**The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan**

Effects of Increasing Autonomy on Tele-Operation Performance

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Abstract— **Tele-operation of robotic platforms has long suffered from the inability of the operator to effectively perform ancillary tasks while controlling the robot. Because of the focus required to perform tele-operation, the operator is limited in their ability to use the robot to improve their situational awareness, with tele-operation often becoming a detriment to their task rather than an enhancement. We present experimental results on the use of a tele-operated robotic system modified to include layered obstacle detection and avoidance routines and an open space planner. These algorithms help the operator shift their focus towards high-level tasks instead of low-level navigation. While experimental data shows that the increase in autonomy did not lead to a reduction in task completion time, obstacle collisions were reduced and has led to further investigation of cognitive load reduction during operation.**

I. INTRODUCTION

The use of unmanned ground vehicles (UGVs) as proxies for humans working in dangerous environments has begun to find traction with field teams. Notable examples include searching for survivors in the World Trade Center rubble [1] and investigation and disposal of Improvised Explosive Devices. Though unmanned vehicle technology allows teams to carry out dangerous tasks with reduced risk to humans, the current approach of having dedicated users performing full teleoperation means that such tasks require extensive training and will always be limited by the availability and attention of individual operators.

The ultimate goal would be to promote semi-autonomous behavior that allows one operator to be responsible for and direct many robots [2], but until such systems can be created and verified, teleoperation remains the state-of-the-art.

The teleoperation interface has long been recognized as a major impediment to the effective deployment of UGV systems. In one field experiment, military reconnaissance teams were given teleoperated robots with a remote camera for use in training exercises, and while the soldiers could control the robots, they had trouble placing the visual feedback into the larger mission context and communicating it to others [3]. This points towards the fundamental need of situation awareness for the required tasks; during a search-and-rescue training exercise, the authors of [4] observed that more than half of all communication interactions between robot drivers and spotters were for the purpose of simply trying to understand the robot state and environment.

However, along the path to the goal of increasing robot autonomy is the goal of introducing autonomous behaviors in a way that enhances the capabilities of users to accomplish their tasks with teloperation. This is the goal that we address here. Beginning with a typical teleoperated PackBot Explorer robot from iRobot [5], we have layered obstacle detection and avoidance (OD/OA) routines [6] and an open-space planner (OSP) [6], [7] on top of the user control in order to help operators focus on high-level tasks instead of low-level local navigation. We set out to establish the efficacy of our approach through trials with human operators, and we show that although the enhanced interface did not lead to a reduction in task completion time, the operators were able to perform their navigation task with less obstacle collisions.

Before presenting the experiments in Section IV, we will discuss, in Section II, previous work on reducing the limitations of current teleoperation and identifying metrics that guide our experiments. Our technical approach on the obstacle detection and avoidance and open-space planning techniques will be covered in Section III, and analysis of the experiments and conclusions will be in Sections V and VI, respectively.

II. PREVIOUS WORK

For reducing the limitations of teleoperation, we have identified the two major directions that researchers have taken: enhancing situational awareness in order to make the operation task more natural for untrained users, and reducing user expectations through robot autonomy that requires little user input. Before robots can be made fully autonomous, we can address the goal of using autonomous behaviors to assist user input and effectively make the operation more natural even without enhanced user feedback. Any efforts must be grounded in an understanding of human-robot interaction and associated metrics for quantifying how well these new technologies transcend pure teleoperation.

The metrics used for evaluating work in human-robot interaction have been studied in [8], addressing task-oriented metrics, and [9], focusing on psychophysiological measurements. These are quantities such as galvanic skin response (for measuring stress), and electro-encephalograms (for measuring brain activity), that give insight into the psychological impact of the interaction. Measuring this impact would allow us to assess the mental burden that our interface places upoen its operators. Currently, such factors are assessed by having users answer math questions during operation and then the speed of their responses allows us to infer how much mental effort the control task is taking [10], [11].

Perhaps because of the dominance of vision in human activity, research into enhancing situational awareness is focused on providing better visual feedback to users. For example, [12], [13], [14] all present the robot state from a third-person point of view that incorporates the current

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environmental model and allows operators to see the robot state within the environment context. In [15] this concept is extended by borrowing interfaces from computer strategy games to allow for third-person high-level control of many robots while allowing for the option of singling out a single robot for traditional first-person control. In [14], there is a focus on making any autonomous behaviors of the robot as explicit as possible for the user with clear visual feedback, with the potential for having the user influence the behaviors by providing high-level cues.

The problem of incorporating user input into autonomous controls was addressed in the context of robot navigation by both [16] and [11]. There are three sources of control actions in these systems: deliberative goals from a high-level planner, reactive goals from an obstacle avoidance routine, and direct user control. The control inputs from each are weighted according to safety and handling criteria and joined together to provide a final control input that is executed by the robot. In [11], the technique was evaluated using a fifty-person study in order to quantify the benefits of such mixed-initiative controls. Our approach most closely matches this work; we are seeking to fuse direct user input with reactive controllers in a way that does not inhibit users ability to complete the task but promotes safety.

III. TECHNICAL APPROACH

A. *Autonomy Software*

In order to achieve the desired behavior of actively avoiding obstacles within a mixed-initiative robotic system, the user's input must be augmented by the robot performing two separate actions. First, any obstacles must be detected and, if a collision is imminent, the platform velocity reduced to avoid contacting the obstacle. This is traditionally called obstacle detection and avoidance (ODOA). Second, a local path around the obstacle must be planned and executed. This is referred to as local path planning or open space planning (OSP). Clearly, these two behaviors must work together to achieve the desired result, as when executing a path new obstacles still must be avoided.

To accomplish this combined behavior, integration of two software components into the existing ARL robotic control infrastructure was required. Because of resource constraints, ARL chose not to implement each behavior from scratch. Rather, ARL worked with SPAWAR San Diego to integrate two components from their Autonomous Capabilities Suite (ACS). These were the Fuzzy Obstacle Avoidance and Open Space Planner components. Details of each component and their integration are provided below.

1) Fuzzy Obstacle Avoidance: SPAWAR's ObstacleAvoidFuzzy software module applies fuzzy logic to the obstacle detection and avoidance problem [6]. The module first builds up an obstacle map using data from any available sensors that provide ranging data. This obstacle map uses range abstractions to bin the obstacles into several discrete regions around a given robot, such as "left side" and "right front", that are robot and sensor dependent. To simplify the obstacle map, when new range data is received, it only tracks the minimum distance to any obstacle in a given region. Each region has its own fuzzy degree of membership (DOM) function which is used to determine to what degree the minimum distance in each region is a member of the "not close", "close" or "very close" fuzzy values. The fuzzy DOM functions allow for smooth sharing and handoffs between different rules. In contrast to traditional "if-then" rules prevalent in AI programming, this methodology can combine the outputs of several rules based on the strength of how well the current situation matches the conditions for triggering that rule.

The ObstacleAvoidFuzzy component takes both commanded translation and rotational speeds as inputs, but produces only an updated translation value. This commanded velocity could be from either the user (tele-operation) or a higher level behavior (autonomous operation such as way-point following), moving it up the sliding architecture scale slightly from a traditional subsumption towards a hybrid architecture that is more deliberative [17]. Doing so helps to eliminate the problem of the ODOA deciding between two output velocity vectors when approaching an obstacle by choosing one more inline with the commanded vector. Robot dependent fuzzy associate memory (FAM) rules for the robot are then used to evaluate each fuzzy value given the current inputs. The resultant decision levels are then defuzzified, producing the updated translational speed output.

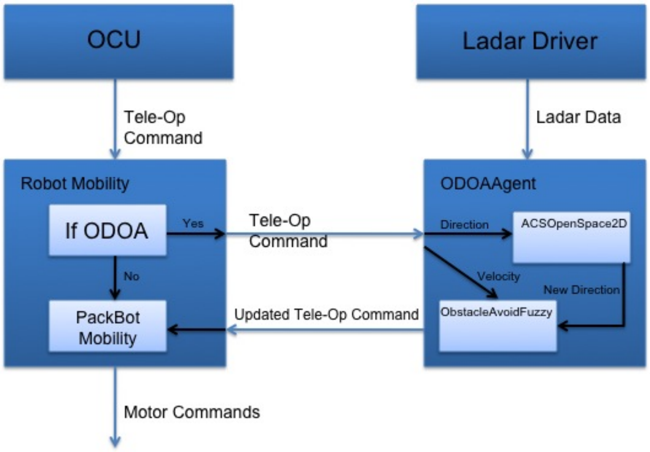

Fig. 1. Block diagram showing command routing

2) Open Space Planner: The OpenSpace2D module determines in which direction there is an open space wide enough for the robot to move and is closest to the behavior's goal direction [6]. This local path planner from SPAWAR is based on the Vector Field Histogram (VFH) approach to real-time obstacle avoidance. The VFH method creates a 2D Cartesian histogram grid from the same range data that ObstacleAvoidFuzzy uses. But rather than building a 2D obstacle map with the data, the VFH method reduces the grid to a one dimensional polar histogram that represents the polar obstacle density. A low obstacle density region can then be selected for the robot to navigate towards [7].

Similar to the ObstacleAvoidFuzzy module, OpenSpace2D takes into account the commanded rotational speed when determining if there is free space to move towards. The software then uses the physical dimensions of the robot and the commanded rotational speed to interact with the polar obstacle density map to determine the best rotational speed for the robot to execute that avoids current obstacles. Again, by taking into account the commanded rotational speed, the potential for conflicting rotational commands is minimized, resulting in much smoother avoidance of obstacles, something desirable in mixed-initiative robotic systems.

B. *Integration*

ODOA and OSP were implemented as separate modules within a software agent called ODOAAgent. As shown in Figure 1, ODOAAgent accepts translational and rotational velocity commands, as well as ladar data, as inputs. The ladar data is converted into a two-dimensional point cloud format and passed to both ODOA and OSP so they can update their internal obstacle maps. Each module produces a velocity output that has been modified to avoid obstacles or navigate towards free space, as appropriate.

Commanded velocities from the OCU are first routed to the OSP module to adjust the heading towards free space. The resulting rotational velocity is then passed, along with the original translational velocity, to the ODOA module to reduce or stop the forward velocity to prevent collisions. The produced vectors are then re-combined and routed to the platform motors.

C. *Tuning*

During integration testing, some minor performance issues related to how the system was tuned were identified and corrected. The robot exhibited difficulty turning in very tight spaces, even though it was not going to contact any obstacles. This was due to the OSP not observing any open space in a given direction, with the net effect being that the robot was not able to execute in place maneuvers, such as turning in place.

The solution was to limit the application of OSP to situations when the rotational speed was greater than 45 deg/s and OSP could not find a suitable open area, indicating a turn in place. Because the ladar used only provided a field-of-view of 240 degrees, OSP was also disabled for commands with a negative translational speed (reverse).

IV. EXPERIMENT DESIGN

The focus of these experiments was to get baseline measurements of various metrics for both the teleoperation and augmented teleoperation of a robotic asset. As more sensors and capabilities are added, future experiments can build on the results from these baseline experiments. To that end, our objective was to compare the navigational performance of users during tele-operation using only tele-operation, tele-operation with ODOA, and tele-operation with both ODOA and OSP.

A. *Equipment*

The robot used in the experiment was an ARL-modified PackBot Explorer. Its stock wide-angle color video camera was used to provide streaming video to the OCU. Pertinent physical modifications to the robot were a Hokuyo URG-LX ladar mounted in the head of the robot and a custom communications payload. The head was propped up with a block of foam to ensure the ladar's FOV remained above the height of the treads, as shown in Figure 2.

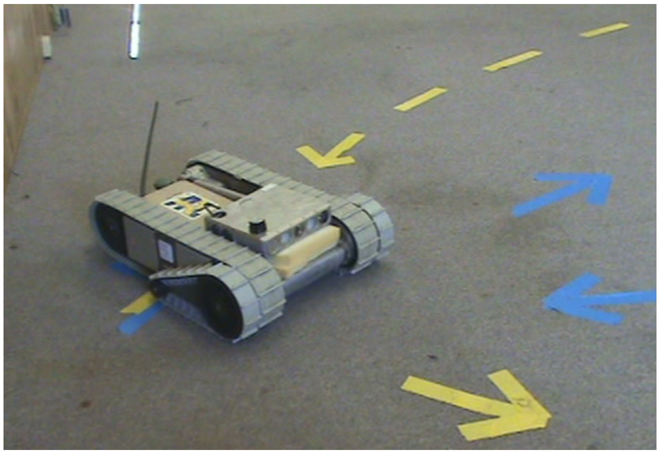

Fig. 2. ARL-modified PackBot Explorer

Custom OCU software was used, operating on a tablet PC that was modified to include joysticks from a stock PackBot OCU attached to either side of the tablet. As shown in Figure 3, the OCU displayed streaming video from the robot, and allowed for simple tele-operational control.

Fig. 3. Tablet PC-based OCU

Both the PackBot and OCU are enabled by a software infrastructure called the Agile Computing Infrastructure (ACI). Developed by ARL, the ACI provides a layer of abstraction between the producers and consumers of information, allowing applications to communicate seamlessly and transparently across a variety of devices and networks [18]. More information about the ACI and its associated components can be found in previous publications by ARL [19] [20] [21] [22].

B. *Operator Training*

To address the fact that operators have different initial abilities in operating the robot, training sessions were conducted to ensure the operators had a reasonable level of proficiency and that changes in task performance could not be attributed to users simply gaining familiarity with the interface. Operators were trained to maneuver the robot around obstacles and through open doorways inside a one-story portable trailer. The training course was created by placing red tape on the ground, similar to how the experiment courses were laid out. Mimicking the experiment, operators controlled the robot from a remote location. This was done so that the operator could not get physical cues from the robot that aid in navigation, such as sound. The time to complete the course was measured along with how often the operator hit an obstacle. Each operator repeated the course three times. Operators who satisfied predetermined metrics were allowed to participate in the actual experiment.

C. *Experiment*

For each record run, the operator was located in a remote location, in this case an adjacent building, to prevent any visual or auditory cues from effecting their performance. The operator was asked to maneuver the robot around one of two marked courses using only the streaming video feed and joystick. The marked courses, shown in Figure 4, contained randomized obstacles that the operator was instructed to avoid. The robot's camera was kept at a fixed height of eight inches above the ground to avoid variation in how proficient the operator was at maneuvering the camera.

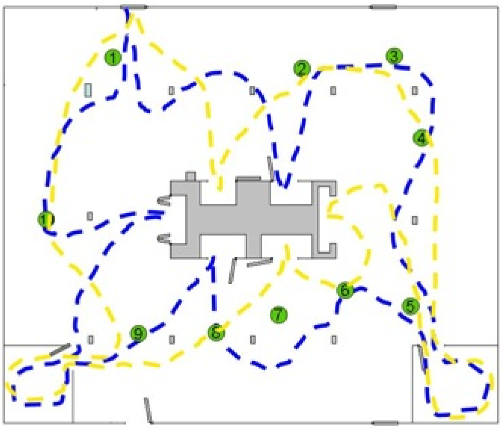

Fig. 4. Diagram depicting the two courses and object locations

The two marked courses were similar to the training course. They differed from the training course only in the color of marking tape used, and the actual paths they followed through the building. The direction of the paths for the yellow and blue courses were opposite (yellow was counterclockwise, blue was clockwise) to make the courses appear completely different, although the frequency and duration of turns on each course was similar. The type of obstacle and its placement on the course were randomized for every run. Five obstacles were placed on the course for reach run, with ten potential obstacle locations on each course.

We focused on task-based metrics for these experiments: for each run, we recorded the course completion time and the number of obstacle collisions.

The experiments took place in two different sessions. During the first session we had all operators perform the blue and yellow courses for both teleoperation and teleoperation with OD/OA. During the second session, we had all operators perform the blue and yellow courses for both teleoperation and teleoperation with OD/OA and OSP. This let us compare both augmented teleoperation systems against baseline teleoperation even though the experiments were separate.

V. RESULTS AND ANALYSIS

In Table I we present the average course completion times and collision counts for each driver under both teleoperation and teleoperation with OD/OA. The results for the blue and yellow courses were averaged together because the course lengths and turn counts were made approximately equal. In Table II we present the results comparing teleoperation to teleoperation with OD/OA and OSP, again with the results for blue and yellow courses average together.

We present this data graphically in Figures 5 and 6. To highlight some observations we make on operators, we have sorted the operators according to their completion times, so the points to the left in both figures are for operators who completed the course faster for baseline teleoperation during the first experiment.

In Figure 5 and Table I, we see how switching from teleoperation to augmented teleoperation affected the course completion time. For all operators, adding just the OD/OA results in longer runs because the OD/OA is simply an inhibitive force. It is interesting to note that the operators who were most aggressive in completing the course under pure teleoperation were most affected by adding in this safety feature, whereas the more cautious drivers were already doing a good job of negotiating the obstacles and experienced less increase in completion times. From the second set of experiments, we see that adding in the OSP for help in navigating led to a smaller time penalty, though for most drivers they still took longer to complete the course. But as we will see, this is balanced by the fact that operators experienced less collisions under augmented teleoperation in general.

In Figure 6 and Table II, we see how switching from teleoperation to augmented teleoperation affected the number collisions that operators made. Collisions were reduced in nearly all cases, and completely avoided in some. The data suggests that the teleoperation variant that includes OSP is more permissive and therefore slightly less effective at preventing collisions than the variant using just OD/OA, but this is balanced by the observation from the analysis

TABLE I

Average course completion times and average collision counts per run for each driver under pure teleoperation and teleoperation with OD/OA.

Operator	Teleop		Teleop+OD/OA		% Increase	
	Time (sec)	Collisions	Time (sec)	Collisions	Time	Collisions
1	241	1.67	308	1.50	0.278	-0.10
3	172	0.67	264	0.00	0.532	-1.00
4	212	0.50	309	1.00	0.461	+1.00
5	179	1.00	244	0.33	0.365	-0.67
6	360	1.00	413	0.33	0.147	-0.67
7	149	3.50	236	1.00	0.584	-0.71
8	379	0.33	455	0.00	0.199	-1.00

TABLE II

Average course completion times and average collision counts per run for each driver under pure teleoperation and teleoperation with OD/OA and OSP.

Operator	Teleop		Teleop+OD/OA+OSP		% Increase	
	Time (sec)	Collisions	Time (sec)	Collisions	Time	Collisions
1	259	1.25	284	0.50	0.097	-0.60
3	163	0.25	217	0.25	0.332	-0.00
4	214	1.00	235	0.25	0.098	-0.75
5	151	1.50	207	0.75	0.368	-0.50
6	337	1.00	323	0.50	-0.043	-0.50
7	276	1.50	266	0.75	-0.037	-0.50
8	152	2.00	190	0.75	0.252	-0.63

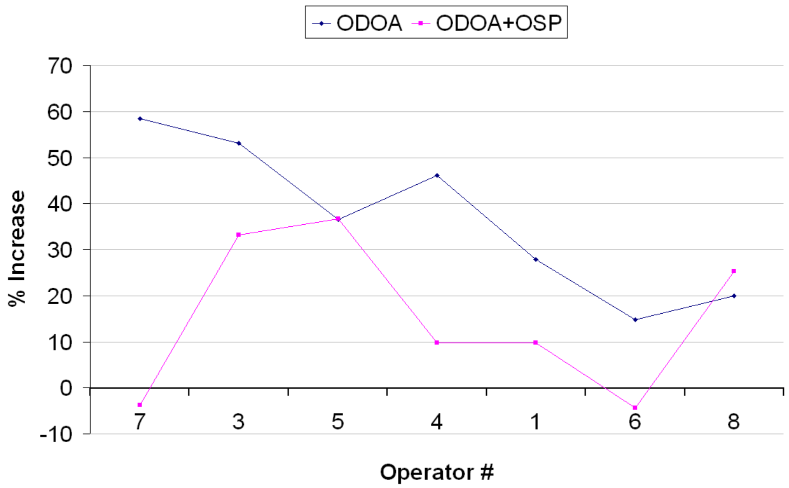

Fig. 5. Percent increase in average course completion time for each operator when switching from teleoperation to augmented teleoperation. The data is presented for both versions of augmented teleoperation: teleoperation with OD/OA, and teleoperation with OD/OA and OSP. The operators are sorted according to increasing course completion time for pure teleoperation during the first experiment set. Note that operators who completed the course faster had more trouble operating using the inhibitive OD/OA controller. In most cases, adding the OSP controller made the navigation easier than with just OD/OA, resulting in less of a course completion time increase.

of the completion time that the OSP variant was also less challenging to use and resulted in less completion time increase.

From these results we conclude that augmented teleoperation offers substantial benefit by increasing safety at the cost of increased operation time. Using just the inhibitive Obstacle-Detection/Obstacle-Avoidance controller to prevent collisions resulted in a strong reduction of collisions but with greatly increased completion time. Incorporating the Open Space Planner made the driving more natural and reduced this completion time penalty but still promoted a large reduction in collisions.

Though we have not fully explored this idea here, we hypothesize that operators can be characterized according to aggressiveness, and our ordering of operators according to completion time under teleoperation was intended to reflect this. Anecdotally, such operators were less concerned with hitting obstacles and instead focused on completing the task as quickly as possible. Because they were already operating in a state of near-collisions, we can expect that these op-

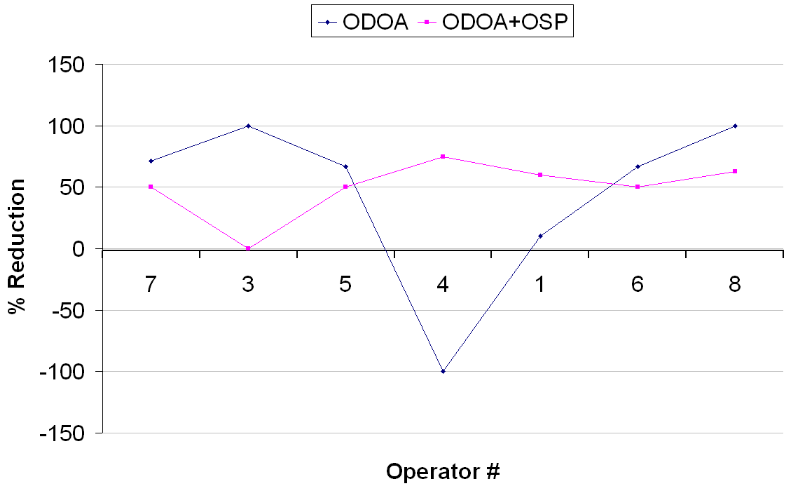

Fig. 6. Percent decrease in average collisions per run for each operator when switching from teleoperation to augmented teleoperation. The data is presented for both versions of augmented teleoperation: teleoperation with OD/OA, and teleoperation with OD/OA and OSP. The operators are sorted as before, according to increasing course completion time for pure teleoperation during the first experiment set. With one exception, the augmented teleoperation modes were safer, resulting in less collisions than pure teleoperation. The variant including OSP was universally beneficial in reducing collisions except for one driver who experienced the same number of collisions but did not increase.

erators would have trouble with the OD/OA controller that inhibits motion when operating in such situations, and the data supports this expectation.

A. *Experiment Notes*

To document our experiences, we present some experimental observations here.

During operation of the training phase, following the path laid out by the red tape was difficult for some of the operators. If the operator veered off course, it was especially difficult to find the correct direction again. Spatial awareness while driving was difficult with the head being in a low position since it can be difficult to see when you have clipped something out of your field of view. To help mitigate the issue, arrows were placed on the course during the actual runs to indicate direction. This was especially helpful when an operator was off course and attempted to get back on course.

It was clear that OD/OA software was clearly impeding the operation of the robot from the operators perspective. Turning in a confined space was difficult with the OD/OA settings. There was a particular doorway that was more narrow than a standard doorway and it was very difficult to cross the threshold. All operators had difficulty getting through the door. Also the controller for the robot allowed the flippers to be deployed by twisting the knob to drive the robot. During operation of the robot with OD/OA many operators inadvertently twisted the knob deploying the flippers which then were seen as an obstacle by OD/OA. The robot would not be able to turn so the operator would have to reposition the flippers out of the FOV of the LADAR.

Glare from sunlight coming in through windows during the first experiment was another issue that affected operator control. Depending on the time of day and the height of the sun, glare on certain parts of the course could blind the operator. In those cases the operator would have to drive blindly until the glare subsided and then try to continue on the correct path. The run schedule was altered to minimize the effect of glare on a particular group. The first group was run in the morning so the next day they were schedule to run in the afternoon. This basically forced the second group to experience the same glare conditions on the second day that the first group had on the first day.

VI. FUTURE WORK AND CONCLUSION

A. *Future Work*

Just as important as the experimental results were the casual comments made by the various operators during the record runs. Many of these comments are driving the future direction of the research and development at ARL.

As alluded to, the most frequent comment was a complaint about the lack of feedback from the robot with regards to its movement. Often the robot would stop in the presence of an obstacle that, because of the field of view of the camera being viewed by the operators, did not appear to exist. Similarly, the PackBot flippers were often erroneously raised by the operator, causing the system to view them as obstacles. These situations gave the operator the impression that the robot was not operating properly, causing them to waste time and effort ”fighting” the autonomy.

Based on this, ARL has begun to modify their autonomy and OCU software to display visual cues to the user that indicate when OD/OA and OSP are augmenting the operator’s commands. The hypothesis is that by alerting users when the autonomy software is preventing commanded movements, the users will learn to trust the system more, easing frustrations with the technology and ultimately reducing the cognitive load during operation.

Recognizing our inability to effectively measure cognitive load is another outcome of these experiments. While the data collected points to tangible benefits of increasing autonomy, chiefly a reduction in collisions, we don't believe it tells the whole story. Traditional measurements of cognitive load when driving robotics have come in the form of survey questions during operation of the vehicle [10]. This approach has inherent disadvantages, including its invasive nature during operation of the robot and reliance on the operator to accurately and honestly attempt to answer the questions.

However, recent advances in moving the physical measurement of cognitive load out of the laboratory into fielded environments provide great promise. Systems including Honeywell's AugCon [23] and QUASAR, Inc.'s BioNode-H [24] are currently being evaluated by the military for their suitability to not only provide useful cognition data, but do so within the confines of traditional military equipment and scenarios. It is in this spirit that ARL intends to leverage these systems to further investigate the possible reduction in cognitive load during autonomy assisted robotic operation.

B. Conclusion

We set out to evalute the benefit of augmenting teleoperation with algorithms for preventing obstacle collisions and planning local obstacle-avoiding paths. After implementing these augmented teleoperation modes on a Packbot, we challenged operators to navigate a course while avoiding obstacles and recorded their completion times as well as collision counts. From the results, we conclude that augmented teleoperation has an overhead in terms of increasing the course completion times for drivers but offers substantial benefit in the form of decreased collisions. The collision reduction was strongest for the augmented teleoperation variant that used only the Obstacle-Detection/Obstacle-Avoidance algorithm to inhibit velocity when collision was imminent, but this mode greatly increased the course completion times because of the unintuitive driving experience it created. By incorporating the Open Space Planner algorithm in addition to the OD/OA algorithm, we introduced a local path planning system that helped guide operators around obstacles rather than inhibiting them. Doing so only slightly muted the benefit of reduced collisions but greatly reduced the time increase penalty incurred by augmented teleoperation.

VII. ACKNOWLEDGMENTS

The authors gratefully acknowledge the help of SPAWAR San Diego engineers Brandon Sights and Gaurav Ahuja during integration and tuning of the ACS software modules.

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