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A Feasibility Study of Time-Domain Passivity Approach for Bilateral Teleoperation of Mobile Manipulator

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Abstract: This paper provides results of feasibility study of time domain passivity approach for bilateral teleoperation of mobile manipulator. Mobile manipulator in this study is a manipulator mounted on mobile platform. We consider bilateral teleoperation system in which human-operator sequentially controls speed of mobile platform (rate mode) or position of manipulator via manipulating haptic master device. Force feedback is transmitted to human-operator based on physical interaction of manipulator end-effector with remote environment. Time-domain passivity has been successfully applied to teleoperation systems in which position of master robot was mapped to position of slave robot. In this paper attempt of application of time-domain passivity control for rate and position control of mobile manipulator is presented. Time-domain passivity application issues are described and analyzed. Experimental results showed possibility of application of time-domain passivity control for rate control in certain range.

Keywords: teleoperation, mobile manipulator, rate control mode, time-domain passivity.

1. INTRODUCTION

In teleoperation, a human-operator conducts a task in a remote environment via master and slave robots [1]. Range of tasks which can be performed in remote environment highly depends on performance capabilities of the slave robot. That is why modern teleoperation applications use multi functional robotic manipulators with mobile platforms [2]. There were several approaches for designing haptic interfaces for teleoperation of mobile manipulators [3, 4]. For such kind of systems stability issue becomes very actual. There have been numerous researches for solving stability problem in bilateral teleoperation.

In 2002, Hannaford and Ryu proposed the concept of "Passivity Observer" and "Passivity Controller" for haptic [5] and teleoperation systems [6]. This control method guarantees stable haptic interaction by monitoring and keeping passivity of system. This concept was applied only to position control systems in which position space of master device was mapped into position space of slave robot or virtual environment. It was successfully applied to bilateral teleoperation of holonomic manipulators. Modern teleoperation systems require high mobility and opportunity to perform task in large workspaces. This involves application of mobile manipulators - manipulators mounted on mobile platforms. These kind of systems are more complex and require different control strategies such as position control for manipulator and rate control mode for mobile platform. In [7] Hashtrudi-Zaad, Mobasser and Salcudean studied stability and performance issues in bilateral teleoperation systems with rate control mode. But their approach required knowledge of teleoperation system dynamics.

We suppose that time-domain passivity approach which doesn't require knowledge about system dynamics can be successfully applied to teleoperation systems with rate control mode. In this paper we present experimental results for feasibility study of time-domain passivity approach for bilateral teleoperation of mobile manipulator.

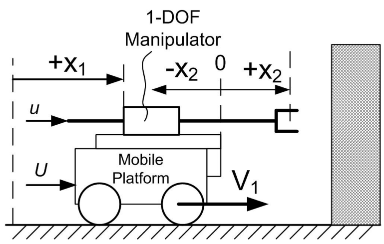

Fig. 1 Simplified scheme of mobile manipulator.

2. SYSTEM DESCRIPTION

2.1 Dynamic model of mobile manipulator

In Fig. 1, simplified dynamic model of mobile manipulator is shown. For simplicity 1-DOF problem is considered. Robot dynamics can be described by the following system:

$$\begin{cases} (M+m)\ddot{x}_1 + B\dot{x}_1 = U - u \\ m\ddot{x}_2 + b\dot{x}_2 = u - F_e \end{cases} \tag{1}$$

where x_1 is position of mobile platform in fixed global frame; x_2 is position of manipulator with respect to mobile platform position; M, B and m, b are masses and damping of platform and manipulator, respectively. F_e is disturbance force from environment, U and u are control forces for platform and manipulator, respectively.

Mechanical interpretation of the mobile manipulator is presented in Fig. 2. Platform and manipulator are modeled as mass-damped systems which are controlled by PD-compensators. We consider speed control of mobile platform and position control of manipulator which

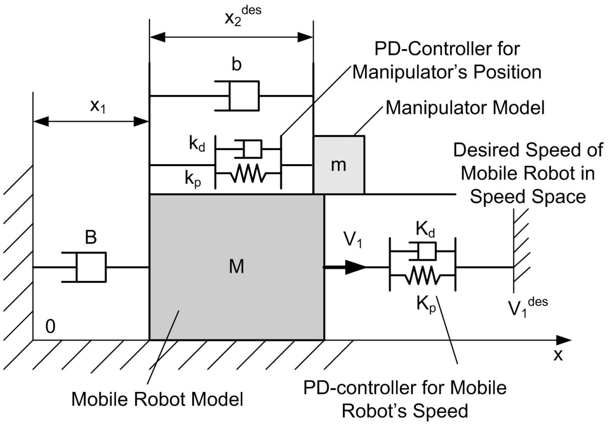

Fig. 2 Mechanical model of mobile manipulator with controllers.

is mounted on top of platform. Eq. (2) defines the law for position control of manipulator:

$$u = k_p(x_2^{des} - x_2) - k_d\dot{x}_2 \tag{2}$$

where x_2^{des} is desired position of manipulator, k_p and k_d are control gains.

Control law for speed control of mobile platform is defined by Eq. (3).

$$\begin{aligned} U = (1 - mode)K_p^V(V_1^{des} - \dot{x}_1) + \\ +mode\left[K_p^p(x_1^{des} - x_1) - K_d^p\dot{x}_1\right] \end{aligned} \tag{3}$$

V_1^{des} and x_1^{des} are desired speed and position of mobile platform, K_p^V, K_p^p and K_d^V are control gains. Parameter $mode$ is defined as follows:

$$mode = \begin{cases} 0, & Speed\ control\ of\ platform \\ 1, & Position\ control\ of\ manipulator \end{cases} \tag{4}$$

If $mode = 0$, then human-operator controls platform's speed while manipulator keeps its actual position. If $mode = 1$, then human-operator controls manipulator's position while platform keeps its actual position. Finally, human-operator can switch between control of two robots with the help of some switching control rule and switching controller. Detailed description of switching control strategies for teleoperation was presented in [8].

Values of desired position and speed for manipulator and platform are based on master device actual position x_m:

$$x_2^{des} = \eta x_m \tag{5}$$

$$V_1^{des} = \beta x_m \tag{6}$$

where η and β are scaling coefficients.

2.2 Force feedback

Force feedback F_m which is displayed to human operator is defined by Eq. (8). where λ and μ are scaling coefficients.

$$F_m = (1 - mode)\lambda F_e + mode\mu U \tag{7}$$

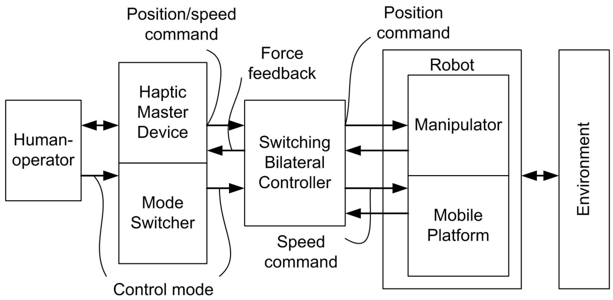

Fig. 3 Overall teleoperation system.

where F_e is the force generated by environment. Environment is modeled as a spring:

$$F_e = \begin{cases} K_e(x_1 + x_2 - x_e), & x_1 + x_2 \geq x_e \\ 0, & x_1 + x_2 < x_e \end{cases} \tag{8}$$

where K_e and x_e stiffness and position of environment.

In this paper, we consider only the case in which physical interactions with remote environment are performed by manipulator's end-effector. During position control of manipulator force feedback is based on information from force-torque sensor. In order to display the difference in dynamic responses of platform and master device during speed control of mobile platform, force feedback is based on control input U. Slow response of mobile platform speed control occurs due to its large mass and damping. We suppose that it is important to display state information of the mobile platform during teleoperation in order to improve stability of overall system. At the same time, during manipulator interaction with environment when speed of the platform is controlled control force U will increase proportionally with F_e. That means that F_m during speed control of the platform will give information about interaction with environment, as well. Overall structure of teleoperation system is shown in Fig. 3.

3. APPLICATION OF TIME-DOMAIN PASSIVITY APPROACH TO MOBILE MANIPULATOR TELEOPERATION

The following definition of passivity was used. System with initial energy storage $E(0) = 0$ is $passive$ if and only if,

$$\int_0^t f(\tau)v(\tau)dt \geq 0,\ \forall t \geq 0 \tag{9}$$

holds for admissible forces (f) and velocities (v), where their product is defined to be positive when power enters the system port [9]. For discrete time systems the following "Passivity Observer" (PO) was defined [5]:

$$E(t_k) = \Delta T \sum_{j=0}^{k} f(t_j)v(t_j) \tag{10}$$

where ΔT is a sampling period, and $t_j = j\Delta T$. If PO value is negative then energy comes out from system

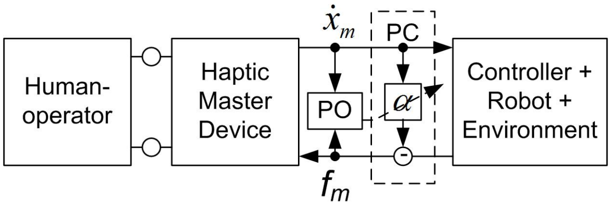

Fig. 4 Block diagram of a teleoperator with PO and PC. Series PC is attached to master side port.

which means system is potentially unstable. "Passivity Controller" (PC) was proposed to dissipate energy which comes out from port [5]. In this paper we used series configuration of PC. In Fig. 4, teleoperation system with PO and PC is shown. PO and PC were placed at the master side in order to monitor and dissipate active energy from mobile manipulator. Every sample time PO calculates energy which is stored in the system:

$$E(t_k) = E(t_{k-1}) + f_m(t_k)(x_m(t_k) - x_m(t_{k-1})) \quad (11)$$

PC is activated in order to reduce amount of force displayed to human-operator when PO value becomes negative.

4. EXPERIMENT WITH SIMULATED MOBILE MANIPULATOR

4.1 Experimental setup

In order to evaluate performance of PO/PC-control in teleoperation of mobile manipulator experiments were performed. Computer model of mobile manipulator, which is based on dynamic model from section two of this paper, was realized. Phantom Premium 1.5A from SensAble was used as a haptic master device. Input/output signals from master device were sent to computer model in real time. Frequency of model calculation and hardware communication was 1000 Hz. View of experimental setup is presented in Fig. 5. Vertical axe of Phantom device was used in order to measure master position and generate force feedback. This allowed to use gravity force instead of force input from human and avoid influence of human arm's damping. The following values of model parameters were used during experiment: $M = 20kg$, $m = 5kg$, $B = 2Ns/m$, $b = 1.5Ns/m$, $k_p = 560N/m$, $k_d = 100Ns/m$, $K_p^V = 200Ns/m$, $K_p^p = 200N/m$, $K_d^p = 10Ns/m$, η=0.01, β=0.02s^{-1}, $K_e = 50kN/m$, $x_e = 1m$, λ=0.005, μ=0.005.

4.2 Position control of manipulator

Position control of manipulator was performed (Fig. 6a). Workspace of master device was mapped into workspace of manipulator. During this, PD-controller of mobile platform was expected to keep its actual position. First, human-operator moved manipulator from zero position in order to contact the stiff wall which was placed 1 m away from initial position of mobile manipulator. In order to model hard contact relatively high stiffness of the wall (50 kN) was used. Second, human-operator kept

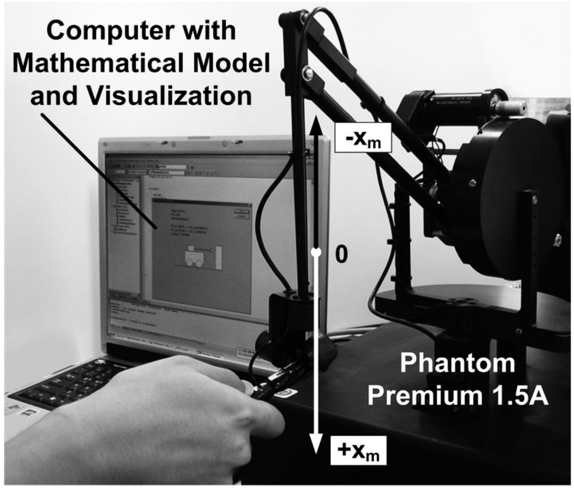

Fig. 5 Experimental setup.

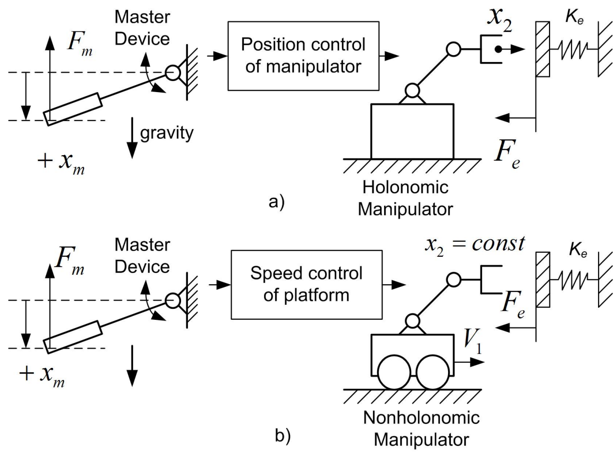

Fig. 6 Scheme for bilateral teleoperation of mobile manipulator when position of manipulator is controlled (a) or when speed of mobile platform is controlled (b).

pushing the wall with manipulator which produced force approximately 100 N. Last step was releasing master device.

In Fig. 7, experimental results for position control of manipulator without PO/PC are shown. Robot moves toward the wall from zero position. Human-operator pushes master device when manipulator interacts with the wall from the time around 4 s to the time around 7 s. As it is shown in 3rd and 4th graph in Fig. 7, force feedback was generated and energy was stored in the system. At time around 7 s master device was released and was moved back due to existence of force feedback. After that master device started oscillating with increasing magnitude. Every next contact with the wall causes higher force feedback. Stored energy quickly went negative which means that system became active.

In Fig. 8, results for same task with application of PO/PC-controller are shown. After releasing master device at time around 6 s, master device starts oscillating but after few seconds its position diverges. At time 10 s,

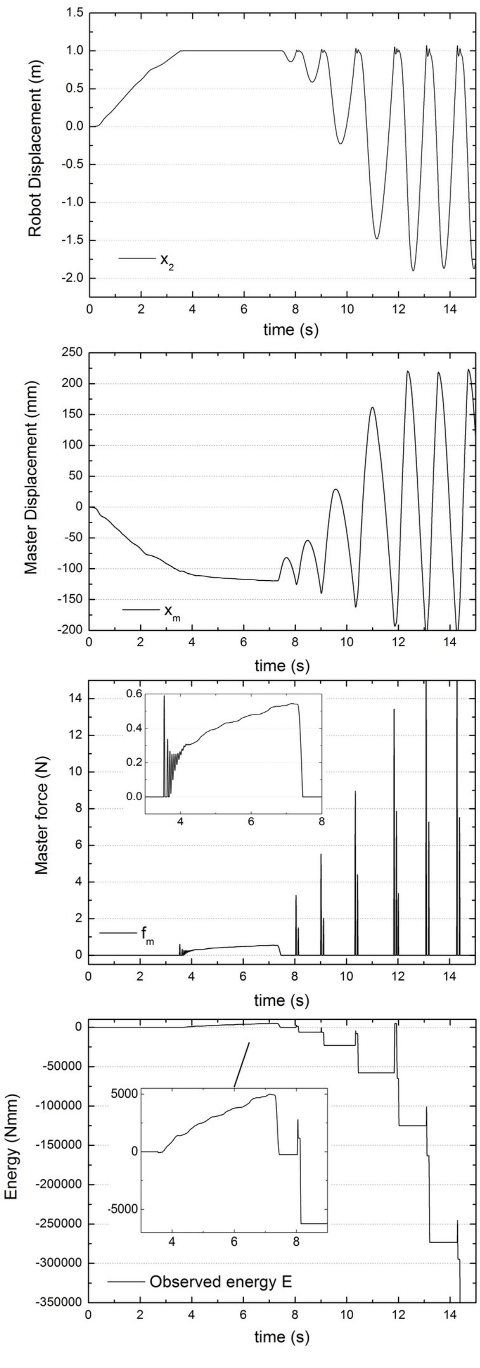

Fig. 7 Position control of manipulator without PO/PC.

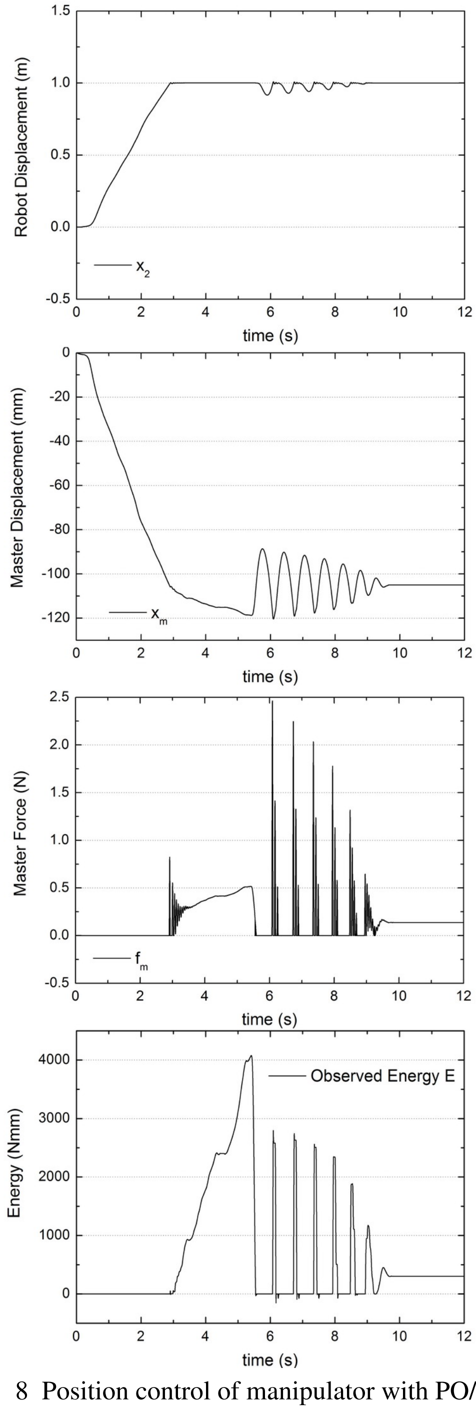

Fig. 8 Position control of manipulator with PO/PC.

robot and master device were stabilized. From last graph in Fig. 8 one can see that almost all the time energy which was stored in system was positive. All active energy flow from mobile manipulator was dissipated by PC.

4.3 Speed control of mobile platform

Speed control of mobile platform was studied. Scheme for this experiment is shown in Fig. 6. Position of master device is mapped to speed space of mobile platform. This case is not conventional for bilateral teleoperation systems. For rate control mode there is no direct energy flow from master device to teleoperated robot. For moving slave robot human-operator can keep constant nonzero position of master device. There will be no physical energy flow from human-operator to slave robot in this case. That makes it difficult to implement passivity based control to mobile manipulator speed control. In this experiment, feasibility of time-domain passivity control was checked. Master device was released from beginning of experiment and no human input was given. Only gravity force was applied to master. PD-controller of manipulator was expected to keep its actual position while the speed of platform was controlled. Platform's control force U was scaled down and transmitted as force

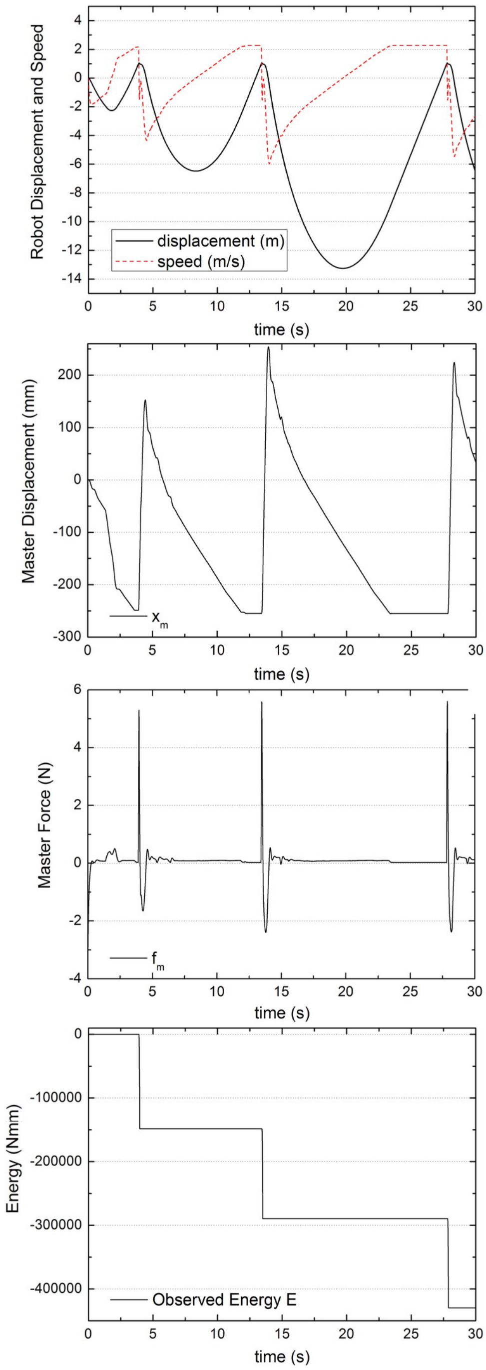

Fig. 9 Speed control of mobile platform without PO/PC.

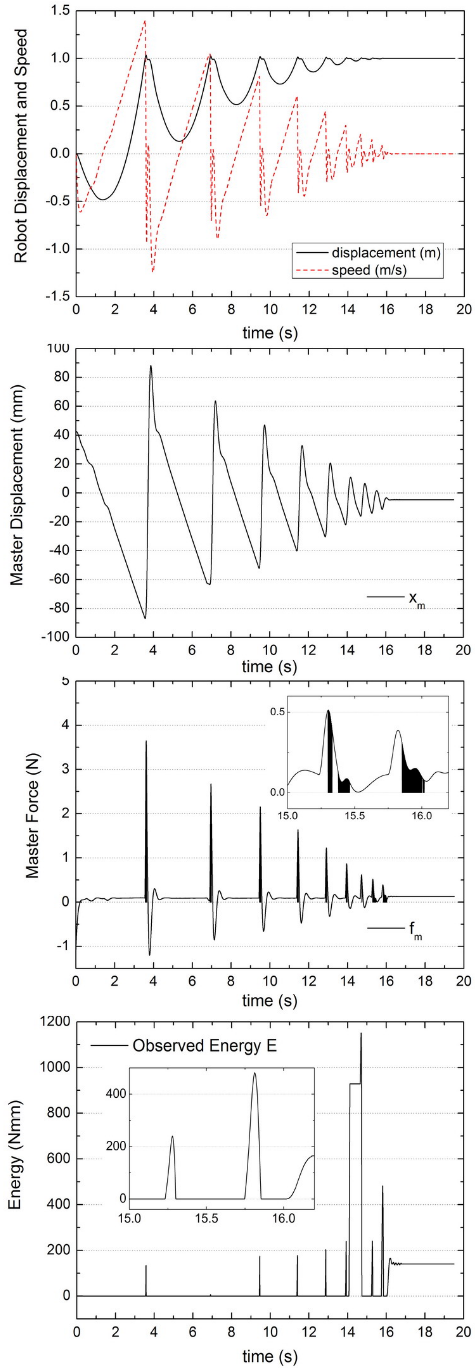

Fig. 10 Speed control of mobile platform with PO/PC.

feedback.

In Fig. 9, experimental results for mobile platform speed control without the PO/PC are shown. Speed of the platform followed master device position (1st and 2nd graph). Every contact of the manipulator with the wall produced high force feedback which caused unstable behavior. Energy was coming out from the system which showed highly unstable behaviour (graph 4).

In Fig. 10, results for the same task with PO/PC are shown. At time around 15 s, system was stable. All negative energy was dissipated which made the system passive.

5. DISCUSSION

As it was mentioned in introduction, PO/PC has been already applied to teleoperation systems in which position of the slave robot is controlled based on the master's position. Application of time-dmain passivity approach to teleoperation of mobile manipulator position control is different from previous approaches because of nonholonomic properties of the system. Position of manipulator is controlled in local coordinate system which is related to mobile platform. If end-effector of manipulator physically interacts with environment then interaction forces effect both manipulator and platform. This can cause motion of mobile platform in a global coordinate system even if local controller of the platform tries to keep desired position. Displacement of platform will cause generation of control force which will effect manipulator. As a result, larger force will be applied to environment, and this can make system more unstable.

Another negative feature of mobile robotic systems is slip. Slip can occur during manipulator's contact with environment when friction between platform wheels and ground and control force applied to platform are not high enough to keep its desired position.

During teleoperation of mobile platform value of desired speed of the platform was sent from the master side. This fact makes mobile robot teleoperation systems different from traditional teleoperation systems in which desired position is transmitted. Experimental results showed that in some range passivity controller could stabilize the system.

Application of PO/PC to teleoperation systems with rate control mode has some differences, as well. Human-operator does not give any energy to the master device in rate mode in free motion when no force feedback is generated. Even if no energy is given to the system, controller of mobile platform produces energy in order to keep constant speed motion. There is no physical energy flow from master side to slave side, but there is energy flow from the slave robot to the master device. Teleoperation systems with rate control mode are characterized by information flow in one direction and energy flow in another direction. For such teleoperation systems it is required to develop new energy concept. We suppose that it is possible to define virtual energy flow from human to teleoperator and this virtual energy is converted to physical energy by controller of platform. We suppose that based on virtual energy flow it is possible to monitor passivity of the system.

6. CONCLUSION AND FUTURE WORKS

This paper provided the feasibility study of time-domain passivity approach for mobile manipulator teleoperation. Experiments with computer model for both position and speed control modes were performed and showed that PO/PC can improve stability of the system. But application of conventional energy concept for speed (rate) control mode had some limitations. Difficulty of physical energy observation at master side is still an open issue. In teleoperation systems with rate control mode we faced conversion of information at master side to energy at slave side.

In future, we plan to extend time-domain passivity approach by modifying energy observation methods. We suppose that it is possible to define virtual energy which flows from master to slave instead of physical energy. It is necessary to assume that master position is measured in a new not fixed virtual coordinate system which is moving with respect to slave robot. This virtual energy flow corresponds to information flow from master side. We expect to design new PO and PC in order to operate with virtual energy flow at master side and physical energy flow at slave side.

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