# A Preliminary Experimental Study on Haptic Teleoperation of Mobile Robot with Variable Force Feedback Gain


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## Abstract

In this paper, new force feedback rendering scheme for mobile robot teleoperation is presented. Previous research indicated the problem of the low quality of mobile robot's motion control during the teleoperation with feedback force based on obstacle range information. Human-operator's commands were distorted by the feedback force, as a result, mobile robot could not follow human-operator's intention. To solve this problem, a new force rendering approach with variable feedback gain is proposed. Force feedback gain is variable based on measured distances to the obstacle and derivatives of the distances. Simulation and experimental study showed that the variable haptic feedback improves the quality of mobile robot teleoperation. variable feedback force improved the quality of mobile robot teleoperation by making robot's trajectory smooth and accurate.



**Index Terms:** H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces—Haptic I/O; I.2.9 [ARTIFICIAL INTELLIGENCE]: Robotics—Operator interfaces


## 1 Introduction

Mobile robot teleoperation has many promising application areas such as planets exploration, navigation in hazardous environments, inspection of complicated industrial constructions, etc. In all these application examples human-robot interfaces play the key role in successful completion of required task.

At the moment, haptic interfaces are becoming more popular as an interaction channel in mobile robot teleoperation. There have been several researches on haptic interfaces for mobile robot teleoperation. An event based direct control of mobile robot with force feedback was proposed in [1]. Advanced interfaces for vehicle teleoperation were investigated in [2]. In [13], the effectiveness of force feedback for safe navigation was measured in teleoperation in virtual environment. In [3], obstacle map based haptic interface was proposed. Haptic, audio and visual feedback were investigated in [4]. In [5], multi modal interface for variable control of a simulated telerobotic system was investigated. The concept of virtual cone for intuitive and safe mobile robot haptic teleoperation was developed in [6]. Vision-based force guidance for improving teleoperation of mobile manipulator was described in [7]. In [8], a group ecological human-robot interfaces for mobile robot teleoperation was proposed and described. Remote control of mobile robot with force reflection and fuzzy logic based velocity control was presented in [9]. In [14], a teleoperation paradigm for human-robot interaction for Internet based mobile robot teleoperation was presented. Vibrotactile display for hand-held input device and its application for mobile robot teleoperation was described in [15].


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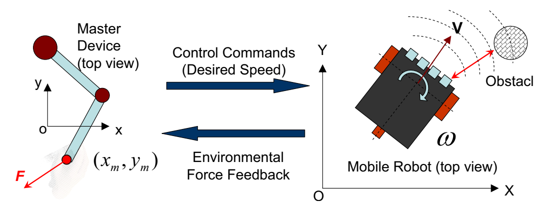


Figure 1: Configurations of master manipulator and mobile robot

Recently, hybrid command strategy for mobile robot teleoperation was proposed in [10]. It allowed human-operator to achieve higher accuracy during teleoperation. However, experimental study showed that combination of hybrid command strategy with environmental force feedback reduced the task performance in teleoperation [11]. In teleoperation with force feedback based on obstacle range information, force feedback distorted human-operator's intent. Force feedback modified the reference position/speed input from master device, as a result mobile robot did not follow original human-operator's commands. Teleoperation with force feedback was characterized by error between expected and actual motions of the mobile robot.

In this paper, we present a new approach for rendering feedback force based on variable feedback force gain. We suppose that application of the variable feedback force improves the quality of human-robot interaction during teleoperation. Usage of variable feedback force in mobile robot teleoperation provides human-operator with more intuitive and stable control interface. The proposed approach allows human-operator maintain high task performance and at the same time provide useful information to prevent potential collisions of the robot with environment. Simulation and experimental study are done and results are presented in order to support the proposed idea. This paper presents new results of simulation and experimental studies on time and accuracy performance of the teleoperation system. Discussion and possible application areas are given.

## 2 Overview of Mobile Robot Teleoperation

We consider bilateral teleoperation of a wheeled mobile robot. A human-operator gives motion commands through the master haptic manipulator. Control commands are sent to the mobile robot via communication networks. In Fig. 1, configuration of a two link master manipulator (left) and mobile robot (right) are shown. Control inputs for mobile robot are based on the position of end-effecter $(x_m, y_m)$. $V$, $\omega$ are linear and angular velocities, respectively. Obstacle range information, which is obtained from the robot's sensors (sonar, laser range sensors), is sent back to the master device. Force feedback is generated by the master device based on obstacle range information.

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

$$\begin{pmatrix} V \\ \omega \end{pmatrix} = \begin{pmatrix} k_V & 0 \\ 0 & k_w \end{pmatrix} \begin{pmatrix} y_m \\ x_m \end{pmatrix}, \tag{1}$$

where $k_V$, $k_w$ are scaling coefficients.

## 3 ENVIRONMENTAL FORCE FEEDBACK

### 3.1 Conventional Force Rendering Method

In this paper, we consider feedback force based on the obstacle range information only (environmental force feedback). This kind of haptic feedback is rendered based on measured distances from the mobile robot to the obstacles. We define the following vectors:

$$R = \begin{pmatrix} r_1 & r_2 & \dots & r_n \end{pmatrix} \tag{2}$$

$$R_o = \begin{pmatrix} r_{o1} & r_{o2} & \dots & r_{on} \end{pmatrix} \tag{3}$$

where $i = 1..n$, $n$ is a number of range sensors in the mobile robot. $R$ is a vector of measured distances to the obstacles $r_i$ from each sensor. $R_o$ is a vector of fixed distances $r_{oi}$ from which generation of feedback force starts. Once distance between the robot and the obstacle is less than $r_{oi}$ then measured distance to the obstacle is reflected to human-operator via force feedback. $\Delta$ is defined as a difference between $R_o$ and $R$ for each sensor:

$$\Delta = R_o - R = \begin{pmatrix} \delta_1 & \delta_2 & \dots & \delta_n \end{pmatrix}. \tag{4}$$

Each range sensor has a fixed location on the robot's body. Therefore, we define vector $\Theta$ to describe position (angular orientation) of each sensor:

$$\Theta = \begin{pmatrix} \theta_1 & \theta_2 & \dots & \theta_n \end{pmatrix} \tag{5}$$

where $\theta_i$ defines the lateral angle which describes position of $i_{th}$ range sensor.

In conventional approach [12], [13] the following basic law was used for calculating environmental feedback force:

$$f_i = \begin{cases} k_i\delta_i, & r_i \le r_{oi} \\ 0, & r_i > r_{oi} \end{cases} \tag{6}$$

$$F = \begin{pmatrix} f_1 & f_2 & \dots & f_n \end{pmatrix} \tag{7}$$

$f_i$ is a relevant force feedback calculated based on spring model by multiplication of virtual stiffness $k_i$ by distance $\delta_i$ measured from $i_{th}$ sensor. Vector $F$ includes $n$ the forces from $n$ sensors, respectively. The maximum force $f_m$ is selected from vector $F$ and applied to human-operator in direction opposite to the obstacle:

$$f_m = \begin{pmatrix} \max\{F\} \equiv f_j \\ \theta_j + \pi \end{pmatrix}. \tag{8}$$

In (8), $f_j$ is a maximum force, $j$ is an index of selected maximum force value in vector $F$, and $\theta_j$ is a relevant angle which shows direction to the nearest obstacle. Fig. 2 shows the plot of feedback force which was described above. Due to constant feedback gain $k_i$ feedback force is always linearly proportional to the distance to the obstacle.

Experimental study on haptic mobile robot teleoperation was done in [13]. Experiments proved that usage of environmental feedback force improves safety of teleoperation by significant reducing the number of collisions between the robot and environment. But, it was also shown that feedback force with constant feedback gain degrades the quality of mobile robot motion control [12]. Experiments on mobile robot positioning showed that feedback force based on obstacle range information acts as a disturbance for the master device. When the operator wants to place accurately the mobile robot in a certain position feedback force generated on the master device may modify the reference command given by human-operator. As a result, real movements of the mobile robot can greatly differ from the desired one.

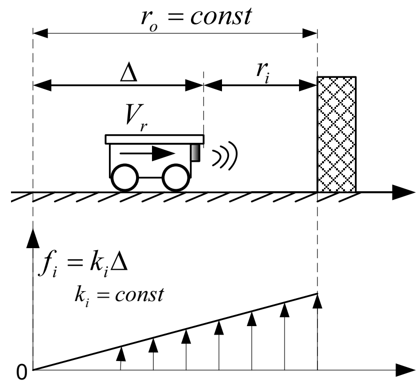


Figure 2: Scheme for rendering feedback force based on obstacle range information

### 3.2 Motivation

In this section, we propose the variable force feedback which will not degrade performance of mobile robot motion control. In cases when mobile robot is located in large workspaces without many obstacles, mobile robot has more spare place for moving without collisions with static obstacles. Therefore, the probability of collisions between mobile robot and environment during teleoperation in large workspace with less obstacles is low. On the contrary, in small workspace, mobile robot will have higher probability to collide with obstacles due to limited spare space. Force feedback which is based on obstacles in large workspace will be smaller and will give less negative effect on the quality of motion control than force feedback which is generated in small environment. It is also important to consider relative speed of mobile robot and obstacles. If the mobile robot moves with high speed then the probability of collision with obstacles is high. In cases, when it is required to perform accurate motion control, the mobile robot is teleoperated with low velocities. In this case, the distance between the robot and the obstacles decreases slowly and probability of collision is low. In many teleoperation applications mobile robots operate in dynamic environments where obstacles can appear, disappear and/or change their locations. In such cases, force feedback should not unpredictably change its magnitude and direction. Based on the conditions, described above, we propose to render haptic feedback which will be variable to distances to the obstacles and absolute speed of the mobile robot.

### 3.3 Variable Feedback Gain

A new approach for rendering variable feedback force is presented in this subsection. Main idea is modification of stiffness $k$ in (6) based on distance vector $R$ and its time derivative $dR/dt$. We define variable gain $k_i^*$ for generating force feedback based on distance measured from $i_{th}$ sensor as follows:

$$k_i^* = \begin{cases} k_{\min}, & \frac{dr_i}{dt} \ge 0 \\ \frac{1}{\gamma}(k_{\max} - k_{\min})\frac{dr_i}{dt} + k_{\min}\ , & -\gamma < \frac{dr_i}{dt} < 0\ , \\ k_{\max}, & \frac{dr_i}{dt} \le -\gamma \end{cases} \tag{9}$$

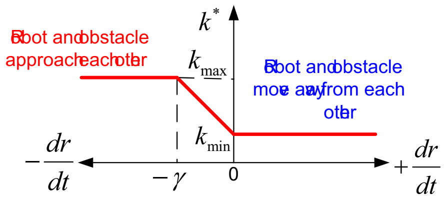


Figure 3: The value of variable force feedback gain depends on the value of the derivative $dr/dt$


Figure 4: Human-operator and master setup during simulation and experiments (a) and the mobile robot during teleoperated by human-operator (b)

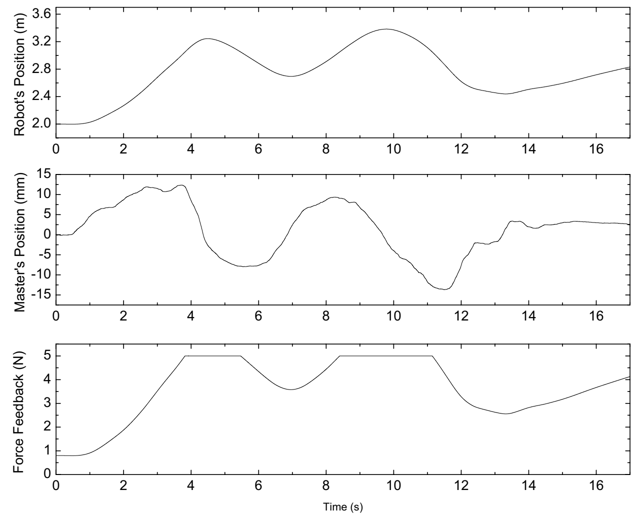


Figure 5: Mobile robot teleoperation with nonvariable force feedback gain

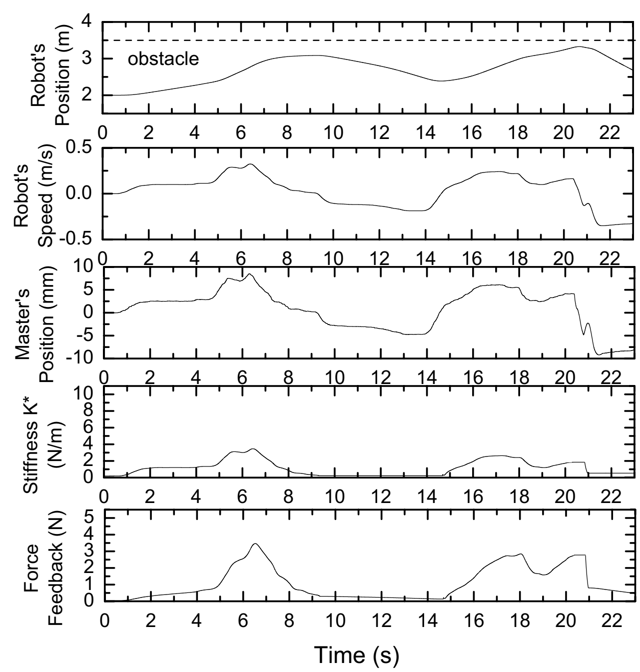


Figure 6: Mobile robot teleoperation with variable force feedback gain

where $k_{min}$ and $k_{max}$ are minimum and maximum marginal values of feedback gain; $\gamma$ is a boundary relative speed of mobile robot and obstacle. In Fig. 3 graphical explanation for (9) is shown. If the derivative of a distance to the obstacle $dr/dt$ is positive then the obstacle and the robot move away from each other and minimum value of feedback gain is used. If $dr/dt$ is less than $\gamma$ then robot and obstacle approach each other with high speed and maximum value of gain is used. If value $dr/dt$ is between $-\gamma$ and 0 then force feedback is proportional to $dr/dt$.

## 4 Simulation

### 4.1 Teleoperation with Variable Force Feedback Gain

The human-operator controlled the mobile robot via manipulating haptic master device. Phantom Premium 1.5A from SensAble Technologies, Inc. was used as a master manipulator. For easy explanation 1-DOF problem was considered. Mobile robot was modeled as a mass-damper system. Dynamics of mobile robot is described by (10)

$$M\ddot{x}_r + B\dot{x}_r = U, \tag{10}$$

where $x_r$ is position of the robot, $M$ and $B$ are mass and damping of the robot. $U$ is a control input. Speed of the robot was controlled by P-controller with control gain $K_v$. The following values of the model parameters were used: $M = 20kg$, $B = 2Ns/m$, $K_v = 200Ns/m$, $R_o = 1.7m$, $K_{min} = 0.2N/m$, $K_{max} = 4N/m$, $\gamma = 0.4m/s$. Phantom Premium 1.5A was connected to the computer with the model of the mobile robot and environment. The human-operator could see visualization of the mobile robot and the obstacle on the screen. Fig. 4 shows human-operator and master setup during simulations and user study. In simulation, the human-operator was asked to move the virtual robot towards the obstacle which was placed 2.5 $m$ away from the origin.

In Fig. 5, experimental result for mobile robot teleoperation with conventional feedback force which is calculated based on (8). Stiffness $K$ was constant and equal to $k_{max}$. Obstacle was placed 3.5 $m$ away from the initial position of the robot. Force feedback was generated when the robot approached the obstacle. The force was limited by 5 $N$ due to the master device characteristics. However,

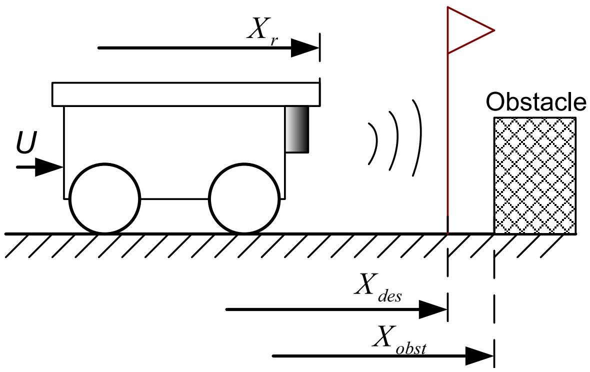


Figure 7: Scheme of experiments with simulated model of mobile robot

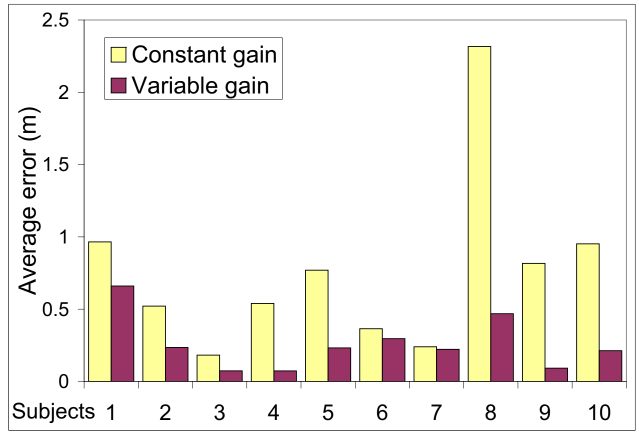


Figure 8: Summary of results: average positioning errors for teleoperation

the force generated on the master device was quite high, so that it might be difficult for human-operator to manipulate the master device and perform accurate motion of the mobile robot. Usage of lower value of stiffness $k$ can reduce amount of force displayed to the operator, but this may dramatically effect on the safety of the teleoperation process.

Fig. 6, shows time history of the mobile robot's position and speed, master device's position, variable feedback gain (stiffness) and feedback force. Mobile robot's speed was controlled based on master's position. All the time the absolute speed of the mobile robot did not exceed $\gamma = 0.4\ m/s$, that is why feedback force was rendered based on variable feedback gain $K^*$. When the robot approaches the obstacle (2-6 s), feedback gain was increased; when the robot slows down (7-10 s), feedback gain decreases. As a result, we can see that based on proposed approach, large amount of force feedback is generated and displayed to human-operator only in cases when the robot moves toward the obstacle with high speed. Small amount of force feedback is displayed to the human-operator if the robot moves toward the obstacle with low speed.

### 4.2 Mobile Robot Positioning

In order to evaluate the influence of feedback force to the quality of teleoperation, simulation on mobile robot positioning was done. Scheme of the simulation task is shown in Fig. 7. Mobile robot started from the origin and was expected to move forward exactly 2 $m$ ($X_{des}$=2 $m$). Obstacle was placed 2.5 $m$ away from the origin. Position command strategy was used for the mobile robot teleoperation. Positioning error was calculated as follows:

$$e = \frac{1}{T}\int_0^T |X_{des} - X_r| dt, \qquad (11)$$

where $T$ is completion time. Positioning error was selected as a metric for measuring the quality of human-robot interaction in mobile robot teleoperation. Average position error in teleoperation can tell us how well the robot follows reference input from the master side in different conditions. That is why error is a good metric for evaluating performance of the system. In experiment, time was limited by 5 $s$. Each subject had five trials and average positioning error was reported. Summary from 10 subjects is presented in Fig. 8(a). In all cases, variable feedback force allowed subjects to position the robot with smaller errors than with feedback force with constant feedback gain. Average improvement for all subjects is 57.5%.

## 5 Experimental Study

Teleoperation of mobile robot Pioneer 3DX from MobileRobots was done in order to evaluate the influence of proposed variable force feedback for the quality of the system. Teleoperation was done via manipulating Phantom Premium 1.5A using the scheme shown in Fig. 1 and control strategy described by (1) was implemented. Six sonar sensors were attached to mobile robot. Sensors were attached every $60^o$ as it is shown in Fig. 9 (s1-s6). The following control parameters were used in all experiments: $K_{min} = 0.0001N/mm$, $K_{max} = 0.02N/mm$, $\gamma = 50mm/s$, $R_o = 2m$.

### 5.1 Navigation in Narrow Spaces

In this subsection we describe teleoperation experiment for navigation of the mobile robot in a narrow space. In Fig. 10, map of environment which was used in the experiment is shown. The human-operator was asked to navigate the robot through narrow corridor without collisions. The human-operator could see the remote environment with the help of USB camera attached on top of the robot. Sonar sensors measured the distance to the walls of environment. Example of measured distances and map of the environment built by the robot is shown in Fig. 10. Five different subjects asked to teleoperate the robot with conventional and variable force feedback rendering methods. Trajectories of the mobile robot were recorded for each case and compared with each other. Fig. 11(a) and Fig. 11(b) show robot's trajectories from experiments with five subjects for conventional and variable force feedback rendering methods, respectively. It is easy to notice that trajectories from experiments with variable force feedback rendering method are smoother than trajectories from experiments with conventional method. Trajectories for proposed variable force feedback are more neat and similar to each other while trajectories for conventional method are messy and chaotic. Time required for passing through the coridor for each subject was measured as well. Results are presented in Fig. 12. In cases when variable force feedback was used subjects could complete the navigation task faster. Trajectories of the mobile robot in these cases were shorter and velocity was higher.

In both cases due to existence of environmental force feedback there was no collisions with the walls. However, the quality of the robot's motion was different. During teleoperation with conventional force feedback large amount of force feedback was reflected to human-operator because distances to the walls around the robot were small. These high values of force feedback gave high impact to position of the master device which was often unexpected

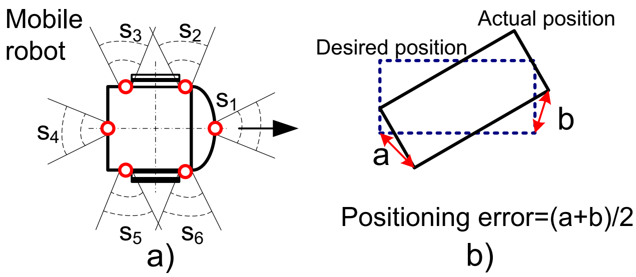


Figure 9: Scheme of the mobile robot with range sensors (a) and method for measuring object positioning error (b)

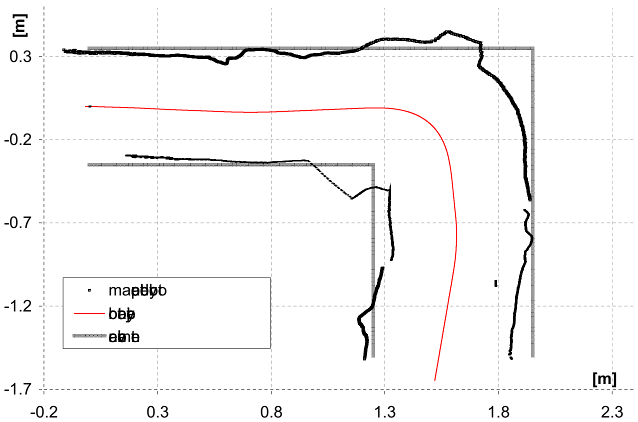


Figure 10: Map and task for teleoperation of the mobile robot in a narrow space

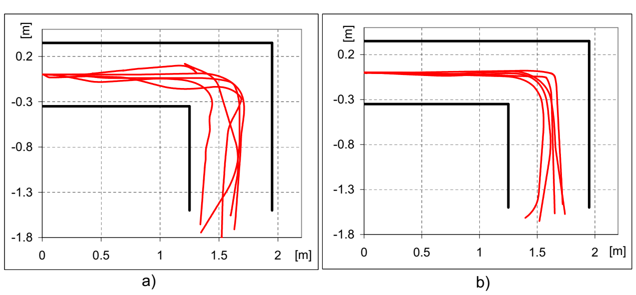


Figure 11: Trajectories of the mobile robot during teleoperation with constant force feedback (a) and variable force feedback (b)

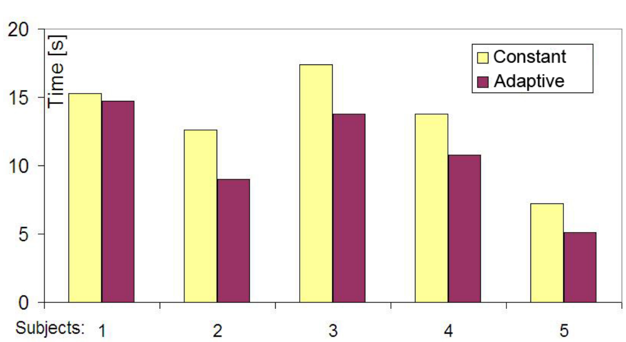


Figure 12: Time required for navigation in narrow space for five subjects with constant force feedback and variable force feedback

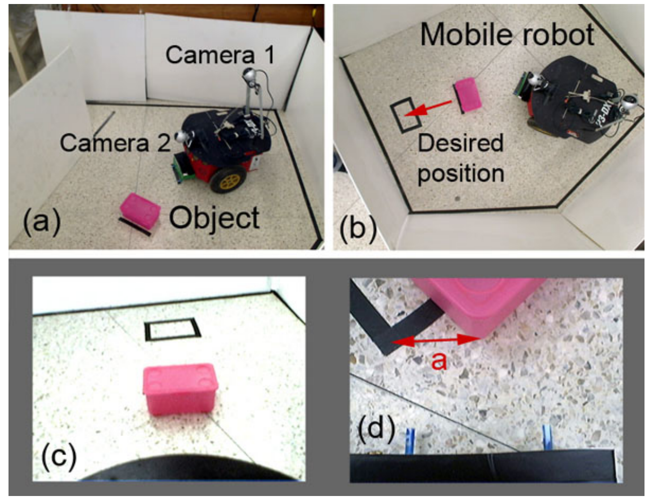


Figure 13: Photo of experimental environment and robot (a,b) and view from cameras (c,d)

to human-operator. That caused relatively large change for robot's linear and angular velocities. In teleoperation experiments when variable force feedback was used force feedback was proportional to the speed of the robot, and that is why it was not so high and did not distort the human's input in the master device.

### 5.2 Object Manipulation in Narrow Space

In the next experiment accuracy of the mobile robot's motion was compared in teleoperation with conventional and variable force feedback. In Fig. 13(a) and Fig. 13(b), photo of designed experimental environment is shown. Mobile robot was placed in a narrow space (average distance from the robot to the walls was less than 50 cm) and human-operator was supposed to move the box-type object (Fig. 13(a)) from initial to desired position (Fig. 13(b)). The height of the object was small, that is why there was no force feedback generated based on distance measured from the sonar sensors. The human-operator could see the experimental environment via two USB cameras (Fig. 13(a)) which showed the general view (Fig. 13(c)) and the view of the object (Fig. 13(d)). Five subjects were asked to do the positioning of the object task with conventional and variable force feedback. They were asked to move the object to desired position. Time limit (60 $s$) was given for each trial.

To evaluate performance of task completion object positioning error was measured. In Fig. 9(b) and Fig. 13(d), measurement of errors $a$ and $b$ is shown. Average error $(a+b)/2$ was reported after each trial for each subject. The results are shown in Fig. 14. For all the subjects error was higher in experiments with conventional force feedback rendering method. Positioning was more accurate in experiments with variable force feedback. During positioning task, the human-operator controlled the robot using low speed commands in order to perform accurate motions. That is why distance to the walls was changing slowly and smaller force feedback gain was used. In teleoperation with conventional force feedback human-operator could not perform accurate motion because of relatively high forces which were reflected via the master device. These forces distorted desired input from the human-operator and degraded the accuracy of positioning.

## 6 Discussion

As it was expected variable haptic feedback reduces amount of force which is displayed to human-operator. One can say that on the one hand it can decrease the safety of teleoperation process. On

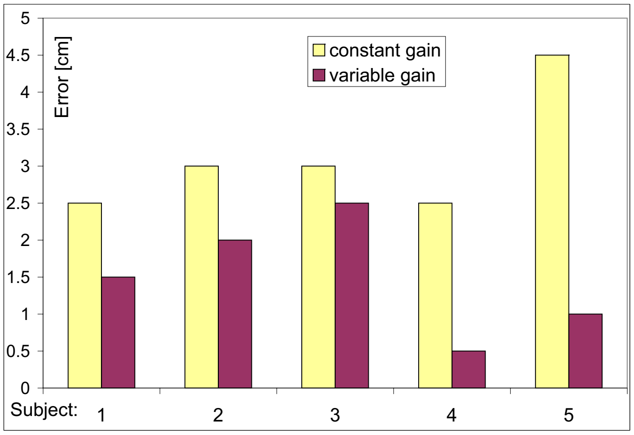


Figure 14: Experimental results for errors measured during positioning of the object task

the other hand it improves the quality of motion control when input from the human is not distorted by reflected forces. However, in comparison to nonvariable feedback force generation scheme, variable approach provides the optimal way for maintaining safety and high quality of the motion control at the same time. Application of variable feedback gain makes the trajectory of the mobile robot more smooth. Human-operator is provided by an opportunity to control the displacement of the mobile robot accurately. As a result, quality of the motion control is improved by introducing variable feedback force gain. There are many cases when proposed approach can significantly improve the teleoperation process in real applications. For instance, it can be applied to the teleoperation of mobile manipulator which is placed in remote environment with high concentration of obstacles. In this case, when human-operator moves the robot slowly or performs manipulations with some objects usage of variable feedback will not distort the desired intention of the operator.

## 7 Conclusion

In this paper simulation and experimental study of variable force feedback rendering method for the mobile robot teleoperation was presented. Described approach is based on consideration of the distances to the obstacles around the robot and relative speed of the robot and the obstacles. Simulation and experimental study was done in order to evaluate performance of the proposed variable force feedback rendering method.

Simulation result showed that application of variable feedback gain improves the accuracy of mobile robot teleoperation. Experiments showed that the use of variable feedback force improves the quality of mobile robot teleoperation by making robot's trajectory smooth and accurate. variable force feedback is useful for teleoperation of mobile robots which are placed in narrow environments with many obstacles. Proposed force feedback helps human-operator to keep mobile robot away from the obstacles while maintaining high motion accuracy.

In general the study showed that usage of proposed variable force feedback improves the quality of mobile robot teleoperation and provides safe and intuitive human-robot haptic interface.

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