Bilateral Telemanipulation with Time Delays: A Two-Layer Approach combining Passivity and Transparency

Michel Franken, Stefano Stramigioli, Sarthak Misra, Cristian Secchi and Alessandro Machelli

Abstract—**In this paper a two layered approach is presented to deal with time delays in the communication channel of bilateral telemanipulation systems. Time delays are a well known source for instability as they can cause "virtual" energy to be generated in the communication channel. Various schemes have been proposed to handle this problem by either scaling down the transmitted variables, or by applying an encoding scheme to prevent this energy from being generated. The approach which is proposed in this paper is very different in nature as it splits the control architecture in two separate layers. The hierarchically top layer is used to implement a strategy that addresses the desired transparency and the lower layer ensures that no "virtual" energy is generated. This means that any bilateral controller can be implemented in a passive manner. Separate communication channels connect the layers at the slave and master side so that information related to exchanged energy is completely separated from information about the desired behavior. By completely separating the properties of passivity and transparency each layer can accommodate any number of different implementations allowing for almost independent optimization. Experimental results are presented which show the benefit of the proposed framework.**

Index Terms—**Telemanipulation, bilateral control, time delay, stability, passivity, transparency.**

I. Introduction

A telemanipulation chain is composed of a user, a master system, a communication channel, a slave system, and a remote environment for the user to act upon. The master and slave system both consist of a physical device and a controller (implemented on an embedded system). Typical applications of these chains are the interaction with materials in environments which are remote, difficult to reach, and/or dangerous for human beings. Bilateral telemanipulation occurs when the user is presented with force information about the interaction between the slave system and the remote environment, Fig. 2. Such a haptic feedback is likely to increase the performance of the user with respect to effectiveness, accuracy and safety in many practical applications, e.g. for robotic surgery as discussed by Bethea et al. [5].

Two important criteria in bilateral telemanipulation are transparency and stability. Transparency is a performance measure of how well the complete system is able to convey to the user the perception of directly interacting with the environment [14]. Many different control algorithms have been proposed in literature which try to obtain transparent bilateral teleoperation. Sheridan [26], [27] and Hokayem et al. [14] have written extensive survey papers discussing various approaches to implement bilateral telemanipulation.

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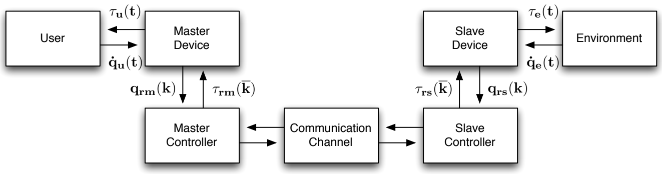

Fig. 1. **Schematic overview of a bilateral telemanipulation chain.** Both the master and slave device are impedance type displays. The information exchanged over the communication channel depends on the implemented controller.

The master and slave system can be located at different sites. Therefore it is likely to assume that a certain amount of time delay will be present in the communication channel. Time delays however can also occur due to various other processes other than physical distance, e.g. the coding and decoding of the signals exchanged between the master and slave system. These time delays can destabilize many of the in literature proposed bilateral telemanipulation algorithms. A destabilizing effect which we will consider here is the generation of "virtual" energy in the communication channel. This can occur for algorithms that use a direct exchange of velocities and forces through the communication channel. Velocities and forces are dual variables, which means that their product is power, therefore they are called power variables. The time delay in the communication channel destroys the colocation in time of the power variables at the master side. This means that the power flowing out of the system at the master side does not necessarily equal the power injected at the master side. Time delays are therefore said to turn the communication channel into an active element which can produce "virtual" energy [22]. If this additional energy is not properly dissipated by one of the elements in the telemanipulation chain, it can destabilize the system [23].

As generated "virtual" energy poses a stability problem, a simple and effective solution would be to remove this energy from the system. Control schemes that prevent "virtual" energy from being generated have been developed, e.g. the scattering and wave variable approaches described by Anderson et al. [1] and Niemeyer et al. [22]. Such energy neutral schemes are called passive. Arcara et al. [2] and Lawn et al. [16] have compared several passivity-based algorithms to non passive algorithms with respect to stability and the level of transparency that could be achieved. Passivity-based approaches are indeed found to be stable in the presence of time delays, but the level of transparency that was obtained was criticized.

Passivity is thus an effective and elegant solution to the stability problem, but a higher level of transparency is desired. The problem with current passivity based methods is that they are specifically designed around a certain type of information exchange. This places strict limitations on the rest of the controller. As we will discuss there are a multitude of control architectures designed for transparency that do not fit within those passivity based methods. Given the benefits of passivity with respect to guaranteed stability, we want to design a framework in which any controller can be implemented in a passive manner given arbitrary time delays.

In this paper we will present a new control framework for passive bilateral telemanipulation. The framework is composed of two layers placed in a hierarchically structure. Each layer is furthermore designed for a specific purpose, either to obtain transparency or to maintain passivity. In the top layer, the *Transparency Layer*, a control structure can be implemented to provide the best possible transparency of the telemanipulation chain, taking into account all available information about the system, the environment, and the task which the user is executing. The commands which are computed in this layer are passed to the bottom layer, the *Passivity Layer*. This layer contains an algorithm to maintain passivity of the total system. The key element of this algorithm is to define two communicating energy storage tanks from which the motions of both the slave and master are powered. The use of two control layers to combine passivity and transparency and the working of the *Passivity Layer* are the main contributions of this paper.

In the rest of this paper an impedance causality for both the master and slave systems (velocities as input and forces as output to the robotic devices) is assumed. For these devices the energy exchanged with the outside world can precisely be determined, which is at the heart of Section V. The paper is organized as follows: Sections II and III discus the basic concepts of passivity and transparency under the influence of time delays and will discuss related work. Section IV further discusses the two-layered framework. Section V contains the theory of the *Passivity Layer*. Section VI presents a full implementation and experimental results which were obtained with the proposed framework and demonstrate its effectiveness. The paper concludes and provides directions for future work in Section VII.

II. Passivity

In the previous section passivity was mentioned as a solution for stable time delayed telemanipulation. The concept of passivity will be used in Section V to develop the *Passivity Layer*. Therefore we will a give a more thorough explanation of the concept in this section.

A system is said to be passive if the energy which can be extracted from it is bounded by the injected and initial stored energy. Passivity of a system is a sufficient condition

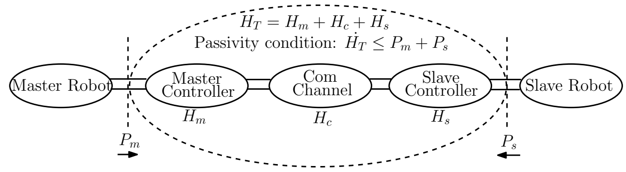

Fig. 2. Energy balance of the telemanipulation chain

for stability and any proper combination of passive systems will again be passive [30]. Independent of anything else, including the goal of the system, an energy balance of the telemanipulation system can be formulated composed of the energy present in all of its components.

$$H_T = H_m + H_c + H_s \tag{1}$$

where $H_T(t)$ represents the total energy present in the control system at instant t which is composed of all the energy present on the master side $H_m(t)$, all the energy present on the slave side $H_s(t)$ and the energy present in the communication channel $H_c(t)$, Fig. 2.

The user and the remote environment are assumed to be passive systems. Therefore, passivity of the telemanipulation chain guarantees stability. Physical energy exchange during operation is taking place between the user and the master system and between the slave system and the environment. The only requirement therefore necessary to ensure passivity of the entire system is:

$$\dot{H}_T(t) \leq P_m(t) + P_s(t) \tag{2}$$

where $P_m(t)$ and $P_s(t)$ are respectively the power flowing from the master and slave robot into the master and slave controller and $\dot{H}_T(t)$ is the rate of change of the energy balance of the system.

As discussed in Section I the direct transmission of power variables generates "virtual" energy in the presence of time delays in the communication channel. The scattering and wave variables approaches developed by Anderson et al. [1] and Niemeyer et al. [22] apply a coding scheme to the power variables to turn the time delayed communication channel into a passive element. When the controllers at both the master and slave side are furthermore passive, the complete system is passive according to (2), such a complete approach is described by Secchi et al. [25].

A different solution to the passivity problem was proposed by Ryu et al. [23]. There the Passivity Observer/Passivity Controller (PO/PC) structure developed by Hannaford et al. for passive interaction with virtual environments was applied to bilateral telemanipulation. However, Ryu et al. required for their algorithm simultaneous information about the energetic interaction at the master and the slave side according to (2). Artigas et al. [3] extended this approach to the time delayed situation by incorporating an energy reference algorithm. Artigas et al. [4] further extended this approach to also include a passive coupling between the continuous and discrete domain.

The passivity based algorithms mentioned above are designed as a serial linkage of components which exchange energy. Each component is therefore implemented in a passive manner, or alternatively, passivity enforcing structures are placed between the components to create a passive connection.

This means that at each connection adaptation of the transmitted/received signals occurs, which limits the achievable transparency. Furthermore, it requires each of the control blocks to exchange power variables, which limits the type of controllers that can be implemented using these approaches. However, as far as passivity according to (2) is concerned energetically active elements can be permitted in the telemanipulation control structure as long as this energy cannot flow into the physical world. Furthermore (2) doesn't impose any restrictions on the information being exchanged between the master and the slave.

It will be shown in Section V that it is possible to make a direct energetic connection between the interaction port at the master and the slave side, and make passivity an independent property to be monitored and enforced. This will make the entire system passive irrespective of the implemented controller. As a direct connection between the interaction ports is established, the control signals to achieve transparency only need to be adapted to maintain passivity just prior to being applied to the system. This will also allow control architectures to be implemented in a passive manner where there is no energetic coupling in the information exchanged between the master and slave side, or architectures which contain energetically active components.

III. TRANSPARENCY

In the previous section we have discussed passivity as a means to guarantee stability of bilateral telemanipulation systems in the presence of time delays. In this section we will treat the influence that time delays have on transparency and give a small overview of several promising control algorithms to obtain transparency, but which are not necessarily passive.

The main goal of bilateral telemanipulation is to increase the perception of the user about the interaction with the remote environment. Ideally the user should get the experience that he/she is manipulating the environment directly. The transparency of a telemanipulation system refers to the degree of success a system has in obtaining this goal. In a perfectly transparent system the dynamics of the system itself are not discernible to the user.

As transparency relates to how a human perceives the interaction with the remote environment, the effectively achieved transparency of a telemanipulation system can only be evaluated in psychophysical experiments as conducted by Lawn et al. [16] and Hirche et al. [13]. However, the technically achievable transparency of bilateral controllers can be defined as an objective metric. In order to show the influence of time delays on transparency and therefore on useful control structures we will use an approach applied by Secchi et al. [24] and define the interaction at both the master and the slave side by the associated power variables.

A perfectly transparent system without time delays ensures:

$$\begin{aligned} \dot{q}_s(t) &= \dot{q}_m(t) \\ \tau_m(t) &= \tau_s(t) \end{aligned} \tag{3}$$

where $\dot{q}_m, \dot{q}_s$ are the velocities of the master and slave device, respectively. While τ_m, τ_s are the interaction forces between the master device and the user and between the environment and the slave device, respectively.

When increased time delays, ΔT, are introduced in the communication channel between the master and slave device, it is not enough to simply reflect the measured interaction forces towards the user, not even considering the possible problems with stability, as in the ideal situation this would lead to:

$$\begin{aligned} \dot{q}_s(t+\Delta T) &= \dot{q}_m(t) \\ \tau_m(t+\Delta T) &= \tau_s(t) \end{aligned} \tag{4}$$

and a mismatch in the display of the interaction occurs which becomes worse with increasing time delays, ΔT. If the haptic feedback is introduced in e.g. a surgical telemanipulated robot system in order to safely interact with soft and delicate tissue then clearly this situation is not desirable as the tissue could be damaged before the imposed forces on the tissue are reflected to the user. Therefore a truly transparent system in the presence of arbitrary time delays should ensure:

$$\begin{aligned} \dot{q}_s(t+\Delta T) &= \dot{q}_m(t) \\ \tau_m(t) &= \tau_s(t+\Delta T) \end{aligned} \tag{5}$$

meaning that the behavior at both interaction ports is equal but delayed in time. As this requires an acausal system, true transparency cannot be achieved. The best achievable result requires a predictor at the side of the master device that predicts the future interaction forces between the slave device and the remote environment, which requires a local model of the remote environment. Several of such predictor based transparency enhancing algorithms have already been proposed in literature. Ching et al. [7] extend the wave-variable algorithm of Niemeyer [21] with a Smith Predictor to reduce the mismatch in time from (4) by correcting the incoming wave variable with the predicted future value of that variable without loss of passivity. An adaptive transfer function of the remote environment is used for this prediction.

Algorithms based on the haptic interaction with an (adaptive) local model of the remote environment in the time domain, generally referred to as impedance reflection, have also been proposed, e.g. by Hannaford [12], Mobasser et al. [20] and Tzafestas et al. [29]. A benefit of such an approach is also that the communicated values (setpoints and/or estimated parameter values) between the master and slave are not necessarily power conjugated. The master and slave system can in a sense be energetically decoupled. Therefore no "virtual" energy can be generated in the communication channel due to time delays. A passivity property is therefore not necessary to prevent instabilities due to that specific problem, but can still be desirable as added safety measure. A passivity property can safeguard the remote environment from excessive forces being applied by the slave robot when the estimated parameters are not correct as shown in simulation by Franken et al. [11]. A first attempt to extend such an impedance reflection based transparency algorithm with a passivity property is described by Kawashima et al. [15], where a time domain PO/PC is used to adapt the locally computed feedback force based on the actual measured, but delayed, interaction force to make the system passive.

A. Choice of control method to address transparency

The choice of control structure that achieves the desirable transparency in a bilateral telemanipulation system is influenced by several factors. These factors include, but are not limited to, the available sensors and *a priori* knowledge about the remote environment and the time delay which is present between the master and the slave. Assume that there exists some *a priori* knowledge about the remote environment and a force measurement at the interaction point between the slave device and the remote environment is available. Than based on the previous discussion when larger time delays are present, a sensible choice to obtain a high level of transparency would be an impedance reflection algorithm.

However, when the time delays are relatively short than the added complexity of parameter estimation might be dropped in favor of a simpler control approach as the time delays will have a less significant influence on the human perception [13]. Examples could be the Force Reflection controller as used by Ferrell [10], or the 4 channel control architecture by Lawrence et al. [17]. When no force measurement is available at the interaction point a position-position controller, as used by e.g. Mahvash et al. [19], could be used or a modified Force Reflection controller, as will be used in Section VI, can be applied.

For all these controllers, deviations from the assumed parameters can result in unwanted and even damaging behavior of the telemanipulation system. An example of such an unwanted effect due to a bounded workspace will be treated in Section VI. In the next section we will present a framework that allows any of these control approaches which address transparency to be extended with a passivity property to circumvent to those problems. As the passivity property is not inherent to those controllers, the achievable transparency will be reduced, but only to the minimum extend to make the system passive.

IV. Proposed Two-Layer Framework

Without making any assumptions about the type of controllers implemented we can formulate the control goals of a passive bilateral telemanipulation system as follows *The slave device needs to display the behavior desired by the user and the master device needs to accurately display haptic information about the remote interaction, unless this violates the passivity condition of the telemanipulation system*

In this light a natural layering in control objectives arises. First a desired control action needs to be computed so that the master and slave device display the desired behavior/information. Then a "check" is to be performed of how this desired action will influence the energy balance of the system. If passivity will not be violated it can directly be applied to the physical system, but if passivity is expected to be lost due to the desired control action it should be modified before application to the physical system. Such an approach allows for the highest possible transparency given that passivity needs to be preserved.

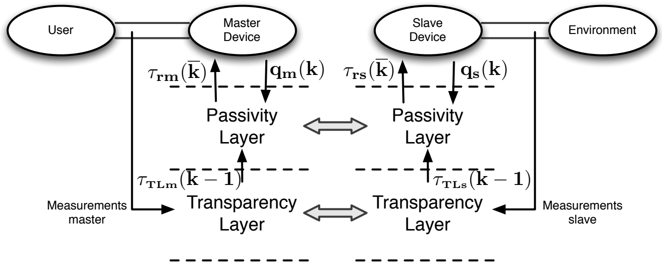

Fig. 3. **Two layer algorithm for bilateral telemanipulation.** The double connections indicate an energetic interaction.

This natural layering can also be directly transformed into a control structure. An algorithm that combines transparency and passivity in the discussed manner would be a two-layer structure as shown in Fig. 3. The *Transparency Layer* contains a control algorithm to display the desired behavior and obtain transparency. This can be any type of control algorithm discussed in Section III. In order to compute the desired control action $\tau_{TL*}(k)$ access is required to a specific part of the measured interaction data, e.g. forces F_*, positions q_*, and/or velocities $\dot{q}_*$, where m and s instead of $*$ indicate the master and slave, respectively. The *Passivity Layer* on the other hand monitors and enforces the energy balance of the system according to the algorithm discussed in Section V.

The benefit of the strict separation into layers is that the optimization of the strategy used to ensure optimal transparency does not depend on the strategy used to ensure passivity and vice versa. The only requirement we will place on the *Transparency Layer* is that it computes a desired torque, $\tau_{TL*}(k)$, to be applied to the master and slave system. This allows a wide variety of controllers to be implemented to address transparency, of which examples have been treated in Section III. Furthermore, as passivity does not have to be considered in the design of the *Transparency Layer* the whole range of control techniques which are non-passive, e.g. most filtering techniques, can be applied without problems.

Most schemes only incorporate a single, possibly mixed control layer and as a result a single two-way communication connection between the master and slave system exists. In this algorithm the passivity and transparency are dealt with in separate layers and therefore we can easily define two two-way communication channels between the master and slave system. One channel is used to communicate energy exchange related information between the *Passivity Layers* and the second channel to communicate information related to the desired behavior to be displayed by the devices between the *Transparency Layers*.

V. Passivity Layer

In this section we will discuss how the *Passivity Layer*, which was introduced in the previous section, works. The only thing that is needed to know about the *Transparency Layer* is that it generates desired torques to be applied to the master and slave devices.

Assume that the slave device is operating under position control of the master device. Every movement the slave device makes will have an associated energetic cost. This energy will therefore have to be present at the slave side at the moment the movement is executed. In order to maintain passivity according to (2), the same amount of energy will also have to be injected previously by the user at the master side. The same applies in reverse to energy extraction at the master side. This clearly requires the transport of energy between the master and the slave system.

Due to the time delays separating the master and slave device, it is not possible to simultaneously monitor the energy exchange at both interaction ports. This means that when the user commands a motion to be executed by the slave, it is not known *a priori* (exactly) how much energy is required by the slave device to execute that motion. To this end, the concept of a lossless energy tank is introduced in the *Passivity Layer* at both the master and the slave side, which can exchange energy. The level of these tanks can be interpreted as a tight energy budget from which controlled movements can be powered and which are continuously being replenished by the user at the master side, or if possible also at the slave side. If the energy level in the tanks is low, the controlled movements the device can make are restricted. An extreme situation occurs when the tank is completely empty in which situation the device cannot make a controlled movement at all. Passivity will always be maintained as all the energy present in the system has been injected by the user and each device cannot use more energy than is available in its energy tank. As indicated in Section III this approach can have a negative influence on the achievable transparency by the telemanipulation system. This decrease however is the absolute minimum required to maintain passivity.

Several other algorithms exist in literature that exploit the concept of transferring energy between the master and slave system to maintain passivity, e.g. the algorithms discussed by Artigas et al. [3] and Lee et al. [18] are good examples. Artigas et al. apply forward and backward passivity controllers to monitor and shape the energy transfer between master and slave and is centered around the transmission of power port variables. Lee et al. implement an algorithm where the setpoint of the damped spring coupling between master and slave position is updated in a passive manner. The update is restricted in magnitude by the available energy which is harvested from the damping action in the controller and stored in an energy tank. This algorithm contains similar elements as the approach in this paper, but unlike the two-layer algorithm it is specifically designed for a single type of controller. As we will show, the user in this approach directly makes the required energy available at the slave side regardless of the implemented controller for the desired behavior. This strict separation of energetic passivity and desired behavior is the key property of the two-layered approach.

In the following subsections the 4 components of the *Passivity Layer* at each side are discussed. As these operations are implemented at both sides in the same manner, subscripts indicating the master and slave have been omitted for now. In order to illustrate the working of the *Passivity Layer* a flow chart of all the steps in the *Passivity Layer* for either side of the telemanipulation system is presented in Fig. 6 at the end of this section.

A. Monitoring energy flows

At both the master and the slave side three energy flows can be identified

- an energetic interaction with the physical world,
- an energy flow to the other system,
- and an energy flow from the other system.

In the following we will show how each of these flows can be monitored and regulated in order to maintain passivity according to (2).

On the master and slave side the controllers will have to control two robots which will interact with the user and the environment. As the controller is implemented on some sort of embedded processing unit there is a connection between the continuous and discrete domain. Let $\dot{q}(t)$ represent the velocity vector of the actuators at time t and $q(k)$ the sampled position vector of the actuators at sample instant k. Consider the sample period $\overline{k}$ between sample instants $k-1$ and k, respectively. The torques exerted by the actuators on the robot during sample period $\overline{k}$ is given by $\tau_r(\overline{k})$, which is held constant during the sample interval. Thus, the energy exchange between the discrete time controller and the physical world, $\Delta H_I(k)$, during the sample interval between the time instants, $k-1$ and k is

$$\begin{aligned} \Delta H_I(k) &= \int_{(k-1)\Delta T_s}^{k\Delta T_s} \tau_r(\overline{k})\dot{q}(t) \\ &= \tau_r(\overline{k})(q(k)-q(k-1)) \\ &= \tau_r(\overline{k})\Delta q(k) \end{aligned} \tag{6}$$

where ΔT_s is the length of the sample period. Therefore, only a position measurement is required to determine the energy exchange, which was introduced by Stramigioli et al. [28]. As (6) only holds for impedance type devices (force out causality) we require the entire control structure, and thus the *Transparency Layer*, to adhere to this causality.

As far as energy exchange between the master and slave is concerned, we can consider the possibility to send energy quanta from the master to the slave when energy is available in the energy tank at the master side and vice versa. These quanta can be transmitted in the form of packets containing the amount of energy send. Several possible communication protocols for this energy transfer will be discussed in Section V-C. When such an energy packet arrives at the other side it is stored in a receiving queue. Both master and slave can implement completely asynchronously the following operations

$$H_+(k) = \sum_{i \in Q(k)} \bar{H}(i) \tag{7}$$

where $Q(k)$ represents the set of all energy packets present in the receiving queue of the master at sample instant k, $\bar{H}(i)$ represents the i^{th} energy packet. Therefore, $H_+(k)$ represents the total amount of energy which is present in the receiving queue at that time instant. At each sample instant k the receiving queue is emptied, meaning that the energy present in the receiving queue, $H_+(k)$ is added to the level of the energy tank. The exchanged energy with the physical world during the previous sample period is computed according to (6) and

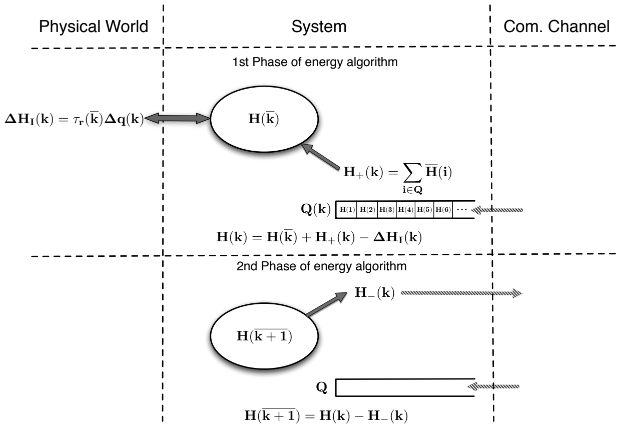

Fig. 4. **Processing energy flows.** The energy received out of the communication channel is added to the level of the energy tank and the energy exchanged with the physical world is subtracted from the the energy level (1st phase). An energy packet is transmitted to the other system (2nd phase). The double arrow indicates that the energy exchange with the physical world can both be positive and negative.

subtracted from the level of the energy tank. The energy level of the tank after these operations, $H(k)$ is

$$H(k) = H(\bar{k}) + H_+(k) - \Delta H_I(k) \tag{8}$$

where $H(\bar{k})$ is the energy level of the tank before the operations at sampling instant k. Based on the chosen energy transport protocol an energy quanta is determined to transmit to the other side. The amount of energy to be transmitted to the other side is at least limited to $H(k)$ to preserve passivity. This energy quanta, $H_-(t)$ is extracted from the energy tank. The energy which is left in the tank after these operations and thus available during the coming sampling period, $H(\overline{k+1})$ is

$$H(\overline{k+1}) = H(k) - H_-(k) \tag{9}$$

With this algorithm we are therefore able to compute the exact energy balance at each instant of time when sampling occurs and passivity according to (1) and (2) is guaranteed. The level of the energy tanks is the total energy present on the master and slave side, H_m and H_s respectively. The sum of all the energy packets in the communication channel gives the total energy present in the communication channel, H_c. A graphical representation of (6) through (9) is given in Fig. 4 indicating the two phases of the energy flow computation.

B. Energy tanks

In the previous section we have shown that there exist three energy flows at both the master and the slave side. The desired control actions determined by the *Transparency Layer* will influence the energy exchange with the physical world and thus how much energy is flowing into or out of the total system. In order to completely separate the *Passivity Layer* from the *Transparency Layer* a method is required to regulate the energy level independent of what the *Transparency Layer* is commanding.

To this end a Tank Level Controller (TLC) is defined in the *Passivity Layer* at the master side. The function of this TLC is to monitor the energy level of the local tank H_m with respect to a desired level H_d. Whenever $H_m(\overline{k+1})$ is lower than H_d at a sampling instant k the TLC is to extract a small additional amount of energy from the user during the coming sampling period $\overline{k+1}$ to replenish the tank. Using such a TLC will enable the control architecture to always recover from a deadlock situation in a passive manner when all the energy stored in the system is depleted.

An implementation of a TLC could be a modulated viscous damper, which applies a small opposing torque, τ_{TLC} to the user's movement to extract energy from the user into the energy tank

$$\begin{aligned}\tau_{TLC}(k) &= -d(k)\dot{q}_m(k) \\ d(k) &= \begin{cases}\alpha(H_d - H_m(\overline{k+1})) & \text{if } H_m(\overline{k+1}) < H_d \\ 0 & \text{otherwise}\end{cases}\end{aligned} \tag{10}$$

where α is a parameter that can be used to tune the rate at which energy is extracted from the user. If α is set to a high value and/or the user moves very fast an overshoot of the energy level in the system with respect to the desired energy level can occur. The value to be set for α and H_d is highly dependent on the device characteristics.

It is important to note that although this strategy might appear similar at first glance to the PO/PC strategy by Ryu et al. [23] its purpose is in fact very different. The PO/PC structure is used to dissipate virtually generated energy whereas in this application the damper is primarily activated to make energy available in the system. It should also be noted that the presented strategy is only one way to extract energy from the user and that the framework can accommodate many alternatives.

C. Energy transport

The TLC will make energy available at the master side. A protocol is now required to regulate the energy transfer between the master and slave system. A simple way to accomplish energy level synchronization between the master and slave system is for each tank to transmit a fixed fraction, β, of its energy level (when energy is available) to the other system. Assume the total system can be described as a discrete linear time invariant (LTI) system and there is no energy exchange between the slave and the robot. Then it can be proven mathematically that the energy levels in the two tanks will converge to the same value. The discrete LTI condition states that both system operate on the same sampling frequency, that they are synchronized, that the time delay is constant and such that at each moment in time a constant number of packages are present in the communication channel. When the energy tanks and each package is represented as a discrete state, the eigenvalues of the system can then be computed to be given by

$$z^{2+n} + 2\beta z^{1+n} + (1 - 2\beta + \beta^2)z^n - \beta^2 = 0 \tag{11}$$

where n is the number of packages in the communication channel. For $0 < \beta < 1$ all eigenvalues are stable indicating that the system will converge to a steady state, albeit that the settling time can be extremely large for large n and/or β. The steady state of the system dictates that the value of the incoming and outgoing energy packet will have to be equal.

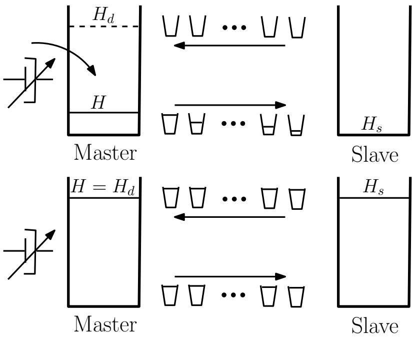

Fig. 5. **Illustration of level synchronization between energy tanks.** The modulated damper extracts energy from the master and the implemented energy transport protocol forces the energy level in the master and slave tank to synchronize.

Therefore the level of both tanks has to be equal. For $\beta = 1$ all eigenvalues are on the unit circle which indicates a purely oscillatory system and all energy in the system will bounce back and forth between the master and the slave.

Due to the TLC and the absence of initially stored energy, the convergence level of both tanks will be the set desired level for the master tank. This is illustrated in Fig. 5, where the energy tanks are depicted as water barrels, each packet as a glass, and the energy quanta of each packet as the water level inside the glass.

This protocol however implies that energy quanta are being exchanged continuously between the master and slave system. This indicates that the user besides filling both tanks with energy will also have to saturate the communication channel with energy packets. Assume again that the system is LTI and operating in steady state (no energy exchange with the physical systems). The total amount of energy present in the communication channel in steady state operation, $\overline{H}_c$ can be expressed as

$$\overline{H}_c = n\beta H_d \tag{12}$$

The total amount of energy in the communication channel can therefore become quite large for larger time delays.

More complex transfer protocols can be implemented, each with its own specific benefits and drawbacks. A transfer protocol that is still simple, but does not have constant energy exchange between master and system, is to change the positive energy quanta being send from the slave to the master into energy requests. The transfer protocol at the master side will then send an initial amount of energy to the slave side to fill the tank and the slave will only send energy requests to the master when the level in the tank drops below that desired level due to energetic interaction with the physical world. The master side records the total energy request by the slave and will send a percentage of its available energy towards the slave until the energy request is satisfied. A drawback of this protocol is that the energy request and the subsequent delivery are separated in time by the round trip time of the communication channel. This will have to be taken into account when selecting the desired energy level of both tanks.

Now assume that an *Impedance Reflection* algorithm is implemented in the *Transparency Layer*. As the interaction forces are now predicted at the master side, it is possible to record the energy exchange and transmit this energy directly to the slave side. The energy tanks are then solely used to deal with model inaccuracies and the time delays in the communication channel.

The above shows that although the *Transparency Layer* and *Passivity Layer* are completely separated and can be tuned independently, the energy transfer protocols that can be implemented in the *Passivity Layer* are restricted by the chosen implementation of the *Transparency Layer*.

D. Saturation of controlled effort

The *Transparency Layer* computes a controlled torque, $\tau_{TL}(k)$ at each side, to be applied to the master and slave device during sampling period $\overline{k+1}$ to display the desired behavior. At both sides the *Passivity Layer* is used to limit the torque, $\tau_{PL}(k)$ with respect to what the *Transparency Layer* at that side requests in order to maintain passivity.

The fundamental limit which the *Passivity Layer* enforces is that when no energy is available at a side, the controlled effort that can be applied during the coming sampling period is zero

$$\tau_{max1}(k) = \begin{cases} 0 & \text{if } H(\overline{k+1}) \leq 0 \\ \tau_{TL}(k) & \text{otherwise} \end{cases} \tag{13}$$

Between two samples there will be no way to detect, act upon, and therefore prevent a possible loss of passivity. If we know that the interval before a next sample will last ΔT_s seconds, the available energy is $H(\overline{k+1})$, and the worst case velocity (highest in module) of the device for the coming sample period $\overline{k+1}$ is estimated to be $\dot{q}_{max}(\overline{k+1})$, an upper bound can be estimated for the value of the applied torque, $\tau_r(\overline{k+1})$, to which it should be constrained not to lose passivity. This tries to enforce

$$\Delta T_s \tau_r(\overline{k+1}) \dot{q}_{max}(\overline{k+1}) \leq H(\overline{k+1}) \tag{14}$$

so

$$\tau_{max2}(k) = \frac{H(\overline{k+1})}{\Delta T_s \dot{q}_{max}(\overline{k+1})} \tag{15}$$

An additional saturation method that can be useful is for instance to define a mapping, $g(H(\overline{k+1}))$, from the current available energy in the tank to the maximum torque that can be applied. Meaning:

$$\tau_{max3}(k) = g(H(\overline{k+1})) \tag{16}$$

This mapping can be designed in such a way that a safe interaction in complex situations is guaranteed. Assume for instance that the slave is stationary but grasping an object in the environment and as a result no energy is exchanged between the slave and the environment. If at some point in time a loss of communication occurs, it could be desirable that the slave will smoothly release the object not to damage it by a continuous application of force. If the energy transfer protocol between master and slave is designed such that the energy level in the tank is decreasing when communication is lost, the energy level in the tank will drop even if no energy is exchanged with the environment. This means that the force exerted on the object in the environment will decrease over time and the storage function can be used to shape the manner

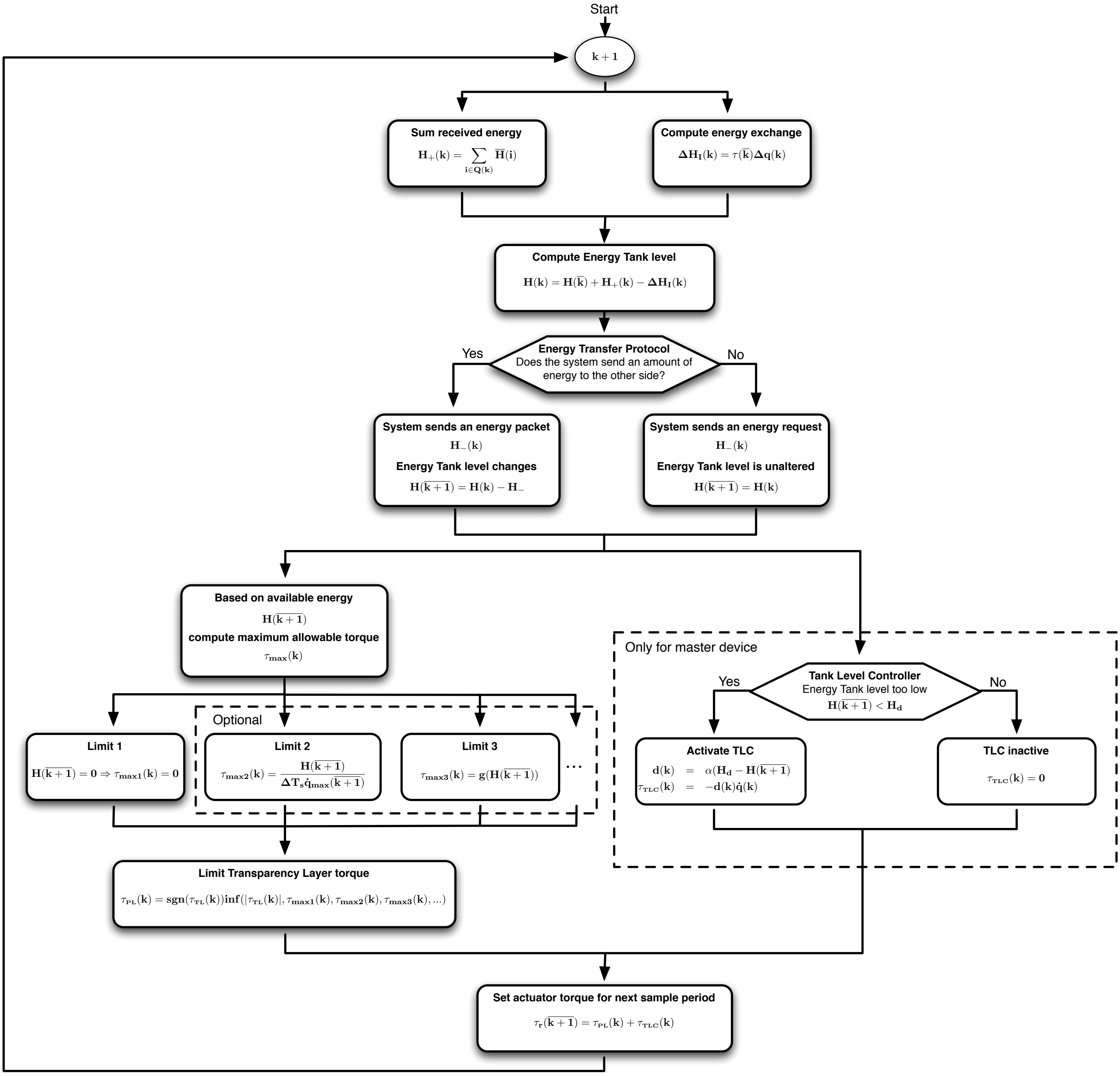

Fig. 6. **Workflow of the complete *Passivity Layer* at either side of the telemanipulation system**. This workflow assumes that $\tau_{TL}(k)$ has already been computed. First the incoming energ flows are evaluated. Afterwards the energy flow towards the other system is computed and handled. Finally the limiting values for the torque originating from the *Transparency Layer* are computed. For the master system the Tank Level Controller is activated if necessary. The limited *Transparency Layer* torque and TLC torque combined form the feedback force to the user for the coming sampling period.

in which it is released. This is possible for the simple open loop transfer protocol as discussed by Franken et al. [11].

The maximum allowable torque, $\tau_{max}(k)$, is the lower bound of all the various limiting/saturation functions

$$\tau_{max}(k) = inf(\tau_{max1}(k), \tau_{max2}(k), \tau_{max3}(k), ...) \tag{17}$$

where ... indicate other limiting/saturation functions that can be implemented. These additional functions for instance could be beneficial for a specific device, environment, and/or task to be executed. Note that all limiting functions except τ_{max1} are optional, although the exclusion of τ_{max2} and/or τ_{max3} can result in unwanted switching behavior of the *Passivity Layer*.

The torque, $\tau_{PL}(k)$, which is the bounded version of the torque, $\tau_{TL}(k)$, requested by the *Transparency Layer* is computed as

$$\tau_{PL}(k) = sgn(\tau_{TL}(k))inf(|\tau_{TL}(k)|, \tau_{max}(k)) \tag{18}$$

At the master side $\tau_{TLC}(k)$, which results from the modulated damper of (10), is superimposed on $\tau_{PL}(k)$ before application to the device. So the final torques to be applied to the robotic devices, $\tau_r(\overline{k+1})$ during the sample period $\overline{k+1}$ are

$$\begin{aligned} \tau_{rm}(\overline{k+1}) &= \tau_{PLm}(k) + \tau_{TLC}(k) \\ \tau_{rs}(\overline{k+1}) &= \tau_{PLs}(k) \end{aligned} \tag{19}$$

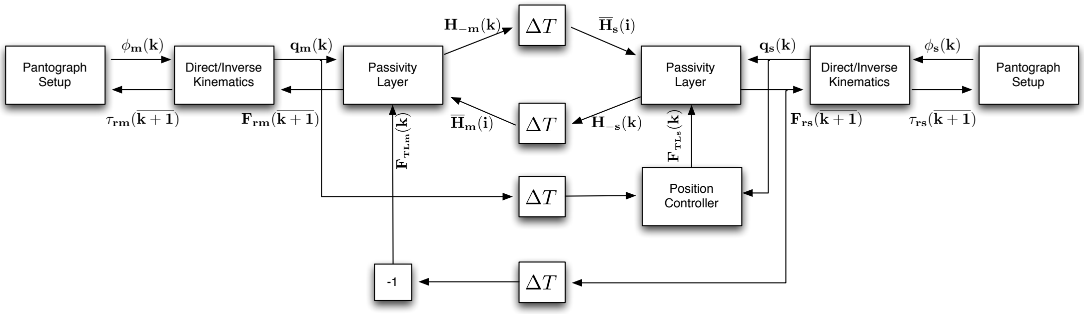

Fig. 7. **Overview of a complete implementation of the two-layered framework**. The implemented *Transparency Layer* is a modified Force Reflecting controller.

where the added subscripts m and s indicate the master and slave, respectively.

VI. Implementation

In this section a full implementation of the theory of Sections IV and V will be combined and used in an experimental setup. The experimental setup, Fig. 8 consists of two Pantograph Mk-II devices developed by Campion et al. [6]. Two DC motors (Maxon RE25), without gearbox, controlled by motor amplifiers (Maxon ADS 50/5) operating in current control mode, power each device. The position of each motor is measured with an incremental encoder (Gurley R119) with 65k pulses per rotation. Each device contains an M-ATX motherboard with an Intel E4500 dual core processor running a local embedded controller under real-time Linux. The devices are communicating over a TCP/IP connection through a local router. Artificial time delays are induced by a first-in-first-out shift register in the control software of the master device. The real-time executable code for the controllers is generated directly from the simulation models of the setup developed using the program 20sim [9] using the internal automatic code generation. This executable code is configured for the specific target, uploaded and managed on the targets through a TCP/IP connection using the 4C toolchain [8].

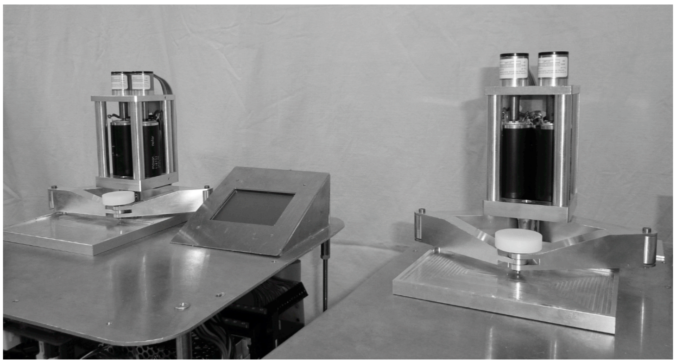

Fig. 8. Photo of the experimental setup consisting of two Pantograph Mk-II devices with separate embedded controllers.

The Panthograph Mk-II is a device with a closed kinematic chain and a two-dimensional Cartesian workspace. The degrees of freedom of the interaction point are modelled as independent and the control action of the two-layer control algorithm is defined to apply at the interaction point in the Cartesian space. This means that a mapping from and to the joint space occurs before and after each control iteration. A complete block diagram of the implemented controller is depicted in Fig. 7.

A. Transparency Layer

As controller to address transparency we have implemented a modified Force Reflecting controller, Fig. 7. The controller at the slave side controls the position of the slave to follow the received position of the master device and the master controller applies a received force to the actuators of the master device. The controller is modified in the sense that there is no force measurement available at the interaction point on the setup and therefore a true Force Reflecting controller, where the measured interaction force between the slave robot and the environment is displayed by the master device, cannot be implemented. Instead we transmit the inverted force applied by the actuators of the slave device to the master. In this situation the feedback force to the user contains the environment force, but the user also experiences the slave device dynamics in series with the stiffness of the position controller at the slave side.

A PD-controller is used to control the position of the slave device to the received position of the master device

$$\tau_{TLs}(k) = k_p(\bar{q}_m(k) - q_s(k)) - k_d\dot{q}_s(k) \tag{20}$$

where $\bar{q}_m(k)$ is the received (time-delayed) position of the master device. A second order low-pass Butterworth filter is applied to the velocity estimate obtained by differentiation of the computed position to reduce noise.

The controller at the master side sets the force received from the slave as desired control action

$$\tau_{TLm}(k) = \bar{\tau}_s(k). \tag{21}$$

where $\bar{\tau}_s(k)$ is the received (time-delayed) inverted force applied by the slave device.

B. Passivity Layer

The *Passivity Layer* is implemented as discussed in Section V. The implemented saturation functions implemented at both the master and slave side are (13) and (16). The mapping $g(H(\overline{k+1}))$ associates a linear spring with stiffness k_g with the level of each energy tank to saturate the control effort

$$g(H(\overline{k+1})) = \sqrt{2k_g H(\overline{k+1})}. \tag{22}$$

C. Experimental Results

In this section we will compare the performance of the controller in the *Transparency Layer* with and without the *Passivity Layer* to demonstrate the added benefit of the *Passivity Layer*. The parameters used during these experiments are listed in Table I. A fixed time delay, ΔT, is implemented in all experiments. The parameters of the position-controller at the slave side, k_p and k_d, are chosen relatively small. A stiff controller causes high frequent oscillations of the device due to the low mass mass and low internal friction.

Parameter	Value	Parameter	Value
H_d	0.005 J	α	1000
β	0.001	k_g	500 N/m
k_p	10 N/m	k_d	2 Ns/m
ΔT	0.1 s		

TABLE I
PARAMETER VALUES USED IN THE SIMULATION

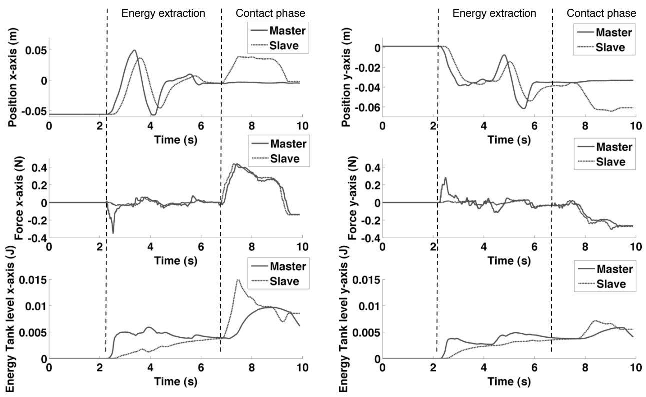

Fig. 9. **System response of the two layered controller**. The change from freespace motion, in which energy extraction takes place, to the contact phase occurs at approximately $t = 7s$.

In the first experiment the system moves initially in free space after which a contact phase is induced in which the user grabs both the master and slave device. Fig. 9 shows the system response of the two-layered controller during this experiment. The slave system moves around in free space until $t = 7s$. An opposing force is initially applied to the movements of the user to extract the required energy to fill the tanks and saturate the communication network. This phase last approximately until $t = 6s$. At $t = 7s$ the position of the master is kept constant and the slave device is first moved along the positive x-axis, then along the negative y-axis and finally back to the position of the master device along the x-axis. A good (delayed) correspondence in the transmitted force by the slave and the force applied by the master is visible after $t = 6s$ indicating a minimal influence of the *Passivity Layer* during this experiment.

To show the added benefit of the *Passivity Layer* we now consider a situation in which the user is not touching the master device and an impulsive disturbance force is applied to the slave device. This extreme situation is considered as the forces which are applied by the position controller at the slave are limited and the additional damping by the operator is enough to keep the system stable in this situation.

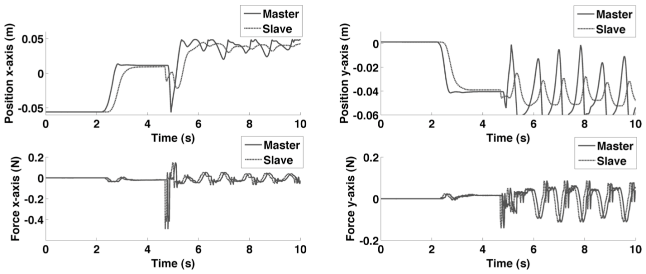

Fig. 10. **System response without the *Passivity Layer* to a disturbance at the slave side at $t = 5s$.** The system enters a non-passive limit cycle.

Fig. 10 shows the system response when the *Passivity Layer* is absent. The impulsive disturbance force is applied to the slave device at approximately $t = 4.5s$. it is clearly visible that due to this disturbance the system enters a sort of limit cycle in which the master system continuously hits against the boundaries of its workspace. Clearly this is a non-passive system as no energy injection takes place and both the master and slave system exhibit sustained movements.

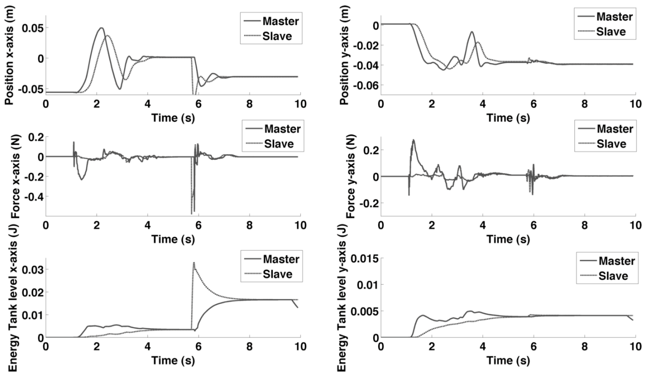

Fig. 11. **System response using the *Passivity Layer* to a disturbance at the slave side at $t = 5.7s$.** It is clearly visible that the system now remains stable and does not enter the limit cycle visible in Fig. 10.

Fig. 11 shows the system response to a similar disturbance force when the *Passivity Layer* is present. It is clearly visible that the master device moves only a little due to the impulsive force, at $t = 5.7s$. The complete system remains stable and reaches a new equilibrium position within $1s$. In order to show how the *Passivity Layer* influences the response in this situation a close-up of the signals around the application of the disturbance is given in Fig. 12. As the disturbance does not affect the y-axis only the response of the x-axis is shown in Fig. 12.

Due to the disturbance force, the slave is pushed away from the position of the master system. Therefore the position controller at the slave side generates a "large" force to restore the position of the slave system to that of the master system. This force is transmitted to the master system, where it is applied to the master device. As the user is not touching the master device, it will move in the direction of the applied force. Energy is spend to perform this movement and as such the energy level of the tank at the master side decreases. Two things are now activated in the *Passivity Layer*

- due to the decrease of the energy level the maximum allowable torque from the *Transparency Layer* is decreased

according to (22),
- the TLC is activated and additional damping is applied to the system.

Therefore, the force which is subsequently applied to the master system is much lower than the force transmitted by the slave system, as indicated in Fig. 12. The initial decrease in available energy visible in Fig. 12 triggers the mechanisms of the *Passivity Layer*, which keep the system response stable. After this initial decrease and the resulting stabilizing actions, the energy level in the tank starts to rise again as kinetic energy from the master device is extracted back into the tank and part of the additional energy injected at the slave side is transferred to the master side due to the implemented energy transfer protocol.

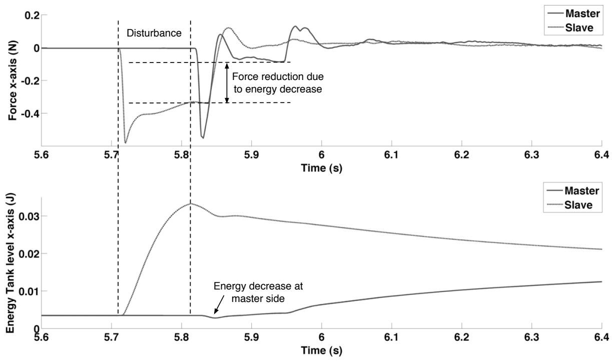

Fig. 12. **Closeup of the stable system response.** Indicated are the disturbance at the slave side, the decrease of available energy and the subsequent lowering of the applied force by the *Passivity layer* at the master side.

The presented experimental results of Fig. 10 and 11 have a somewhat hypothetical nature as the user is not touching the master device. However, this constraint is due to the limitations of the setup. A similar performance increase will occur in an upscaled experiment with more powerful devices, a stiff position control of the slave, and hard contacts in the remote environment.

VII. Conclusions and Future Work

In this paper a new framework for bilateral telemanipulation was presented. The two-layered approach allows the combination of passivity and transparency in a very intuitive manner. Using this framework any control architecture with an impedance causality can be implemented in a passive manner. Furthermore the framework contains a lot of design freedom. Especially the energy transfer protocol and saturation functions can be designed and optimized for a specific device, environment, and/or task. The presented experimental results show how the two-layered implementation of a modified Force Reflecting controller removes unwanted oscillations which are generated due to a disturbance at the slave side, the time delays in the communication channel, and the bounded workspace.

As this framework contains a lot of design freedom, future work will focus on the systematic implementation of the various design options and tuning of the parameters in the *Passivity layer*.

The passivity layer presented in this paper makes the system passive with respect to the actuators at both the master and slave side. All the energy spend by the actuators at the slave side is extracted from the user. This means that transparency is adversely influenced by friction in the slave device. Therefore future research will also be directed to friction compensation techniques to extend this approach to manipulators with high internal friction.

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