A Pilot Study on Teleoperated Mobile Robots in Home Environments

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Abstract – **Mobile robots operating in home environments must deal with constrained space and a great variety of obstacles and situations to handle. This article presents a pilot study aiming at identifying design specifications of a new user interface and robot specifications to improve efficiency and security for novice teleoperators of a mobile robot used in home environments. This pilot study is part of the familiarization phase of an iterative interdisciplinary design process aiming at outlining critical design and experimental issues before engaging into detailed design processes, elaborated experimental methodology and rigorous testing of the various capabilities of mobile robots for home care applications. More specifically, we evaluated, with a small set of trained and untrained operators, two conceptually different user interfaces for teleoperated mobile robotic systems. These results demonstrate the challenges and the necessity of conducting trials in home environments to evaluate such teleoperated systems, and outline distinct preferences regarding robot capabilities, user interface navigation method and evaluation methodology.**

Index Terms – **Service robot, Teleoperation, User interface, Home care, Navigation.**

I. Introduction

The demographic imperative of an aging population and its impact on the reorganization of health care systems worldwide create unique opportunities to look at new approaches to delivering health care services [1]. Telehealth, defined broadly as the use of electronic information and communication technologies to provide and support health care when distance separates the participants, has recently emerged as a new mechanism for delivery of home care services (i.e., home telehealth). The concept of teleoperated mobile robots to support the provision of home telehealth services is currently being investigated by several groups [2]. The Nursebot project was conceived in 1998 by a multidisciplinary team of investigators from three universities (Michigan, Pittsburg and Carnegie Mellon University) aiming to develop mobile robot assistants for elderly people having mild cognitive impairments and living in an assistive living facility [3]. Another interesting project is the RoboCare project [4] in Italy resulting from collaboration between the Italian National Research Council and the University of Rome. The aim of this project is to study issues and challenges involved in the design of systems for the care of the elderly using fixed and mobile agents (intelligent sensors, robots, persons). However, none of these works report experimental results conducted in home environments.

Our group is currently establishing, through focus groups [5] and field trials, design specifications of a teleoperated mobile robot in telehealth applications for elderly people with disability living at home. The teleoperation of a mobile robot in a home environment is an endeavor fraught with challenges. Locomotion and perceptual modalities of the platform must be adapted to home environments (e.g., stairs, door steps, obstacles of different types of material and size). Ensuring the safety of the individual in the home where the robot is used and the safety of the robot itself are primary concerns [6-7]. The quality of the robotic teleoperation user interface and the operator experience in teleoperating the robot are two factors that seem to have a direct impact on the safety and performance of such systems. Indeed, the teleoperation link (i.e., communication bandwidth) and the visual environment supporting the robotic teleoperation user interface generally restrict the amount of information available to the operator. Thus, an optimal robotic teleoperation user interface must provide pertinent information about the robot's states and environmental conditions (objects, persons, free space, etc.) in conjunction with an efficient command system to the operator. The expertise of the operator is also an influence. Following the intervention of a rescue team equipped with telerobotic systems during the World Trade Center, Casper [8] reported that the user interface is a critical element in the performance of search and rescue missions. She also noted that operator training with the telerobotic system is important: expert operators can cope with stress and information overload to a certain degree, while novice or infrequent operators seems to have difficulty with that. Expert and novice operators have been shown to have differing opinions regarding the utility and usability of different features in user interfaces [9].

The objective of the pilot study is to gather more information, through experimental field trials, for the complete design of a new teleoperation system more appropriate for home environments. There are just too many factors (ranging from robotics, human and environmental) to take into consideration to start elaborating design specifications without conducting preliminary trials and assess their combined effects, or to initiate extensive testing in home environments to quantify the usability of user interfaces in such settings. So we decided to proceed following an iterative elucidation process inside a requirements engineering activity [10], using existing robotic platforms and interfaces, and four operators (two roboticists, and two clinical researchers). The focus of this work is on the user interface, the operators and the operating conditions, using existing telerobotic systems. The aim is not to conduct an in-depth study (e.g., statistical analysis with a probabilistic sample) but to identify critical elements that must be considered in the design of such system. Such study (with n=30) will be conducted once the designed of the complete teleoperation system is completed. The paper presents the methodology used, along with observations made that will affect our design guidelines.

II. Field Trials with Telepresence Systems in Home Environments

We conducted trials with two different mobile robotic platforms using distinct navigation interfaces, one by waypoints and the other by position points. With waypoint navigation, the operator has a visual view of the scene in front of the robot that can be used to specify a destination for the robot. Position point navigation consists of using a map representation (in 2D) where the robot's location is shown and a destination can be given. Waypoint navigation is the method used with the CoWorker robot, shown in Figure 1.

Fig. 1. CoWorker robotic platform (top) and its user interface (bottom).

The CoWorker is designed for telerobotic applications such as having specialists or business people visit a shop or an industrial plant from a distant site. It is the equivalent of a mobile teleconferencing station. The robot is equipped with sixteen medium proximity infrared sensors (for obstacle avoidance) and ten near proximity infrared sensors (to create a virtual bumper), located all around its body. The rotating sonar located in front of the robot was not used since it was not operational. A color camera, a microphone and a laser pointer are located on top of a moving neck that can move forward or backward. The robot's teleoperation user interface provides a visual display (generated by the camera's video stream) of the scene in front of the robot, direction control using arrows (each arrow click makes the robot move in 2 inch increments and 5 rotation degrees), a rotational bar and a red "STOP" button. Waypoint navigation is done by clicking in the visual display. The robot then navigates autonomously to the destination using an approximation of the distance to travel derived from the visual display. The distance traveled is measured using wheel encoders. Obstacles are also avoided autonomously, and the robot stops when it detects an object within its near proximity infrared sensor range. A special green "GO" button allows the operator to override this mode in order for the robot to push small objects for instance. The upper left window in the user interface is a top view of the robot's sensors showing detected obstacles.

Position point navigation is done using the Magellan robot shown in Figure 2. The Magellan robotic platform is

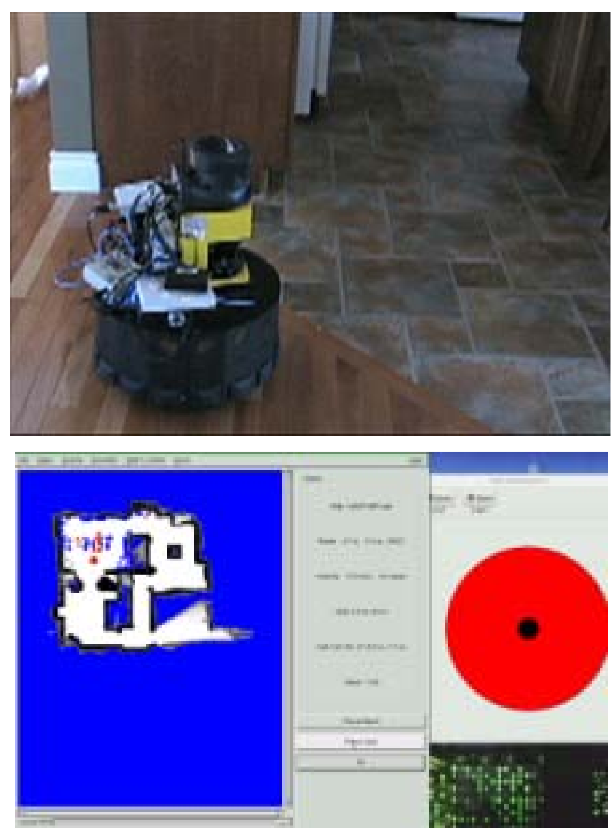

Fig. 2. Magellan robotic platform (top) and its user interface (bottom).

equipped with sixteen infrared proximity sensors, sonars and bumpers distributed uniformly all around its circular body. A SICK laser range finder is also placed on the robot, providing a 180 degree view of the obstacles in front. A color camera is placed on top of the laser range finder, but was not used in our trials. The user interface designed for the Magellan presents a map representation of the environment, as generated using CARMEN, the Carnegie Mellon navigation toolkit [11]. CARMEN allows the robot to navigate without colliding with obstacles to a specified destination, following a previously generated map of the environment. A virtual joystick, shown on the right of the interface, provides velocity and direction control for the robot by simply dragging the black dot in the desired position. Position point navigation is done in two steps: the operator positions a target point on the map and click on the "GO" command (the last button in the middle part of the interface); the robot then navigates autonomously to the target position using data coming from its laser range finder. The operator can override the path of the robot at any time using the joystick. In order to generate the map of the test sites (which are unstructured environments compared to our prior laboratory conditions), laser range data were first taken as we controlled the robot. Data were then processed using a mapping algorithm, and refined manually to ensure safe navigation of the robot.

The system is programmed using MARIE (Mobile Autonomous Robotic Integrated Environment) [12], a middleware programming environment allowing multiple applications, operating on one or multiple machines/OS, to work together in an implementation of mobile robotic nature. This environment provides a software architecture that avoids making a choice on particular programming tools, and makes it possible to share code and applications.

Both teleoperated systems were tested in controlled laboratory conditions before being used in homes. In these conditions, we observed that both telerobotic systems worked very well and the robots navigated easily between obstacles and people. Therefore we expected great efficiency and ease of use in home environments.

Then, field trials were conducted in two home environments. Site A, shown in Figure 3, is a close space type, 30 feet by 30 feet with ceramic tiles and two door thresholds of approximately half an inch in the kitchen doorways, and hardwood floors in the other rooms. Site B, shown in Figure 4, is an open space type occupying also 30 feet by 30 feet, without any threshold between the different areas. The floors are ceramic tiles in the kitchen and hardwood in the other areas.

Experimental trials consisted in having each of the robots visit all rooms and go back to their initial position. Robots were teleoperated using a laptop computer from a room on the second floor of each site (i.e., with no direct visual cues on the robot's position or environment).

In Mission 1, no obstacles were placed in the robot's path. In Mission 2 (conducted only with the CoWorker since it was the only one capable of handling these situations), the robot had to go over a drape placed on the floor, push a medium-size ball and push a small door. All missions were executed safely with the exception of one minor incident in which the CoWorker hit a corner because of an incorrect command from the operator and an uncovered region in its proximity sensor range.

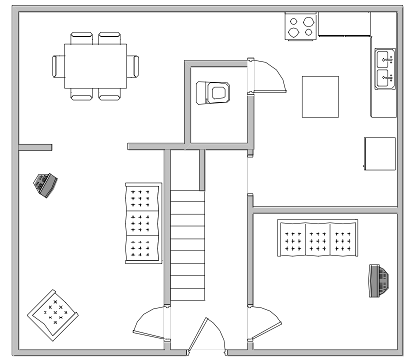

Fig. 3. Floor plan for Site A

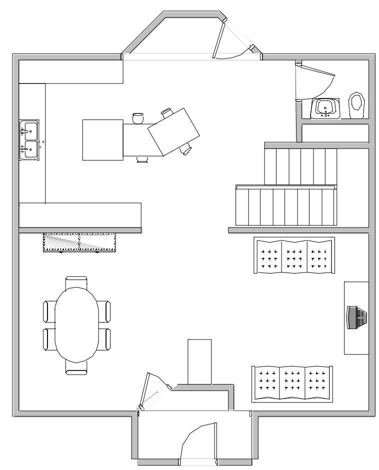

Fig. 4. Floor plan for Site B

III. Evaluation Protocol

While research on particular aspects of user interfaces has been conducted, such as filtering information [13] automating their presentation on the interface display [14], or create ecological interface by integrating map information and video information in a coherent display [15], a complete design specifications for an efficient and secure user interface for mobile robots teleoperated in home environments are still unknown. To make progress on this issue, the development of evaluation methodologies focusing on the usability of user interfaces is needed [9,16]. Conducting standardized evaluations through a common test site and use task-specific metrics to evaluate human-robot interactions [8,17] are required. Among the six different metrics reported by Olsen and Goodrich [18] (task effectiveness, neglect tolerance, robot attention demand, free time, fan out and interaction effort), we choose in our analysis the most pertinent and popular one, the task effectiveness.

For each trial, screen captures of the user interface and video of the robot movements were recorded and synchronized using time stamps. Time to complete a navigation mission was used to measure operator's performance. Operators (n = 4) were divided into two categories: two trained operators (roboticists with more than four hours of training by an expert in laboratory and real conditions with the teleoperated systems) and two untrained operators (clinical researchers only receiving a 10 minute demonstration and explanation of the user interface of each system). The performance of an expert operator with more than 100 hours of practice with both systems served as a baseline for comparison of times to complete missions. The performance of this operator was under 10% of the optimal performance of the systems. An operator was previously considered trained when the time to complete a mission in laboratory environment was not more than 20% greater than the expert's time. Comparison time $t\%$ of a trial using a telerobotic system is evaluated using Equation (1). Benchmarking and system effectiveness are reported to be difficult to establish if data come from trials having different bias factors [13]. The proposed comparison facilitates the true assessment of the capabilities of the operators by removing bias that may come from the robot's capabilities and the environmental conditions.

$$t\% = \left(\frac{t_{Mission}}{t_{expert}} - 1\right) \times 100 \qquad (1)$$

Evaluation of the usability of the teleoperated robotic platform and its user interface are also important in such experiments in order to gain a better understanding of what determines efficient and secure teleoperation of the robot [19-20]. After completing the missions in each home, the operators had to fill out a questionnaire regarding the usability of the teleoperated robotic platform and the usability of the user interface.

IV. Observations

As indicated in the introduction, our objective with these trials was to provide initial guidelines for the design of new telerobotic system that will be more appropriate for home environments and secure operation by novices or infrequent operators. Conducting trials with a large set of robots, missions, operators and homes would be inappropriate at this stage, since we are more interested in examining the robotics, human and environmental involved in the teleoperation of a mobile robots in home environment and gaining a good understanding on how they will affect our design project. Therefore, we chose to conduct trials with very limited set of conditions (two telerobotic systems, two environments, two untrained and two trained operators). Even though the resulting observations are not supported by a (probabilistic sample), they outlined interesting considerations for the design of our telerobotic system and how to evaluate performance of such system in home environments.

A total of 30 trials were conducted with one expert, two trained (operators 1 and 2) and two untrained operators (3 and 4) using two robots performing the two missions. For all these trials, only once did a trained operator outperform the expert (by being 9% faster).

Table I presents the results for Mission 1, Site A and Site B, and for the two categories of operators. The higher $t\%$ represent the longer it takes for the operator to complete the mission compared to the expert operator. The column *Difference t%* shows for a given operator the difference in performance for the CoWorker and the Magellan. A positive value indicates that the operator is better at teleoperating the CoWorker using waypoint navigation, while a negative value indicates that the operator is better at operating the Magellan using position point navigation.

For the trained operators, the median performance value for Mission 1 is 6.5% with the CoWorker and 17.1% with the Magellan. Both median performance values are under the limit used to qualify the operator as a trained operator (i.e., $\%t < 20\%$). Note that the bad performance of operator 1 with the Magellan resulted from a problem that the navigation software had trying to negotiate a passage through a doorway.

TABLE I
Results for Mission 1

Operator	Site	Category	*t%* CoWorker	*t%* Magellan	*Difference t%*
1	A	Trained	6.8%	36.3%	29.6%
2	A	Trained	6.3%	17.5%	11.2%
1	B	Trained	10.9%	10.8%	-0.1%
2	B	Trained	0.0%	16.7%	16.7%
		Median	6.5%	17.1%	10.6%
3	A	Untrained	118.8%	57.3%	-61.5%
4	A	Untrained	28.5%	15.8%	-12.7%
3	B	Untrained	82.1%	43.4%	-38.7%
4	B	Untrained	23.4%	12.8%	-10.6%
		Median	55.3%	29.6%	-30.9%

For untrained operators, the corresponding values are 55.3% for the CoWorker and 29.6% for the Magellan. This indicates that trained operators outperformed untrained operators for both types of navigation interfaces. Since biases from the robotic platforms are removed by using Equation (1) to express performances, these results make it possible to compare the navigation interfaces. While waypoint navigation reveals to be better for trained operators, position point navigation is what untrained operators use the most efficiently. This contradicts our first hypothesis from trials conducted in laboratory conditions with the expert and trained operators that the CoWorker system (with waypoint navigation) would outperform the Magellan (position point navigation) for both categories of operators.

Although trained operators using the CoWorker's waypoint navigation reached similar level of performance as the expert, untrained operators were far worst (48.8% difference with trained operators). For position point navigation, this difference is much smaller (12.5%).

Trained operators also show a zero or positive difference (10.6% median difference) when comparing performances between the two telerobotic systems, indicating slightly better performance with the CoWorker compared with the Magellan. On the other hand, untrained operators show a negative median difference value of -30.9%, indicating that performance with the CoWorker was worst than with the

Magellan. This suggests that training has a more significant effect on teleoperation performance with the CoWorker than with the Magellan. Position point navigation seems to be less dependant to training effects, as the performance difference between categories of operators was significantly less (from 17.1% for trained to 29.6% for untrained operators) compared with waypoint navigation (6.5% vs 55.3%). Screen captures showed that using position point navigation required about three times less commands than with waypoint navigation. This seems to decrease the influence of training on the performance of the operators.

TABLE II
Results for Mission 2 (CoWorker only)

Operator	Site	Category	*t*% CoWorker	Median Site A	Median Site B
1	A	Trained	36.9%	38.3%	
2	A	Trained	39.6%		
1	B	Trained	13.3%		8.4%
2	B	Trained	3.6%		
		Median	25.1%		
3	A	Untrained	98.2%	96.4%	
4	A	Untrained	94.6%		
3	B	Untrained	36.6%		48.2%
4	B	Untrained	59.9%		
		Median	77.2%		

Table II shows results for Mission 2 (using only the CoWorker) with obstacles in the robot's path. Again, operator training seems to make a big difference in the performance of the operators. Both categories had more difficulty to complete Mission 2 in approximately the same proportion: 6.5% for Mission 1 and 25.1% for Mission 2 with trained operators, resulting in a difference of 18.6%; 55.3% for Mission 1 and 77.2% for Mission 2 with untrained operators, for a 21.9% difference. But, using Equation (2) to express performance drop (*d*) for each group of operators observed in Mission 2 compared to Mission 1, the trained category seems to have a degradation in performance of 2.85 times compared to 0.4 for the untrained category. This indicates not just that missions with small obstacles to overcome are harder for both trained and untrained operators, but also that trained operator performance seems to degrade proportionally more than for untrained operators.

$$d = \left(\frac{\%t_{Mission2}}{\%t_{Mission1}} - 1\right) \qquad (2)$$

Table II also shows the median by sites for each category of operators, indicating that Site A was a more difficult environment than Site B. It is worth noting that the first set of trials were conducted in Site A, so untrained operators got a certain amount of experience using the telerobotic systems before doing Site B trials. Also, Site A has corridors and doorways that had to be managed by the robotic system, while Site B is basically open space areas. These reasons explains this result, which is also noticeable in Table I but to a lesser degree.

At last, a usability questionnaire was administered to the operators after each trial. Regarding the robotic platform usability, the CoWorker system outperforms the Magellan. Even the waypoint navigation interface seems to be easier to use than position point navigation for untrained operators, even though they performed better with position point navigation. However, learning to use the user interface seems to be harder on the CoWorker than on the Magellan system. Only two buttons were required to operate the Magellan, while four were used on the CoWorker. The CoWorker was also perceived to be not as safe to operate than the Magellan. This is explained by the fact that the CoWorker's user interface presents a visual view of the scene covering only 85 degree in front of the robot, while the Magellan's laser range finder provided 180 degree coverage. In addition, with the CoWorker, the operator frequently lost sight of the selected waypoint while the robot was avoiding obstacles by turning left or right.

V. Discussion

From the observations made from the small set of trials conducted in this pilot study, specifications of our telerobotic system are affected in the following ways:

- The presence of small obstacles, corridors and doorways substantially increase the level of difficulty for both trained and untrained operators in comparison with an expert operator. A user interface combining the advantages of waypoint navigation and position point navigation could potentially improve operator performances. This interface must facilitate understanding of the environment (from video images complemented with 2D map and sensor reading representations, which provide limited perspective requiring a high level of cognition using visual memory and complex mental models [21]). Figure 5 partially illustrates our user interface currently being implemented. The central window shows a 3D model of the environment, on which the camera view is placed. Controls are on the bottom window. A 2D map and a robot sensor's representations are placed on the left side windows.

Fig. 5. Concept for the user interface.

- The robotic platform must be small but clearly visible (not to become a hazard for elderly people), equipped with cameras to see forward and backward, detect stairs, capable to operate over carpets not fixed to the floor and go over a door step in a stable and secure fashion. The design we came up with is shown right in Figure 6, and should be completed by Spring 2006. Locomotion is realized using two motorized wheels with rocker-boggie suspension.

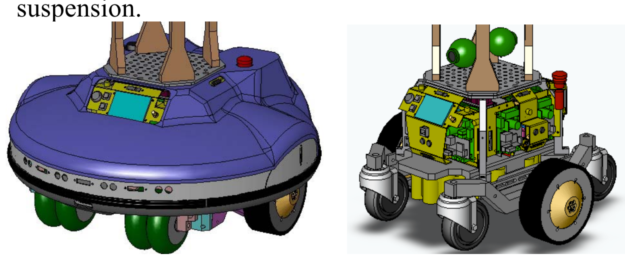

Fig. 6. Concept for the robotic platform, with and without bodywork.

VI. Conclusion

Designing a mobile robotic telepresence system for homes requires identifying operational and environmental constraints. The findings reported in this paper illustrate what we identified in a pilot study conducted with two existing robotic platforms in home environments instead of traditional laboratory spaces, and how they are influencing our design. The paper also explores the use of an evaluation methodology of telerobotic systems used in such environments, comparing operator performances with respect to the performance of an expert, thus eliminating potential bias from the robotic platform and the environment. This approach may provide a solution to the problem of extracting information for designing better user interfaces, as mentioned in Scholtz et al. [6].

This work is the first iteration in our project of designing a teleoperated mobile robotic system, including both the platform and the user interface, for telehealth applications in home environments. Instead of designing the system and then evaluate it in different contexts, we adopted a holistic and iterative design approach during which all potential influences (environmental, operational, technological, needs [5]) are considered with an increasing level of sophistication from one iteration to the other. For the second iteration, with our user interface and mobile robotic system are designed, we intend to conduct extensive experimentations with a large set of operators and operating conditions. A novel evaluation methodology will also be elaborated. The addition of other criteria such as the number and the sequence of commands made by an operator during a mission might be useful to evaluate performance. Incorporating other metrics might improve the evaluation methodology. Other statistical analysis methods can also be used, depending on the number of operators participating in the trials.

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