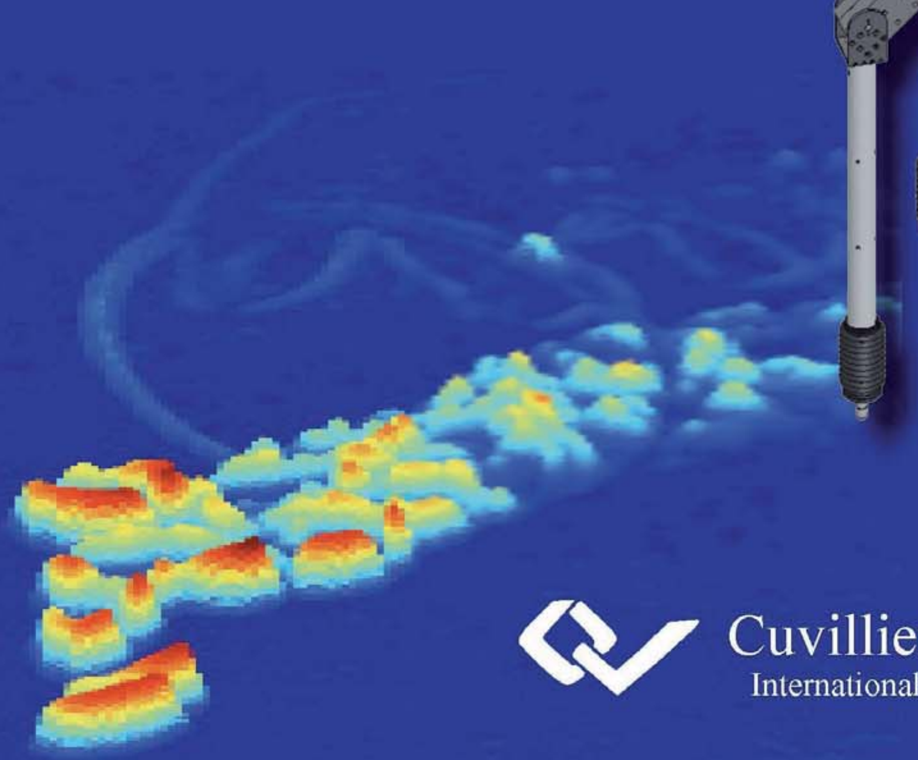
Edgar A. Martínez García / Abril Torres Méndez (eds.)

AUTONOMOUS ROBOTS

CONTROL, SENSING AND PERCEPTION



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CONTROL, SENSING AND PERCEPTION

Editors

Edgar A. Martínez García
Assistant Professor
Laboratorio de Robótica
Institute of Engineering and Technology
Universidad Autónoma de Cd. Juárez
Ave. del Charro No. 450 Norte,
Col. Raúl García, 32315
Juárez, Chihuahua, MEXICO
E-mail: edmartin@uacj.mx

Luz Abril Torres Méndez
Assistant Professor
Robotics and Advanced Manufacturing Group
CINVESTAV, Unidad Saltillo
Carr. Saltillo-Monterrey Km. 13,
Ramos Arizpe, Coahuila, 25205, MEXICO
E-mail: abril.torres@cinvestav.edu.mx

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Preface

In 1961, George Devol was granted a patent for the world's first digitally operated programmable robotic arm. That same year, Unimation, a company founded by Joseph Engelberger, and which had licensed Devol's patent, installed the world's first industrial robot in a General Motors assembly line near Trenton, New Jersey. The age of robotics had begun.

In the next decade, researchers in the field of artificial intelligence (AI) began to investigate the possibility of endowing these programmable robots with higher-level reasoning capabilities, including planning and perception. By the end of the nineteen sixties, robots had taken their place in AI labs at Stanford, MIT and Edinburgh. The age of intelligent robots was underway.

The following years saw an explosion of robotics research, in universities, government laboratories, and industry. By the nineteen eighties, robotics researchers optimistically predicted that robots would soon dominate the manufacturing workplace, replacing most human workers. It seemed only a matter of time until robots would move from the realm of science fiction to the everyday, real world. Those predictions failed to materialize, and consequently, robotics fell somewhat out of favor, beginning in the late nineteen eighties. It would be years before robotics one again captured the excitement of a new generation of young researchers, and even longer before robotics regained its reputation as a credible and fundamental area of research, deserving of significant funding resources.

At this moment, fifty years after the installation of the first industrial robot, it is interesting to look back at that initial optimism, to evaluate why it was not realized, and to consider what has driven the recent resurgence of robotics research. In many ways, the disappointments of the nineteen eighties are due not so much to the failings of robotics, as to the limitations of the technology of those years. Computers had limited power and limited memory. Real-time processing of large data sets (e.g., image streams) was impossible. Sensing capabilities were limited by the quality and type of sensors that were available. Analog cameras required special-purpose hardware to create digital images, which were often processed off-board in special-purpose (and very expensive) image processing systems. Tactile sensors, accelerometers, and force-torque sensors were both expensive and low-resolution. Faced with these limitations in technology, there was no possibility to implement advanced approaches to control (e.g., methods that require real-time solution of inverse dynamics equations), computer vision, probabilistic localization, etc. As a consequence, applications such as mobile robotics, humanoid robotics, or medical robotics failed to impress. Worse, the inability to effectively demonstrate advanced ideas on actual robotics platforms had the effect of stifling, to some extent, creative innovation in the robotics community. Much creative energy was spent attempting to solve the problems of limited technological capabilities, rather than the fundamental problems in robotics.

In the late nineteen nineties, technology (particularly computing) began to catch up to the needs of robotics, and a new wave of robotics research began. The present collection, edited by Luz Abril Torres-Méndez and Edgar A. Martínez-García rides the crest of that wave. The papers in this collection cover a vast assortment of topics essential to the progress of modern robotics research. They consider fundamental problems in control, planning, sensing, and perception. They deal with teloperated, wheeled, legged, and humanoid robots. They consider applications such as surveillance, navigation, rescue, and elder care. They bring perspectives from areas ranging from biological systems to modern control theory. In this first year of the second half-century of the age of robotics, the present collection will serve as an excellent guide to current research, and a roadmap for future exploration.

Seth Hutchinson
Urbana, Illinois

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Chapter 1

A Proposal for Dealing with Long Delay in Teleoperation Systems

*Adha Cahyadi[1,2], Rubiyah Yusof[2], Marzuki Khalid[2] and Yoshio Yamamoto[3]

Dept. of Electrical Eng, Gadjah Mada University, Indonesia[1]

Centre of Artificial Intelligent and Robotics (CAIRO)
Universiti Teknologi Malaysia, International Campus,
Jalan Semarak Kuala Lumpur, Malaysia[2]

Dept. of Precision Engineering, Tokai University, Kanagawa-Ken, Japan[3]

***Corresponding author: masimam@ic.utm.my**

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Abstract

In this chapter, a method to deal with long delayed teleoperation systems is studied. By transforming the teleoperation systems into Functional Differential Equations (FDE) systems, a concept that is applied to a class of nonlinear teleoperation systems with telecommunication delay is proposed. To show the effectiveness of the proposed method, numerical studies will be presented. It is shown that for arbitrarily long time delay and uncertain environmental contacts, the system remains stable in certain level of transparency.

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1 Introduction

Robotics have quickly been matured by increasing efforts of the untired researchers [19, 28]. However, a lot of works still have to be done related to the growing applications in the future. For instance, applications in hazardous environment or applications that are almost impossible to be done by human beings such as in nuclear power plants [24, 12], mining industries [8], space robots [1], virtual reality [17], unmanned vehicle operations [22], medical applications [16], cell/micro-organism applications [13], semiconductor industries [27] and so on. The research direction concerning the above mentioned works is known as robot teleoperation. In a common setting, in a teleoperation system as shown in Fig. 1, the operator will exert a force on the master manipulator which in turn, results in a displacement or velocity that is transmitted to the slave side as the order or command. In order to sense the manipulated object, some informations have to be returned from the slave side to the operator side. These information could be distance measurement, velocity measurement, force measurement or their combination. By sending the information back to the master side, the human operator will be able to feel what happened in the environment for example tactile senses. However, it may cause instability in the system if the model is not exactly known or the delay presents in the communication channel. These problems have been the main challenges faced by researchers for many years. Another problem that is also considered is about how to provide the capability to give the operator the feeling of what happened in the remote environment which is known as *transparency*. As stated by many researchers, stability and transparency are usually conflicting [15] and many works failed to compromize these two situations [10]. According to [26], in the mid of 1940s Goertz

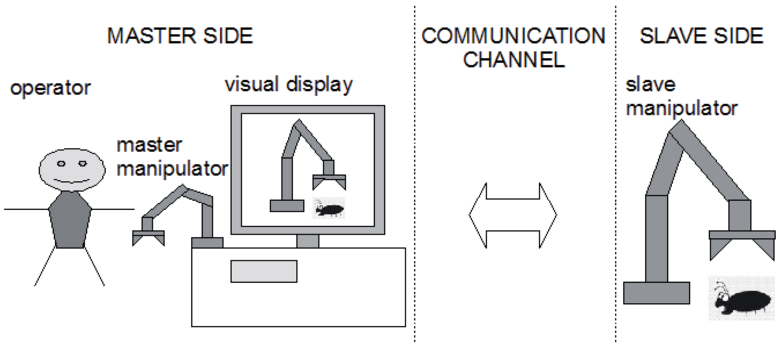


Figure 1: Illustration of a teleoperation system

developed robotic systems that was considered to be the first teleoperation system. After some years vacant, in the early of 1960s the research in teleoperation systems started increasing interests. Some preliminary concept to deal with the teleoperation problem were proposed, for instance, *move and wait scheme* [5], supervisory control [6], software languages [7, 25] and predictive visual display [3]. From 1980s, many stabilization methods for teleoperation systems started to appear, such as Lyapunov-based theorem [18], impedance scheme [23], hybrid scheme [9], scattering theory and passivity-based control [2, 20]. Since the works of [14], the passivity-based approach started its fame until now. However, in spite of being well-known and considered to be standard for so many teleoperation applications, the scenario of using local passivity based controller plus wave variables transformation have some disadvantages especially due to wave reflection (see [14, 30]). Some efforts have been done to compensate this issue and possibly growing in the future. One of the outcomes comes from [20] with their impedance matching scheme. However, this kind of impedance matching block can give serious effect to the position tracking.

In most of these works, however, only few are devoted to solve the long delay in the telecommunication channel. Moreover, it was summarized by

Imaida et. al [11], using the above control schemes, it is always difficult to control the teleoperation systems when delay is longer than one second. Considering these, in this chapter, we will deal specifically with the long delay issue. Using a simple phylosophy that if we are able to transform the teleoperation system into FDE form then we will able to stabilize the teleoperation system naturally. Therefore, we are going to start by building a concept for the FDE stabilization. Firstly we will deal with the simplest stability condition of scalar FDE systems. It is found that a simple algebraic condition will ensure the boundedness of the solution. Furthermore, the systems is Input to State Stable (ISS). From these facts, we extend the concept into the higher dimensional systems in order to develop the similar conditions. Finally, the stabilization of teleoperation systems with arbitrary long communication delay will be proposed. Numerical studies of many classes of teleoperation systems will also be presented to verify the effectivenes of the method. A bit further, we also pursue the transparency issue of our proposed scheme. Here we propose a new definition of transparency and how to achieve it as well as to find out the relationship between the stability and transparency.

Throughout this chapter the following notations are used. Suppose there is a given constant $\tau \geq 0$, $\mathbb{R}$ and $\mathbb{R}^n$ a real number and n-dimensional vector space over $\mathbb{R}$, respectively. Define $C([a,b],\mathbb{R}^n)$ a function that maps the interval $[a,b]$ into $\mathbb{R}^n$ with norm $\|x\|_\infty = \sup_{t\in[a,b]} \|x(t)\|$, where $\|\cdot\|$ is Euclidean norm. A function $f : [0,s) \rightarrow [0,\infty)$ is said to be class $\mathscr{K}_\infty$ function if it is increasing, continuous and zero at zero. We call it class $\mathscr{K}_\infty$ if $\lim_{r\rightarrow\infty} f(0,r) \rightarrow \infty$. Finally we define $f : [t,s) \rightarrow [0,\infty)$ as class $\mathscr{K}\mathscr{L}_\infty$ function if for fixed t the function is increasing while for fixed s the function is monotonically decreasing to zero.

2 Stabilization under uncertain delay

Let us consider the following delayed nonlinear system that is in the form of FDE

$$\Sigma : \begin{cases} x'(t) = f(t,x(t),x(\cdot),u(t)), & t \in [0,+\infty) \\ x(t) = \varphi(t), & t \in [-\tau,0) \end{cases} \tag{1}$$

where $f \in [-\tau,+\infty) \times \mathbb{R}^n \times \mathbb{R}^k \rightarrow \mathbb{R}^n$ is locally Lipschitz continuous function on $\mathbb{R}^n$, $\varphi(t)$ is smooth differentiable function, $x(\cdot)$ means $x(t-\tau)$ and $u(t)$ on $\mathbb{R}^n$ is the input to the system. It is noted that the above class covers very general nonlinear delayed systems.

For developing stabilization tool, we are going to start with the following lemma.

Lemma 2.1. *Suppose*

$$\dot{s}(t) = \alpha s(t) + \sum_{i=1}^{N} \beta_i s(t-\tau_i) \tag{2}$$

and

$$\alpha + \|\sum_{i=1}^{N} \beta_i\| \leq 0, \tag{3}$$

then every solution of (2) $\rightarrow 0$ *as* $t \rightarrow \infty$. *Moreover, the solution is bounded by*

$$s(t) \leq \left(\exp(-\int_0^t \alpha(\eta) d\eta) + \sum_{i=1}^{N} \int_0^t (\beta_i(\zeta) \exp(-\int_\zeta^t \alpha(\eta) d\eta) d\zeta) \right) \max_{-\tau \leq \zeta \leq 0} s(\zeta). \tag{4}$$

Proof. The characteristic equation of (2) is given as

$$\lambda = \alpha + \sum_{i=1}^{N} \beta_i e^{-\lambda h_i}.$$

In order to be stable, we need to show that if under (3), the real parts of all of possible eign values are negative. Let us set $\lambda = \sigma + j\omega$, then

$$\begin{aligned} \sigma + j\omega &= \alpha + \sum_{i=1}^{N} \beta_i e^{-\sigma h_i} e^{-i\omega h_i} \\ &= \alpha + \sum_{i=1}^{N} \beta_i e^{-\sigma h_i} (\cos \omega h_i - i \sin \omega h_i). \end{aligned}$$

Here we require that

$$\sigma - \alpha = \sum_{i=1}^{N} \beta_i e^{-\sigma h_i} \cos \omega h_i \leq 0$$

Let us assume that $\sigma \geq 0$ then we have

$$-\alpha \leq \sigma - \alpha \leq \sum_{i=1}^{N} \|\beta_i\| e^{-\sigma h_i} \leq \|\sum_{i=1}^{N} \beta_i(t)\|$$

$$\alpha + \|\sum_{i=1}^{N} \beta_i\| \geq 0$$

that contradicts (3). Therefore, every solution of (2) $\rightarrow 0$ as $t \rightarrow \infty$.

To find the bound (4), let us set

$$Q(t) = p(t)\{s(t) + \delta(q_1(t) + q_2(t) + \cdots + q_N(t))\}$$

where

$$\begin{aligned}
p(t) =& \exp(-\int_0^t \alpha(\eta)d\eta) \\
q_1(t) =& -[p(t)]^{-1}\exp(-\int_0^t \beta_1(\zeta)p(\zeta)d\zeta) \\
q_2(t) =& -[p(t)]^{-1}\exp(-\int_0^t \beta_2(\zeta)p(\zeta)d\zeta) \\
&\cdots \\
q_N(t) =& -[p(t)]^{-1}\exp(-\int_0^t \beta_N(\zeta)p(\zeta)d\zeta),
\end{aligned}$$

while δ is a constant to be determined later. Differentiation on $p(t)$ and $q_i(t)$ will give

$$\begin{aligned}
\dot{p}(t) =& -\alpha(t)p(t) \\
\dot{q}_1(t) =& \alpha(t)q(t) - \beta_1(t) \\
\dot{q}_2(t) =& \alpha(t)q(t) - \beta_2(t) \\
&\cdots \\
\dot{q}_N(t) =& \alpha(t)q(t) - \beta_N(t).
\end{aligned}$$

Therefore,

$$\begin{aligned}
\dot{Q}(t) =& -\alpha(t)p(t)\left\{s(t) + \delta\sum_{i=1}^{N}(q_i(t))\right\} + \dot{s}(t)p(t) + \delta\alpha(t)p(t)\sum_{i=1}^{N}(q_i(t) - \beta_i(t)) \\
\leq& p(t)\sum_{i=1}^{N}\beta_i(t)(s(t-\tau_i) - \delta).
\end{aligned}$$

Choosing δ as

$$\delta = \max_{-\tau\leq\zeta\leq t} s(\zeta)$$

where $\tau = \max \tau_i$, will make $\dot{Q}(t) \leq 0$, thus Q is a decreasing function. By rearranging $Q(t_2) - Q(t_1)$ where $-\tau \leq t_1 < t_2$, the following bound applies

$$\begin{aligned}
s(t_2) \leq & \exp(\int_{t_1}^{t_2} \alpha(\eta)d\eta)s(t_1) + \left(\int_{t_1}^{t_2} \sum_{i=1}^{N} \beta_i(\zeta)\exp(\int_{\zeta}^{t_2} \alpha(\eta)d\eta)d\zeta\right)\delta \\
\leq & \left(\exp(\int_{0}^{t_2} \alpha(\eta)d\eta) + \int_{0}^{t_2} \sum_{i=1}^{N} \beta_i \exp(\int_{\zeta}^{t_2} \alpha(\eta)d\eta)d\zeta\right)\delta \qquad (5) \\
\leq & \left(\exp(\int_{0}^{t} \alpha(\eta)d\eta) + \sum_{i=1}^{N} \int_{0}^{t} \beta_i(\zeta_i)d\zeta_i\right)\delta.
\end{aligned}$$

Therefore the inequality bound (4) follows. □

Remark 2.1. *The necessary condition for the boundedness of solution of (2) is* $\alpha \leq 0$.

Remark 2.2. *The lemma can be read as, if we can find* $\alpha \leq 0$ *such as negative enough to overcome* $\|\sum_{i=1}^{N} \beta_i\|$ *then we can guarrantee that the solution of (2) is bounded.*

Corollary 2.1. *With finite nonzero input, i.e.,* $\|u(t)\|_\infty \leq \infty$ *the system (1) under Lemma 2.1 is ISS.*

Proof. Using input (2) will be

$$\begin{aligned}
\dot{s}(t) &= \alpha(t)s(t) + \sum_{i=1}^{N} \beta_i(t)s(t-\tau_i) + u(t) \\
\dot{s}(t) &\leq \alpha(t)s(t) + \sum_{i=1}^{N} \beta_i(t)s(t-\tau_i) + \|u(t)\|_\infty.
\end{aligned} \qquad (6)$$

Therefore, by following the step as before we will arrive at

$$\begin{aligned}
s(t) \leq & \left(exp(\int_{0}^{t} \alpha(\eta)d\eta) + \int_{0}^{t} \beta(\zeta)exp(\int_{\zeta}^{t} \alpha(\eta)d\eta)d\zeta\right)^{\frac{1}{2}} \|s(\zeta)\|_\infty \\
& + \left(\int_{0}^{t} exp(\int_{\zeta}^{t} \alpha(\eta)d\eta)d\zeta\right)^{\frac{1}{2}} \|u(t)\|_\infty \qquad (7) \\
\leq & \pi(t, \|s(t)\|_\infty) + \rho(\|u(t)\|_\infty).
\end{aligned}$$

where we have defined

$$\pi(t,\|s(t)\|_\infty)=\left(\exp(\int_0^t\alpha(\eta)d\eta)+\int_0^t\beta(\zeta)\exp(\int_\zeta^t\alpha(\eta)d\eta)d\zeta\right)^{\frac{1}{2}}\|s(\zeta)\|_\infty$$

and $\rho(\|u(t)\|_\infty)=\exp(\overline{\alpha}t)\|u(t)\|_\infty$. One can see that $\pi(t,\|s(t)\|_\infty)$ belongs to Class $\mathcal{KL}_\infty$ function while $\rho(\|u(t)\|_\infty)$ belong to Class $\mathcal{K}_\infty$. Therefore, the systems is ISS. □

Theorem 2.1. *If*

$$2\left\langle x(t),f(x(t),x(\cdot))\right\rangle\leq\alpha(t)\|x(t)\|^2+\beta(t)\|x(\cdot)\|^2. \tag{8}$$

and

$$\alpha(t)+\beta(t)\leq 0. \tag{9}$$

then system (1) with zero input is stable under the bound (4).

Proof. Let us set $s=x^T(t)x(t)$, by differentiation we get

$$\begin{aligned}\dot{s}=&2x^T(t)\dot{x}(t)\\ \leq&\alpha(t)\|x(t)\|^2+\beta(t)\|x(\cdot)\|^2\\ =&\alpha(t)s(t)+\beta(t)s(\cdot).\end{aligned} \tag{10}$$

Therefore Lemma 2.1 follows. □

Definition 2.1. *The system (1) is said to be* FDE-stable *if (8) and (9) hold.*

3 Teleoperation stabilization

In this section we aim to answer the question on how to solve a teleoperation system problem via feedback *FDE-stabilization*. In many works, teleoperation systems usually have many different representations. Therefore, in order to be well-arranged, when *teleoperation system* is mentioned, it will mean that its manipulator part is modelled in the following form

$$\Sigma_i:\begin{cases}\dot{x}_i=F_i(x_i,u_i)\\ y_i=H_{xi}^T(x_i,u_i),\quad i\in\{m,s\}\end{cases} \tag{11}$$

where m,s refer to master and slave, respectively, Σ_i means the subsystem, x_i denotes the state variables of the subsystem, $F_i(\cdot)\in\mathbb{R}^n$ and $H_{xi}(\cdot)\in\mathbb{R}^m$

with $m \leq n$ are the smooth differentiable functions. The matrices $F_i(\cdot)$ and $H_i(\cdot)$ refer to dynamical matrix and output matrix, respectively. It should be noted that (11) is very general equation as the above equation will include all of nonlinear or linear manipulator systems. For some classes, teleoperation systems can also be written in affine form as

$$\Sigma_i : \begin{cases} \dot{x}_i = F_i(x_i) + G_i(x_i)u_i \\ y_i = H_{xi}^T(x_i) + H_{ui}^T u_i, \quad i \in \{m,s\} \end{cases} \tag{12}$$

where $G_i(\cdot) \in \mathbb{R}^n$ and $H_{ui}(\cdot) \in \mathbb{R}^m$ with $m \leq n$ are the smooth differentiable functions.

Definition 3.1. ***(Solving teleoperation problem via FDE-stabilization)*** *For a given delayed nonlinear teleoperation systems (11), find state feedback controllers for each subsystem*

$$u_i = \gamma_i(x, x(\cdot), v) \tag{13}$$

such that the overall closed loop system is FDE-stable.

The above problem seems not an easy one since there is no direct relationship between teleoperation system and FDE. However, it is turned to be clear when we merge together the separated system (*e.g.,* master and slave manipulators) into a single system. Let us define

$$\begin{aligned} x(t) &= [x_m(t)\, x_s(t)] \\ x(\cdot) &= [x_m(t - T_2(t))\, x_s(t - T_1(t))] \\ T &= [T_1,\, T_2]^T \end{aligned} \tag{14}$$

and also $u = [u_m,\, u_s]^T$ and $v = [v_m,\, v_s]^T$ where

$$\hat{F}_i(x, x(\cdot), v) = F(x, u(x(\cdot), v)) \tag{15}$$

then the teleoperation system (11) can be re-written as

$$\begin{aligned} \dot{x} &= F(x, u(x(\cdot), v)) = \hat{F}(x, x(\cdot), v) \quad t \in [0, +\infty) \\ x &= \phi(t) = x(t - T), \quad t \in [-\max\{T_m, T_s\}, 0). \end{aligned} \tag{16}$$

Equation (16) shows that the teleoperation systems indeed belong to FDE. Therefore, we have successfully translated the teleoperation stabilization problem into feedback FDE-dissipasiton.

In order to stabilize the teleoperation systems, we propose the following algorithm:

1. Transform the original system in form of system (1).
2. Consider $\langle x, f(x, x(\cdot), u(x, x(\cdot), v(t)))\rangle$ then set our condition of interest satisfying (8).
3. Set $u(x, x(\cdot), v(t))$ until (9) is met.
4. (Extra step) Using this $u(x, x(\cdot), v(t))$, minimize $\alpha(t)$ to speed up the response. For any bounded external input $v(t)$, the system will be ISS.

4 Applications

4.1 Linear case

Consider linear manipulators arranged as master and slave with communication delay as follows

$$\Sigma_i : \begin{cases} M_i\ddot{x}_i + C_i\dot{x}_i + N_i x_i = \tau_i + u_i(x_i, y_j(t - T_j)) \\ y_i = H_i(x_i), \quad i, j \in \{m, s\}, i \neq j \end{cases} \tag{17}$$

where $\tau = \{\tau_{human}\ \tau_{env}\}$ defined to be the external forces/torques from respectively, human and environment acting on the manipulators. It can be seen that all of the matrix are constants. If we interpret M_i, C_i and N_i are respectively, inertia matrix, Coriolis and centrifugal term, and gravity and external force term, it is very common in many literatures to express (17) in simpler form as follows

$$\Sigma_i : \begin{cases} M_i\ddot{x}_i + C_i\dot{x}_i = \tau_i + u_i(x_i, y_j(t - T_j)) \\ y_i = H_i(x_i), \quad i, j \in \{m, s\}. \end{cases} \tag{18}$$

For simplicity, we can augment (18) into a single system including delay. Defining,

- $x = [x_m,\ x_s]^T$
- $M := \mathrm{diag}\{M_m, M_s\}$,
- $C := \mathrm{diag}\{C_m, C_s\}$,
- $\tau := \mathrm{col}\{\tau_m, \tau_s\}$,
- $T \in \{T_m, T_s\}$,
- $u := \mathrm{col}\{u_m, u_s\}$ and

- $y := \mathrm{col}\{y_m, y_s\}$,

then we can express (18) as

$$\Sigma : \begin{cases} M\ddot{x} + C\dot{x} = \tau + u(x, y(t-T)) \\ y = \mathrm{col}\{H_m(x_m),\, H_s(x_s)\}. \end{cases} \tag{19}$$

As y is a function of x, we can further simplify (19) as follows

$$M\ddot{x} + C\dot{x} = \tau + \hat{u}(x, x(t-T)) \tag{20}$$

where $\hat{u}(x, x(t-T)) := u(x, y(t-T))$. As M is invertible, by defining $x_1 = x$, $x_2 = \dot{x}$ finally our system can be written in state space form as follows

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ -M^{-1}Cx_2 \end{bmatrix} + \begin{bmatrix} 0 \\ M^{-1}\hat{u}(x, x(t-T) + M^{-1}\tau) \end{bmatrix}. \tag{21}$$

It can be seen from (19) to (21) that the system is no longer linear as delays are already included in the system. Moreover, implicitly (21) is already in FDE from. As the teleoperation system (17) is always governed by the time delay, it is always possible to express it explicitly in the form of (16). For sake of simplicity, let us choose the control law to be in the form of

$$\hat{u}(x, x(\cdot)) = u_a(x) + u_b(x(\cdot)), \tag{22}$$

which leads to

$$\begin{aligned} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} &= \begin{bmatrix} x_2 \\ M^{-1}[-Cx_2 + u_a(x)] \end{bmatrix} \\ &\quad + \begin{bmatrix} 0 \\ M^{-1}u_b(x(\cdot)) + M^{-1}\tau \end{bmatrix} \\ &:= f_l(x) + g_l(x(\cdot)) + h_l(\tau) \end{aligned} \tag{23}$$

that is clearly in the form of (16).

Remark 4.1. *In teleoperation system, in order to achieve coordination control, the delayed part of the control law (22) is not allowed to be trivially zero.*

Proposition 4.1. *The delayed linear system (23) can be rendered to be FDE-stable system with the control law*

$$u = \underbrace{-Mx_1}_{u_a(x)} \underbrace{-diag\{k_{di}(x_{1i}^2(\cdot) + x_{2i}^2(\cdot))\}x_2}_{u_b(x(\cdot))} \tag{24}$$

where $i \in \{1, 2, \cdots n\}$ is the link number and k_{di} are positive constants.

Proof. The proof relies on Theorem 2.1. According to the theorem, it is necessary for (23) to satisfy (8) and (9) in order to be FDE-stable system. Therefore, the following inequality has to be satisfied

$$2\langle z, f(z,\psi(\cdot),\chi(t))\rangle \leq \alpha(t)\|z\|^2 + \beta(t)\|\psi(\zeta)\|^2.$$

Using $z = [x_1, x_2]^T$ and substituting all terms, we get

$$\begin{aligned} 2\langle z, f_l(z,\psi(\cdot)\rangle &= x_1^T x_2 + x_2^T M^{-1}[-Cx_2 + u_a(x)] + x_2^T M^{-1} u_b(x(\cdot)) \\ &= -x_2^T M^{-1} C x_2 + x_2^T M^{-1} x_2 diag\{k_{di}\} x^T(\cdot) x(\cdot) \\ &\leq \alpha(\|x_1\|^2 + \|x_2\|^2) + \beta(\|x_1(\cdot)\|^2 + \|x_2(\cdot)\|^2). \end{aligned}$$

Here we have defined α and β, respectively, as

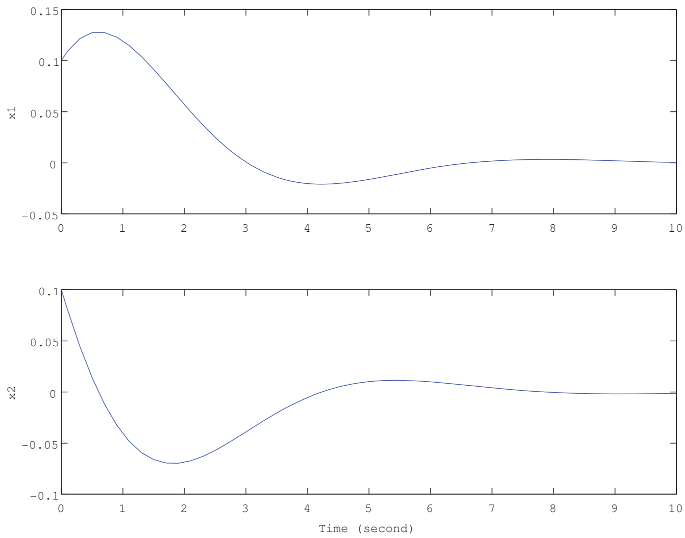
$$\alpha := \min\{\lambda(M^{-1}C)\}, \text{ and}$$

$$\beta := k_d \max\{\lambda(M^{-1})\}\}$$

where $\lambda(\cdot)$ means the eigenvalue of a matrix. □

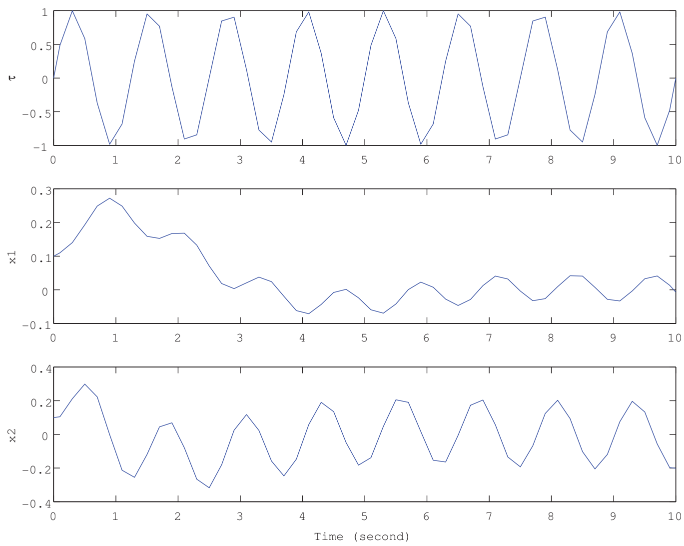
To get the intuitive idea about what we have just obtained, we will demonstrate the use of control law (24). However, we are not going to talk about teleoperation system, instead, a trivial example is given. Let us consider a delayed first order linear system (23) whose parameters M, C, k_d are set respectively as 0.1, 1, 1. Moreover, both of the initial condition for x_1 and x_2 are set to 0.1 and the delay is set to a constant arbitrarily high, say 10 seconds. The numerical results when no external forces are exerted are given in Figure 2. It is seen from the simulation results that, in the absence of external forces, the states are converged to zero thus the system is asymptotically stable. The simulation results when the system is excited with external input are depicted in Figure 3. It is also seen that the system is stable in the sense of ISS, more exactly it is FDE-stable system. Despite it is seen that in the above case the system can be rendered to be FDE-stable, it, however, says nothing about teleoperation system. Even if we connect both master and slave sides using the above control law, it still does not have any teleoperation sense since the slave manipulator cannot follow the given command. In orther words, the both sides will act independently thus the slave side cannot track the master side position. Therefore, the system (23) with the control law (24) has to be re-written in order to have teleoperation sense. Hence let consider a replacement of the slave side as follows

$$\Sigma_s : \begin{cases} M_s \ddot{x}_e + C_s \dot{x}_e + N x_e = \tau_e + u_s(x_e, y_m(t - 2T_m)) \\ y_s = H_s(x_s) \end{cases} \tag{25}$$



(Top) State x_1
(Bottom) State x_2

Figure 2: State dynamics



(Top) External force
(Middle) State x_1
(Bottom) State x_2

Figure 3: Effect of the external force

where x_e is defined to be $x_s - x_m(\cdot)$. This can be transformed into state space form to replace (24) and (23)as

$$\begin{bmatrix} \dot{x}_{1m} \\ \dot{x}_{1e} \\ \dot{x}_{2m} \\ \dot{x}_{2e} \end{bmatrix} = \begin{bmatrix} x_{2m} \\ x_{2e} \\ M_m^{-1}[-C_m x_{2m} + u_{am}(x_m)] \\ M_s^{-1}[-C_s x_{2e} + u_{as}(x_e)] \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ M_m^{-1} u_{bm}(x_m(\cdot)) \\ M_s^{-1} u_{bs}(x_e(\cdot)) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ M_m^{-1} \tau_{hum} \\ M_s^{-1} \tau_{env} \end{bmatrix} \tag{26}$$

$$\begin{aligned} u_m &= -M_m x_{1m} - diag\{k_{mi}(x_{1mi}^2(\cdot) + x_{2mi}^2(\cdot))\} x_{2m} \\ u_s &= -M_s x_{1e} - diag\{k_{si}(x_{1ei}^2(\cdot) + x_{2ei}^2(\cdot))\} x_{2e} \end{aligned} \tag{27}$$

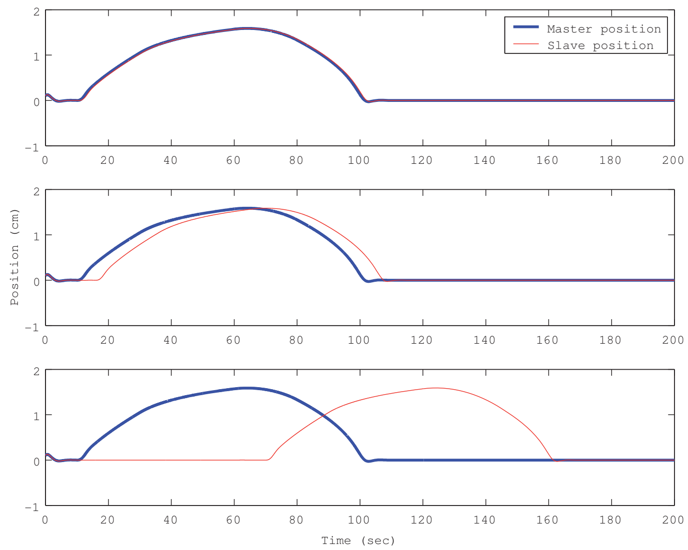
where $i \in \{1, 2, \cdots n\}$ is the link number, k_{mi}, k_{si} are positive constants. By explicitly expressing x_e back into $x_s - x_m(\cdot)$ finally we arrive at the following corollary.

Corollary 4.1. *The control law*

$$\begin{aligned} u_m &= -M_m x_{1m} - diag\{k_{mi}(x_{1mi}^2 + x_{2mi}^2)\} x_{2m} - F_{ed} \\ u_s &= M_s \ddot{x}_m(\cdot) - M_s(x_{1s} - x_{1m}(\cdot)) - diag\{k_{si}((x_{1si} - x_{1mi}(t - 2T_m))^2 \\ &\quad + (x_{2si} - x_{2mi}(t - 2T_m))^2)\}(x_{2s} - x_{2m}(\cdot)) \end{aligned} \tag{28}$$

where $i \in \{1, 2, \cdots, n\}$ is the link number, k_{mi}, k_{si} are positive constants, and F_{ed} is the delayed force sent from the slave side, is able to render the closed loop system FDE-stable.

Using the same parameters as the previous example for both master and slave system, Here we simulate the tracking response for constant time delays set to respectively 0.6 second, 6 seconds and 60 seconds. The tracking responses are shown in Figure 4, we can see that the slave manipulator can track the master manipulator in reasonably good manner irrespective of the communication delay. It is seen that the due to the delay, when the same human force is applied (see Figure 5), the shape of the response acts diffrently because of the dynamics of the manipulator. However, the stability can be well maintained even the delay is varying 100 times. Let us now place a virtual rigid wall with stiffness $10000 N/m$ placed at 0.5 cm in front of the slave manipulator. The responses are shown in Figure 6. It is shown from the figure that even with environmental interaction, the overall stability still can be maintained. Let us now set the master side control law to be (28). The tracking responses for, respectively, 0.6 second, 6 seconds and 60 seconds delays are depicted in Figure 4. It is seen now that the tracking responses can maintain the shape of the responses irrespective of the communication delays. Moreover, when a virtual rigid wall with stiffness $10000 N/m$ is placed at 0.5 cm in front of the slave manipulator, the responses shown in Figure 6 tell us that the stability can be maintained with almost the same shape of the responses. For comparison purposes, we simulate the performance of the teleoperation system using passivity based controller with wave variable transformation [21]. Using the same manipulators for both master and slave sides, the controller is given by



(Top) Delay= 0.6 second
(Middle) Delay= 6 seconds
(Bottom) Delay= 60 seconds

Figure 4: Tracking responses

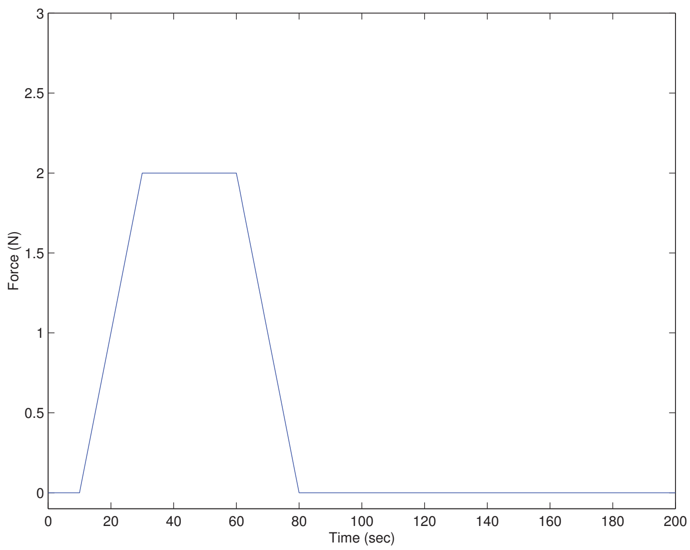
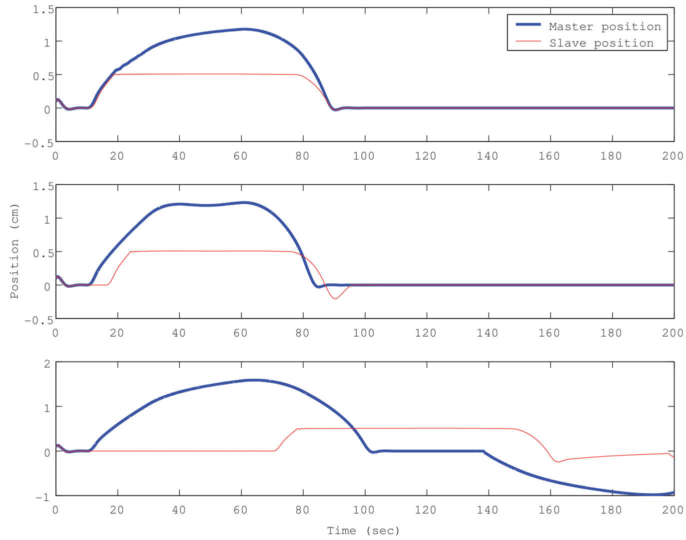


Figure 5: Human force applied to the master side

$$u_m = k_{fm} f_s(t-T) + k_{vm}\dot{x}_m$$
$$u_s = k_{vs}\left(\int_0^t (\dot{x}_m(\tau - T) - k_{fs}F_e)d\tau - x_s\right)$$

where the controller parameters, *i.e.*, k_{fm}, k_{vm}, k_{vs} and k_{fs} are, respectively, set to 1, 1, 1 and 0.1. The simulation results are depicted in Figure 7 and Figure 8. It is seen that the tracking responses, compared with the above



(Top) Delay= 0.6 second
(Middle) Delay= 6 seconds
(Bottom) Delay= 60 seconds

Figure 6: Responses under environmental contact

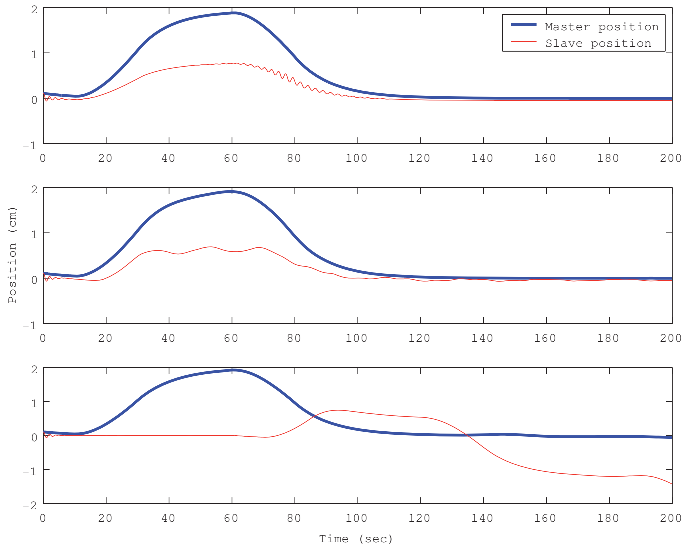
proposed schemes, are not satisfactory and depend highly on the amount of the delay. Moreover it has significant tracking error. In Figure 8, the wall is replaced with the soft one with stiffness 0.3 N/m and also shifted to 0.2 cm because the response becomes highly unstable for the very stiff wall. In spite of this replacement, the responses are still not satisfactory and only achieve marginally stable for 60 seconds delay.

4.2 Nonlinear teleoperation stabilization

It is possible to extend the principle that we have applied to the linear systems into more general nonlinear systems especially for Euler-Lagrange representation as follows.

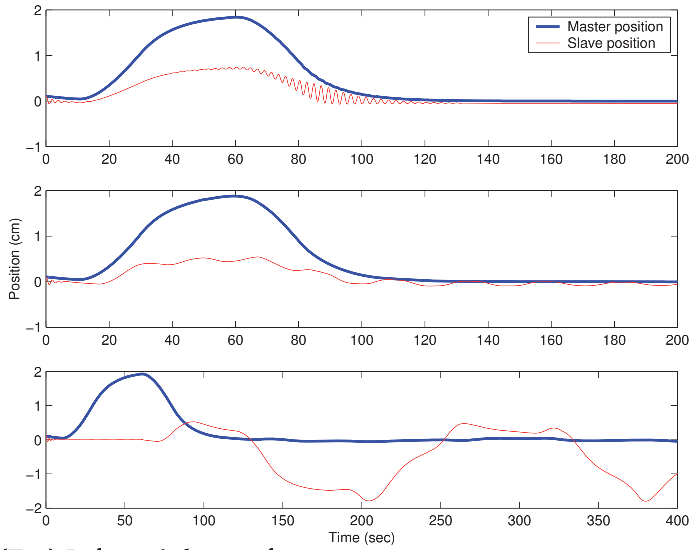
$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + N_i(q_i,\dot{q}_i) = \tau_i \tag{29}$$

where m, s refer to master and slave, respectively, $q_i \in \mathbb{R}^n$ represents link generalized coordinates, $M(q_i) = M^T(q_i) > 0$ is the robot inertia matrix, $C_i(q_i,\dot{q}_i)$ is the Coriolis and centrifugal forces term, and $N_i(q_i,\dot{q}_i)$ is the gravity force and external forces term. It is known from literature that the kinetic energy and potential energy of the above system are,*respectively*, given by $T_i(q_i,\dot{q}_i) = \frac{1}{2}\dot{q}_i^2 M_i(q_i)\dot{q}_i$ and $V_i(q_i)$ with $g_i(q_i) = \frac{\partial V_i(q_i)}{\partial q_i}$, where $g_i(q_i)$ is the gravity force term. Let us choose the same control law in the same form as (22). As



(Top) Delay= 0.6 second
(Middle) Delay= 6 seconds
(Bottom) Delay= 60 seconds

Figure 7: Tracking responses of passivity based control [21]



(Top) Delay= 0.6 second
(Middle) Delay= 6 seconds
(Bottom) Delay= 60 seconds

Figure 8: Responses under soft environment contact using passivity based control [21]

$M(q)$ is invertible, by defining $x_1 = q$, $x_2 = \dot{q}$ our teleoperation system can be written in state space form as follows

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ -M(x_1)^{-1}C(x_1,x_2)x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -M(x_1)^{-1}N(x_1,x_2) \end{bmatrix} + \begin{bmatrix} 0 \\ M(x_1)^{-1}\tau \end{bmatrix} + \begin{bmatrix} 0 \\ M(x_1)^{-1}\hat{u}(x,x(t-T)) \end{bmatrix}. \tag{30}$$

Similar to Proposition (4.1), the following proposition provide a similar control law for Euler Lagrange version

Proposition 4.2. *The Euler Lagrange systems (29) can be rendered FDE-stable with the control law*

$$u = \underbrace{-M(x)x_1 + N(x_1,x_2)}_{u_a(x)} \underbrace{-diag\{k_{di}(x_{1i}^2(\cdot) + x_{2i}^2(\cdot))\}x_2}_{u_b(x(\cdot))}. \tag{31}$$

where $i \in 1,2,\cdots,n$ is the link number, k_{di} are positive constants.

Proof. The proof is very similar with Proposition 4.1 except here we have to generalize into Euler Lagrange systems. Therefore, we skip the overall proof for convenience. □

We are going to demonstrate the stabilization of the Euler Lagrange systems using control law (31). In order to avoid the use of gravity compensation, a two links SCARA robot as shown in Figure 9 from [4] is used in this example. The dynamics of this manipulator is given by

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\theta = u - \tau_e \tag{32}$$

where u is the control input torque, τ_e is the torque due to interaction with the environment, and

$$M(\theta) = \begin{bmatrix} p_1 + 2p_3\cos\theta_2 & p_2 + p_3\cos\theta_2 \\ p_2 + p_3\cos\theta_2 & p_2 \end{bmatrix},$$

$$C(\theta,\dot{\theta})\dot{\theta} = \begin{bmatrix} -p_3\dot{\theta}_2(2\theta_1 + \theta_2)\sin\theta_2 \\ p_3\theta_1^2\sin\theta_2 \end{bmatrix}$$

where

$$\begin{aligned} p_1 = &\; I_1 + I_2 + I_{3c} + I_3 + I_4 + I_p + (M_3 + M_4 + M_p)L_1^2 \\ &\; + M_2L_3^2 + M_4L_4^2 + M_pL_2^2 \\ p_2 = &\; I_3 + I_4 + I_p + M_4L_4^2 + M_pL_2^2 \\ p_3 = &\; M_4L_1L_4 + M_pL_1L_2. \end{aligned}$$

The value of the parameters in the above dynamic equation are as follows

$$\begin{aligned} p_1 = &\ 3.316\,\mathrm{kg}/m^2 \\ p_2 = &\ 0.117\,\mathrm{kg}/m^2 \\ p_3 = &\ 0.163\,\mathrm{kg}/m^2. \end{aligned}$$

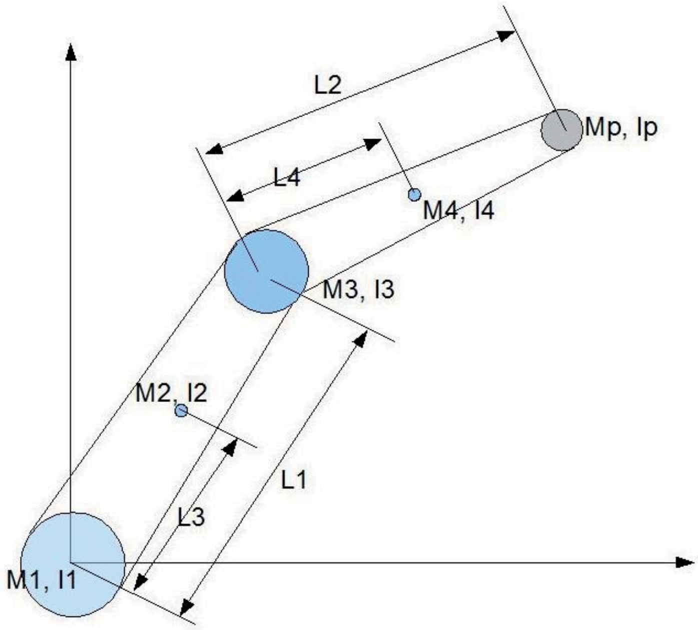


Figure 9: Two links SCARA robot

Considering the same technique with the linear case, we can develop more general control law to achieve stable teleoperation system as summarized as follows.

Theorem 4.1. *The teleoperation systems (30) can be rendered FDE-stable by the following control law*

$$\begin{aligned} u_m =& -M_m(x_{1m})x_{1m} + N_m(x_{1m}, x_{2m}) - diag\{k_{mi}(x_{1mi}^2(\cdot) + x_{2mi}^2(\cdot))\}x_{2m} - F_{ed} \\ u_s =& N_s(x_{1s}, x_{2s}) + M_s(x_{1s})\dot{x}_{2m}(\cdot) - M_s(x_{1s})(x_{1s} - x_{1m}(\cdot)) \\ & - diag\{k_{si}((x_{1s} - x_{1m}(\cdot))^2 + (x_{2s}^2 - x_{2m}(\cdot))^2)\}(x_{2s} - x_{2m}(\cdot)), \end{aligned} \tag{33}$$

where $i \in \{1, 2, \cdots, n\}$ is the link number while k_{mi} and k_{si} are positive constants.

Proof. The proof is built based on Theorem 2.1. The theorem says if the teleoperation system (29) with the control law (31) satisfies (8) then it is

FDE-stable. However, in order to simplify the proof, we can use Proposition 4.2. Let us consider the transformation of (29) as follows

$$\Sigma : \begin{cases} M_m(x_m)\ddot{x}_m + C_m(x_m,\dot{x}_m)\dot{x}_m + N_m(x_m,\dot{x}_m) = \tau_h + u_s(x_m, x_s(\cdot)) \\ M_s(x_e)\ddot{x}_e + C_s(x_e,\dot{x}_e)\dot{x}_e + N_s(x_e,\dot{x}_e) = -\tau_e + u_s(x_e, x_e(\cdot)) \end{cases} \tag{34}$$

where x_e is defined to be $x_s - x_m(\cdot)$. This can be transformed into state space form to replace (30) and (31) as

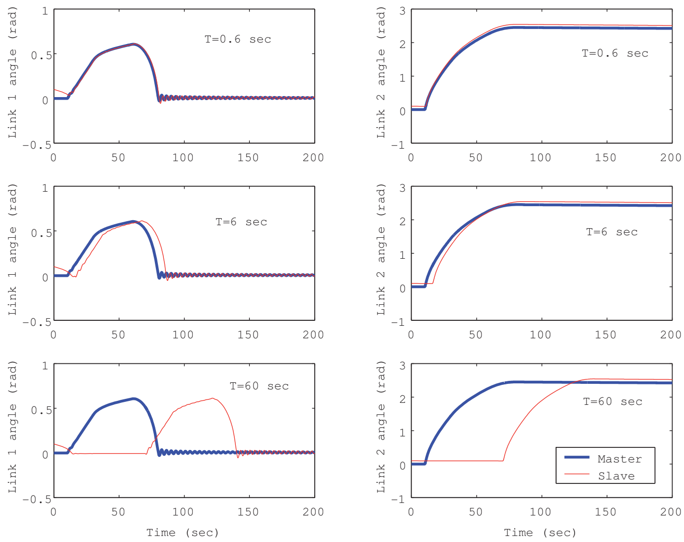
$$\begin{bmatrix} \dot{x}_{1m} \\ \dot{x}_{1e} \\ \dot{x}_{2m} \\ \dot{x}_{2e} \end{bmatrix} = \begin{bmatrix} x_{2m} \\ x_{2e} \\ M_m^{-1}(x_{1m})[-C_m(x_{1m},x_{2m})x_{2m} - N_m(x_{1m},x_{2m})] \\ M_s^{-1}(x_{1e})[-C_s(x_{1e},x_{2e})x_{2e} - N_s(x_{1e},x_{2e})] \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ u_{am}(x_m) \\ u_{as}(x_e) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ M_m^{-1}(x_{1m})u_{bm}(x_m(\cdot)) \\ M_s^{-1}u_{bs}(x_e(\cdot)) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ M_m^{-1}(x_{1m})\tau_{hum} \\ M_s^{-1}(x_{1e})\tau_{env} \end{bmatrix} \tag{35}$$

$$\begin{aligned} u_m &= -M_m(x_m)x_{1m} + N_m(x_{1m},x_{2m}) - diag\{k_{mi}(x_{1mi}^2(\cdot) + x_{2mi}^2(\cdot))\}x_{2m} - F_{ed} \\ u_s &= -M_s(x_{1e})x_{1e} + N_s(x_{1e},x_{2e}) - diag\{k_{si}(x_{1ei}^2(\cdot) + x_{2ei}^2(\cdot))\}x_{2e}. \end{aligned} \tag{36}$$

where, as the previous discussions, $i \in \{1, 2, \cdots n\}$ is the link number, k_{mi}, k_{si} are positive constants. We can always set the delay that is appear in the local control law to be zero without sacrificing the FDE-disipativity property. Finally, by explicitly expressing x_e into $x_s - x_m(\cdot)$ finally we arrive at control law (33). $\square$

In this example we are going to consider two identical SCARA robots (32) as in the previous system (see also Figure 9) for both master and slave sides. The controller gains: k_{m1}, k_{m2}, k_{s1} and k_{s2} are set to 100, 200, 1000 and 2000, respectively. The same human torque input with the previous examples are exerted at first and the second link of the master manipulator. In order to verify tracking performance, both sides are set to have different initial conditions, *i.e.*, all of initial states in master manipulator are set to 0, and all of the initial slave states are set to 0.1.

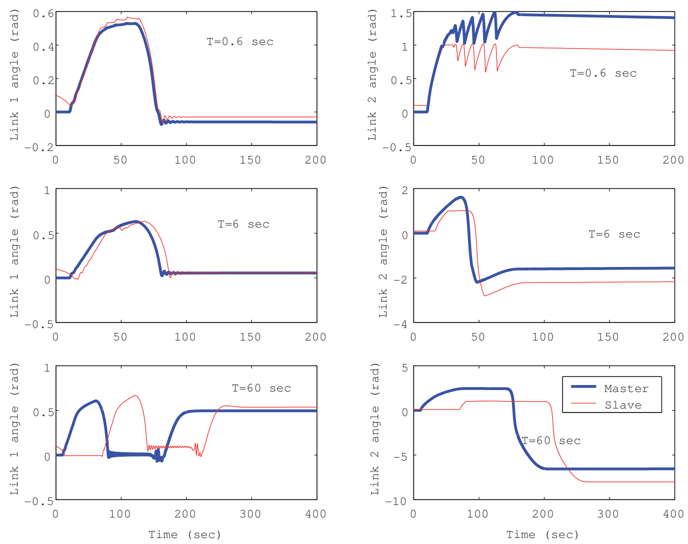
The tracking performance, *i.e.*, the responses without any environmental interactions are depicted in Figure 10. Beside their stable nature that is irrespective of the amount of delay, it is seen that for the first link, the tracking response are better than the second link. It is not surprising since the second link are influenced by the first link. Therefore, the tracking error is propagated from the first link to the second link. Fortunately, this effect can be suppressed by giving higher control gains for the second links for both master and slave manipulators although sometimes too high gains are undesirable.



(Top) Delay= 0.6 second
(Middle) Delay= 6 seconds
(Bottom) Delay= 60 seconds

Figure 10: Tracking responses

In the second simulation, in order to observe the stability effect under the environmental interaction, we place a very stiff wall in the slave side with stiffness 10000kg/rad such that it will collide with the second link of the SCARA manipulator at 1 rad. The controller gains are kept to be the same as the previous. The responses under this situation are shown in Figure 11. It is seen that the overall responses are still stable in spite of wide variations of delay. From the numerical results, it is seen that for both contact (free motion) and non contact responses the capability of the slave manipulator to track the master manipulator is almost irrespective of the amount of delay. Other the control laws (24) to (33) are able to stabilize the teleoperation system under any uncertain long delay.



(Top) Delay= 0.6 second
(Middle) Delay= 6 seconds
(Bottom) Delay= 60 seconds

Figure 11: Responses under environmental contact

5 Achieving transparent teleoperation

After the stability is obtained, a highly transparent teleoperation system is the next goal to be achieved. Here we will chase a certain level in transparency from our previous stand point, *i.e.,* without altering the controller. To analyze the transparency let us assume that the interaction with the environment can be exactly given as follows

$$F_e = m_e \ddot{x}_e + b_e \dot{x}_e + k_e x_e + f_{ext} \tag{37}$$

where

$$x_e = \begin{cases} x_s & \text{if } f_s > 0 \\ 0 & \text{otherwise.} \end{cases}$$

Usually the interactions can be divided into two, *i.e.,* contact (free motion) and non contact interaction. Fortunately, both types are well described in a single equation by (37). While the slave side is in free motion, ideally the force exerted by human operator should be zero as (37) will output zero force. However, both of the manipulators are still subjected to the gravity and external term $N_i(q_i, \dot{q}_i)$ that generate gravity related force. In fact, the control laws described in the previous section come with the gravity and external term compensations. It, however, is almost impossible to cancel these terms exactly.