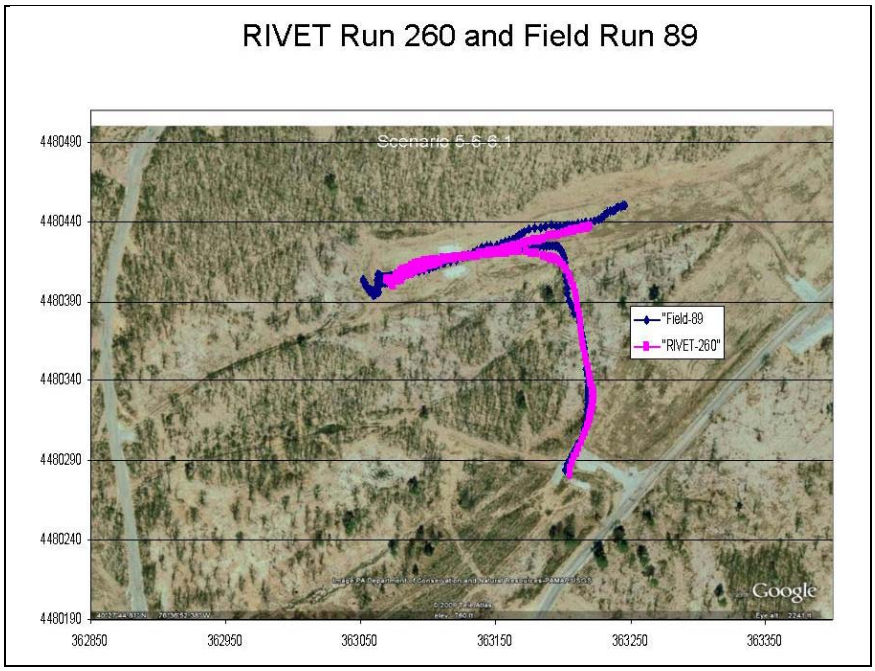


Figure 23. Example of closely matching RIVET and field runs.

Table 15 shows the extent to which the XUV tracks in field runs matched the XUV tracks in RIVET runs. Overall, about half (48%) of the field runs closely resembled a RIVET run.

Table 15. Correlations between RIVET and field results.

| | | Scenario | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Planner | Result | 1 | 2 | 3 | 5 | 6 | 7 | | |
| AM | RIVET | DNF | DNF | DNF | DNF | DNF | DNF | 8/15 | |
| | Field match | 1/1 (100%) | 1/4 (25%) | 2/2 (100% | 2/2 (100% | 1/1 (100% | 1/5 (20%) | (53%) | |
| | | | | | | | | | |
| DR | RIVET | Complete | Complete | Complete | Complete | Complete | Complete | 14/28 | 33/68 |
| | Field match | 2/5 (40%) | 0/4 (0%) | 0/4 (0%) | 5/5 (100% | 5/5 (100% | 2/5 (40%) | (50%) | (48%) |
| | | | | | | | | | |
| FCI | RIVET | DNF | DNF | DNF | Complete | Complete | Complete | 11/25 | |
| | Field match | 2/3 (66%) | 1/4 (25%) | 1/3 (33%) | 2/5 (40%) | 5/5 (100% | 0/5 (0%) | (44%) | |

## 18.3 Lack of Variability in RIVET

For all scenarios and each planner, the three RIVET runs produced the same end result and almost identical tracks. There was no variability between runs. There was at least one field run for each experimental condition that was very similar to corresponding RIVET runs; however, for any given set of conditions, the lack of variability in RIVET is a significant limitation. The plots in figure 24 show the repeatability of RIVET runs. Ideally, in subsequent studies, there would be the ability to introduce degrees of variability into the terrain to elicit a distribution of behaviors. That distribution would then serve as a reference for observed performance evaluations. There is no guarantee that the specific lay down of simulated terrain for each scenario in this study was in any way the best lay down. Further, the capability to easily introduce variable terrain would likely enhance the developers' opportunities to experience interesting planner behaviors in the lab, where the feedback loop in software development is more efficient.

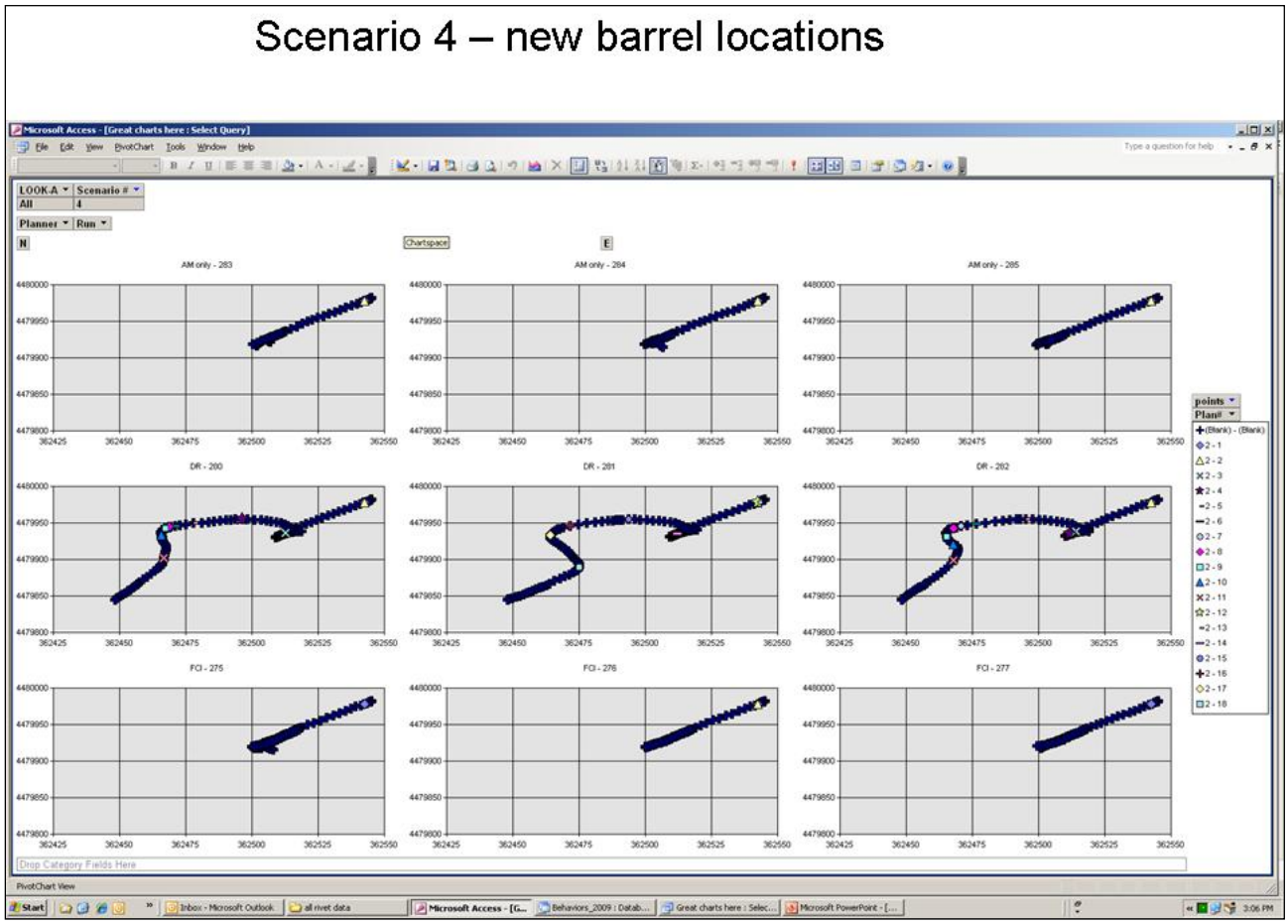


Figure 24. Examples of lack of variability in RIVET.

## 18.4 E-stops

There were no e-stops in RIVET. All RIVET runs ended in a completed run or in max backups. In the current implementation, HMP was allowed to back into unknown areas, resulting in some e-stops in the field but with no consequences in RIVET. An effort might be considered to elicit from program participants the anatomy of an e-stop and include that run outcome in RIVET.

## 18.5 HMP

During the DR runs, the XUV spent considerably less time in HMP in RIVET vs. field runs (see figure 25). HMP works flawlessly in RIVET and achieves much higher speeds than in the field runs.

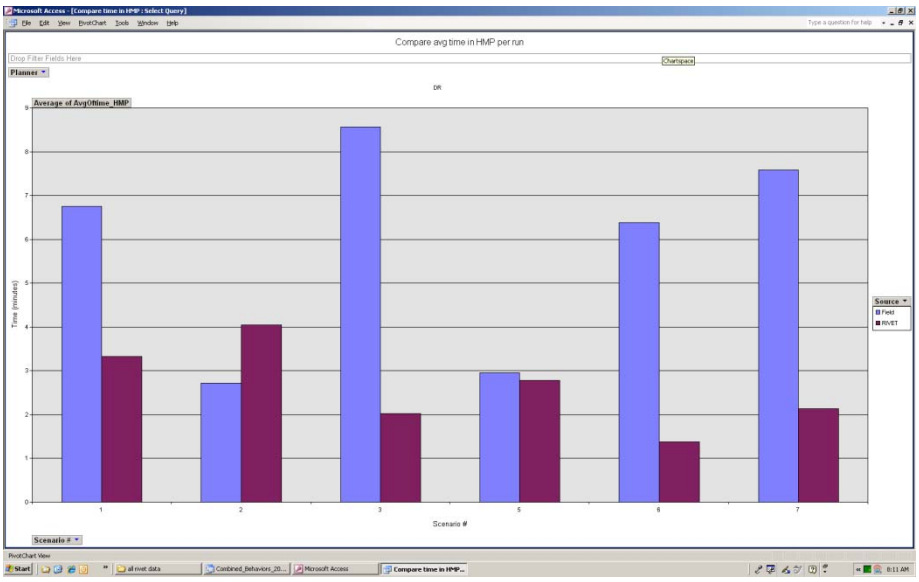


Figure 25. Time spent in HMP.

## 18.6 Backups

There appears to be no significant difference in the number of backups the XUV performed in RIVET vs. field runs. Reasons for the two spikes in the number of backups in figure 26 are not clear. In RIVET, scenario 3, FCI run 286 had 27 backups, run 287 had 3 backups, and run 288 had 13 backups. In RIVET, scenario 6, AM run 261 had 5 backups, run 262 had 6 backups, and run 263 had 12 backups. An explanation would require additional investigation.

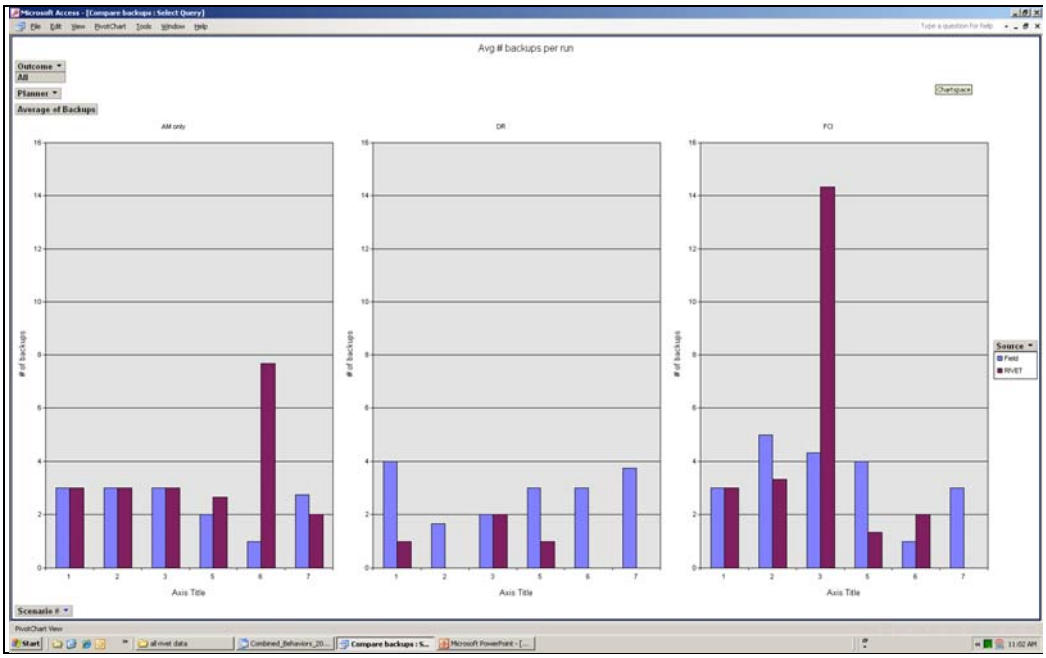


Figure 26. Number of XUV backups.

## 18.7 Performance of FCI in Scenarios 5 and 6

As discussed previously, FCI runs in scenario 5 and 6, which successfully solved the cul-de-sac or were halted after numerous circles of the cul-de-sac area, circled the area an average of 4.1 times when CellScale was set to 0.2. Corresponding runs in RIVET are shown in table 16.

Table 16. Number of FCI circles in scenarios 5 and 6 using RIVET.

| Run No. | No. of Circles | CellScale | Source |
|---|---|---|---|
| 12 | 2 | 0.2 | RIVET |
| 13 | 1 | 0.2 | RIVET |
| 215 | 1 | 0.2 | RIVET |
| 251 | 1 | 0.2 | RIVET |
| 254 | 1 | 0.2 | RIVET |
| 255 | 1 | 0.2 | RIVET |
| **Average No. of Circles = 1.2** | | | |

Although FCI solved scenarios 5 and 6 consistently in the field, this data shows a significant difference in the “efficiency” of FCI in those scenarios relative to the corresponding RIVET runs.

### 18.8 Reasons for End of Mission

Table 17 summarizes the reasons that an early end of mission was called on experimental runs that were not completed.

Table 17. Reasons for early end of mission calls.

| Source | Planner | Reason | Count |
|---|---|---|---|
| Field | AM only | E-stop | 3 |
| Field | AM only | Max backups | 3 |
| Field | AM only | Stuck | 1 |
| Field | AM only | Three circles | 5 |
| Field | DR | E-stop | 3 |
| Field | DR | E-stop HMP | 5 |
| Field | DR | Max backups | 1 |
| Field | DR | Stuck | 1 |
| Field | FCI | E-stop | 4 |
| Field | FCI | Max backups | 9 |
| Field | FCI | Three circles | 1 |
| RIVET | AM only | Max backups | 18 |
| RIVET | FCI | Max backups | 12 |

Five runs were ended prematurely for DR runs when HMP backed the XUV into unknown areas that were brush or trees, causing the e-stop. This is a known condition for HMP and has been addressed for future implementation.

FCI runs were ended nine times for max backups. Although plans generated by FCI take into account the kinematics of the XUV, this precludes the kinds of tight maneuvers possible under HMP control. It appears that integration of HMP into the FCI planner would significantly improve its performance.

## 19. Implications for Operator Performance

This field assessment did not assess operator performance or the need for operator interventions. However, there are potential implications for operator performance resulting from these kinds of planning algorithms.

As UGV intelligence becomes greater and increasingly autonomous tactical behaviors are implemented, the role of the human operator will change. Planning algorithms, such as those described and assessed in this report, will allow the robot to execute plans and reach the end goal with less human intervention. The robot will have the capability to achieve the end goal with flexibility as to the specific route taken. The UGV will be able to pick and choose its route even as the actual terrain presents obstacles and challenges. The operator will have fewer direct control tasks and be called for fewer interventions, thus reducing operator workload.

It is important, though, to consider other potential implications for operator performance. While there may be less direct control tasks required, the operator will still be required to periodically monitor and supervise the UGV progress. For some activities, such as the cul-de-sac problem (e.g., see scenario 6), the operator could see, at first, the UGV moving toward the goal and then, some time later, see the same UGV heading in the exact opposite direction. For the operator, this behavior may be inexplicable.

A major need will be some way for the operator to understand UGV actions and determine if its behavior is appropriate or unreliable. What information is needed and how it is conveyed to the operator is an open question and should be considered as the technology develops. Considering and addressing the implications for operator performance will enable more successful interaction between humans and unmanned intelligent systems so that such systems can be used to their full capability in an operational environment.

## 20. Conclusions

Both DR and FCI are significant improvements over AM in improving the ability of the XUV to solve complex terrain blockages and to plan and execute alternate routes to a goal point. For a quick summary, the results are again presented in tables 18 and 19. Overcoming such challenges represents a major improvement in maneuvering in complex terrain and is an enabler for tactical behaviors.

It is not fair to compare DR and FCI results because of the effects of HMP that are integrated with DR but not FCI. HMP seemed to enhance the capability of DR, allowing some intricate maneuvers to follow a new global route. At the same time, HMP was the direct cause of five e-stops because of a known limitation allowing an XUV back up into an area unknown to its map. FCI was stopped in nine runs because of max backups, meaning it could not maneuver out of the tight constraints around a blockage, a capability provided by HMP.

Changes in FCI parameters that affect the weighting between local and global plans significantly affect the efficiency of FCI in solving terrain blockages (see excursion 6.2).

Table 18. Goal achieved/runs attempted.

| Goal Achieved | | | | | | |
|---|---|---|---|---|---|---|
| | RIVET | | | Field | | |
| Scenario | AM | DR | FCI | AM | DR | FCI |
| 1 | 0/3 | 3/3 | 0/3 | 0/1 | 3/5 | 1/3 |
| 2 | 0/3 | 3/3 | 0/3 | 3/4 | 3/4 | 2/4 |
| 3 | 0/3 | 3/3 | 0/3 | 0/2 | 0/4 | 2/3 |
| 4 | 0/3 | 3/3 | 0/3 | — | — | — |
| 5 | 0/3 | 3/3 | 3/3 | 0/2 | 5/5 | 2/5 |
| 6 | 0/3 | 3/3 | 3/3 | 0/1 | 5/5 | 5/5 |
| 7 | 0/3 | 3/3 | 3/3 | 2/5 | 2/5 | 0/5 |

Table 19. Challenges solved/challenges attempted.

| Challenges Solved | | | | | | |
|---|---|---|---|---|---|---|
| | RIVET | | | Field | | |
| Scenario | AM | DR | FCI | AM | DR | FCI |
| 1 | 0/3 | 3/3 | 0/3 | 0/1 | 4/5 | 1/3 |
| 2 | 0/3 | 3/3 | 0/3 | 3/4 | 3/4 | 3/4 |
| 3 | 0/3 | 3/3 | 0/3 | 0/2 | 1/4 | 2/3 |
| 4 | 0/3 | 3/3 | 0/3 | — | — | — |
| 5 | 0/3 | 3/3 | 3/3 | 0/2 | 5/5 | 2/5 |
| 6 | 0/3 | 3/3 | 3/3 | 0/1 | 5/5 | 5/5 |
| 7 | 0/3 | 3/3 | 3/3 | 3/5 | 4/5 | 0/5 |

Lack of variability of performance in RIVET limits its usefulness and its validity with respect to field runs toward building a complete reference distribution of expected behaviors. Still, 48% of the field runs are very similar to corresponding RIVET runs. Even without variability introduced, RIVET is invaluable in confirming/augmenting SME notional understanding of planner behavior in the scenario planning stages.

DR and FCI greatly reduce the need for operator intervention to assist the XUV in overcoming an unexpected terrain blockage. On DR and FCI runs, no operator intervention was required. No measure of operator workload reduction was collected.

For DR and FCI, locally sensed data was used to update or replace a priori data in both the local and global maps. Both planners were able to explore alternate routes through areas where a priori data did not exist.

The one instance of the use of false a priori data (scenario 3) was inconclusive. One DR run attempted to use the false a priori trail in its plan, but the locally sensed data showed the area as impassible and alternate routes were generated (see field run 65).

The scenarios used in this technology assessment to evaluate the performance of the planning algorithms offered significant challenges to the XUV. The results show that beneficial improvements have been made over the previous ability of the vehicle to take advantage of sensed data for recognizing a blockage and planning alternative paths to the goal. It is hoped that as improvements are made in sensor range and resolution (e.g., midrange sensing) and these capabilities are integrated into the planning hierarchy, the UGV will be able to maneuver more effectively. This should reduce the number of pitfalls encountered by the vehicle, such as entering a cul-de-sac or a blocked road. The value of continued research in sophisticated path planning algorithms is that the vehicle will, at some point, be able to learn from its environment and self-adjust the parameters required to accommodate scenarios that differ in terrain type and complexity. Although significant progress has been made in enabling an unmanned autonomous vehicle to use local and global planning to overcome a number of difficult scenarios, a considerable amount of work will be required to realize a system that can perform in a robust manner when faced with the challenges found in the various unstructured, dynamic environments that a UGV will undoubtedly encounter.

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# Appendix A. Graphics and Narrative of All Runs

## A.1 Scenario 1

### A.1.1 Autonomous Mobility Only

The three robotic interactive visualization and exploitation technology (RIVET) runs with the Autonomous Mobility (AM)–only Planner resulted in identical behaviors. The experimental unmanned vehicle (XUV) moved down the trail, saw the blockage, and backed up three times; the run was then halted (figure A-1).

Figure A-1. Run 238-AM-RIVET.

One field run (run 33) with AM only was conducted and similarly ended after max backups. AM only was unable to find an alternate route (figure A-2).

Figure A-2. Run 33-AM-Field.

### A.1.2 Dynamic Replanner

The three RIVET runs with the Dynamic Replanner (DR) resulted in identical behaviors. The XUV moved down the trail and saw the blockage. The High-Maneuverability Planner (HMP) then maneuvered the XUV back to the point where an opening existed to the southeast. The XUV then drove through the opening and discovered an unmarked trail to its left and parallel to the original plan, and followed that trail to the goal. In the RIVET runs, HMP was invoked 99.7% of the time. All three RIVET runs achieved the goal. The orange triangles appearing in the figures of DR runs represent the location of the XUV when a new global plan to the goal is accepted by the XUV (figure A-3). Hence, many new plans are observed in cul-de-sac situations, and fewer new plans are observed in less congested environments where the XUV is moving easily toward the goal.

Figure A-3. Run 231-DR-RIVET.

Three of the five field runs achieved the goal. On runs 31.3 and 42 (figures A-4 and A-5), the XUV saw the blockage, returned to the opening on the southeast, discovered the unmarked trail to its left, and proceeded slowly down the unmarked trail under HMP control. The DR continuously generated plans that directed the XUV back to the original trail, beyond the blockage. However, the XUV was unable to find a clear path through the brush and trees, and eventually the DR gave a plan that followed the unmarked trail to the goal.

Figure A-4. Run 31.1-DR-Field.

Figure A-5. Run 42-DR-Field.

On run 35 (figure A-6), the XUV followed a similar path but found a clear path back to the original trail and completed the run this way.

Figure A-6. Run 35-DR-Field.

Runs 38 and 43 (figures A-7 and A-8) ended in e-stops when the HMP backed the XUV into the dense brush, which was an unknown area.

Figure A-7. Run 38-DR-Field

Figure A-8. Run 43-DR-Field.

Two of the five field runs closely resembled the RIVET runs.

### A.1.3 Field Cost Interface

None of the three RIVET runs achieved the goal point. All Field Cost Interface (FCI) runs in RIVET saw the blockage and backed up three times; the runs were then halted. Run 226 (figure A-9) is typical.

Figure A-9. Run 226-FCI-RIVET.

Field runs 34 and 39 (figures A-10 and A-11) were very similar to RIVET runs, stopping after three backups.

Figure A-10. Run 34-FCI-Field.

Figure A-11. Run 39-FCI-Field.

On run 32 (figure A-12), the XUV backed up three consecutive times without moving forward. This combined 60-m backup enabled it to discover the opening to the southeast and the unmarked trail paralleling the original path to the goal. The XUV proceeded down the unmarked trail to the goal.

Figure A-12. Run 32-FCI-Field.

## A.2 Scenario 2

### A.2.1 Autonomous Mobility Only

The three RIVET runs with the AM-only planner resulted in identical behaviors (figure A-13). The XUV moved down the trail, saw the blockage, and backed up three times. The runs were ended after three consecutive backups. AM only was unable to find an alternate route.

Figure A-13. Run 241-AM-RIVET.

Three of the four AM-only field runs (47, 51, and 52) were able to successfully, but unexpectedly, find an alternate route to the east of the blockage (figures A-14–A-16). This was probably the result of sparse enough brush in the area for AM to find a local path and move the XUV through to the goal. With each successful run through the brush, the next run became easier for the planner to find a path through the brush.

Figure A-14. Run 47-AM-Field.

Figure A-15. Run 51-AM-Field.

Figure A-16. Run 52-AM-Field.

Run 57 (figure A-17) ended in an e-stop when the XUV backed too close to a high-mobility multipurpose wheeled vehicle (HMMWV) used for blockage.

Figure A-17. Run 57-AM-Field.

None of the field runs were similar to the RIVET runs.

### A.2.2 Dynamic Replanner

The three RIVET runs with the DR resulted in identical behaviors (figure A-18). The XUV moved down the trail and saw the blockage. HMP then maneuvered the XUV back to the point where an opening existed to a trail to the east. The XUV then followed the trail to the goal. In the RIVET runs, HMP was invoked 76%–86% of the time.

Figure A-18. Run 206-DR-RIVET.

Three of the four field runs achieved the goal. On runs 48, 49, and 53 (figures A-19–A-21), the XUV saw the blockage, generated new plans to the east of the blockage, and found its way to the goal. No plans were generated on these runs that would have utilized the trail to the west, leading to speculation that the alternate trail was not in the a priori data as it was in RIVET. As with AM only, the more trips through the shrubs, the wider and easier the path became.

Figure A-19. Run 48-DR-Field.

Figure A-20. Run 49-DR-Field.

Figure A-21. Run 53-DR-Field.

On run 56 (figure A-22), the XUV was e-stopped after two backups because it backed into dense shrubs.

Figure A-22. Run 56-DR-Field.

None of the field runs resembled the RIVET runs.

### A.2.3 Field Cost Interface

None of the three RIVET runs achieved the goal point; all RIVET runs ended after three backups shortly after encountering the blockage (figure A-23).

Figure A-23. Run 220-FCI-RIVET.

Runs 50 and 54 (figures A-24 and A-25) achieved the goal. These runs were similar to the successful DR and AM-only runs because the XUV saw the blockage, moved off the trail to the east of the blockage through high shrubs, and found its way to the goal. As with previous runs, the more trips through the shrubs, the wider and easier the path became.

Figure A-24. Run 50-FCI-Field.

Figure A-25. Run 54-FCI-Field.

Run 46.2 (figure A-26) was e-stopped because of max backups, and run 55.1 (figure A-27) was e-stopped because it backed too close to the HMMWV used in the blockage.

Figure A-26. Run 46.2-FCI-Field.

Figure A-27. Run 55.1-FCI-Field.

One field run was similar to the three unsuccessful RIVET runs.

## A.3 Scenario 3

### A.3.1 Autonomous Mobility Only

The three RIVET runs with the AM-only planner resulted in identical behaviors (figure A-28). The XUV moved up the trail, saw the blockage, and backed up three times. The runs were ended after three consecutive backups. AM only was unable to find an alternate route.

Figure A-28. Run 293-AM-RIVET.

The two field runs with the AM-only planner (runs 63 and 64) resulted in behavior identical to the RIVET runs (figures A-29 and A-30). The XUV moved up the trail, saw the blockage, and backed up three times. The trail at the point of the blockage was steep and deeply rutted, making any maneuver difficult. The runs were ended after three consecutive backups. AM only was unable to find an alternate route.

Figure A-29. Run 63-AM-Field.

Figure A-30. Run 64-AM-Field.

### A.3.2 Dynamic Replanner

The three RIVET runs with the DR resulted in identical behaviors. The XUV moved up the trail and saw the blockage. HMP then maneuvered the XUV back to the point where an opening existed to the west. DR then generated successive plans to move the XUV to the goal through an unmarked trail. The a priori road to the east was not explored. In the RIVET runs, HMP was invoked 57%–77% of the time.

None of the four field runs achieved the goal. On runs 62 and 68 (figures A-31 and A-32), the XUV saw the blockage and generated new plans back to the point where an opening existed to the west. However, HMP was unable to maneuver the XUV back down the steep trail, and both runs were e-stopped when HMP backed into high brush.

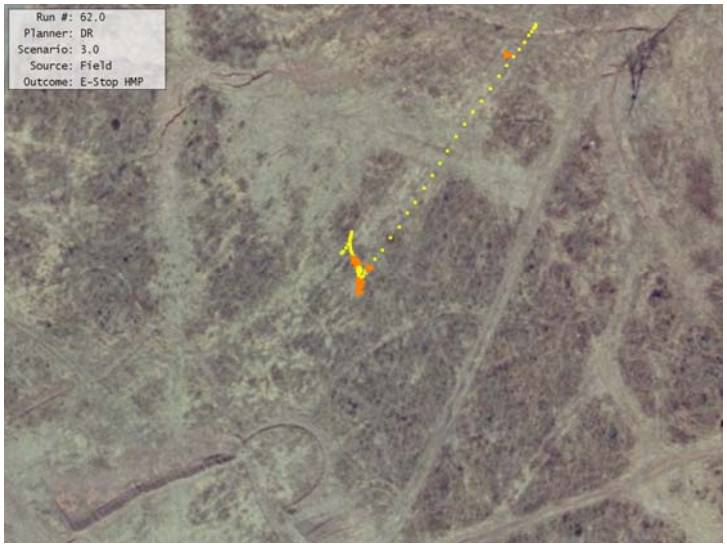


Figure A-31. Run 62-DR-Field.

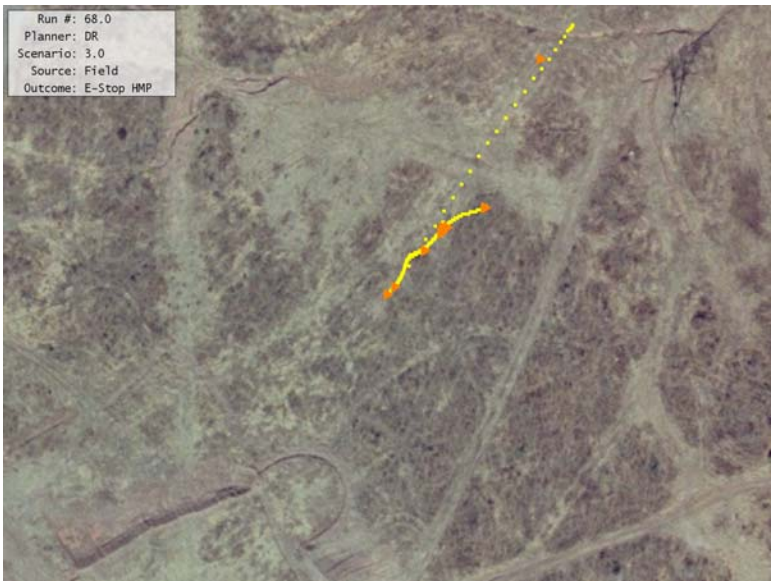


Figure A-32. Run 68-DR-Field

During run 72 (figure A-33), the XUV went through the barrels at the blockage and was e-stopped.

Figure A-33. Run 72-DR-Field.

On run 65 (figure A-34), the XUV maneuvered back to the base of the hill, explored the “false” a priori trail to the east, found it impassable, and generated plans to the west of the original plan toward the unmarked trail to the goal. However, the XUV failed to find the small opening in the brush for the unmarked trail and was e-stopped short of the goal. In the field runs, HMP was invoked 25%–85% of the time.

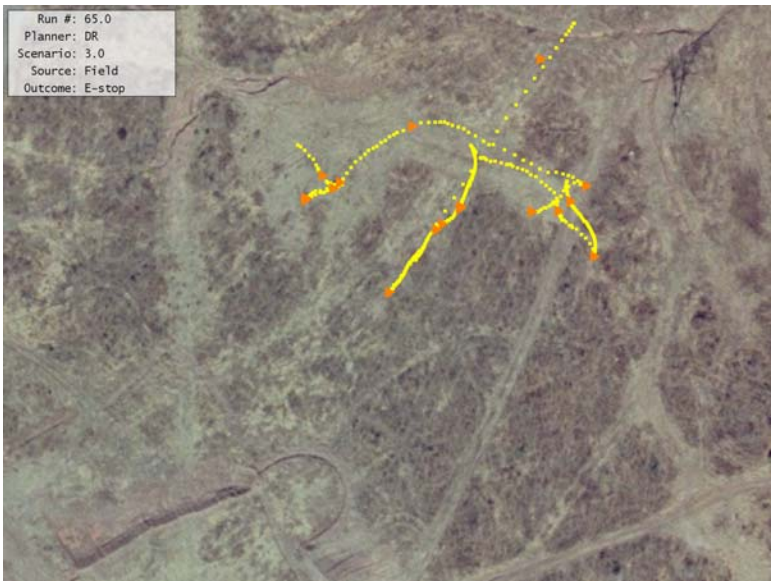


Figure A-34. Run 65-DR-Field.

None of the field runs resembled the RIVET runs.

### A.3.3 Field Cost Interface

The three RIVET runs with the FCI planner resulted in identical behaviors (figure A-35). The XUV moved up the trail, saw the blockage, and backed up three times until the run was halted for max backups.

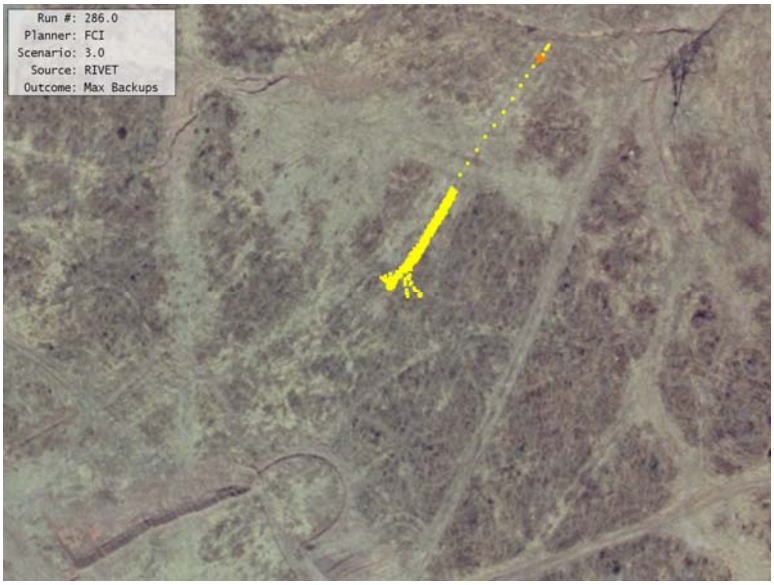


Figure A-35. Run 286-FCI-RIVET.

Two of the three FCI field runs achieved the goal. On runs 61 and 69 (figures A-36 and A-37), the XUV saw the blockage, backed to the base of the hill, and immediately explored the area to the west of the original plan, discovering the unmarked trail to the goal.

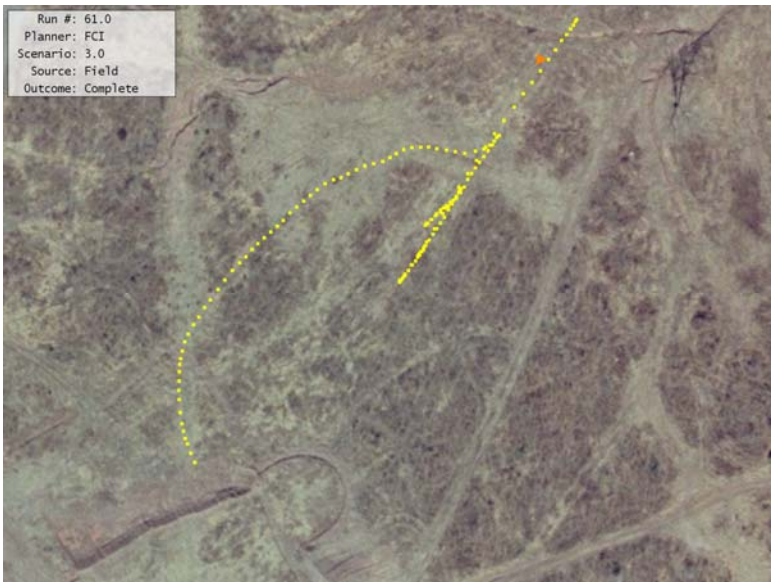


Figure A-36. Run 61-FCI-Field.

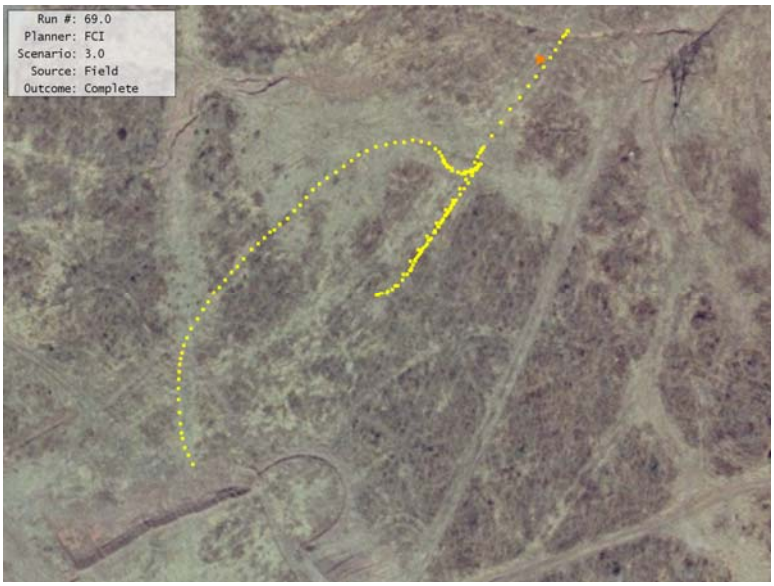


Figure A-37. Run 69-FCI-Field.

In run 66 (figure A-38), the XUV moved up the trail, saw the blockage, and backed up six times until the run was halted for max backups.

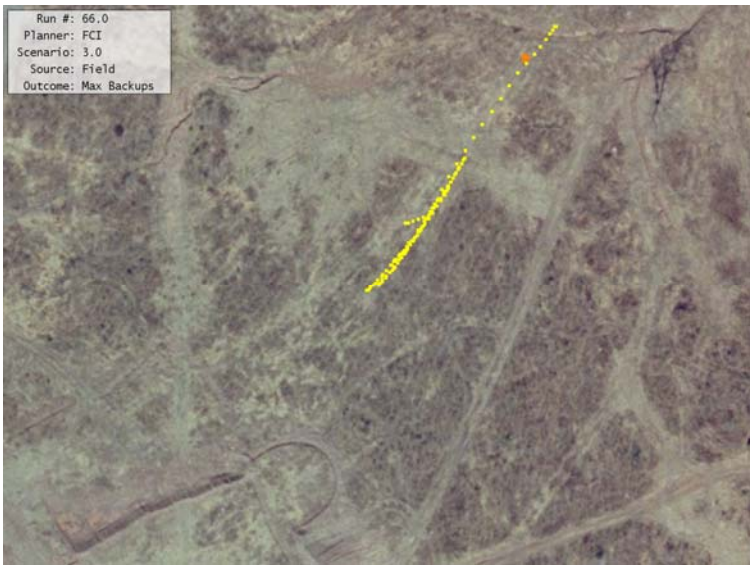


Figure A-38. Run 66-FCI-Field.

## A.4 Scenario 4

### A.4.1 Autonomous Mobility Only

Scenario 4 was only run in RIVET. The three RIVET runs with the AM-only planner resulted in identical behaviors (figure A-39). The XUV moved up the trail, saw the blockage, and backed up three times. The runs were ended after three consecutive backups. AM only was unable to find an alternate route.

Figure A-39. Run 283-AM-RIVET.

### A.4.2 Dynamic Replanner

The three RIVET runs with the DR resulted in identical behaviors (figure A-40). The XUV moved up the trail and saw the blockage. HMP then maneuvered the XUV back to the point where an opening existed to the west. DR then generated successive plans to move the XUV to the goal through an unmarked trail.

Figure A-40. Run 280-DR-RIVET.

### A.4.3 Field Cost Interface

The three RIVET runs with the FCI planner resulted in identical behaviors (figure A-41). The XUV moved up the trail, saw the blockage, and backed up three times until the run was halted for max backups.

Figure A-41. Run 275-FCI-RIVET.

## A.5 Scenario 5

### A.5.1 Autonomous Mobility Only

All three RIVET runs ended on max backups immediately upon encountering the blockage on the initial planned path (figure A-42). AM only would see the blockage of the original path, back up, and be unable to find a plan through the blockage.

Figure A-42. Run 234-AM-RIVET.

In the two field runs (16.1 and 20) with the AM-only planner, the XUV circled repeatedly in the cul-de-sac, trying to find an acceptable way along the planned path (figures A-43 and A-44). After circling three or more times, the runs were e-stopped.

Figure A-43. Run 16.1-AM-Field.

Figure A-44. Run 20-AM-Field.

### A.5.2 Dynamic Replanner

In the three RIVET runs, the XUV proceeded along the planned route and saw that the path was blocked. It attempted to go through the alternate route nearby to the north but saw that it, too, was blocked. The XUV then replanned back east past the starting point, around the a priori trees and south toward the tank trail and a clear path to the goal (figure A-45). These runs spent 49%–54% of the time in HMP at the cul-de-sac while generating and trying alternate plans.

Figure A-45. Run 23-DR-RIVET.

The five field runs (figures A-46–A-50) resembled very closely the RIVET runs. The field runs tended to spend additional time and distance exploring alternate routes in the cul-de-sac, probably because of the highly varied vegetation on/around the alternate paths out of the cul-de-sac. These runs spent 28%–53% of the time in HMP at the cul-de-sac while generating and trying alternate plans.

Figure A-46. Run 30-DR-Field.

Figure A-47. Run 27-DR-Field.

Figure A-48. Run 22-DR-Field.

Figure A-49. Run 19-DR-Field.

Figure A-50. Run 18-DR-Field.

### A.5.3 Field Cost Interface

In the three RIVET runs, the XUV proceeded along the planned route, saw that the path was blocked, circled several times while attempting to find a way through the original and alternate trails, and then eventually replanned back past the starting point, around the a priori trees and south toward the tank trail and a clear path to the goal (figure A-51).

Figure A-51. Run 12-FCI-RIVET.

Two of the five field runs were successful in finding an alternate route. Runs 23 and 28 (figures A-52 and A-53) were successful in achieving the goal but were 100–200 m longer than the corresponding RIVET runs because these runs spent additional time and distance circling in the cul-de-sac and building up local terrain data before deciding to replan back past the starting point, around the a priori trees and south toward the tank trail and a clear path to the goal.

Figure A-52. Run 23-FCI-Field.

Figure A-53. Run 28-FCI-Field.

Three of the runs (17, 25.2, and 21.1) saw the blockage and spent additional time and distance circling in the cul-de-sac, but FCI never generated a plan back toward the start point (figures A-54–A-56). The runs were ended after three or more circles.

Figure A-54. Run 17-FCI-Field.

Figure A-55. Run 25.2-FCI-Field.

Figure A-56. Run 21.1-FCI-Field.

Two of the five field runs resembled very closely the RIVET runs.

## A.6 Scenario 6

### A.6.1 Autonomous Mobility Only

All three RIVET runs were ended on max backups after circling and repeatedly trying to go through the blocked area (figure A-57).

Figure A-57. Run 261-AM-RIVET.

In the one field run with AM only, the XUV circled repeatedly in the cul-de-sac, trying to find an acceptable way along the initial planned path (figure A-58). After circling three or more times, the run was stopped.

Figure A-58. Run 78-AM-Field.

### A.6.2 Dynamic Replanner

In the three RIVET runs, the XUV proceeded along the planned route, saw that the path was blocked, attempted to go through the alternate route nearby to the north but saw that it also was blocked, then replanned back past the starting point and discovered a path through the trees south toward the tank trail and a clear path to the goal (figure A-59). These runs spent 40%–42% of the time in HMP at the cul-de-sac while generating and trying alternate plans.

Figure A-59. Run 258-DR-RIVET.

The five field runs (figures A-60–A-64) resembled very closely the RIVET runs. The field runs tended to spend additional time and distance exploring alternate routes in the cul-de-sac, probably because of the highly varied vegetation on/around the alternate paths out of the cul-de-sac. These runs spent 31%–77% of the time in HMP at the cul-de-sac while generating and trying alternate plans.

Figure A-60. Run 77.1-DR-Field.

Figure A-61. Run 89-DR-Field.

Figure A-62. Run 86-DR-Field.

Figure A-63. Run 84-DR-Field.

Figure A-64. Run 80-DR-Field.

### A.6.3 Field Cost Interface

In the three RIVET runs, the XUV proceeded along the planned route, saw that the path was blocked, circled several times while attempting to find a way through the original and alternate trails, and then eventually replanned back past the starting point and discovered a route through the trees south toward the tank trail and a clear path to the goal (figure A-65).

Figure A-65. Run 251-FCI-RIVET.

All five field runs (figures A-66–A-70) were successful in finding an alternate route similar to the runs in RIVET. These runs spent additional time and distance circling in the cul-de-sac, building up local terrain data before replanning back past the starting point and discovering a path through the trees south toward the tank trail and a clear path to the goal.

Figure A-66. Run 88-FCI-Field.

Figure A-67. Run 85-FCI-Field.

Figure A-68. Run 82-FCI-Field.

Figure A-69. Run 79.1-FCI-RIVET.

Figure A-70. Run 76-FCI-Field.

All five field runs resembled very closely the RIVET runs.

## A.7 Scenario 7

### A.7.1 Autonomous Mobility Only

All three RIVET runs were successfully completed as the XUV sensed the blockage and turned around 180° to return to the place in the trail where an alternative trail existed to the goal (figure A-71). The RIVET-modeled foliage around the blockage allowed this maneuvering (this was not expected).

Figure A-71. Run 248-AM-RIVET.

The field runs varied considerably. Run 8 (figure A-72) completely ignored the original path and skirted to the south of the cul-de-sac, directly to the goal. Run 4 (figure A-73) found the cul-de-sac but backed up three times and was then positioned in a location where it was able to find an open path along the trail to the west and went directly to the goal. Run 2 (figure A-74) was e-stopped at the blockage site, run 10 (figure A-75) was e-stopped when the XUV backed into a rock, and run 13 (figure A-76) was ended for max backups.

Figure A-72. Run 8-AM-Field.

Figure A-73. Run 4-AM-Field.

Figure A-74. Run 2-AM-Field.

Figure A-75. Run 10-AM-Field.

Figure A-76. Run 13-AM-Field.

### A.7.2 Dynamic Replanner

In the three RIVET runs, the XUV proceeded along the planned route and saw that the path was blocked. HMP directed a 180° turn, and the XUV followed a new plan back the trail and around the southern side of the trees to the goal (figure A-77).

Figure A-77. Run 212-DR-RIVET.

In the field runs, after the blockage was encountered, HMP backed the XUV the entire distance out of the cul-de-sac on four of the five runs.  Two of those runs ended in completions (figures A-78 and A-79).

Figure A-78.  Run 1-DR-Field.

Figure A-79.  Run 6-DR-Field.

The remaining three runs were able to escape the cul-de-sac but were unable to complete the run. A suspected navigation problem ended run 7 (figure A-80), and an HMP problem ended run 11 (figure A-81). Run 15 ended for max backups (figure A-82).

Figure A-80. Run 7-DR-Field.

Figure A-81. Run 11-DR-Field.

Figure A-82. Run 15-DR-Field.

### A.7.3 Field Cost Interface

In the three RIVET runs, the XUV proceeded along the planned route, saw that the path was blocked, circled for a 180° turn out of the cul-de-sac, and followed a new plan back the trail and around the southern side of the trees to the goal (figure A-83).

Figure A-83. Run 224-FCI-RIVET.

In the five field runs, the XUV encountered the blockage and backed up three times, but not far enough to enable the XUV to see the unobstructed path to the goal below the tree line. All five runs ended with max backups (figures A-84–A-88).

Figure A-84. Run 14-FCI-Field.

Figure A-85. Run 9-FCI-Field.

Figure A-86. Run 5-FCI-Field.

Figure A-87. Run 3-FCI-Field.

Figure A-88. Run 12-FCI-Field.

## A.8 Excursion Scenario 1.1

### A.8.1 Situation

Scenario 1.1 was the same as scenario 1 except that the NBC area was removed in order to see if the DR would plan to use the low-cost main tank trail to the west as an alternate route (figure A-89).

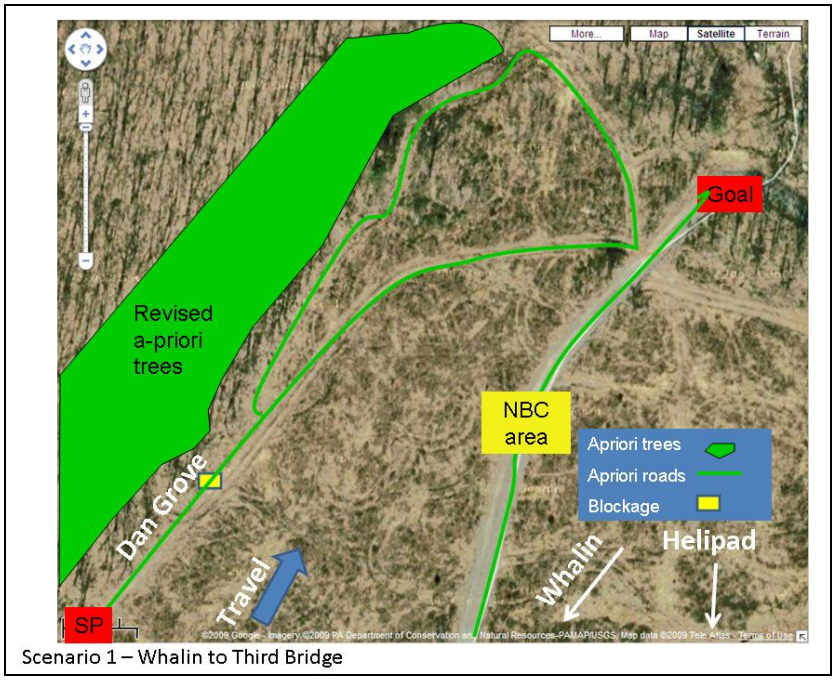


Figure A-89. Scenario 1.1 description.

### A.8.2 Dynamic Replanner

On neither run did the DR plan a path that utilized the main tank trail to the west. Run 116 (figure A-90 [right]) was typical of the DR runs 31.3 and 42, where the XUV saw the blockage, returned to the opening on the right, discovered the unmarked trail to the left, and proceeded slowly down the unmarked trail under HMP control. The DR generated plans that directed the XUV back to the original trail, beyond the blockage. However, the XUV was unable to find a clear path through the brush and trees, and eventually the DR gave a plan that followed the unmarked trail to the goal. On run 114 (figure A-90 [left]), the XUV was e-stopped when the HMP backed it into an unknown area of high brush near the blockage.

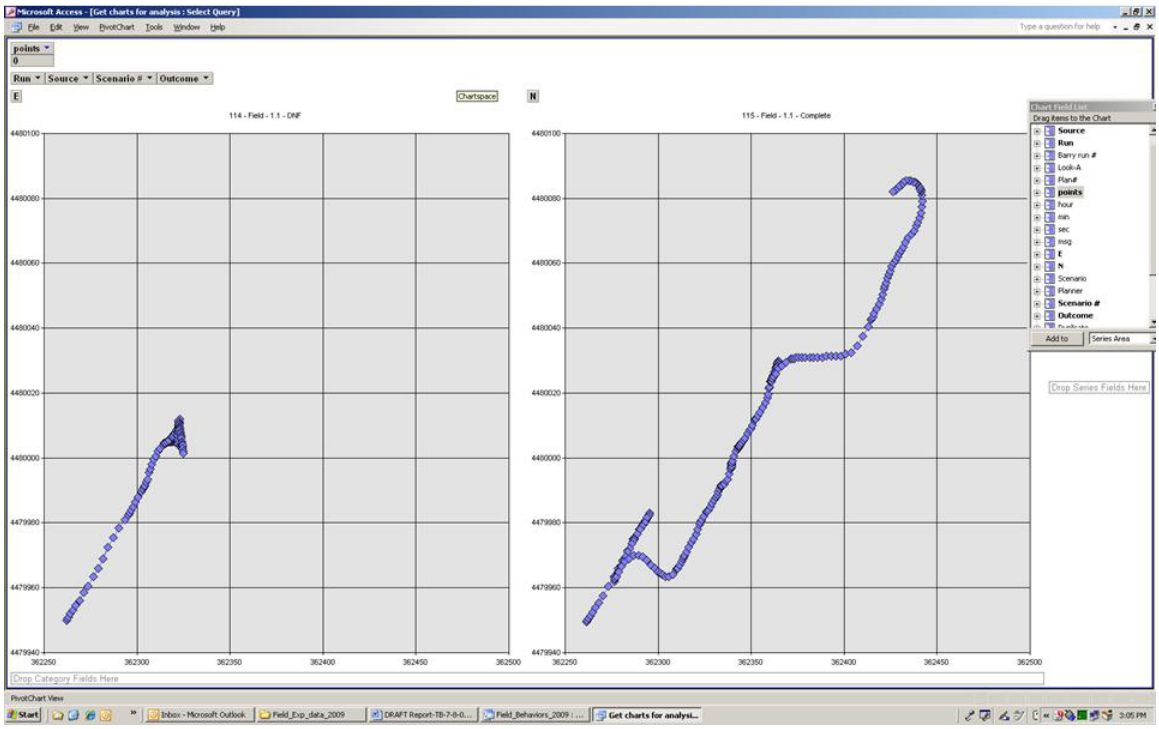


Figure A-90. Scenario 1.1 runs with no NBC blockage.

## A.9 Excursion Scenario 6.1

### A.9.1 Autonomous Mobility Only

In the two field runs, the XUV repeatedly circled in the cul-de-sac and never came close enough to the unblocked trail in the north to see the opening (figures A-91 and A-92). After circling three or more times, the run was e-stopped.

Figure A-91. Run 113.9-AM-Field.

Figure A-92. Run 108.9-AM-Field.

### A.9.2 Dynamic Replanner

In the two field runs, the XUV sensed the blockage in the original path and quickly generated and executed a new path through the alternate trail to the north (figures A-93 and A-94). These runs spent 37% and 92% of the time in HMP at the cul-de-sac while generating and trying alternate plans.

Figure A-93. Run 106.9-DR-Field.

Figure A-94. Run 111.9-DR-Field.

### A.9.3 Field Cost Interface

In the two field runs, the XUV sensed the blockage in the original path and quickly generated and executed a new path through the alternate trail to the north (figures A-95 and A-96). This occurred quickly and seamlessly on both runs.

Figure A-95. Run 112.9-FCI-Field.

Figure A-96. Run 107.9-FCI-Field.

## A.10 Excursion Scenario 6.2

### A.10.1 Field Cost Interface

As expected, on both runs, the XUV exited the cul-de-sac area after circling twice near the blockages (figures A-97 and A-98). One run was completed and the second run was e-stopped when the XUV ran into undetected and unmarked water after exiting the cul-de-sac.

Figure A-97. Run 110.9-FCI-Field.

Figure A-98. Run 109.9-FCI-Field.

# Appendix B. Experimenter's Observation of All Runs

This appendix appears in its original form, without editorial change.

| Source | Run | Run | Scenario # | Planner | Outcome | Reason | RC Comments | JP Comments | MC Comments | SH Comments | BB Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Field | 1 | 1 | 7 | DR | Complete | | | Great run. HMP plan on red in the beginning | | Start backup out of road – HMP | Backed out from barrels. Turned toward goal. HMP backed it out of cul-de sac. Complete | |
| Field | 2 | 2 | 7 | AM only | DNF | E_stop | | e-stopped before detecting barrels. went around and into bushes. E-stopped. | | Changed backup to 10,20,30m. Rerun. Backup 10, 20 (almost to road). Backup – starts to left. Estop – going where it can't go. End of mission called by Test Director (TD) | Turn up the hill. E-stop at barrels. Re-ared. Two backups, went forward and stopped. Backed all the way out to road. Turned toward goal. Looped left. Headed back to start point. Killed it. | |
| Field | 3 | 3 | 7 | FCI | DNF | Stuck-max backups | | max backups | | After turn, stop to look around – continued forward. Backkup, then goes forward. Backup into intersection, continues forward. Stuck – end of mission by TD | BU from barrels almost to road. Again should have seen alternative path. Stuck. End of mission. | |
| Field | 4 | 4 | 7 | AM only | Complete | | | admin e-stop twice for safety. Plan complete | | Backup, backup, take same road to right. Estop (admin) to make sure its clear, rearm. Backup into interaction. Turn left onto left path. Turn to right – Estop (admin), Rearm, resume. Complete | Estop. Rearm. 30 m BU to road. Positioned correctly. Cut across up to road. Complete. | |
| Field | 5 | 5 | 7 | FCI | DNF | Stuck-max backups | | max backups | | Backup, backup into intersection. Goes back up to the right. Stuck – Max Backups | Up to barrels. BU to road. Far enough, but went back up to barrels. Stuck max Backups. | |
| Field | 6 | 6 | 7 | DR | Complete | | | admin e-stop. Plan complete | | "R:26" on status bar on displays showing replanning using DR. "U: Need plan" on status bar shows requesting plan from HMP. Estop (Admin) to get "eyes on" XUV. Complete [Note: after run, Mike removes rock from middle of road] | 5 m from barrels stop. BU 3/4 way down and move forward. BU res of way down. Off to goal. Admin e-stop clear. Crossed up from road to path. Complete. | |
| Field | 7 | 7 | 7 | DR | DNF | Nav problem | | E-stopped. Saw path blocked ahead (wrong) and turned left (bushes) for alternative. Possibly issues with IRU calibration | | HMP – making K turn. Estop – because of terrain. Backup. End of mission – called because could not assess terrain in front of bot (called by TD). Turned to left off road because road looked completely blocked due to "position error" | To barrels. Then partway back down. Charge woods to left. Turned around. Out to road forward. Turned to goal. Overshot crossover. Turned left into trouble in high brush. (Suspect run after lunch, NAV) | In. IRU was a problem shortly afterward. Inconclusive here. |
| Field | 8 | 8 | 7 | AM only | Complete | | | Didn't turn right!!! no idea why. Possibly issues with IRU calibration | | Went straight ahead then stopped when within 20m of endpoint (did not make right turn)Complete [showed that the bot was within path tolerance of 30m so did not show "out of path" error] [could be that going fast and debating whether to go left or right; maybe going too fast to make right turn] | Overshot the road to cul-de sac completely. Straight to goal. | In. IRU was a problem shortly afterward. Inconclusive here. |
| Field | 9 | 9 | 7 | FCI | DNF | Stuck-max backups | | Engine stalled. Max backups | | Stalled coming up hill. Backup 10, 20, 30. Operator Max Backups – Stuck – End of mission [at intersection, RCI couldn't find a path to the left] | Max backups. | In. IRU was a problem shortly afterward. Inconclusive here. |
| Field | 10 | 10 | 7 | AM only | DNF | E_stop | Estop-backed into big rock | backup 3 times and was stuck | Saw barrels, backed up, went in toward barrels again, backed up, E-Stop (backing into rock), Stuck, E.O.M. | | | |
| Field | 11 | 11 | 7 | DR | DNF | E_stop | Estop-HMP stuck on obstacles | knocked over 3 barrels on hmp.11:38 End of mission hmp could not plan off of obstacle | Saw barrels, backup, backup, HMP dance, k-turn, accidental e-stop, XUV is clear of brush but hesitating, backup, came out of trail, turned right towards alternative path but overshot the turn, accidental e-stop, HMP planning for long time, HMP cannot find path (XUV is "sitting" on obstacles), E.O.M. | | | HMP Failure to get off obstacle. |
| Field | 12 | 12 | 7 | FCI | DNF | Stuck-max backups | Stuck-max backups | backed up 3 times and was stuck | Stalled going up hill, backup, backup, backup, Stuck (Max backups), E.O.M. | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Field | 13 | 13 | 7 | AM only | DNF | Stuck-max backups | Stuck-max backups | stuck max backup | Backup, Backup, Backup, accidental e-stop, max backups, E.O.M. | | | |
| Field | 14 | 14 | 7 | FCI | DNF | Stuck-max backups | Stuck-max backups | 3 backups stuck | Accidental e-stop, backup, backup, backup, backup, backup, Stuck, E.O.M. | | | |
| Field | 15 | 15 | 7 | DR | DNF | Stuck-max backups | Stuck-max backups, filled in road path | For some reason the map on idisp got blocked so the bot could not plan localy to the goal. stuck maxbackups | Saw barrels, HMP turned XUV around, backup, admin stop, came out of trail, overshot slightly on turn, HMP maneuvering to take alternative, accidental e-stop, backup, backup, backup, HMP maneuvered away from path towards our location, HMP backed up and oriented XUV to face alternative path, started to go, Stuck, E.O.M. | | | |
| Field | 16 | 16 | 5 | AM only | DNF | E_stop | | nicely drove into bushes. E-stopped | | Estop when went through middle pathway. Added more blockage and rerun | Closed on barrels. BU 10 m. Turned north. Charged brush. Estop. | |
| Field | 16.1 | 216 | 5 | AM only | DNF | E_stop | | placed HMWVV into bushes. run into bushes. E-stoped. killed log. Restarted log. Continuation of Run16a. 11:11 E-stopped. Unable to find way out. | | Estop (admin) to get truck out of the way. Estop – heading into bushes on left. Stop after 3-circle rule | Stopped at barrels. Move north. Circe. Stop. Three to four circles and we stopped it. | same as 16.2 |
| Field | 17 | 17 | 5 | FCI | DNF | | | 11:17 bot stuck after one backup. admin e-stop. seing things on the road. went exploring... e-stopped. Possibly issues with IRU calibration. engine not sounding right. E-stop. continue from here. didn't find alternative goal. Stopped | | Approached middle path, stalled, “Bot Stuck”, resumed. Estop for safety (too near HMMWV). Estop for safety (too near Robert). Resume. Estop- stalled – stuck on hill and ditch. Resume – circling around many times. Suspend – End of mission by TD | Multiple loops. Ultimately we stopped it. | |
| Field | 18 | 18 | 5 | DR | Complete | | 64 plans, looks like lost NAV, got past the short end point | 11:54 e-stopped before puddle. Teleop around. Continue. 11:59 AM sign on the road. E-stop to pull it out | | Poked around and then headed out. Teleop around puddle. [dark blue dotted line appears every time there is a new C2 plan] | Successful recognition of blockage. Routed around apriori data. Went to goal. | |
| Field | 19 | 19 | 5 | DR | Complete | | | goto haven't moved. 1:38 admin e-stop. 1:47 redraw puddle. 1:53 mission complete | | Estop (admin) for safety near HMMWV. Resume. Poked around and then went back out of finger. Estop for water hole | Charged into brush, got its bearing and looped around th apriori. | |
| Field | 20 | 20 | 5 | AM only | DNF | | | 2:10 pm accidental e-stop. 2:13PM unable to get out | | Accidental Estop. Poking around. End of mission – 3 circle rule (AM stuck in cul-de-sac) | Many circles and stopped it. | |
| Field | 21 | 21 | 5 | FCI | DNF | | | | | Not recovering well from Estop. Thinking the NBC location is expanding and screwing up planning | Circled many times but turned out of the football field. Then got to puddle (barrels added) and stopped. Brought it back an AM cut across. | NBC took a good run and made it bad. We need Marshal to weigh in on this. |
| Field | 21.1 | 221 | 5 | FCI | DNF | E_stop | | e-stopped for puddle. unable to resume | | | Circled around. Estop on puddle at the point. Finish run. | |
| Field | 22 | 22 | 5 | DR | Complete | | | removed puddle from SMI. Placed barrels in front of puddle. accidental e-stop. Complete | | Accidental Estop. Stalled going up hill. Complete [only way operator knows what mode is by the replan] | Quickly sized up barrels and blockage and headed out of finger. | |
| Field | 23 | 23 | 5 | FCI | Complete | | | stopped for puddle. going slowly (2.5m/s). Plan complete | | JP walked in front of XUV to create obstacle so it won’t go thru bigger puddle | Circled once or twice. JP walked in front to create obstacle at puddle to south and west of barrels. FCI found its way out to goal. | |
| Field | 25 | 25 | 5 | FCI | DNF | E_stop | estop-water | had to estop the bot because it was heading to a huge puddle | Drove over cones in center area, backup, drove into mud puddle, backup, circled round, drove into cones in center area, backup, drove out of cul-de-sac, turned around and came back (reportedly Prim data is scrolling off of map and causing this bungie cord effect), E.O.M. | | | |
| Field | 25.1 | 225 | 5 | FCI | DNF | Circled | circled | had to estop but because of puddle again. idisp capture failed-had to restart idisp | Backup, headed into mud over cone, E-stop, E.O.M. (moved barrels (3) to block puddle) | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Field | 25.2 | 226 | 5 | FCI | DNF | Circled | circled, exited 3x, came back | fci just oscillated back and for and would not leave culdesac | Drove over cones in center area, backup, drove into mud puddle, backup, circled round, drove into cones in center area, backup, drove out of cul-de-sac, turned around and came back (reportedly Prim data is scrolling off of map and causing this bungie cord effect), E.O.M. | | | |
| Field | 27 | 27 | 5 | DR | Complete | | good at culdesac, exitted | succussfully reached road ended mission due to lack of range time | Looked right and backed up, looked left, backup, looked in the center area, backup | | | |
| Field | 28 | 28 | 5 | FCI | Complete | | got to road, circled, EOM | obstHeight=0.5. successfully turned around. Once it got to road, headed in the wrong direction, turned around and saw chase vehicle. e-stopped | 0.5m obstacle height, XUV inspected blocked path, circled round a couple of times, chose alternative path out of sul-de-sac | | Three circles, one back up. Went out , turned to road. One more circle at the road. | |
| Field | 30 | 30 | 5 | DR | Complete | | | hmp on obststacle. paused as it entered the road back. mission complete | XUV detected obstacles, assumed full blockage, replanned, maneuvered on alternative path out of cul-de-sac | | Forward and back several times probing varrels. Plan to left. Finally HMP and DR showed a way out. | |
| Field | 31 | 234 | 1 | DR | DNF | | | could not find its way. | Took right turn immediately, admin stop, backup 5m, 10m, 15m, E.O.M. declared - recommended to reduce barrel height (obstacle height = 1.5m) | | | |
| Field | 31.1 | 233 | 1 | DR | DNF | | HMP backed into brush | reduced barrel height and started closer to the start point. bot backing up into unknown in hmp. 10:35 stopped | XUV went further down path, saw barrels, then invoked HMP, drove backwrds through brush along new path, E-stop, E.O.M. | | Went into woods to right. HMP moving it in that direction. | |
| Field | 31.2 | 231 | 1 | DR | DNF | | new barrel locations+10m: saw alt rt as blocked | starting farther back and barrles moved. failed to find way out | Saw obstacles, stopped adjacent to opening, hesitated because HMP could not find valid path, backup 5m, turned right at opening, took left at next opening, backed up, turned right and drove into brush (searching for path), E.O.M. | | | comments |
| Field | 31.3 | 232 | 1 | DR | Complete | | new barrel locations+10m | obst height 1.5. complete: but goal moved before ending and had to pause | E-stop, backup, HMP backed XUV down alternative, backed over tall brush and small trees, turned around, went forward over small tree, round road, maneuvered to goal | | Backed into second path. Eventually turned down alternatie path and completed. | look at JP |
| Field | 32 | 32 | 1 | FCI | Complete | | 3 Bus for 60m, found alt rt, direct to goal | obst height=1.5, coverheight=3.0. plan complete | Obstacle height = 0.5m, saw barrels, veered right, backup 10m, backup 20m, backup 30m, cut corner to alternative path, E-stop, maneuvered to goal | | 10 m BU, 20 m BU, 30 m BU. Admin e-stop. Found path to right. (Effectively a 40-50 m backup.) Did nt do NBC. 60 m BU total. | |
| Field | 33 | 33 | 1 | AM only | DNF | Stuck-max backups | ran thru barrels 3x, 3BUs, stuck on log | changing obst height to 1.4. stuck backing up | Obstacle height = 1.4m, saw blockage, backup, dove left, backup, drove forward, backup into trees, Stuck (physically), E.O.M. | | BU got physically stuck. Height 1.4 m. | |
| Field | 34 | 34 | 1 | FCI | DNF | Stuck-max backups | backed up ~40m, max backups | 10:34 stuck max backups | Saw barrels, backup, dove left, backup 20m, backup 30m, backed into trees, Stuck (Max backups), E.O.M. | | Stuck max BU. Only came back 40 m total. | |
| Field | 35 | 35 | 1 | DR | Complete | | | seoCoverHeight=3.0. 1:35 complete | Saw barrels, backed up, HMP maneuvered XUV to path on right, XUV followed path and took left down alternative, XUV is hunting and pecking to back to original path (reportedly the global planner did not consider the barrels to be a full blockage), XUV went through brush and went behind barrels to join the road, admin stop, maneuvered to goal [Planning to get to road beyond the barrels.] | | Complete. | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Field | 38 | 38 | 1 | DR | DNF | Stuck-max backups | found alt rt, HMP backed into brush | 1:50 bot stuck. AM didn's see a path forward | Saw barrels, stopped, backed up, turned right on alternative, turned left to go down path (looking to get back on original path), XUV backed up (but was to right off path)backed into small trees, E-stop, Resume, Stuck, E.O.M. | | Backed into small trees. HMP failure. Incomplete. | HMP Failure |
| Field | 39 | 39 | 1 | FCI | DNF | Stuck-max backups | | stuck max backups | Saw barrels, stopped, trying to go around to left, E-Stop, Resume, backup, backup 20m, backup 30m, Stuck (Max backups), E.O.M. | | Incomplete | |
| Field | 42 | 42 | 1 | DR | Complete | | tried to return to left rd, continued to right to goal | 11:01 plan complete | Saw barrels, stopped, HMP backup and k-turn, came back along original path, turned left on alternative path, left again, cut left into brush, backup, backup, Admin stop (to move truck), Resume, backup, backup, took left shorcut again, backup (near trail), backup,k took path o right to road, | | Complete | Ilustration Run |
| Field | 43 | 43 | 1 | DR | DNF | E_stop | HMP backed into brush on k-turn at barrels | hmp vehicle on red. ACC2 planning through obstacles...?? backup path not safe | Saw barrels, backup, HMP backed into unknown terrain, E-stop, Resume, backing into unknown terrain again, E.O.M. | | Incomplete | HMP Problem but DR did not make a strong case. |
| Field | 46 | 46 | 2 | FCI | DNF | broke steering | lost steering | hit rock and broke steering | XUV bounced down path, saw blockage, backed up in a zig zag fashion, backed into brush, backed in a circle, E-Stop, E.O.M. | | | Scenario 2 not what was intended. |
| Field | 46.1 | 146 | 2 | FCI | DNF | | | obst height=1.4. coverheight=3. speed 3.5 m/s. bot backed up from the begginning | XUV immediately backed up, XUV hit barrels | | | |
| Field | 46.2 | 147 | 2 | FCI | DNF | Stuck-max backups | | AM stuck becau se of e-stop. Stuck | XUV saw the blockage (but bumped barrels), backup 10m, backup 20m, XUV found alternative path, E-Stop (went right into brush), Resume, backup 10m, Admin stop (to allow truck to clear), Resume, Stuck (Operator Stuck), E.O.M. | | | |
| Field | 47 | 47 | 2 | AM only | Complete | | | knocked down two barrels. plan complete | XUV saw blockage but bumped barrels as it stopped, backup, took right path, backup, E-stop (rock), achieved goal | | | |
| Field | 48 | 48 | 2 | DR | Complete | | | not running hmp. starting it mid-run | XUV saw barrels and bumped the first as it stopped, backup 10m, backup 20m, took right alternative path, found goal | | | |
| Field | 49 | 49 | 2 | DR | Complete | | | 11:24 plan complete | XUV ran into 2 barrels, E-stop, Resume, Backup, HMP looking for path, trying to go left, nosing into trees, backup, pushing trees, backup, took right path, got near goal and tried to cut corner, HMP backup and dancing, found goal, E.O.M. | | | |
| Field | 50 | 50 | 2 | FCI | Complete | | | hit barrels again. fw000.sav. plan complete! | XUV charged barrels, E-stop, Resume, backup 10m, backup 20m, turn right on alternative, turned left into brush, backup, backup 20m, continues along alternative path, went across main raod toward helipad, backup 10m, backup 20m, backup 30m, maneuvered to goal | | | |
| Field | 51 | 51 | 2 | AM only | Complete | | | hit barrels again. e-stop. plan complete (too early?) | XUV bumped barrels, backup 10m, backup 20m, took alternative path to right, backup 30m, admin stop, Resume, admin stop, Resume, cutting left, backup 10m, cut right to road, then to goal | | | |
| Field | 52 | 52 | 2 | AM only | Complete | | | plan complete (after adjusting steeting … see run53e) | AM saw barrels and turned to right w/out entering cul-de-sac, backup 10m, maneuvered to goal | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Field | 53 | 53 | 2 | DR | Complete | | | plan complete | Immediately took right turn backup, Admin stop, proceeded to goal | | | |
| Field | 53.9 | 153 | 2 | DR | Complete | | | after adjusting steering, laser pan. obst height 1.3. seoAngleOffsetPan=-0.0667. plan complete. HMP not working well | XUV saw barrels and stopped short, backup 5m, backup 2m, backup 2m, backup 3m, backup 5m, took alternative path to the right, E-stop (Rock), Resume, reached goal | | | |
| Field | 54 | 54 | 2 | FCI | Complete | | | plan complete | Saw barrels and immediately headed right, stopped, resumed, found goal | | | |
| Field | 55 | 155 | 2 | FCI | DNF | | | placing HMWWV in path to right. found gap. | Saw barrels and stopped in cul-de-sac, backup 10m, backup 20m, E-stop (backed too close to HMMMWV), backup 30m, drove into cul-de-sac and stopped short, backup 10m, E-stop (tried to cut in front of HMMWV, E.O.M. Place HMMWV to block right alterntive path. Stopped in cul-de-sac, backup, backup, headed toward left path, backed up into trees, E-stop, Resume, backup into trees, E-stop, Max backups, Resume, forward toward cul-de-sac, backup into trees, E-stop, E.O.M. | | | |
| Field | 56 | 56 | 2 | DR | DNF | | | backed up into unknown | E-stop (headed for HMMWV), Resume, entered cul-de-sac, backup, HMP dancing, backing up into unknown, Admin stop, Resume, backing into trees again, E.O.M. | | | |
| Field | 57 | 57 | 2 | AM only | DNF | | | too close to HMMWV | E-stop (headed for HMMWV), Resume, entered cul-de-sac, E-stop (charging barrels), backup towards HMMWV (E-stop), Resume, backing close to HMMWV, E-stop, E.O.M. | | | |
| Field | 61 | 61 | 3 | FCI | Complete | | 3 BUs and around to right | obst height 1.5. cover height 3.0. original prior data. complete!!! | XUV went up hill, saw barrels, backup, backup 20m, E-stop (headed for truck), found alternative path, drove to goal | | FCI on 3rd Back up 30 m. Found path to right. | |
| Field | 62 | 62 | 3 | DR | DNF | | did not see 1 barrel, went into weeds, HMP problem | hmp backed into bush. bot not moving. canceled mission | XUV drove up hill and saw an opening in left most barrel, backup, HMP tried to execute k-turn, XUV trying to go around barrels, HMP backed XUV into brush, E.O.M | | Right up to barrel. Move to left. Stopped. Repeat. HMP backed way up into woods to north. HMP in weird mode. | HMP Failure but DR not demonstrated yet. |
| Field | 63 | 63 | 3 | AM only | DNF | Stuck-max backups | 3 BUs, stuck | 2:55pm stuck | Stopped at barrels, backup 10m backup 20m, backup 30m, looked right and went up hill again, Max backups, E.O.M. | | AM to barrels. Backups 10, 20, 30. Could have seen alternative route but did not. | |
| Field | 64 | 64 | 3 | AM only | DNF | Stuck-max backups | 3 BUs, stuck | stuck b/c engine stalled. re-executing. 3:02 pm stuck | Backup 10m, stuck, backup 10m, backup 20m, backup 30m, Stuck (Max backups), E.O.M. | | All the way to barrels. 10 m BU (actually 8), another 10 m, then 20, then 30. Stuck max BU. | |
| Field | 65 | 65 | 3 | DR | DNF | E_stop | tried apriori rd to left, crossed trail, couldn't find alt rt | 3:20pm hmp not moving. restart hmp. 3:24 vehicle started exploring too far from path. e-stopped. | Engine stalled, detected partial blockage, backup, HMP backed down hill, turned left and took false a priori road, admin E-stop, XUV sees partial blockage in road, turned round, drive over to alternative path (on right), backup, Stuck in HMP mode, killed HMP, Resume | | Stopped right at barrels. Backing straight slowly down the hill. Oscillate back and forth for a while. Look for false apriori road. False apriori blocked. Overshot trail to north. Backed up toward trail. Up path. Explore to right. Brush too thick. | Film worthy. |
| Field | 66 | 66 | 3 | FCI | DNF | Stuck-max backups | 3 BUs, stuck | 3:35pm stuck (max backups) | Saw barrels, stopped just shy, backup, accidental e-stop, backup 20m, backup 10m, backup 20m, backup 30m, Stuck (Max backups), E.O.M. | | All the way to barrels. Backups of 10, 20 m. New set of Bus to 10, 20, 30 m. Max backups. | |
| Field | 68 | 68 | 3 | DR | DNF | E_stop | backed into weeds on left, HMP problem, backed into tree | stuck into tree | Saw barrels, backup, HMP k-turn/backup (filling in blockage), backup (filling in more of blockage), HMP is stuck (won't move), backing into trees, E-stop, E.O.M. | | All the way up to barrels. Slow back up progression down hill. Forward and back, filling map. HMP Back up in funny mode. End mission. | HMP Failure |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Field | 69 | 69 | 3 | FCI | Complete | Stuck-max backups | 3 BUs and around to right | stuck max backups. almost cleared. resumed. plan complete!!! | Saw barrels, backup 10m, backup 20m, backup 30m, turned right on alternative path, Stuck (Max backups), Resume, found alternative and drove to goal | | Back up few times. Turn to right . Stuck max BU. Resume and found hill. Overruled max back up in this case. | |
| Field | 72 | 72 | 3 | DR | DNF | E_stop | ran thru barrel | hit barrels and kept moving | XUV climbed hill, hesitated (but didn't stall), continued through barrels, E-stop, E.O.M. | | Right up to barrels. Went through them. End of mission. Thought LADAR was looking over top of barrels. | |
| Field | 76 | 76 | 6 | FCI | Complete | | | | | Estop – cause? Complete mission [***Note that run number was incorrect wrt the original run sheet, but went with the run #s listed here] | Found its way out. | |
| Field | 77 | 77 | 6 | DR | DNF | E_stop | | Plgr fill changed. found opening through the bushes | | Estop – into path – rearm to see if it would back up, it didn't. End of run by TD. | Bot found a hole to right of upper trail. Redo. | |
| Field | 77.1 | 277 | 6 | DR | Complete | | | safety e-stop. Not enough blockage. hmp didn't move for a while . e-stopped - going through ditch | | Complete. Estop – tried to go thru path at right. Estop – stuck Several other Estops. End of mission by TD – seen the most interesting part of the run | Finally got out of cul-de sac. Got stuck in woods. Got out. Then out of cul-de-sac. Ran into water almost. Called end of mission. | |
| Field | 78 | 78 | 6 | AM only | DNF | | | stopped. going in circles | | 3-circle rule. End of mission called by TD | Many loops. Finally killed it. | |
| Field | 79 | 79 | 6 | FCI | DNF | E_stop | | e-stopped because of large puddle | | Ran circles. Headed out of finger, but then turned around again for a big circle. End of mission called by TD | Run to water. | |
| Field | 79.1 | 279 | 6 | FCI | Complete | | | seoMinObstHeightFast/Slow=0.5. got out of cul-de-sac... maybe faster??. 11:02 stopped because of puddle. drove nicely through narrow path | | Reduce obstacle height to 0.5m. (on previous runs, height has been 0.75) | | |
| Field | 80 | 80 | 6 | DR | Complete | | | obstHeight back to 0.75. 11:33 back-forth w/o moving. 11:42 plan complete | | Obstacle height at 0.75m. Complete | Complete | |
| Field | 82 | 82 | 6 | FCI | Complete | | | obstHeight 0.5. 12:02 plan complete | | Inconclusive. Obstacle height 0.5m. 3 times around | Complete | |
| Field | 84 | 84 | 6 | DR | Complete | | | 2:01 global path not blocked. 2:19 goto no plan message but everything fine. 2:20 plan complete | E-stop to prevent from heading over bank, E-stop (went over barrels) - walked in front of XUV to create obstacle, hit a branch-barrel combo, stopped, replanned out of culd-de-sac | | More lost than usual. Had to walk in front at end barrels to fill map. Got out of field to the side. Cutting through to the road. | |
| Field | 85 | 85 | 6 | FCI | Complete | | | reduced prior data. obst height 0.5. 10:12 AM e-stopped before puddle. Otherwise good run | 0.5m obstacle height, XUV made several turns, went away from blockage, charged safety truck, made some more passes, assumed full blockage, took alternative path out of cul-de-sac | | Four circles, one "S", two ellipses. Made it out to cut-off down toward road. Complete to pond out by road. | |
| Field | 86 | 86 | 6 | DR | Complete | | | obstHeight=0.75. hmp back and forth w/o moving. turned onto obstacle grade... need to check!!! | XUV looked at obstacles, made one pass, then turned around and maneuvered out of cul-de-sac | | Charge barrels to the north side. BU a few times and down toward cutoff path. Tur right to a drop off close to road. | |
| Field | 88 | 88 | 6 | FCI | Complete | | | complete until before puddle. unable to find idisp capture. | 0.5m obstacle height, XUV took one pass by blockage, turned and took high path around safety truck, took first rght turn (shortcut) | | Two circles, took high road. Went behind truck. | |
| Field | 89 | 89 | 6 | DR | Complete | | | obst height 0.75. e-stopped before cutting corner into density grade | XUV looked at blockage, probed a little, HMP turned XUV around, maneuvered out of cul-de-sac via shortcut | | Went to barrels. Backup for new plan. Back up to north. Turn left and gone. | |
| Field | 107 | 106 | 6.1 | DR | Complete | | found unblocked upper road | North road open. stopped (chase could not follow) bot found north road | Drove directly to and up the upper trail | | Upper road open. Commited vary quickly. Good. | |
| Field | 108 | 107 | 6.1 | FCI | Complete | | found unblocked upper road | North road open. set obst height 0.5. stopped(chase could not follow) bot found north road 2:53 | Drove directly to and up the upper trail | | Complete up the path. | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Field | 109 | 108 | 6.1 | AM only | DNF | Circled | circled, did not find unblocked upper road | North road open. bot circled but did not found road. stop 15:08 | Drove directly to barrels and bumped one, stopped, drove in circles repeatedly, E.O.M. declared | | AM did not see the upper path. | |
| Field | 110 | 109 | 6.2 | FCI | Complete | | out of culdesac but stuck later | egofccellscale=0.1. The bot went all the way around instead of NS trail. 3:33 stopped bot going to pond. bot saw edge of road as obstacle | Drove to cul-de-sac, looked at abarrles, circled and looked at HMMWVs, took path out of finger, chose long route (because of cost of hard right turn?) | | Got out of the finger after ony one circle or so. Missed turn. Too tight. Around the point it is trying to get back in. Ended run. 0.1 instead of 0.2 weight. Upper road blocked. | |
| Field | 111 | 110 | 6.2 | FCI | DNF | E_stop | out of culdesac but stuck later | egofcCellScale=0.1. bot tried to take the closest NS trail but turned around and started heading to a puddle.15:52-stopped due to puddle | Circled in front of obstacles a few times, looked over bank, stopped, bacup 10m, took path out of cul-de-sac, took first right turn (short cut), turned around, came back out of short cut, E-stop (headed for ditch) | | Circled around and was headed out. Took first path to right and got into water trouble. Weight was 0.1 not 0.2. Upper road blocked. | |
| Field | 112 | 111 | 6.1 | DR | Complete | | found unblocked upper road | removing blockage from upper trail. almost hit tree. Stopped after committing to the upper trail | Entered cul-de-sac, saw blockage, saw opening in upper trail and took it | | Came down, detected blockage. Path to upper finger accepted. Shot up to it. Good film! | |
| Field | 113 | 112 | 6.1 | FCI | Complete | | found unblocked upper road | obst height 0.5. good run. | Entered cul-de-sac, paused 65m from blockage, was opening in upper trail and took it | | FCI came to middle of finger. Quickly recognized blockage and hole to upper trail. Traveled to upper trail. | |
| Field | 114 | 113 | 6.1 | AM only | DNF | Circled | circled, did not find unblocked upper road | obst height 0.75. circling around | XUV probed the blockage, circled, repeated this behavior three times, E.O.M. | | Max circle rule incomplete. | |
| Field | 115 | 114 | 1.1 | DR | DNF | E_stop | No NBC, backed into weeds on rt, HMP problem | removing NBC 11:43 stuck backing up | Barrel fell over, E-Stop, reposition barrel, Resume, dove right, trying turn around, backed into opening, Estop, Resume, backup, HMP backing into unknown terrain, E.O.M. | | HMP failure. No NBC | |
| Field | 116 | 115 | 1.1 | DR | Complete | | No NBC, found trail to right, not main road | repeat from 114. hmp not moving restarting. plan complete | Stopped, backup (early), backup, took alternative path to right, took first left, dove left into brush, HMP stuck mode, killed HMP, backup, turned right, maneuvered down alternative path, found goal | | Complete | |

## List of Symbols, Abbreviations, and Acronyms

| | |
|---|---|
| AM | Autonomous Mobility |
| ARL | U.S. Army Research Laboratory |
| C2 | Command and Control |
| DR | Dynamic Replanner |
| e-stop | emergency stop |
| FCI | Field Cost Interface |
| FTIG | Fort Indiantown Gap |
| HMP | High-Maneuverability Planner |
| NBC | Nuclear, Biological, Chemical |
| RCTA | Robotics Collaborative Technology Alliance |
| RIVET | robotic interactive visualization and exploitation technology |
| TRL | technology readiness level |
| TVMA-B | Tactical Vehicle Maneuver Area-Bravo |
| UGV | unmanned ground vehicle |
| XUV | experimental unmanned vehicle |

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