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Hybrid Position-Position and Position-Speed Command Strategy for the Bilateral Teleoperation of a Mobile Robot

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Abstract: In this paper a control method for the bilateral teleoperation of a mobile robot was proposed, which is combining position-position and position-speed command strategies. We consider bilateral teleoperation of a wheeled mobile robot. Our main objective is to combine position-speed command strategy, which is usual for mobile robot control, with position-position command strategy. Generally teleoperation scheme has two control modes, which are position-speed mode and position-position mode. In position-speed mode, a master haptic manipulator's position defines the linear velocity and heading angle of the mobile robot. In position-position mode, the position of the robot is controlled based on the position of the master device. In this paper we propose a strategy to adapt a reasonable control mode automatically. Sonar sensors were used to detect obstacle range information, which is the source of force feedback to human operator. Developed scheme was tested with numerical simulations and experiments. The different types of navigation tasks were evaluated. Productivity, accuracy and usability of hybrid control strategy are analyzed. Flexible and intuitive control was achieved.

Keywords: Mobile robot, teleoperation, haptic interface, navigation.

1. INTRODUCTION

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. Different aspects of mobile robot bilateral teleoperation were studied. Several haptic interfaces were proposed to improve performance of teleoperation.

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 is 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. Bilateral teleoperation of a mobile robot over communication channels with constant delays is studied by D. Lee et al. [12].

All mentioned researches were concentrated on developing and studying haptic 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 control strategy in previous researches. In this paper, we designed a new control strategy for a mobile robot bilateral teleoperation. A hybrid control method of mobile robot teleoperation is proposed, which combined position-position and position-speed command strategies.

2. SYSTEM OVERVIEW

2.1 System configuration

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. Hybrid control strategy is used for mobile robot navigation. 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.

Dynamics of wheeled mobile robot is described by

$$D(x)\begin{pmatrix}\dot{V}\\ \ddot{\phi}\end{pmatrix}+Q(x,\dot{x})\begin{pmatrix}V\\ \dot{\phi}\end{pmatrix}=\begin{pmatrix}u_1\\ u_2\end{pmatrix}+\begin{pmatrix}\delta_1\\ \delta_2\end{pmatrix}, \quad (1)$$

where V,ϕ are the linear velocity and the heading angle of the robot, $x=(x_r, y_r, \phi, \Theta_r, \Theta_l)$ defines the position (x_r, y_r) and the rotation of the wheels (Θ_r, Θ_l), (δ_1, δ_2) are the external forces, (u_1,u_2) are the control forces, applied to the wheels [13]. *D(x)* and *Q(x)* are the inertia and the Coriolis matrixes, respectively. Fig. 1(a) shows the configuration of the mobile robot. *S* is the traveling distance of the robot.

In Fig. 1(b), configuration of two link master manipulator is shown. Control method combining position-speed and position-position command strategies is implemented based on position of end-effecter (x_m, z_m).

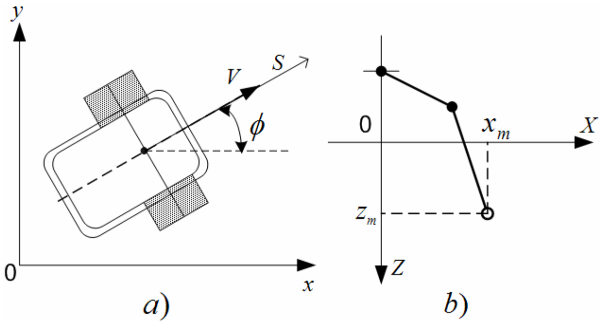


Fig. 1. Configurations of the master manipulator and the mobile robot.

2.2 Control strategies

Position-speed command strategy is used for most of 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 (2)

$$\begin{pmatrix} V \\ \phi \end{pmatrix} = \begin{pmatrix} k_V & 0 \\ 0 & k_A \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}, \qquad (2)$$

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

$$q_1 = \begin{cases} -z_m, |z_m| > z_{dz} \\ 0, |z_m| \le z_{dz} \end{cases}, \qquad (3)$$

$$q_2 = \begin{cases} x_m, |x_m| > x_{dz} \\ 0, |x_m| \le x_{dz} \end{cases}, \qquad (4)$$

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

$$\begin{pmatrix} S \\ \phi \end{pmatrix} = \begin{pmatrix} k_S & 0 \\ 0 & k_A \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}, \qquad (5)$$

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.

3. HYBRID CONTROL STRATEGIES

In this section, we propose hybrid control strategies, which enable us to switch between position-position and position-speed command modes. 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. Three kind of switching methods are introduced and one of the described control strategies can be applied according to the condition of the mobile robot, its environment and task to execute.

3.1 Manual method

In this mode, human-operator decides what control strategy should be used. Master device should have additional control switch for realizing switching two control modes. 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. Vision system can provide human with this information.

3.2 Manual-automatic method

For teleoperation in known environment, we propose manual-automatic method. Location of desired areas, where some accurate motion or operations are necessary to realize, can be given by human-operator before teleoperation starts. But there is no necessity to give accurate coordinates of desired areas. This information depends on the task for the mobile robot navigation. During teleoperation process the robot will automatically switch to position-position strategy when the robot's location is close to desired area. Equation (6) describes this rule

$$strategy = \begin{cases} position - speed, r \ge r_c \\ position - position, r < r_c \end{cases}, \qquad (6)$$

where r is the distance from the mobile robot to desired area and r_c is a constant distance, which defines how close the robot should be to the desired area for switching the strategy.

3.3 Automatic method

We consider velocity of the master device and distance from the robot to an obstacle for designing an automatic switching method. Position-position control mode is used when human-operator moves master device slowly or when there is an obstacle in front of the robot. This rule for automatic switching is defined as follows:

$$strategy = \begin{cases} position - speed, (\dot{z}_m \ge V_c)\ and (L \ge L_c) \\ position - position, (\dot{z}_m < V_c)\ or\ (L < L_c) \end{cases}, \qquad (7)$$

where L is the distance from the mobile robot to the obstacle, L_c and V_c are user designed constant parameters.

We suppose that automatic method can be applied for the mobile robot teleoperation in unknown environment even when human has no vision feedback.

4. GENERATING 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

$$F = F_e + iF_i, \tag{8}$$

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

$$F_e = \begin{cases} \frac{k_e}{L}, L < L_o \\ 0, L \geq L_o \end{cases}, \tag{9}$$

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

$$F_i = -k_i z_m, \tag{10}$$

where k_i 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 equations (2) and (3), 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 (8) is set to zero to remove the force. In position-speed strategy i=1.

5. SEMI-EXPERIMENT

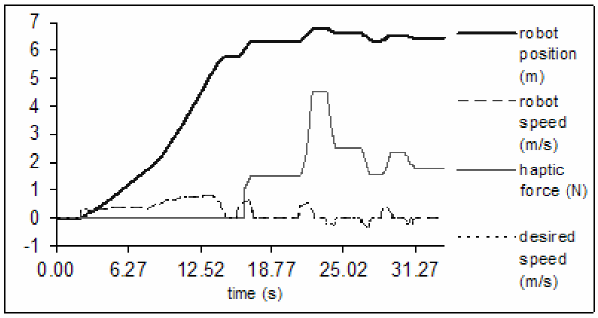
For testing described control strategies a group of semi-experiments were done. Phantom Premium 1.5A was used as a master device (Fig. 2). Computer model of a mobile robot and virtual environment were used. The master device was connected to control computer which was exchanging data with remote computer through internet. Numerical model of a mobile robot was realized on remote computer.

Fig. 2. Haptic device Phantom Premium 1.5A from SensAble Technologies, Inc.

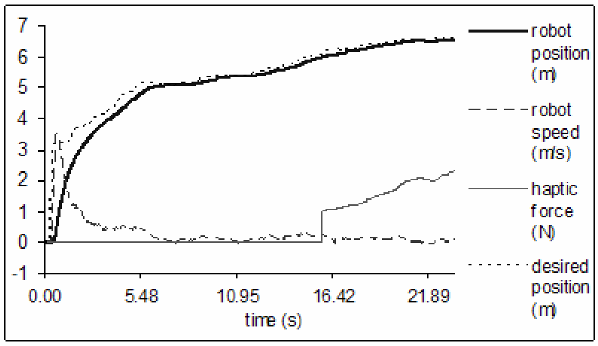
A simple task was given to compare different control methods. Robot was started from origin and expected to move 6.5 m. Obstacle was placed 7 m away from the original position. Feedback force was generated from sonar sensor obstacle range information only when the position of the robot was more than 6 m.

Fig. 3 shows experimental results for evaluating this task with position/speed, position/position and hybrid control strategies.

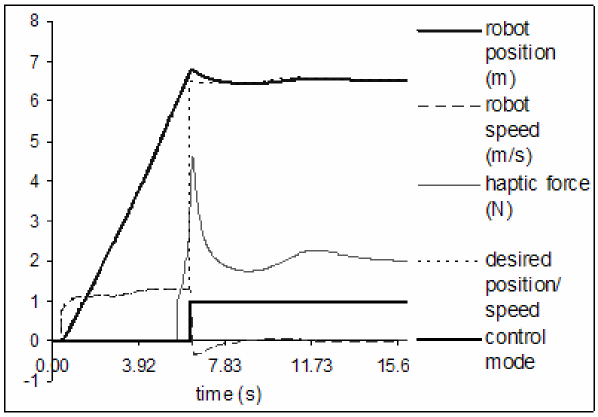
Navigation times are about 18 s, 21 s and 10 s. Hybrid strategy showed best performance in navigation time. In Fig. 3(c), control mode is changed around 6 seconds from position-speed mode to position-position mode (see bold line in Fig. 3c). At the beginning position-speed strategy was used to run the robot as fast as possible. After the robot was close to the desired point, human-operator switched to position-position strategy and the robot's position was corrected according to the desired task. As a result navigation in hybrid control mode required least time to finish the task.



a)



b)



c)

Fig. 3. Semi-experiment results for different command strategies: a) position-speed strategy; b) position-position strategy; c) hybrid strategy with manual switching.

6. EXPERIMENT

6.1 Experimental setup

We implemented our idea to a bilateral teleoperation system with the Activmedia Pioneer 3-DX mobile robot (Fig. 4). Sonar sensors installed on the mobile robot were used to obtain obstacle range information.

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

Phantom Premium 1.5A was used as a master device. Wireless network using TCP/IP protocol was used for information exchange between the desktop computer and the embedded computer of the mobile robot. Fig. 5 shows simple speed control experiment. Linear speed of the mobile robot is following the speed command of the master device.

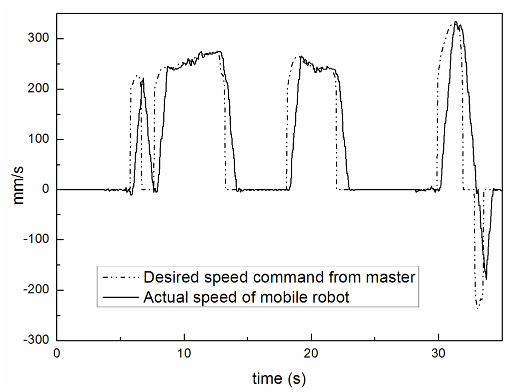


Fig. 5. Desired speed command from master device and actual speed of mobile robot graphs.

6.2 Task for experiments

A group of experiments were performed to test different control strategies. In Fig. 6, map of the environment for mobile robot teleoperation is presented. Mobile robot was expected to navigate the real environment from an initial position (P0) to a final position (P5). Four stopping points (P1, P2, P3, P4) were included into the task. Mobile robot was expected to stay at the stopping points for a time about 5 s. Navigation time and motion accuracy were the main objectives to analyze.

We performed 5 experiments of the mobile robot teleoperation with control strategies described in part 3 of this paper.

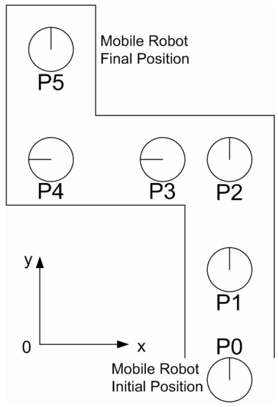


Fig. 6. The map for mobile robot teleoperation.

6.3 Position-speed command strategy

Around 70 s was required for navigation using position-speed control strategy (Fig. 7a). Average speed of the mobile robot was about 75 mm/s. At time around 12 s robot reached first stopping point P1 (see Fig. 6) and stayed there for 5 s. After this, at time around 23 s, mobile robot was moved to point P2 and faced the wall. In that case force feedback F was generated at the master side, so that human-operator felt obstacle in front of the robot.

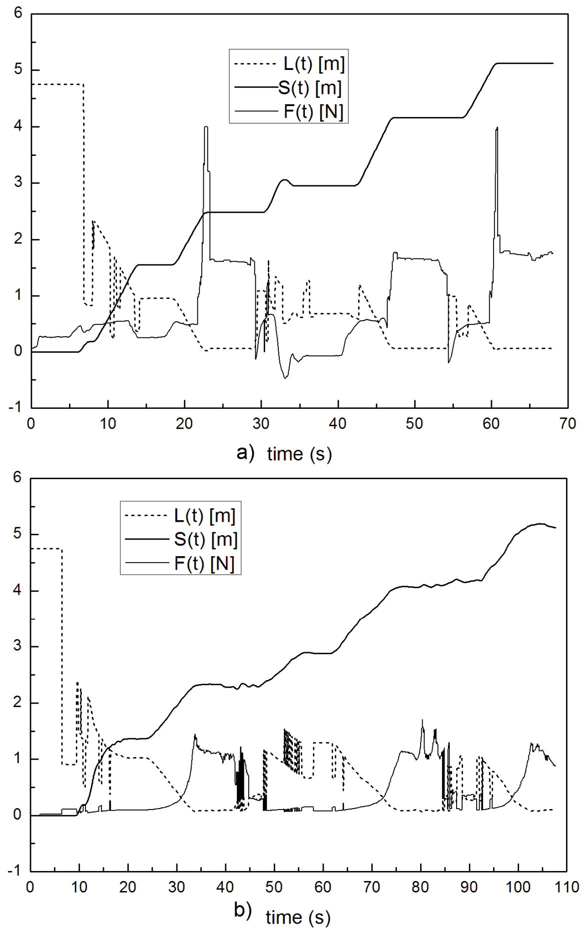


Fig. 7. Experimental results for position-speed (a) and position-position (b) command strategies.

From graph we can see that distance to obstacle L was decreasing while the robot was reaching the wall. At times around 36 s, 48 s, and 60 s the robot reached points P3, P4 and P5, respectively. Points P4 and P5 represent positions of the mobile robot near the wall, so at these points force feedback F was generated.

6.4 Position-position command strategy

For navigation with position-position strategy (Fig. 7b), required time was near 110 s. Relatively large navigation time can be explained by low average speed which was 47.61 mm/s (Fig. 8). To navigate the mobile robot using position-position control strategy large value of position scaling factor k_S should be used. Limited workspace of the master device is the main reason of the necessity to use large scaling values. In that case master device was sensitive and human-operator should be careful while remote controlling to prevent collisions and implement desired task carefully. As a result, completing the task using position-position control strategy took more time.

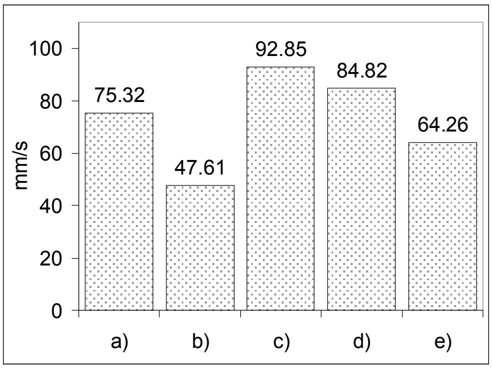


Fig. 8. Average speed of the mobile robot in teleoperation with different command strategies:
a) position-speed strategy; b) position-position strategy;
c) hybrid strategy with manual switching;
d) hybrid strategy with manual-automatic switching;
e) hybrid strategy with automatic switch.

6.5 Hybrid control strategy

In Fig. 9a, b, c, value of mode indicates each strategy. When mode is 2, it means position-position strategy is used. When mode is 0, it means position-speed strategy is used.

Fig. 9(a) shows the result for teleoperation with hybrid command strategy with manual switching. It took the robot near 50 s to complete the task for navigating with manual switching. Average speed of the mobile robot was about 93 mm/s. As we can see from the graph position-position strategy was used more often. Position-speed strategy was used for moving between stopping points. Position-position strategy was used to stop the robot and to correct its position. Position-position control strategy is more suitable for precision operations in limited environment.

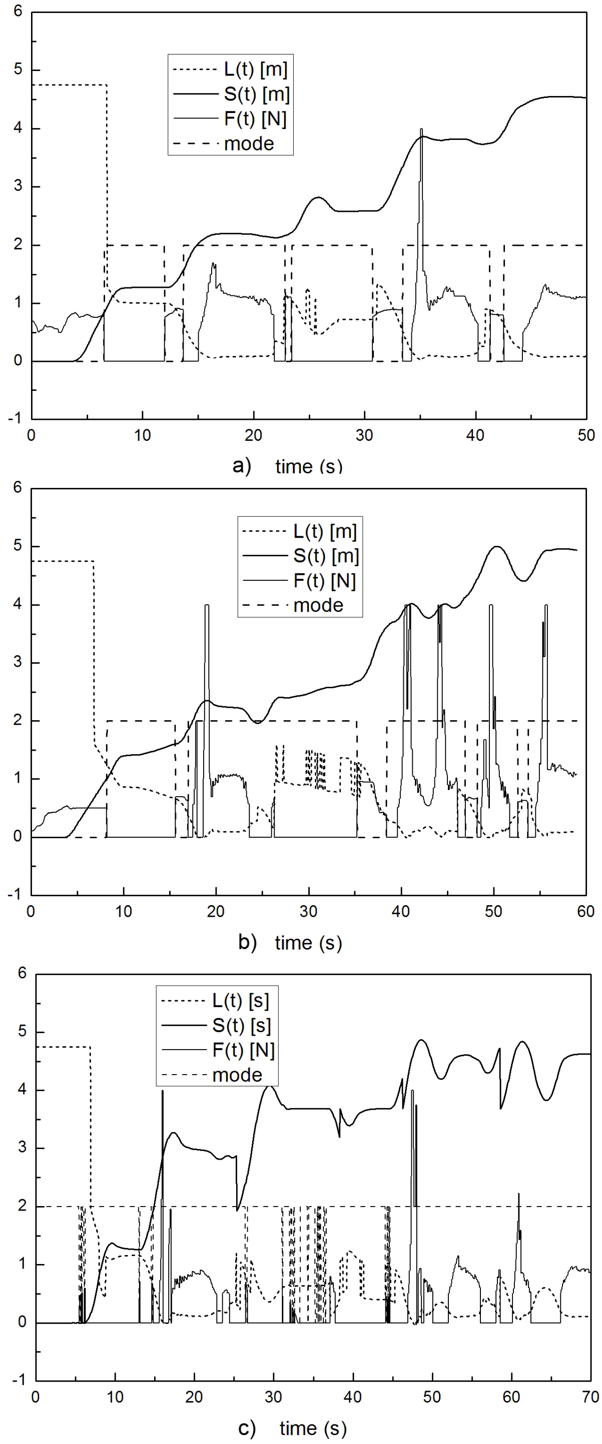


Fig. 9. Experimental results for hybrid command strategy with manual (a), manual-automatic (b) and automatic (c) switching methods.

Graph (b) in Fig. 9 represents results for teleoperation using hybrid control strategy with manual-automatic switching. Control mode was changed from position-speed to position-position strategy automatically when the robot was close to desired locations which were included into the robot's control program in advance. Navigation time was about 60 s and average robot speed was 84.82 mm/s.

Experimental results for hybrid control strategy with automatic switching are shown in Fig. 9c. Navigation time was 70 s, and average robot speed was about 64 mm/s. Experiments with automatic switching strategy were more complex. Experiment showed importance of training process for human-operator. Adjusting control system's parameters V_s and L_s can improve performance of the mobile robot navigation. In our case without any special training system showed relatively low performance.

Best performance was achieved in teleoperation using hybrid control strategy with manual switching. Navigation time was improved for about 30% compare to position-speed strategy. Human operator could control robot easier and faster.

5. CONCLUSION AND FURTHER WORK

The hybrid teleoperation control scheme for mobile robot navigation was proposed. Series of simulations and experiments were conducted to analyze performance, accuracy and convenience of the scheme. A new hybrid control method, which combines position-position and position-speed strategies, showed better performance in terms of accuracy and required navigation time. Proposed control scheme enables human operator to control a mobile robot faster and easier.

In future, we are going to improve hybrid strategy by adjusting control parameters and applying artificial intelligence to the mobile robot control. A detailed user study to compare different human-machine interfaces for navigation of the mobile robot will be done.

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