Improving Mobile Robot Bilateral Teleoperation
by Introducing Variable Force Feedback Gain

Ildar Farkhatdinov and Jee-Hwan Ryu

Abstract— This paper presents new feedback force rendering scheme for the bilateral teleoperation of mobile robot. Previous research indicated that the feedback force based on obstacle range information prevented accurate motion control of the mobile robot since human operator's commands were distorted by the feedback force. To solve this problem, a new force rendering approach with variable feedback gain is proposed. In proposed scheme, force feedback gain is adaptively tuned based on measured distances to the obstacle and time derivatives of the distances. Stability of the proposed bilateral teleoperation architecture was analyzed and the performance is proved by simulations. Results of simulation and experimental study proved that the quality of the mobile robot bilateral teleoperation with variable force feedback gain is significantly better than the conventional approach with constant feedback gain.

I. INTRODUCTION

An important research issue of the bilateral mobile robot teleoperation (MRT) is which kind of information should be transmitted to human-operator via force feedback in order to improve performance of teleoperation. Diolaiti and Melchiorri proposed a distance based environmental force feedback for teleoperation of mobile robot in order to increase human-operator's perception of the remote environment [1]. They also proved the passivity of the system which guaranteed the stability of haptic interaction. Similar approach was proposed by Lee et al. in [2]. It was proposed to convert obstacle range information from mobile robot into force field reflected to human-operator. Extensive experiments in a real test environment with a user population showed that the added haptic feedback significantly improved not only operator performance but also subjective presence [3]. Remote control of mobile robot with force reflection and fuzzy logic based velocity control was presented in [4]. Lim et al. used impedance based force reflection scheme for Internet teleoperation of mobile robot to help an operator to control the robot in absence of good quality video feedback [5]. In [6], the cooperative Internet-based teleoperation system in which several operators controlled multiple mobile manipulators was described. It was proposed to generate the force feedback based on measured distances to the obstacles together with consideration of the desired velocity of the mobile robot. In [7], force feedback reflected to human-operator while teleoperation was proportional to mobile

Ildar Farkhatdinov is with Institute of Intelligent Systems and Robotics, Université de Pierre and Marie Curie (Paris 6), CNRS UMR 7222, 75005, 4 place Jussieu, cc 173, Paris, France. `ildar@isir.upmc.fr`

Jee-Hwan Ryu is with School of Mechanical Engineering, Korea University of Technology and Education, Cheonan, 330-708, 307 Gajeon-ri Byeongcheon-myeon, R. of Korea. `jhryu@kut.ac.kr`

robot's control input which is similar to classical manipulator master-slave systems. This kind of force feedback provides operator information about the dynamics of the mobile robot, but does not provide perception of the obstacles around the mobile robot. In [8], Mullins et al. proposed to use force feedback to reflect the state of the mobile robot measured by inertial sensors. Human-operator could feel the orientation of the robot with respect to the gravity vector. Vision-based force guidance for improving teleoperation of mobile manipulator was described in [9]. It was proposed to coordinate force reflection based on vision signals received from the robot's camera. Later, Horan et al. explored several different types of haptic feedback for teleoperation of mobile robots in [10] and they proposed the concept of virtual haptic cone for intuitive and safe teleoperation in [11]. In [12] it was shown experimentally that in some cases force feedback can act as a disturbance to human-operator and reduce the accuracy of position control of the robot. To solve this problem it was proposed to consider velocity of the mobile robot together with the distances to the obstacles for force feedback calculation. Later, in [13] a rule for force feedback calculation which considered both velocity of the robot and the distances to the obstacles was proposed.

There are two major differences in MRT when it is compared with conventional teleoperation systems of manipulators. First, MRT mainly uses rate mode teleoperation due to the limited workspace of the master device and unlimited workspace of the slave (mobile) robot. Second, the feedback force, displayed to the human operator, is not the reaction force from physical interaction between mobile robot and environment. Therefore MRT should be considered as specific type of bilateral teleoperation systems with different architecture and feedback force rendering method. In this paper, we analyze stability of MRT with environmental force feedback considering dynamics of human-operator. Analytical solution for designing the environmental force feedback was derived. Disadvantages of MRT with constant force feedback gain are shown through simulations. New force feedback rendering method based on variable force feedback gain was proposed. Experiments proved that proposed force rendering method improves the quality of MRT.

II. OVERVIEW OF MOBILE ROBOT TELEOPERATION

A. Control Strategy

In Fig. 1a, configuration of a two link master manipulator and mobile robot are shown. Operator gives motion commands through the master haptic manipulator. Control inputs
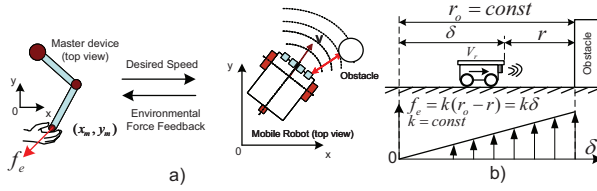
Fig. 1. Configurations of master manipulator and mobile robot (a). Conventional environmental force feedback rendering method (b)

for mobile robot are based on the position of end-effecter (x_m, y_m). V, ω are linear and angular velocities, respectively. Obstacle range information, which is obtained from the robot's 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)

$$\left(\begin{array}{c} V \\ \omega \end{array} \right) = \left(\begin{array}{cc} k_V & 0 \\ 0 & k_w \end{array} \right) \left(\begin{array}{c} y_m \\ x_m \end{array} \right), \qquad (1)$$

where k_V, k_w are scaling coefficients.

B. Environmental Force Feedback

1) Conventional Force Rendering Method: In this paper, we consider feedback force based on the obstacle range information only (environmental force feedback) [2]. This feedback is rendered based on measured distances from the mobile robot to the obstacles. We define the following:

$$\Delta = R_o - R = \left(\begin{array}{cccc} \delta_1 & \delta_i & ... & \delta_n \end{array} \right) \qquad (2)$$

where $i = 1..n$, n is a number of range sensors. 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. Δ is defined as a difference between R_o and R. In conventional approach [2] the following basic law was used for calculating environmental feedback force:

$$f_i = \left\{ \begin{array}{ll} k_i \delta_i, & r_i \leq r_{oi} \\ 0, & r_i > r_{oi} \end{array} \right. \qquad (3)$$

$$F = \left(\begin{array}{cccc} f_1 & f_2 & ... & f_n \end{array} \right) \qquad (4)$$

f_i is a force feedback calculated by multiplication of gain k_i by distance δ_i measured from i_{th} sensor. The maximum force f_e is selected from vector F and applied to human-operator in direction opposite to the obstacle:

$$f_e = \max \{F\} \qquad (5)$$

Fig. 1b 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 MRT was done in [3]. Experiments proved that usage of environmental feedback

force improved 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 degraded the quality of mobile robot motion control [12]. Experiments on mobile robot positioning showed that feedback force based on obstacle range information acted as a disturbance for the master device. When the operator wanted to place accurately the mobile robot in a certain position feedback force generated on the master device significantly modified the reference command given by human-operator. As a result, real movements of the mobile robot greatly differed from the desired one.

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 sparer place for moving without collisions with static obstacles. Therefore, the probability of collisions between mobile robot and environment during teleoperation in large workspace with fewer 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 speed of the mobile robot.

3) Variable Feedback Gain: We propose a scheme for online modification of force feedback gain in mobile robot teleoperation system. The main idea is modification of gain k_i in (3) 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:

$$k_i^* = \left\{ \begin{array}{ll} k_{\min}, & \frac{dr_i}{dt} \geq 0 \\ -\frac{1}{\gamma}(k_{\max} - k_{\min})\frac{dr_i}{dt} + k_{\min} , & -\gamma < \frac{dr_i}{dt} < 0 \\ k_{\max}, & \frac{dr_i}{dt} \leq -\gamma \end{array} \right. , \qquad (6)$$

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. In Fig. 2 graphical explanation for (6) is shown.
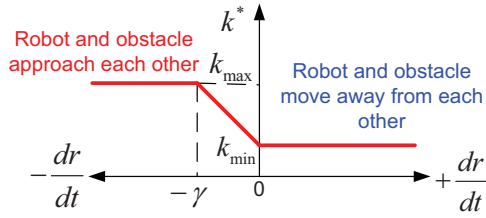
Fig. 2. The value of variable force feedback gain depends on the value of the derivative dr/dt
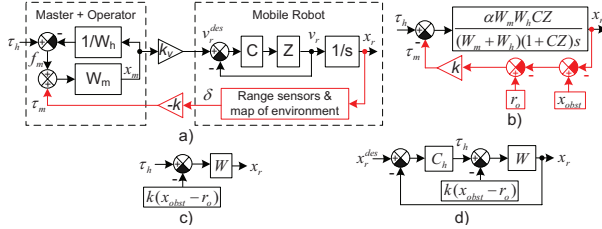

Fig. 3. Linearized models for MRT system

III. STABILITY ANALYSIS

In this section, we consider one-DOF case for easy explanation. We describe the dynamics of operator, master device and slave (mobile) robot in similar way as it was done in [14]:

$$
\begin{aligned}
\tau_h - f_m &= m_h \ddot{x}_m + b_h \dot{x}_m + k_h x_m \\
\tau_m + f_m &= m_m \ddot{x}_m + b_m \dot{x}_m \\
\tau_r &= m_r \ddot{x}_r + b_r \dot{x}_r
\end{aligned}
\tag{7}
$$

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. f_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. 3a, 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. 3a can be transformed into the system in Fig. 3b 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 distance to the obstacle can never be negative. In order to analyze system's stability we obtain closed loop system depicted in Fig. 3c. Transfer function of this closed loop system can be represented as follows:

$$
W \equiv W(s) = \frac{\alpha W_m W_h C Z}{(W_m + W_h)(1 + CZ)s + \alpha k W_m W_h C Z} = \\
= \frac{n_o}{d_4 s^4 + d_3 s^3 + d_2 s^2 + d_1 s + d_o}
\tag{8}
$$

where we have the following coefficients:

$$
\begin{aligned}
n_o &= \alpha C, \, d_o = \alpha k C, \\
d_1 &= (C + b_s)k_h, \, d_2 = (b_s + C)(b_m + b_h) + m_s k_h \\
d_3 &= (b_s + C)m_m + (b_m + b_h)m_s + (b_s + C)m_h, \\
d_4 &= (m_m + m_h)m_s
\end{aligned}
\tag{9}
$$

Using the Hurwitz stability criteria we get the following conditions:

$$
\begin{aligned}
&d_i > 0, i = 0..4 \\
&d_1(d_3 d_2 - d_4 d_1) - d_3^2 d_o > 0
\end{aligned}
\tag{10}
$$

As a result, we can get the bounding conditions for the force feedback gain k:

$$
0 < k < \frac{d_1(d_3 d_2 - d_4 d_1)}{d_3^2 \alpha C}
\tag{11}
$$

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

However, the system in Fig. 3c 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 will be stable, we analyze the system shown in Fig. 3d. x_r^{des} is desired robot's 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:

$$
W_{cl} = \frac{\alpha W_m W_h C Z C_h}{(W_m + W_h)(1 + CZ)s + (k + C_h)\alpha W_m W_h C Z}
\tag{12}
$$

Hurwitz stability criteria gives the following bounding relation for force feedback gain k:

$$
0 < k < \frac{d_1(d_3 d_2 - d_4 d_1)}{d_3^2 \alpha C} - C_h
\tag{13}
$$

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.

IV. SIMULATION

In simulation operator was given a task to move mobile robot towards the obstacle to desired position x_{des} and to stop it near the obstacle. Scheme shown in Fig. 3d was used for simulation. The following values of parameters were used in all simulations: $m_h = 2 \ kg$, $b_h = 2 \ Ns/m$, $k_h = 10 \ N/m$, $m_m = 1 \ kg$, $b_m = 0.05 \ Ns/m$, $k_V = 0.3 \ s^{-1}$, $C_s = 30 \ Ns/m$, $m_s = 20 \ kg$, $b_s = 1 \ Ns/m$, $C_h = 7 \ N/m$, $x_{obst} = 1.2 \ m$, $x_{des} = 1.1 \ m$, $r_o = 0.5 \ m$. Based on (13) the value of force feedback gain is bounded: $0 < k < 25.0652 \ N/m$.

Fig. 4. Simulation results for MRT with constant feedback gains
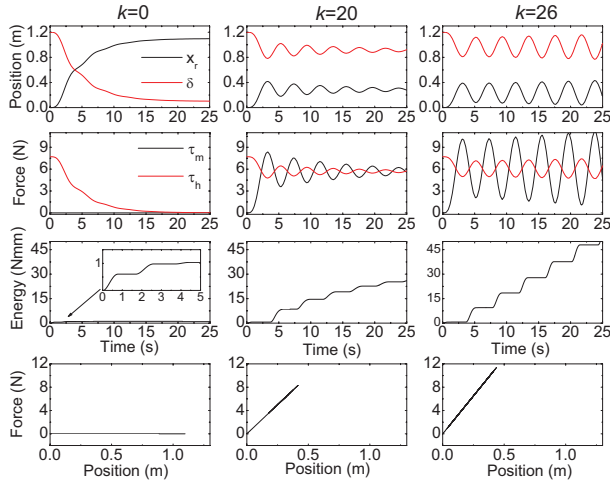

Fig. 5. Simulation results for MRT with variable feedback gain

Simulation results with $k = 0$ (no force feedback), $k = 20$ (with force feedback, stable) and $k = 26$ (with force feedback, unstable) are shown in Fig. 4. 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 might lead to collisions and teleoperation might not be safe [2]. In case when $k = 26$, it was very difficult for the operator to stabilize position of the mobile robot due to high impact from force feedback. Therefore, position of the robot was oscillating and the teleoperation system was unstable. In 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. Physical workload of human-operator [15] was compared in teleoperation with constant and variable force feedback gains. Average force generated by human's muscles was measured: $1.51\ N$ for $k=0\ N/m$, $5.80\ N$ for $k=20\ N/m$ and $6.10\ N$ for $k=26\ N/m$. In addition, positive energy flow [16] from human-operator to haptic master device was measured. Results are shown in Fig. 4 (third row). Energy produced by human-operator increased together with the force feedback gain.

Based on these simulation results we can see that existence of force feedback cause 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: operator had no opportunity to approach the area near the obstacle due to high values of 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 Fig. 5, results of simulation with variable force feedback gain based on (6) are shown. In simulation $\gamma = 2.5\ m/s$, $k_{max} = 20\ N/m$, $k_{min} = 0$. In Fig. 5, the mobile robot reached the desired position and stopped near the obstacle. Velocity of the robot got lower near the desired position and
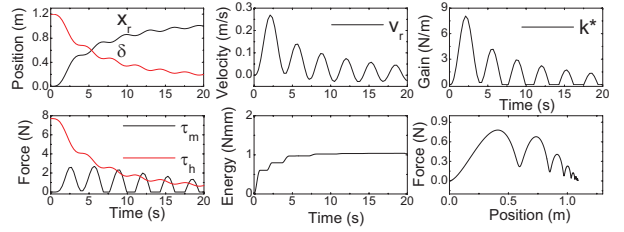
that is why lower force feedback gain k^* was used. This led to a decrease of amount of force feedback displayed to operator. As a result, it was easy for operator to achieve the control goal. Operator's physical load was reduced in teleoperation with variable force feedback. Average muscle force was $1.70\ N$ approximately same as in teleoperation without force feedback when $k=0$. Energy flow from human-operator was significantly smaller. Last graph in Fig. 5 shows force feedback signal vs robot's position. In comparison to "force vs position" graphs in Fig. 4, we can see that force feedback in Fig. 5 gain is non-linear and this allows safely move the robot close to the obstacle.

V. EXPERIMENT WITH SIMULATED MODEL

A. 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 (14)

$$M\ddot{x}_r + B\dot{x}_r = U, \tag{14}$$

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: $M = 20\ kg$, $B = 2\ Ns/m$, $K_v = 200\ Ns/m$, $R_o = 1.7\ m$, $k_{min} = 0.2\ N/m$, $k_{max} = 4\ N/m$, $\gamma = 0.4\ m/s$. 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. In simulation, the human-operator was asked to move the virtual robot towards the obstacle which was placed $1.5\ m$ away from the origin of the mobile robot.

In Fig. 6a, experimental result for MRT with conventional feedback force which was calculated based on (5). Feedback gain k was constant and equal to k_{max}. Force feedback was generated when the robot approached the obstacle. The force was limited by $5\ N$ due to the master device characteristics. However, 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
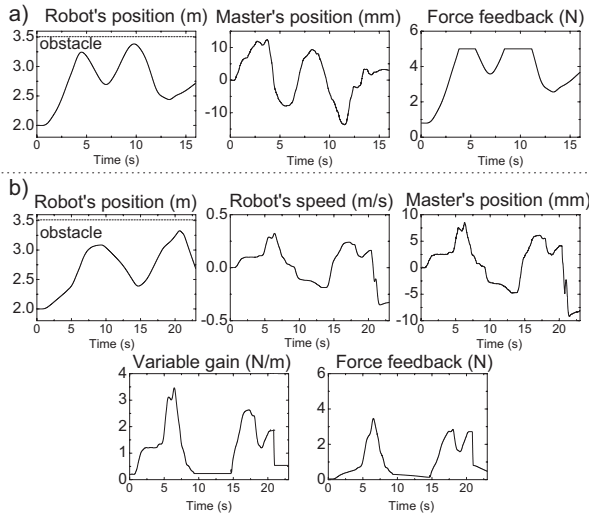
Fig. 6. MRT with nonvariable force feedback gain (a); MRT with variable force feedback gain (b)

reduce amount of force displayed to the operator, but this may dramatically effect on the safety of the teleoperation process.

Fig. 6b, 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 approached the obstacle (2-6 s), feedback gain was increased; when the robot slowed down (7-10 s), feedback gain decreased. As a result, we can see that based on proposed approach, large amount of force feedback was generated and displayed to human-operator only in cases when the robot moved toward the obstacle with high speed. Small amount of force feedback was displayed to the human-operator if the robot moved toward the obstacle with low speed.

B. Mobile Robot Positioning

In order to evaluate the influence of feedback force to the quality of teleoperation, simulation on mobile robot positioning was done. 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 MRT. Positioning error was calculated as follows:

$$e = \frac{1}{T} \int_0^T |X_{des} - X_r| dt, \qquad (15)$$

where T is completion time. Positioning error was selected as a metric for measuring the quality of human-robot interaction in MRT. 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. 7a. 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 was 57.5%.

VI. EXPERIMENTAL STUDY

Teleoperation of mobile robot P3DX 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 device using the scheme shown in Fig. 1a and control strategy described by (1) was implemented. Sonar sensors measured the distance to the obstacles. The following control parameters were used in all experiments: $k_{min} = 0.0001\ N/mm$, $k_{max} = 0.02\ N/mm$, $\gamma = 50$ mm/s, $r_o = 2\ m$. Five subject participated in the study. The sequence of experiments was randomly ordered.

In first experiment, the operator was asked to navigate the robot through narrow corridor with conventional and variable force feedback rendering methods. Fig. 7b and Fig. 7c show the robot's trajectories from the experiments with constant and variable force feedback gain respectively. Trajectories from experiments with variable force feedback gain were smoother than trajectories from experiments with constant gain. Trajectories for proposed variable force feedback were more neat and similar to each other while trajectories for conventional method were messy and chaotic. Time required for passing through the corridor for each subject was measured as well (Fig. 7d). In cases when variable force feedback was used subjects could complete the navigation task faster.

In both cases due to existence of environmental force feedback there were 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 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 to 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.

Accuracy of the mobile robot's motion was compared in teleoperation with conventional and variable force feedback in second experiment. Mobile robot was placed in a narrow space and operator was supposed to move the box-type object from initial to desired position. The operator could see the experimental environment via cameras. Subjects were asked to do the positioning of the object task with conventional and variable force feedback.

The results for positioning errors are shown in Fig. 7e. For all cases error was higher in experiments with conventional
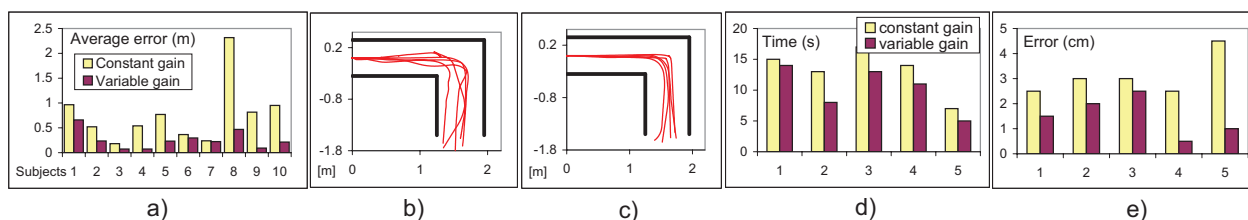
Fig. 7. Experimental results: average positioning errors for teleoperation (a), trajectories of the mobile robot during teleoperation with constant force feedback (b) and variable force feedback (c), time required for navigation in narrow space (d), positioning errors (e)
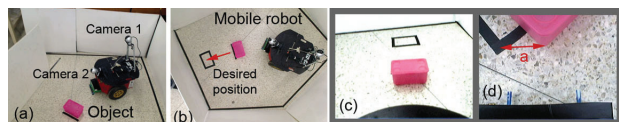

Fig. 8. Photos of experimental environment and robot (a,b) and view from cameras (c,d)

TABLE I

RESULTS OF STUDENT'S T-TEST

Results	with constant gain	with variable gain	T-test
Fig. 7a	$0.766\pm0.612\ m$	$0.257\pm0.185\ m$	$t=2.52>2.31$ $p=0.05$
Fig. 7d	$13.2\pm3.76\ s$	$10.2\pm3.70\ s$	$t=1.27<2.35$ $p=0.10$
Fig. 7e	$3.1\pm0.82\ cm$	$1.5\pm0.79\ cm$	$t=2.52>2.35$ $p=0.10$

force feedback rendering method. During positioning task, the 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 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 operator and degraded the accuracy of positioning.

Table I presents results for Student's T-test for experimental study. Difference for positioning errors in teleoperation with conventional and proposed force feedback generation schemes was significant. Difference in results for time measurements was not significant.

VII. CONCLUSION

In this paper analytical and experimental study of MRT with constant and variable force feedback gain was presented. Stability criteria for feedback gain were driven. Experimental study showed advantages of proposed force rendering method. As it was expected variable haptic feedback reduces amount of force which is displayed to operator. One can say that on the one hand it can decrease the safety of teleoperation process. However as a result, it improves the quality of motion control since input from the human is not distorted by reflected forces. However, when it is compared with constant gain scheme, variable approach provided better way for maintaining safety and high quality of the motion

control at the same time. Application of variable feedback gain made the trajectory of the mobile robot smoother. Operator could control position of the mobile robot more accurately. As a result, quality of the motion control was improved.

REFERENCES

[1] N. Diolaiti and C. Melchiorri "Haptic teleoperation of a mobile robot," *In Proc. of the 7th IFAC SYROCO*, pp. 2798-2805, 2003.
[2] S. Lee, G. S. Sukhatme, G. J. Kim, C.-M. Park, "Haptic control of a mobile robot: A user study," *In Proc. of IEEE/RSJ IROS 2002*, Lausanne, Switzerland, Oct. 2002.
[3] S. Lee, G. J. Kim, G. S. Sukhatme, C-M. Park, "Effects of Haptic Feedback on Telepresence and Navigational Performance", ICAT 2004.
[4] J.B. Park, B.H. Lee, M.S. Kim, "Remote control of a mobile robot using distance-based reflective force," *Proc. of IEEE ICRA 2003*, pp. 3415-3420 vol.3.
[5] J. N. Lim, J. P. Ko, and J. M. Lee, "Internet-based Teleoperation of a Mobile Robot with Force-reflection," CCA 2003, Proceedings of 2003 IEEE Conf. on Control Applications, Istanbul, Turkey, June 2003 vol.1 pp.680-685.
[6] W-t. Lo, Y. Liu, I. H. Elhajj, N. Xi, Y. Wang, and T. Fukuda, "Co-operative Teleoperation of a Multirobot System With Force Reflection via Internet", IEEE/ASME T. on Mechatronics, Vol. 9, NO. 4, Dec. 2004.
[7] D. Lee, O. Martinez-Palafox, M. W. Spong, "Bilateral teleoperation of a wheeled mobile robot over delayed communication network," In Proc. of IEEE ICRA 2006.
[8] J. Mullins, B. Horan, M. Fielding, S. Nahavandi, "A Haptically Enabled Low-Cost Reconnaissance Platform for Law Enforcement", Proc. of the 2007 IEEE Int. Workshop on Safety, Security and Rescue Robotics, Rome, Italy, September 2007.
[9] C.H. Park, A. Howard, "Vision-based Force Guidance for Improved Human Performance in a Teleoperative Manipulation System", *Proc. IEEE/RSJ IROS*, San Diego, CA, Oct. 2007.
[10] B. Horan, Z. Najdovski and S. Nahavandi, "Exploiting Ungrounded Tactile Haptic Displays for Mobile Robotic Teleoperation", Proc. of the World Automation Congress'08, pp. 1-6, IEEE, Piscataway, N.J.
[11] B. Horan, Z. Najdovski, S. Nahavandi and E. Tunstel, "3D Virtual Haptic Cone for Intuitive Vehicle Motion Control", IEEE Symposium on 3D User Interfaces 2008, 8-9 March, Reno, Nevada, USA.
[12] I. Farkhatdinov, J-H. Ryu, J. Poduraev, "A user study of command strategies for mobile robot teleoperation," *J. on Intelligent Service Robotics*, Volume 2, Issue 2 (2009).
[13] I. Farkhatdinov, J-H. Ryu, Jinung An, "A Preliminary Experimental Study on Haptic Teleoperation of Mobile Robot with Variable Force Feedback Gain," In Proc. of IEEE Haptics Symposium 2010, March 24-25, Waltham, Boston, USA.
[14] Y. Yokokohji, T. Yoshikawa, "Bilateral control of master-slave manipulators for ideal kinesthetic coupling - formulation and experiment," IEEE T. on Robotics and Automation, Vol. 10, N.5, October 1994.
[15] K. H. Eberhard Kroemer, "Human strength: terminology, measurement, and interpretation of data," Human factors, 1970, 12(3), 297-313.
[16] J-H. Ryu, C. Preusche, "Stable bilateral control of teleoperators under time-varying communication delay: time domain passivity approach," in Proc. of IEEE ICRA 2007.