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A Study of Bilateral Control with Time Delay

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Abstract

In robotics and other fields of engineering, techniques for artificial reality or virtual reality are focused on and studied extensively, e.g., virtual existence for tele-operator systems in robotics, and virtual reality of designed objects in architecture. In order to realize the system we should create physical stimulations according to internal models created by experiences in a human brain. The internal model does not have to have direct connections to the real world, however, the stimulation must be signals such that the internal model are retrieved in a human brain.

In this paper we propose a technique for tele-virtual reality of dynamic mechanical models, which means that one dynamic mechanical model can be shared by peoples in distant places. Since a stability issue due to time delays arises in the system, we employed a scattering technique developed for a tele-operator system and a kind of passive adaptive controllers. Furthermore, restrictions due to a simple digital implementation of the scattering transformation are discussed and some conditions for stability are shown. The proposed method is applied to a remote tug of war system and the effectiveness is verified.

1. Introduction

In robotics and other fields of engineering, techniques for artificial reality or virtual reality are focused on and studied extensively, e.g., virtual existence for tele-operator systems in robotics, and virtual reality of designed objects in architecture. In order to realize the system we should create physical stimulations according to internal models created by experiences in a human brain. The internal model does not have to have direct connections to the real world, however, the stimulations must be signals such that the internal model can be retrieved in a human brain.

In this paper we propose a technique for tele-virtual reality of dynamic mechanical models, which means that one dynamic mechanical model can be shared by people in distant places. A difference between the proposed method and that of tele-existence for master-slave systems is that the latter tries to re-create a real world around a slave system as possible as real, but the former tries to create exact stimulations from a model. Of course the model can be an real object but it can be an artificial one. Since a stability issue due to time delays arises in the system, we employ a scattering technique developed for a tele master-slave system [1][2][3] and a kind of passive adaptive controllers based on [4]. Further, restrictions due to a simple digital implementation of the scattering transformation are discussed and some conditions for characteristic impedance [4] are shown. The proposed method is applied to a miniature remote tug war system which is a small model of that depicted in Fig.1, and the effectiveness is verified.

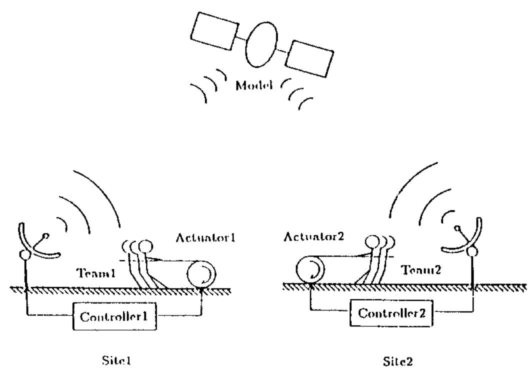


Fig.1 Remote tug of war system

2. Tele-Operator System and Scattering Transformation

Usually tele-operator system can be modeled as a block diagram in Fig.2a. A network analogy of electrical circuit composed of three two-port elements and two one-port elements for the tele-operator system is also shown in Fig.2b. The variables are defined as in Table 1. In the system an operator commands a position (velocity) to a slave system through a transmission line, and the slave system sends back a reaction force against an environment. (Actually the communications are done simultaneously.) In an ideal situation the movement of the master arm is identical to that of slave one, and the force exerted on the slave arm is identical to that the operator feels. The situation, however, can not be realized because of extra dynamics of master and slave arms and effects of transmission lines. Especially, the transmission delay makes the system unstable very easily if velocity and force information are sent individually. [1]

v_m	velocity of master arm
v_s	velocity of slave arm
v_{sd}	desired velocity to slave arm
f_e	reactance force against environment
f_h	exerted force given by an operator
F_s	compliant force according to error
F_{md}	desired force to master arm

Table 1. Table of variables for a tele-operator system

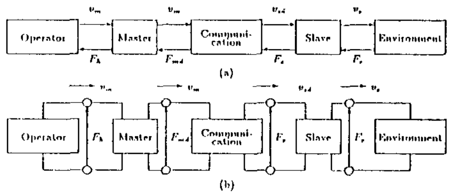


Fig.2 Block diagram and its network representation of tele-operator system

In order to overcome the difficulty, scattering transformation which mimics a lossless line was proposed to use in tele-operator systems. [1][2][3] The algorithm is given by

$$F_{md}(t) = bv_m(t) + (F_s(t-T) - bv_{sd}(t-T)) \quad (2.1)$$

$$v_{sd}(t) = \frac{1}{b}\{(F_{md}(t-T) + bv_m(t-T)) - F_s(t)\} \quad (2.2)$$

where b is a characteristic impedance [3] and T is a transmission delay. It has been shown that the delay line behaves as a passive element using this coding, and any delay T does not affect the stability.[1][2] A remarkable point of the coding is that controllers for master and slave arms can be designed as there were no time delay, and time delay T can be unknown (but fixed). A block diagram of the scattering transformation is shown in Fig.3. Typical example of the tele-operator system whose master and slave arms have single degree of freedom and its circuit equivalent are shown in Fig.4. The dynamic equations governs the system are given as :

$$M_m\dot{v}_m + B_m v_m + K_m\int v_m dt = f_h - F_{md} \quad (2.3)$$

$$M_s\dot{v}_s + B_s v_s + K_s\int v_s dt = F_s - F_e \quad (2.4)$$

$$K_d(v_{sd} - v_s) + K_p\int (v_{sd} - v_s)dt = F_s \quad (2.5)$$

Variables above are defined in Table 2. In the figure symbolic conventions are used, i.e., voltage, current, coil, resistance and condenser are corresponding to force, velocity, mass, damper and spring, respectively. From the figure it is obvious that the system is stable if the input power from the operator is bound since all elements are passive.

f_h	force command given by an operator
F_{md}	desired force for a master arm
F_s	imperdance or control force for a slave arm
F_e	reactance force from environment
v_m	velocity of a master arm
v_{sd}	desired velocity for a slave arm
v_s	velocity of a slave arm
Z_e	mechanical impedance of the environment
M_m	inertia of a master arm
D_m	damping coefficint of a master arm
K_m	spring constant of a master arm
M_s	inertia of a slave arm
D_s	damping coefficent of a slave arm
K_s	spring constat of a slave arm
K_d	feedback gain of velocity error
K_p	feedback gain of position error

Table 2. Table of variables of an equivalent circuit for a tele-operatorsystem

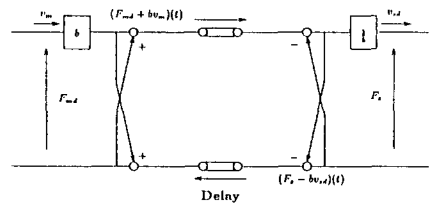
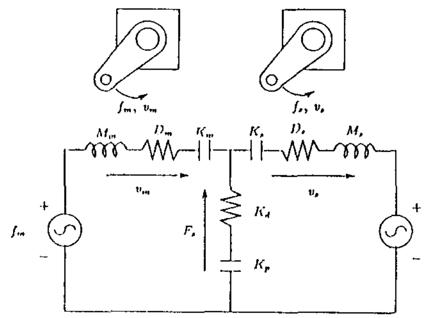
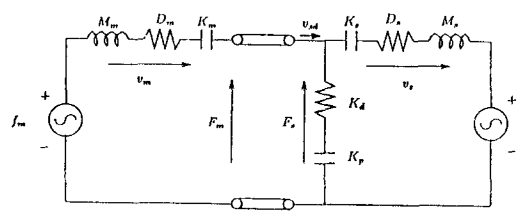


Fig.3 Block diagram of scattering transformation



(a)



(b)

Fig.4 An example of a simple tele-operator system: physical structure and its circuit representation

3. Tele-Virtual Realization of Dynamic Mechnical Model

3.1 Mater-Slave Realization of Tug of War System

In this section we will design a remote tug of war system as an example of virtual realization of dynamic mechanical model. Experimental setup is illustrated in Fig. 5. The purpose of the system may be as follows:

- The exerted tension at each side of the rope is same, i.e., $f_1 = -f_2$.
- Movements of the ropes are completely complement, i.e., $x_1 = -x_2$.

If the system satisfies the conditions above, players in distant places can play the tug of war game, and they may feel as they pulled single rope. Since the actual rope, however, has some dynamics, ropes connected to the motors should achieve the dynamic motion, and the values are not completely complement due to the dynamics. As the system considered here has actual ropes at each ends, actuators merely can mimic the dynamics of a part of the rope but whole dynamics of the rope. The dynamic model of the part of the rope is shown in Fig. 6. In the figure, the movement of the small part of the rope is assumed to be represented by a mechanical system. The dynamic model can be considered as a model which is tele-virtually realized by the proposed method.

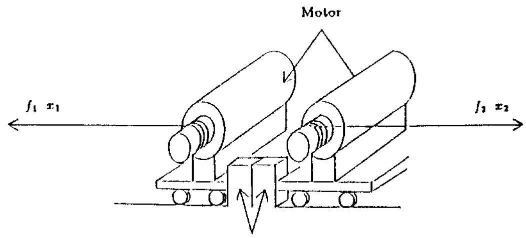


Fig.5 Experimental setup of the tug of war system

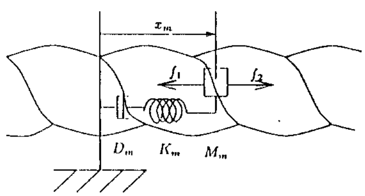


Fig.6 Dynamic model of a part of a rope

In a case where there is no time delay, a system has been proposed in [5] and a model following controller was employed. If the game is played between Japan and U.S.A., transmission delay will cause stability problem as in the case of the tele-operator system since the system is bilateral. One of the possible structure of the system is given in Fig.7(a) and its equivalent circuit is shown in Fig.7(b). (The structure will be refereed as a master-slave realization, later) In an actual system for the Japan-U.S.A. game, the model may be located in Hawaii. The variables are defined in Table 3. In the system the model acts as a slave system including environment dynamics, and players does as an operator in the tele-operator system. The dynamic equation of the model is given by:

$$M_m\ddot{x}_m + D_m\dot{x}_m + K_m x_m = F_{m1} - F_{m2}, \qquad (3.1)$$

and that for a plant 1 is represented by:

$$\left\{ \begin{array}{rcl} M_1\ddot{x}_1 + D_1\dot{x}_1 + K_1x_1 &=& f_1 - F_{c1} \\ F_{c1} &=& K_{d1}\dot{e}_1 + K_{p1}e_1 \end{array} \right. \qquad (3.2)$$
$$(\text{where } \dot{e}_1 := \dot{x}_1 - \dot{x}_m)$$

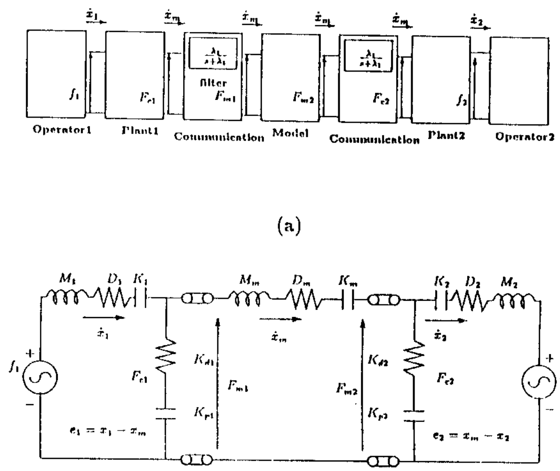
vspace0.5cm and that for a plant 2 is:

$$\left\{ \begin{array}{rcl} M_2\ddot{x}_2 + D_2\dot{x}_2 + K_2x_2 &=& F_{c2} - f_2 \\ F_{c2} &=& K_{d2}\dot{e}_2 + K_{p2}e_2 \end{array} \right. \qquad (3.3)$$
$$(\text{where } \dot{e}_2 := \dot{x}_m - \dot{x}_2)$$

From the figure the stability of the system is obvious. A problem of the structure is that the model is not driven by the actual force given by the players because of the actuator dynamics. In the next section the problem is overcome by an adaptive controller.

f_i	force generated by players (i=1,2)
F_{mi}	driving force to a model form plant i
F_{ci}	control input to plant i
$\dot{x}_m$	velocity of a model
M_m	mass of a model
D_m	damping coefficint of a model
K_m	spring constant of a model
M_i	mass of a plant i
D_i	damping coefficent of plant i
K_i	spring constat of plant i
K_{di}	feedback gain of velocity error in plant i
K_{pi}	feedback gain of position error in plant i

Table 3. Table of variables of an equivalent circuit for a remote tug of war system



(a)

(b)

Fig.7 Master-slave realization of tug of war system

3.2 Adaptive Realization of Tug of War System

As mentioned in the previous section, master-slave type realization is not suitable for tele-virtual realization of a dynamic model. A preferred structure for the system is that the actuators dynamics are precluded in the loop as shown in Fig. 8. In the network presentation of the system, the circuit for the actuators are short-circuited. If we knew exact values of parameters of the actuators, the network could be realized by the following control:

$$F_{c1} = K_{d1}\dot{e} + K_{p1}e - M_1\ddot{x}_m - D_1\dot{x}_1 - K_1x_1 \qquad (3.4)$$
$$F_{c2} = K_{d2}\dot{e} + K_{p2}e + M_2\ddot{x}_m + D_2\dot{x}_2 + K_2x_2 \qquad (3.5)$$

Since it is difficult to obtain exact value of the parameters in the actual situation, an adaptive controller which attains the equivalent controller above is proposed based on a Bounded-Gain-Forgetting (BGF) adaptive controller [4]. In the following one controller is considered but it can be applied to the another plant. First, the plant dynamics is transformed into a linear form of the parameters as:

$$\left[\begin{array}{ccc} M & D & K \end{array}\right]\left[\begin{array}{c} \ddot{x} \\ \dot{x} \\ x \end{array}\right] = Y^T a = u + f \qquad (3.6)$$

where

$$Y^T = [\ M \quad D \quad K\ ],\quad a = \begin{bmatrix} \ddot{x} \\ \dot{x} \\ x \end{bmatrix} \tag{3.7}$$

The proposed adaptive control algorithm is given by the following equations;
Control input:

$$\begin{aligned} u &= Y_c^T \hat{a} - f \\ Y_c^T &= [\ \ddot{x}_d - \dot{F}_f - \lambda s \quad \dot{x} \quad x\ ] \\ s &= \dot{e} + F_f \\ \dot{F}_f &= k_0 e + k_1 \dot{e} - f,\ e := x_m - x \end{aligned} \tag{3.8}$$

Parameter estimation:

$$\dot{\hat{a}} = -P(t)(Y_c^T s + W^T R(t) \hat{U}_e) \qquad R(t) > 0 \tag{3.9}$$

where

$$\begin{aligned} \frac{d}{dt} P^{-1}(t) &= -\lambda(t) P^{-1}(t) + W^T W \\ \lambda(t) &= \lambda_0 (1 - \|P\|/k_0), \qquad k_0, \lambda_0 > 0 \\ W^T(t) &= \int_0^t e^{-\lambda_f (t-\tau)} \lambda_f \begin{bmatrix} \ddot{x} \\ \dot{x} \\ x \end{bmatrix} d\tau \\ \hat{U}_e &= W\hat{a} - Wa \\ W\hat{a} &= W \cdot \hat{a} \\ \frac{d}{dt} Wa &= -\lambda_f Wa + \lambda_f (u + f) \end{aligned}$$

[Theorem]
If the adaptive controller above is used and x_m is sufficient rich to estimate the parameters, furthermore, if $\ddot{x}_m$, $\dot{x}_m$, x_m, and $\int x_m dt$ are bounded, and the disturbance force f is bounded and absolute integrable, then $(\dot{e}, f)$ becomes a passive pair, i.e.,

$$\int_0^t \dot{e} f dt \geq -\eta \qquad \exists\, \eta,\ \forall t \tag{3.10}$$

Further, the error converges to zero exponentially if the force is zero.
(Proof) See Appendix
A network representation of the adaptive controller is given in Fig.8 and the two port network is passive. The port variable is as same as those at the time invariant controller in Fig.9, then it can be simply replace by the adaptive controller, and the stability is maintained. Tracking performance of the adaptive controller is guaranteed by (3.8).

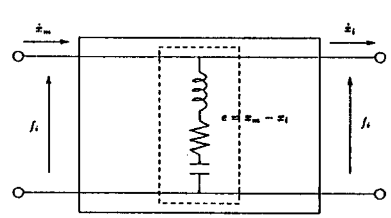


Fig.8 Network representation of passive adaptive controller

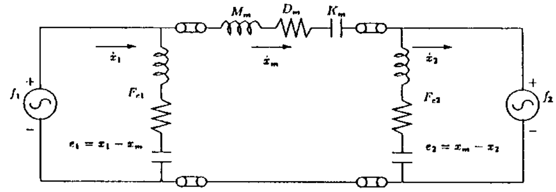


Fig.9 Suitable structure of tug of war system

4. Digital Implementation of Scattering Transformation

In this section we will discuss about restrictions of characteristic impedance due to a simple digital implementation of the scattering transformation. In the continuous case, characteristic impedance has no restrictions but it is positive. It has, however, some bounds if the transformation is realized with digital elements. Recall the block diagram of the scattering transformation shown in Fig.3. One of simple digital implementations of the scattering transformation is given as follow:

$$F_{md}(kT_c) = bv_m((k-1)T_c) + (F_s(kT_c - T) - bv_{sd}(kT_c - T)) \tag{4.1}$$

$$v_{sd}(kT_c) = \frac{1}{b}\{(F_{md}(kT_c - T) + bv_m(kT_c - T)) - F_s((k-1)T_c)\} \tag{4.2}$$

where k is integer and T_c ($<< T$) is a control period. First, we consider about a master part. Assume that T is infinity. Since F_{md} is fed to a master system being sign changed, the velocity, v_m is negatively fed back to the system. In the continuous case, however large the charasteristic impedance is, it has no problem since the term make the system more stable. In a discrete case, however, the term can make the master system unstable if the value is so large. Therefore, b have a upper bound $\bar{b}$ which is dependent of the control period and the plant parameters.

Next, we consider the slave part. Assume that T is infinity and an impedance of the slave system is infinity, furthermore F_s is simply determined by

$$F_s(kT_c) = K_d e(kT_c) = K_d v_{sd}(kT_c) \tag{4.3}$$

Then (4.2) becomes

$$v_{sd}(kT_c) = -\frac{K_d}{b} v_{sd}((k-1)T_c) + \frac{1}{b}\{(F_s(kT_c - T) + bv_m(kT_c - T))\} \tag{4.4}$$

Therefore, b must satisfy the following condition for $v_s d$ to be stable:

$$K_d \leq b \tag{4.5}$$

In the last, we will consider about the model part in Fig. 6b. Assume that transmission delays in both sides are infinity and the model is represented by

$$D_m \dot{x}_m(t) = F_{m1}(t) - F_{m2}(t) \tag{4.6}$$

According to (4.1), $F_{c1}(kT_c)$ and $F_{c2}(kT_c)$ are given by

$$F_{m1}(kT_c) = -b\dot{x}_m((k-1)T_c) + (F_{c1}(kT_c - T) + b\dot{x}_1(kT_c - T)) \tag{4.7}$$

$$F_{m2}(kT_c) = b\dot{x}_m((k-1)T_c) + (F_{c2}(kT_c - T) - b\dot{x}_2(kT_c - T)) \tag{4.8}$$

Substituting the above two equations into (4.6), we have

$$\dot{x}_m(kTc) = -\frac{b}{D_m}\dot{x}_m((k-1)T_c) + \frac{1}{D_m}\{(F_{c1}(kT_c - T) + b\dot{x}_1(kT_c - T)) - (F_{c2}(kT_c - T) - b\dot{x}_2(kT_c - T))\} \tag{4.9}$$

Therefore, b must satisfy the following inequality for $\dot{x}_m$ to be stable:

$$b \leq \frac{D_m}{2} \tag{4.10}$$

The above discussion shows that the characteristic impedance has its lower and upper bound which depends on the control period and parameters of actuators and the model.

5. Experimental Results

The proposed algorithms were applied to an experimental system shown in Fig.5. In the follwing experiments the time delay was set to 100 [msec] which was simulated by ring buffers in a computer, and the charasteric imperdance was selected as 0.8. For the signals to be smooth, a wave filter whose transfer function is given by

$$\frac{\lambda_1}{s + \lambda_1} \tag{5.1}$$

was used in one line of the scattering communication as shown in Fig. 7(a). If the scattering was not used, the filter was used for both velocity and force signals for comparisons.

Fig.10 shows a result when the scattering transformation was not used for the master-slave realization of the tag of war system. The rope was pulled once quickly and it began to diverge with oscilations as shown in the figure. Fig.11 shows a result when the scattering transformation was used. As shown in the figure, there was no oscilations and the system was stable. Tracking offset was remained since PD gains were not high enough. In the both experiments λ_1 was set to 100 and the control period was 3 [msec].

Fig.12 shows a result by the adaptive realization of the system. In the experiment a foregeting factor $\lambda(t)$ in the parameter estimation routine was set to zero, and an acceleration term corrsponding to $\ddot{x}_d$ was not fed forward since it had to be calculated by numerical differenciation and it was too noisy. λ in the wave filter was set to 10. As in this experiment PD gains were set ten times as large as the previous ones, the tracking offset was reduced but signals were not so smooth.

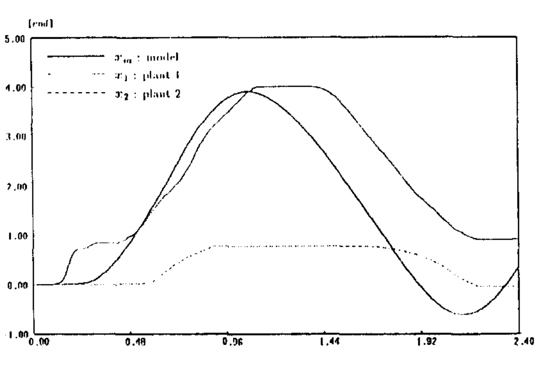


Fig.10 Responses of the master-slave realization without the scattering transformation

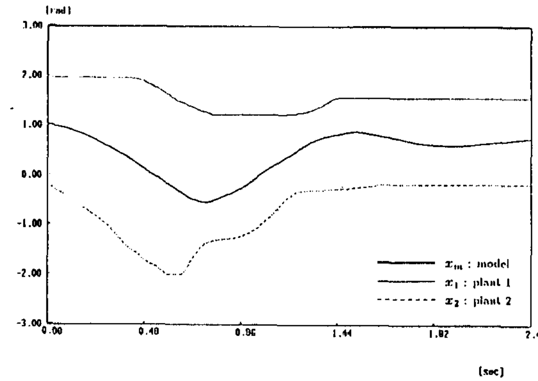


Fig.11 Responses of the master-slave realization with the scattering transformation

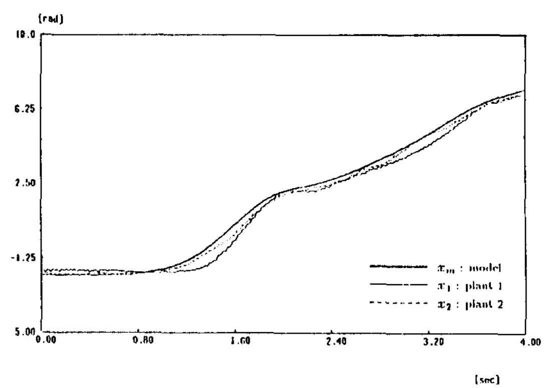


Fig.12 Responses of the adaptive realization with the scattering transformation

6. Experimental Results

The proposed algorithms were applied to an experimental system shown in Fig. 5. In the following experiments the time delay was set to 100 [msec] which was simulated by ring buffers in a computer, and the characteristic impedance was selected as 0.8. For the signals to be smooth, a wave filter whose transfer function is given by

$$\frac{\lambda_1}{s + \lambda_1} \tag{6.1}$$

was used in one line of the scattering communication as shown in Fig. 7a.[3] If the scattering was not used, the filter was used for both velocity and force signals for comparisons. The controllers were realized by a personal computer whose CPU was 80386 (16MHz) with 80387.

Fig. 10 shows a result when the scattering transformation was not used for the master-slave realization of the tug of war system. The rope was pulled once quickly and it began to diverge with oscillations as shown in the figure. Fig. 11 shows a result when the scattering transformation was used. As shown in the figure, there was no oscillation and the system was stable. Tracking offset was remained since PD gains were not high enough. In the both experiments λ_1 was set to 100 and the control period was 3 [msec].

Fig. 12 shows a result by the adaptive realization of the system. In the experiment a forgetting factor $\lambda(t)$ in the parameter estimation was set to zero, and an acceleration term corresponding to $\ddot{x}_d$ was not fed forward since it had to be calculated by numerical differentiation and it was too noisy. λ_1 in the wave filter was set to 10 and the control period was 5 [msec] due to the adaptive contorl low. As PD gains were set ten times as large as the previous ones in this experiment , the tracking offset was reduced but signals were not so smooth.

7. Appendix

From the conditions, the error converges to the sliding surface, s, exponentially as in [4] since the disturbance force, f,is canceled by control input, i.e.,

$$|s(t)| < s_0 e^{-\lambda_s t} \qquad \exists\, \lambda_s > 0 \tag{7.1}$$

Since f is absolute integrable, then

$$|\dot{e} + k_1 e + \int_0^t k_0 e dt| < s_0 e^{-\lambda_s t} + \int_0^t |f| dt < const. \tag{7.2}$$

Therefore $\dot{e}$,e,$\int edt$ are bounded and $\dot{x}$,x are bounded. On the other hand, since the control input is determined by:

$$u = Y_c^T \hat{a} - f, \quad Y_c^T = [\ \ddot{x}_d - \dot{F}_f - \lambda s \quad \dot{x} \quad x\ ] \tag{7.3}$$

it is bounded. The acceleration is given by

$$\ddot{x} = \frac{1}{M}(-C\dot{x} - Kx + u + f) \tag{7.4}$$

then it is bounded and $\ddot{e}$ becomes bounded.

Next, we will show that $(\dot{e}, f)$ is passive. Taking an inner product between $-\ddot{e}$ and f, we have

$$\int_0^t -\ddot{e} s dt \le \int_0^t |\ddot{e}||s| dt \le \|\ddot{e}\|_\infty s_0 \int_0^t e^{-\lambda_s t} dt \le \frac{\|\ddot{e}\|_\infty s_0}{\lambda_s} \tag{7.5}$$

Therefore,

$$\begin{aligned} \int_0^t -\ddot{e} s dt &= \int_0^t -\ddot{e}(\dot{e} + F_f) dt = \int_0^t -\ddot{e} \cdot \dot{e} dt - \int_0^t \ddot{e} F_f dt \\ &= -\left[\frac{1}{2}\dot{e}^2\right]_0^t - [\dot{e}F_f]_0^t + \int_0^t \dot{e} \cdot \dot{F}_f dt \\ &= -\left[\frac{1}{2}\dot{e}^2\right]_0^t - [\dot{e}F_f]_0^t + \int_0^t \dot{e}(k_1\dot{e} + k_0 e - f) dt \\ &\le \frac{\|\ddot{e}\|_\infty s_0}{\lambda} \end{aligned} \tag{7.6}$$

From the above inequality we have

$$\begin{aligned} \int_0^t \dot{e} f dt &\ge -\left[\frac{1}{2}\dot{e}^2\right]_0^t - [\dot{e}F_f]_0^t + k_1 \int_0^t \dot{e}^2 dt + k_0 \left[\frac{e^2}{2}\right]_0^t - \frac{\|\ddot{e}\|_\infty s_0}{\lambda} \\ &= -(\frac{1}{2}\dot{e}^2(t) - \frac{1}{2}\dot{e}^2(0)) - (\dot{e}F_f(t) - \dot{e}F_f(0)) \\ &+ k_0(\frac{\dot{e}^2(t)}{2} - \frac{\dot{e}^2(0)}{2}) + k_1 \int_0^t \dot{e}^2 dt - \frac{\|\ddot{e}\|_\infty s_0}{\lambda_s} \end{aligned} \tag{7.7}$$

From the above discussion, right hand-side of (7.7) has a lower bound, $-\eta$, for any t, then $(\dot{e}, f)$ is passive. Furthermore, if the external force, f, is zero, s is given by

$$s = \dot{e} + F_f = \dot{e} + \int (k_1\dot{e} + k_0 e) dt = \dot{e} + k_1 e + k_0 \int edt \tag{7.8}$$

Therefore, the exponential convergence of s implies that of e.

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