

Evaluating Robot Technologies as Tools to Explore Radiological and Other Hazardous Environments

12th Topical Meeting on Robotics and Remote Systems for Hazardous Environments

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The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

March 2008

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EVALUATING ROBOT TECHNOLOGIES AS TOOLS TO EXPLORE RADIOLOGICAL AND OTHER HAZARDOUS ENVIRONMENTS

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There is a general consensus that robots could be beneficial in performing tasks within hazardous radiological environments. Most control of robots in hazardous environments involves master-slave or teleoperation relationships between the human and the robot. While teleoperation-based solutions keep humans out of harms way, they also change the training requirements to accomplish a task. In this paper we present a research methodology that allowed scientists at the Idaho National Laboratory to identify, develop, and prove a semi-autonomous robot solution for search and characterization tasks within a hazardous environment. Two experiments are summarized that validated the use of semi-autonomy and show that robot autonomy can help mitigate some of the performance differences between operators who have different levels of training and robot experience, and can improve overall performance over teleoperated systems.

I. INTRODUCTION

There is a general consensus that robots could be beneficial in performing tasks within hazardous radiological environments. The use of robots for tasks in radiological environments is not a new concept. The Idaho National Laboratory (INL) and others have used robotic arms directed by human operators for years to handle and manipulate radiologically “hot” materials in hot cells^{1,2}. Additionally, robots have been sent to inspect areas of the damaged reactor at Chernobyl where a man could receive a lifetime dose of radiation in minutes³. These and many other applications have significantly reduced personnel radiation exposure primarily using robots under teleoperation control.

While remote robot teleoperation has proven to remove the human from the radioactive environment, it is not without its shortcomings. In particular, successful teleoperation of a remote robot is a challenging task that requires skill and training with respect to robot control and obtaining remote situation awareness regardless of the actual task that is to be accomplished with the robot. The consequence of this is that mission success depends not only on how well personnel have been trained to handle the mission, but also how well the personnel have been trained with, and experienced robot technologies as

the primary tool to interact with the environment and gather information about the environment.

It is well known that humans and computers, and therefore robots, have different and often orthogonal strengths and weaknesses. The challenge is to find a way to capitalize on the strengths of the human and the robot such that the human-robot team would be able to accomplish remote, hazardous tasks more effectively. Although understanding the strengths of the human and the robot is important, the real effort lies in the presentation and efficacy of the human-robot interaction itself, the overall goal being to minimize the training required to apply the robot to the domain which the operator had been previously trained.

The purpose of this paper is to present the approach used at the INL to support the operator’s use of semi-autonomous robot behaviors as tools in exploration tasks that involve radiological and other hazardous environments. To validate the research, we summarize two experiments that demonstrated the effectiveness of the semi-autonomous behaviors and their corresponding human-robot interactions in comparison to traditional teleoperation-based robotics.

II. BUILDING THE RIGHT SOLUTION

While technology is interesting for the sake of invention and demonstration of new ideas, it is more beneficial to get the right technology into the hands of the people who will be the ones using it on a daily basis. To ensure that we were addressing the right problem and finding the right solution, we met frequently with Civil Support Team (CST) and Explosive Ordinance Disposal (EOD) personnel over a period of two years. From these meetings we identified a few main points concerning what is usually done in an emergency and what the end-users hoped the technology would provide. Primary issues of concern included: mapping; safety zones; better situation awareness; and dynamic human-robot interaction.

II.A. Mapping

In hazardous environments, responding personnel often sketch maps of the environment so that information gained from the first trip into the environment can be used to plan subsequent trips. The maps may be annotated

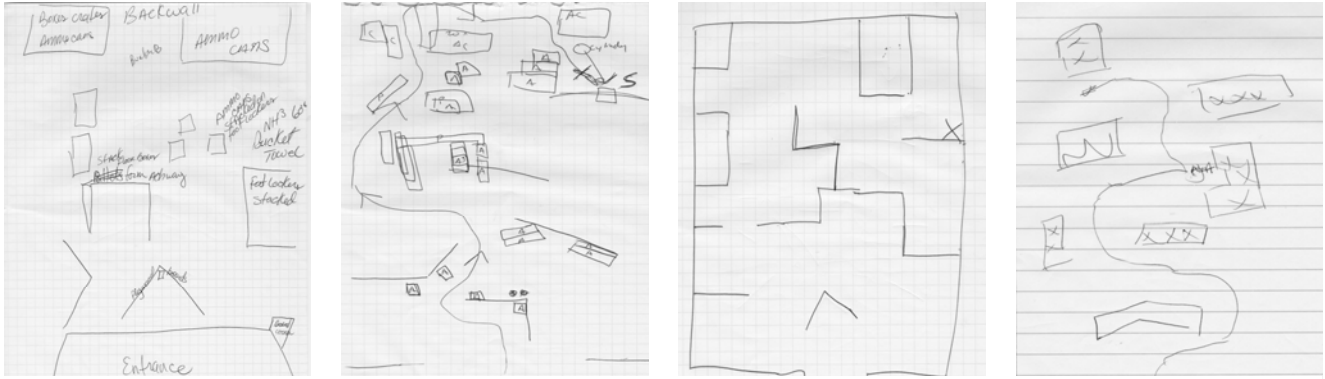


Fig. 1. Hand drawn maps made by soldiers in a hazardous environment search task at Ft. Leonard Wood, MO in October 2007.

with radiation readings, obstacles, and other key features that might facilitate future missions within the environment. While responders are generally given training to observe, internalize, and sketch a map of the environment, the final maps sketched by operators often vary significantly depending on individual skill and attention to detail. As an example consider the hand-sketched maps shown in Fig. 1 which were generated by soldiers in an experiment at Ft. Leonard Wood, MO in October 2007. The maps each show different approaches to the mapping task. Some maps show the path of the robot, some do not. Other maps show the traversable areas while some are focused more on the visible landmarks. Some of the maps have significant annotations about observations in the environment while others have nothing but the structure drawn. Despite the fact that all of the maps were drawn while the operators teleoperated a robot through the same environment, the maps and illustrations do not immediately appear to represent the same environment.

In contrast, when the robot has the ability to automatically construct a map of the environment, the mapping information is immediately improved because the basic structure of the map is the same for each of the robot operators independent of their own skill at sketching a map. To address the issue of mapping, the INL robot solution uses a laser-range finder to scan the environment and build a map representation of the environment based on a simultaneous localization and mapping (SLAM) algorithm developed by the Stanford Research Institute (SRI)⁴. The constructed map and the relative location of the robot within the map are then transmitted to an operator interface to support the operator's understanding of the remote environment.

II.B. Safety Zones

One of the sets of information recorded by personnel in hazardous environments is the hazard sensor readings

throughout the environment. According to the individuals interviewed, it would be valuable to have a system that automatically records the hazard sensor readings as they relate to a physical map of the environment. When this is done manually with robots, it requires the operator to have some sort of feedback and understanding about the sensor's location within the remote environment. Consider, for a moment, how the user might record the data from a robot that has multiple sensor types such as radiation, explosives, and chemicals. To gather data throughout the exploration, the operator would have to drive the robot forward a distance and then cycle through all the sensors to observe their values and record, on paper, readings and locations that were relevant. Since the information recorded on paper is dependent on the operator's perspective of relevance, this approach naturally lends to differences between what information individuals consider relevant to record and the accuracy of the recorded information.

Discovering the safety levels of an environment is an important task even when robots are not used. Without robots, human personnel are required to suit up in the most protective gear often including anti-C clothing, bulky equipment, and oxygen supplies. The sensor equipment carried by personnel in a hazardous environment usually includes a warning sound that goes off when the measured substance is greater than a given threshold. A second warning sound is emitted when the measured readings exceed the "dangerous" level indicating that the conditions are very hazardous to humans. If multiple types of hazards must be evaluated then the response personnel must carry multiple sensors.

In response to the issues regarding personnel safety zones we have developed plug-and-play sensor payloads that tie into the INL robot's navigational package and integrate the readings from a variety of radiological, chemical, and explosive sensors into the robot's operational map of the environment. The data is transmitted to an operator interface that abstracts the sensor readings



Fig. 2. Abstracted sensor readings illustrating locations of radiation sources.

into color bands that indicate the relative safety levels of the hazards within the environment. For example, green indicates safe zones, yellow indicates the first hazard threshold, and red indicates the second threshold. Moreover, to facilitate the robot operator's ability to localize the source of the hazard based on the abstractions, the colors bands are each given a gradient of light to dark to indicate lower readings to higher readings within the color bands. An example of the abstractions and representations of the sensor readings is shown in Fig. 2, which is a map taken from an experiment performed at the INL in July 2007. The image illustrates the obstacles detected by the robot as blue walls. The radiation readings are illustrated by the various color levels throughout the map. In this particular case, there were two radiation sources found by the operator.

II.C. Situation Awareness

Situation awareness has been defined for the aviation domain as "the *perception* of elements in the environment within a volume of time and space, the *comprehension* of their meaning, and the *projection* of their status in the near future"⁵. One of the concerns of end-users is that when robots are used, operators often lose situation awareness with respect to the remote environment because of the minimal information available to the operator and the reliance on video for all of the feedback from the environment. Relying only on video for navigation has been shown to be cognitively challenging and has been described as using a key-hole

for navigation because of the limited field-of-view of conventional cameras⁶.

The issue with the loss of situation awareness is that the operators lose most of the environmental cues that help them make decisions regarding the actions of the robot within the environment. Furthermore, as communications begin to lag and drop out, a fight for control often emerges as the operator loses awareness of which commands have been received and acted upon by the robot and which ones have not due to latency in the communications. All of these facets affect the operator's ability to correctly and adequately control the robot.

To facilitate the operator's awareness of the situation and environment around the robot we provide an interface that allows the operator to control the robot from a tight "ego-centric" perspective or, when more information about the environment is required, an "exo-centric" or bird's eye perspective⁷. The transition between these perspectives is actuated through the use of the wheel button on the mouse or key commands on the keyboard. Combining the perspective of the robot with the map of the environment and the abstracted sensor readings has been shown to facilitate the operator's development of situation awareness at the remote location--at least as it relates to the subtasks of robot navigation and source localization.

II.D. Dynamic Robot Interaction

One of the comments made by the CST and EOD personnel was that they wanted a "click and go" behavior on the robot to get the robot down range and return from the incident, however, as the robot approached the critical or target area, they wanted the system to allow the operator more direct control.

To answer this request, the challenge was not only to provide various levels of human-robot interaction or "robot autonomy," but also to provide a simplified means to switch between modes of interaction. When we consider "levels" of autonomy or human-robot interaction, the real question we are asking is which elements of the task should be performed by the human and which ones should be performed by the robot. Fig. 3 shows a chart of the common modes of operation that we use with our robot and the ownership of responsibilities for the different aspects of the task.

One of the pitfalls that we often fall into when developing robot behaviors and intelligence is to neglect the operator's role in the task. In particular, it is the operator that will generally decide where the robot should go, and it is generally the operator that is responsible for deciding the best level of autonomy for the robot to use to accomplish the task and to decide when the level of autonomy should change. The problem with this is that to perform this task well, the operator needs a very good understanding of the capabilities of the system and the

Mode of Autonomy	Defines Task Goals	Supervises Vehicle Direction	Motivates Motion	Prevents Collisions
Teleop	Human	Human	Human	Human
Safe	Human	Human	Human	Robot
Shared	Human	Human	Robot	Robot
HLTasking	Human	Robot	Robot	Robot
Autonomous	Robot	Robot	Robot	Robot

Fig. 3. The common modes of human-robot interaction along with the ownership of the responsibilities for different aspects of the task.

nuances of the different interaction modes. As an example, consider the interface shown in Fig. 4. This interface is a screen shot of one of our previous interfaces that supports a wide variety of functionality but requires the operator to choose the autonomy mode of the robot and be aware of the various capabilities of the robot and the behaviors of the robot intelligence for each of the distinct modes. The red ellipses indicate the different options that the user would have to navigate in order to change the modes of the human-robot interaction.

In order to address the issue of dynamic human-robot interactions, we have spent considerable effort simplifying the human-robot interface such that most of the complexity of the human-robot system is hidden from the operator and automatically handled by the system whether through intelligence embedded into the interface or through intelligent robot behaviors. Removing the requirement for the operator to understand the inner-workings of the system allows the operator more of their cognitive resources and attention for the high-level or mission tasking of the system which in turn allows the operator to apply their domain-specific training instead of requiring that the operator also become a “robot-expert.” The interface simplification has resulted in an interface like the one shown in Fig. 5 where the operator’s interactions have been reduced to a few mouse clicks and movements and some keyboard and joystick commands.

In response to the end-user’s request for a “click and go” behavior, we have developed tools for metaphors such as “look here” and “go here” that allow the operator to easily indicate high-level mission relevant tasks and require the robot to perform the low-level navigation and behavior algorithms to accomplish the task⁸. In this manner we allow robot operators to focus on the mission, which is what they are trained for while the robot is responsible to handle the navigational details of the task, which is what it was designed for.

Even though the robot intelligence and autonomy associated with the click and go behaviors are beneficial, there will still be occasions when the operator will want to take direct control of the robot to either modify the autonomy or to perform a task that is not supported by the autonomy. One of our goals to support switching levels of interaction is to reduce the operator’s requirement to



Fig. 4. A previous version of our interface that allowed the operator to choose the interactions.



Fig. 5. A simplified INL interface for supporting dynamic autonomy.

explicitly change modes of interaction. To accomplish this, the interface automatically recognizes input from different sources and adjusts the autonomy of the robot accordingly. As an example, if the robot were autonomously exploring the environment and the operator wanted the robot to go in a particular direction, the operator could just use a joystick or the arrow keys on the keyboard to direct the robot without explicitly selecting a “mode” of operation. To switch back to the “click-and-go” mode, the user would drag the “go-here” icon to a new location. Simplifying the transition between interaction modes can help the operator focus on the mission and not concern themselves with the underlying technical system.

III. EVALUATING THE TECHNOLOGY

As we work to develop robotic technology for end-users, it is important that we can show how the technology will affect the operator’s use of the system and performance on the task. To do this, it is first beneficial to understand the types of users that can be used to evaluate the technology and what can be learned from the different groups of end-users. We will then

summarize two experiments that evaluated the technology in the hands of end-users.

III.A. Defining the participants

Participants in user-studies are generally classified into two main groups: novices and experts, depending on their experience within the domain of interest. To really understand the skills of the operator, how they should be compared with other operators, and how they should be evaluated, we need to divide the novice and expert categories a little further. Moreover, as we work to introduce robotics into fields where personnel do not have significant training with robots, we again come to the question of novice versus expert, but this time with respect to the end-user's experience with robotics. When evaluating robotic systems there are two types of experts: domain experts (those with knowledge about the domain) and there are robotics experts (those trained in the use of robots). The types of participants with the varying levels of experience are shown in Table I and discussed below.

Robot – No Domain: Members in this group are usually the robot developers and engineers who are intimate with the workings of the robot, but not particularly with the domain groups. This group of users makes sure the system works and responds to requests from other groups to update and improve the system. When working with other user-groups, members of this group can determine the complexity of desired changes.

No Robot – No Domain: Members in this group are those unfamiliar with the domain and who have not used robots previously. This group could include students and the general public and is particularly valuable at making the core system and fundamental robot behaviors easier to use for general purposes. This group also serves as a sanity check to verify that the system is working correctly before putting the system in the hands of domain users.

No Robot – Domain: Members in this group are those who have been trained in a specific area and could be considered subject matter experts (SMEs), but who have not used robots in their domain. This group could further be divided into a variety of levels depending on experience and training within the domain, however, it suffices to say that they either have general training regarding issues relevant to the domain, or specific training regarding the domain itself. As an example, a nuclear engineer might have generic radiation training and a Civil Support Team might have general radiation training as well as emergency response training specific to radiation hazards.

Robot – Domain: Members in this group are similar to the SMEs in the previous group with the additional

TABLE I. User Group Experience		
	No Robot Experience	Robot Experience
No Domain Experience	Students The public	Engineers Developers
Domain Experience	SME-General SME-Specific	SME-Specific.

requirement that they have had experience using robots to perform their tasks. As an example, a participant in this category might be an EOD trained individual with experience or training using a robot to accomplish the EOD task.

III.B. Experiment 1

The first experiment was designed for participants to detect and localize radiological sources within a large industrial facility located in the INL critical infrastructure test range complex (CITRC). There were 19 participants for this experiment who were divided into three groups of SMEs depending on their expertise in hazardous emergency response, robotics, and radiation knowledge:

- *Explosive Ordinance Disposal (EOD) Soldiers:* These participants had robot and domain training including 1-2 years of regular, hands-on use of the Packbot and Talon robots in-theatre.
- *Weapon of Mass Destruction – Civil Support Team (WMD-CST) Personnel:* These participants had domain training in radiological emergency response, but no previous robot training.
- *Nuclear Engineers (NE)* had general domain training (knowledge about radiation), but no emergency response training, and no prior robot training.

The experiment compared three modes of human-robot interaction using the INL robot: Joystick + Safe, Joystick + Map, and Target + Map. The conditions for the experiment are described next and the interfaces for the modes are shown in Fig. 6:

- *Joystick + Safe:* The interface showed the real-time video and a radiation meter similar to the ones on a hand-held device. The operator navigated the robot with a joystick. The robot was in “safe” mode which allowed it to prevent collisions with obstacles in the environment (Fig. 6a).

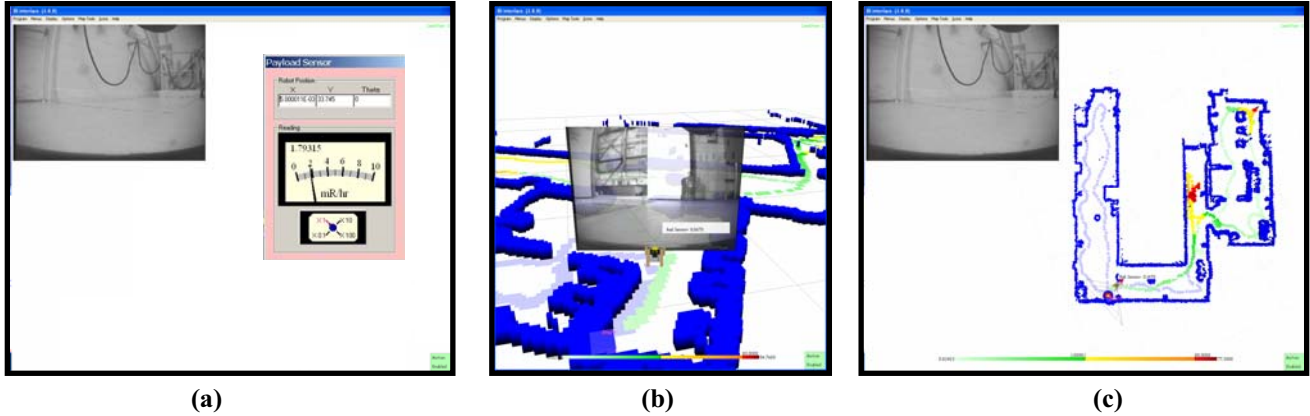


Fig. 6. The Interface designs used for Experiment 1. a) Joystick + Safe, b) Joystick + Map, c) Target + Map.

- *Joystick + Map*: The interface showed the video from the environment and illustrated the robot's map of the environment from a bird's eye perspective that included color-coded sensor abstractions indicating low, medium, and high radiation readings. The operator navigated the robot with the joystick and the robot was in "safe" mode (Fig. 6b).
- *Target + Map*: The interface showed the video and the map of the environment (including color-coded sensor readings) as well as the robot's intended path. The operator navigated the robot with the use of a "target icon" that designated the desired destination for the robot. The robot planned routes to follow through the environment while avoiding obstacles (Fig. 6c).

The experiment was designed such that each participant used the three different modes of human-robot interaction in a counter-balanced manner to mitigate overall learning effects. Participants were told that their task was to find two Cesium-137 radiation sources hidden in the environment and then to return to the door from which they started. Furthermore, participants were asked to identify the location of the sources on a paper floor plan of the building that was 80% accurate with respect to the actual building. Emphasis for this experiment was placed on source detection and localization rather than speed. The robot used for the experiment was an iRobot PackBot (Fig. 7) that included the INL robot intelligence kernel and an AMP-50 Germanium tube-based low range radiation detector. The interface for all three conditions was run on a Dell Optiplex GX280 desktop computer.

III.C. Experiment 2

The second experiment was designed for participants to detect and localize the source of an ammonia chemical



Fig. 7. The iRobot Packbot that was augmented with INL navigation payload and radiation sensor and used in Experiment 1.

hazard within underground bunkers at Ft. Leonard Wood, MO. Participants for this experiment were from the Edgewood Chemical and Biological Center and consisted of 10 individuals who had training in emergency response with half of them also having significant prior robot training.

This experiment compared the INL's PackBot with the Army's state-of-the-art CBRNE Unmanned Ground Vehicle (CUGV). The CUGV is a traditional iRobot PackBot EOD that has been augmented to support a variety of hazard sensors. The CUGV is operated through the use of two hockey-puck shaped actuators and a variety of levers and switches. The robot is fully teleoperated with the exception that the arm can move into predetermined positions with the click of a button. The interface has been augmented over a traditional PackBot interface to show the readings of the various sensors attached to the robot. The CUGV along with some of the sensors and the operator interface are shown in Fig. 8a.

The INL robot was the same one used in the first experiment with the exception of upgraded tracks and that instead of the radiation sensor, a RAE Systems MultiRAE Plus chemical sensor was used. The look and feel of the INL interface was similar to the third condition of the first experiment where the operator was given a real-time map of the obstacles and the hazard chemical readings and video from the robot (See Fig. 8b). The robot was

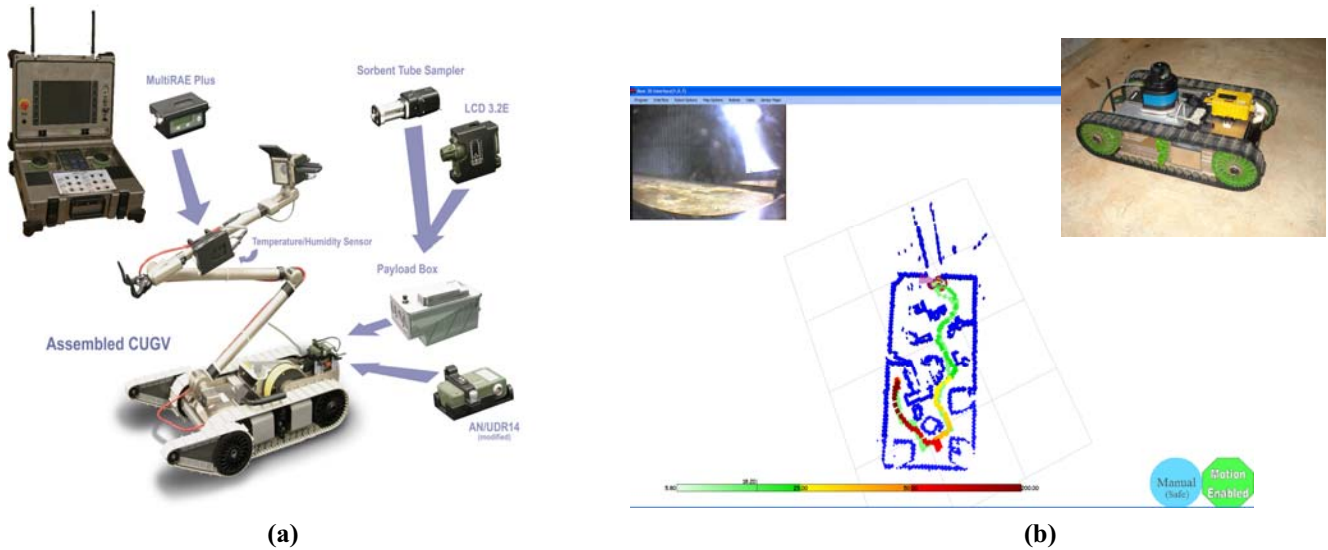


Fig. 8. Systems used for Experiment 2. a) INL interface and robot, b) CUGV and interface

controlled by dragging a “target icon” to the desired destination. Teleoperation control was provided through the arrow keys on the keyboard and the interface was run on a Dell XPS M1710 Laptop.

The experiment was designed so each participant used both the INL Packbot and the CUGV in a simple and a complex environment in a counter-balanced manner to mitigate overall learning effects. Participants were told that they had complete control of the robot and it was up to them to decide how much to let the robot do and how much they should do themselves. Operators were told that emphasis should be placed on minimizing the time to find the source and exit the bunker.

III.D. Results

The results from these experiments showed that operators performed the search and detection tasks best with the INL robot system when they had the semi-autonomous target mode available.

From the first, subjective surveys administered after each test indicated that participants felt a decreased workload, lower effort, and lower frustration with the Target + Map condition. Moreover, objective measures indicated that participants in the Target + Map condition had fewer collisions with the environment, fewer instances of operator error, and fewer instances when the robot had to take action to avoid a collision. Furthermore, there is a significant reduction in the amount of time that the operator was spent interacting with the system and an improved ability to localize the sources on a paper map. As autonomy is increased, each group of participants did better localizing the source than when lower autonomy levels were used. Moreover, participants with different

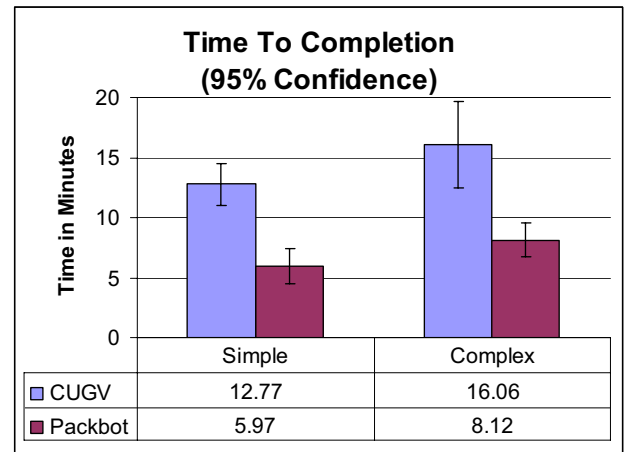


Fig. 9. Time to completion for experiment 2.

training and experience performed more similarly as autonomy increased. A detailed discussion of the first experiment was presented previously⁹.

From the second experiment we observed that operators finished the task in about half the time with the INL robot and semi-autonomy as compared to the CUGV (see Fig. 9). Moreover, with the INL robot, there were zero collisions over the two day experiment whereas there were 81 collisions with obstacles from operators using the CUGV system.

With respect to subjective questions regarding the relative value of the different autonomous capabilities, all of the participants reported that automatically building a map of the area was valuable. In addition 90% of the participants believed the concepts to direct and drive robots would be useful in the field. Moreover, nearly 75% reported that the ability to drive itself and avoid collisions was valuable to the task and 60% of the participants

thought that the chemical plume on the map was beneficial to the mission.

Overall, participants indicated that they felt comfortable with the INL robot, that it was easy to use and that they trusted the robot. Some of the participant's comments included:

- "With mapping I knew exactly where the robot was."
- "I know that in auto mode, if at any time I need to change the route, I could manually take control."
- "It was easy to see when the area was getting more and more concentrated from the colors and numbers."
- "Once the plume was confirmed, I used the target mode to let me drive the robot back."

III.D. DISCUSSION

These experiments showed clear advantages to using a semi-autonomous human-robot interaction approach in a hazardous material search task as compared with more traditional teleoperation approaches including our own INL system and the current state-of-the-art CBRNE Unmanned Ground Vehicle.

One of the most striking results from both studies was that the individuals less experienced with robotics performed nearly as well, with autonomy, as those who had more experience with robotics. This suggests that if semi-autonomous robots are designed appropriately, they may be able to mitigate some performance differences based on training and experience. Moreover, the experiments showed that operators using semi-autonomous robots were able to finish the task significantly faster in some cases as compared to the current state-of-the-art teleoperated system. Another advantage of the automated mapping system is that all maps, regardless of the operator, have the same basic structure. One of the questions to consider next is how to support the annotation and "mark-up" of the maps so that operators can easily record ancillary information related to the environment such as comments and snapshots¹⁰.

IV. CONCLUSION

This paper illustrated the steps that we went through to identify, develop, and prove technology that meets some of the needs of end-users in regards to tasks related to the discovery and characterization of environments containing radiation or other hazardous chemicals. While the experiments illustrated the value of autonomy in some domains (flat environment with discrete, large obstacles), there remains much work to be done. Of interest is the ability to do the same type of work in outdoor environments where the environment may be rugged and where traversable obstacles such as grass and weeds may interfere with sensors. Future work will also address the testing of a variety of hazardous material sensors

including explosives and anti-personnel and anti-tank landmines. Moreover, the interface system used for the experiments is a research laptop and is not military hardened and barely daylight readable. Future work will address the types of interactions that can and should be supported for first responders and combatants to utilize robots effectively in specific hazardous domains.

ACKNOWLEDGEMENTS

The authors would like to thank Maj. Werkmeister and Sgt. Jones of the Manuever Support Center (MANSCEN) for their help in organizing the experiment and for Maj. Ugarte, Steve Pranger, and Tom Anderson from TRAC Monterey for assisting with the experiment plan and the data analysis.

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