PHYSICAL HUMAN-ROBOT INTERACTION

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

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Paper

Bilateral Telemanipulation With Time Delays: A Two-Layer Approach Combining Passivity and Transparency

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***Abstract*—In this paper, a two-layer approach is presented to guarantee the stable behavior of bilateral telemanipulation systems in the presence of time-varying destabilizing factors such as hard contacts, relaxed user grasps, stiff control settings, and/or communication delays. The approach splits the control architecture into two separate layers. The hierarchical 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 sides so that information related to exchanged energy is completely separated from information about the desired behavior. Furthermore, the proposed implementation does not depend on any type of assumption about the time delay in the communication channel. By complete separation of the properties of passivity and transparency, each layer can accommodate any number of different implementations that allow for almost independent optimization. Experimental results are presented, which highlight the benefit of the proposed framework.**

***Index Terms*—Bilateral control, passivity, stability, telemanipulation, time delay, transparency.**

I. Introduction

A TELEMANIPULATION chain is composed of a user, a master system, a communication channel, a slave system,

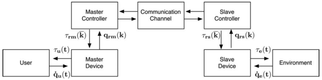


Fig. 1. Schematic overview of a bilateral telemanipulation chain. Both the master and slave devices are impedance-type displays. The information exchanged over the communication channel depends on the implemented controller. τ_* and $\dot{q}_*$ represent torques/forces and velocities, respectively. The subscripts u, rm, rs, and e indicate the interaction between the user and the device, the actuators of the master device, the actuators of the slave device, and the interaction between the slave device and the environment, respectively.

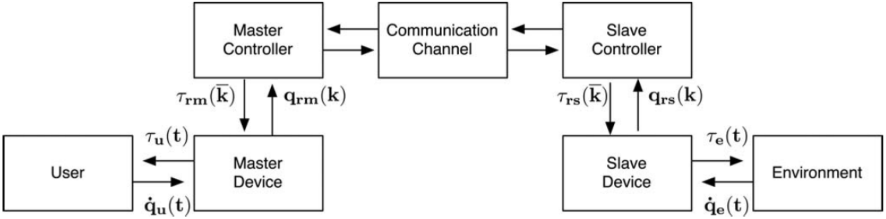
teraction between the slave system and the remote environment; see Fig. 1. Such a force feedback is likely to increase the performance of the user with respect to effectiveness, accuracy, and safety in many practical applications, e.g., for robotic surgery, as discussed by Bethea *et al.* [1].

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 direct interaction with the environment [2]. Many different control algorithms have been proposed in the liter-

Outline

- presence of time-varying destabilizing factors such as hard contacts, relaxed user grasps, stiff control settings, and/or communication delays
- two-layer approach: The hierarchical top layer is used to implement a strategy that addresses the desired transparency, and the lower layer ensures that no “virtual” energy is generated
- no assumption about the time delay in the communication channel
- each layer can accommodate any number of different implementations that allow for almost independent optimization

Block diagram



- $\tau_\star$ torques/forces
- $\dot{q}_\star$ torques/forces
- *m* master, *s* slave, *u* user, *e* environment, *r* reference
- *k* discrete-time, *t* continuous-time
- $\bar{k}$ sample interval between the sampling instant $k-1$ and k

Criteria

1. TRANSPARENCY: how well the complete system is able to convey to the user the perception of direct interaction with the environment

2. STABILITY: $\rightarrow$ passivity

PROBLEM: Passivity-based approaches are stable in the presence of (even significant) time delays, but the level of transparency that could be obtained is (sometimes) not good enough

OBSERVATION: many control architectures designed for transparency do not fit within passivity-based methods

New control framework for passive bilateral telemanipulation

HIERARCHICAL TWO-LAYER APPROACH:

1. transparency layer: a control structure is 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 the user is executing

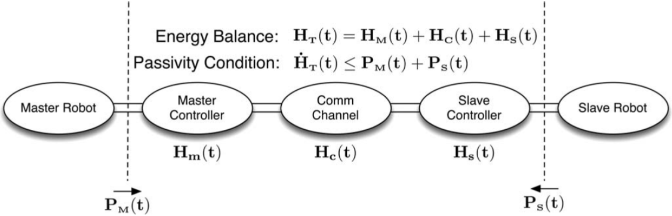
2. passivity layer: given the command computed by the transparency layer, this layer contains an algorithm to maintain passivity of the total system.

KEY ELEMENTS: two communication *energy storage tanks* from which the motions of both the slave and the master are powered.

Assumptions

(A1) impedance causality for both the master and slave systems (i.e. velocities as input and forces as output to the robotic devices)

(A2) initial storage energy equal to 0



Passivity condition

$$H_T(t) \geq 0$$

or (with respect to the interconnection with the physical systems)

$$\dot{H}_T(t) \leq P_M(t) + P_S(t)$$

where $P_M(t)$ and $P_S(t)$ are the power flowing from the master robot into the master controller, and from the slave robot into the slave controller.

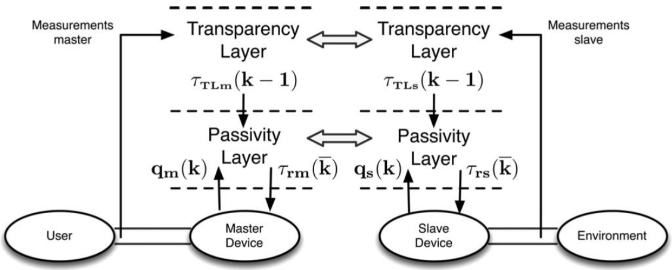
Goal

GOAL: "The slave device needs to display the behavior desired by the user, and the master device needs to accurately provide force feedback about the interaction between the slave device and the remote environment, unless this behavior violates the passivity condition of the telemanipulation system."

In other words:

- compute the desired command actions
- check the energy balance
- eventually modified the desired command actions

Control structure



REQUIREMENT: the implemented controller (transparency layer) computes forces to be applied to the master and slave devices

OBSERVATION 1: passivity does not have to be considered in the design of the transparency layer

OBSERVATION 2: there are two two-way communication channels:
(1) energy-exchange-related information, and (2) desired behavior

Passivity layer

FACT 1: Due to the time delays, it is not possible to simultaneously monitor the energy exchange at both interaction ports

FACT 2: 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

$$\downarrow$$

The level of these tanks can be interpreted as a tight energy budget from which controlled movements can be powered and which are being replenished by the user at the master side when necessary or if possible/desired also at the slave side

Four components:

1. Monitoring Energy Flows
2. Energy Tanks
3. Energy Transport
4. Saturation of Controlled Torque

Contributions:

- *energy exchange with the physical world*

  Let k be the sampling instant and $\bar{k}$ be the sample period (between $k-1$ to k). The energy exchange between the discrete-time controller and physical world is

$$\begin{aligned}\Delta H_I &= \int_{(k-1)T_s}^{kT_s} \tau_r(\bar{k})\dot{q}(t)dt = \tau_r(\bar{k})\int_{(k-1)T_s}^{kT_s} \dot{q}(t)dt = \\ &= \tau_r(\bar{k})(q(k)-q(k-1)) = \tau_r(\bar{k})\Delta q(k)\end{aligned}$$

- *energy flow to/from the other side*

  These quanta can be transmitted in the form of packets that contain the amount of energy send. Energy stored in the receiving queue

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

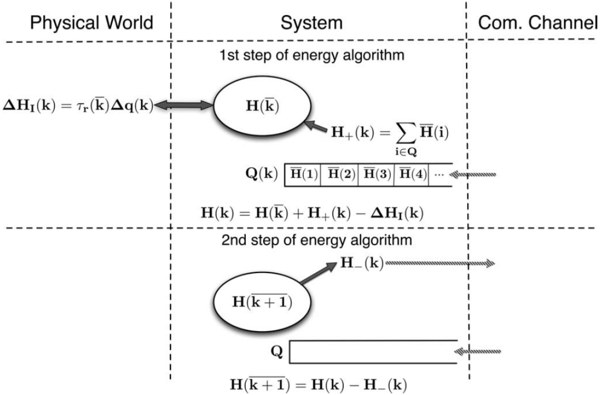
  where $Q(k)$ represents the set of all energy packets that are present in the receiving queue of the master at sample instant k, and $\bar{H}(i)$ represents the i-th energy packet.

Energy level of the tank:

$$H(k) = \underbrace{H(\bar{k})}_{past} + \underbrace{H_+(k)}_{received} - \underbrace{\Delta H_I(k)}_{used}$$

Based on the chosen energy transport protocol, an energy quantum $H_-(k)$ is determined to transmit to the other side

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



Monitoring Energy Flows

The above computations should be done to compute H_M at the master side and H_S at the slave side

The change of energy $\Delta H_C(k)$ in the communication channel at the sample instant k can be expressed as

$$\Delta H_C(k) = H_{-M}(k) - H_{+M}(k) + H_{-S}(k) - H_{+S}(k)$$

Total energy

$$H_C(k) = \sum_{i=1}^{k} \Delta H_C(i) = \sum_{i=1}^{k} [H_{-M}(i) - H_{+M}(i) + H_{-S}(i) - H_{+S}(i)]$$

Due to the time delays

$$\begin{aligned} H_{-S}(i) &= H_{+M}(i + d_{SM}(i)) \\ H_{-M}(i) &= H_{+S}(i + d_{MS}(i)) \end{aligned}$$

with $d_*(i) \geq 0$.
This means

$$\begin{aligned} \sum_{i=1}^{k} H_{-S}(i) &\geq \sum_{i=1}^{k} H_{+M}(i) \\ \sum_{i=1}^{k} H_{-M}(i) &\geq \sum_{i=1}^{k} H_{+S}(i) \end{aligned}$$

and so

$$H_C(k) \geq 0$$

i.e., the communication channel can never produce energy.

Energy Tanks

To completely separate the passivity layer from the transparency layer, a method is required to regulate the energy level independently of what the transparency layer is commanding

A tank level controller (TLC) is defined in the passivity layer at the master side

GOAL: The function of this TLC is to monitor the energy level of the local tank $H_M(\overline{k+1})$, 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 extracts a small additional amount of energy from the user during the next sampling period $\overline{k+1}$ to replenish the tank.

HOW: the TLC is a modulated viscous damper, which applies a small opposing torque $\tau_{TLC}(k)$ to the user's movement to extract energy from the user into the energy tank

$$
\begin{aligned}
\tau_{TLC}(k) &= -d(k)\dot{q}_m(k) \\
d(k) &:= \begin{cases} \alpha(H_D(k) - H_M(\overline{k+1})), & \text{if } H_D(k) > H_M(\overline{k+1}) \\ 0, & \text{otherwise} \end{cases}
\end{aligned}
$$

where the tuning parameter α is strictly positive.

Energy Transport

Energy Transport: regulate the distribution of energy through the system

- **Simple Energy Transfer Protocol** (SETP)

  Both the master and slave systems transmit a fixed fraction β of its energy level (when energy is available) to the other system. This will cause the total energy in the system to be distributed over the master and slave systems and the communication channel

  Problem: the total amount of energy in the communication channel can be large

$$\bar{H}_C = 2d\beta H_D$$

  where d is the delay and H_D is the equilibrium point

- **Advanced Energy Transfer Protocols**

  Ex 1. send energy when required: request-delivery protocol. Drawback: round-trip time

  Ex 2. suppose that an impedance reflection (IR) algorithm is implemented (i.e. the feedback force to the user is predicted based on a local, possibly adaptive, model of the remote environment)

  Then: 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

Saturation of Controlled Torque

$\tau_{TL}(k)$: controlled torque computed by the transparency layer (master/slave side)

$\tau_{PL}(k)$: limited torque computed by the passivity layer based on $\tau_{TL}(k)$ (master/slave side)

This torque:

- is computed knowing the energy level in the tank $H(\overline{k+1})$
- will be applied during the sample period $\overline{k+1}$

Upper bounds:

$$\begin{aligned} \tau_{max1} &= \begin{cases} 0, & \text{if } H(\overline{k+1}) \leq 0 \\ \tau_{TL}(k), & \text{otherwise} \end{cases} \\ \tau_{max2} &= \frac{H(\overline{k+1})}{\dot{q}(\bar{k})T_s} \qquad [\dot{q}(\bar{k}) \text{ is an approximation}] \end{aligned}$$

and so

$$\tau_{PL}(k) = \mathrm{sgn}(\tau_{TL}(k)) \min\{|\tau_{TL}(k)|, \tau_{max*}\}$$

Saturation of Controlled Torque

Torque at the master side

$$\tau_{rm}(\overline{k+1}) \quad = \quad \tau_{PLm}(k) + \tau_{TLC}(k)$$

Torque at the slave side

$$\tau_{rs}(\overline{k+1}) \quad = \quad \tau_{PLs}(k)$$


Project

PROJECT – Assignment # 7

To do

- Implement the Tank-based bilateral teleoperation architecture for the
  1. Force-Position case
  2. Position-Position case
- Compare positions, velocities, forces, commands in free motion and in contact
- Create another simulink model and (a) add the measurement noise to the position/force signals, and (b) estimate velocities from positions (if needed)