# A User Study of a Mobile Robot Teleoperation

Ildar Farkhatdinov
Korea University of Technology and Education
ildar@kut.ac.kr

Jee-Hwan Ryu
Korea University of Technology and Education
jhryu@kut.ac.kr

***Abstract*** - In this paper several interfaces for teleoperation of a mobile robot are described and analyzed. We consider teleoperation of a wheeled mobile robot when control commands are given by human operator through a haptic master device. Described human-robot teleoperation interfaces were tested by performing experiments. Main objective was to verify the role of different types of feedback information and command strategies for improving the performance of the system. Position-speed and position-position command strategies were used for mobile robot teleoperation. In position-position strategy desired speed of a mobile robot is defined by a master manipulator's position. In position-speed command strategy robot's position is controlled by position of master device. Hybrid command strategy, combining position-speed and position-position strategy, was introduced and used also. First, unilateral teleoperation was studied. Experiments with position-speed, position-position and hybrid command strategies were evaluated. Second, bilateral teleoperation of a mobile robot was studied using two types of force feedback: force feedback related to obstacle range information and force feedback including information about the state of the robot. For experiments with bilateral teleoperation different command strategies were applied. Advantages and disadvantages of each type of human-robot interaction interface were described.

***Keywords*** - Mobile robot, teleoperation, haptic interface.

## 1. Introduction

Teleoperation as one of the first domain of the robotics has a long history. In teleoperation, human executes a task in a remote environment with the help of master and slave devices. Robot teleoperation is widely used in industry, science, medicine, education, entertainment and military applications [1]. Examples of robot teleoperation in different environments are presented in [2, 3].

The quality of such robotic systems greatly depends on their control systems. The addition of feedback to a teleoperator system benefits the operator by providing more information about the remote environment. In this paper force feedback and visual feedback in the mobile robot teleoperation were studied.

Several researches referred to a problem of designing haptic interfaces to implement force feedback. An event based direct control of mobile robot with force feedback was proposed by Elhaji et al. [4, 5]. In [6], advanced interfaces for vehicle teleoperation were investigated. The effectiveness of force feedback for safe navigation was measured in teleoperation in virtual environment by S. Lee et al. [7]. Haptic interface using information from force sensors was designed in [8]. In [9], visual computer interface for mobile robot teleoperation was proposed. N. Diolaiti and C. Melchiorri proposed obstacle map based haptic interface in [10]. In [11], effectiveness of force feedback was verified by conducting an experiment in a real environment. Recently, the authors have proposed a hybrid control strategy for mobile robot teleoperation [12].

In this paper, previously proposed control strategy and different types of feedback information in mobile robot teleoperation have been tested. In order to analyze the role of feedback information for a mobile robot teleoperation with different control strategies experiments were done.

## 2. System Overview

We consider bilateral teleoperation of a two wheeled mobile robot. Human operator gives motion commands through the master haptic manipulator. Human-operator can control speed or position of the mobile robot. Control signals are transmitted to mobile robot by wireless computer network. Obstacle range information, which is obtained from the robot's sensors, is sent to human-operator as a force feedback. Fig. 1a shows the configuration of the mobile robot. $V, \phi$ are the linear velocity and the heading angle, respectively, $S$ is the traveling distance of the robot. In Fig. 1b, configuration of two link master manipulator is shown. Mobile robot control signals are based on the position of end-effecter ($x_m$, $z_m$). Vision system is also used for providing visual information to human-operator.

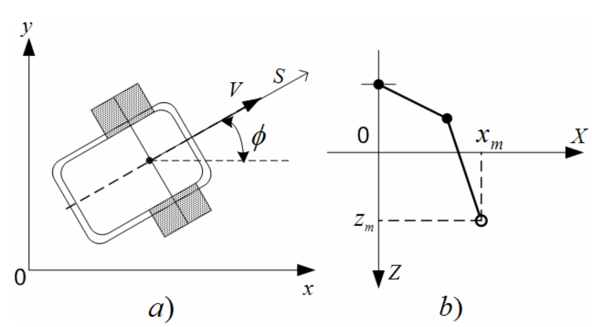


Fig. 1. Configurations of a two-wheeled mobile robot (a) and a master device (b).

## 3. Hybrid Control Strategy Overview

Position-speed command strategy is used for most of the remote control applications of the mobile robots. The speed of the robot is changed with respect to the position of the master device. This control mode is based on equation (1).

$$\begin{pmatrix} V \\ \phi \end{pmatrix} = \begin{pmatrix} k_V & 0 \\ 0 & k_A \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}, \tag{1}$$

where $q_1$, $q_2$ define the position of master device and $k_V$, $k_A$ are proportionality constants. $q_1$ and $q_2$ are calculated using the following rules

$$q_1 = \begin{cases} -z_m, |z_m| > z_{dz} \\ 0, |z_m| \le z_{dz} \end{cases}, \tag{2}$$

$$q_2 = \begin{cases} x_m, |x_m| > x_{dz} \\ 0, |x_m| \le x_{dz} \end{cases}, \tag{3}$$

where $z_{dz}$, $x_{dz}$ are positive constants. These rules implement dead-zone for preventing sensitive movement of the robot due to small displacement of the master device.

Position-position command strategy is described by

$$\begin{pmatrix} S \\ \phi \end{pmatrix} = \begin{pmatrix} k_S & 0 \\ 0 & k_A \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}, \tag{4}$$

where $k_S$ is proportionality constant. Such control strategy is not usual for mobile robot teleoperation, because of the limited workspace of master manipulator. But combining these two strategies for haptic teleoperation of the mobile robot might be useful in a variety of application. For combining those, master device is used in two control modes: position-position mode and position-speed mode.

In [12], we proposed hybrid control strategy, which enabled human-operator to switch between position-position and position-speed command modes. Several rules for switching between position and speed control modes were designed also. In position-speed strategy human-operator can stop the robot and keep zero velocity easily. It can be achieved because of the dead-zone which removes sensitivity in control. But in this case human has no chance to move the robot accurate and correct its position. Position-position control strategy is more accurate, so that operator can easily move robot to the desired location. However position-position control mode is highly sensitive due to large scaling factor.

Human-operator can decide what control strategy should be used. Position-speed command strategy is suitable for moving the mobile robot for a large distance, so that human operator can control the speed of the robot. Position-position control mode can be used for accurate positioning of the mobile robot.

Manual switching is suitable for teleoperation when human-operator has enough information about the robot's current state and environment. That is why it is important to study the role of different types of feedback information. We suppose that hybrid control strategy can improve performance of the teleoperation system and give human-operator more opportunities to control the robot safer and easier.

## 4. Feedback information

### 4.1 Visual Feedback

Human-operator is provided by visual feedback information while teleoperation. We can divide this information into two types: textual information and graphical information. Values of mobile robot's position, speed, heading angle and obstacle range information are represented in text format. Graphical information can be represented by the interactive map of the environment and/or video stream from the vision system attached on a robot. In our research we concentrate on textual information as a visual feedback.

### 4.2 Force Feedback

Force feedback is implemented to make navigation more intuitive, safe and reliable. We consider that force feedback will give operator additional information about the distance between the robot and the obstacles, and the current state of the robot. Generated force is given by

$$F = F_e + iF_i, \tag{5}$$

where $F_e$ is the force inversely related to the obstacle range information $L$. This force is calculated by

$$F_e = \begin{cases} \dfrac{k_e}{L}, L < L_o \\ 0, L \ge L_o \end{cases}, \tag{6}$$

where $k_e$ is a scaling constant, $L_o$ is a constant distance for generating force feedback. $F_i$ is the force calculated by the following equation

$$F_i = -k_i z_m, \tag{7}$$

where $k_i$ is a scaling constant. The main usage of this force is to return the master device to its initial position, which means that the robot will be stopped. But at the same time, according to equations (1) and (2), value of $F_i$ is proportional to the speed of the robot $V$, so that $F_i$ reflects the state of the robot also. In the case of position-position strategy, this force will have no physical meaning, that is why variable $i$ in equation (5) is set to zero to remove the force. In position-speed strategy $i$=1.

## 5. Experiment

### 5.1 Experimental Setup

For testing described control strategies several experiments were done. A simplified scheme of experimental setup is shown in Fig. 2.

Human-operator was giving control commands and choosing proper control strategy through haptic master device. Phantom Premium 1.5A from SensAble Technologies, Inc. was used as a master manipulator (Fig. 3). Additional switcher on Phantom's stylus was used to define control strategy. Haptic manipulator was connected to a desktop computer with control program. Control strategy switcher was realized as a part of this program. TCP/IP protocol and wireless network were used to exchange information with onboard computer of the mobile robot. Activmedia Pioneer 3-DX platform was used as a mobile robot (Fig. 4).

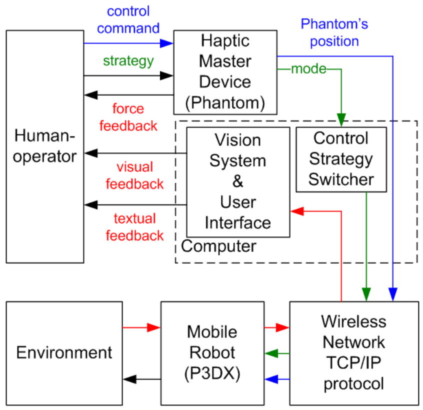


Fig. 2. Architecture of the experimental setup.

Fig. 3. Haptic device Phantom Premium 1.5A from SensAble Technologies, Inc.

Fig. 4. Mobile robot Pioneer 3-DX from MobileRobots, Inc.

Sonar sensors, which were installed on the mobile robot, were used to obtain obstacle range information. Vision system was attached on the mobile robot to provide operator with visual feedback.

All kinds of feedback information were transmitted to the control computer. Textual and visual feedbacks were transmitted to human via vision system and user interface. Force feedback was generated by master haptic device. Five subjects participated in the experiments. Each subject was trained to control the mobile robot in order to understand control strategies and get used to haptic and computer program interfaces.

### 5.2 Navigation Time and Control Strategies

In this section we describe experiment, in which navigation time was measured. We checked which control strategy, mentioned in section 3 of this paper, gave the best performance in terms of navigation time. A simple task was given to subject in order to compare different control methods.

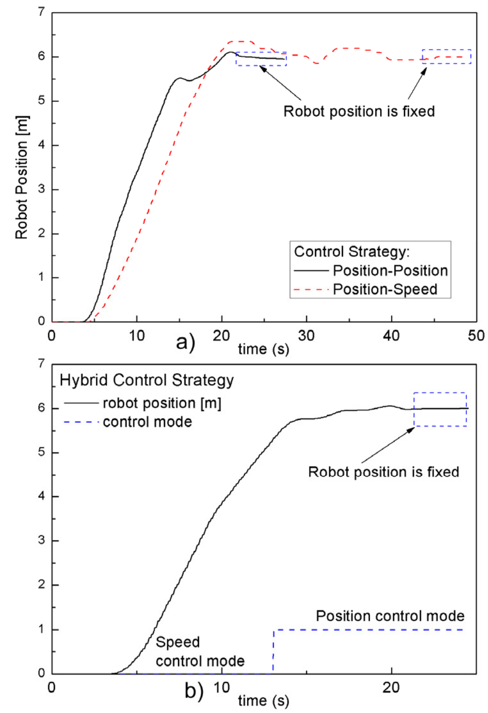


Fig. 5. Experimental results for mobile robot positioning when only textual feedback is provided to human-operator.

Robot was started from origin and was expected to move 6 m as quick as possible. The subject was expected to control the robot and to stop it at 6 m and, then, fix its position. In this case, force feedback was not transmitted to the subject. Human-operator could only receive textual information about the robot's actual position. Time for completing the task was the main objective to analyze. Results are represented in Fig. 5, which shows mobile robot's position graph when robot was teleoperated using position-speed, position-position (Fig. 5a) and hybrid control strategies (Fig. 5b).

In teleoperation with position-speed command strategy it took about 43 s to complete the task. First, subject set approximately constant desired speed and when the robot approached desired position, subject decreased the speed in order to stop the robot.

It took about 25 s to complete the task when position-position control strategy was used. In this case, human could directly control position of the mobile robot by changing the position of the Phantom device.

Fig. 5b shows position graph when robot was controlled using hybrid command strategy. First, position-speed strategy was used, which means that position of the master device defined the robot's position. This speed control mode is suitable for the task of quick but not accurate movement for large distances. When the robot traveled about 5 m and approached desired area, subject switched to position control mode (at time about 13 s on Fig. 5b). This mode allowed to control the robot accurately and intuitively. As a result, navigation time was reduced.

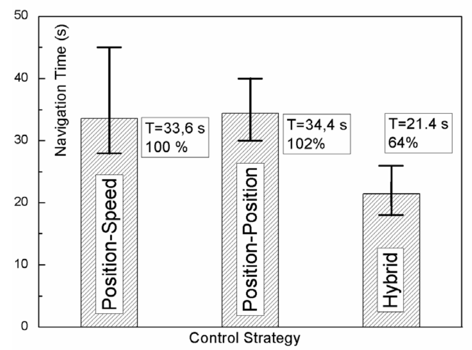


Fig. 6. Navigation time diagram for different control strategies.

Summary of experiments with all subjects is shown in Fig. 6. We compared average navigation time for positioning task using three different control strategies. Hybrid control strategy showed highest performance. Compare to position-speed strategy, proposed hybrid control strategy reduced navigation time by 36%.

### 5.2 Accuracy Analysis Experiment

If we compare the quality of the robot's motion from position graphs in Fig. 5, we can easily understand that positioning accuracy differs from one experiment to another. In order to compare positioning accuracy when different types of feedback and control strategies are used accuracy analysis experiment was performed.

Method which was used for accuracy analysis is illustrated by Fig. 7. We suppose that human-operator wants to stop the robot at point 2 m. In order to fix the position, constant position command or zero speed command should be sent to the mobile robot by human-operator. Each sampling time we can measure robot's position and calculate absolute error. To get the value of the average error the following equation is used:

$$\sigma_X = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_{des} - x_i)^2}\,, \tag{8}$$

where $N$ is the quantity of measured position points, $x_{des}$ is desired position; $x_i$ is an actual measured position of the robot. This error can give us a quantitative representation of the accuracy during positioning of the robot.

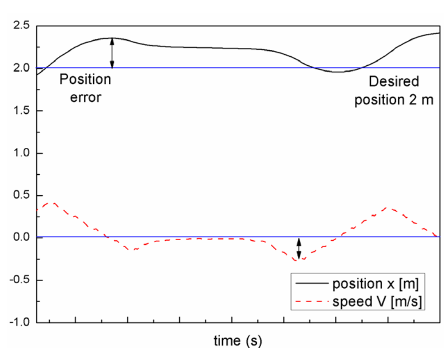


Fig. 7. Positioning error in teleoperation.

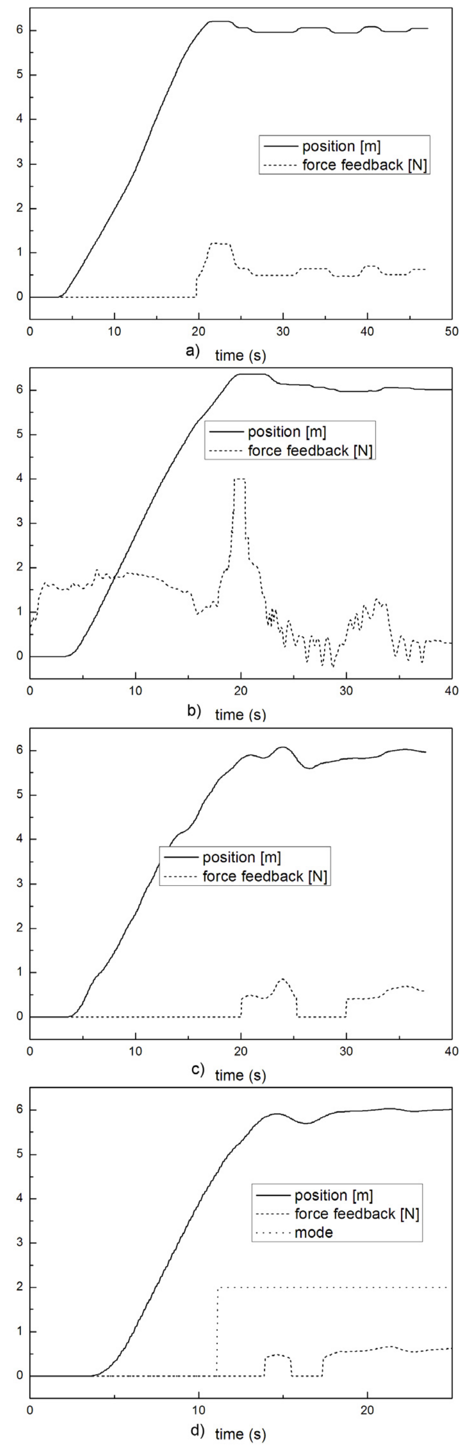


Fig. 8. Experimental results for mobile robot positioning, when textual information and force feedback is provided to human-operator. (a, b) position-speed, (c) position-position and (d) hybrid control strategies.

We analyzed the influence of force feedback and different control strategies to the accuracy of the mobile robot positioning. Experimental results are represented in Fig. 8.

Positioning experiments using position-speed, position-position and hybrid control strategies with and without force feedback were preformed. As it was described in previous part, robot was started from origin and expected to move 6 m. Obstacle was placed 6.5 m away from the original position, so that human-operator could feel force feedback, generated according to obstacle range information. Position error was calculated and analyzed.

In Fig. 9, summary of experiments with five subjects is shown. The smallest average error was achieved, when position-position control strategy without force feedback was used. The largest average error was achieved during teleoperating with position-position control strategy and with force feedback.

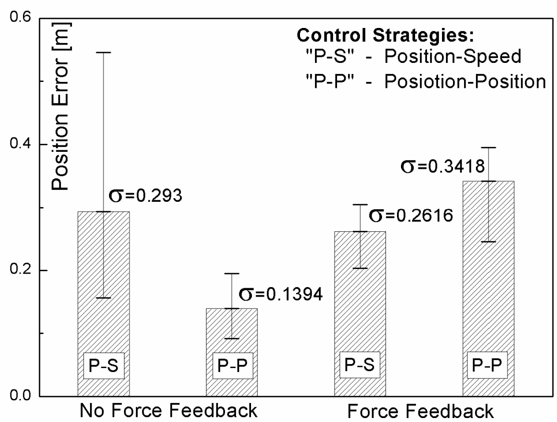


Fig. 9. Position error diagram for different control strategies with and without force feedback.

### 5.3 Discussion

In teleoperation with textual feedback, subject could see actual robot position and speed on the screen of computer. Based on these values, subject manipulated master device. In teleoperation with position-speed command strategy and textual feedback average navigation time was 33.6 s (Fig. 6). Absence of force feedback and any additional information about the obstacles gave some limitations for the speed of the robot. Subject was afraid to give large speed command due to the probability of collision and there was no opportunity to prevent that collision. That is why average navigation time was relatively large. As we can see from graph (a) in Fig. 5, it was difficult to human-operator to fix the position of the robot at point 6 m. Human could only control the speed of the mobile robot based on information about actual robots position in textual form. That caused an overshooting and oscillations of the robot's position. As a result average position error was 0.293 m - larger, than in other experiments.

In Fig. 5a, the robot's position graph when position-position command strategy was used is shown. In this case average navigation time was 34.4 s (Fig. 6). Subject could directly control position of the mobile robot by changing the position of the Phantom device. As a result there is almost no overshooting of the position and navigation time was decreased in comparison with the previous case. Average position error was 0.1394 m. The best accuracy was achieved due to direct position control and absence of force feedback.

For the last experiment with textual feedback hybrid control strategy with manual switching was used (Fig. 5b). First, position-speed control strategy was activated to move robot from origin to desired area as quick as possible. At that time, textual value of the robot's position was used by operator to verify the location of the robot. After operator understood that the robot was near to the desired point he switched to position-position mode. In this case, exact value of the robot's position was used to implement accurate motion. There was no position overshooting. Average navigation time was 21.4 s - the smallest value among all experiments (Fig. 6). Hybrid control strategy showed high performance.

In the next group of experiments additional force feedback was provided to the human operator. This force feedback was generated according to obstacle range information. Results for these experiments are shown in Fig. 8.

In Fig. 8a force feedback was calculated according to equation (5) where parameter $i=0$. This feedback contained only obstacle range information. In Fig. 8b feedback was calculated with $i=1$, which means that force included information about the speed of the robot. In the first case (see Fig. 8a), we have oscillation of the robot's position, but adding additional force feedback related to the speed of the robot removed this oscillations and made the teleoperator system more stable (see Fig. 8b). As a result, this kind of force feedback is useful for proper positioning of the robot when position-speed command strategy is used for navigation. Average position error was 0.2616 m, smaller then in teleoperation without force feedback (Fig. 9).

For the case of position-position command strategy (Fig. 8c), force feedback had a negative effect. When the robot approached the obstacle, force was applied to the master device and its position changed in order to prevent collision. Large value of scaling factor $k_S$ (see equation 4) caused high sensitivity of the teleoperator system. That is why generated force feedback caused positioning errors at time around 25 s (see Fig. 8c). We received the same negative effect of force feedback for teleoperation with hybrid control strategy (see Fig. 8d). Average position error was the largest (Fig. 9).

## 6. Conclusion

Teleoperation of the mobile robot with different types of feedback and control strategies was studied. Several types of feedback information were described. Experiments were conducted to analyze performance, accuracy and convenience of described human-robot interfaces.

Previously proposed hybrid control strategy showed high performance in terms of navigation time. It allows human-operator to control the robot easier and implement desired task accurately.

Experiments showed the use of textual feedback as a source of information about the state of the mobile robot. Textual feedback is suitable for direct and accurate control of the mobile robot's position or speed. But information about the state of the robot is not enough to guarantee safety of the navigation process.

Force feedback can provide important information about environment in which the robot is placed. In our research, force feedback was used to transmit obstacle range information, which guaranteed safe and careful navigation. But at the same time, force feedback decreased the motion accuracy when position-position control strategy was used. In this case, mobile robot's motion can be characterized like unstable. In future, we are going to design a controller for mobile robot bilateral teleoperation which will guarantee system's stability.

Visual feedback, such as video stream from camera attached on the robot and textual information about the robot's state, allows human-operator to implement accurate motion and place the robot into the desired location quickly. Vision system provides operator with useful and complex information. This information can gave human general representation of the state of the mobile robot and its environment.

Proper usage of the described control strategies and types of feedback information can improve performance and safety of teleoperation system. Application area, complexity of task, human factors and environmental properties should be considered in order to choose proper balance of used control strategies and types of force feedback.

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