Assisted Driving of a Mobile Remote Presence System: System Design and Controlled User Evaluation

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Abstract— **As mobile remote presence (MRP) systems become more pervasive in everyday environments such as office spaces, it is important for operators to navigate through remote locations without running into obstacles. Human-populated environments frequently change (e.g., doors open and close, furniture is moved around) and mobile remote presence systems must be able to adapt to such changes and to avoid running into obstacles. As such, we implemented an assisted teleoperation feature for an MRP system and evaluated its effectiveness with a controlled user study, focusing on both the system-oriented dimensions (e.g., autonomous assistance vs. no assistance) and human-oriented dimensions (e.g., gaming experience, spatial cognitive abilities) (*N*=24). In a systems-only analysis, we found that the assisted teleoperation helped people avoid obstacles. However, assisted teleoperation also increased time to complete an obstacle course. When human-oriented dimensions were evaluated, spatial cognitive abilities and locus of control had large effects upon speed of completing the course, surpassing the system-level effects of autonomous assistance vs. no assistance. Implications for future research and design are discussed.**

I. INTRODUCTION

Mobile remote presence (MRP) systems are not new technologies, e.g., the personal roving presence (PRoP) system [1] and the mutually immersive telepresence system [2]), but they are becoming increasingly available for everyday use. As such, we are learning more about the use cases and user needs for such systems. Based on our own experiences with our MRP system and watching others drive them, we have learned that many remote operators feel embarrassed in front of their colleagues when the MRP collides with obstacles. Although operators do not necessarily want to give up driving control to a fully autonomous system, it is ideal to avoid embarrassing (and potentially dangerous) situations such as collisions with walls, doors, and other objects in the environment.

Because the remote presence systems represent and embody the remote human operator, it is important for the operator to have control over the behavior of the system. However, there are times when operators prefer to rely upon more autonomous capabilities, e.g., autonomously parking in a charging station or avoiding obstacles. As such, the current system was designed to allow operators to drive the MRP system, but to have the system assist the operator by detecting obstacles and helping the MRP system to avoid collisions with those obstacles.

We present the design for this assisted teleoperation system, which we implemented and tested with 24 remote operators. Each of the remote operators drove both the unassisted teleoperation system and the assisted teleoperation system.

II. RELATED WORK

There are many degrees of autonomy that could be used for assisted teleoperation (in this case, navigation) tasks. There are autonomous forklifts [3], autonomous simultaneous localization and mapping (SLAM) wheelchairs [4], and autonomous personal robots [5] that assume operator commands at a very high-level, e.g., specifying a final destination and orientation on a map. Because the current MRP system is operated remotely through a web-based interface, there are constraints such as bandwidth and latency of the network connection between the operator and the machine. These constraints may require the system to sometimes behave more autonomously. Previous work, using a Pioneer AT mobile robot, has explored how to use a dynamic map interface to allow operators to allocate navigation commands to the robot from a distance, letting the robot do the path planning and obstacle avoidance [6].

There are also shared control systems that allow for high-level control by the operator along with low-level control by the autonomous system. Crandall and Goodrich [7] developed an interface loop and autonomy loop model of human-robot interaction that helps to understand shared control systems. They investigated the influences of shared vs. direct control on a navigating robot, using the time-to-task-completion as a performance metric for evaluating the effectiveness of the system; this study found that operators were about 35% more efficient at the task when using shared control than direct control. In this sense, shared control systems help to "relieve" operators of some of the burden to complete a task, as depicted by Verplank in [8]. Unlike supervisory control systems along Sheridan's scale of degrees of automation [8], the user is not necessarily given choices to select from; instead, the operator is sometimes overridden by the autonomous system (and might not even be informed about that behavior).

Shared control systems have been developed and used in a variety of other contexts. Wheelesley, a shared control wheelchair, assessed operators routes and used sensor data to avoid obstacles [9]. Other forms of semi-autonomous

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wheelchairs features such as guide following, automatic gear ratio selection, and automatic stability augmentation have also been proposed [10]. Similarly, shared control arm manipulators have been designed to allow the operator to provide "global" motion planning commands while letting the machine do the local path finding and collision detection [11]. Shared control systems are also found in the domain of balancing; the Gyrover was controlled by a human operator at the mid-level and high-level behaviors while the autonomous module controlled low-level tilt motor when the operator failed to give a command to keep the Gyrover upright [12]. A shared control ATRV was also built to "monitor-correct irrational operator actions," and avoided obstacles by using a combination of vector field histograms and modified distance transforms [13]. Finally, automobiles are becoming increasingly autonomous systems, e.g., using shared control strategies for identifying and modifying dangerous lane departure maneuvers with a feature called "emergency lane assist" [14].

Like previously discussed shared control systems, the current MRP assisted teleoperation system gives the autonomous module low-level control. The autonomous obstacle avoidance only activated when the MRP systems laser range finder detected proximate obstacles. While some of these previous works used controlled user studies to evaluate the effectiveness of their share control systems (e.g., [9], [7]), most of these reports are presented as a proof of concept with anecdotal, limited (three or four participants), or no user studies at all. The current MRP assisted teleoperation system presents a new type of hardware and application space (mobile remote presence) with a fully controlled laboratory experiment to evaluate the influences upon the successful use of this shared control system. In addition to measuring system dimensions (e.g., autonomous assistance vs. no assistance), we also measured human dimensions (e.g., spatial cognitive ability, personality, gaming experience, etc.), which significantly influenced task performance. By making the source code available (as a ROS package) and using a more rigorous user study evaluation, we aim to move toward a more rigorous scientific quality of system evaluations [15] for such human-robot shared control systems.

III. THE MOBILE REMOTE PRESENCE SYSTEM

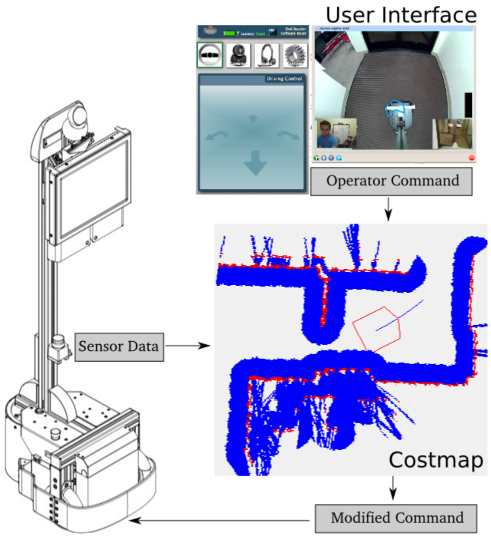
The mobile remote presence system used in the current study was a Texai Alpha prototype, which is primarily used by remote co-workers in the office space. This prototype consists of a mobile base, driven by a single PR2 smart caster in the back, two passive wheels in the front. It has two laser range finders–one on the base and one at the bottom of the touch screen. The "head" has a touch screen to visualize the operator's video stream, webcam for looking around, wide angle camera for navigation, microphone for listening, and speakers for talking. Operators of this MRP system typically control the system through a web-based graphical user interface (GUI) by clicking and dragging a point in a 2-dimensional space in the GUI. See Figure 1.

Fig. 1. Operator using the mobile remote presence system in an office place standing meeting

IV. ASSISTED TELEOPERATION DESIGN AND IMPLEMENTATION

The assisted teleoperation software used in this work was designed to help operators avoid obstacles in an unobtrusive way. The operator provides input to the system in the form of a desired velocity command specified through the web-based user interface. The assisted teleoperation system then takes this command and determines whether or not it is safe to execute through forward simulation. If the command is deemed safe, the assisted teleoperation system passes the command on to motor control. If, however, the command would cause the MRP system to collide with an obstacle, the assisted teleoperation system attempts to find a velocity command that is similar to the desired command of the user, but will not result in a collision. The three main components of the assisted teleoperation software–the costmap, the trajectory simulator, and the user interface–are described in detail below, and are arranged as shown in Figure 2.

Fig. 2. The assisted teleoperation software architecture. The user gives a desired command through the web interface, collision checking and trajectory simulation is performed, and a modified command is passed to the remote presence system.



A. *Costmap*

The costmap builds a recent history of obstacle information from sensor data that is provided by the laser mounted on the base of the MRP system. The costmap consists of a planar grid that is 10 meters by 10 meters in size at a resolution of 0.05 meters per cell. Each hitpoint in a given laser scan is projected into the grid and raytracing is performed from the origin of the laser to each hitpoint to clear any previously observed obstacles that the sensor now sees through. Once the grid is updated with new obstacle information, inflation is performed to propagate cost from obstacles out to an inflation radius of 0.55 meters.

The costmap is also used to check whether or not a given position and orientation of a MRP system footprint collides with obstacles. It looks up the cost value for the center point of the cell occupied for the footprint and performs two checks. First, the costmap checks whether the cost corresponds to the inner circle of the MRP system footprint being in collision with an obstacle. Next, it checks whether the cost corresponds to the outer circle of the MRP system footprint being in free space. If neither of these checks are satisfied, the footprint of the MRP system is rasterized into the grid and checked for intersection with any cells marked as obstacles.

One limitation of the assisted teleoperation software's ability to avoid obstacles stems from the fact that only a planar laser is used to provide sensor input. This means that the software is unable to prevent the operator from driving into obstacles that do not intersect the plane of the laser mounted on the MRP system's base. Troublesome examples include, tables, feet, chairs, etc. The costmap's internal structure does support tracking obstacle information in full three-dimensions. However, the system used in these experiments had no three-dimensional sensor to take advantage of this capability.

B. *Trajectory Simulator*

The trajectory simulator attempts to find a trajectory that does not collide with obstacles and that is as close as possible to the original trajectory specified by the operator. To explore the velocity space around the operator's requested velocity command, we use a modified version of the Dynamic Window Approach (DWA) to forward simulate and select among potential commands based on a cost function [16]. In the case of the assisted teleoperation software, trajectories are scored by their distance from the operator's original command and are checked for collision using the costmap described above. If no valid trajectory is found in the window of velocity space explored, the assisted teleoperation system does not allow the MRP system to move.

The assisted teleoperation system provides a parameter that specifies the size of the window to explore around the operator's requested velocity. This, in turn, controls how much assistance the system is allowed to give to the operator. A small window gives the operator of the MRP system more fine-grained control in the presence of obstacles, which is often desirable in cases where the operator wants to approach an obstacle, like a person, closely. However, a small window also limits the ability of the MRP system to correct for an operator when performing tasks like moving through a tight doorway, where a larger window would be preferred. In practice, the assisted teleoperation software runs with a window that allows for 20 degrees difference from the original velocity command's angular component. This seeks to provide a balance between fine-grained control and the ability to correct for errors in tight spaces.

C. *User Interface*

The operator controls the MRP system through a web application. This web application shows the user video from a downward-facing camera, and provides them a simple interface for driving where they drag a ball in the direction they want to go with their mouse. The user is also given feedback in the form of an arrow overlaid on top of the video feed, pointing in the direction that the MRP system is currently driving. The operator can also switch between assisted and unassisted driving modes with a checkbox.

V. CONTROLLED EXPERIMENT DESIGN

To evaluate the effectiveness of assisted teleoperation on this remote presence system, we ran a controlled experiment that varied assisted vs. unassisted teleoperation (within-participants) and measured task performance in terms of time to complete an obstacle course, number of obstacles hit, etc. We also measured demographic information about each participant, including their spatial cognitive abilities, cognitive workload, gaming experience, perceptions of the system, etc. Each participant drove both assisted and unassisted teleoperation versions of the MRP system. The conditions were counterbalanced to address ordering effect and learning effect issues; half of the participants were randomly assigned to drive with assisted teleoperation first and half of the participants to drive unassisted first.

A. *Hypotheses*

Because assisted teleoperation was designed to help operators avoid obstacles, we anticipated that the number of errors (i.e., bumping into obstacles) would decrease when people used the assisted teleoperation feature instead of the unassisted control. We did not have a preconceived hypothesis about whether it would take more or less time to complete the obstacles course.

- H1. Participants will hit fewer obstacles when using assisted teleoperation instead of unassisted teleoperation.

Because participants may differ in their experience and skills levels, we hypothesized that several of these factors would also influence task performance.

- H2. Participants with greater spatial cognitive abilities will (a) complete the course faster and (b) hit fewer obstacles than people with lesser spatial cognition abilities.
- H3. Participants with more video gaming experience will (a) complete the course faster and (b) hit fewer obstacles than people with less experience.

Other human-centered factors such as gender were measured, but were not included in generating hypotheses about the outcomes of the current study.

B. User Study

To design the full user study, we first conducted a pilot experiment with three users, allowing people to navigate from one end of our office building to the other end, following a specific path. These participants drove the MRP from point A to point B, using assisted or unassisted teleoperation. Then they turned around and drove from point B to point A, using the other form of teleoperation (unassisted or assisted). This pilot study allowed us to identify what types of environment characteristics and obstacles in are problematic for piloting this MRP system. We found that turning corners and avoiding tables and trash bins were problematic maneuvers so we designed a controlled, compressed obstacle course that included these difficult environmental features and obstacles for the full user study.

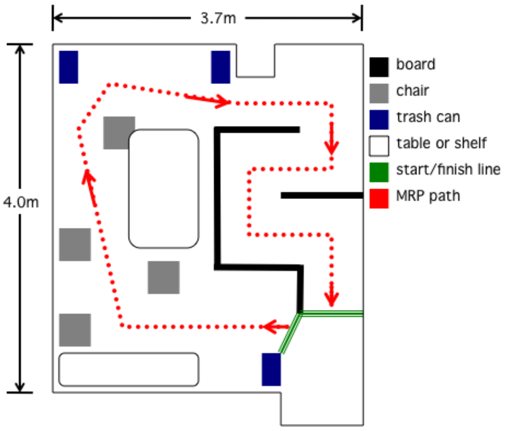
1) Participants: 24 adult volunteers participated in the study, including 12 women and 12 men. Their occupations varied, including engineer, attorney, game programmer, and systems analyst. The participants were not roboticists and had never used the MRP system before participating in the study. Participants were recruited by email and were paid with a 15 USD gift certificate as compensation for their time and effort.

2) Methods and Procedures: Participants remotely logged in to the system web-based GUI from their own home or office locations, not necessarily even in the same state as MRP systems location. They were required to have at least 1 MB of download and upload bandwidth and less than 300 ms of latency in their network connections. This is consistent with the MRP system requirements to operate effectively. Upon completing a network speed test, participants remotely logged in to the MRP system that was located in our lab room, which was set up with an obstacle course.

Once participants had successfully logged in, they were greeted by the experimenter and instructed to complete the first of three online questionnaires. This pre-task questionnaire gathered demographic information, including technology use, personality measures, and spatial reasoning abilities. None of the participants had prior experience with the MRP system, so they were given training and practice sessions. The training consisted of teaching participants how to drive the MRP system forward, backward, to the left and right, and how to turn in place. Following the training session, the participants were asked to practice driving by make three untimed laps around a T-shaped obstacle placed in the middle of the experiment room. The shape of the object and the narrow space between it and the wall forced participants to practice their turning and hone their control of the MRP system.

After completing the practice laps, participants made their way to a starting line in preparation for their first obstacle course run. See Figure 3. Objects that would typically be found in an office, such as tables, chairs, and whiteboards, were used as obstacles around the room. The participants were instructed to drive as best as possible and consider both speed and accuracy (running into objects). Once the participant was clear on the instructions, the experimenter counted down, “3-2-1-Go,” then started a stop watch. As the participant drove the MRP system in a clockwise direction around the room, the experimenter filmed session and noted the number of times the MRP system collided with an obstacle. When the MRP system crossed the finish line, the experimenter recorded the finish time.

Fig. 3. Obstacle course for assisted teleoperation experiment



The participants were then instructed to complete a second online questionnaire that asked about their perceptions of MRP piloting experience. Once the questionnaire was completed, the MRP system was again lined up at the starting line for a second obstacle course run. The two obstacle course runs remained the same with the exception of the MRP system configurations. Each participant drove one obstacle course with the unassisted MRP system settings and one run with the assisted teleoperation settings. The participants were guided through a web interface to change from one configuration to another. They were informed that the assisted teleoperation feature was designed to help avoid some obstacles. Additionally, the experimenter explained how the MRP system laser range finder would detect objects and walls based on their height and that the MRP system would slow down or stop completely when an obstacle was detected. The second obstacle course run was followed by a third questionnaire, duplicating the items of the second questionnaire. Once participants finished the third questionnaire they were debriefed about the study and engaged in a discussion about the study before logging off.

3) Measures: Task performance metrics were the most important measures for this study. Time on task (i.e., seconds until the completion of the obstacle course) and number of errors (i.e., the number of times the MRP hit an obstacle) were the primary measures of task performance. We also calculated an adjusted time on task, which accounted for the time spent getting unstuck in the assisted teleoperation condition. In the assisted teleoperation condition participants occasionally became stalled because the system would detect obstacles and prevent the pilots from moving. Participants were given thirty seconds to attempt to free the MRP system from its stalled state. After thirty seconds with no forward progress the experimenter would physically move the MRP system from its stuck position and note that the participant had been stalled. The adjusted time measure was calculated by taking the total time to completion and subtracting thirty seconds for every time the participant was stalled. Human dimensions were measured because individual differences may affect the participants ability to operate the MRP system. Spatial cognitive abilities were evaluated using the Mental Rotation Task [17]. In this task, participants viewed a 2-D version of a 3-D geometric shape and were asked to identify which two out of four multiple-choice images match the original geometric shape; the matches are presented at different rotational angels from the original. We also asked participants about their automobile driving experience (e.g., number of driving violations), knowledge about robots, video gaming experience, locus of control, etc. Using a principle components analysis (PCA), we found that experience with the following types of video games created a single index (Krippendorfs α=.94): action, adventure, fighting, first-person shooter, role playing game, simulation, sports, and strategy.

The personality dimension of locus of control [18] was also used; people with a more internal locus of control believe they have control over events in the world whereas people with a more external locus of control believe that they have less control over events in the world.

Cognitive workload and perceptions of the MRP system were also measured in a post-task questionnaire [19]. This cognitive workload measure is a self-reported questionnaire that is administered immediately after completing a task, including questions about the mental, physical, and temporal demands experienced while doing the task.

Finally, ratings of 12 adjectives were used to assess users perceptions of their experiences with using the MRP system, including items such as comfortable, confusing, fun, frustrating, enjoyable, annoying.

C. Data Analysis

First, we ran a simple t-test analysis to see if the time-on-task and error rates were significantly different between the assisted and unassisted versions of the system, using a difference score (assisted minus unassisted). We tested the hypothesis that the difference score between the two different conditions would be significantly different from zero.

Second, we ran a more complex analysis to see if other factors influenced time-on-task, error rates, and other dimensions of the MRP user experience. Because each participant was exposed to both experiment conditions, we used repeated measures analysis of variance (ANOVA) to analyze the data. In this way, we were able to statistically evaluate the effectiveness and impact of the assisted teleoperation feature as used by naive users. To simplify the data analysis, we used a median split on the following continuous variables: mental rotation task performance, locus of control, and video gaming experience.

TABLE I

MEAN AND STANDARD ERRORS FOR ASSISTED VS. UNASSISTED TELEOPERATION TASK PERFORMANCE

Mean (SE)	Seconds on Task	Number of Collisions
Assisted Teleop	199.4 (17.8)	1.08 (0.26)
Unassisted Teleop	135.0 (12.5)	3.46 (0.61)

Fig. 4. Mean and SEs for assisted vs. unassisted teleoperation's influence upon task completion times and error rates (from simple t-test)

VI. RESULTS

A. How Assistance Affects Task Performance

First, we analyzed how assisted vs. unassisted teleoperation affected time-on-task and error rates. We found that MRP operators completed the obstacle course with fewer errors when they had assistance than when they had no assistance ($M_{(assisted-unassisted)}$=-2.38, SE=0.64), t(23)=-3.71, $p<.01$. However, they took longer to complete the obstacle course with the assistance ($M_{(assisted-unassisted)}$=64.38, SE=11.73), t(23)=4.59, $p<.0001$. This was true for the adjusted time calculations, too, ($M_{(assisted-unassisted)}$=38.13, SE=10.09), t(23)=3.78, $p<.0001$. See Figure 4.

For the remainder of the data analyses, we present the results of repeated measures ANOVAs that accounted for the experiment condition (assisted vs. unassisted) as a within-participants variable.

B. How Human Dimensions Affect Performance

For these analyses, we added the between-participants factors of spatial cognitive ability (as measured by the mental rotation task score), locus of control, and gaming experience. Assisted vs. unassisted teleoperation control was the within-participants factor.

Thus, the assisted vs. unassisted teleoperation variable was tested along with other human-centered factors to see which of the variables accounted for more of the variance in task performance scores. When including these human factors in the equation, the assisted vs. unassisted teleoperation manipulation was not found to have a significant effect upon time-on-task or error rates.

People who had greater spatial cognitive abilities [17] were significantly faster at completing the obstacle course (M=147.8, SE=17.1) than people with lesser spatial cognitive abilities (M=190.2, SE=15.4), F(1,41)=9.66, $p<.01$. People with more of an internal locus of control [18] took longer to complete the obstacle course (M=210.0,

TABLE II

RESULTS OF REPEATED MEASURES ANOVA ANALYSIS

	df	*MS*	*F*	*p*
Assisted vs. Unassisted	1	835	0.30	0.589
Spatial Cognitive Ability	1	27134	9.66	0.003**
Locus of Control	1	54877	19.53	0.00007***
Gaming Experience	1	10120	3.60	0.065
Residuals	41	115221		

* = $p<.05$. ** = $p<.01$. *** = $p<.001$.

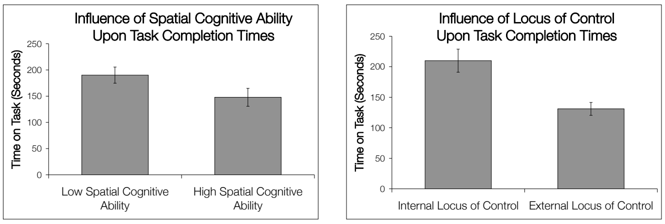


Fig. 5. Mean and SEs for human influences upon task completion times (from repeated measures ANOVA)

SE=18.9) than people with more of an external locus of control (M=131.0, SE=10.5), F(1,41)=19.5, $p<.001$. Gaming experience had an effect on time-on-task that approached significance, F(1,41)=3.6, p=.07, but did not reach it. See Figure 5.

None of these factors were found to have a significant effect upon error rates.

C. Influences on Cognitive Load and Perceived User Experience

Because the NASA-TLX cognitive load measure consisted of six items [19], we used a Bonferroni correction to set the significance cut-off value at 0.008 (=0.05/6). Although most of the NASA-TLX cognitive load measures were not found to reveal significant differences between assisted and unassisted driving, we did find differences in one item from that TLX scale: How physically demanding was the navigation task? On a scale of 1 (very low) to 7 (very high), gamers felt that the task was less physically demanding (M=2.17, SE=0.37) than non-gamers (M=3.83, SE=0.25), F(1,41)=19.94, $p<.001$. See Figure 6.

Because the questionnaire included 12 adjective ratings, we used a Bonferroni correction to set the significance cut-off vlaue at 0.0041 (=0.05/12). One item showed a significant difference in perceptions of the MRP user experience: Enjoyable. On a scale of 1 (disagree) to 5 (agree), gamers felt that using the MRP system was more enjoyable (M=4.58, SE=.10) than non-gamers (M=3.58, SE=0.22), F(1,41)=17.70, $p<.001$. See Figure 6.

Enjoyment and perceived physical effort were moderately correlated, r=-.06, $p<.001$.

VII. DISCUSSION

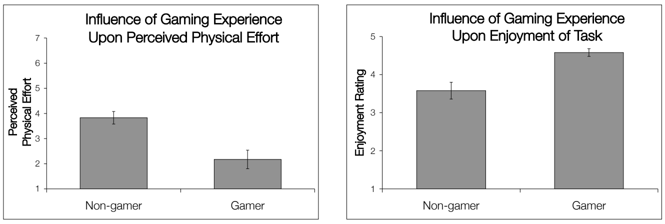


Fig. 6. Mean and SEs for gaming experience's influence upon user experience (from repeated measures ANOVA)

Hypothesis 1, which stated that autonomous assistance would help people to hit fewer obstacles, was supported by these data, but only in the absence of the human variables (i.e., spatial cognitive ability, locus of control, and gaming experience). When the human variables were added to the equation, then the presence of assistance did not significantly influence the number of obstacles hit or the time spent in completing the task.

Hypotheses 2a, which stated that greater spatial cognitive abilities would improve task performance (time to task completion) were supported by these data, but Hypotheses 2b, regarding a decrease in error rates, was not supported.

Hypothesis 3, which stated that more video gaming experience would improve task performance (time to task completion) and decrease error rates, was not supported. Instead, video gaming experience was found to influence perceptions of the user experience. It decreased how physically demanding the task felt and improved how enjoyable the participants perceived the task. This is consistent with previous findings that video gaming experience is correlated with how positively people rate human-robot interactions [20].

The current study also identified other statistically significant relationships between variables that did not have hypotheses at the beginning of the study. We found that autonomous assistance slows people down from completing the obstacle course (in the absence of human dimensions). This suggests that there may be a speed-accuracy trade-off when selecting to use assisted vs. unassisted teleoperation settings. Also, an operators locus of control influenced their task performance in terms of how long it took to complete the obstacle course. Contrary to previous work, we did not find a strong correlation between gender and spatial ability [21].

VIII. CONCLUSIONS AND FUTURE WORKS

We have presented the results of a system design, implementation, and controlled user study (N=24). A simple data analysis that only included the predictive factors of assisted vs. unassisted teleoperation found that the assisted teleoperation helped operators to collide with fewer obstacles, but it took them longer to complete the obstacle course. In contrast, when we conducted a more complex analysis that included human dimensions, we found that spatial cognitive ability and locus of control outweighed the assisted vs. unassisted teleoperation predictor in terms of how long it took operators to complete the obstacle course. Furthermore, operators with more video gaming experience found the task to be less physically demanding and more enjoyable than people who had less video gaming experience.

A. Implications for Research and Design

Altogether, these results indicate that human dimensions influence the way in which people use MRP systems (e.g., human dimensions influence task performance) and can even outweigh the effects of autonomous driving assistance. While a simpler analysis that calculated the difference scores between assisted vs. unassisted teleoperation had shown significant differences in task performance, those results did not hold up in the face of other human influences upon task performance, e.g., the operators spatial cognitive ability. In terms of future research in this area, it is critical to include human dimensions, not only system-level dimensions (e.g., assisted vs. unassisted teleoperation), when assessing performance.

Based on the results, a number of design recommendations can be proposed. First, by assessing performance only, the assisted teleoperation feature allowed for more accurate performance; however, a speed-accuracy trade off existed. Due to this trade-off, it is recommended that the assisted teleoperation is an option that may be more useful in some situations than others. For example, assisted teleoperation may be beneficial when the system is operating in an environment where accuracy is of high priority (e.g., a crowded room, or a space with fragile obstacles), but navigation time is not.

Additionally, previous assessments of teleoperation primarily assessed only task performance (speed and accuracy). However, the results of this study suggest that it is crucial for designers to also consider individual differences and human variables when developing MRP systems.

The purpose of this study was to share the results of this work so that others can use this code and these methods to better understand the influences upon task performance and user experience in mobile remote presence and assisted driving. The current system may help in terms of future system designs; it may be important to have a better sense of the human dimensions of the user that ones system is aiming to support.

B. Limitations and Future Works

As with any single system or single study, there are many limitations that can be addressed by follow-up work. First, this study was only conducted with one robotic system so future work can and should conduct follow-up studies on other hardware platforms, using other sensors, drive systems, etc. Second, this study was only conducted with one type of assisted teleoperation; future work could extend this work to examine other forms of shared control. Third, this study was only conducted with novice MRP operators; future work could look at more experienced operators and their changes in task performance, user experiences, and preferences over time. Fourth, this particular obstacle course may not be the best representation of difficult driving situations for other types of systems so future work could look at other forms of obstacle courses for evaluating such shared control navigation systems.

The current study provides open source code for others to use, build upon, and compare new algorithms against. This evaluation shows how both human and robotic system dimensions can be used to systematically evaluate the factors that influence task performance. Together, this system and evaluation provide one step along the way to providing a more systematic exploration of human-robot shared control.

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