2013

A comparison of performance on a tele-robotic search task under different conditions of navigation

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A comparison of performance on a tele-robotic search task under different conditions of navigation

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:
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Ames, Iowa

2013

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CHAPTER 1. GENERAL INTRODUCTION

Introduction

Tele-robots are a unique class of robots because their use involves collaboration between the robotic technology and the human operator(s). The level of this collaboration can range from a master-slave relationship, where the operator directly controls all of the robot's actions, to a fully autonomous operation, where the robot functions independently of the operator. Technological advances in both robotic hardware and software have expanded the list of domains and applications where the use of tele-robots is both desirable and feasible. These areas include planetary exploration, remote surgery, military surveillance, and—the domain of this work—urban search and rescue (USAR). The use of tele-robots in these varied domains brings a number of challenges along with the possibilities. Many of these challenges relate to determining how to obtain and present the information the operator needs to achieve the best possible performance on the given task(s). In the area of USAR, the primary tasks are navigating a robot around a search area and perceiving any targets that are present. These seemingly simple tasks become quite difficult when performed in a remote location from the point of action. Although researchers have studied this problem for many years, generalizable protocols to accomplish these tasks at a consistently high level of performance have yet to be identified. The work described in this thesis represents another step towards the accomplishment of this goal.

Thesis organization

Chapter 2 describes a study which examines the effects of using different methods to navigate a tele-robot around a search area on tele-operators' performance. Chapter 3 provides some general thoughts on this work and how it fits within the general body of tele-robotics work.

CHAPTER 2. A COMPARISON OF PERFORMANCE ON A TELE-ROBOTIC SEARCH TASK UNDER DIFFERENT CONDITIONS OF NAVIGATION

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A paper to be submitted to *Human Factors: The Journal of the Human Factors and Ergonomics Society (HFS)*

Abstract

This study investigated the impact of the design of robotic navigation algorithms on human performance in a searching task. Participants searched for targets in a real-world environment using a tele-robot in the context of an urban search-and-rescue task. Participants were assigned to one of three conditions for the navigation of the tele-robot around the search area: tele-operation or automated navigation using one of two different algorithms.

Participants in the left-wall algorithm condition found significantly more targets that were of medium-high difficulty to identify. In addition, participants in the tele-operation condition used two distinctly different approaches to navigate around the search area. This evidence suggests that the development of path planning algorithms needs to be tailored to the operator. The knowledge that there are differences in algorithms from the human perspective provides an additional metric for the robotics community to decide between algorithms that are otherwise equivalent. Acknowledging the effect of differences in these algorithms when making design choices is important for the success of the human-robot partnership.

Introduction

What is the future of tele-robotic systems? The National Research Council deemed that robots are vital in the future of rescue technology (National Research Council, 2002). The first

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known use of tele-robots in urban search-and-rescue (USAR) was during the World Trade Center disaster in 2001 (Casper, 2002). Small robots demonstrated their usefulness to send back data about the situation during the disaster and subsequent rescue operations (Murphy, 2004). Since then, tele-robots have been increasingly used as integral members of teams conducting safety-critical missions (Yanco and Drury, 2004). Their use is a particularly attractive option in search areas which are not conducive to direct human involvement, such as areas with small openings, voids or dangerous environmental hazards (Murphy, 2004; Casper & Murphy, 2002). Research suggests that future USAR tele-robotic systems will make significant use of autonomous navigation algorithms (Chien, et al., 2010). This study investigated how the design of autonomous navigation algorithms can affect the performance of a tele-robotic system operator.

Current State

Current rescue robots typically are tele-operated (Casper & Murphy, 2002) where the operator's input is translated directly into the robot's motion. In these cases, robots are sent into the search area to act as the remote eyes of the rescuers; navigating the area while an operator controls them from a stationary location outside of the disaster area (Ruangpayoongsak, Roth, & Chudoba, 2005). The problems that arise during tele-operation of a robot have been well documented and most notable include cognitive overload and spatial disorientation (Murphy, 2004; Hughes & Lewis 2004; Yanco & Drury, 2002). To help overcome these issues, tele-robots are most often controlled by a minimum of two people (Murphy, 2004; Casper, 2002). This method requires extensive communication and teamwork between the operators to effectively navigate around and search an area (Murphy, 2004) and it reduces the number of people available for other critical tasks (Birk & Carpin, 2006). Despite these limitations, tele-operation continues to be the primary method of controlling tele-robots because it leverages the perception ability of the human operator. In the domain of USAR, this perception ability involves accurate distinction between targets and debris. The technological capabilities of autonomous perception lag far behind that of human capabilities (Murphy and Burke, 2005). Current object recognition algorithms are often successful at finding targets in simple environments, but fail to find them as the search area becomes more complicated (Worrall, 2008).

Autonomous navigation

Previous work has established a link between perceptual problems and decreased performance (Jones & Endsley, 1996; Burke, 2004; Casper & Murphy, 2002). Given these findings, the focus of improvements for future tele-robotic systems should involve efforts to support human performance by making perception easier. A number of studies have demonstrated that autonomous navigation has the potential to provide significant support for human perception as well as allow a single operator to control a robot, or even multiple robots (Chien et al,. 2010; Worrall, 2008; Hughes & Lewis, 2004; Ruangpayoongsak et al., 2005; Goodrich et al., 2001; Lewis et al., 2003; Wang et al., 2009; Casper & Murphy, 2002; Kitano et al., 1999). Instead of using multiple operators to reduce the cognitive load and improve performance, autonomous navigational path planning would alleviate the cognitive burden of navigating an unknown environment while simultaneously searching for rescue targets (Goodrich, Olsen, Crandall, & Palmer, 2001; Crandall & Goodrich, 2002). By eliminating the navigational component of the task, operators can direct more of their attention to the search for targets and developing an awareness of the environment.

For the navigation of tele-robots to be automated, the robot's path planning algorithm needs to provide complete coverage of the search area while avoiding collision with obstacles or becoming immobilized, as well as support the human in their perception. However, the vast majority of research on the design of robot navigation algorithms has neglected to consider the impact of design choices on a human operator partnered with the robot. The testing of the algorithms is typically completed using a simulated search environment and focuses on testing the ability of the algorithm to achieve complete area coverage (Chien, Wang, & Lewis, 2010; Worrall, 2008; Ruangpayoongsak et al., 2005; Goodrich, Olsen, Crandall, & Palmer, 2001; Lewis, Sycara, & Illah, 2003). Studies that do test the algorithms using robots in the real-world often only involve the algorithm designers and still only focus on the area coverage of the robot as compared with the predictions from simulations (Wang, et. al., 2009; Casper, 2002; Kitano et al., 1999). The assumption behind these studies is that any type of navigational automation is beneficial. To some extent this assumption is valid. As previously mentioned, the automation reduces the cognitive load of the operator and allows him/her to focus on target perception. However, for these algorithms to be most effective, they need to be tailored to maximize human performance.

Human wayfinding

This consideration is particularly important when humans use tele-robots to perform a searching task because research focused on the way in which people orient themselves in physical space and navigate from place to place, known as wayfinding, suggests that there are distinctive ways that humans navigate around an unfamiliar landscape (Chin-Teng et al., 2012). In addition, human search-and-rescue teams commonly use certain navigation algorithms, such as right- or left-wall-following, to systematically maneuver around an area (Casper, 2002). In contrast, the paths created by traditional robotic path planning algorithms are distinctly differently from those created by humans, with the robotic paths being more tortuous and the human paths more linear (Chien et al., 2010). Thus, in the area of autonomous navigation of a tele-robot, a key issue presents itself in determining how humans versus a robotic algorithm search an environment, and how the search approach influences the operator's performance on the perception task (Chien et al., 2010). We believe that robots that follow navigation algorithms that are more in line with the natural way that human conduct wayfinding will improve human performance on the perception task. This study investigates the more general hypothesis that, given the same search area, differences in the robot paths produced by different algorithms will have an impact on the human operator's performance. In this study, a comparison was made of the performance of operators conducting a searching task in a real-world environment under three different conditions: single operator tele-operation or autonomous navigation using one of two different algorithms. Specifically, the study was conducted to answer the following research questions:

- Will the operators in the autonomous navigation conditions identify more targets than those in the tele-operation condition?
- Will the operators in one autonomous navigation condition identify more targets than those in the other autonomous navigation condition?
- Will there be a difference in the false alarm rate between any of the conditions?
- Will there be a difference in memory between any of the conditions?
- Will there be a difference in mental workload between any of the conditions?

Methods

<u>Participants</u>

A total of sixty participants selected from the population of students at a large Midwestern university were randomly assigned to one of three experimental conditions. The three conditions were: Condition 1-tele-operation (henceforth called "manual" or "M"), Condition 2-autonomous navigation using an algorithm (henceforth called "left-wall algorithm" or "L"), and Condition 3-autonomous navigation using a different algorithm (henceforth called “center-spin algorithm” or “C”). Table 1 shows the distribution of population characteristics across conditions. All participants were inexperienced with tele-navigation and search-and-rescue operations. All participants had normal or corrected-to-normal vision.

Table 1: Participant characteristics

Condition	# of participants	Age	Sex
Manual	20	Avg=25, SD=6.4	8 Male, 12 Female
Left-wall	20	Avg=22, SD=4.4	10 Male, 10 Female
Center-spin	20	Avg=22, SD=2.8	10 Male, 10 Female

<u>Materials</u>

A simulated disaster area was constructed using 1.2 meters tall particle boards. Standards from the National Institute of Standards and Technology (NIST) were used to guide the design of the constructed area. These standards describe the state of buildings in various stages of collapse and as a result varying levels of search difficulty: yellow is the simplest level, orange is a more difficult level, and red is the most difficult level (Jacoff et al., 2003). For this simulation, the area was designed with elements from the yellow and orange levels, with objects on the floor, narrow passageways, and wall materials such as Plexiglas. An image of the constructed area is shown in Figure 1. A schematic of the area with dimensions is shown in the Appendix.

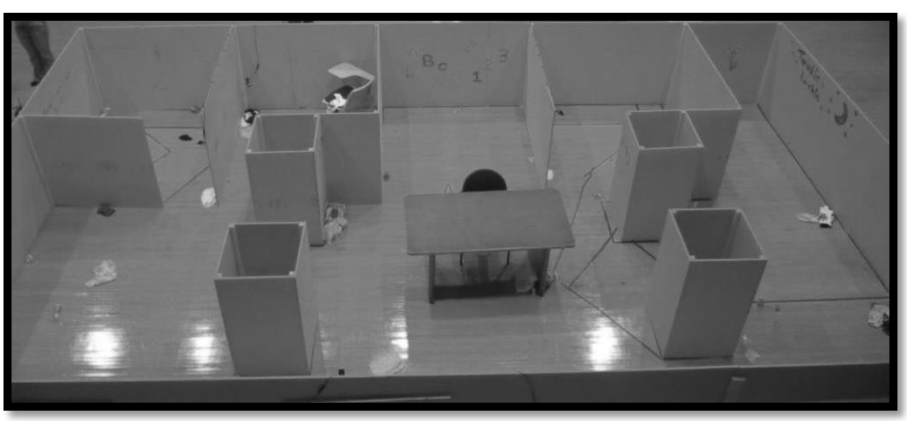

Figure 1. Image of the constructed search area

Five targets were placed within the search area. The targets were baby dolls which were used to simulated babies who were trapped in a daycare center. The five targets used are shown in Figure 2. Keeping with this theme, the debris strewn around the area consisted of baby-related materials (ex. toys, small clothes, bottles). This debris served as distractor items during the target search. Examples of the debris used as distractor items are shown in Figure 3.

Target 1 	Target 2 	Target 3 
Target 4 	Target 5 	

Figure 2. Images of targets

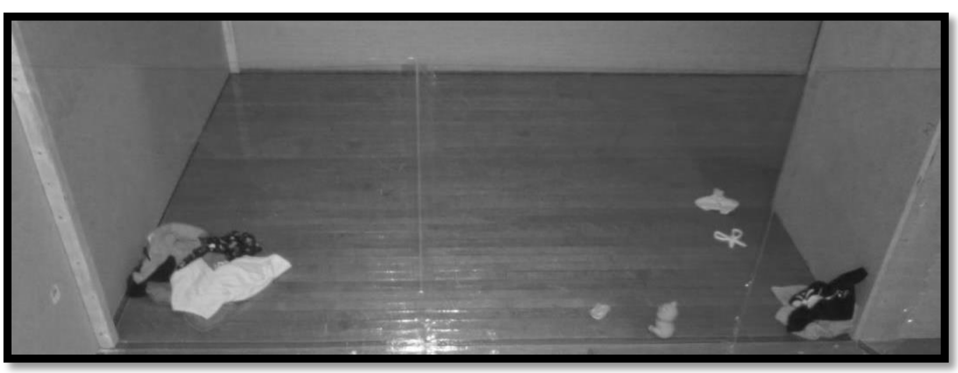

Figure 3. Image of distractor items

For the manual condition, participants used a programmable RC robot, the Spy Video TRAKR, to explore the area. This system, which does not have sensors or other capabilities for “intelligence”, was selected in order to minimize the effect of any technological aid on the performance of the operator. The operators, who were stationed in a remote location from the robot, navigated the robot with a joystick while observing on a computer screen the scene in front of the robot. The scene was obtained via a wireless camera attached to the robot. The wireless camera had a resolution of 640x480 pixels and a frame rate of 10 frames per second. An image of the robot is shown in Figure 4. The video feed was recorded for later analysis using Debut Video Capture software.

Figure 4. Image of robot

For the left-wall condition, the same robot used in the manual condition was navigated around the search area by the experimenters using the left-wall-following algorithm (Casper, 2002). The path of the robot around the area is shown in Figure 5. A video was made of the scene, using the same camera as in the manual condition, as the robot was navigated along the preset path. Participants watched this video on the same computer screen used during the manual condition. Complete visual coverage of the area was provided by this algorithm. The video lasted for seven minutes, thirteen seconds.

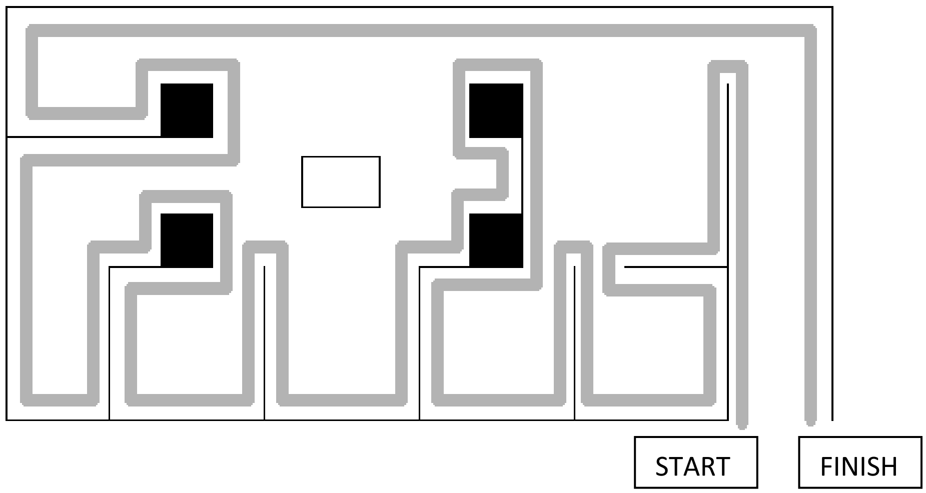

Figure 5. Image of Left-wall algorithm path

The procedure for the center-spin condition was similar to the procedure used for the left-wall condition. The robot was navigated around the search area by the experimenters along a preset path. The path of the robot around the area is shown in Figure 6. Circles indicate where the robot completed a 360º spin. A video was made of the scene, using the same camera as in the manual condition, as the robot was navigated along the preset path. Participants watched this video on the same computer screen used during the manual condition. Complete visual coverage of the area was provided by this algorithm as well. The video lasted for seven minutes, two seconds.

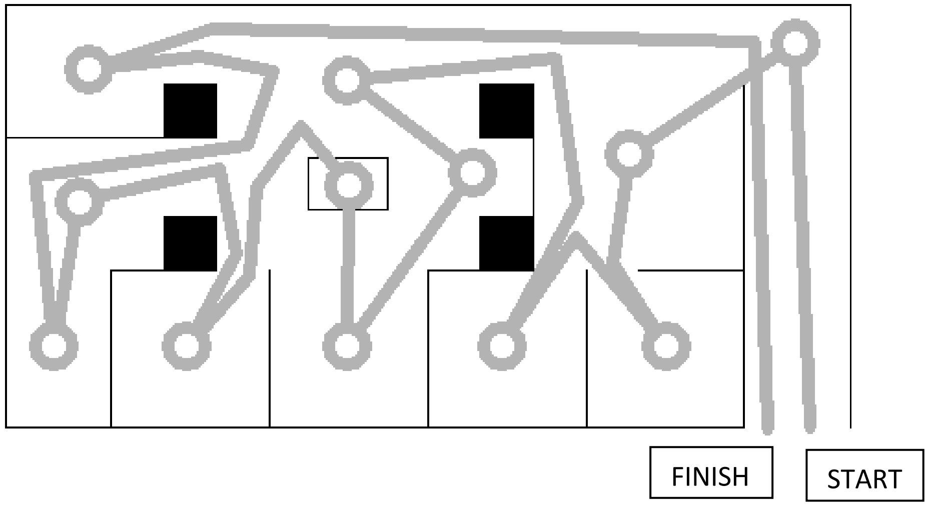

Figure 6. Image of Center-spin algorithm path

After the search task was completed, the participants were asked to complete a mental workload survey (NASA-TLX: Hart & Staveland, 1988) and answer a set of demographic questions. The participants completed these forms electronically using Qualtrics. After completing these surveys, the participants were given a paper map of the search area and asked to mark on the map the location of the targets. A picture of the paper map is shown in Figure 7. All of the data collected from the participants was coded so that it could not be traced back to a particular participant.

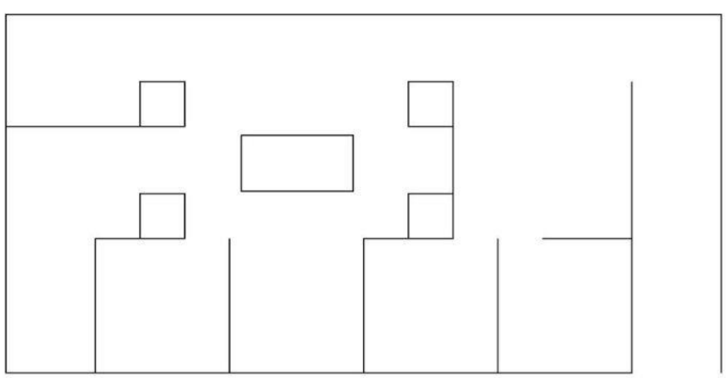

Figure 7. Image of paper map given to participants

Procedure

Manual condition

After obtaining consent, the participant was informed that this experiment would involve remotely navigating a robot. The robot would be maneuvered using a joystick and the path in front of the robot would be observed via a video feed viewed on a computer. (S)he was then shown the robot and given instructions on its operation. Next, (s)he was allowed to practice navigating, first while observing the robot directly and then indirectly by viewing the video feed of the practice area. Once the participant indicated that (s)he felt comfortable operating the robot (usually 5-7 minutes of practice), the robot was taken to the search area and placed at the entrance. The participant was then instructed that there were an unknown number of children, simulated by baby dolls, deserted in a daycare and their task was to locate all of the victims by navigating the robot through the search area. (S)he was also informed that due to the time-sensitive nature of the task, there would be only ten minutes to navigate around the area. The participant then started the task. When (s)he felt a target had been observed, (s)he indicated the identification verbally and an experimenter recorded the identification and whether it was an actual target or a distractor item. When the ten minutes expired, the participant was stopped from navigating. During the task, the video feed observed by the participant was recorded for later analysis. After the main task was completed, the participant was asked to complete the questionnaires. After completing the electronic forms, the participant was given a paper map of the search area and asked to mark on the map the location of the targets. The participant was not told how many targets were located in the area.

Algorithm (left-wall and center-spin) conditions

After obtaining consent, the participant was informed that this experiment would involve identifying targets as a robot autonomously navigated through a search area. (S)he was informed that (s)he would first be shown a demo video, made using the same robot, in order to acclimate them to the camera angle, video quality, relative size of objects, etc. Once the demo video ended, the participant was informed that for the real search area, there were an unknown number of children, simulated by baby dolls, deserted in a daycare and their task was to locate all of the victims by identifying them as the robot navigated through the search area. The participant then started watching the video associated with one of the two algorithms, depending on the condition (s)he had been assigned. When (s)he felt a target had been observed, (s)he indicated the identification verbally and an experimenter recorded the identification and whether it was an actual target or a distractor item. After the main task was completed, the participant was asked to complete the questionnaires. After completing the electronic forms, the participant was given a paper map of the search area and asked to mark on the map the location of the targets. The participants were not told how many targets were located in the area.

Results

Four types of data were collected in the manual condition: the list of targets and distractors identified during the searching task, the mental workload scores (NASA-TLX), the paper maps where the participants indicated where they thought targets were located, and the video recording of the path taken by the participant through the search area. For the two algorithm conditions, the same data were collected, with the exception of the video recordings. The analysis used for each of these datasets is described in the following sections. All analyses were performed at a 95% confidence interval.

Target identification analysis

In order to compare the conditions in terms of the performance of the participants in identifying the targets, the total number of targets identified (out of 5) was tallied for each trial. This tally was called the total hit rate. ANOVA was used to compare the means of the conditions. A significant difference was found and post-hoc Tukey-Kramer tests reveal the difference to be between the total hit rate for the manual condition and the left-wall condition ($p<0.0001$) as well as between the manual condition and the center-spin condition ($p<0.0001$). No significant difference was found for the total hit rate between the left-wall condition and the center-spin condition ($p=0.898$).

In addition to the total number of targets identified, the total number of distractors identified was tallied for each trial. This tally was called the false alarm rate. ANOVA was used to compare the means of the conditions. No significant difference was found between any of the conditions.

In order to further analyze the differences in target identification performance between the conditions, the hit rate for each target was calculated. These tallies were collectively called the target-specific hit rates. ANOVA was used to compare the means of the tallies across conditions. A significant difference was found and post-hoc Tukey-Kramer tests reveal the difference to be for targets 2, 4, and 5. The results are summarized in Table 2.

Table 2: T-test results for target specific hit rate comparisons

	Target 1	Target 2	Target 3	Target 4	Target 5
M vs. L	P=0.924	P<0.0001*	P=0.444	P=0.080	P=0.006*
M vs. C	P=0.731	P=0.006*	P=1.000	P=0.002*	P=0.039*
L vs. C	P=0.497	P=0.460	P=0.444	P=0.390	P=0.755

Due to the recognition of difference in performance across conditions based on the target, a further analysis was conducted to compare the target-specific hit rates within each condition. Student’s pairwise t-test was used to compare the means for each pair of targets, for each condition. These comparisons produced groupings for the targets based on which means were significantly different. The hit rate means that were found to not be significant were grouped together, while those means that were found to be significantly different were grouped separately. These groupings are shown in Tables 3 through 8. In the tables, S stands for a significant difference, and NS stands for no significant difference. All significant values are below p=0.05.

Table 3: Grouping results from pairwise t-tests for center-spin condition-part 1

	Target 1	Target 2	Target 3	Target 4	Target 5
Target 1					
Target 2	S				
Target 3	S	S			
Target 4	S	S	NS		
Target 5	S	NS	S	S	

Table 4: Grouping results from pairwise t-tests for center-spin condition-part 2

Target 1	Target 2	Target 3	Target 4	Target 5
Group A	Group B	Group C	Group C (targets 3 and 4 alike)	Group B (targets 2 and 5 alike)

Table 5: Grouping results from pairwise t-tests for left-wall condition-part 1

	Target 1	Target 2	Target 3	Target 4	Target 5
Target 1					
Target 2	S				
Target 3	S	NS			
Target 4	S	NS	NS		
Target 5	S	NS	NS	NS	

Table 6: Grouping results from pairwise t-tests for left-wall condition-part 2

Target 1	Target 2	Target 3	Target 4	Target 5
Group D	Group E	Group E (targets 2, 3, 4 and 5 alike)	Group E (targets 2, 3, 4 and 5 alike)	Group E (targets 2, 3, 4 and 5 alike)

Table 7: Grouping results from pairwise t-tests for manual condition-part 1

	Target 1	Target 2	Target 3	Target 4	Target 5
Target 1					
Target 2	NS				
Target 3	S	S			
Target 4	S	NS	S		
Target 5	NS	NS	S	NS	

Table 8: Grouping results from pairwise t-tests for manual condition-part 2

Target 1	Target 2	Target 3	Target 4	Target 5
Group F	Group F-I (targets 2 and 5 alike)	Group H	Group I	Group F-I (targets 2 and 5 alike)

Once the groups were identified, meaning was assigned to the differences and similarities by observing the raw target-specific tallies. These tallies are shown in Table 9. Since there were 20 participants in each condition the maximum tally amount is 20.

Table 9: Target-specific hit rate totals

	Target 1	Target 2	Target 3	Target 4	Target 5
Manual	4	8	20	12	8
Center-spin	6	16	20	20	15
Left-wall	3	19	19	17	17

Table 9 shows that for target 1, the hit rate is very low for each of the conditions. This distinction is reflected in groups A, D, and F. As a result these groups were each labeled as high difficulty. Table 9 also shows that for target 3, the hit rate is very high for each of the conditions. The hit rate is also very high for target 4 in the center-spin condition, and for targets 2, 4, and 5 in the left-wall condition. This distinction is reflected in groups C, E, and H. As a result these groups were each labeled as low difficulty. For groups B and I, the hit rate total was more than that of the high difficulty groups but less than that of the low difficulty groups. As a result, these groups were labeled as medium difficulty. Finally, group F-I was associated with both the high difficulty groups and the medium difficulty groups. As a result this group was labeled high-medium difficulty to reflect a difficulty that is more than the medium groups, but less than the high difficulty groups. These labels are shown in Table 10. Of particular note is the change in difficulty level for targets 2, 4, and 5 as the conditions change. For target 2, the difficulty decreases from the manual condition (high-medium difficulty), to the center-spin condition (medium difficulty), to the left-wall condition (low difficulty). For target 4, the difficulty decreases from the manual condition (medium difficulty), to the center-spin and left-wall conditions (low difficulty). For target 5, the difficulty decreases from the manual condition (high-medium difficulty), to the center-spin condition (medium difficulty), to the left-wall condition (low difficulty).

Table 10: Groups derived from pairwise t-tests within each condition

	Target 1	Target 2	Target 3	Target 4	Target 5
Manual	High difficulty	High-Medium difficulty	Low difficulty	Medium difficulty	High-Medium difficulty
Center-spin	High difficulty	Medium difficulty	Low difficulty	Low difficulty	Medium difficulty
Left-wall	High difficulty	Low difficulty	Low difficulty	Low difficulty	Low difficulty

Mental workload analysis

Mental workload scores (NASA-TLX) were calculated for each participant. ANOVA was used to compare the mean scores. A significant difference was found and post-hoc Tukey-Kramer tests reveal the difference to be between the scores for the manual condition and those for the center-spin condition, with the scores for the manual condition being higher. The results are summarized in Table 11.

Table 11: T-test results for comparing survey scores

	mental workload
C vs. L	P=0.501
M vs. C	P=0.011*
M vs. L	P=0.160

<u>Paper map analysis</u>

Since each mark on the paper maps indicated a target from the participant's perspective, the total number of marks on the map can be considered how many targets the participant remembered identifying during the duration of the searching task. Thus, the total number of marks is a measure of memory. To compare the memory of the participants across conditions, the total number of marks on the paper map was compared to the sum of the targets and distractors actually identify by the participants during the task. The comparison was done using a Pearson's correlation test. Memory was most closely correlated with the total number of items identified in the left-wall condition followed closely by the manual condition. The results are summarized in Table 12.

Table 12: Summary of correlations for marks on map vs. total number of identifications

	Manual	Left-wall	Center-spin
Correlations	R=0.6319, P=0.0028*	**R=0.6628, P=0.0014***	R=0.3765, P=0.1018

<u>Video recording analysis</u>

To analyze the videos, first, the path taken by the robot as it was tele-operated by the participant was transferred to a paper map of area. The path distance travelled by each participant was calculated by tracing the path drawn on these maps with a Scale Master Classic digital plan measure and scaled by the appropriate factor (1:4). In addition to recording the path of the tele-robot, the videos were review for patterns in the movement of the tele-robot around the area.

Particular attention was paid to the amount of turning, stationary periods, and linear motion. Two approaches were identified from the patterns observed in the video data. The first approach, which was adopted by ten of the participants, was termed the driver method. For this approach, participants spent most of the time in linear motion with stop or turning primarily occurring only when an obstacle was encountered. The second approach, which was adopted by ten of the participants, was termed the searcher method. For this approach, participants spent a significant portion of the time stationary or in rotation with liner motion primarily occurring only when the surrounding area was observed repeatedly. Further support for this distinction was found after comparing the distances travelled by the participants to the type of approach adopted. Distance travelled was found to be highly correlated with navigational approach ($r=0.8072$, $p<0.0001$*) with those who adopted the driver method traveling farther distances. It should be noted that the increased distance travelled did not necessarily lead to increased area coverage due to considerable path overlap. Pearson's correlation test was used to identify if the choice in navigational approach was correlated with performance. Neither approach was correlated with performance.

Discussion

The hypothesis for this study stated that, given the same search area, differences in the robot paths produced by different algorithms will have an impact on the human operator's performance. Following is a discussion of the implications of the results with respect to the hypothesis.

Target identification analysis

The target identification data was used to answer the following research questions:

- Will the operators in the autonomous navigation conditions identify more targets than those in the tele-operation condition?
- Will the operators in one autonomous navigation condition identify more targets than those in the other autonomous navigation condition?
- Will there be a difference in the false alarm rate between any of the conditions?

When determining if there were differences in performance between the three experimental conditions in terms of target identification, the data shown that the comparison needed to be made on a target-specific basis. For those targets which were very difficult to identify or very easy to identify, there was no significant difference between the three conditions. However, for those targets that were of medium-high to medium difficulty there was a significant difference between the manual condition and the two autonomous navigation conditions. This difference is also reflected in the total hit rate comparisons where the data showed that the participants in the autonomous navigation conditions (left-wall and center-spin) identified significantly more targets than those in the tele-operation (manual) condition. These results are in line with previous research which shows that target identification performance increases when the secondary task of navigating a tele-robot is removed and the operator is allowed to focus on the perception task.

A further difference was identified between the two autonomous navigation conditions for the medium-high difficulty targets. The data showed that these targets were easier to identify under the left-wall condition versus the center-spin condition. This finding provides direct support for the hypothesis.

Finally, no significant difference between the conditions was found for the false alarm rate. This indicates that the differences identified between the target hit rates were not confounded by one group being more prone to identify an object in the search area as a target.

Mental workload analysis

The mental workload data was used to answer the following research question:

- Will there be a difference in mental workload between any of the conditions?

The mental workload scores for the manual condition were significantly higher than those for one of the autonomous navigation conditions. These results are in line with previous research showing that mental workload increases with the addition of secondary tasks (Recarte & Nunes, 2003). No significant difference was found between the autonomous navigation conditions. Since participants in the autonomous navigation conditions were engaged in the same number of tasks, it was expected that any differences in mental workload would be smaller than the difference between the manual navigation condition and the autonomous navigation conditions. The NASA-TLX measure has been shown to be limited in its effectiveness to capture small differences (Liu & Wickens, 1994). As a result the mental workload measure may not have been sufficient to capture this more subtle result, if it was present.

Paper map analysis

The data from the paper maps was used to answer the following research question:

- Will there be a difference in memory between any of the conditions?

When the participants were given the paper map test they were directly asked to demonstrate their ability to translate the location of the targets from the egocentric spatial frame of reference to an allocentric spatial frame of reference (Friedman, 2005). They were also indirectly asked to remember and record how many items they had identified during the searching task. This memory measure serves as a secondary performance measure along with the hit rate. The most significant correlation between the actual number of items identified and the number indicated on the maps was for the left-wall condition. An almost equally high correlation was found for the manual condition. In contrast, a low correlation was found for the center-spin condition. These results suggest that features of the center-spin algorithm reduced the participants' ability to develop a mental map of the search area.

Video recording analysis

The primary focus of this study was to explore the effect of using different, but equivalent navigation algorithms on the human operator's performance in terms of hit rate. However, a second issue was raised during the course of the study: what characteristics would a navigational algorithm need to have to provide support for the human operator? To provide some clarity for this question, this study sought to observe patterns in the way the participants in the tele-operation condition navigated the robot and from these patterns, determine general approaches preferred by humans during tele-navigation. The video recordings were used as the data source for this information. From the data two distinct approaches were identified. One approach observed in this study was termed the driver method in which participants spent most of the time in linear motion with stop or turning primarily occurring only when an obstacle was encountered. The second approach was termed the searcher method in which participants spent a significant portion of the time stationary or in rotation with liner motion primarily occurring only when the surrounding area was observed repeatedly. Neither approach was shown to be more advantageous in terms of identifying more targets or identifying fewer distractors. The driver method was shown to be more efficient in terms of distance travelled versus time and, given a different task, this feature may have proven advantageous. These results suggest that operators are not homogenous in their preferred method for tele-navigation. Algorithms may need to be customized for the operator.

Conclusion

This study investigated the impact of the design of robotic navigation algorithms on human performance in a searching task. Additional fidelity was provided for this study by conducting it in a real-world environment with participants who were previously unfamiliar with the robotic system. The results of this study provide strong support for the hypothesis that the choices decided by a navigation algorithm of how to survey an area have an effect on a tele-operator's performance. Also, evidence was found to support the existence of certain tele-navigation approaches which can be used as design principles in future algorithm development. This evidence also indicated that the development of these algorithms needs to be tailored to both the task and the operator.

The knowledge that there are differences in algorithms from the human perspective provides an addition metric for the robotics community to decide between algorithms that are otherwise equivalent. This understand may also allow for the design of simpler algorithms, if in certain circumstances the information needs of a human operator to have a sense of complete coverage of an area is less than what a robot would need to have a similar conclusion. In summary, realizing the effect of these algorithm design choices is important for the success of the human-robot partnership.

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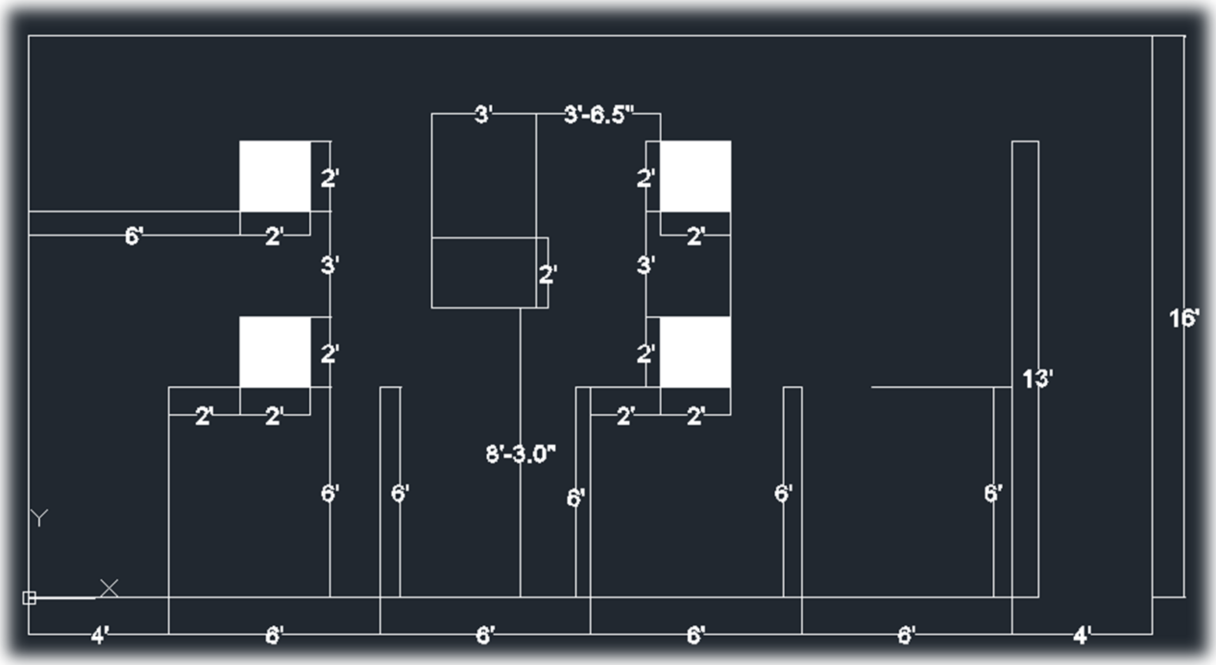
CHAPTER 3. GENERAL CONCLUSIONS

Limitations and Future Work

This study was a first step in exploring the topic of the relationship between tele-robot navigational algorithm design and tele-operator performance. As such, the study had some limitations that should be addressed in future work. Several simplifications were used in this study to allow for the effects of the independent variables to be more clearly observed. These simplifications include the use of a more simplistic search area as compared to a real disaster area, the use of novice participants instead of the intended users of the tele-robotic system, and the use of a tele-robotic system which was stripped of any technological aids. Future studies need to be conducted to test if the findings from this study persist under higher fidelity conditions. In addition, this study would have benefited from a more direct measure of the participants' spatial performance as well as a more refined measure of mental workload. Future work should also include an expansion the types of algorithms tested. Despite these limitations, this study provides a significant basis for understanding how to improve tele-robotic operations through the design of robotic algorithms.

APPENDIX



Appendix: Search area schematic with dimensions