Developing an Intelligent and Integrated Unmanned Ground Vehicle System: A Case Study

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Abstract

In October, 2005 the US Army Maneuver Support Center(MANSCEN) together with the US Army Test and Evaluation Command (TECO) conducted a test of the INL Autonomous Robotic Countermine System (ARCS). ARCS features the Idaho National Laboratory (INL) Robotic Intelligence Kernel (RIK) operating on a countermine platform developed at Carnegie Mellon University with ground marking equipment developed at the Space and Naval Warfare Systems Center San Diego (SPAWAR.) The rigorous 10 day test showed dramatic results for this unique unmanned system.

Highlights of the results showed:

- 124 of 131 inert mines detected (95%) with 1 false detection. Missed mines were tactics related, not platform related.
- All mines detected were correctly marked on the ground and in the operator interface.
- Proofing and marking a 50 meter lane took 5 to 6 minutes, compared to approximately 24 minutes for a soldier in training to accomplish the same task.
- The overall operation required less than 1% human involvement

- The overall Autonomy Levels for Unmanned Systems (ALFUS) rating for the ARCS was calculated to be approximately 7.5-8 out of 10.

The INL Robot Intelligence Kernel (RIK) operates on numerous research platforms and is being ported to various military robots. The countermine behaviors used in the experiment were written as an integral “conduct” within the RIK. A significant aspect of the October experiment was intended to evaluate the portability and reconfigurability of the countermine behaviors. To do this, MANSCEN verified that the behaviors could be moved easily from one robot platform to another, that the behaviors could be run in simulation and that multiple sensor suites could be plugged and played. These studies showed that the Countermine Behavior demonstrated is adaptable to variable sensor configurations and payload needs. The operator interface provides an augmented virtual reality to aid operators with task accomplishment and supports levels of autonomy ranging from teleoperated to fully autonomous. This test provided confirmation of the adaptability and robustness of the INL Intelligence Kernel in a real world application.

Introduction

The Autonomous Robotic Countermine System (ARCS) is a cooperative effort to provide behaviors which enable teams of small Unmanned Ground Vehicles (UGVs) and Unmanned Air Vehicles (UAVs) to collaboratively conduct semi-autonomous countermine operations in live and virtual environments. The participants in this project include the Department of Energy (DOE) Idaho National Laboratory (INL), Carnegie Mellon University (CMU), the Space and Naval Warfare Systems Center San Diego (SPAWAR), and the US Army Maneuver Support Center Futures Center (MANCEN). Significant input was also provided by the US Army Night Vision and Electronic Sensors Directorate at Ft. Belvoir, Virginia.

The first phase, which concluded in October 2005, was to develop and test behaviors to detect mines, mark their location on the ground, report the location to an operator control station, and mark the boundaries of a proofed clear lane for dismounted troops. The second phase will be to develop coordinated behaviors for teams of multiple UGVs, including a marsupial “mother” vehicle that can deploy smaller UGVs, and at least one UAV. The experiment at the conclusion of the first phase showed a high level of success in countermine behaviors and a demonstration during the experiment showed that all phase one requirements had been successfully achieved. Details can be found below.

Phase One - UGV Countermine Experiment

The purpose of the pahse one experiment was to test the effectiveness and capabilities of the ARCS, especially the behaviors of the INL Robot Intelligence Kernel (RIK), which included obstacle avoidance, path planning, terrain mapping and localization in addition to mine detection and reporting. The experiment evaluated the effectiveness of ARCS to prove a 1-meter lane by finding mines, marking the mine location on the ground, reporting the mine location to the OCU, and marking the boundaries of the proofed lane.

Challenges inherent in countermine operations that this experiment addresses are:

- Unreliability of communications between the robot and the OCU
- Unreliability and imprecision of GPS
- Unreliability of prior terrain map data
- Necessity to clearly and precisely mark the mine locations
- Extended workload for the soldier/operator

Equipment

The equipment developed and integrated for the experiment includes a robot platform, a mine sensor payload, a dye marking package, the RIK, and an operator control unit.

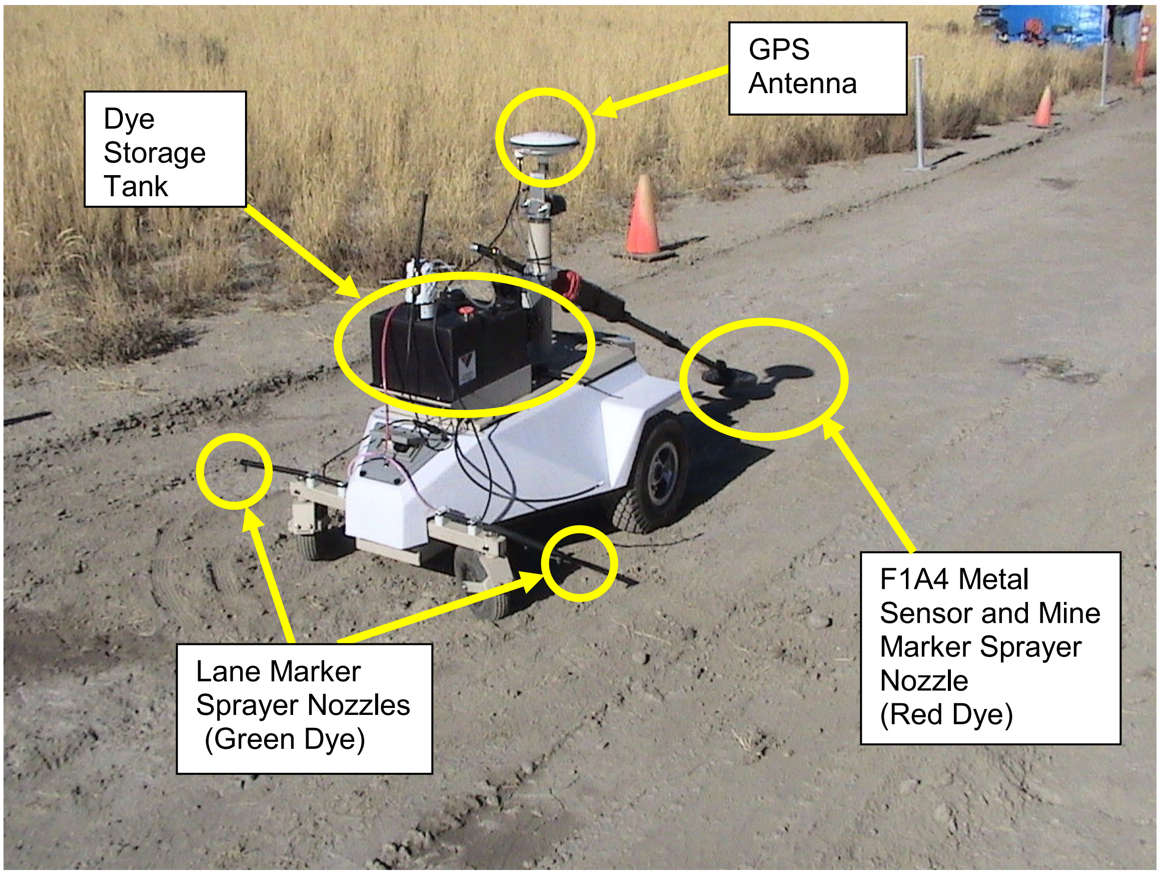

Figure 1 The ARCS System

The robot platform selected was the FCS Learning Applied to Ground Robotics (LAGR) robot developed by CMU. Two robots were built and modified by CMU for this experiment and delivered to INL for integration. The modifications to the robot included a mechanism and control package for the mine sensor. This mechanism provided a mount for the MineLab F1A4 metal detector, which is the standard issue mine detector for the US Army. The mechanism provided a height adjustment and a pivot system for sweeping the mine sensor over the ground, and a torque sensor to recognize when the sensor was touching the ground. Included was the software control system for the robot platform and sensor payload that were linked to the RIK. The dye marking system was designed and built by SPAWAR and mounted on the rear deck of the robot. The marking system consists of two dye tanks, a larger one for marking the cleared lane and a smaller one for marking the mine location. The system also included pumps, hoses and nozzles for dispensing the dye, and a control system that linked to the RIK.

The RIK and operator control station were developed at the INL and were extended over the course of this project to provide a plug and play mine detection and marking capability to any platform that uses the RIK and can carry a countermine sensor payload. The operator control station was modified to recognize when the countermine capability is available on the robot and provide the appropriate tasking options.

The Robot Intelligence Kernel

The INL has designed an autonomous control architecture that includes a variety of reactive and deliberative behaviors. Reactive behaviors are mappings between sensing and action, such as: obstacle avoidance; maneuver; get-unstuck; and follow. The INL architecture uses a subsumption scheme such that each reactive behavior can override or blend with the output of other behaviors. Within the INL's architecture, each reactive behavior runs independently. Behaviors such as obstacle avoidance may run continuously, supporting a spectrum of reactive and deliberative capabilities that operate in parallel. Although this subsumption architecture provides a strong foundation of basic capabilities, INL has also incorporated deliberative behaviors, which exploit a world model and function at a level above the reactive behaviors by combining the abilities afforded by the reactive behaviors. Once the reactive behaviors are "satisfied," the deliberative behaviors may take control, allowing the robot to accomplish high-level behaviors such as “area search,” “patrol perimeter,” and “follow route.” This architecture was extended to include control behaviors for countermine operations.

The intelligence which INL has developed adapts automatically to a robot’s sensors and geometry through a process of self-discovery. The software is not only portable to different robots, but can also exploit a wide variety of sensor suites. For this reason it was selected for use on the ARCS. Essentially, RIK provides the ability to develop and evaluate behaviors for future robots which may not yet exist.

The RIK includes four modes of operation. They are Teleoperation, Safe Mode, Shared Control, and Collaborative Tasking Mode. Teleoperation is the traditional remote control of the robot. No regard is made of the sensor inputs for motion control, only the operator commands are used. Safe Mode integrates the robots sensors to evaluate the environment and protect the robot from objects around it. The operator drives, but the robot protects itself. Shared Control adds a level of autonomy while accepting control inputs from the operator. The robot attempts to accomplish an assigned task but the operator may direct its motion by “suggestions” from the control inputs. In Collaborative Tasking Mode the robot is given a task or objective and the robot acts independently to accomplish the task. This is the level at which the robot operated in the countermine experiment. The chart below shows the responsibilities of the robot and human in each mode of control.

Mode of Autonomy	Defines Task Goals	Supervises Vehicle Direction	Motivates Motion	Prevents Collisions
Teleop	***Human***	***Human***	***Human***	***Human***
Safe	***Human***	***Human***	***Human***	***Robot***
SSM	***Human***	***Human***	***Robot***	***Robot***
CTM	***Human***	***Robot***	***Robot***	***Robot***

Note that each of these modes may be used to accomplish the countermine task. In fact, the dynamic autonomy offered by the RIK provides users with an ability to task the system differently depending on the task constraints such as available operator workload and communication connectivity

The RIK uses a method of maintaining its location called Simultaneous Localization and Mapping (SLAM) which uses sensors such as a laser range finder, wheel encoders, gyro, compass, and ultrasonic sensors to develop an occupancy map of the local environment. While GPS is useful outdoors, it is nearly impossible to use indoors and is not accurate enough for precision placement of the robot or obstacles. A significant effort was dedicated to ascertaining a method for filtering the localized pose based on probabilistic reasoning about the terrain and GPS. In the end, the technique which worked best was to kalman filter the wheel encoder information, gyro and compass information before sending it to the SLAM localization engine. In turn this localized pose was combined with two forms of GPS data used simultaneously on each robot. The first was a Wide Area Augmentation System (WAAS) enabled GPS which provided less accuracy, but higher availability and a high precision DGPS system which provided higher accuracy, but less availability. By using these two GPS systems together with the localized pose, the ARCS system was able to provide accurate mine location reporting. .

The INL has also developed a unique operator control unit (OCU) that provides control and tasking for multiple robots. The RIK is an onboard component of the robot which communicates with the OCU over a low-bandwidth high-reliability long-distance capable serial radio link. In order to operate from long distances, the ARCS OCU was designed to use terrain data without the need for visual feed. A camera could be added to the ARCS in which case the

OCU is designed to overlay the video feed on top of the terrain map. However the phase one experiment was run with no camera on board.

Once tasked the robot is capable of operating independently of the OCU. Collaboration with Brigham Young University provided an added component to the OCU that presents the operator with a 3D virtual world displaying entities from the real world as virtual entities in the display. The 3D interface presents relationships between different sources of information such as aerial imagery, GPS position, video, and obstacles to provide the operator with a clear perspective of the information around the robot. In this experiment, aerial imagery, GPS position, and detected obstacles were used to populate the 3D interface.

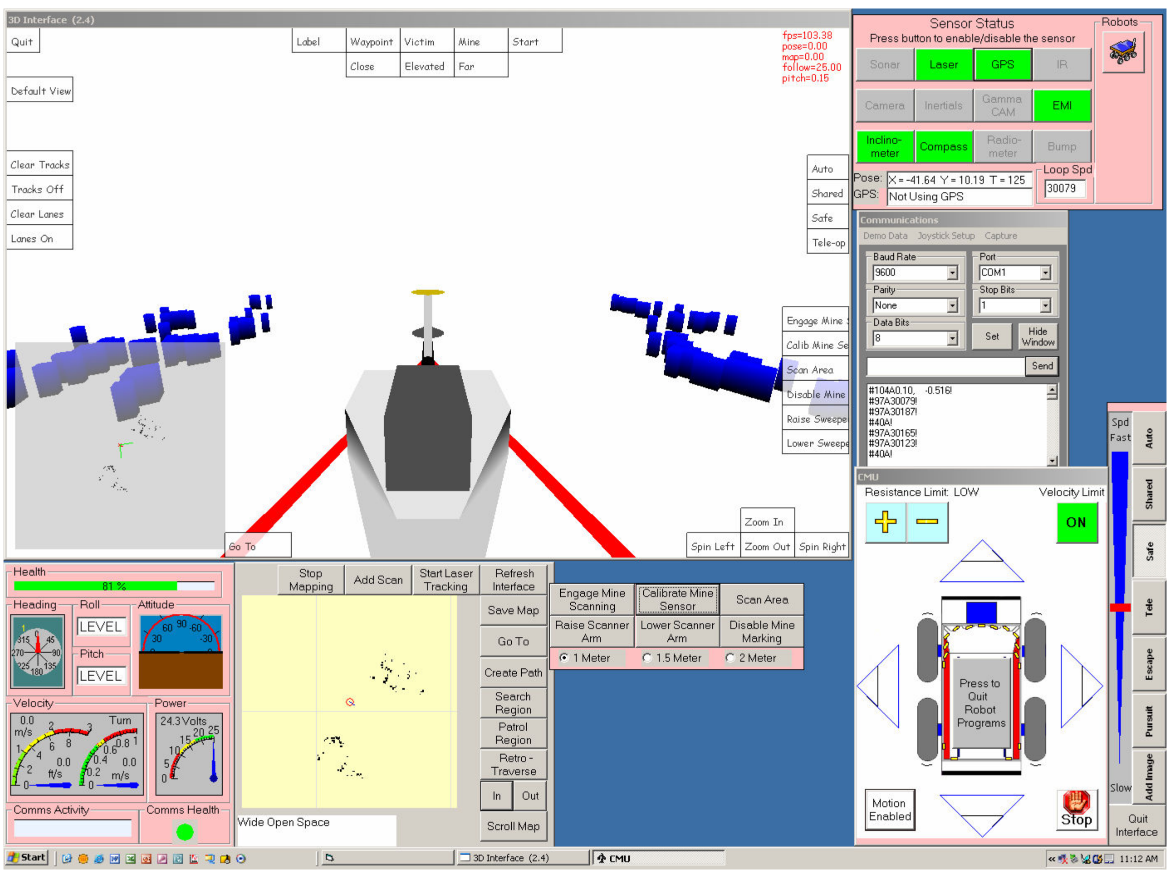

Figure 2 The INL Operator Control Unit Screen

Experiment Setup

The experiment was conducted October 20-28, 2005 at the INL's UAV airstrip by personnel from the US Army Maneuver Support Center (MANSCEN) and the Test and Evaluation Command (TECO), both based at Ft. Leonard Wood, Missouri along with support from INL personnel. A test lane was prepared on a 50 meter section of an unimproved dirt road near the INL airstrip. Six anti tank (AT) land mine surrogates were buried on the road at depths of 6-8 inches. Sixteen runs were conducted with no obstacles on the lane and 10 runs had various obstacles scattered on the lane.

Figure 3 Experiment Lane and AT Mine

Because the repeated use of marking dye over the same course would result in confusing marks, clear water was used in the marking system and poker chips were placed at the center of each spray pattern for both lane boundary and mine marking. An operational check list was created and followed for each run to assure consistency of data.

A run consisted of the operator positioning the robot at the starting point of the lane, setting the mine sensor to the correct height, and starting the robots mine scanning and marking behavior. The robot would then proceed down the land, marking the lane, sweeping the sensor, detecting

Figure 4 Examples of Mine Marking and Burying a Mine

mines, marking mines, and avoiding obstacles. As the robot proceeded, test personnel following the robot placed poker chips at the location of each marking spray with red chips being used for mine marks. At the conclusion of the run the distance from each mine mark to the center of the mine was measured and recorded. All mine locations reported to the OCU were checked and a copy of the data log and a screen shot of the markings from the OCU were saved. A photograph of each mine and their location was taken and a video of each run was recorded. Data sheets recorded meteorological data, mine marking errors, missed mines, false detections, and other comments from those conducting the experiment.

Experiment Results

There were four criteria to the tested requirements in this experiment: finding mines, marking mines, reporting mines, and marking proofed lanes.

Finding Mines

During the 26 runs executed during the experiment the robot correctly detected 124 mines. Over the course of the experiment, seven mines in the lane were not detected. The overall success rate for detecting mines was 95% with a 99% lower confidence bound of 88%.

Of the seven mines not detected two were due to a miscalibration of the height of the sensors, two were due to low battery levels on the sensor, and three were not detected during sharp turns to avoid obstacles. All missed mines were at or near the edge of the proofed lane.

ARCS had a single false detection during all the runs. A single mine was detected and reported twice, once on the leading edge of the mine and once on the trailing edge. This gives a false detection rate of 1% with a 99% upper confidence bound of 5%.

Marking Mines

All mines detected by ARCS were marked on the ground. The accuracy of the markings for 91 mines (the first 16 runs with no obstacles in the lane) is shown in table 1.

	Mine #1 Marking cm Error	Mine #2 Marking cm Error	Mine #3 Marking cm Error	Mine #4 Marking cm Error	Mine #5 Marking cm Error	Mine #6 Marking cm Error
	10	8	7	15	20	Miss
	23	8	24	4	0	7
	6	16	10	7	17	16
	4	8	7	20	1	3
	13	0	Missed	13	5	0
	15	15	20	15	0	10
	12	8	12	0	0	7
	12	16	18	19	15	15
	1	8	16	8	8	Missed
	26	18	15	14	4	24
	7	28	27	31	33	21
	20	39	17	26	22	26
	3	16	5	13	9	8
	12	23	5	12	0	15
	16	0	0	4	4	22
	16	18	Missed	20	12	Missed
# of Marks	**16**	**16**	**14**	**16**	**16**	**13**
Average	**12.25**	**14.31**	**13.07**	**13.81**	**9.38**	**13.38**
St Dev	**7.09**	**10.06**	**7.84**	**8.24**	**9.76**	**8.29**
CI (+/-) 99%	**5.22**	**7.41**	**6.31**	**6.07**	**7.19**	**7.02**

Table 1. Mine Marking Error

The average marking error for all 91 mines was 12.67 cm with a standard deviation of 8.56 cm and a 99% confidence interval +/- 2.36 cm. The mine diameter was 33.4 cm.

Reporting Mines

Of the 124 mines detected only one mine was not reported to the OCU. All the rest were automatically reported and logged. A text file with the UTM coordinates of each mine was logged in a separate run file and screen shots of each run were made showing the location of each mine in the robots internal map.

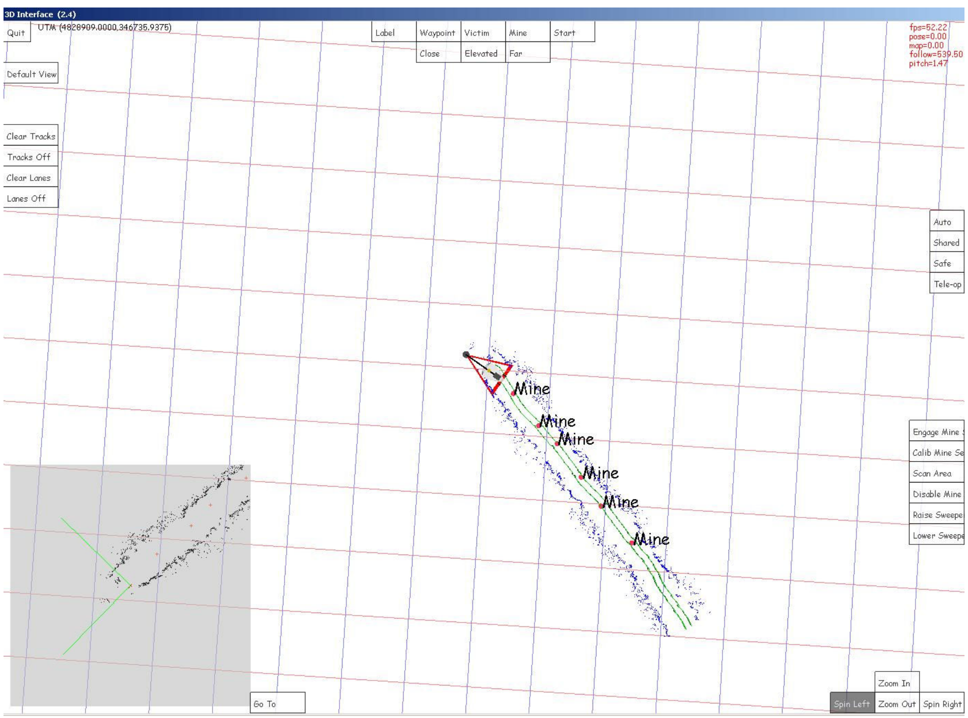

Figure 5. Mine and Proofed Lane Display on OCU

Marking Proofed Lanes

The ARCS was successful in all runs in autonomously negotiating the 50 meter course and marking a proofed 1-meter lane. The 26 runs had an average completion time of 5.75 minutes with a 99% confidence interval of +/- 0.31 minutes. The maximum time taken was 6.367 minutes.

Interestingly, the presence of obstacles on the course seemed to improve the speed at which the robot performed. Closer examination of the data showed that the speed up was not due to the obstacles, but rather to the fact that the trials with obstacles were performed on a wider stretch of road. In other words, the robot behaviors allowed it to move slightly faster since it judged the open route to be slightly wider. On the 16 runs without obstacles the average time to complete was 6.058 minutes with a 99% confidence interval of 0.216 minutes. The 10 runs with 7 obstacles on the course showed an average completion time of 5.267 minutes with a 99% confidence interval of 0.585 minutes.

Figure 6 Proofed Lane Marking

UAV-UGV Countermine Demonstration

As part of the project's phase one experiment a demonstration of UAV-UGV cooperative behaviors was presented. The demonstration consisted of the following scenario:

- A UAV was deployed to survey the terrain surrounding the airstrip
- The real-time geo-referenced imagery from the UAV was analyzed and a possible minefield was detected
- This imagery was mosaiced to form a backdrop for tasking and was imported seamlessly into the ARCS operator control station.

- The aerial imagery was correlated with the ground robot terrain map (an occupancy grid constructed throughout its operation) to allow for efficient tasking and monitoring of the ARCS UGV.
- The ARCS was deployed to the minefield
- The ARCS detected and physically and digitally marked mines
- A proofed lane was marked through the minefield

The INLs UAV team launched an Arcturus T15 UAV to provide aerial imagery of the airstrip and surrounding terrain. It autonomously provided geo-referenced imagery which was imported into the UGV control station. The UGV was then remotely tasked and autonomously performed a sweep of a suspected minefield, marking mines and a proofed lane. An additional countermine operation was then conducted in a small open area near the airstrip. The operator designated the perimeter of a region of interest and directed the robot to scan this area. It successfully navigated the area, detecting the three mines in the region and avoided all obstacles, including a soldier who repeatedly stepped in front of the robot as it was scanning. Despite the presence of dynamic and static obstacles, the entire region was successfully searched. This demonstration provides confidence that phase two of the countermine project is an attainable goal.

Level of ARCS Autonomy

The ARCS received overall Autonomy Levels for Unmanned Systems (ALFUS) rating of 7.5-8 out of 10. The ALFUS rating has been developed over the past year under the leadership of the National Institute of Standards and Technology. Many governmental institutions have taken part in the development of the ALFUS metrics. The result is the adoption of a three dimensional assessment tool that indicates the overall level of autonomy exhibited by an unmanned system during the course of a real world task. The rating given of 7.5 – 8 reflects the efforts of the MANSCEN and TECO evaluators to apply this rating scheme to the ARC experiment.

Human Intervention

1	100%	
2	50%	
3	25%	
4	10%	
5	5%	
6	2.5	
7	1%	
8	.5%	
9	.25%	
10	.13%	

Environment Complexity

1	Clear Paved Road	
2	Dirt Road	
3	V Obstacles on Dirt Road	
4	Clutter on Dirt Road	
5	Off Road	
6	Trails, Water	
7	Foot Path	
8	No Path	
9	Forested	
10	Cluttered Urban	

Mission Complexity

1	Send Video Image	
2	Way Point Navigate	
3	Navigate and Avoid Obstacles	
4	Navigate, Perform Single Task	
5	Navigate Perform Multiple Tasks	
6	System Collaboration	
7	Collaborate with Robots	
8	Collaborate with Robots and Soldiers	
9	Independent Operations	
10	Cognitive Decision Making	

Conclusion

The results of the ARCS experiment showed success in all goals of the first phase of the countermine initiative. The robot was able to reliably find mines, mark them on the ground, report them correctly to the operator, and mark a proofed lane correctly. The joint efforts of the INL, CMU, SPAWAR, MANSCEN and others showed that a successful collaboration is not only possible but effective.

Acknowledgement

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