Passivity of Delayed Bilateral Teleoperation of Mobile Robots with Ambiguous Causalities: Time Domain Passivity Approach

Ha Van Quang[1], Ildar Farkhatdinov[2] and Jee-Hwan Ryu[1]

***Abstract*— Rate mode commanding together with obstacle based force feedback makes mobile robot teleoperation difficult to stabilize even without time-delay. This paper proposes a method for stable time-delayed teleoperation of a mobile robot. Rate mode teleoperation with three different types of force feedback is considered to develop generally applicable method. We reformulate mobile robot bilateral teleoperation architecture based on recently proposed Time Delayed Power Network framework. It allows clarifying ambiguous energy ports and makes it possible to implement Time Domain Passivity Approach in order to secure the system stability. Experimental results show the effectiveness of the proposed formulation for a mobile robot teleoperation with time-delay.**

I. INTRODUCTION

Various types of human-machine interfaces are known to be effective in mobile robot teleoperation systems [1]. Among these interfaces significant role belongs to haptic interfaces which secure safe collision-free mobile robot's motion [2], [3], [4], [5], provide human-operator with additional information on the system's state [6], help to perceive remote environment [7], [8] and facilitate the control of a mobile robot [9], [10]. In many mobile robot teleoperation applications it is common to use obstacle avoidance force feedback, when the force displayed at the master device shows how to control the mobile robot in order not to collide with an obstacle in remote environment [6]. This obstacle based force feedback should be directly related to the distance between the mobile robot and an obstacle. Note, that this force calculation is based on a distance to an obstacle do not act in a direct way on the slave (mobile) robot, but acts directly to the master device. This makes mobile robot teleoperation system with obstacle based force feedback different from classical master-slave manipulator bilateral teleoperation system in which a slave robot interacting with environment is directly affected by environmental forces. The second difference of the mobile robot teleoperation system from classical teleoperation system is the rate mode control which is not often used in manipulator teleoperation, while the rate mode control is essential for mobile robot teleoperation due to its kinematic properties.

The crucial problem of mobile robot teleoperation systems with force feedback is stability which may become critical when time delay is introduced in a communication channel between the haptic master device and the slave mobile robot. Passivity-based control design is one of the effective approaches to maintain the system's stability. In [11], [12], analytical passive model based controllers for the bilateral mobile robot teleoperation system were proposed. However, the force feedback signals used in [11], [12] were based on coordination errors for the mobile robot's linear and angular velocities. The force perceived by human-operator was not directly related to obstacles around the robot, therefore operator might feel continuous force even in free motion in cases when velocity controller was not fast enough, or the surface of the environment was inclined. In [13], energy bounding approach was applied to rate mode teleoperation. But, similar to [11], [12], force feedback was calculated based on coordination error, which is not applicable to mobile robot teleoperation if we want to have force feedback directly related to the obstacles around the robot. In [14], it was shown that the mobile robot teleoperation system with obstacle based force feedback is characterized by ambiguous causalities and direct application of passivity methods such as Time Domain Passivity Approach (TDPA) [15] cannot guarantee passivity in some situations.

In this paper we apply the concept of Time Delay Power Networks (TDPN) published in [16] to present mobile robot teleoperation system in a form which allows to remove ambiguous causalities. This system restatement allows us to apply TDPA for the delayed network systems [17] to the mobile robot teleoperation system which maintain the passivity for any type of force feedback signals. The following sections describe the overall design process and implementation.

II. MOBILE ROBOT TELEOPERATION SYSTEM

In the mobile robot teleoperation system a human-operator controls velocity of a mobile robot via manipulating a master device. Human-operator applies force f_h to the handle of a master device which causes the change of its velocity, v_m. By changing master's position, x_m, operator defines desired velocity of the mobile robot, v_{sd}:

$$v_{sd} = k_v x_m \tag{1}$$

where k_v is a mapping coefficient from position of the master device to the mobile robot's velocity. Velocity controller of the mobile robot generates required force (torque), f_s to compensate an error between desired velocity, v_{sd}, and actual velocity of the robot, v_s. Feedback signals which depend on the mobile robot's operational state and environment are used to calculate force feedback, f_m, which is generated on the

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master device and displayed to a human-operator. In this paper, for simplicity and clarity of explanation we consider only linear velocity of the mobile robot. Nevertheless, proposed controller design is applicable to the full model of the mobile robot with linear and angular velocities consideration.

Three types of force feedback schemes for the bilateral mobile robot teleoperation system are shown in Fig. 1. First we consider the force feedback which calculation is based on mobile robot's velocity:

$$f_1 = k_1 v_s \tag{2}$$

where k_1 is scaling coefficient (Fig. 1a). This force feedback displays to human-operator the value of the mobile robot's linear velocity and pushes the master device to zero position in order to restore zero velocity of the mobile robot. In this case the force feedback acts like a spring with one end attached to zero position of the master device coordinate system and the other end attached to the handle. This type of force feedback plays two important roles in teleoperation of the mobile robot: 1) preventing a human-operator from increasing the velocity of the mobile robot to unsafe levels; 2) restoring zero position of the master device when a human-operator stops acting on its handle (free motion) which stops the robot, as a result.

In Fig. 1b teleoperation system with force feedback based on velocity control error is shown. This force feedback is calculated as follows:

$$f_2 = k_2(k_v x_m - v_s) \tag{3}$$

where k_2 is scaling coefficient. The force feedback is proportional to velocity control error. This type of force feedback provides human-operator with information on the dynamic mass-inertia characteristics of the mobile robot and its velocity controller. In cases when the velocity controller of the mobile robot due to some external disturbances cannot produce enough effort to track the desired velocity, force feedback on the master device will prevent human-operator from increasing the slave's velocity too fast. For instance, this type of force feedback can be useful when the mobile robot moves on inclined surfaces and its controller is not able to track the desired velocity.

Next type of force feedback for mobile robot teleoperation system is shown in Fig. 1c. This is force feedback which is based on obstacle information and prevents the mobile robot from collisions with obstacles. The force is calculated based on the distance from the mobile robot to the obstacles around it:

$$f_3 = \begin{cases} k_3(r_0 - r), & r \leq r_0 \\ 0, & r > r_0 \end{cases} \tag{4}$$

where k_3 is a scaling coefficient, r - distance from mobile robot to the nearest obstacle, r_0 - constant distance which defines the area around the obstacle in which the force feedback is activated. Distances to the obstacles can be measured with laser scanner(s) installed on the mobile robot. If the distance to one of the obstacles around the robot is less then r_0, then the force is generated on the master device preventing human-operator from increasing the velocity of the robot towards the nearest obstacle. This force feedback is proportional to displacement of the robot within the area of the obstacle defined by the distance r_0. The obstacle range based force feedback acts like a spring 'pushing' the mobile robot out of the obstacle area but physically acting to the master device.

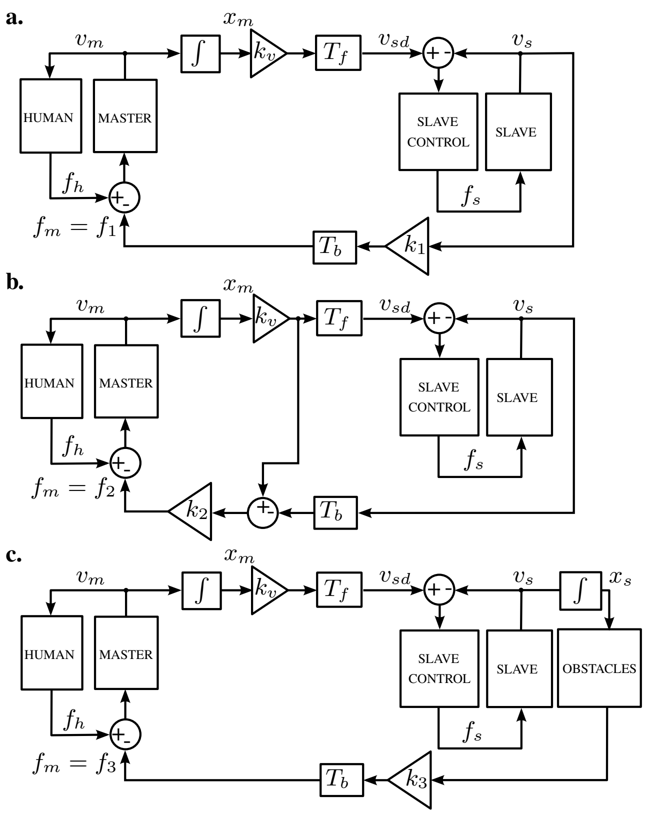

Fig. 1. Mobile robot bilateral teleoperation systems with three types of force feedback: **a.** force feedback based on mobile robot's velocity; **b.** force feedback based on velocity error; **c.** force feedback based on obstacle range information

Different types of force feedback signals can be used together in combinations such as:

$$f'_m = f_1 + f_3, \tag{5}$$

$$f''_m = f_2 + f_3. \tag{6}$$

In case when communication networks have time delays in forward, T_f, and backward, T_b channels (as shown in Fig. 1) velocity commands arrive to mobile robot with delay T_f, while force feedback signals arrive to the master side after time T_b which can easily cause unstable behavior. One of the methods to assure stability of the bilateral teleoperation systems with time delay is securing passivity of the system by monitoring and dissipating active energy flows. Application of time domain passivity approach to mobile robot teleoperation system is described in next section.

III. SYSTEM REPRESENTATION WITH TDPN

The time domain passivity approach requires unambiguous definition of energy ports in the system. In case of mobile robot teleoperation system we have to deal with ambiguity of network causality. The power of the master device by definition is $(f_m v_m)$ and the power of the mobile robot is $(f_s v_s)$. However, because of the use of the rate mode control, mobile robot's power is not zero when the power flow at the master device is zero (when $x_m \neq 0$ and $v_m = 0$). This is the first difficulty for application of time domain passivity approach. The second difficulty is related to force feedback channel. All types of force feedback which were introduced in section II act directly on the master device. Only controller force, f_s, is applied to the mobile robot. In classical master-slave manipulator teleoperation systems, slave manipulator in addition to controller forces is affected by environmental forces (for instance, contact with a wall). We consider safe motion of the mobile robot when there are no collisions between the mobile robot and obstacles around it and therefore the mobile robot do not interact with obstacles in direct way. As a result it is ambiguous to define the input-output energy relations for the force feedback channel in the system. Although the energy is transmitted through the communication channel, the outgoing and incoming flow signals do not define the ports at each side of the system since they are not power correlated.

However, following the approach described in [16] it is possible to represent the system's energy flow signal with the help of the ideal flow and effort sources and TDPN. This approach can replace unambiguous energy ports by the ideal flow (velocity) and effort (force) sources whose values are dependent on some past signals in the system. The main idea is to find the causes of command and feedback flows, and to represent dependent delayed network circuit with the ideal effort or flow source. In Fig. 2 mobile robot bilateral teleoperation system (with all three types of force feedback signals from section II) is represented with the help of TDPN. We propose to discriminate four channels in the system: velocity command channel, velocity based force feedback channel, error based force feedback channel and obstacle based force feedback channel. Velocity command channel and error based force feedback channels are represented by the ideal flow sources. Velocity based force feedback and obstacle based force feedback channels are represented by the ideal effort sources. TDPNs are used to separate delayed and non-delayed time instances. Note, that there is no physical energy port between the mobile robot and the obstacles.

IV. PASSIVITY ANALYSIS AND CONTROLLER DESIGN

A. Passivity Observer

In this subsection we present passivity analysis of the system using the approach presented in [16], [17] and design the passivity observers and passivity controllers which maintain systems passivity and therefore stability.

For each TDPN represented in Fig. 2 we calculate input and output energy (see [17] for details on input and output energy). To do this we consider a discretized system in which measurement/control action is done with sampling time dT

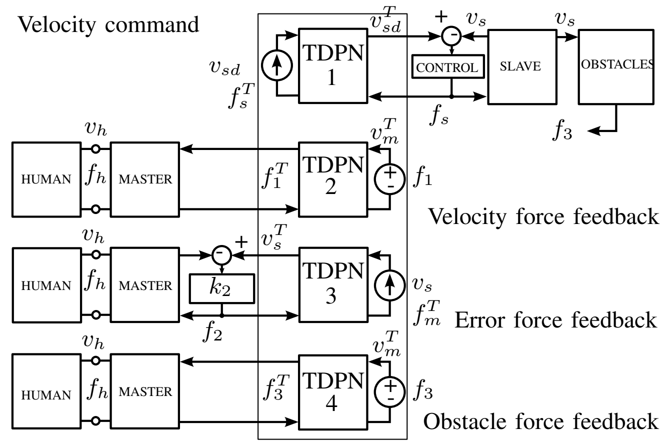

Fig. 2. Representation of mobile robot teleoperation system with the help of TDPN. Delayed signals are defined as: $v_{sd}^T \equiv v_{sd}(t-T)$, $f_1^T \equiv f_1(t-T_b)$, $v_s^T \equiv v_s(t-T_b)$, $f_3^T \equiv f_3(t-T_b)$. Time delay: $T \equiv T_f = T_b$.

and computationally integrate the input and output power flow. Input energy in velocity command channel at the master side at discrete time instance n:

$$E_{in}^{M1}(n) = \begin{cases} E_{in}^{M1}(n-1) + f_s(n-D)v_{sd}(n)dT, \\ \qquad \textbf{if } f_s(n-D)v_{sd}(n) > 0 \\ E_{in}^{M1}(n-1), \\ \qquad \textbf{if } f_s(n-D)v_{sd}(n) \leq 0 \end{cases} \tag{7}$$

where D is amount of one way time delay in communication channel. The output energy in velocity command channel at the slave side is:

$$E_{out}^{S1}(n) = \begin{cases} E_{out}^{S1}(n-1) + f_s(n)v_{sd}(n-D)dT, \\ \qquad \textbf{if } f_s(n)v_{sd}(n-D) > 0 \\ E_{out}^{S1}(n-1), \\ \qquad \textbf{if } f_s(n)v_{sd}(n-D) \leq 0 \end{cases} \tag{8}$$

The input energy in velocity based force feedback at the slave side:

$$E_{in}^{S2}(n) = \begin{cases} E_{in}^{S2}(n-1) + f_1(n)v_m(n-D)dT, \\ \qquad \textbf{if } f_1(n)v_m(n-D) > 0 \\ E_{in}^{S2}(n-1), \\ \qquad \textbf{if } f_1(n)v_m(n-D) \leq 0 \end{cases} \tag{9}$$

The output energy in velocity based force feedback at the master side:

$$E_{out}^{M2}(n) = \begin{cases} E_{out}^{M2}(n-1) + f_1(n-D)v_m(n)dT, \\ \qquad \textbf{if } f_1(n-D)v_m(n) > 0 \\ E_{out}^{M2}(n-1), \\ \qquad \textbf{if } f_1(n-D)v_m(n) \leq 0 \end{cases} \tag{10}$$

The input energy in error force feedback channel at the slave side:

$$E_{in}^{S3}(n) = \begin{cases} E_{in}^{S3}(n-1) + f_2(n-D)v_s(n)dT, \\ \qquad \textbf{if } f_2(n-D)v_s(n) > 0 \\ E_{in}^{S3}(n-1), \\ \qquad \textbf{if } f_2(n-D)v_s(n) \leq 0 \end{cases} \tag{11}$$

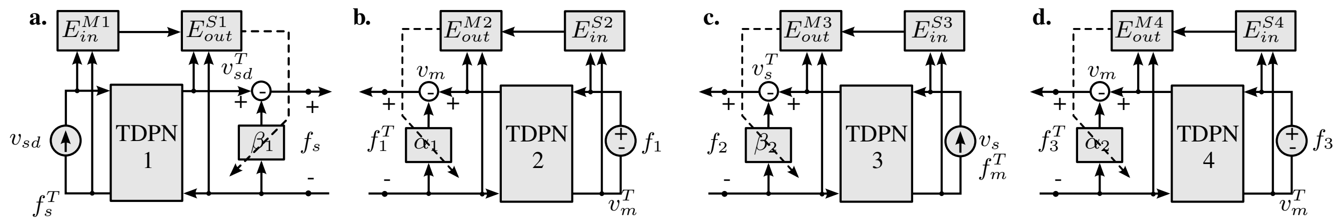

Fig. 3. Passivity observers and passivity controllers attached to different energy exchange channels of the mobile robot teleoperation system: **a.** velocity command channel; **b.** velocity based force feedback; **c.** error based force feedback; **d.** obstacle based force feedback

The output energy in error force feedback channel at the master side:

$$E_{out}^{M3}(n) = \begin{cases} E_{out}^{M3}(n-1) + f_2(n)v_s(n-D)dT, \\ \quad \textbf{if } f_2(n)v_s(n-D) > 0 \\ E_{out}^{M3}(n-1), \\ \quad \textbf{if } f_2(n)v_s(n-D) \leq 0 \end{cases} \tag{12}$$

The input energy in obstacle force feedback channel at the slave side:

$$E_{in}^{S4}(n) = \begin{cases} E_{in}^{S4}(n-1) + f_3(n)v_m(n-D)dT, \\ \quad \textbf{if } f_3(n)v_m(n-D) > 0 \\ E_{in}^{S4}(n-1), \\ \quad \textbf{if } f_3(n)v_m(n-D) \leq 0 \end{cases} \tag{13}$$

The output energy in obstacle force feedback channel at the master side:

$$E_{out}^{M4}(n) = \begin{cases} E_{out}^{M4}(n-1) + f_3(n-D)v_m(n)dT, \\ \quad \textbf{if } f_3(n-D)v_m(n) > 0 \\ E_{out}^{M4}(n-1), \\ \quad \textbf{if } f_3(n-D)v_m(n) \leq 0 \end{cases} \tag{14}$$

Each of the TDPN will be passive if output energy is never greater than the input energy. For each of the above four energy channels, respectively, we can write the passivity conditions:

$$E_{in}^{M1}(n) - E_{out}^{S1}(n) \geq 0, \tag{15}$$
$$E_{in}^{S2}(n) - E_{out}^{M2}(n) \geq 0, \tag{16}$$
$$E_{in}^{S3}(n) - E_{out}^{M3}(n) \geq 0, \tag{17}$$
$$E_{in}^{S4}(n) - E_{out}^{M4}(n) \geq 0. \tag{18}$$

Straightforward verification of these passivity conditions on the master or slave side is impossible because one of the energy signals will always be delayed. However, as it was explained in [17] it is sufficient to satisfy non-delayed passivity conditions if the delayed input energy, calculated at the source port and transmitted to the other port with delay, is greater than the output energy at the other port. Then, the above passivity conditions can be rewritten as follows:

$$E_{obs}^{1}(n) \equiv E_{in}^{M1}(n-D) - E_{out}^{S1}(n) \geq 0, \tag{19}$$
$$E_{obs}^{2}(n) \equiv E_{in}^{S2}(n-D) - E_{out}^{M2}(n) \geq 0, \tag{20}$$
$$E_{obs}^{3}(n) \equiv E_{in}^{S3}(n-D) - E_{out}^{M3}(n) \geq 0, \tag{21}$$
$$E_{obs}^{4}(n) \equiv E_{in}^{S4}(n-D) - E_{out}^{M4}(n) \geq 0. \tag{22}$$

where with E_{obs} we have defined the passivity observers (PO) for each TDPN.

B. Passivity Controller

To maintain the mobile robot teleoperation system stable it is necessary to dissipate all produced active energy which is registered by the passivity observers. We design passivity controllers (PC) which play the role of dissipative elements (damping) activated at each channel when active energy flow is registered. Damping coefficients must be such that they dissipate that amount of active energy. The following equations are used to realize the adaptation of damping in PC for each channel:

$$\beta_1(n) = \begin{cases} 0 & \textbf{if } E_{obs}^1(n) > 0 \\ -\dfrac{E_{obs}^1(n)}{f_s^2(n)dT}, & \textbf{else, if } |f_s(n)| > 0 \end{cases} \tag{23}$$

$$\alpha_1(n) = \begin{cases} 0 & \textbf{if } E_{obs}^2(n) > 0 \\ -\dfrac{E_{obs}^2(n)}{v_m^2(n)dT}, & \textbf{else, if } |v_m(n)| > 0 \end{cases} \tag{24}$$

$$\beta_2(n) = \begin{cases} 0 & \textbf{if } E_{obs}^3(n) > 0 \\ -\dfrac{E_{obs}^3(n)}{f_2^2(n)dT}, & \textbf{else, if } |f_2(n)| > 0 \end{cases} \tag{25}$$

$$\alpha_2(n) = \begin{cases} 0 & \textbf{if } E_{obs}^4(n) > 0 \\ -\dfrac{E_{obs}^4(n)}{v_m^2(n)dT}, & \textbf{else, if } |v_m(n)| > 0 \end{cases} \tag{26}$$

Fig. 3 shows how PO/PCs are attached to TPDNs from the system depicted in Fig. 2. Each PC modifies the corresponding control signal, so that the energy flow in TDPN remains passive. For example, in case when TDPN1 produces active energy PC would modify the desired slave velocity signal:

$$v_{sd}^{T*}(n) = v_{sd}^T(n) - \beta_1(n)f_s(n), \tag{27}$$

where $v_{sd}^{T*}(n)$ is modified by PC desired velocity for the mobile robot. It is sufficient to apply PC only to the output energy side of TDPN because it is considered that the ideal flow (velocity) can supply and absorb unlimited power forever (see [16] for the proof).

V. EXPERIMENT

A. Setup

Experiments were done to test the work of PO/PC in the mobile robot teleoperation with force feedback and time delay in communication channel. Pioneer 3DX mobile robot with two independently controlled wheels and with onboard

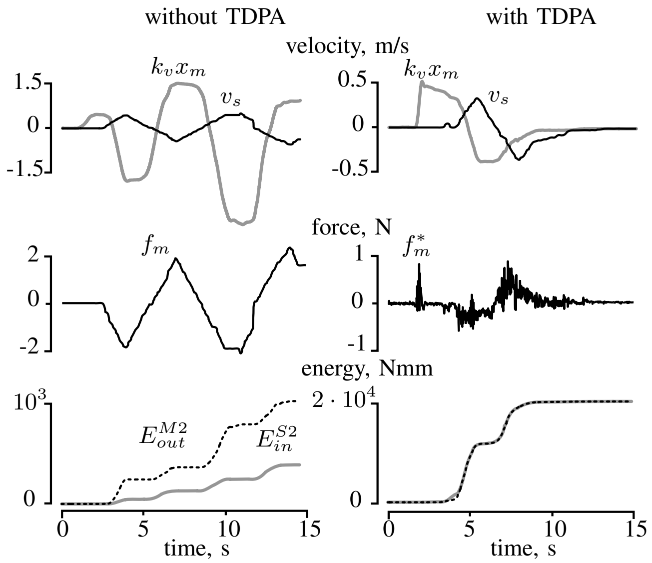

Fig. 4. Experimental results for teleoperation with velocity based force feedback without TDPA (left) and with TDPA (right).

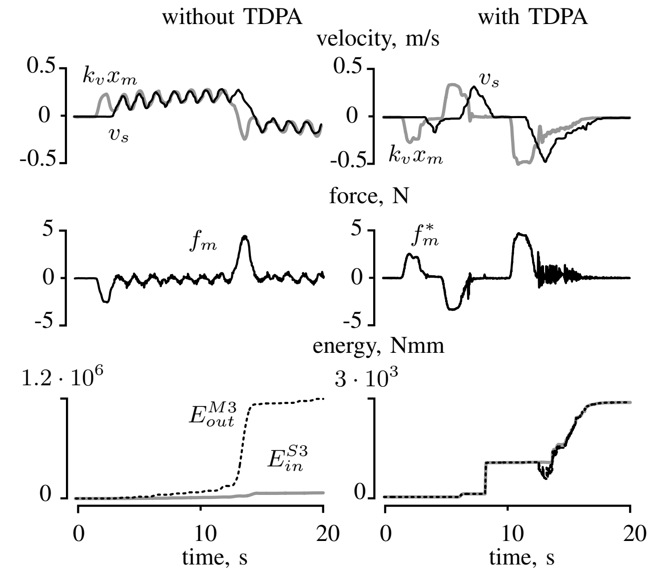

Fig. 5. Experimental results for teleoperation with velocity error based force feedback without TDPA (left) and with TDPA (right).

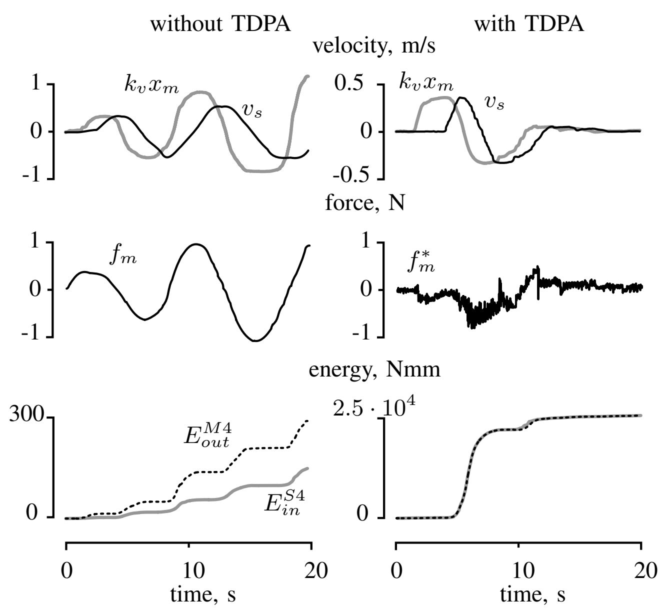

Fig. 6. Experimental results for teleoperation with velocity based force feedback without TDPA (left) and with TDPA (right).

embedded system running under ROS was used. Phantom Premium 1.5A was used as a master device. Communication between the mobile robot and the master setup was done with the help of local wireless network. Linear velocity of the mobile robot was controlled based on the displacement of the master's stylus along it's z-direction, while x-direction of the master device was used for controlling angular velocity of the robot. Built-in mobile robot's velocity controller which was configured to achieve reasonable tracking performance was used. The following reasonable values of control parameters were used: k_v=10 s^{-1}, k_1=0.01 N·s/mm, k_2=0.005 N·s/mm, k_3=0.001 N/mm, r_0=2 m. Absolute linear speed of the mobile robot was limited up to 0.5 m/s for safety reasons. Time delay in the wireless communication channel was about 200 ms in one direction and was varying during experiments. All the data presented in next subsection was recorded at the master side.

B. Results

Three experiments were performed for testing the proposed passivity control system for each type of force feedback. In the first experiment mobile robot's velocity based force feedback was used based on (2). Results are presented in Fig. 4. Time plots for mobile robot's desired and actual velocities, force feedback displayed at the master side, and input and output energies for TDPN2 are presented in the results. Human-operator controlled the velocity of the mobile robot based on the position of the master device. It was almost impossible for a human to stop the robot due to the delayed force feedback. TDPN was producing significant amount of energy, and passivity condition was not secured. For a human-operator it was very hard to stop the robot. Therefore, instead of helping force feedback reduced performance of teleoperation greatly. However, when TDPA was used, system became stable. Force feedback was proportional to the mobile robots velocity, which was helping human-operator to control the robot and stop it whenever it was necessary.

In the second experiment error based force feedback was used which was calculated based on (3). Results are presented in Fig. 5. Human-operator tried to move the mobile robot with constant velocity, but it was very difficult to stabilize master's position due to delayed information about the velocity control error. Oscillations were removed when TDPA was used. Human-operator could easily control the velocity of the mobile robot and could stop the robot at last.

In the last experiment obstacle based force feedback was used which was calculated based on (4). Results are presented in Fig. 6. Two obstacles were placed in front and behind the robot 1 m away from its initial position. Force feedback was calculated as a resulting vector sum of the force feedback from each of the obstacles. The human-operator was asked to move the robot slowly between the obstacles. In the case when TDPA was not used the mobile robot and the master device were oscillating due to existence of time delay. The human-operator could not dissipate all the active energy produced on the master side. Oscillations were removed when TDPA was applied. The operator could easily move the mobile robot between the obstacles and 'feel' the distance to the obstacles at the same time.

From the presented plots we can see that force feedback signal, f_m^*, which is the signal modified by PC actions was noisy during some time periods. This happened due to frequent due to frequent PC activation/deactivation. This noise can be felt by a human-operator if the noise to signal ratio is high enough. One of the ways to solve the problem of this noisy behavior is introducing intermediate virtual coupling between PC and the master device, as it was done in [17].

We have tested experimentally the cases when force feedback signals are combined, as in (5)-(6), and similar to previous cases TDPA improved the teleoperation system's performance.

VI. CONCLUSION

Experiments have shown that TDPA together with TDPN are useful and powerful tools for designing controllers for time delayed bilateral teleoperation systems with different types of force feedback and ambiguities in defining the energy ports. Ambiguity of the power ports in the mobile robot teleoperation system with obstacle and velocity based force feedback was the main difficulty for proper configuration of PO and PC. System restatement with TDPN allowed us to apply time domain passivity control to the mobile robot teleoperation system. Experiments showed how easy does the system become unstable and how useless the force feedback is when time delay is introduced in communication channels. Designed controller secured the passivity of the system and granted the stable behavior of the mobile robot and the master device when different types of the force feedback were used. The human-operator could easily control the robot while receiving meaningful force feedback information. Proposed TDPA formulation and design can be extended to mobile robot teleoperation systems with any other types of force feedback, including to recently proposed obstacle based force feedback with variable gain [19].

Future research may include a study on the noisy behavior in the force feedback signal and its influence on performance of the overall mobile robot teleoperation system during performing various task.

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