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Position Drift Compensation in Time Domain Passivity based Teleoperation

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***Abstract*— The Time Domain Passivity Control Approach is gathering interest in the robotics field. Simplicity and flexibility and the fact that system design emerges from ideal cases make it a powerful stability tool for teleoperation systems. Communication time delay is an inherent attribute of nearly every realistic teleoperation system. Unless the communication channel guarantees transmission delays of less than the system sampling time, the delay must be considered in the design in order to guarantee stability and satisfy a desired degree of performance. In previous work it has been shown how passivity can be considered in the time domain and how control rules are derived from it in order to dissipate the energy produced by the delayed communication. However, a weakness of these approaches is the impossibility of observing the exact amount of energy stored in the communication channel due to its delayed nature. A passive estimation is therefore needed which outcomes in an over-dissipation and in turn impacts on transparency. In constrained communications over-dissipation may become apparent in the form of a non-neglectful position drift between master and slave. This paper tackles the over-dissipative behavior of the Passivity Controller by resembling the energetic behavior of an ideal communication, i.e. where no delay is present and the transmission is lossless. Thus, the communication channel is not just controlled to be passive, as has been the case up to now, but also lossless. Energy can be dissipated to prevent activity, but activity can be also produced to prevent dissipative behaviors. The approach is sustained with experimental results.**

I. INTRODUCTION

Telepresence is the feeling of existing in a location other than the one where the individual actually is, and the capacity of interacting in it. Feelings of being present somewhere else can be artificially produced to individuals by using a set of technologies which capture sensorial data from the distant reality, such as vision, audio or tactile information, and reproduce it locally by means of a Man-Machine-Interface (MMI). Interaction between individual and distant environment takes place by conveying individual's actions and reactions, such as spoken commands or manipulation actions, to the distant location. A robot manipulator in the remote environment reproduces the individual's commands.

The haptic channel is specially challenging due to its real time control requirements, distributed nature through often constrained communication channels and the inclusion of elements, such as the human operator and the environment, which are hard to model. After stability, the main goal of a telepresence system is transparency, meaning in its ideal form that the user is not able to distinguish remote presence to local presence.

The pursuit of stability often compromises transparency once the system constraints are established. This trade-off is a common denominator in every single approach dealing with bilateral control [1], [2]. In this sense, one of the most accounted issues in haptic telemanipulation scenarios is the time delay that affects the communication channel. This often leads to the design of conservative control laws in order to achieve the unconditional system stability, which in turn often results in system transparency losses.

One of the most remarkable approaches in dealing with time-delayed telepresence is the passivity criteria. Passivity is a sufficient condition for stability and provides the nice feature that system passivity is granted by passivity of all its subsystems. Moreover, passivity of a system can be analyzed without an exact knowledge of its contents. It is therefore a useful tool which can be used as a design rule in those systems which incorporate communication elements, since, as it has been shown [3], delay is source of activity. A good example are the Scattering transformation [3] and its Wave Variables formulation [4], which has become the classical approach in delayed teleoperation. [5] tackles varying delay communications within the wave variables framework. Further, [6], deals with the steady state position error of wave variables and presents a method for compensating it.

Most approaches that deal with delayed teleoperation end up using conservative techniques to detriment of the transparency and usability of the teleoperation system. In order to ensure passivity of the system the bilateral control often introduces elements which dissipate more energy than the strictly needed to compensate the energy introduced by the delayed communications. The time domain passivity control approach (TDPA) [7], [8] presents some advantages which have gathered attention within the haptics and telerobotics fields. First, the employment of a variable damping rather than fixed ones allows less conservative designs; Second, the fact that the design is performed considering the ideal case, i.e. no time delay in the communication channel and perfect data transmission; And third, only the observed active energy is dissipated. Both translate into a simple and flexible design aimed at transparency rather than at passivity. Previous work [9]–[12], have shown feasibility and good results.

Depending on the causality of the Passivity Controller (PC), i.e. admittance or impedance, energy is dissipated by modifying velocity or force respectively on the time domain. If too much energy is dissipated the system may outcome

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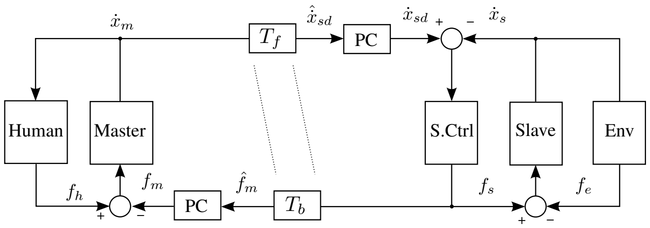

Fig. 1: Block diagram of a P-F teleoperation architecture.

in different transparency losses. This paper investigates the reasons why an exact observation of the energy flow is not possible, but rather the need of a passive estimation, and how much over-dissipation takes place in the process. In the admittance configuration, over-dissipation translates in position drift. This article analyzes this issue and proposes a method to reduce the drift to virtually null without violating system passivity conditions. Inspired by the characteristics of an ideal communication, i.e. zero delay and lossless energy exchange, the PC for time delayed teleoperation, [9], is reformulated in order to emulate the behavior of a lossless, ideal communication network, rather than assuring classical passivity.

The paper is structured as follows: Sec. II presents the teleoperation system under study and reviews the TDPA for delayed teleoperation. Sec. III investigates the causes of over-dissipation and the origin of the position drift. The main approach is presented in Sec. IV. Feasibility and effectiveness of the proposed method is then evaluated in an experimental setup, in Sec. V. The paper concludes and gives future directions in Sec. VI.

II. BACKGROUND

A. System Description

The analysis will be based on the scheme shown in Fig. 1. This is a typical Position - Force (PF) architecture, where current master velocity is sent toward the slave side, where it becomes the reference input for a PD controller which computes the force or torque to move the slave robot. This force is as well fed back to the master, where, in its bare configuration, it becomes the force input to the master haptic device.

B. Time Domain Passivity Control for Delayed Teleoperation

Briefly, the TDPC has two main elements: the Passivity Observer (PO), which monitors the energy flow of a network in the time domain; and the Passivity Controller (PC), which acts as a variable damper to dissipate active energy observed by the PO, i.e. introduced by the network. The communication channel becomes active due to the inclusion of time delay [3]. Formulation, proof and performance analysis of the TDPC can be found in [7], [8].

This section reviews how the equations used by the POs for a 2-port delay network are derived and underlines two steps in the process which are responsible position drift.

The energy stored in a communication channel with time delay is given by:

$$E^{Ch}(t) = E^M(t) + E^S(t), \quad \forall t \geq 0, \tag{1}$$

where E^M and E^S are left and right port energy contributions. The passivity condition for this 2-port network (see Fig. 2 is given by:

$$E^{Ch}(t) = \geq 0, \quad \forall t \geq 0, \tag{2}$$

which means that the network should never generate more energy than dissipated. Each port energy, E^M and E^S, can be split into positive and negative contributions. The sign of a power contribution indicates the direction of propagation, i.e. flow from master to slave, or from slave to master. [1] Positive power contributions are regarded as *in*, denoting an *in*nput *to* the communication channel, i.e. E^M_{in} and E^S_{in}. Negative contributions are regarded as *out*, denoting they are an *out*put *from* the channel, i.e. E^M_{out} and E^S_{out} [2]. See Fig. 2 and Appendix. This is the same convention used in [9]. The splitting is thus as follows:

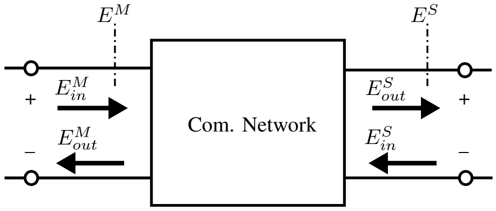

Fig. 2: In and out energies of the Position - Force Delay Network.

$$\begin{aligned} E^M(t) &= E^M_{in}(t) - E^M_{out}(t), \quad \forall t \geq 0, \\ E^S(t) &= E^S_{in}(t) - E^S_{out}(t), \quad \forall t \geq 0. \end{aligned} \tag{3}$$

The passivity condition Eq. 2 can be therefore rewritten as follows:

$$E^{Ch}(t) = E^M_{in}(t) - E^M_{out}(t) + E^S_{in}(t) - E^S_{out}(t) \geq 0. \tag{4}$$

III. ORIGIN OF THE POSITION DRIFT

In order to make Eq. 4 useful, it must be *observable* by the Passivity Observer. The observability however comes at the price of adding conservatism to the passivity condition. This is exposed in the following two subsections:

A. 1st Conservative Postulate: Decoupled Flows

The first step in making Eq. 4 useful, i.e. to extract conclusions about channel passivity from it, is to split channel energy flow into flows from left to right, E^{L2R} and from right to left, E^{R2L} as:

$$\begin{aligned} E^{L2R}(t) &= E^M_{in}(t) - E^S_{out}(t), \\ E^{R2L}(t) &= E^S_{in}(t) - E^M_{out}(t). \end{aligned} \tag{5}$$

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[1] Note that power can be negative in a passive system. It is the energy flow, which if negative, describes an active system.

[2] Both positive defined.

E.g., E^{L2R}, is the energy flow fed into the channel from the master side minus the energy coming out from the channel at the slave side. Condition Eq. 4 becomes:

$$E^{Ch}(t) = E^{L2R}(t) + E^{R2L}(t) \geq 0, \tag{6}$$

Eq. 6 allows to *analyze* passivity on a *decoupled* manner, since:

Proposition 3.1: If both energy flows, $E^{L2R} \geq 0$ and $E^{R2L} \geq 0$, Eq. 6 is satisfied and therefore Eq. 2 as well. This is a conservative postulate since it forces both flows to be greater than zero in order to satisfy Eq. 2.

B. 2nd Conservative Postulate: Observable Flows

The flows identified in Eqs. 5 are not yet *observable*, i.e. usable by the POs, at either side because they are dependent on current values from opposite sides. The following observable versions are thus defined:

$$\begin{aligned} E^{L2R}_{obs}(t) &= E^{M}_{in}(t-T) - E^{S}_{out}(t), \\ E^{R2L}_{obs}(t) &= E^{S}_{in}(t-T) - E^{M}_{out}(t), \end{aligned} \tag{7}$$

where now, E^{L2R}_{obs} and E^{R2L}_{obs}, are visible at right and left sides of the channel respectively, since delayed signals (instead of current ones), $E^{M}_{in}(t-T)$ and $E^{S}_{in}(t-T)$, are taken from the opposite side where the observer is placed. Therefore, the right PO observes $E^{L2R}_{obs}(t)$ and the left PO $E^{R2L}_{obs}(t)$.

Eqs. 7 allow to *check* for passivity on a *decoupled* manner, since:

Proposition 3.2: If both observable energy flows, $E^{L2R}_{obs} \geq 0$ and $E^{R2L}_{obs} \geq 0$, Eq. 6 is satisfied and therefore Eq. 2 as well.

Proof: If $E^{L2R}_{obs} \geq 0$ and $E^{R2L}_{obs} \geq 0$ then $E^{L2R} \geq 0$ and $E^{R2L} \geq 0$ since

$$\begin{aligned} E^{L2R}_{obs}(t) &\leq E^{L2R}(t) \; \forall t \geq 0, \\ E^{R2L}_{obs}(t) &\leq E^{R2L}(t) \; \forall t \geq 0. \end{aligned} \tag{8}$$

See Appendix for proof of Eqs. 8.

■

The result are the two, master and slave, Passivity Observers, each one placed on either side of the communication channel. The Passivity Controllers make use of such observed energies to dissipate any activity coming from the channel. Fig. 3 shows the cascade network connection of the forward PC, the communication network and the backward PC. The implementation of the PC will be seen in Sec. IV-C.

C. Origin of the Position Drift

At the slave side, the Passivity Controller slows down slave motions according to energy behavior captured by the PO. The PC applies a variable damper aimed for dissipating active energy observed by the PO. The commanded velocity to the slave is thus modified as:

$$\dot{x}_{sd}(n) = \hat{\dot{x}}_{sd}(n) + \beta(n) f_s(n), \tag{9}$$

where $\hat{\dot{x}}_{sd}(n)$ is the *untouched* velocity signal coming from the master and β is the variable damper. Eq. 9 is analogous to the *normal PC operation* mode in Eq. 18.

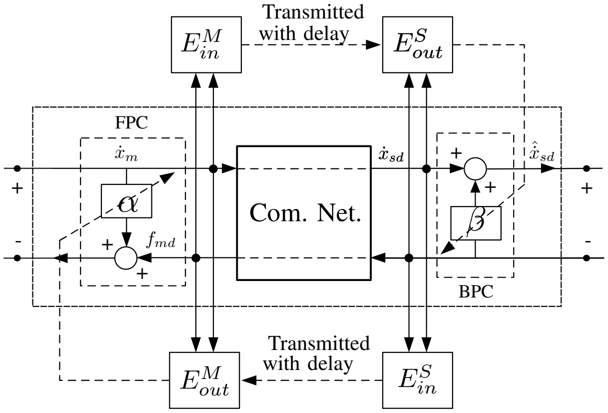

Fig. 3: Passivated communication channel with time delay using master and slave PO / PC.

The desired velocity must be integrated in order to be commanded as desired position to the slave robot:

$$x_{sd} = \int_0^t \dot{x}_{sd} d\tau. \tag{10}$$

The desired position, x_{sd}, is an input to the robot or to a PD controller (or similar) as suggested in Fig. 1. Since $x_{sd}$is the integral of a modified velocity (as a function of passivity), it accumulates the history of passivity corrections. There is therefore a drift between the integral of the *untouched* velocity and the modified one:

$$\Delta x_{err} = \int_0^t \dot{x}_{sd} d\tau - \int_0^t \hat{\dot{x}}_{sd} d\tau. \tag{11}$$

Δx_{err} is the cause of position drift between master and slave devices.

IV. THE APPROACH: LOSSLESS COMMUNICATION EMULATION

There are mainly two options to prevent this position drift:

- a) Dissipate less energy, if possible the exact amount stored in the communication. By doing so, drift will not occur because the PC will only modify velocity in order to dissipate the exact amount of energy introduced by the channel.
- b) Generate energy to actively prevent the drift as allowed by passivity of the communication.

The first one avoids over-dissipation from scratch. The second one accepts over-dissipation but avoids its potential effects. Clearly, avoiding over-dissipation from scratch would be the preferred approach. However, this seems to be unfeasible due to the impossibility of having both port flows available at the same time. Even if the conservative assumption of having previous knowledge of the delay is used, the energy observed on one of the sides will still need to travel to the other side.

The proposed approach in this paper is based on the second option. The reasoning behind is to emulate the behavior of an ideal communication channel, this is, a communication channel with a perfect and instantaneous data transmission.

In particular, the lossless property is here exploited by forcing the channel to exhibit null energy rather than positive energy, i.e. classic passivity.

A. Over-dissipation

Over-dissipation comes as a result of applying Eq. 6 and Eq. 7. Clearly, the passivity condition in Eq. 2 and in Eq. 7 (using *decoupled observed* energy flows) differ in restrictionism, in that the second one is obviously more restrictive than the first one. In other words, by using Eq. 7, the controller dissipates more than strictly needed, i.e. Eq. 2.

Using the flow from left to right as example, over-dissipation due to the *2nd Postulate* (Sec. III-B) is given by:

$$\begin{aligned} E^{L2R}(t) - E^{L2R}_{obs}(t) &= \\ E^{M}_{in}(t) - E^{S}_{out}(t) - E^{M}_{in}(t-T) + E^{S}_{out}(t) &= \\ E^{M}_{in}(t-T,t). & \end{aligned} \tag{12}$$

Unfortunately, since it is the right-side PO (slave) which makes use of the flow left to right (Eq. 7), Eq. 12 cannot be used on the right side since it would imply a non-casual system. It could be argued that the extra amount of energy on the left (master) can be compensated on the right (slave) side by using previous knowledge of the time delay. However, a) such an assumption adds considerable conservatism and hindrance to the field of application; and b) both possibilities, compensating the extra energy at the master side, or injecting energy from the master side to the channel, do not allow passivity proof. Due to obvious space limitation this proof is omitted.

Over-dissipation due to the *1st Postulate* (Sec. III-A) seems more difficult, if not impossible, to compute due to the splitting of the passivity condition, Eq. 2, in the two sub-conditions, Eq. 7.

B. Resembling Ideal Communications

Looking at Fig. 1, the ideal communication channel is given by the following equations:

$$T_f = 0 \quad ; \quad T_b = 0, \tag{13}$$

$$\dot{x}_m(t) = \hat{\dot{x}}_{sd}(t), \tag{14}$$

$$\hat{f}_m(t) = f_s(t), \tag{15}$$

$$E^{Ch}(t) = 0. \tag{16}$$

Eq. 13 is obviously impossible to satisfy. Approaches based on prediction and estimation typically minimize the errors between both sides of Eq. 14, Eq. 15 or both. The approaches pursued in this paper resemble Eq. 16 as faithful as allowed by the system, and as a consequence Eq. 14 is minimized.

The energy behavior of a communication channel network is rather stochastic. Unless the delay is constant and fixed parameters are used in the system, the energy behavior of a delay network is unpredictable. Often, telerobotic applications involve complex communication infrastructures characterized by highly variable time delays and package loss (e.g. if UDP protocol is used over the Internet or in space communications [13]).

From the energy point of view, the communication channel exhibits a similar behavior to that of a spring. Energy is continuously being accumulated and released during master and slave motions. Activity occurs when more energy is released than accumulated. This is exactly what the PC typically prevents, i.e. the variable damper is triggered in order to compel the energy lower boundary to zero. However, the channel often exhibits accumulation periods, *passivity gaps* from now on, which allow some margin for acting oppositely. By injecting energy (as opposed to dissipating) the energy null boundary can also be compeled during those passivity gaps.

C. Lossless Controller for Compensating the Position Drift

The main idea is to generate energy during passivity gaps in order to correct (and thus prevent) position drift. In other words, the PC is augmented in a way that energy is injected during the passivity gaps observed by the PO. Thus, the Passivity Observer and the augmented PC are defined as follows:

- Passivity Observer

  $$E^{S}_{obs}[n] = E^{M}_{in}[n-T] - E^{S}_{out}[n] + E_{PC}[n-1]. \tag{17}$$

  Where $E_{PC}[n-1]$ is the energy update corresponding to the PC previous operation.
- Passivity Controller with Energy Injection

$$\beta[n] = \begin{cases} -\dfrac{E^{S}_{obs}[n]}{T_s f_s[n]^2} & \text{if } E^{S}_{obs}[n] \le 0 \quad \textit{(classic PC)} \\[2ex] \dfrac{\varphi[n]}{f_s[n] T_s} min(|\Delta x_{err}[n]|, |\Delta x_{max}[n]|) & \text{else.} \end{cases} \tag{18}$$

$$\varphi[n] = sgn(T_s \sum_{0}^{n} \hat{\dot{x}}_{sd}[n] - x_{sd}[n]), \tag{19}$$

$$\dot{x}_{sd}[n] = \hat{\dot{x}}_{sd}[n] + \beta[n] f_s[n], \tag{20}$$

$$E_{PC}[n] = T_s \beta[n] f_s[n]^2 + E_{PC}[n-1]. \tag{21}$$

Where $\beta[n]$ is the dissipation coefficient, T forward time delay, and T_s the sampling time. φ determines the sign of the correction and E_{PC} is the energy dissipated or injected by the PC. Furthermore, the maximum allowed position drift compensation in order not to violate passivity of Eq. 17 is given by:

$$\Delta x_{max}[n] = \frac{E^{S}_{obs}[n]}{f_s[n]}. \tag{22}$$

The current drift, Δx_{err}, is given by Eq. 11. Therefore, in passivity gaps, i.e. $E^{S}_{obs}[n] \ge 0$, a complete drift compensation, Δx_{err}, will be possible as long the passivity gap gives enough margin, $E^{S}_{obs}[n]$. Otherwise, the maximum allowed compensation, Δx_{max}, will be commanded.

Fig. 4: Experimental Setup with a pair of Phantoms 1.5.

V. EXPERIMENTS

Fig. 4 shows the experimental setup with two PHANToMs controlled from the same computer at a sampling rate of 1Khz.

The PD controller was parametrized for maximum performance assuming a nearly ideal case, i.e. high stiffness (P) and null damping (D). The sampling rate was set at 1000 Hz. Overall, the bare system configuration (without any PO / PC) presented very narrow stability regions, allowing a maximum round-trip delay of $T_{rt} = 10ms$. The presented experiments show the response without and with the drift compensator at $T_{rt} = 200ms$ and $T_{rt} = 400ms$. Each figure is divided within six plots: 1) master and slave positions; 2) master and slave forces; 3) E^M_{in} vs. E^S_{out}; 4) E^S_{in} vs. E^M_{out}; 5) E^M_{obs} and 6) E^S_{obs}.

Fig. 5 shows how the drift becomes significant after a few seconds in a free environment motion due to the dissipation of the slave PC. Note the drift is related to the operation of the slave PC. The sixth plot, i.e. E^S_{obs}, shows Eq. 17 (removing the energy injection component). Positive intervals (passivity gaps) indicate passive behaviors, null intervals reveal the PC operation, i.e. the active tendency is regulated by the controller by dissipating energy. Fig. 6 shows the responses in hard contact situations. Note how the passivity conditions in *Proposition 2* are satisfied in both figures (plots 3 and 4).

Fig. 7 shows a similar test in free environment using the proposed drift compensator. Plot 6 shows the operation of the augmented PC: The passive gaps are exploited to compensate for the drift. As a result, the total observed energy becomes nearly null during whole operation since energy was injected, as allowed by the channel passiveness, in order to avoid accumulation of the dissipation error in the integral of $\dot{x}_{pc}$. Fig. 8 shows the response is hard contact conditions $T_{rt} = 400ms$.

VI. CONCLUSION

The approach presented here is inspired by the behavior of an ideal communication, this is, with a null energy flow response. Previous work was appropriately concerned with passivation of the communication channel on the time domain as a mean to guarantee system stability. Over-dissipation was found to be a limiting performance factor, which, depending on the causality of the PC (i.e. admittance or impedance) may outcome in different transparency losses. The case under study in this article tackles position drift as a consequence of an admittance configured PC located at the slave side. Errors in the modified velocity due to over-dissipation are accumulated in the integral responsible for computing the ultimate position command to the slave device.

The method is based on injecting extra energy, as allowed by the passiveness of the channel, to compensate the drift. Passivity gaps occur naturally in delayed communications and can be used to inject energy to the slave controller in order to compensate position drift. The amount of energy needed to fully compensate the drift is bounded by the magnitud of the passivity gap. Therefore, system passivity (and thus stability) is not violated.

Experiments show the effectiveness of the approach, bringing the system closer to the ideal paradigm with null time delay and showing clear increase in transparency. Future work will focus on generalization of the approach for more complex architectures, as for instance the 4 channel [1].

APPENDIX

A. In and Out Energy flows

Positive and negative port power contributions are split as:

$$\begin{aligned} P_+(t) &= P(t) \quad \forall f(t), v(t) \ s.t.\ f(t)v(t) > 0,\ \forall t\ \geq 0, \\ P_-(t) &= -P(t) \quad \forall f(t), v(t) \ s.t.\ f(t)v(t) < 0,\ \forall t\ \geq 0. \end{aligned}$$

Where $f(t)$ and $v(t)$ are force and velocity respectively at the port, i.e. the conjugated pair. Positive and negative contributions of the energy are

$$\begin{aligned} E_+(t) &= \int_0^t P_+(t) d\tau, \quad \forall t\ \geq 0, \\ E_-(t) &= \int_0^t P_-(t) d\tau. \quad \forall t\ \geq 0, \end{aligned}$$

being both monotonic functions positive.

Definition 1: Input and output components of left and right port Energies are related to positive and negative power as:

$$\begin{aligned} E^M_{in}(t) &= E^M_+(t), \quad \forall t\ \geq 0 \\ E^M_{out}(t) &= E^M_-(t), \quad \forall t\ \geq 0 \\ E^S_{in}(t) &= E^S_+(t), \quad \forall t\ \geq 0 \\ E^S_{out}(t) &= E^S_-(t), \quad \forall t\ \geq 0. \end{aligned} \tag{23}$$

B. Proof of Eqs. 8.

Theorem 1.1: If both observed energy flows are $E^{L2R}_{obs}(t) \geq 0$ and $E^{R2L}_{obs}(t) \geq 0$ then the system is passive.

Proof: To check passivity means to prove Eq. 2. Since both E^S_{out} and E^M_{out} are monotonic the following holds:

$$\begin{aligned} E^S_{out}(t - T_b) &\leq E^S_{out}(t), \quad \forall t\ \geq 0, \\ E^M_{out}(t - T_f) &\leq E^M_{out}(t). \quad \forall t\ \geq 0, \end{aligned} \tag{24}$$

Observed decoupled energy expressions, E_{obs}^{L2R} and E_{obs}^{R2L} from Eq. 7, are thus lower bounded by the decoupled *real*[3] expressions, E^{L2R} and E^{R2L} from Eq. 5. This is:

$$\begin{aligned} E_{obs}^{L2R}(t) &\leq E^{L2R}(t), \quad \forall t \geq 0, \\ E_{obs}^{R2L}(t) &\leq E^{R2L}(t). \quad \forall t \geq 0. \end{aligned} \tag{25}$$

Therefore if constrains $E_{obs}^{L2R}(t) \geq 0$ and $E_{obs}^{R2L}(t) \geq 0$ are satisfied, so do Eqs. 6 and thus Eq. 2. ■

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(See figures next page.)

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[3] "real" is used to distinguish actual from "observed" energy.

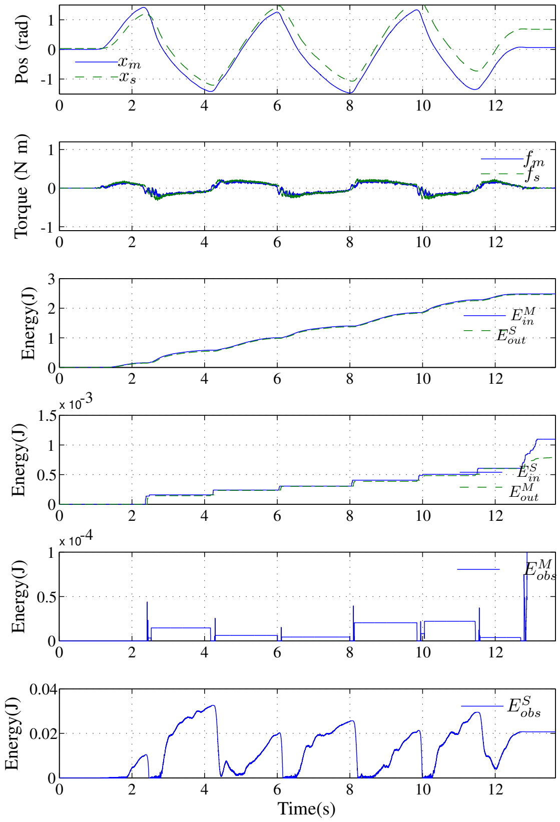

Fig. 5: $T_{rt} = 200ms$. Drift Compensator off. Free env.

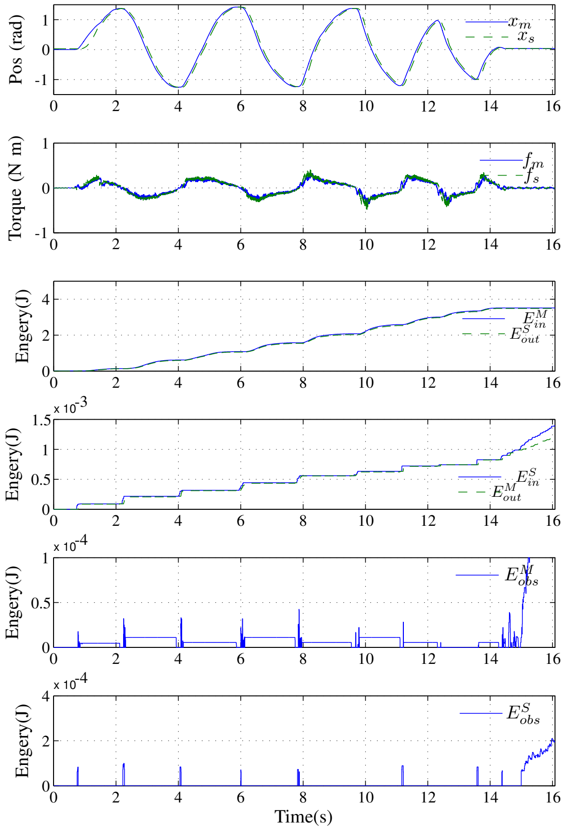

Fig. 7: $T_{rt} = 200ms$. Drift Compensator on. Free env.

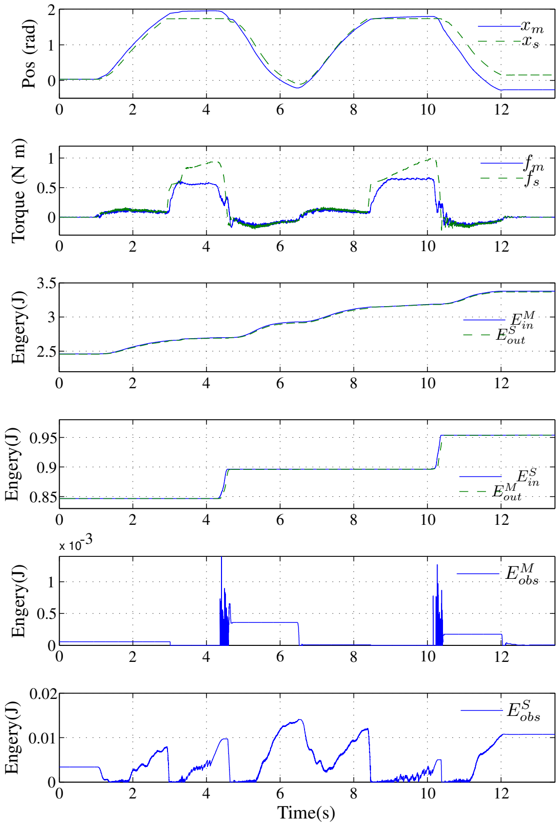

Fig. 6: $T_{rt} = 200ms$. Drift Compensator off. Hard contact

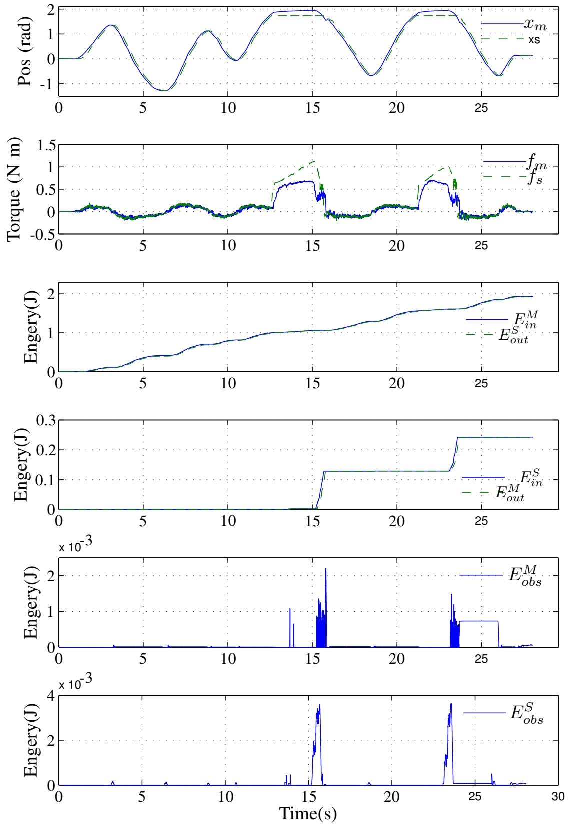

Fig. 8: $T_{rt} = 400ms$. Drift Compensator on. Hard contact