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ORIGINAL RESEARCH PAPER

A user study of command strategies for mobile robot teleoperation

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Abstract This article presents a user study of mobile robot teleoperation. Performance of speed, position and combined command strategies in combination with text, visual and haptic feedback information were evaluated by experiments. Two experimental tasks were designed as follows: positioning of mobile robot and navigation in complex environment. Time for task completion and motion accuracy were measured and compared for different command strategies and types of feedback. Role of haptic, text and visual feedback information in combination with described command strategies is outlined.

Keywords Mobile robot · Teleoperation · Human–robot interaction · Haptic interface

1 Introduction

Teleoperation as one of the first domains 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]. Mobile robot teleoperation is a promising application area of telerobotics. There were many successful applications of remote mobile robot control in space exploration, military, underwater and other hazardous environment robotics, etc [2–4]. Recently, with high development of communication systems and computer networks mobile robot teleoperation can be effectively used in service and home robotics, rehabilitation systems, social robotics.

There have been many research efforts on mobile robot teleoperation. An event based direct control of mobile robot with force feedback was proposed by Elhajj et al. [5]. Advanced interfaces for vehicle teleoperation were investigated [6]. The effectiveness of force feedback for safe navigation was measured in teleoperation in virtual environment by Lee et al. [7]. Diolaiti and Melchiorri [8] proposed obstacle map based haptic interface. Haptic, audio and visual feedback were investigated by Richard and Coiffet [9]. Kaber et al. [10] investigated multimodal interface for adaptive control of a simulated telerobotic system. In [11], a group ecological human–robot interfaces for mobile robot teleoperation was proposed and described. Internet-based human–computer interface for vehicle teleoperation is described in [12]. Role of haptic interface for improving productivity of mobile robot teleoperation was shown in [13]. The concept of virtual cone for more intuitive and safe mobile robot haptic teleoperation is proposed in [14].

Previous researches were concentrated on developing and studying haptic and visual interfaces for mobile robot teleoperation. Position–speed strategy, in which the speed of the robot is changed with respect to the position of the master device, has been used as a main command strategy in previous researches.

Main objective of this article is to analyze the performance of different types of command strategies and feedback when they are combined, and their influence on the quality

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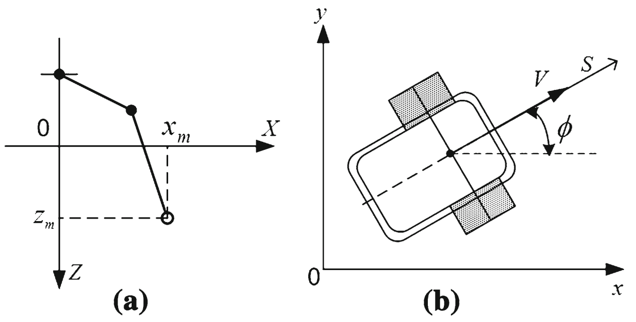

Fig. 1 Configurations of master manipulator (**a**) and mobile robot (**b**) (*top view*)

of mobile robot teleoperation system. We introduce a new command strategy for a mobile robot bilateral teleoperation. Hybrid control method, based on combining position–speed and position–position command strategies, is proposed. Human–computer–robot interfaces, based on haptic and visual feedback in mobile robot teleoperation system are described. Combination of command strategies and different types of feedback is studied by performing user study.

2 System overview

We consider bilateral teleoperation of a two wheeled mobile robot. Human operator gives motion commands through the master haptic manipulator which is connected to personal computer (PC). Control commands are sent from PC to onboard computer of the mobile robot through wireless network. In Fig. 1a, configuration of two link master manipulator is shown. Mobile robot control signals are based on the position of end-effecter (x_m, z_m). Figure 1b shows the configuration of the mobile robot. V, ϕ are the linear velocity and the heading angle, respectively, S is the traveling distance of the robot. Obstacle range information, which is obtained from the robot's sonar sensors, is sent to PC. Finally, force feedback is generated based on obstacle range information and it is applied to operator's hand. Vision system is also used for providing visual information to human-operator.

3 Command strategies

3.1 Position–position and position–speed strategies

Position–speed command strategy is used for most of remote control applications of the mobile robots [5–7]. The speed of the robot is changed with respect to the position of the master device. This control mode is based on Eq. (1)

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

where q_1, q_2 define the position of master device and k_V, k_w are proportionality constants. q_1 and q_2 are based on master's position and calculated using the following rules

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

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

Equations (2) and (3) describe dead zone for master's end-effecter's position. Size of dead zone is defined by z_{dz} and x_{dz}.

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 and k_A are proportionality constants. Such command 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 as follows: position–position mode and position–speed mode.

3.2 Combined command strategy

In this section, we describe combined command strategy, which enables us to switch between position and speed command modes. First, this combined strategy was proposed in [15]. 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 command strategy is more accurate, so that operator can easily move robot to the desired location. However position command strategy is highly sensitive due to the usage of large scaling factor.

Human-operator can decide what command 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. To do this it is always necessary to save current master's position during each switching.

Special resetting algorithm should be applied to master's position when switching is done. It is necessary to set to zero master's coordinate system in order to prevent sudden jump of controlled position or speed value.

Manual switching is suitable for teleoperation when human-operator has enough information about the state of the robot and environment. That is why it is important to study the role of different types of feedback information. We suppose that hybrid command 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

In many applications of telerobotics human-operator is provided by visual feedback information. This information can be divided into two types as follows: text 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 video stream and text information were used 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

$$F = F_e + i F_{\text{init}}, \tag{5}$$

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

$$F_e = \begin{cases} \frac{k_e}{L}, & L < L_o \\ 0, & L \geq L_o \end{cases}, \tag{6}$$

where k_e is a scaling constant, L_o is a constant distance for generating force feedback. F_{init} is the force calculated by the following equation

$$F_{\text{init}} = -k_{\text{init}} z_m, \tag{7}$$

where k_{init} is a scaling constant. The main aim 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 Eqs. (1) and (2), value of F_{init} is proportional to the speed of the robot V, so that F_{init} 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 Eq. (5) is set to zero to remove the force. In position–speed strategy, when $i = 1$, theoretically there is possibility that $F_e = F_{\text{init}}$ which means no force feedback will be generated. However, this can happen only if $z_m = -k_e/(k_{\text{init}} \cdot L)$ and we consider this as a rare case. The following force feedback gains were used as follows: $k_e = 0.5\,\text{Nm}$, $k_{\text{init}} = 10\,\text{N/m}$.

5 Experiment

5.1 Experimental setup

For testing described command strategies and different types of feedback information experimental setup was designed and several experiments were done. Human-operator was giving control commands and choosing proper command strategy through haptic master device. Phantom Premium 1.5A from SensAble Technologies, Inc. was used as a master manipulator. Additional switch on Phantom's stylus was used to define command strategy. Speed command strategy was applied when switch was off, and position command strategy was used when switch was on. Haptic manipulator was connected to a desktop computer with control program. command strategy switcher was realized as a part of this program. Detailed structure of command strategy switcher can be found in [16]. TCP/IP protocol and 3COM commercial 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.

All kinds of feedback information were transmitted to the control computer. Textual and visual feedback were transmitted to human via vision system and user interface. Sonar sensors, which were installed on the mobile robot, were used to obtain obstacle range information. Force feedback was generated by master haptic device.

Figure 2a shows master side. Human-operator received vision information from computer display and haptic feedback based on obstacle range information from master device. Figure 2b shows mobile robot with two cameras. One camera was mounted on top of the robot in order to capture general view of environment. Second camera was mounted in

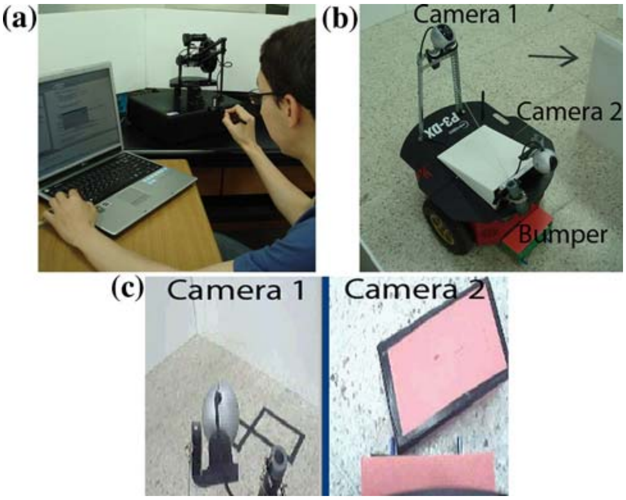

Fig. 2 Human-operator with master device (**a**) and mobile robot with vision system (**b**). Human-operator's view from vision system (**c**). Camera 1 gives general view, camera 2 gives the view of the object

front of the robot and recorded the view in front of the robot. Bumper was attached to the robot in order to move objects, as well. Figure 2c shows the view from two cameras attached on robot.

Five different subjects (3 male and 2 female with ages from 22 to 26 years old) participated in experiments. Rules for switching between speed and position control modes were explained to subjects, therefore they could make optimal decisions for combining command strategies. Every subject had two training sessions for each command strategy. After training session, every subject was asked to complete full task three times and average result of the subject was reported.

The following values of control parameters for speed and position command strategies were used for all experiments as follows: $k_v = -5\ \mathrm{s}^{-1}$, $k_w = -0.5°/(\mathrm{mm\,s})$, $k_s = -40\,\mathrm{mm/mm}$ and $k_A = -2°/\mathrm{mm}$ (for experiment in Sect. 5.2). For experiment described in Sect. 5.3, values of scaling factors were several times smaller than in previous case as follows: $k_s = -1.5\,\mathrm{mm/mm}$, $k_A = -0.25°/\mathrm{mm}$. This allowed subjects to control mobile robot more accurate. Additional master device coordinate system resetting scheme was used for solving the problem of workspace mapping in position control mode. Master device resetting was done every time during position command strategy when limit of master device's workspace was achieved. Both for speed and position control of mobile robot PD-control law was used. In all cases, Pioneer 3DX mobile robot was controlled by sending desired speed values. For speed control mode, value of desired speed was calculated based on position of the master device. For position control mode, desired speed was calculated based on error between desired and actual positions of the mobile robot. For mobile robot positioning experiment absolute linear speed of mobile robot was limited by 700 mm/s and for teleoperation in complex environment absolute speed was limited to 400 mm/s.

5.2 Positioning of mobile robot

In this section, we describe experiment in which quality of mobile robot positioning was evaluated. We checked which command strategy, mentioned in Sect. 3 of this article, gave the best performance in terms of task completion time. A simple task was given to subject in order to compare different control methods. 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.

First, no obstacles were placed into the workspace. In this case, force feedback was not transmitted to the subject. Human-operator could only receive text information about the robot's actual position. Time for completing the task was the main objective to analyze. Results are presented in Fig. 3, which shows mobile robot's position graph when robot was teleoperated using position–speed, position–position (Fig. 3a) and hybrid command strategies (Fig. 3b). In Fig. 3c, time history of desired speed of the robot is shown.

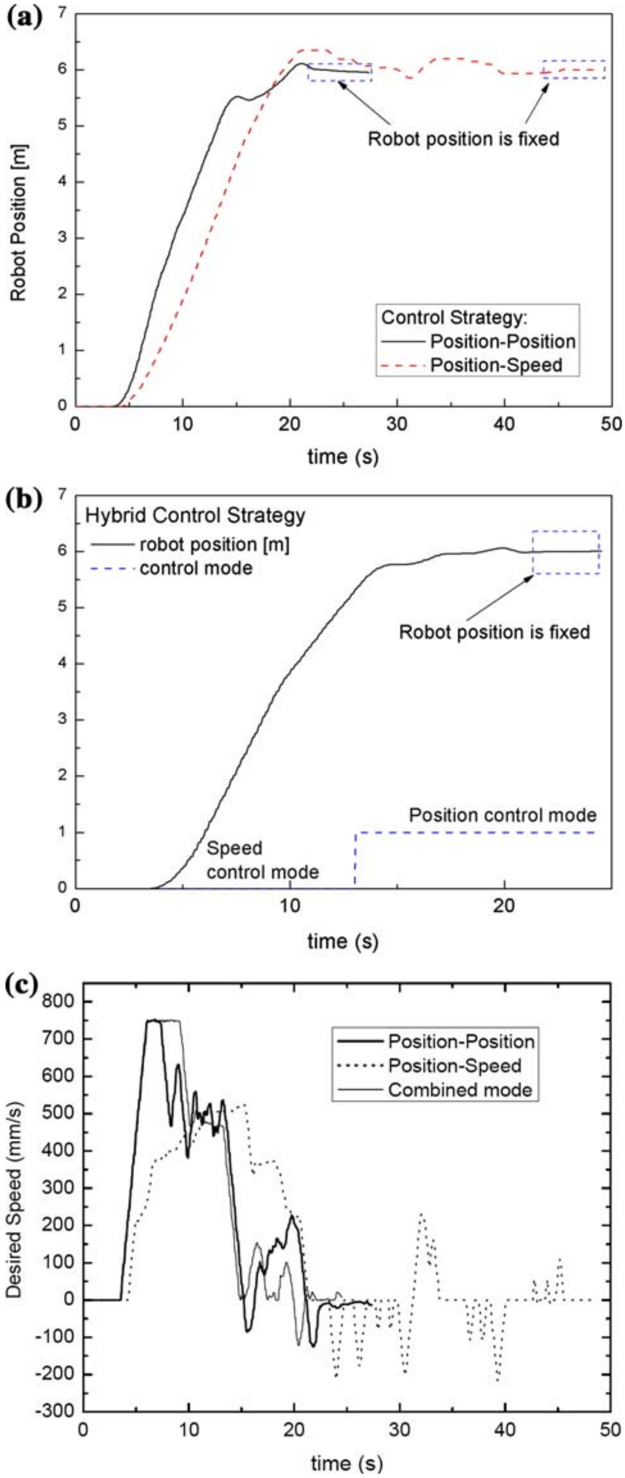

Fig. 3 Experimental results for mobile robot positioning when only text feedback was provided to human-operator. Plot **c** shows desired speed of mobile robot for different command strategies

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 command strategy was used. In this case, human could directly control position of the mobile robot by changing the position of the Phantom device. However, mobile robot can't follow position of master device in position command strategy due to significant difference in dynamic response of the robot and master device.

Figure 3b 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. 3b). This mode allowed to control the robot accurately and intuitively. As a result, navigation time was reduced.

Summary of experiments with all subjects is shown in Fig. 4. We compared average navigation time for positioning task using three different command strategies. Hybrid command strategy showed highest performance. Compare to position–speed strategy, proposed hybrid command strategy reduced navigation time by 36%.

If we compare the quality of the robot's motion from position graphs in Fig. 3, 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 command strategies were used accuracy analysis experiment was performed. Similar as an previous case, the subject was expected to control the mobile robot and to stop it at 6 m and then, fix its position. Obstacle was placed 6.5 m away from the original position, so that human-operator could feel force feedback generated based on obstacle range information.

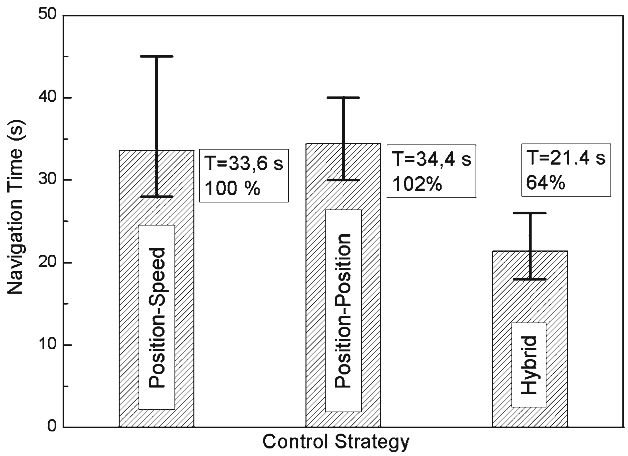

Fig. 4 Navigation time diagram for different command strategies. *T* is navigation time

We analyzed the influence of force feedback and different command strategies to the accuracy of the mobile robot positioning. Each sampling time robot's actual position was measured and absolute error was calculated. To obtain the value of the average error the following equation was used

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

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.

Experimental results are represented in Fig. 5. Positioning experiments using speed, position and hybrid command strategies with and without force feedback were performed. As it was described in previous part, robot was started from origin and expected to move 6 m. Position error was calculated and analyzed.

In Fig. 6, summary of experiments with five subjects is shown. The smallest average error was achieved, when position–position command strategy without force feedback was used. The largest average error was during teleoperation with position–position command strategy and with force feedback. Existence of force feedback gave a strong effect for both speed and position control modes. In speed command strategy, usage of force feedback improved accuracy of positioning. However, in position control force feedback was critical, and significantly reduced accuracy of motion.

5.3 Mobile robot teleoperation in complex environment

In previous section, experimental results for positioning of the mobile robot was presented. Positioning of mobile robot is easy, but frequently used operation during remote control tasks. For full study of the role of combined speed and position control in mobile robot teleoperation it is necessary to evaluate experimental study in a complex environment.

In Fig. 7, scheme of environment which was used for experiments is shown. There were two rooms connected with a narrow pass. Initially robot was placed in room 1. Human-operator was expected to navigate robot from room 1 to room 2. In room 2 robot should complete a task which included moving two objects from initial positions to desired positions. Desired positions for both objects were visually marked on the floor. To move objects, human-operator had to control mobile robot's position very accurately. For moving objects, bumper was attached in front of the robot's body. After completing the task robot should be placed to the final position. Figure 8 shows mobile robot after completing the task (a) and

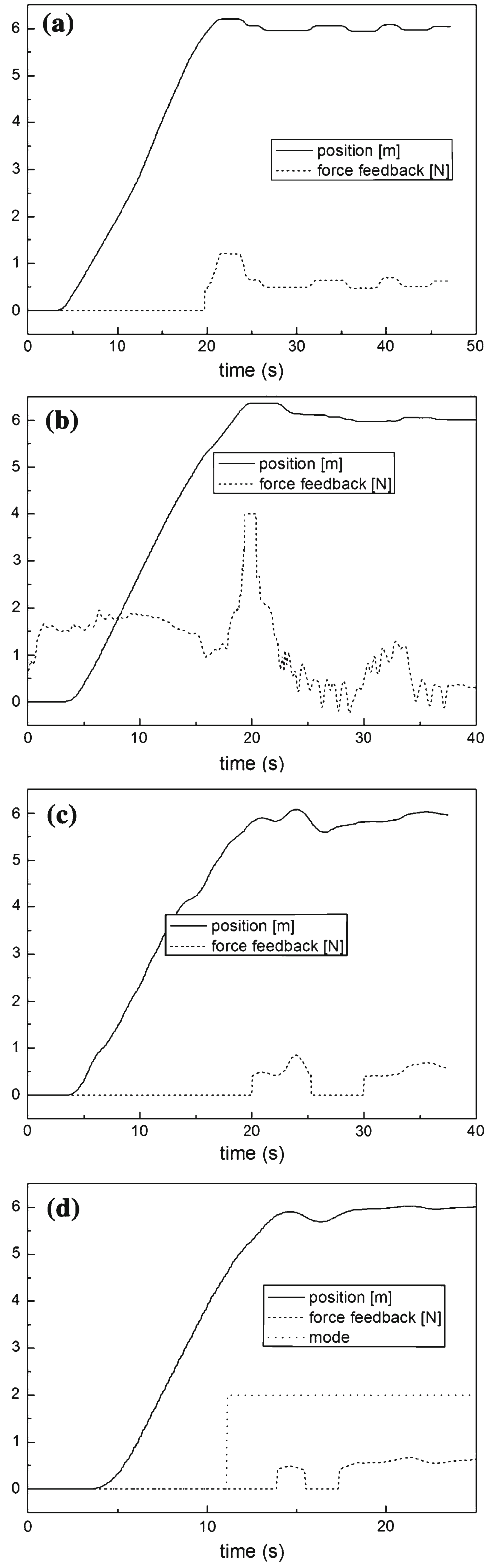

Fig. 5 Experimental results for mobile robot positioning, when text information and force feedback was provided to human-operator. **a** Speed control with force feedback based on Eq. (6); **b** position control with force feedback based on Eq. (5); **c** position control with force feedback based on Eq. (5); **d** combined command strategy with force feedback based on Eq. (5)

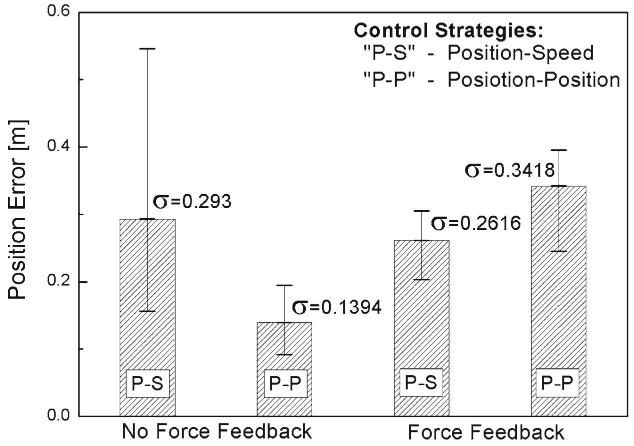

Fig. 6 Position error diagram for different command strategies with and without force feedback

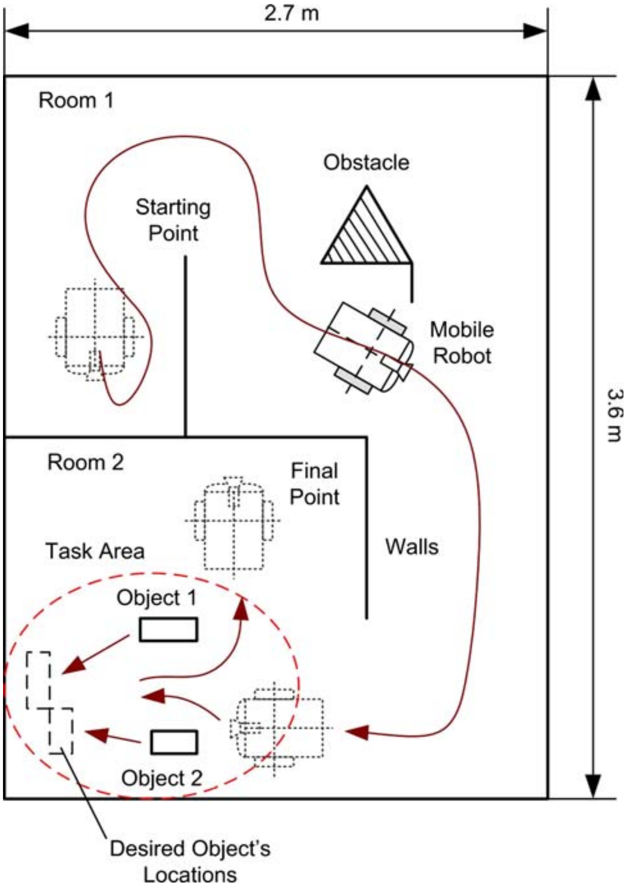

Fig. 7 Map of designed experimental environment

the way positioning errors were measured (b). First, errors a, b, c and d were measured. Then, positioning error e was calculated as follows

$$e = \frac{a+b+c+d}{4} \tag{9}$$

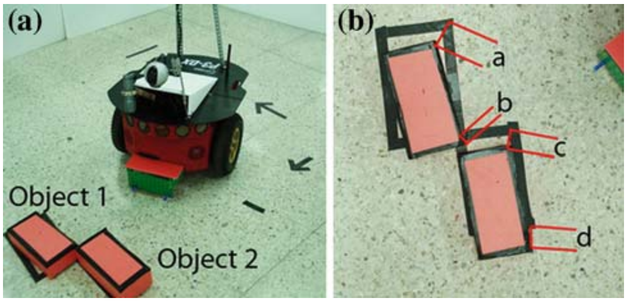

Fig. 8 Mobile robot after completing the task (**a**) and measuring of object positioning error (**b**)

For performance evaluation of proposed combined command strategy productivity and accuracy of task implementation were analyzed. Measuring of total navigation time which was required for completing the task gave information about system's productivity. Error of object positioning was measured in order to analyze accuracy.

6 Discussion

6.1 On the role of text and visual feedback

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. 4). 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. 3, 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. 3a, 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. 4). 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 command strategy with manual switching was used (Fig. 3b). First, position–speed command 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. 4). Hybrid command strategy showed high performance.

6.2 On the role of haptic feedback

In the next group of experiments additional haptic feedback was provided to the human operator. This feedback was generated according to obstacle range information. Results for these experiments are presented in Fig. 5.

In Fig. 5a, force feedback was calculated according to Eq. (5) where parameter $i = 0$. This feedback contained only obstacle range information. In Fig. 5b, feedback was calculated with $i = 1$, which means that force included information about the speed of the robot. In the first case (see Fig. 5a), 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. 5b). 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. 6).

For the case of position–position command strategy (Fig. 5c), 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 Eq. 4) caused high sensitivity of the teleoperator system. That is why generated force feedback caused positioning errors at time around 25 s (see Fig. 5c). We received the same negative effect of force feedback for teleoperation with hybrid command strategy (see Fig. 5d). Average position error was the largest (Fig. 6). For mobile robot teleoperation in environments with many obstacles, existence of force feedback reduces the accuracy of motion.

6.3 Navigation time and command strategies

Performance of three command strategies was tested as follows: position, speed and combined command strategy with switching between position and speed control. In Fig. 9, results for measuring navigation time for five subjects are presented. For speed command strategy for all cases navigation time was the smallest. All subjects could control mobile

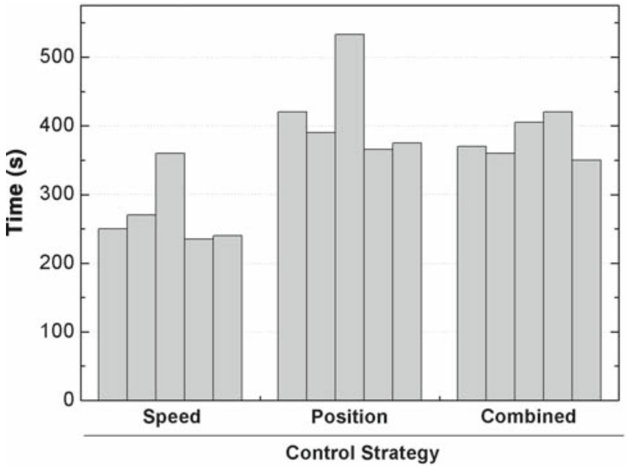

Fig. 9 Experimental results for five subjects: total navigation time versus command strategy for five subjects. Each column within one command strategy indicates average result of three trials from one subject

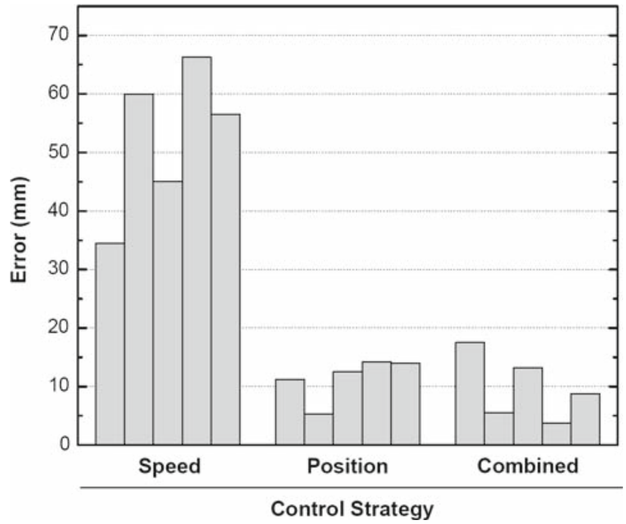

Fig. 10 Experimental results for five subjects: average positioning errors for object 1 and object 2. Each column within one command strategy indicates average result of three trials from one subject

robot successfully. Average navigation time was about 270 s (Fig. 11a).

More time was required for completing the task in position and combined command strategies. For these strategies almost all subjects required approximately same navigation time between 370 and 420 s. In position control mode, human-operator directed robot by controlling its desired position. As it was described in Sect.2, in position control mode human-operator had to sequentially reset coordinate system of the master device for proper mapping master's workspace into mobile robot's workspace. These resetting operations required some certain amount of time, as a result total navigation time was increased compare to conventional speed control mode. Nevertheless, average navigation time for all subjects in combined control mode was less than in position control mode (Fig. 11a). It is so, because in combined command strategy human-operator in addition to position control could use speed command strategy when it was more suitable for the task. For example, in order to move robot from Room 1 to Room 2, human-operator could use speed control of mobile robot. After arriving to room 2, human-operator could switch to position control mode for accurate task implementation. In those case, switching to speed control mode allowed human-operator to navigate robot faster.

6.4 Positioning accuracy and command strategies

In Fig. 10, results for positioning errors of two objects for five subjects are presented. Error was the largest for both objects in speed control mode. Average positioning error for all subjects was more than 50 mm. The smallest error and best accuracy were achieved in position and combined control modes. In position control mode displacement of master device was mapped into displacement of mobile robot. This provided human-operator with intuitive and comfortable way to carefully adjust position of mobile robot. As a result, high performance in accuracy was achieved in position command strategy. The above is true for combined command strategy, as well, because human-operator could switch to position control when it was necessary to complete the task of object moving. Therefore, average error for object moving task in position and combined command strategy was about 12 mm which is more then four times smaller than in speed control mode.

6.5 Productivity and accuracy tradeoffs

Experimental results were compared by quantitative comparison methods (ANOVA and Tukey's post hoc test). Results are presented in Tables 1 and 2. Critical value for Tukey's HSD was 4.51. Analysis showed that both for measuring navigation time and accuracy there was a significant statistical difference in experiments with speed and position command strategies and in experiments with speed and hybrid command strategies. In comparison of hybrid command strategy with position command strategy, statistical analysis did not show significant difference. However, experimental results allow us define the main trend. We can conclude that compare to conventional speed control, usage of combined command strategy for mobile robot teleoperation can significantly improve accuracy of robot's motion and at the same time impair the speed performance. Positioning errors were reduced by 400% while required time was increased by 30%.

In Fig. 12, graph where measured navigation time is plotted versus object positioning error. In this plot, different command strategies are separated by color. It is clear to

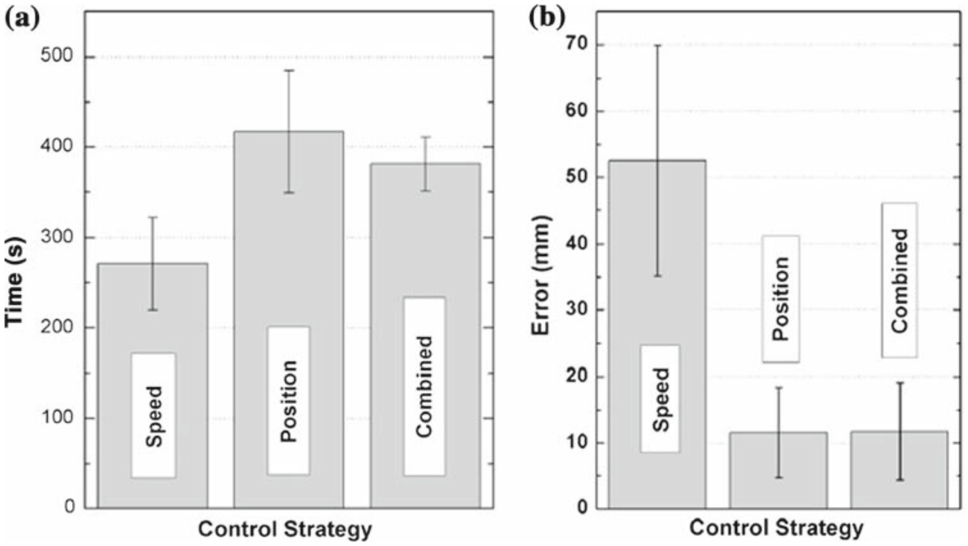

Fig. 11 Experimental results: average navigation time and positioning errors versus command strategies

Table 1 ANOVA and Tukey's post hoc test results for measured navigation time

Command strategy	Speed	Position	Hybrid
Speed	x	6.23597	4.70478
Position	x	x	1.53119

Table 2 ANOVA and Tukey's post hoc test results for measured accuracy

Command strategy	Speed	Position	Hybrid
Speed	x	11.07131	11.53037
Position	x	x	0.459054

notice that results from experiment when speed command strategy was used differ greatly from results in position and combined control mode. Also, both in terms of accuracy position and combined command strategies are very similar, hence combined command strategy is better in terms of productivity.

7 Conclusions and future works

7.1 Conclusions

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

Textual feedback was 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 could 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. However, in some cases force feedback

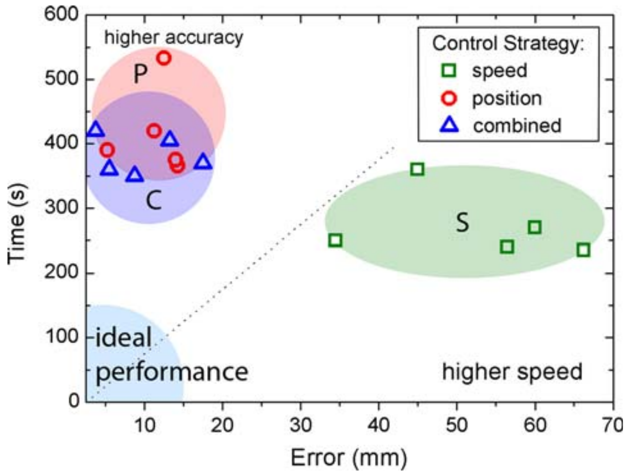

Fig. 12 Experimental results: navigation time versus positioning error. *P*, *S* and *C* indicate position, speed and combined command strategies, respectively

based on obstacle range information is the reason of low accuracy. Therefore, it is important to consider the usage of this force feedback when mobile robot application requires high accuracy in control.

Conventional for mobile robot teleoperation, speed command strategy showed highest productivity while position and combined command strategies showed better performance in accuracy. Combined command strategy allowed human-operator to switch between high productivity and accuracy in order to achieve highest performance. Experimental study showed that combined command strategy improved accuracy of mobile robot teleoperation about five times compare to speed control mode. Productivity of combined command strategy compare to position command strategy was improved by 15%. In general, proposed combined command strategy improved the quality of teleoperation system, made control process more intuitive and safe.

Usage of combined command strategy can enlarge application area of mobile robot teleoperation. Described strategy is suitable both for large or small environments, for tasks where it is important to show high speed navigation or accurate motion.

Proper usage of the described command 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 command strategies and types of force feedback.

7.2 Future works

There are several important issues which are not described in this article but should be solved in future.

First issue is time delay. In modern teleoperation systems time delay caused by long distances and computer networks significantly effects to stability and performance. Existence of variable time delay and possible information loss in communication lines should be considered for future improvement of combined command strategy.

Second, it is important to consider dynamic characteristics of mobile robot, which can be a reason of unexpected behavior of the robot when switching between control modes happens. For example, mobile robot can't be stopped at the same moment when switching happens due to inertia.

More human studies should be done in order to develop and evaluate new design of the master device, which will give human-operator an easy interface for using combined command strategy.

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