Objective Data Analysis for a PDA-Based Human-Robotic Interface*

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Abstract - *This paper describes a touch-based PDA interface for mobile robot teleoperation and the objective user evaluation results. The interface is composed of three screens; the Vision-only screen, the Sensor-only screen, and the Vision with sensory overlay screen. The Vision-only screen provides the robot's camera image. The Sensor-only screen provides the ultrasonic and laser range finder sensory information. The Vision with sensory overlay screen provides the image and the sensory information in concert. A user evaluation was conducted. Thirty-novice users drove a mobile robot using the interface. Participants completed three tasks, one with each screen. The purpose of this paper is to present the user evaluation results related to the collected objective data.*

Keywords: Personal Digital Assistant, human-robot interaction

1 Introduction

Personal Digital Assistants (PDAs) are used for various purposes. They include several features such as: calendar control, address book, word processing, calculator, etc. PDAs can be used to interact with robots and provide are small, lightweight, and portable devices that are easy to use and transport.

Many standard PDA interfaces have been developed for a wide range of applications. Some robotics researchers have focused on PDA based Human-Robot Interaction (HRI). Fong [1] developed the purely stylus-based *PdaDriver* interface to provide the ability to interact with a robot via his collaborative control architecture. This system provides the capability for the operator and the robot to collaborate during the task execution.

Perzanowski et al. [2] have implemented a multimodal interface that integrates a PDA, gestures, and speech interaction. This work developed multimodal human-robotic interaction for single or multiple robots.

Huttenrauch and Norman [3] implemented the *PocketCERO* interface that provides different screens for a service robot used in home or office environments. They believed that a mobile robot should have a mobile interface.

Skubic, Bailey and Chronis [4, 5] have developed a PDA-based sketch interface to provide a path to a mobile robot. The user employs the stylus to provide landmarks as well as a path through a series of landmarks that can be translated into commands for a mobile robot.

Calinon and Billard [6] have developed speech and vision based interfaces by using a PDA to control a mini-humanoid toy robot called *Robota*. The PDA is mounted on the front of the robot. This mini-humanoid robot tracks and imitates the user's arm and head motions while also tracking the user's verbal input with a speech processing engine that runs on the PDA.

Lundberg et al. [7] have implemented a PDA based interface for a field robot that addresses the following tasks: manually driving, setting the robot's maximum speed, collision avoidance, following a person, exploration of a region, displaying a map, and sending the robot to a location. They conducted a qualitative evaluation that does not report formal quantitative usability or perceived workload analysis. The similarity between their work and this work is that they also designed their interface for military or rescue applications. The other similarity is that they employed touch-based interaction for many capabilities but portions of their interface include pull down menus and in some cases very small interaction buttons.

This paper presents a brief explanation of the PDA–based human-robot interaction and provides the objective results. Section 2 provides the interface design. Section 3 provides the evaluation apparatus. Section 4 provides a brief review of the usability and perceived workload results while focusing on the detailed results from the objective data collection. Finally Section 5 presents the conclusions and discussions.

2 Interface Design

Since PDAs are lightweight, small and portable, they provide a suitable interaction device for teleoperation, especially for military users. PDAs naturally provide a touch-screen interaction capability. The interaction method for this work is finger touch-based, thus the designed interface requires no stylus interaction. The interface is designed to provide sufficiently sized command buttons, so the user can command the robot while wearing bulky gloves. PDAs have a limited screen size. Therefore, the interface is also designed to provide maximal viewing of information on the PDA's screen. This maximization and the large command buttons contradict one another. The system uses transparent buttons to provide the button transparency and view underlying information.

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The interface is composed of three screens. Each provides different sensory feedback and the command buttons are consistent across all three screens. (Complete design details can be found in [8, 9]). The robot can be commanded to drive forward or backward, to turn right or left, as well as combination of forward and turning or backward and turning. A stop button is also provided in the lower right corner of the PDA screen, as shown in Figure 1.

The interface was designed for situations where military users need to remotely interact with the robot without viewing the robot and its environment in addition to the situations where they can directly view the robot and the environment. The three screens employ visual, ultrasonic sonar, and laser rage-finder data to provide meaningful information regarding the robot.

The Vision-only screen provides the forward facing camera image along with the general robot command buttons, as shown in Figure 1. The information beneath the buttons can be easily viewed via the transparent buttons.

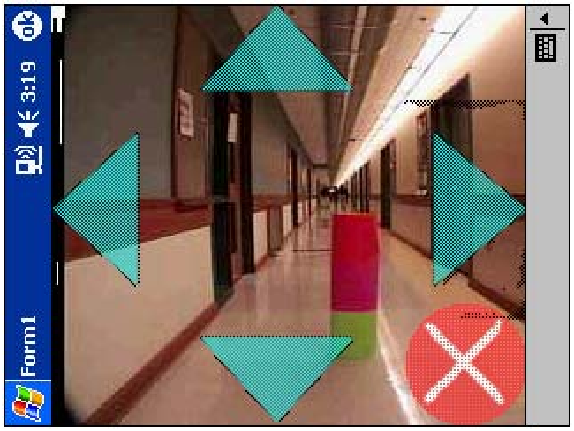

Figure 1. The Vision-only screen.

The current design does not permit camera pan or tilt; therefore a limitation is the user's inability to view the area surrounding the robot when it is located in a remote environment. The user is required to command the robot to physically rotate in order to view other areas.

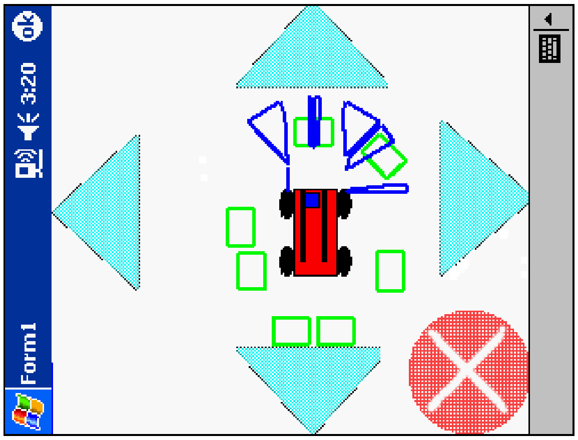

Figure 2. The Sensor-only screen.

The Sensor-only screen provides the ultrasonic sonar and laser range finder information. The ultrasonic sensors provide feedback from the entire area around the robot within their individual field of view. The laser range finder provides a 180º field of view in front of the robot, see Figure 2. The rectangles in the figure represent objects detected by the ultrasonic sonar and the connected lines represent objects detected by the laser range finder.

The Vision with sensory overlay screen combines the presentation of the camera image and the sensory feedback. The forward facing ultrasonic and laser range finder information is overlaid on top of the forward facing camera image. This screen allows viewing of all available information on one screen, as shown in Figure 3. The disadvantage of this screen is that the visible feedback is only from the front of the robot therefore the robot must be rotated to view additional areas.

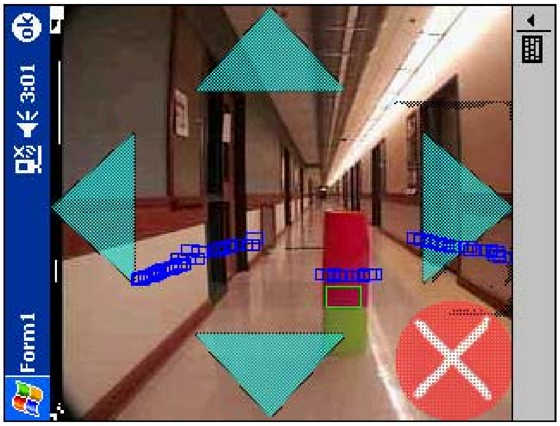

Figure 3. The Vision with sensory overlay screen.

3 User Evaluation

A user evaluation was performed to determine which interface screen was the most understandable and facilitated decision-making. This evaluation also investigated the usability of each screen. The evaluation collected objective information regarding the task completion times, number of precautions, ability to reach the goal location, as well as the number and location of screen touches.

Thirty volunteers completed the evaluation. No participants had prior experience with mobile robots but all had experience using PDAs. Tasks were performed at different locations with similar paths. The participants completed three counter-balanced tasks, one for each screen. Two trials of each task were completed. All but one task was completed from a remote location from which participants were unable to directly the environment. The second trial of the Sensor task permitted participants to directly view the robot and its environment.

After each task was completed, the distance from the robot to the goal point was measured. The goal achievement accuracy was defined as *reached* if the robot was 0 inches vertically from the goal point and 12 inches or less horizontally from the goal point. If the vertical distance was smaller than or equal to 24 inches and the horizontal distance is larger than 12 inches but smaller than 24 inches, the goal achievement accuracy was defined as *almost reached*. The goal achievement accuracy was defined as *passed* if the robot's front passed the goal point. Otherwise the goal achievement accuracy was defined as *not reached*.

The participants completed a post-task questionnaire after each task and a post-trial questionnaire after each trial. The post-task questionnaire contained Likert scale usability questions and NASA TLX [10] scale ratings. The post-trial questionnaire collected usability question rankings and the NASA TLX paired comparisons.

4 Results

The user evaluation data was analyzed using statistical methods. A repeated measure ANOVA and t-tests were conducted on the workload data. A Friedman Analysis of Variance by Ranks and Wilcoxon Signed-Rank test with Bonferroni-correlated alpha ($p < 0.018$) was applied to the Likert scale usability questions and usability ranking questions analyses.

The perceived workload results [11] indicated that the Vision-only screen requires the least workload when participants were required to use all three screens from a remote location. This was the defined condition for all tasks during trial one. During trial two the participants were allowed to complete the Sensor task while directly viewing the robot and its environment. The remaining two tasks were completed as in trial one. This condition change resulted in the Sensor-only screen requiring the least workload. The Vision-only screen was rated as requiring significantly lower workload than the Vision with sensory overlay screen across both tasks.

The usability results [12] related to executing all tasks from the remote environment found that the participants rated the Vision-only screen as significantly easier to use than the Sensor-only and the Vision with sensory overlay screens based upon the usability questionnaire results. The participants also found correcting their errors significantly easier with the Vision-only screen over the other screens. The usability ranking results showed that the Vision-only screen was significantly easier to use than the other two screens, thus supporting the usability question analysis. During trial two, the Sensor-only screen was ranked as easiest to use based upon the usability questionnaire and usability rankings. It was also found that the Vision-only screen was significantly easier to use than the Vision with sensory overlay screen across both trials. The participants provided a significantly higher general overall ranking to the Vision-only screen than other two screens during trial one. The results across screens during trial two indicate that no significant relationship existed.

The detailed user evaluation results can be found in related publications [9, 12]. The following subsections focus on the objective data results related to task completion times, number of precautions, ability to reach the goal location, and the number and location of screen touches. This data was analyzed using descriptive statistics. It should be noted that the Vision with sensory overlay screen required a long processing time which results in a delay between the issuing commands and the robot's action.

4.1 Task Completion Times

During the user evaluation, each task's completion times was recorded. The descriptive statistics are provided in the Table 1. The Sensor task had a shorter path than the paths for the Vision and Vision with sensory tasks, which resulted in different completion times across tasks.

During trial one, the participants completed the Vision task in an average time of approximately 4 minutes 18 seconds, the Sensor task with an average of approximately 3 minutes 36 seconds, and the Vision with sensory task with an average of approximately 4 minutes 51 seconds. During trial two, the participants completed the Vision task with an average time of approximately 4 minutes, the Sensor task with an average of approximately 1 minute 52 seconds, and the Vision with sensory task with an average of approximately 4 minutes 39 seconds.

Table 1. Completion times by trial and task.

	Trial One		**Trial Two**	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
Vision task	4:18	0:54	4:00	0:49
Sensor task	3:36	1:23	1:52	1:12
Vision with sensory task	4:51	0:23	4:39	0:35

Participants completed the Sensor task the fastest and the Vision with sensory task the slowest across all tasks during both trials. All task completion times decreased across the trials. The Sensor task completion time was the shortest across all tasks. One reason for this was that the task had the shortest path length; the other reason was that this screen provided the fastest processing. The processing time is longer when the screen displays an image or the image and sensory information combination.

4.2 Number Precautions

No errors, such as software or hardware failures, were recorded during any of the trials. The term *precaution* represents an action required to protect the environment (walls) against potential harm. In this evaluation, this action was pressing the robot's stop button by a person near the robot. Table 2 provides the descriptive statistics for the number of precautions for each task during both trials.

Table 2. Number of precautions by trial and task.

	Trial One		**Trial Two**	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
Vision task	2.20	1.88	2.73	3.88
Sensor task	2.40	2.21	1.17	0.70
Vision with sensory task	3.23	1.91	3.43	2.13

During trial one, the fewest precautions were issued during the Vision task (mean = 2.20) and the largest number during the Vision with sensory task (mean = 3.23). The mean number of precautions issued during the Sensor task was 2.40. During trial two, the fewest number of precautions were issued during the Sensor task (1.17) with largest during the Vision with sensory task (3.43). During the Vision task, an average of 2.73 precautions were issued.

The number of precautions issued for trial two of the Sensor task was the smallest across all tasks over both trials. This result is due to permitting participants to view the robot and its environment. The number of precautions for the Vision with sensory task was the largest across all tasks during both trials. The reason for this result is the processing delays encountered during this task.

4.3 Number and Location of Screen Selections

The number and location of the screen touches (selections) were automatically recorded during the evaluation. The descriptive statistics for the forward button selections is provided in Table 3. During both trials, the number of forward button selections was highest during Vision task and lowest during Sensor task. The difference across trials decreased for the Vision and Sensor tasks, but increased during Vision with sensory task.

Table 3. Forward button selections by trial and task.

	Trial One		Trial Two	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
Vision task	8.33	3.30	7.07	2.82
Sensor task	5.73	1.96	4.27	3.16
Vision with sensory task	6.00	2.36	6.43	2.43

The backward button selections descriptive statistics are provided in Table 4. During trial one the number of backward button selections was highest during Vision with sensory and Sensor tasks. During trial two, the value was highest during Sensor task and lowest during Vision task. Since the tasks did not require backward movements of the robot, the averages for the backward button were very small. The number of backward button selection for the Sensor task during trial two was the highest when compared to all tasks during both trials. The reason for this result is the task condition change. The participants were better able to safely move the robot when they could directly view it.

Table 4. Backward button selections by trial and task.

	Trial One		Trial Two	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
Vision task	0.37	0.67	0.30	1.15
Sensor task	0.63	1.19	0.70	1.44
Vision with sensory task	0.63	0.85	0.43	0.86

The descriptive statistics for the right button selections are shown in Table 5. During both trials, the number of the right button selections was highest during Vision with sensory task and lowest during Sensor task. The number of selections across trials decreased for the Vision and Sensor tasks; but increased for the Vision with sensory task.

Table 5. Right button selections by trial and task.

	Trial One		Trial Two	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
Vision task	5.27	2.61	4.23	1.98
Sensor task	2.23	1.81	2.10	1.86
Vision with sensory task	5.93	1.87	6.23	2.64

Table 6 provides the descriptive statistics for the left button selections. The number of selections for the left button was highest during Vision task and lowest during Sensor task. During both trials, the number of left button selections decreased across all tasks.

Table 6. Left button selections by trial and task.

	Trial One		Trial Two	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
Vision task	6.43	2.62	6.00	2.89
Sensor task	4.53	2.83	3.73	2.46
Vision with sensory task	4.67	2.58	4.07	2.00

The descriptive selection statistics for the stop button are given in Table 7. During trial one the number of stop button selections was highest during Vision task and lowest during Sensor task. During trial two the number of selections was highest during Vision with sensory task and lowest during Sensor task. The number of selections across trials decreased for Vision task and Sensor task; but increased during Vision with sensory task.

Table 7. Stop button selections by trial and task.

	Trial One		Trial Two	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
Vision task	26.10	15.17	22.57	10.38
Sensor task	15.03	9.14	12.83	10.90
Vision with sensory task	25.27	13.65	26.07	13.87

The term *no button* classifies all screen touches that did not correspond to a particular interface button selection. The number of *no button* touches for the Sensor task during both trials was very high (Trial one – 18, Trial two – 15). The total number of such touches for the other two screens across both trials totaled four. There is no clearly identifiable reason for this result. These touches during the Sensor task centered on four locations, between the stop and turn right buttons, above the move backwards button, just below the move forward button, and on the robot itself.

Overall, the number of the stop button selections was the highest of all selections (21.31). The forward button selections followed (6.3); then the left button selections (4.91), right button selections (4.33), backward button selections (0.51), and *no button* touches (0.21). A large number of forward button selections were expected due to the defined tasks. Similarly, a large number of stop button selections were expected. As well, the tasks require more left button selections over the right button selections as the tasks required more left turns.

4.4 Accuracy of Goal Achievement

The average goal achievement accuracy for all tasks across both trials is provided in Table 8. During trial one of the Vision task 40% of the participants *reached* the goal location, 30% *almost reached* the goal location, 7% *passed* the goal, and 23% did *not reach* the goal location. During trial two, 77% of participants *reached* the goal location, 13% *almost reached* to the goal location, 3% passed the goal point, and 7% did *not reach* the goal location. The percentage of participants that *reached* the goal position dramatically increased across trials for the Vision task. The reason for this dramatic increase may be attributed to learning the interface and how to control the robots.

Table 8. Accuracy of goal achievement by trial and task.

		Vision Task	**Sensor Task**	**Vision with sensory Task**
Trial One	**Reached**	12	14	3
	Almost Reached	9	6	4
	Passed	2	2	0
	Not Reached	7	8	23
Trial Two	**Reached**	23	26	7
	Almost Reached	4	1	2
	Passed	1	2	3
	Not Reached	2	1	18

During the Senor task trial one 47% of the participants *reached* the goal location, 20% *almost reached* the goal location, 7% *passed* the goal, and 26% did *not reach* the goal location. During trial two 87% of the participants *reached* the goal location, 3% *almost reached* to the goal location, 7% passed the goal point, and 3% did *not reach* the goal location. The percentage of participants that *reached* the goal point increased dramatically across trials because of the task condition change that permitted participants to view the robot during the second trial.

During trial one of the Vision with sensory task 10% of the participants *reached* the goal location, 13% *almost reached* the goal location, 0% *passed* the goal, and 77% did *not reach* the goal location. During trial two 23% of the participants *reached* the goal location, 7% *almost reached* the goal location, 10% passed the goal point, and 60% did *not reach* the goal location. During both trials more than 50% of the participants did not achieve the goal position. The reason was the long processing time that occurs with this screen. Since this interface screen shows the camera image and all available sensory data at the same time, there is a long delay between the issuance of commands and the robot's action. For this reason, many participants did not finish the task within the allotted time.

This section has detailed the objective data analysis results including the task completion times, number of precautions, ability to reach the goal locations, and the number of screen touches and locations.

5 Discussion

In general, the results are close to what was anticipated. The goal achievement scores are higher during the second task trials and scores greatly improve when participants are permitted to directly view the robot during a task. The screen touch (selection) locations and counts are as anticipated. The locations generally track to the buttons required to complete the tasks. As well, the completion times are generally those that would be expected. What was not initially anticipated was the poor performance of the Vision with sensory overlay screen.

The participants completed the Vision with sensory task with the longest task completion time. This screen also required the largest number of precautions issued over both trials. This task also resulted in the lowest goal achievement accuracy. These results are attributed to the screen processing delay, as all image and sensory information must be processed. This issue results in about a five second delay from the time the of command issue until the robot begins execution.

The participants completed the Sensor task the fastest of all tasks when they were permitted to directly view the robot and environment. During this particular task execution, the number of precautions was the smallest across all tasks and trials while the goal achievement accuracy was highest. These results are clearly related to the condition change for this task during the second trial.

6 Conclusion

This paper presented the objective data analysis from a user evaluation of a PDA-based human-robotic interface. This interface is composed of three different touch-based screens. The objective data analysis focused on the task completion times, number of errors and precautions, ability to reach the goal locations, and the number of screen touches and locations.

The ability to interpret this data is complicated by the fact that the path lengths for each task were slightly different. In many respects, the objective data appears to support the results from the full statistical analysis of the perceived workload and usability [9, 11, 12]. Further analysis of the data that incorporates normalization of this data is required to completely understand these results.

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