Proceeding of the 2004 American Control Conference
Boston, Massachusetts June 30 - July 2, 2004

On Position Tracking in Bilateral Teleoperation

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***Abstract*— This paper addresses the problem of position tracking in bilateral teleoperation. Passivity based control schemes for bilateral teleoperation provide robust stability against network delays in the feedback loop and velocity tracking, but do not guarantee position tracking in general. Position drift due to environment contact and offset of initial conditions is a well known problem in such systems. In this paper we introduce a new architecture which builds upon the traditional passivity based configuration by using additional position control on both the master and slave robots. Lyapunov stability methods are used to establish the range of the position control gains on the master and slave side. Simulations results using a single-degree of freedom master/slave system are presented showing the performance of the resulting system.**

I. INTRODUCTION

A teleoperator is a dual robot system in which a remote slave robot tracks the motion of a master robot, which is, in turn, commanded by a human operator. To improve the task performance, information about the remote environment is needed. Feedback can be provided to the human operator by many different forms, including audio, visual displays, or tactile. However, force feedback from the slave to the master, representing contact information, provides a more extensive sense of telepresence. When this is done the teleoperator is said to be controlled bilaterally.

In bilateral teleoperation, the master and the slave manipulators are coupled via a communication network and time delay is incurred in transmission of data between the master and slave site. It is well known that the delays in a closed loop system can destabilize an otherwise stable system. Time delay instability in force reflecting teleoperation was a long standing impediment to bilateral teleoperation with force feedback. The breakthrough to the bilateral teleoperation problem was achieved in [1] where concepts from Network Theory, Passivity and Scattering Theory were used to analyze mechanisms responsible for loss of stability and derive a time delay compensation scheme to guarantee stability independent of the (constant) delay. These results were then extended in [7], where the notion of wave-variables was introduced to define a new configuration for force-reflecting teleoperators.

In a bilateral teleoperator, apart from the basic necessity of a stable system, there are primarily two design goals which ensure a close coupling between the human operator and the remote environment. The first goal is that the slave manipulator should track the position of the master manipulator and the second goal is that the environmental force acting on the slave, when it contacts a remote environment, be accurately transmitted to the master. It this paper we primarily address the position tracking problem in a bilateral teleoperation system. The standard approaches to control of bilateral teleoperators over constant delay networks, based on the scattering approach [1] or the equivalent wave variable formulation [7], guarantee robust stability of the teleoperator but lead to sluggish response for high transmission delays, as observed in [5]. In [6], the fundamental limits of performance and design

Research partially supported by the Office of Naval Research under Grant N00014-02-1-0011 and by the National Science Foundation under Grants ECS-0122412, Int-0128656, HS-0233314 and CCR-0209202. The first author was also supported by the Vodafone Fellowship.

trade-offs of bilateral teleoperation, without addressing a particular architecture, were analyzed. Several architectures were quantitatively compared in terms of transparency and stability, and the results demonstrated that although the passivity based approach was stable compared to other schemes such as [4], the passive architecture does not guarantee good transparency. Transparency, as defined in [6], is quantified in terms of a match between the environmental impedance and the impedance transmitted to the human operator. This definition of transparency is more suited for the case where the master and the slave have different workspace, but in this paper we work under the assumption that the master/slave robots have the same workspace ,and therefore aim for correspondence between the master/slave position and force responses to be the measure of transparency [11], [10]. In [8] two methods to solve the position tracking problem were presented. The first one involved sending the integral of the wave variables to communicate direct position data to the slave side while the second method added a correction to the wave variables, based on the position error, to recover good tracking. The integral of the wave-variables contains position and momentum information and thus a passive coupling between the master/slave robots (which are passive from force to velocity) to the communication block transmitting position/momentum information is non-obvious. It was demonstrated in [9] that such a coupling is possible in a single-degree-of-freedom manipulator and a configuration to solve the position tracking problem was presented. Recently in [3], a feedforward position control was advocated to improve the position tracking performance. In this paper we propose a new architecture for bilateral teleoperation, which builds upon the model of [3], to solve the position tracking problem.

II. Position Tracking in Bilateral Teleoperation

A teleoperator consists of the following subsystems: the human operator, the master, the communication block, the slave and the environment. The human operator commands the master with force F_h to move it with velocity $\dot{x}_m$ which is sent to the slave through the communication block and a local control(F_s) on the slave side drives the slave velocity $\dot{x}_s$ towards the master velocity. If the slave contacts a remote environment, the remote force F_e is communicated back from the slave side and received at the slave side as the force F_m.

The standard bilateral teleoperation system of [1] with the scattering transformation is shown in Figure 1. The scattering transformation approach in [1] or the equivalent wave variable transformation proposed in [7] guarantees passivity of the network block in the face of constant delay in the network. This transformation is given, using the notation of [7], as

$$u_m = \frac{1}{\sqrt{2b}}(F_m + b\dot{x}_m)\ ; \qquad v_m = \frac{1}{\sqrt{2b}}(F_m - b\dot{x}_m)$$
$$u_s = \frac{1}{\sqrt{2b}}(F_s + b\dot{x}_{sd})\ ; \qquad v_s = \frac{1}{\sqrt{2b}}(F_s - b\dot{x}_{sd}) \tag{1}$$

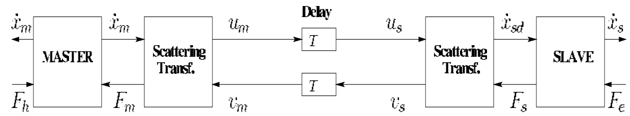

Fig. 1. A standard bilateral teleoperation setup

where $\dot{x}_m$ is the master velocity and $\dot{x}_{sd}$ is the velocity derived from the scattering transformation at the slave side. F_m is the force that is reflected back to the master from the slave robot and F_s is given as

$$F_s(t) \quad = \quad K_s \int_0^t (\dot{x}_{sd} - \dot{x}_s)dt + B_{s2}(\dot{x}_{sd} - \dot{x}_s)$$

This force drives the velocity tracking errors between the master and the slave to zero and also acts as a measure of the environmental force F_e [1] when the slave contacts the remote environment.

This architecture uses the passivity formalism and concepts from network theory to construct an interconnection of passive blocks which is well-known to be dissipative. The master and the slave are passive from force to velocity and the network block is passified by the scattering transformation. This system, when interconnected with a passive human operator and remote environment, is passive. However, this configuration places an inherent limitation on the transparency (measure of position and force tracking) of the system because instead of transmitting position signals, linear combination of velocity and force signals are transmitted from the master to the slave and vice versa.

Position tracking in bilateral teleoperation has emerged to be a two-faceted problem. Consider a task where the slave intermittently contacts the remote environment. During this task, the master and the slave might not have the same initial position after an environmental contact and as only the master velocity is transmitted across the channel codified in the wave variables, and is then integrated to recover the master position, is not possible for the slave to track the master position. This results in a drift between the master and the slave robot which might increase with time due to successive environmental contacts.

The other case is the degradation of position tracking in the event of high network delays of the order of 0.5s or more. It is well known that position tracking in a teleoperation architecture, as described in this section, deteriorates with increase in the network delay. We demonstrate below that loss of tracking is a resulting pitfall of the scattering transformation or the wave-variable approach and in the next section we propose a new configuration to counter this problem. Using (1), the transmission equations can we rewritten as

$$b\dot{x}_{sd}(t) \quad = \quad b\dot{x}_m(t-T) + F_m(t-T) - F_s(t)$$
$$F_m(t) \quad = \quad F_s(t-T) + b\dot{x}_m(t) - b\dot{x}_{sd}(t-T)$$

Using the above equations it follows that

$$b\dot{x}_{sd} = \quad 2b\dot{x}_m(t-T) + F_s(t-2T) - F_s(t) \\ -b\dot{x}_{sd}(t-2T) \qquad (2)$$

Substituting the value of F_s, the above reduces to

$$\begin{aligned} \dot{x}_{sd} = \quad & \frac{2b}{b+B_{s2}}\dot{x}_m(t-T) + \frac{B_{s2}-b}{b+B_{s2}}\dot{x}_{sd}(t-2T) \\ & +\frac{B_{s2}}{b+B_{s2}}(\dot{x}_s(t) - \dot{x}_s(t-2T)) \\ & +\frac{K_s}{b+B_{s2}}(\triangle x(t-2T) - \triangle x(t)) \end{aligned}$$

where $\triangle x(t)$=$\int_0^t(\dot{x}_{sd} - \dot{x}_s)dt$. Thus, the reference position for the slave is given as

$$\begin{aligned} x_{sd}(t) - x_{sd}(0) = \; & \frac{2b}{b+B_{s2}}(x_m(t-T) - x_m(0)) \\ & +\frac{B_{s2}-b}{b+B_{s2}}(x_{sd}(t-2T) - x_{sd}(0)) \\ & +\frac{1}{b+B_{s2}}\int_{t-2T}^{t}(B_{s2}\dot{x}_s(\tau) - K_s\triangle x(\tau))d\tau \end{aligned}$$

To improve the transient performance, impedance matching has been advocated in [7], which entails choosing $B_{s2} = b$. Using this in the above, and assuming that the $x_{sd}(0) = x_m(0)$, the above equation simplifies as

$$x_{sd}(t) = x_m(t-T) + \frac{1}{2b}\int_{t-2T}^{t}(B_{s2}\dot{x}_s(\tau) - K_s\triangle x(\tau))d\tau$$

It is easily seen from the above equation that even in the best-possible scenario, i.e. with matched impedance and no initial offsets, the reference position signal for the slave x_{sd} is a function of the delay and position drift between the master and the slave robot increases with increase in delay. Thus use of the integral of the scattering variables is not a judicious choice in obtaining the reference signal (master position signal) for the controllers on the slave side. In the next section we propose a new architecture which solves the position tracking problem in bilateral teleoperation.

III. A New Architecture for Bilateral Teleoperation

The proposed architecture is shown in Figure 2 where the master and the slave position data are explicitly sent across the communication channel. This configuration is similar to the standard bilateral teleoperation setup but has additional proportional controllers on the master and the slave side which use the delayed position data (from both master and slave) as the reference signal. For simplicity, the master and the slave have been modelled as mass-damper systems. The system dynamics are given by

$$\begin{aligned} M_m\ddot{x}_m + B_m\dot{x}_m &= F_h + F_{back} - F_m \\ M_s\ddot{x}_s + B_{s1}\dot{x}_s &= F_s + F_{feed} - F_e \end{aligned} \qquad (3)$$

where M_m and M_s are the respective inertias and B_m, B_{s1} represent the master and the slave damping respectively.

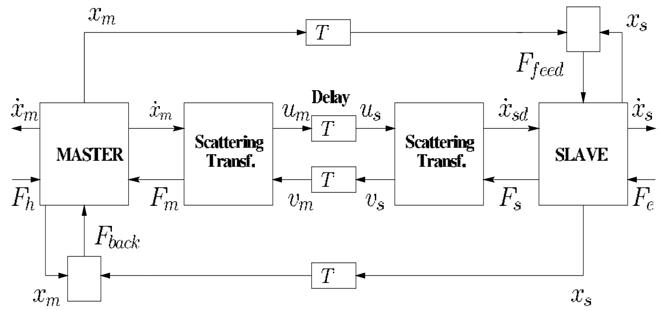

Fig. 2. A New Configuration for Bilateral Teleoperation

F_h is the operator torque, F_e is the environment torque and other torques are defined as

$$\begin{aligned} F_s &= B_{s2}(\dot{x}_{sd} - \dot{x}_s) \\ F_{back} &= K(x_s(t-T) - x_m) \\ F_{feed} &= K(x_m(t-T) - x_s) \end{aligned} \qquad (4)$$

In the analysis that follows we assume that

- The human operator and the environment can be modelled as passive systems.
- The operator and the environmental force are bounded by known functions of the master and the slave velocities respectively.
- All signals belong to $\mathcal{L}_{2e}$, the extended $\mathcal{L}_2$ space.
- The velocities $\dot{x}_m$ and $\dot{x}_s$ equal zero for t $<$ 0.

Define the position tracking error as

$$e = x_m(t-T) - x_s(t) \qquad (5)$$

where $x_m(t-T)$ is the delayed master position received on the slave side.

Proposition 3.1: Consider the system described by (1), (3), (4) and Figure 2. Then for a range of the gain ($0 < K < K^*$), the master and slave velocities asymptotically converge to the origin and the position tracking error defined by (5) remains bounded.

Proof: Define a positive definite function for the system as

$$\begin{aligned} V = \; & \frac{1}{2}\{M_m\dot{x}_m^2 + M_s\dot{x}_s^2 + K(x_m - x_s)^2\} \qquad (6) \\ & + \int_0^t(F_e\dot{x}_s - F_h\dot{x}_m)d\tau + \int_0^t(F_m\dot{x}_m - F_s\dot{x}_{sd})d\tau \end{aligned}$$

The human operator and the remote environment are passive(by assumption). Hence

$$\int_0^t F_e\dot{x}_s d\tau \geq 0 \quad ; \quad -\int_0^t F_h\dot{x}_m d\tau \geq 0$$

Using the scattering transformation (1), we have

$$\int_0^t(F_m\dot{x}_m - F_s\dot{x}_{sd})d\tau = \frac{1}{2}\int_{t-T}^{t}(u_m^2 + v_m^2)d\tau \geq 0$$

which shows that the communication block is passive. Thus the function V is positive-definite. The derivative of (6) along trajectories of the system is given by

$$\begin{aligned}
\dot{V} &= M_m\dot{x}_m\ddot{x}_m + M_s\dot{x}_s\ddot{x}_s + K(x_m - x_s)(\dot{x}_m - \dot{x}_s) \\
&\quad + F_m\dot{x}_m - F_s\dot{x}_{sd} + F_e\dot{x}_s - F_h\dot{x}_m \\
&= \dot{x}_m(-B_m\dot{x}_m + K(x_s(t-T) - x_m) + F_h - F_m) \\
&\quad + \dot{x}_s(-B_{s1}\dot{x}_s + K(x_m(t-T) - x_s) + F_s - F_e) \\
&\quad + K(x_m - x_s)(\dot{x}_m - \dot{x}_s) + (F_m - F_h)\dot{x}_m - F_s\dot{x}_{sd} + F_e\dot{x}_s \\
&= -B_m\dot{x}_m^2 - B_{s1}\dot{x}_s^2 + (\dot{x}_{sd} - \triangle v)F_s - F_s\dot{x}_{sd} \\
&\quad + K(x_s(t-T) - x_s)\dot{x}_m + K(x_m(t-T) - x_m)\dot{x}_s
\end{aligned}$$

where $\triangle v = \dot{x}_{sd} - \dot{x}_s$. Using the fact that

$$x_i(t-T) - x_i = -\int_0^T \dot{x}_i(t-\tau)d\tau \quad ; \quad i = m, s$$

and integrating the above equation we get

$$\begin{aligned}
\int_0^{t_f} \dot{V}dt \le& -B_m||\dot{x}_m||_2^2 - B_{s1}||\dot{x}_s||_2^2 - B_{s2}||\triangle v||_2^2 \\
&- K\int_0^{t_f} \dot{x}_m \int_0^T \dot{x}_s(t-\tau)d\tau dt \\
&- K\int_0^{t_f} \dot{x}_s \int_0^T \dot{x}_m(t-\tau)d\tau dt
\end{aligned}$$

where the notation $||\cdot||_2$ denotes the $\mathcal{L}_2$ norm of a signal on the interval $[0, t_f]$. Using Schwartz inequality and the fact that Arithmetic Mean(A.M.)≥ Geometric Mean(G.M.), it is easily seen that, for any α_1, $\alpha_2 > 0$

$$\begin{aligned}
& 2\int_0^{t_f} \dot{x}_m \int_0^T \dot{x}_s(t-\tau)d\tau dt \le \alpha_1\int_0^{t_f} \dot{x}_m^2 dt \\
& + \frac{1}{\alpha_1}\int_0^{t_f} \Big(\int_0^T \dot{x}_s(t-\tau)d\tau\Big)^2 dt \\
& \le \alpha_1||\dot{x}_m||_2^2 + \frac{T}{\alpha_1}\int_0^{t_f}\int_0^T \dot{x}_s^2(t-\tau)d\tau dt \\
& \le \alpha_1||\dot{x}_m||_2^2 + \frac{T^2}{\alpha_1}||\dot{x}_s||_2^2
\end{aligned}$$

Similarly, it can be shown that

$$2\int_0^{t_f} \dot{x}_s \int_0^T \dot{x}_m(t-\tau)d\tau dt \le \alpha_2||\dot{x}_s||_2^2 + \frac{T^2}{\alpha_2}||\dot{x}_m||_2^2$$

Therefore the integral inequality reduces to

$$\begin{aligned}
\int_0^t \dot{V}dt \le& -B_m||\dot{x}_m||_2^2 - B_{s1}||\dot{x}_s||_2^2 - B_{s2}||\triangle v||_2^2 \\
&+ K\{(\frac{\alpha_1}{2} + \frac{T^2}{2\alpha_2})||\dot{x}_m||_2^2 + (\frac{\alpha_2}{2} + \frac{T^2}{2\alpha_1})||\dot{x}_s||_2^2\}
\end{aligned}$$

So in order for $\dot{x}_m, \dot{x}_s \in \mathcal{L}_2$, the following inequalities are sufficient to be satisfied

$$\begin{aligned}
K(\frac{\alpha_1}{2} + \frac{T^2}{2\alpha_2}) &< B_m \\
K(\frac{\alpha_2}{2} + \frac{T^2}{2\alpha_1}) &< B_{s1}
\end{aligned}$$

The above inequalities have a positive solution α_1, α_2 if

$$K^2T^2 < B_mB_{s1}$$

In principle the damping gains B_m, B_{s1} can be arbitrarily assigned and the above inequality has a solution for any constant value of the delay. Thus we conclude that the signals $\dot{x}_m$, $\dot{x}_s$, $x_m - x_s$ are bounded and it can also be seen that $(\dot{x}_m,\ \dot{x}_s,\ \triangle v) \in \mathcal{L}_2$. As the operator and the environmental force is bounded by known functions of the master and the slave velocities respectively, the forces F_e and F_h are bounded. To demonstrate that these signals converge to zero, we need to show that their derivatives are bounded. Using (2) and (4) we get that

$$\begin{aligned}
\dot{x}_{sd} =& \frac{B_{s2} - b}{B_{s2} + b}\dot{x}_{sd}(t - 2T) + \frac{2b}{b + B_{s2}}\dot{x}_m(t-T) \\
&+ \frac{B_{s2}}{b + B_{s2}}(\dot{x}_s(t) - \dot{x}_s(t-2T))
\end{aligned} \tag{7}$$

As $\frac{B_{s2}-b}{B_{s2}+b} \le 1$, the above equation is a stable difference equation with a bounded input and thus $\dot{x}_{sd}$ is bounded which in turn ensures that F_s is bounded. Hence the slave acceleration is bounded and similarly it can be show that master acceleration is also bounded. Differentiating (7), it can be shown that $\ddot{x}_{sd}$ is also bounded which guarantees asymptotic convergence of the signals $\dot{x}_m$, $\dot{x}_s$, $\triangle v$ to the origin (using Barbalat's Lemma). The tracking error defined in (5) can be rewritten as

$$e = x_m(t) - x_s(t) - \int_{t-T}^t \dot{x}_m(\tau)d\tau$$

Thus the position tracking error is bounded. ■

The above result only guarantees boundedness of the tracking error and not the convergence of the tracking error to the origin. In the next result, we discuss the position tracking abilities of the controller in free space.

Corollary 3.2: In the steady state, i.e. when

$$\dot{x}_i, \ddot{x}_i = 0 \qquad i = m, s \tag{8}$$

and F_e equals zero, the tracking error defined by (5) goes to zero.

Proof: Under the above conditions, the slave dynamics reduce to

$$F_s + F_{feed} - F_e = 0$$

As $\triangle v$ asymptotically approaches the origin, $F_s \to 0$. Thus it can be observed from the above equation that F_{feed} equals zero and hence the result follows. ■

Remark Under the condition that (8) holds, the proposed architecture ensures that when the slave contacts a remote environment, the contact force is accurately transmitted to the master. As before, $F_s \to 0$ and the slave dynamics reduce to

$$F_{feed} = F_e$$

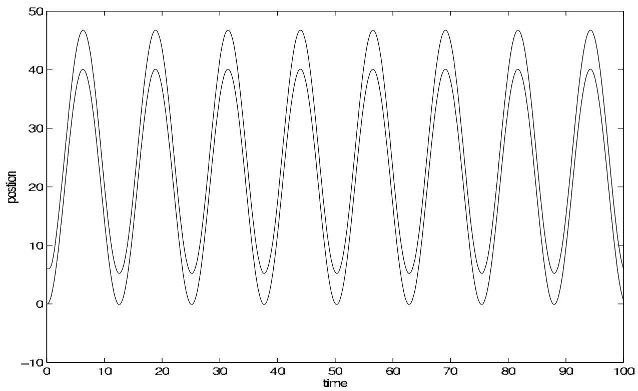

Fig. 3. Reference and slave position for system with an initial offset: Traditional architecture cannot ensure good tracking after an initial offset between the master and the slave robot

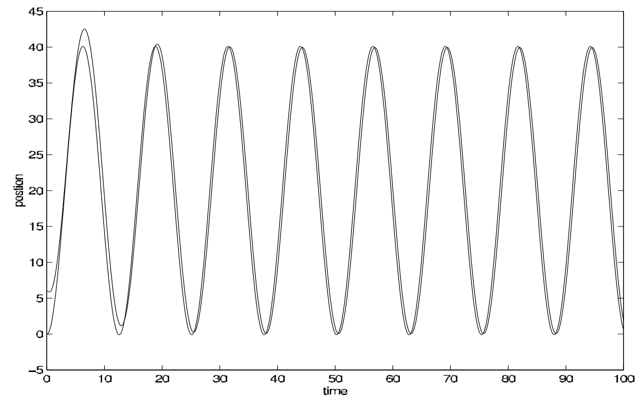

Fig. 4. Reference and slave position for system with an initial offset: The new architecture ensures good position tracking

In steady state

$$\begin{aligned} F_{back} + F_{feed} &= K(x_s(t-T) - x_m(t)) \\ &\quad + K(x_m(t-T) - x_s(t)) \\ &= -K\int_{t-T}^{t} \dot{x}_m(\tau) + \dot{x}_s(\tau) d\tau = 0 \end{aligned}$$

or we have $F_{back} = -F_e$ which guarantees good force tracking on the master side.

IV. Simulations

In this section we verify the efficacy of the proposed architecture. The simulations were carried out on a single-degree of freedom master/slave robots whose dynamics are given by (3). The master was moved sinusoidally and in the scenario, where there is an initial offset between the master and the slave, there is a constant drift between the two robots as shown in Figure 3. However, the proposed architecture ensures that the slave is able to recover from the initial position offset, as shown in Figure 4. We now compare the effect of delays on the transient tracking errors in the traditional and the proposed configuration. In this simulation we assumed that there is no initial position offset between the two robots. The position tracking error (5) in the traditional architecture, with a network delay of 0.8s, is shown in Figure 5. With the proposed architecture and the same network delay, the magnitude of the tracking error decreases as observed in Figure 6. In the last set of simulations, we show that new architecture has force tracking abilities which are comparable to those of the traditional bilateral setup. The environment was assumed to be a passive mass-damper system and the master was commanded with a constant velocity. In the new architecture, the slave position faithfully tracks the master until it impacts the environment at t=20s, as seen in Figure 7, and on contact, the environmental force is accurately reflected (using the signals F_m and F_{back}) back to the master as seen in Figure 8. The two force ($F_m + F_{back}$, F_e) signals, after the impact time of t=20s, literally coincide as seen in Figure 8. The tracking performance is comparable to the tracking performance using the traditional setup as seen in Figure 9. Due to different controllers on the slave side, the interaction of the slave with the environment is different in both cases which leads to different contact force profiles but the point to be taken away from here is that the contact force is faithfully reproduced on the master side with the new configuration. Thus the new architecture has the benefits of better position tracking and retains the force tracking abilities of the bilateral teleoperation setup as proposed in [1].

V. Conclusions

In this paper a new architecture for bilateral teleoperation was proposed which has better position tracking and comparable force tracking abilities than the traditional teleoperator model of [1], [7]. The new configuration builds upon the traditional bilateral teleoperator model but has additional proportional controllers on the master and the slave side which use the delayed position data (from both master and slave) as the reference signal. The range of the corresponding proportional gains was established using Lyapunov analysis has been found to be inversely proportional to the network delay. Future work entails extending these results for time-varying delay networks.

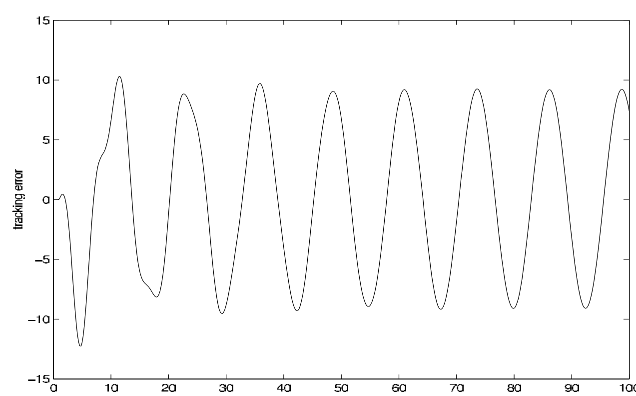

Fig. 5. Tracking error with a delay of 0.8s in the traditional architecture

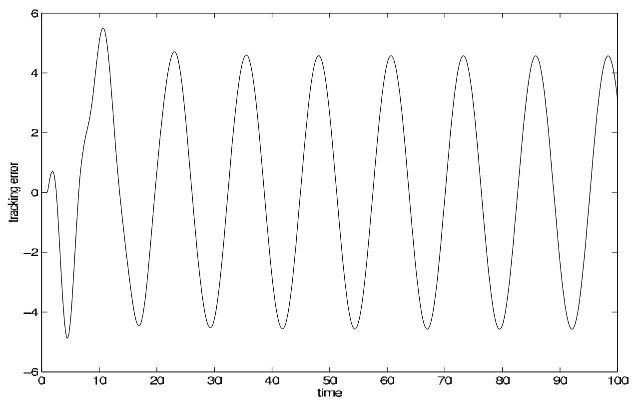

Fig. 6. Tracking error with a delay of 0.8s in the new architecture

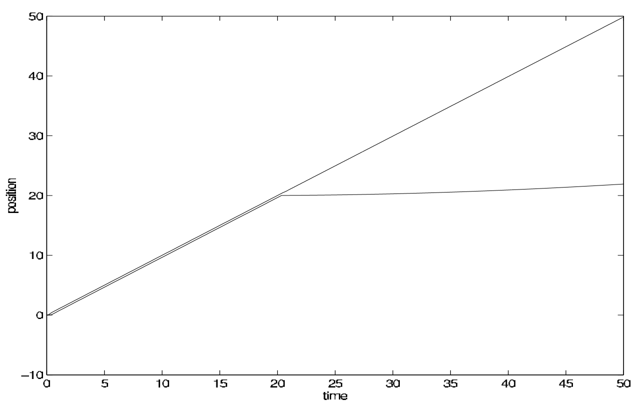

Fig. 7. Reference and slave position on contact with the environment

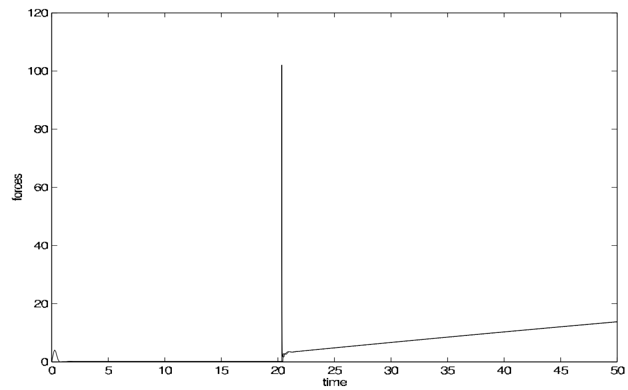

Fig. 8. Forces at the master and the slave side on contact with the environment: The new architecture

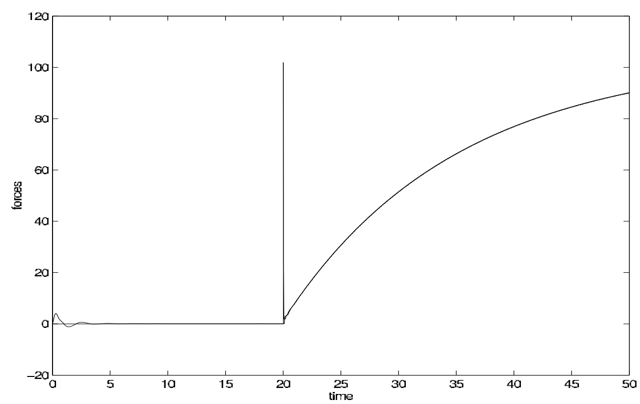

Fig. 9. Forces at the master and the slave side on contact with the environment: The traditional architecture

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