Assessing the Impact of Bi-directional Information Flow in UGV Operation: A Pilot Study

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***Abstract*—**In June 2007, the Robotics Program Office of the U.S. Army Research Laboratory and General Dynamics Robotics Systems (GDRS) engaged in an exploratory assessment of how bi-directional information flow impacts Unmanned Ground Vehicle (UGV) operation. The purposes of the pilot study were to frame scenarios, protocol, infrastructure, and metrics for a more formal experiment planned for the fall of 2007 while providing current data feedback for the architecture developers. The study was conducted at Fort Indiantown Gap, PA over two distinct areas of rolling vegetated terrain using the eXperimental Unmanned Vehicle (XUV). In this paper, we will share the preliminary findings of the impact of bi-directional information flow on observed robotic behavior, discuss the associated impact on the operator, and relate lessons learned to the planning of our fall 2007 experiment.

Keywords: *bi-directional information flow, perceptive planning, deliberative planning, pilot study, unmanned ground vehicles*

I. INTRODUCTION

A brief background helps motivate the current study. In FY 2003, the RPO and GDRS conducted, with testing oversight by the National Institute of Standards and Technology, an extensive three-site experiment of an autonomous navigation system (ANS) [1]. The ANS relied on perceptive level planning to achieve a manually pre-determined route of way points in rolling desert, rolling vegetated and urban terrain. The ANS was given a Technology Readiness Level 6 designation by Future Combat Systems in part due to this study. Interim advances in the Soldier Machine Interface (SMI) greatly simplified manual route planning, while perception algorithms and hardware continued to mature. More recent developments in the architecture allow for deliberative planning in a move toward tactically intelligent behaviors.

Higher level deliberative planning draws on the objective of the operation and the global map of *a priori* information (elevation and feature data). Deliberative planning consists of separate layers to independently assess costs for traversing terrain; the current configuration considers costs associated with mobility, time, coverage, exposure, and threat. Those layers are combined using a weighted heuristic into a single planning layer for use by the route planning algorithm. Different weight combinations map into various tactical concepts, which allows the SMI to provide explicit choices to the user such as “prefer roads” or “stealth”; weights can be individually set during experimentation. Deliberative and perceptive level planning are integrated through the field cost interface (FCI) and best information planning (BIP). Local perception provides costs at ~5 Hz rate for local paths finishing along the arc formed by the sensor range. FCI is a feature that provides a bridge between deliberative layer planning and local planning by assigning costs at ~1 Hz rate along the perimeter of the sensor range representing the entry points for continued routes to the objective way point. BIP uses the sensed data flowing up from the perceptive level to update the deliberative planning map. BIP uses the sensed data flowing up from the perceptive level to update the deliberative planning map. Using this updated information may be especially useful with imperfect *a priori* knowledge of the terrain. It is this bi-directional flow of information that is the focus of the study.

II. DATA COLLECTION

The data collection involves a series of informal comparative tests in which a simple route, with a few widely separated way points, is traversed by the robot. The first condition isolates performance of the perceptive layer planning as a baseline. The second condition makes the global map available for revising the route between pre-determined way points in consideration of mobility. Under this condition, BIP is available to assist perceptive level decisions. A third condition again uses the global map for revising the route between way points but in addition exercises the FCI, taking into consideration the current robot location on the map while the run is in progress. A fourth condition allows the global map information in establishing the initial route and enables the mobility deliberative planning layer through the FCI with BIP assisting perceptive level decisions. Subsequent conditions exercise other deliberative planning layers and vary weights in the aforementioned heuristic.

These planning configurations were exercised over two distinct course areas in situations intended to highlight the value added by the deliberative planning layer. Routes were selected in both locations to provide a stiff challenge for perceptive level planning that may benefit from bi-directional information flow. For example, a vegetation-formed cul-de-sac provides such a challenge. Once in the cul-de-sac, the perceptive level is unlikely to be able to determine an exit path. However, when the BIP feature augments the global map, an exit path may appear. Some runs focused on impacting the route based on these layers.

The first phase of data collection was performed at Area B12 at Fort Indiantown Gap, PA and the second phase at Area A1. Area B12 (Figure 1) is consistent with rolling vegetated terrain and is mostly cross country over open fields with high vegetation, but also contains woods, thick brush, large rocks, gravel road, unimproved trails, and mild changes in elevation. The areas wherein a priori terrain feature data was made available for route planning are highlighted by light green shading; for areas not shaded the only a priori data used for planning was elevation data. An initial pre-planned route consisting of three way points incorporated a cul-de-sac located in the vicinity of the second way point. The XUV traversed the route using an onboard Laser Detection and Ranging (LADAR) sensor and corresponding algorithms to detect and avoid encountered obstacles that were unknown a priori. A trail, high brush and trees were encountered along the way to an elevated position. In figure 1, the route begins on the left in a clearing and continues toward an area of trees and brush not present on the global map. After achieving the second way point, the robot turned toward the final way point marked to the far right. The exact path the robot traveled appears in red.

Area A1 is characterized by relatively flat terrain, with open ground being more grassland; trees and brush occur in patches and dense woods and marshy areas are present. In Figure 2, the planned route in yellow begins on a trail in the lower left portion of the figure and proceeds through woods, which are present in the area but were intentionally removed from the global map to encourage interaction with the feature. After achieving the second way point beyond the woods, this path exhibits the planner response to a defined exposure point located further to the right beyond the figure view. The exposure deliberative layer attempts to minimize the line of sight to a position. The path allows the robot to achieve the second way point, but then directs the robot to the tree line, the best option in consideration of exposure, as it proceeds to the third way point. The route sends the robot toward an opening in the tree line, followed by a small meadow, and finally leads it through some tree clusters where the third way point is located on the way to the fourth and final way point. Notice the robot icon and red track on this run has not achieved the final way point in the upper right. This path to a marsh resulted in an emergency stop (e-stop) which was initiated by the safety operator in order to prevent the vehicle from entering the marsh.

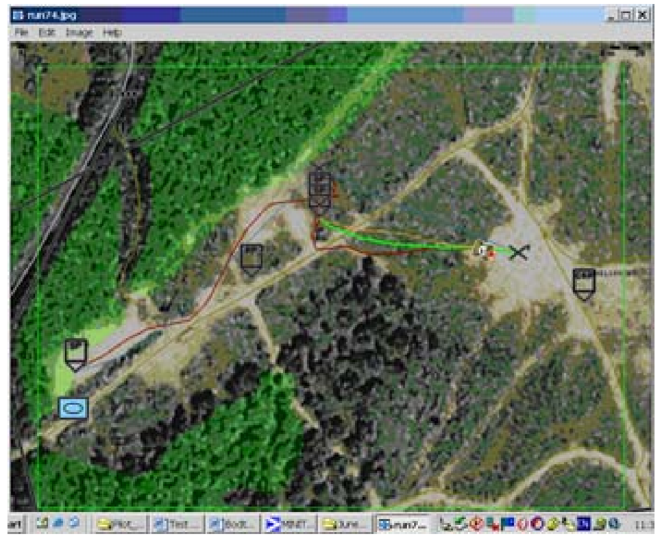

Fig. 1. Area B12

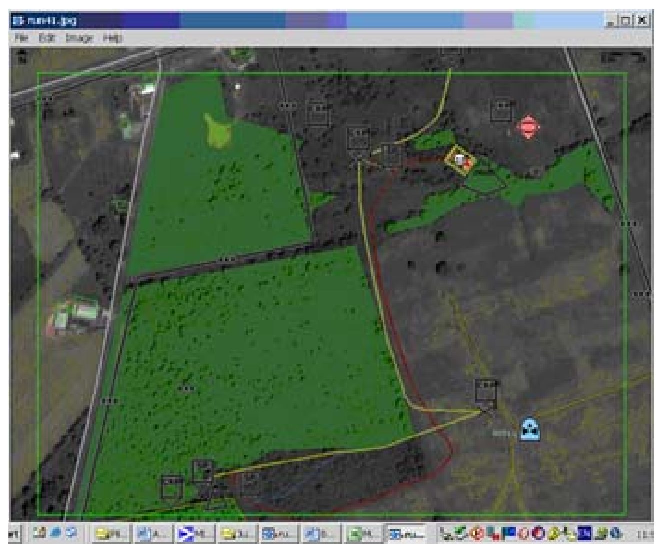

Fig. 2. Area A1

Data collection protocol evolved over the two-week study as performance of technology was observed and as new situations occurred. Initially, rules were established for end of mission, administrative stops, and e-stops, similar to past experimentation. To accommodate BIP, the protocol was refined during the first week at Area B12 to specify when to allow the global map to be updated through BIP. This feature was not automated for the study. Rather, an action on part of the operator to execute a re-plan was required. This re-plan was permitted, when the XUV called for help, usually after three back-ups from the XUV failed to provide a clear path (successive back-ups are part of the ANS and are used to provide better perspective when the robot otherwise does not see a clear path ahead). Re-planning was executed after instructing the XUV to backtrack to the location it occupied after the final, 15m back-up and before the XUV called for help. Another modification was made to this procedure when testing moved to Area A1. There it was determined that when the re-plan was to be executed, the robot should first be repositioned, heading along the re-planned path. Other protocol adjustments responded to a recurrent "off-course" message and allowed aborted runs if the operator was unable to use the cameras for teleoperation.

III. DATA INTERPRETATION

A. Measurement

Measures of performance are elusive. Previous experiments focused on progressing along a pre-determined route safely, as fast as possible, and with minimum operator interventions. Consequently, success or failure, speed, operator intervention frequency and duration were natural metrics for performance. Tactical intelligence, however, provides a far greater challenge due to the qualitative flavor of "how well" the robot has progressed over the route. "How well" must be assessed in consideration of standard tactical considerations that are not crisply defined for this technology and may require trade-off decision making. Measurement of operator workload perspective comes from surveys administered after each run and live observations made during each run, augmented by video record. The operator must oversee the progress of the robot during execution of the selected route (intervening as necessary) and will likely strive for an understanding of the indirectly observed planning decisions made along the way; this presents new cognitive challenges. Quantitative measures for robot behavior would normally include the number and duration of operator interventions, the frequency for required re-planning using BIP, time to complete the route, and exposure time (when the exposure layer is activated); time aspects are not addressed here. In addition, we use observations made by data collectors and plot the differences between pre-planned routes and the alternative routes developed during each run.

B. Descriptive Measures

Simple descriptive statistics appear in the following tables. We recognize they are at best rough and indirect measures of performance but are worth reporting for completeness. Table 1 reports the outcome of each run performed in Area B12. The baseline autonomous mobility (AM) perception runs both resulted in e-stops. BIP alone resulted in the normal end of mission "halt" message to the operator. FCI alone resulted in one normal halt and one end of mission in which the robot traveled far away from the intended final way point. With both BIP and FCI, three runs resulted in two halts and another end of mission where the robot was off course.

TABLE 1

RUN OUTCOME FREQUENCY BY EXPERIMENTAL CONDITION (AREA B12)

	Outcome			
Condition	Halt	Off Course	E-Stop	All
AM	0	0	2	2
BIP	2	0	0	2
FCI	1	1	0	2
BIP+FCI	2	1	0	3
All	5	2	2	9

Table 2 reports the outcomes for conditions run in Area A1, focusing on the mobility benefits of BIP and the FCI. Three runs were aborted due to teleoperation camera failure. The FCI weights were varied, with the larger values yielding more control to the perceptive layer (i.e. FCI=2 means that the weighting of the perceptive layer costs was twice that of the deliberative layer). Results are mixed; FCI alone results in five halts in six attempts, whereas the combined BIP and FCI result in only one halt in seven attempts, one abort and five e-stops. Most e-stops occurred when the XUV tried to cross the marsh, but some were called due to excessive wander of the robot.

TABLE 2

RUN OUTCOME FREQUENCY BY EXPERIMENTAL CONDITION (AREA A1)

	Outcome			
Condition	Halt	Abort	E-Stop	All
AM	2	1	2	5
BIP	0	1	1	2
FCI=1	2	0	0	2
FCI=2	1	0	1	2
FCI=4	2	0	0	2
BIP+FCI=1	0	1	2	3
BIP+FCI=2	1	0	1	2
BIP+FCI=4	0	0	2	2
All	8	3	9	20

Table 3 shows the remaining conditions that were run and corresponding results. Toward the end of the second week, these runs were attempted to explore the impact of additional layers being considered in the deliberative planning. Mobility and FCI weights were also adjusted based on observation from earlier in the week. The weights for the Mobility, Time, and Exposure layers had a possible value of 0 to 1. Five of eight runs resulted in a normal halt. Two runs resulted in an e-stop and one in an abort.

TABLE 3

RUN OUTCOME FREQUENCY AND DELIBERATIVE LAYER WEIGHTS (AREA A1)

	Outcome			
Condition	Abort	E-Stop	Halt	All
BIP+Mob=0.5	1	0	0	1
BIP+Mob=0.5+Exp=1	0	0	1	1
BIP+Mob=0.5+FCI=2	0	1	0	1
BIP+Mob=0.5+Exp=1+ FCI=2	0	0	1	1
BIP+Time=1	0	0	1	1
BIP+Time=1+FCI=4	0	0	1	1
Mob=0.5+FCI=2	0	0	1	1
Mob=0.5+FCI=1+ Exp=1	0	1	0	1
All	1	2	5	8

Table 4 lists the various measures collected during the runs at Area B12. The FCI condition results in fewer back-ups, because the effect of the FCI routed the XUV, unintentionally, away from the cul-de-sac. Teleoperation repositioning was an important measure at Area A1, because it was used after a re-plan that was based on BIP. Repositioning was performed to orient the robot along the re-planned path. A similar summary for Area A1 was produced but is not presented.

TABLE 4

EVENT FREQUENCIES (AREA B12)

	Conditions			
	AM	BIP	FCI	BIP+FCI
Runs	2	2	2	3
Teleop_Obstacle	1	0	1	0
Teleop_Reposition	0	0	0	0
Back-up 5m	9	7	3	6
Back-up 10m	3	4	2	1
Back-up 15m	0	2	2	1
Back-up Total	12	13	7	8
Oper_Max BUs	0	2	1	0
Oper_Off Course	1	1	3	5
Resume_Only	0	1	4	5
Backtrack_15m	0	2	0	0
BU_Stuck	1	0	0	0

C. Path Analysis

Plots of the route traveled were made for each of the runs in the study. The plot, together with summary statistics and narratives collected during the run allow us to interpret events along the run. Figure 3 shows the outcome for a run in Area B12. The yellow line represents the original route plan to visit a second way point prior to traveling to the end way point at the helicopter pad. The global map feature data included for route planning is dated by several years and inconsistent with current vegetation. The red line indicates the path of the robot. The XUV traveled into the high brush near the second waypoint. Several backups were executed by the ANS in the vegetated cul-de-sac. A first re-plan based on BIP appears in blue. Subsequent attempts by the robot still failed to find a path. The operator teleoperated the XUV away from the trees at the end of the cul-de-sac and executed a new re-plan (orange) based on the updated terrain feature data in the global map. This route led the XUV successfully to the goal. Figure 1 in Section II provides a second example of the impact of BIP in which the run required three re-plans (blue, orange, and green) but no teleoperations to successfully reach the objective.

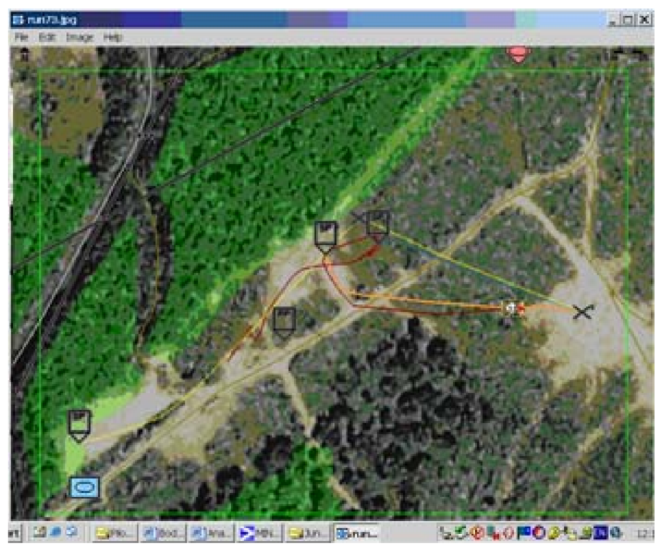

Fig. 3. Area B12 (Mobility =1, BIP)

Area A1 produced several interesting examples. Figure 4 shows one run in which the mobility and exposure deliberative layers were turned on along with BIP and the FCI. The positions from which to limit exposure were to the Southeast (North is up) of the operator control unit (OCU) position, denoted by the blue symbol in the lower right hand corner of the image, and to the Southeast of the final waypoint. The yellow line represents the original plan, passing through an area with dense woods that were intentionally not included on the global map. An early off-course message resulted in the first re-plan (blue); little change in path occurred. Both show the interest in achieving the second way point before retreating to the tree line in consideration of exposure. Although a definitive reason for the XUV traveling wide of that second re-plan before turning to the second way-point is not possible, a plausible reason may be that the deliberative planning layer was attempting to use the tree line along the South edge (not visible on the figure) or subtle changes in elevation to reduce the silhouette of the robot. Past the second way point, another off-course was issued because of the distance between the actual and planned routes. A re-plan (orange) provided a path to the last two way points. After passing through a gap in the trees and progressing through a meadow, the robot traveled to a location, which often produced an off-course message. At that point a final re-plan (green) was provided to guide the XUV to the final way point.

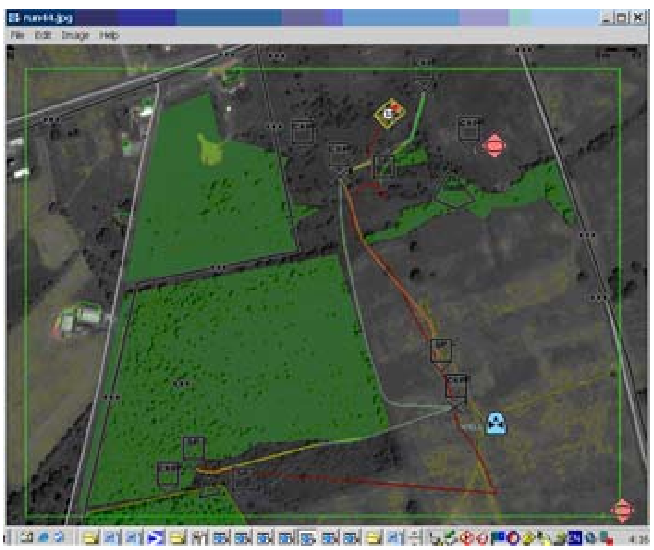

Fig. 4. Area A1 (BIP+Mobility=0.5+FCI=2+Exposure=1)

Figure 5 shows a situation with the deliberative layers for mobility and exposure turned on but only BIP operating during the run. This run also shows three re-plans. During the run, the robot does not appear to wander to the extent apparent in the run depicted in Figure 4.

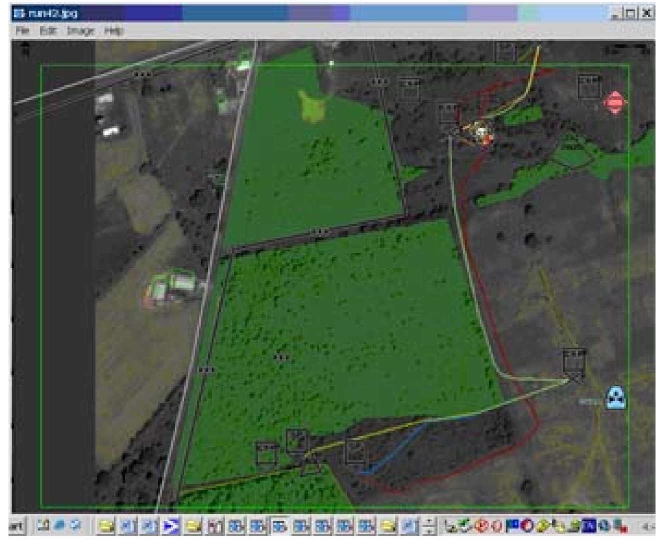

Fig. 5. Area A1 (BIP+Mobility=0.5+Exposure=1)

Not all runs were successful, clearly since we report a total of 11 e-stops in this area. Figure 6 illustrates one such run where the XUV appears lost after 6 re-plan attempts. An e-stop was called for safety reasons when the robot came too close to the OCU position. Figure 7 shows a typical path leading to an e-stop due to the XUV proceeding down a cul-de-sac to an impassable marsh. Actually, this particular run had to be aborted due to inclement weather.

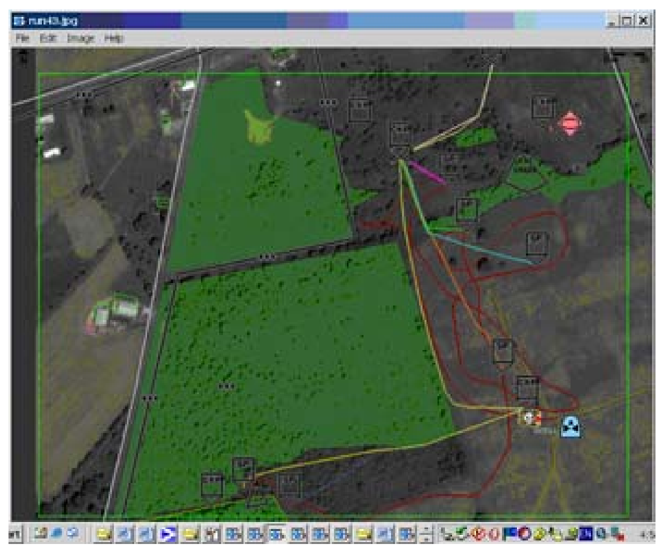

Fig. 6. Area A1 (BIP+Mobility=0.5+FCI=2)

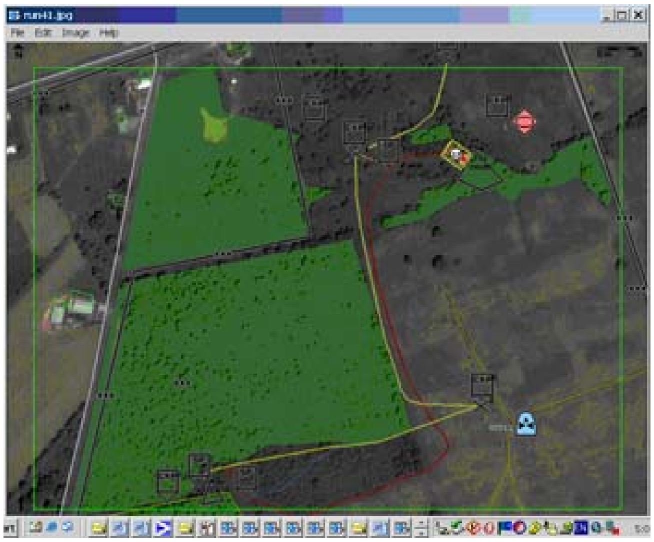

Fig. 7. Area A1 (BIP+Mobility=0.5)

Additionally, two real time displays (not shown) aid interpretation. One shows how the terrain around the robot is being assessed by the dynamic planner in terms of safe progression and another illustrates how the global map is being updated with local terrain features that the robot encounters during route traversal.

D. Operator Workload

Although the pilot study focused primarily on the integration of the bi-directional flow of information into UGV operation, the potential impacts on operator performance were considered as well. Three GDRS software developers (co-authors of this paper) acted as operators of the XUV during all the pilot study runs. Certainly these operators were not intended as representative of Soldier users; however, it was decided that useful operator feedback on workload and situation awareness (SA), as well as methods to measure the workload and SA, could be obtained from the pilot test operators during this early integration assessment.

Operator tasks included set-up for each run, execution of initial route plan, monitoring of XUV status, and intervention where required. There were some required teleoperation interventions. There were also re-plans during runs that implemented BIP. In these cases, the recalculation of routes was automated using the bi-directional flow of data, however, the call for, and execution of, the new plan were operator tasks (the objective is for this to be an automated process in the future). The operators were asked to make ratings of their overall workload (on a scale from 0-10), adapted from the Overall Workload Scale in [2] and [3]. Ratings (on scales of 1-7) of situation awareness (SA) were obtained for the three areas of 1) ability to perceive information, 2) ability to understand information, and 3) ability to predict what would happen. These situation awareness questions were drawn from the definition of SA in [4]. A final question on expectations ("Did the XUV do what you expected...?") was asked, also. In addition to the subjective ratings, video recordings of the OCU, over the shoulder of the operator, were also obtained.

Ratings from 26 trials were collected across all operators. In general, workload ratings were relatively low (mean= 3 (out of 10)) and situation awareness ratings were relatively high (mean=6 (out of 7)). When asked if the XUV behaved as expected, operators responded "yes" for twenty of the 26 trials. It should be noted, however, that some of these "yes" responses had qualifiers attached. For example, five of the "yes" responses also said something like "except for this one part of the run which was unexpected." Interestingly, one operator said that the XUV behaved as expected because "I had different expectations based on what it did for the last [similar] runs." Based on the ratings and additional responses, then, it seems as if the robot behavior at times was unexpected, puzzling the operators, and some expectations were changed based on observed behaviors. This question of expectations and changing expectations needs to be explored further for its implications on information and decision support for operators.

The issues that are highlighted here include the ability of the operator to perceive and understand information relevant to intelligent behavior by the robot, and then know what will happen in the future (as shown by prediction and expectation). What does the operator need to know? How involved does the operator need to be (or want to be) in planning decisions made automatically by the robot; when is permission to execute and proceed needed? Issues of trust in automation and complacency arise. Workload associated with these tasks, for single and multiple robots, as well as all other operational tasks being performed, are important to consider.

IV. CONCLUSION

As a result of the June 2007 exercise, the developers learned a great deal about the technology performance, necessitating changes for later releases. The Army sponsors recognized many issues to be addressed in further testing. With regard to changes, the FCI could benefit from an investigation of the balance of deliberative planning layers and perceptive planning. It was suspected that weighting played a role in some of the unexpected behaviors observed. A desirable change would enable, at the end of the mission, the field cost planner to yield to the original planner so that the end way point can be more consistently achieved. Some runs, especially in Area B12, resulted in end of missions being called when the XUV was far removed from its destination. Further, improved tracking is sought to keep synchronized the robot and the OCU. It is suspected that the run illustrated in Figure 6 was probably due to the instructions coming to the robot at an inappropriate time for where the robot actually was at that time. Improved handling of off-course messages is also being worked; during the experiment, this message resulted in "resume mission" or a "re-plan" and execute.

Several improvements related to the BIP are also ongoing. The range of local sensing is being increased from 20 m to 60 m. This should increase the potential path options seen by BIP. A planned improvement is to increase the scan sweep upon robot back-up and when the robot slows, the latter taking advantage of the opportunity not to compete with processing that supports the ANS. During the June 2007 exercise, we observed instances when the XUV missed opportune paths in very close proximity, most likely because the scan was not wide enough to see them. When the opportunity called for using BIP to suggest a re-plan for execution, current protocol requires the operator to reorient the robot to the new route; this process is being automated. Efficiencies in sensed data logging are also being pursued.

With regard to the design of the study, several issues were recognized. The test protocol must be sufficiently robust to handle the new situations created by enhanced robot behaviors. Data consistency depends on a tight, strictly adhered to protocol. Communications continue to present a challenge; to work this problem more time is warranted prior to the experiment to evaluate base station locations. Scripts will be developed to automatically set configurations for each run. In the present study, this work was done anew each time, sometimes at both the OCU and at the XUV, taking more time and introducing more opportunity for set-up error.

The terrain and mission context of runs must also be revisited. In the present study, we relied on one classic case, the cul-de-sac, to exercise the new technology. Other interesting cases must be determined to highlight "problem solving" over an array of challenges. Further, the terrain must be expanded and more varied for the coming experiment. Elevation data, for example, changed very little in either area, minimizing the technology's ability to leverage it in consideration of, for example, an exposure layer. And by restricting the length of the run in the present exercise (run lengths for Area B12 and Area A1 were less than 1 kilometer), we limited the FCI in leveraging mobility and time layers as well. An expanded area is available for testing in the fall. Finally, to provide a richer environment for workload assessment and to experiment with a maturing Reconnaissance Surveillance, and Target Acquisition (RSTA) capability, RSTA mission elements should be rolled into the subsequent experiment.

The glaring issue remains of how to measure the success or failure of this intelligent system. Our approach is merely to identify elemental challenges for the system to overcome and then to determine whether or not they were overcome. But the question of exactly how to determine success and to what degree remains elusive. In a large scale study, changes in the frequency of e-stops, teleoperation, etc. would be revealing. Elements of time to complete the mission and the duration required to overcome a course obstacle would also serve as a basis for comparison. A decision tree developed post hoc to be evaluated using subjective utilities from a Soldier scout has been considered. The authors welcome input on measurement that could be helpful in subsequent evaluations.

REFERENCES

[1] R. Camden, B. Bodt, S. Schipani, J. Bornstein, T. Runyon, F. French, C. Shoemaker, A. Jacoff, A. Lytle, "Autonomous Mobility Technology Assessment Final Report," ARL-TR-3471, 2005.

[2] M. Vidulich and P. Tsang, "Absolute Magnitude Estimation and Relative Judgment Approaches to Subjective Workload Assessment," in Proceedings of the Human Factors Society 31st Annual Meeting, 1987, pp. 1057-1061.

[3] S. Hill, H. Iavecchia, J. Byers, A. Bittner, A. Zaklad, and R. Christ, "Comparison of Four Subjective Workload Rating Scales," *Human Factors*, 34(4), pp. 429-439, 1992.

[4] M. Endsley, "Design and Evaluation for Situation Awareness Enhancement," in Proceedings of the Human Factors society 32nd Annual Meeting, 1988, pp. 97-101.

[5] M. Endsley, "Towards a Theory of Situational Awareness in Dynamic Systems," *Human Factors* 37(1), pp. 32-64, 1995.