Stability Analysis of Mobile Robot Teleoperation with Variable Force Feedback Gain

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Abstract. We analyze the stability of previously proposed mobile robot teleoperation system [7]. Unlike to other approaches human-operator dynamics is included for the stability analysis. Mobile robot teleoperation systems have two major differences when they are compared with conventional bilateral teleoperators: first, rate mode control is used; second, absence of physical interaction of the robot with the environment (except with the ground). Environmental force feedback based on measured distances to the obstacles is considered in the analyzed teleoperation system. Simulations showed advantages and disadvantages of teleoperation with environmental force feedback. It was shown that the quality of position control of mobile robot during teleoperation with previously proposed variable force feedback gain was better than with conventional approach.

Keywords: Teleoperation, mobile robot, force feedback, haptic interface.

1 Introduction

We consider mobile robot teleoperation (MRT) system, which mobile robot is remotely controlled by haptic master device. MRT systems have two major differences with conventional teleoperation systems for manipulators. First, rate mode control is used due to limited workspace of the master device and unlimited workspace of the slave (mobile) robot. Second, the force feedback displayed to the human-operator is not the reaction force from physical interaction of the slave robot with the environment. The goal of this study is stability analysis of such systems. There were several researches which addressed stability issues of MRT. In [1], it was shown experimentally that haptic feedback improves the safety of MRT. Passivity of such systems was studied in [2], but dynamics of operator and environment was not considered the model. More sufficient passivity and stability analysis of MRT was presented in [3]. However, the case of the environmental force feedback which is important for safety of MRT was not considered. In [4], authors proposed a collision vector based method for mobile robot teleoperation. The main contribution of this paper is proposing an analytical solution for designing

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the environmental force feedback gain. The disadvantages of MRT with constant force feedback gain are shown with the help of simulations.

2 Overview of Mobile Robot Teleoperation

In Fig. 1(a), configuration of a two link master manipulator and mobile robot are shown. The operator gives motion commands through the master haptic manipulator. Control inputs for the mobile robot are based on the position of the end-effecter (x_m, y_m). Linear and angular velocities of the robot are defined as V, ω, respectively. The force feedback is generated by the master device based on obstacle range information. 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.

We consider feedback force based on the obstacle range information only (environmental force feedback). In conventional approach [1] the following basic law was used for calculating the force feedback:

$$f_e = \begin{cases} k(r_o - r), & r \le r_o \\ 0, & r > r_o \end{cases} \tag{2}$$

f_e - force feedback, k - gain (stiffness), r - distance to the obstacle, r_o - distance from which generation of force feedback starts (See Fig. 1(b)). The force f_e is applied to operator through master device to the opposite direction of the obstacle. Experiments proved that the usage of environmental feedback force improves safety of teleoperation by reducing the number of collisions [1]. But, it was also shown that feedback force with constant feedback gain degrades the accuracy of mobile robot motion control [5]. In order to improve the accuracy of control while keeping it safe the authors proposed the variable force feedback which help the operator control the robot's position easily near the obstacle without collisions [7]. Here we give a brief explanation of the proposed approach. In cases, when it is required to perform accurate motion control, the mobile

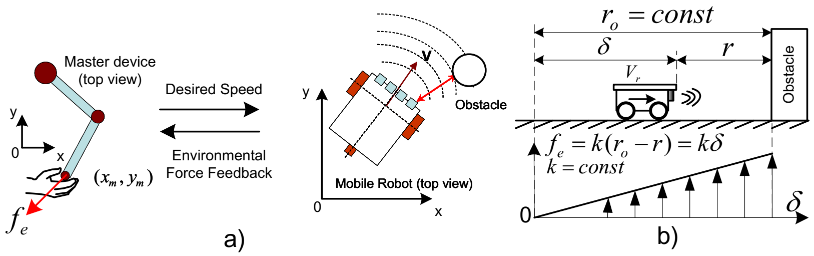

Fig. 1. Configurations of master manipulator and mobile robot (a). Conventional environmental force feedback rendering method (b).

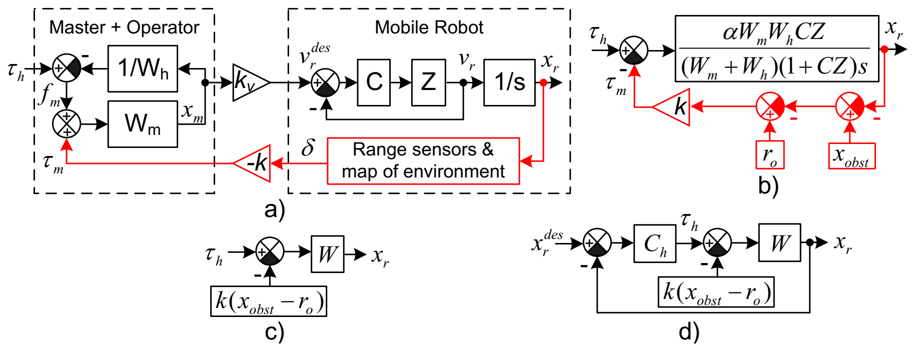

Fig. 2. Linear models for mobile robot teleoperation system

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. We propose to render force feedback with a variable gain based on relative speed of the mobile robot and obstacles. Main idea is modification of gain k in (2) based on distance to the obstacle r and its time derivative dr/dt. We define variable gain k^* for generating force feedback as follows:

$$k^* = \begin{cases} k_{\min}, & \frac{dr}{dt} \geq 0 \\ \frac{1}{-\gamma}(k_{\max}-k_{\min})\frac{dr}{dt}+k_{\min}\,, & -\gamma < \frac{dr}{dt} < 0 \\ k_{\max}, & \frac{dr}{dt} \leq -\gamma \end{cases}, \qquad (3)$$

where k_{min} and k_{max} are minimum and maximum marginal values of feedback gain; γ is a boundary relative speed of mobile robot and obstacle. The values k_{min} and k_{max} should be designed with consideration of haptic device maximum force and stiffness capabilities and minimum distances between the mobile robot and the environment from which generation of the force feedback starts. In the next section we prove stability of MRT with the environmental force feedback and find the applicable range of feedback gain variation.

3 Stability Analysis

Usually, in MRT system the slave (mobile) robot does not interact with the environment and that is why the environmental force feedback displayed to the operator is calculated based on virtual potential force field. The potential force field does not effect the mobile robot directly, but it effects the operator who controls velocity of the mobile robot. We consider one-DOF case in stability analysis for easy explanation. Dynamics of operator, master device and slave robot (mobile robot) are described in similar way as it was done in [6]:

$$\begin{aligned} \tau_h - f_m &= m_h\ddot{x}_m + b_h\dot{x}_m + k_h x_m \\ \tau_m + f_m &= m_m\ddot{x}_m + b_m\dot{x}_m \\ \tau_r &= m_r\ddot{x}_r + b_r\dot{x}_r \end{aligned} \qquad (4)$$

where x_m and x_r are positions of master device and mobile robot, respectively. m, b and k represent mass, viscous coefficient and stiffness, where lower indexes h, m and r correspond to operator's arm, master device and mobile robot, respectively. τ_h is the force generated by the operator's muscles; f_m denotes the force that the operator applies to the master device. τ_m and τ_r are actuator driving forces for master device and mobile robot, respectively. Note, that in MRT with environmental force feedback τ_m corresponds to the force feedback based on obstacle range information ($\tau_m = -f_e$). In Fig. 2(a), overall MRT system with force feedback based on obstacle range information is shown. W_h and W_m are transfer functions of operator and master device in s-domain; Z is impedance of the robot, C is the robot's velocity controller. The system in Fig. 2(a) can be transformed into the system in Fig. 2(b), where negative feedback represents f_e. Note that in our model we consider the cases when $(x_{obst} - x_r) \geq 0$ and $(x_r - x_{obst} + r_o) \geq 0$ which physically means that the distance to the obstacle can never be negative. In order to analyse system's stability we obtain closed loop system depicted in Fig. 2(c). Transfer function of this closed loop system can be represented as follows:

$$\begin{aligned}
&W = \frac{\alpha W_m W_h C Z}{(W_m+W_h)(1+CZ)s+\alpha k W_m W_h C Z} = \frac{n_o}{d_4 s^4+d_3 s^3+d_2 s^2+d_1 s+d_o}\\
&n_o = \alpha C, d_o = \alpha k C, d_1 = (C+b_s)k_h, d_2 = (b_s+C)(b_m+b_h)+m_s k_h\\
&d_3 = (b_s+C)m_m+(b_m+b_h)m_s+(b_s+C)m_h, d_4 = (m_m+m_h)m_s
\end{aligned} \tag{5}$$

Using the Hurwitz stability criterion we get the following bounding conditions for the force feedback gain k:

$$0 < k < \frac{d_1(d_3 d_2 - d_4 d_1)}{d_3^2 \alpha C} \tag{6}$$

If k satisfies the above condition then MRT system will be stable.

However, the system in Fig. 2(c) does not represent the real application of MRT. Usually, in MRT operator is given a task to move the robot to desired remote location. Visual information (image from remote cameras, interactive maps) is used to track the robot's position. Therefore, in MRT tasks human deals with position tracking control in which human's brain, vision, neural and muscle systems are used as tracking controller. In order to find the permissible range of feedback gain k, in which the overall teleoperation system remain stable, we analyze the system shown in Fig. 2(d). x_r^{des} is desired robots position defined by the task. C_h represents the human's brain and neural system as a position controller. For simplicity, we assume that C_h is a constant scalar value which means that operator does linear P-control of mobile robot's position. The closed loop system with consideration of position control is defined as follows:

$$W_{cl} = \frac{\alpha W_m W_h C Z C_h}{(W_m+W_h)(1+CZ)s+(k+C_h)\alpha W_m W_h C Z} \tag{7}$$

Hurwitz stability criterion gives the following bounding relation for gain k:

$$0 < k < \frac{d_1(d_3 d_2 - d_4 d_1)}{d_3^2 \alpha C} - C_h \tag{8}$$

Admissible range of gain k is reduced by C_h. The range of C_h can vary a lot for different humans and conditions. That is why it is important to consider the uncertainty of human-based control during select the value of k.

4 Simulation

In simulation operator was given a task to move a mobile robot towards the obstacle to desired position x_{des} and to stop it near the obstacle. Scheme shown in Fig. 2(d) was used for simulation. The following values of parameters were used in all simulations: $m_h = 2\ kg$, $b_h = 2\ Ns/m$, $k_h = 10\ N/m$, $m_m = 1\ kg$, $b_m = 0.05\ Ns/m$, $k_V = 0.3\ s^{-1}$, $C_s = 30\, Ns/m$, $m_s = 20\, kg$, $b_s = 1\, Ns/m$, $C_h = 7\, N/m$, $x_{obst} = 1.2\, m$, $x_{des} = 1.1$, $r_o = 0.5$ m. Based on (8) the value of force feedback gain was bounded: $0 < k < 25.0652\, N/m$. Simulation results with $k = 0$ (no force feedback), $k = 20$ (with force feedback, stable), $k = 26$ (with force feedback, unstable) and with variable force feedback gain are shown in Fig. 3. In first case ($k = 0$), the mobile robot moved to desired position near the obstacle while the operator did not feel any force feedback. Absence of environmental force feedback could lead to collisions and teleoperation might not be safe [1]. In the case when $k = 26$, it was very difficult for the operator to stabilize position of the mobile robot due to the high impact from the force feedback. Therefore, position of the robot was oscillating and the teleoperation system was unstable. In the case when $k = 20$, the robot stopped at position about 0.4 m and could not move further because the force generated by operator's muscle and the force feedback from the master device compensated each other. Based on these simulation results we could see that existence of force feedback caused two effects. On the one hand force feedback prevented collisions of the robot with environment. On the other hand, force feedback reduced the accuracy of position control: the operator had no opportunity to approach the area near the obstacle due to the high values of the force feedback. Based on this conclusion we suppose that it is possible to improve the quality of position control by online modification of force feedback gain.

In simulation with variable feedback gain, $\gamma = 2.5\ m/s$, $k_{max} = 20\, N/m$, $k_{min} = 0$. The mobile robot reached the desired position and stopped near the obstacle. Velocity of the robot was lower near the desired position and that is why lower force feedback gain k^* was used. This led to a decrease of amount of force feedback displayed to operator. As a result, it was easy for operator to achieve the control goal. Preliminary experimental prove of effectiveness of variable force feedback gain was presented in [7].

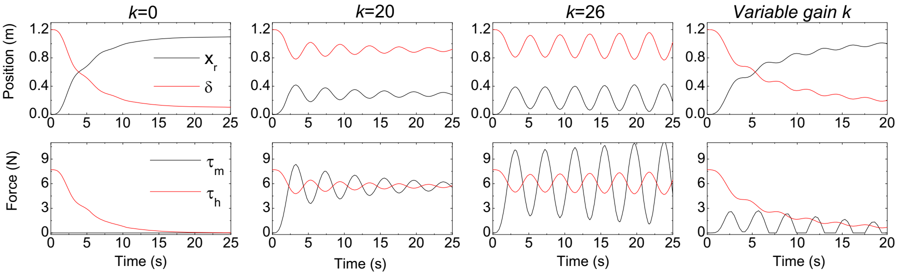

Fig. 3. Simulation results for MRT with constant and variable feedback gains

5 Conclusion

Stability criterion for the force feedback gain in the mobile robot teleoperation system was driven. A method for variation of force feedback gain based on the mobile robot's velocity was proposed and verified by simulation. One can say that the proposed variable force feedback can decrease the safety of teleoperation. However it improved the quality of motion control when the input from the human was not distorted by reflected forces. When it is compared with constant gain scheme, variable approach provides a better way for maintaining safety and accuracy of the motion control at the same time.

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References

1. Lee, S., Sukhatme, G.S., Kim, G.J., Park, C.-M.: Haptic control of a mobile robot: a user study. In: Proc. of IEEE/RSJ IROS, Lausanne, Switzerland (October 2002)
2. Diolaiti, N., Melchiorri, C.: Haptic teleoperation of a mobile robot. In: Proc. of the 7th IFAC Symposium of Robot Control, pp. 2798–2805 (2003)
3. Lee, D., Martinez-Palafox, O., Spong, M.W.: Bilateral teleoperation of a wheeled mobile robot over delayed communication network. In: Proc. of IEEE ICRA (2006)
4. Ko, J.-P., Lee, J.-M.: Tactile tele-operation of a mobile robot with a collision vector. Robotica 24(1), 11–21 (2006)
5. Farkhatdinov, I., Ryu, J.-H., Poduraev, J.: A user study of command strategies for mobile robot teleoperation. J. on Intelligent Service Robotics 2(2), 95 (2009)
6. Yokokohji, Y., Yoshikawa, T.: Bilateral control of master-slave manipulators for ideal kinesthetic coupling - formulation and experiment. IEEE T. on Robotics and Automation 10(5), October
7. Farkhatdinov, I., Ryu, J.-H.: A Preliminary Experimental Study on Haptic Teleoperation of Mobile Robot with Variable Force Feedback Gain. In: Proc. of IEEE Haptics Symposium 2010, Waltham, Boston, USA, March 24-25 (2010)