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A contribution to control and observation of networked control systems

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ÉCOLE CENTRALE DE LILLE

THÈSE

présentée en vue d'obtenir le grade de

DOCTEUR

Spécialité : Automatique et Informatique Industrielle

par

JIANG Wenjuan

Doctorat délivré par l'École Centrale de Lille

Contribution à la commande et à l'observation des systèmes en réseaux

A contribution to control and observation of networked control systems

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Acronyms

CPU : Central Processing Unit

HDS : Hybrid Dynamical Systems

IP : Internet Protocol

ICMP : Internet Control Message Protocol

LYF : Lyapunov-Razumikhin Function

LKF : Lyapunov-Krasovskii Functional

LMI : Linear Matrix Inequalities

LTI : Linear, Time Invariant

M-S : Master - Slave

NCS : Networked Control Systems

NID : Network-Induced Delays

NTP : Network Time Protocol

RTT : Round-Trip-Time

TCP : Transfer Control Protocol

UDP : User Datagram Protocol

Notations

- $M > 0$: square symmetric positive definite matrix,
- $M < 0$: square symmetric negative definite matrix,
- $M < N$: the $M - N$ matrix is a square symmetric negative definite matrix,
- $\|M\|$: induced euclidean norm of M ,
- $\|x\|$: induced euclidean norm of a vector x ,
- M^{-1} : inverse of a non-singular matrix M ,
- M^T : transpose of M ,
- $M = \begin{bmatrix} A & B \\ * & D \end{bmatrix}$: symmetric matrix M , where $*$ means B^T ,
- $diag(a_1, a_2, \dots, a_n)$: diagonal matrix with a_1, a_2, \dots, a_n on the main diagonal,
- \mathbb{R}^n : the n dimensional Euclidean space with vector norm $\|\cdot\|$,
- $\mathbb{R}^{n \times m}$: the set of all $n \times m$ real matrices,
- \mathcal{C} : set of continuous functions from $[-h, 0]$ into \mathbb{R}^n ,
- $x(t; t_0, \varphi_0) \in \mathbb{R}^n$: the vector of \mathbb{R}^n represents the solution at the instant t , with the initial state $\varphi_0 \in \mathcal{C}$ at the time t_0 ,
- $x_t(t_0, \varphi_0)$: the state \mathcal{C} function at the instant t , with the initial state $\varphi_0 \in \mathcal{C}$, and defined by $x_t(\theta) = x(t + \theta), \forall \theta \in [-h, 0]$,
- $\|x_t\|_{\mathcal{C}}$: uniform norm of the function $x_t \in \mathcal{C} : \|x_t\|_{\mathcal{C}} = \text{Sup}_{\theta \in [-h, 0]} \|x(\theta)\|$,
- $co(\mathcal{S})$: convex hull of the set \mathcal{S} .

General Introduction

According to the survey on Networked Control System (NCS) by Zampieri [Zampieri S. 2008], "*activities in this field can be categorized into three major fields: control of networks, control over networks, and multi-agent systems. Control of networks is mainly concerned with providing a certain level of performance to a network data flow, while achieving efficient and fair utilization of network resources. Control over networks deals with the design of feedback strategies adapted to control systems in which control data is exchanged through unreliable communication links. Multi-agent systems deals with the study of how network architecture and interactions between network components influence global control goals.*"

In this work, we address the question of the control over networks. It means that the kind of NCS to be considered is a type of closed-loop control system with real-time communication networks imported into the control and feedback channels. The signals exchanged among the system's components are in the form of information packets through a network.

More precisely, we will consider the problem of output stabilization *via* a communication link. This general problem has some complexity since it includes a remote observer. In particular, the observer to be designed here is also a predictor, since it reconstructs the present state of the process on the basis of delayed output data.

Networked control systems

With the development of control science, computer network and communication technologies, networked control systems become more and more popular and complicated, which demand much higher performance. Real-time control over networks becomes possible and has caught many research attentions: see [Hespanha J.P. *et al.* 2007; Richard J.-P. & Divoux T. 2007; Tipsuwan Y. & Chow M.-Y. 2003; Zampieri S. 2008] for a general overview on control trends

and approaches for NCS, as well as an overview of the protocol and networks aspects in the first chapter of [Witrant E. 2005]. As the traditional control theory cannot solve the problem in the network situation, there is not a systematical theory and method, so there are still a lot of research work on this subject.

In this work, a special attention will be devoted to controlling a basic single-loop system (thus, with two communicating parts). As it was noted by Hespanha in his recent survey [Hespanha J.P. *et al.* 2007], such a single-loop architecture, although considerably simpler than the multi-loop systems (see Figure 1.2 in the first chapter), still captures many important characteristics of NCS such as bandwidth limitations, variable communication times, packet dropouts, sampling effects...

As it will be recalled, most of these various perturbations, arising in any networked situation, can be modeled under the same formalism of time delays systems. In this work, it will be referred to as “Network-Induced Delays” (NID). This class of infinite dimension models already received a large research effort (see the survey [Richard J.-P. 2003]), which makes it suitable and powerful for our networked control problems. In particular, the stability issues for time-delay systems have been widely considered, involving several classes of results: independent-of-delay *versus* delay-dependent conditions [Verriest E.I. *et al.* 1993], and constant delays *versus* variable delays. In our NCS field, the most relevant issues concern delay-dependent conditions (since we need to compute admissible bounds of the perturbations with regard to some desired performance) and variable delays (less simple, but much more realistic).

This last point, *i.e.* the consideration of variable time delays, is to be argued in more detail. Network-induced delays vary depending on the network hardware, the different protocols, packet losses, the traffic load... For the case of a deterministic network (such as token ring local area network), data "throughput" is fixed and there is a guaranteed maximum time delay for data transfer from node to node. On the contrary, a non-deterministic network does not. The preeminent example of a non-deterministic network is Ethernet, where the nodes rely on random time-delay circuits to reset and re-attempt transmission after a collision. Being that a node's transmission of data could be delayed indefinitely from a long series of re-sets and re-tries after repeated collisions, there is no guarantee that its data will ever get sent out to the network. In order to guarantee the QoS (Quality of Service) of the network, some type of fast network like ATM (Asynchronous Transfer Mode) can be applied, but at the price of a higher cost.

Due to its low cost and flexibility for reconfiguration, Internet is widely introduced into control systems. However, as it covers different types of networks and is the widest heterogenic network, the structure becomes very complicated. The QoS varies according to the network loads and the network-induced delay during the different period of time, which may create unstable behaviors. A principal consideration for real-time control networks, where the monitoring and control of real-life processes must often occur quickly and at set times, is the guaranteed maximum communication time from one node to another. For instance, controlling the position of a nuclear reactor coolant valve with a digital network, it has to be guaranteed that the valve's network node will receive the proper positioning signals from the control computer at the right times. If not, it will be dangerous (in such a case, the communication system cost is not the more crucial point!). So, in order to get the best performance for the system, it is necessary to take several strategies to cope with the changing values of time-delay.

Structure of the thesis

Chapter 1

The first chapter is a literature survey. The general features of NCS are given as well as the main research directions in the domain. Aside of the advantages of the network in the closed-loop control systems, the existing problems – especially Network-Induced Delays (NID) – are analyzed, which are necessary to the comprehension of our work. Then, some recent research results are recalled in the order of the different modeling method of NID.

Chapter 2

The second chapter is focused on the experimental system architecture and the main functions of computer programs. As our control stability theory is based on the continuous model, the sampling period has to be small enough to compensate the effect of quantization. So, the technique of multi-thread is applied to enhance the performance of the program. As the time-stamp is used in every packet, the clock synchronization has be considered to have a unique time reference. Then, the structure of the programs at the two sides of the NCS is explained by the function of each thread. Note that when packet lost happens, the most recent received one will be applied. But if the consecutive lost packets exceeds the maximum number tolerable

to the stability of the system, the control of "Stop" will be sent to the plant to avoid possible danger.

Chapter 3

In Chapter 3, stability conditions for general interval variable time-delay systems are analyzed by means of the Lyapunov-Krasovskii approach. They are given in the form of Linear Matrix Inequalities (LMI), which make the problem easy to be resolved. The comparison between our results and the others shows the merits of our method. Then, the result is further extended to exponential stability conditions respectively by the polytopic method and exponential Lyapunov-Krasovskii Functional (LKF). The theoretical result has been proved in our NCS and experimental results are also given at the end of the chapter.

The output stabilization results we develop in this chapter, as well as in chapter 4, are based on an event-driven strategy for the controller side, and a driven strategy for the plant side (the plant waits until it is the time to apply the received control). By this way, the observer can predict the instant when the control will be applied to the plant.

Chapter 4

This fourth chapter studies the stability problems for switched time-delay systems. In the previous chapter, the controller was designed so to cope with the whole range of variation of the delays, including the largest values. After showing that a big range of variation decreases the performance (the higher the delay, the lowest the performance), we study a way to improve the performance by adapting the controller accordingly to the present, estimated QoS. We present a solution which consists in switching the controller depending on the estimated RTT (Round-Trip-Time). With this aim in mind, two approaches for switching systems are applied to our time-delay system. One is to find a common LKF for all the switching modes to get arbitrary switches. The second one is to use multiple LKF for different modes, which is less conservative but requires a minimum dwell time to be satisfied before switching so as to guarantee the global stability. Since the RTT estimation is not instantaneous, we also develop this strategy for the switching time-delay systems with delayed detection of time-delays. For each method, the analyzed results are given as well as the experimental ones.

Chapter 5

In the previous chapters, the observer design was based on the fact that the control side knows the instant when the control is to be applied to the plant side. This hypothesis was satisfied by implementing a time-driven strategy for the plant side. In Chapter 5, we want to release this additional waiting time and implement a full event-driven NCS. In other words, the driven mode at the side of the plant becomes event-driven. This new structure may be more sensitive to the packet-loss phenomenon that is inherent to the User Datagram Protocol (UDP) we use for the network communication. This last chapter aims at designing the output stabilization despite such packet drop-outs, that will be treated as a kind of additional time-delay. In particular, when a packet sent by the controller is dropped out, the time of control application is unknown to the controller, which makes the observer a bit more complex to be designed. In the theoretical view, the performance is further enhanced, which is proved by the experimental results.

Chapter 1

Preliminaries

The ubiquitous development of communication technologies reinforces the desire for real-time control over wired/wireless networks. Among the numerous research attentions, a broad range of application has been achieved in NCS, such as for the tele-operation over the Internet [Hespanha J.P. *et al.* 2000; Hikichi K. *et al.* 2002; Shirmohammadi S. & Woo N.H. 2004], automated highway systems and unmanned aerial vehicles [Seiler P.J. 2001; Seiler P.J. & Sengupta R. 2005], remote surgery [Meng C. *et al.* 2004], wireless networks [Ploplys N.J. *et al.* 2004], mobile sensor networks [Ogren P. *et al.* 2004], to mention few. In this chapter, related works will be recalled according to the different research direction. Special emphasis will be made on the modeling of the time-delays in NCS as well as the most important stability theoretical results.

1.1 Networked control systems

1.1.1 Two related research directions

In the introduction, we have mentioned three main trends in NCS as reported in [Zampieri S. 2008]: control of networks, control over networks, and multi-agent systems. The latter will not be detailed here since we mainly address the question of the remote output control of one plant over a network or, as a possible extension, of a few nodes of interconnected controllers and plants. It means we do not take into account the question of the distributed control of a large number of agents, with such problems as distributed optimal control, distributed estimation for sensor networks, consensus, randomly switching topology, task allocation or distributed motion

coordination of robot swarms.

Thus, our small-scale situation is more connected to the two following fields:

1. control of networks,
2. control over networks.

The former direction of research mainly focuses on improving the Quality of Service (QoS), which aims to achieve efficient and fair utilization of the communication network resources, see [Toguyeni A. & Korbaa O. 2007]. Of course, such quality has a great influence on the performance one can expect from the system. The latter deals with the design of feedback strategies adapted to control systems in which control data is exchanged through unreliable communication links [Canudas de Wit C. 2006; Richard J.-P. & Divoux T. 2007].

1.1.1.1 Control of networks

This is a large research field about the QoS of networks, which mainly studies such problems as network architecture, congestion control, routing control, protocols and scheduling and so on, in order to reduce network-induced delay and data loss to the minimum. The model of the NCS is usually considered as a discrete system.

TCP/IP

Application	<i>XDR, RPC...</i>
Transport	<i>TCP, UDP</i>
Internet	<i>IP, ARP, ICMP...</i>
Network	<i>Ethernet TokenRing...</i>

Figure 1.1: TCP/IP structure and protocols

As the traditional centralized point-to-point communication architecture is not suitable for the expanding physical setups and functionality, the network architecture has been widely applied into the feedback control systems due to the modularization technique. For the case of

Internet, a layer model has been used, which is illustrated in Figure 1.1. At the core, the layer of the Internet Protocol (IP) stack provides primitive packet transport service, which deliver packets between nodes identified by their IP address. Packets may be dropped, duplicated or delivered out of order. The advantage of layered architecture is that it can be used to heterogeneous networks, such as Ethernet (also known as IEEE 802.3), wireless network (IEEE 802.11), point-to-point links and cellular networks while it is not ideal for cross-layer designs.

The tremendous complexity of the Internet makes it difficult to be controlled and analyzed. In addition, the classical dynamic routing protocols always forward packets to the shortest path which leads to imbalanced traffic distribution. This is a cause of network congestions even if the traffic load is not particularly heavy. Some mathematical theories have been applied to deal with the congestion control problem, as showed in [Kelly F. *et al.* 1998; Kelly F. 2001; Tang A. *et al.* 2007; Paganini F. *et al.* 2005; Alpcan T. & Basar T. 2005; Han H. *et al.* 2006; Ying L. *et al.* 2006; Johansson K.H. 2007; Årzén K.-E. *et al.* 2007]. As sensor networks raise especial interests, growing importance has been focused on the congestion control and resource allocation for wireless networks, such as [Abate A. *et al.* 2006; Alpcan T. *et al.* 2006a; Ying L. *et al.* 2007].

1.1.1.2 Control over networks

Some years ago, control over networks was identified as one of the key future direction for control [Murray R.M. *et al.* 2003]. It is based on the combination of control and communication theories. As showed in Fig. 1.2, NCS are spatially distributed systems in which the communication between sensors, actuators and controllers occurs through a shared band-limited digital communication network [Hespanha J.P. *et al.* 2007]. Thanks to the low cost and the flexibility of communication networks (CAN, Ethernet, the Internet, Wi-Fi ...), easy re-configurability, adaptation capability and robustness to failure, remote control has been widely used in industrial, communicational, medical systems, to cite a few. However, alongside all of these advantages, due to the characteristic features of the communication methods, the network inevitably brings problems to the closed-loop controlled system, such as delay variation, data-packets loss and disorder, which may cause poor performance, instability or danger (see for instance the chapter 1 of [Richard J.-P. & Divoux T. 2007], [Georges J.-P. *et al.* 2005] and the references herein). The main research issues lie in dealing with the network communication delays in the closed-loop controlled systems [Richard J.-P. & Divoux T. 2007; Canudas de Wit C. 2006], packet loss due to the traffic congestion [Hespanha J.P. *et al.* 2007; Seuret A. & Richard J.-P.

2008; Yu M. *et al.* 2004] and performance of control with adaptation of network QoS [Juanole G. & Mouney G. 2006; Jiang W.-J. *et al.* 2009c].

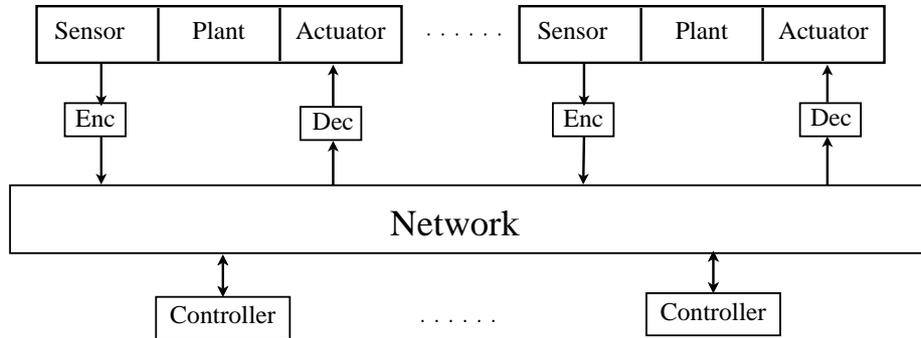


Figure 1.2: General NCS architecture

1.1.2 Structures for the control over networks

Generally speaking, the structure of a control system over a network can be designed in two ways [Chow M.Y. & Tipsuwan Y. 2001; Tipsuwan Y. & Chow M.-Y. 2003]: *direct structure* and *hierarchical structure*, as depicted respectively in Fig. 1.3 and Fig. 1.4. In both of the structures, the network is included in the closed-loop control system. In Fig. 1.3, sensors and actuators are directly connected to a network and all the control signals and sensor measurements are sent in the form of frames or packets *via* the network. This structure is widely adapted for the smart/intelligent actuators and sensors networks [Bayart M. *et al.* 1999; Caufriez L. *et al.* 2004]. Some autonomy is given to the sensors to make them capable of processing and communicating. All the functionalities related to the measurement and control process can be carried out directly by the sensors. These network nodes are made up of devices that must be capable of sensing, computing and communicating a wide range of physical parameters in order to be “intelligent” nodes. Some other typical applications include remote teaching labs [Overstreet J.W. & Tzes A. 1999] and remote control of electromechanical devices [Tipsuwan Y. & Chow M.-Y. 2001].

In Fig. 1.4, besides of the local centralized controller, NCS with hierarchical structure could have several subsystems at the remote site. *Via* the network, the controller sends to the remote system the reference signals and, according to these signals, the remote controller completes the closed-loop control system. This structure is often adapted to the NCS with exigence of

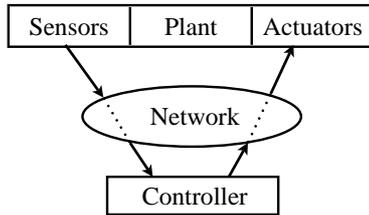


Figure 1.3: Direct structure

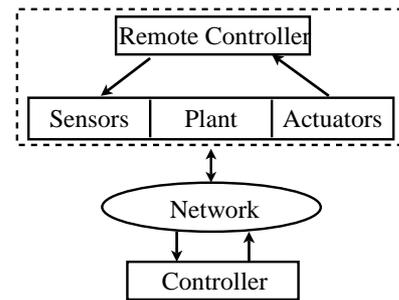


Figure 1.4: Hierarchical structure

stability and precision, such as tele-operated surgery. For example, the operation “Lindbergh” (http://en.wikipedia.org/wiki/Lindbergh_Operation) in 2001 has been successfully carried out between New York and Strasbourg. The surgeons operated a patient located in Strasbourg for a removal of the gallbladder by manipulating the arms of a robotic system from New York [Marescaux J. *et al.* 2002]. Connections between the sites were done with a high-speed terrestrial network of Asynchronous Transfer Mode (ATM) service. The operation was carried out successfully in 54 minutes with a round-trip distance of more than 14,000 km and the mean time lag for transmission of 155 ms. This structure is also applied for remote control of automobiles [Gäfvert M. 2003] and aerial vehicles [Seiler P.J. 2001], etc.

Both structures have their advantages. The direct one demands faster reaction of the network and has better interaction between system components, while the hierarchical one is more modular and has better robustness. In our work, a light-inertia robot is the plant to be controlled. As it does not have buffer memories nor high computation abilities, a PC works as a remote controller and communicates with it *via* Bluetooth, and this combination serves as the remote part. Another PC with high performance serves as the controller. So, in our case, the hierarchical structure is applied.

1.2 Time-delays for NCS

Time-delay is one of the most used and powerful tools in the modeling of NCS. This section will present the different sources of delay effect arising in NCS and, then, the different types of research works in the literature.

1.2.1 Three types of Network Induced Delays (NID)

To give a concrete idea of the delay sources appearing in NCS, and that we call “Network Induced Delays” (NID) all over the manuscript, we consider the networked control system depicted in Fig. 1.5.

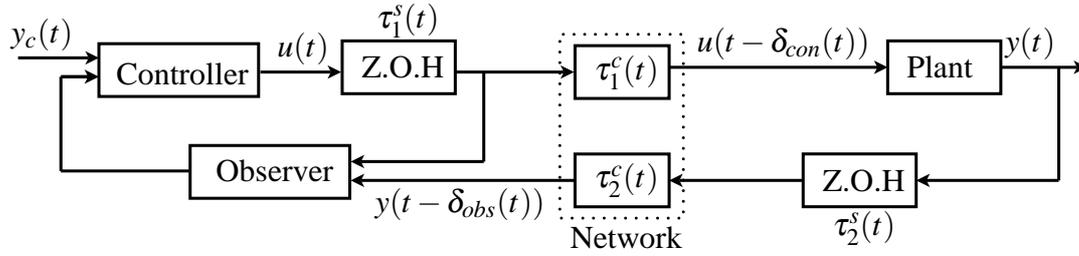


Figure 1.5: Time-delay sources in an NCS

Using this structure for the presentation of NID has two advantages: it is the one we consider in this work; and, although it may not be the most general one, it is generic enough to catch the delay sources that we want to explain. The figure presents the control part, including a remote observer, the plant to be controlled and the communication network included in the closed-loop: The actuator channel from the controller to the plant, and the measurement channel from the plant to the controller. It also depicts the Network-Induced Delays (NID) (τ and δ letters) coming from different sources.

The delays, which are going to be detailed in the sequel, come from:

1. The communication through the Internet showed in Fig. 1.6;
2. The data-sampling showed in Fig. 1.7: In this figure, we consider the case of a constant sampling period noted as T , but it may be variable in the general case;
3. The possible packet losses as in Fig. 1.8.

In the sequel, $\tau_1^c(t)$ and $\tau_2^c(t)$ denote the communication delays, $\tau_1^s(t)$ and $\tau_2^s(t)$ denote the sampling delays and NT represents the delay of packet losses. The total controller-to-plant delay $\delta_{con}(t)$ results from the addition of these three delays, which is depicted in Fig. 1.9. The same phenomenon stands for the plant-to-controller delay which is denoted $\delta_{obs}(t)$.

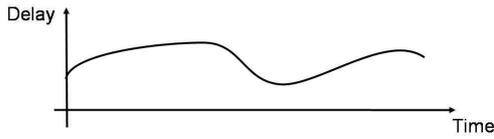


Figure 1.6: Communication delay

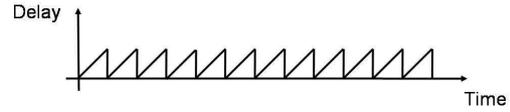


Figure 1.7: Sampling delay

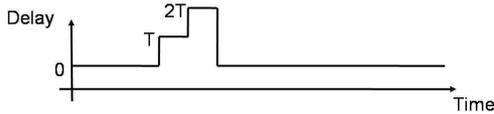


Figure 1.8: Delay from packet loss

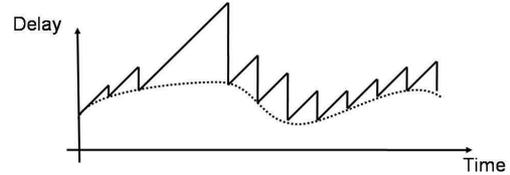


Figure 1.9: Total time-delay of NCS

1.2.1.1 Communication delays, QoS and RTT

Communication delays vary depending on the network hardware, on the different protocols, on the traffic load... This delay variation is known as the Jitter phenomenon. In some cases, such as in token ring local area network, the time-delay is bounded; for other networks like Internet, the time-delay is possibly unbounded and varying. The sum $\delta_{con}(t) + \delta_{obs}(t)$ defines the Round-Trip-Time (RTT) of the network. The RTT is an important element of the Quality of Service (QoS) of a network: a high QoS means a low RTT.

Communication delays are generally asymmetric. This last characteristic means that the time-delays of two channels (actuator channel and measurement channel) do not equal. For simplification purpose, some authors consider the assumption of a symmetric delay, i.e. $\delta_{con}(t) = \delta_{obs}(t) = \frac{1}{2}RTT$, but this does not hold in Internet for instance, because the routers and the pathes are not necessarily the same in the two ways.

In order to measure the RTT (or each of the communication delays), the method of time-stamp [Nilsson J. *et al.* 1998] is often used in the data packets. Whenever a packet is received, its communication time-delay can be calculated with the assumption that the time clock of all the nodes of the network is unique.

However, as it can be understood from Fig. 1.5, when the controller sends out a packet, it cannot know the real communication delay of the network until it receives another packet containing the information of the former one. That is to say, *there is also a time-delay for the RTT measurement, which is equal, at least, to one Round-Trip-Time (RTT) of the network.* This problem will be taken into account in Chapter 4, where the QoS-adaption of the controller will

be considered.

1.2.1.2 Data sampling

Another source of variable time-delay comes from the sampling effect. Modeling of continuous-time systems with digital control in the form of continuous-time systems with delayed control input was introduced by [Mikheev Y.V. *et al.* 1988; Astrom K. & Wittenmark B. 1989; Fridman E. 1992], mainly for asymptotic approximations for small enough sampling intervals [Fridman E. *et al.* 2004a]. The paper [Fridman E. *et al.* 2004a] gave a new impulse to this approach, by considering general sampling intervals and deducing stabilization conditions in the form of Linear Matrix Inequalities (LMI), obtained from Lyapunov-Krasovskii Functionals. A similar model is also considered in [Yu M. *et al.* 2004] by using the LRF (Lyapunov-Razumikhin Function) approach and in [Seuret A. *et al.* 2006] with LKF.

Indeed, the digital control law coming from a usual sample-and-hold of zero order, may be represented as delayed control as follows:

$$u(t) = u_d(t_k) = u_d(t - (t - t_k)) = u_d(t - \tau(t)), \quad t_k \leq t < t_{k+1}, \quad \tau(t) = t - t_k, \quad (1.1)$$

where the t_k are the sampling instants, u_d is a discrete-time control signal and the time-varying delay $\tau(t) = t - t_k$ is piecewise-linear with derivative $\dot{\tau}(t) = 1$ for $t \neq t_k$. Moreover, $\tau \leq t_{k+1} - t_k$.

In the case of uniform sampling (see the previous figure 1.7), one has $t_{k+1} - t_k = h$. for small enough sampling intervals $t_{k+1} - t_k$.

Some other sampling models have been raised by [Branicky M.S. *et al.* 2000; Zhang W. *et al.* 2001; Lin H. & Antsaklis P.J. 2004; Lee J.-W. & Dullerud G.E. 2006; Flavia F. *et al.* 2008] with periodic sampling and [Nesic D. & Teel A. 2004; Walsh Gregory C. *et al.* 2002] with variable sampling for hybrid or switching systems.

1.2.1.3 Packet Loss

Another question arising in NCS is that data may be lost while in transit through the network. The research results in the design of control systems that take into account the effect of packet loss have been surveyed by Hespanha in [Hespanha J.P. *et al.* 2007]. The packet dropout is due to the transmission errors in physical network links, or the buffer overflows resulting from the network congestions. Note that in the application of wireless networks, the phenomenon of data loss is more frequent, and more relative results can be found.

Generally, there are two directions of researches in the area.

- Firstly, packets dropouts are modeled as stochastic phenomena [Seiler P.J. & Sengupta R. 2001, 2005; Aberkane S. 2006]. Some of the researches have taken the packet dropout into account in the state estimation over networks: The method of optimal estimation for Bernoulli dropouts is applied in [Liu X. & Goldsmith A. 2004; Matveev A. & Savkin A. 2003; Sinopoli B. *et al.* 2004], the number of sensors measurements are controlled by the remote estimator to reduce network traffic [Xu Y. & Hespanha J.P. 2005; Smith S.C. & Seiler P. 2003; Yook J.K. *et al.* 2002].
- Secondly, deterministic approach is considered. [Zhang W. *et al.* 2001; Jia N. *et al.* 2007] includes the time averages of the number of consecutive dropouts into the design of a controller. In [Naghshabrizi P. & Hespanha J.P. 2005; Yue D. *et al.* 2004], the worst case bounds of the packets dropout is analyzed. In fact, data losses in the actuator channel mean there is no control, *i.e.*, the system is in open-loop. In this case, switched system is used to model the system [Zhang W. *et al.* 2001].

For the case of reliable transmission protocols, such as TCP, the delivery of packets is guaranteed. But, as in our NCS case the retransmission of old data is generally not useful and, what is worse, increases the transmission load, these protocols are not appropriate. In fact, when a packet loss occurs, it is possible to include it in the sampling delay phenomenon: If it is considered that the sent packets contain sampled data coming from the control or the sensors, then losing one packet means to double the sampling period. In the same way, losing N successive packets corresponds to getting a sampling period of $(N + 1)T$ instead of T .

1.2.2 Various hypothesis concerning the delays in the NCS literature

1.2.2.1 Continuous-time models

A variety of stability and control techniques have been developed for general time delay systems with continuous-time models, *i.e.* for functional differential equations [Niculescu S.-I. 2001; Richard J.-P. 2003]. Some of these results are based on simplifying assumptions such as considering the delay as constant [Azorin J.M. *et al.* 2003; Huang J.Q. & Lewis F.L. 2003; Fattouh A. & Sename O. 2003; Garcia C.E. *et al.* 2000; Niemeyer G. & Slotine J.-J. 1998]. Although such an assumption is actually unrealistic due to the dynamic character of the network, a technical solution may adapt the system to this constraint: A delay maximizing strategy

[Estrada-García H.J. *et al.* 2007; Lelevé A. *et al.* 2001; Ploplys N.J. *et al.* 2004] (“virtual delay”, “buffer”, or “waiting” strategy) can be carried out to make the delay become constant and known. This requires the knowledge of the maximum delay value. However, adapting the web technology so to make it fit a mathematical hypothesis may restrict the potential of this technology: Here, it is obvious that maximizing the delay up to its largest value decreases the achievable performances of the remote system. However, this still represent as a possibility for simplifying the theoretical analysis of a complex problem. For instance, in the thesis work of [Estrada-García H.J. 2008], two inverted pendulums were synchronized while communicating between Ensenada-Mexico and Nantes-France: During some periods of the day, successful experiments were obtained by maximizing the Internet delay up to 300 ms.

Anyway, keeping the delay as small as it is, and being able to deal with its jitter, remains an interesting goal. In [Witrant E. 2005; Witrant E. *et al.* 2003, 2007], Witrant designed a predictor technique for systems with variable, but predictable, delays. Then, by assuming that a dynamical ordinary differential equation model of the network delay is available, this interesting approach allowed for designing networked controllers based on state prediction. The deterministic network is considered as a time-delayed system with a delay of known dynamic. The class of *secure networks* with the transfer protocol TCP (Transfer Control Protocol) can guarantee that there is no loss of information in the communication process (all the lost packets are re-emitted), which results in a bounded transmission delay. Based on this assumption, several methods combining the state predictor are introduced including the design of the time-varying predictor horizon, frequency approach, H^∞ control with a time-varying delay, explicit use of the network dynamics and observer-based control. However, it is to be noted that, in the Internet case, the network delays cannot be modeled nor predicted. Because of this lack of knowledge, such predictor-based control laws cannot be applied.

Considering the variable time-delay bounded in an interval may be more realistic, since during a fixed period of time, we can find an upper bound of the time-delay. Although the time-delay of Internet is variable and not bounded, in our case such an assumption is reasonable since, if the time-delay surpasses the bound value, the packet can be treated as lost. Thus, this is the kind of hypothesis we will use. In a first time (Chapter 3), it will be considered that the global delays ($\delta_{con}(t)$ and $\delta_{obs}(t)$) stay in some interval, so to ensure an exponential stability performance. In Chapter 4, several possible intervals will be considered, with a different exponential rate for each of them.

1.2.2.2 Discrete-time models

As computer and network is introduced to the closed-loop control system, the discrete model of time-delay is naturally considered, which means to use difference equations. NCS are analyzed in the discrete-time domain by [Nilsson J. *et al.* 1998; Nilsson J. 1998], a discrete controller is designed. In the thesis of Nilsson, the network delays are treated as: 1) constant; 2) independently random; and 3) random but governed by an underlying Markov chain that generates the probability distributions of the time delays. Measurements of transfer delays are presented for two commercially used networks, a CAN-network (Controller Area Network) and an Ethernet network. For the various delay models, the LQG-optimal control problem is solved. The resulting controller is the combination of a state feedback controller and a Kalman filter with separation principle.

Note that the time-stamping method is applied to the data packets, *i.e.* all the transferred signals are marked with the time they were generated. We also use this strategy for evaluating the delays.

However, note that these results are limited to time-delay whose value is less than the sensor and controller sampling periods [Chen Z. *et al.* 2005; Nilsson J. *et al.* 1998; Nilsson J. 1998]. In the Internet case, this constraint leads to increase the sampling periods up to the maximal network delay, which may be constraining for high dynamic applications. A more recent work by Hetel [Hetel L. 2007; Hetel L. *et al.* 2007; Donkers M.C.F. *et al.* 2009] overcomes this limitation and considers delays greater than the sampling periods. Although this approach also involves discrete-time models, the sampling periods may vary continuously thanks to a robustness-like approach coupled with switched system techniques.

1.2.3 Delays in-the-loop and stability

Even if it happens that a delay may improve a dynamic behaviour (see results and references in [Seuret A. *et al.* 2009]), delays in a control loop are mostly known to degrade system performances. This is the case for the network delays in an NCS, because their are neither chosen nor predicted. In such situations, the time-delay may lead the generation of oscillations or be the source of instability [Kolmanovskii V. & Myshkis A. 1992; Kolmanovskii V.B. & Richard J.-P. 1999].

To well illustrate the effect of time-delay on the performance of the system, we consider

here a simple LTI (Linear, Time-Invariant) system [Gouaisbaut F. & Peaucelle D. 2006] with a constant time-delay τ :

$$\dot{x}(t) = \begin{bmatrix} -2 & 0 \\ 0 & -0.9 \end{bmatrix} x(t) + \begin{bmatrix} -1 & 0 \\ -1 & -1 \end{bmatrix} x(t - \tau) \quad (1.2)$$

The trajectories are depicted in Fig. 1.10 and Fig. 1.11, with the initial condition function $x(t_0 + \theta) = \phi(\theta)$, $\theta \in [-\tau, 0]$ and $\phi(\theta) = (5, 0)^T$. The figures show the effect of time-delay to the control system, which is asymptotically stable (without oscillation) for a zero delay, but makes more and more oscillations appear for increasing delays: When the delay surpasses the upper bound 6.17s [Briat C. 2008] that the system can tolerate, instability occurs as shown in Fig.1.11.

1.3 Conclusion

This chapter has given an overview of structures, questions and recent researches in the field of NCS. The existing problems such as time-delays, packet losses and QoS of network have been concisely analyzed. Different delay sources were discussed and for the closed-loop NCS, we obtain the notation δ_{con} and δ_{obs} as showed in Fig. 1, defined as the sum of the respective delays between the controller and the plant.

Different results and modeling assumptions have been mainly introduced. With regard to the technical solution which consists in maximizing the delays so to make them constant, our global point of view can be posed as follows:

- **Try to keep the delays as small as they are, and be able to deal with their jitter so to earn time and increase the speed performance of the global NCS.*
- **Consider any fast variation of the delays within some interval (to be defined properly), without any model of this variation.*
- **In order to benefit from the Lyapunov-Krasovskii methods and LMI tools, restrict the work to the control of a linear model.*

Thus, only linear systems with interval time-delay are to be considered.

Last, we can conclude with some words on the kind of control to be implemented:

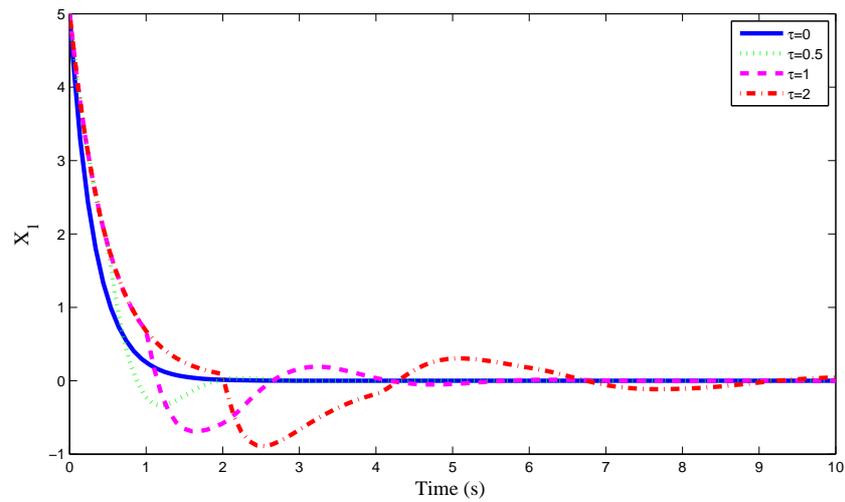


Figure 1.10: System performance degradations caused by delay in-the-loop.

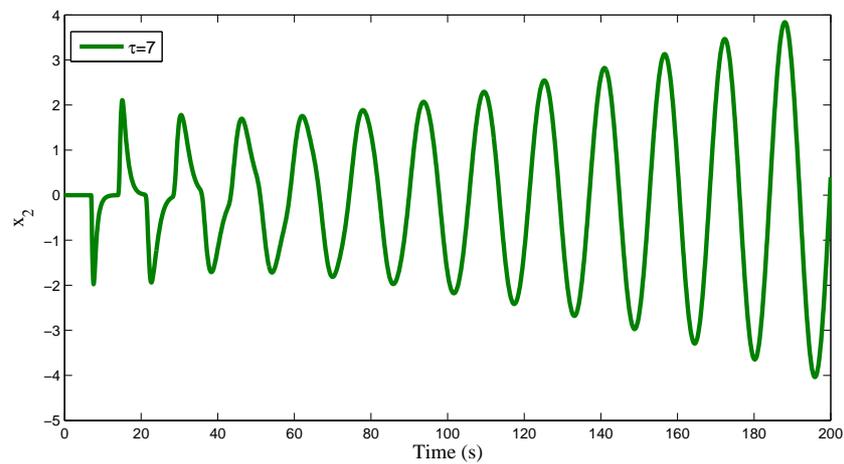


Figure 1.11: The system becomes unstable because of the delay.

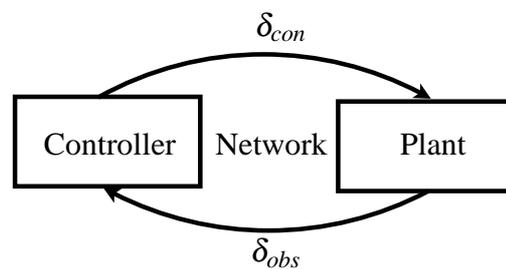


Figure 1.12: Time-delays between the controller and the plant

Generally speaking, three kinds of controllers can be considered : the static output feedback controller, the dynamic output feedback controller and the observer based state feedback controller. The static output feedback controller is easy to construct but cannot be considered for a NCS because of its implementation simplicity (no resource consuming). The dynamic output feedback controller often leads to a more robust behavior of the closed loop but its design is harder. In our case, the controller based on a Luenberger-like observer will be considered. It is a good compromise between results and design difficulty. Moreover, using observer based controller allows the remote estimation of the state variable which can be used for any other purpose than just control.

In the following chapters, we intend to provide robust control methods for stability analysis and scheduling gain strategy for the controller according to the current QoS of the network.

Chapter 2

Implementation of the remote control system

In this chapter, the experimental platform is described. The NCS program is based on Master-Slave structure. As real time control is considered, the performance of the Master is critical. In addition, the discretization period used for the observer implementation has to be sufficiently small to make the continuous-time model feasible, which also requires some high speed performance. So, multi-thread technique is used in the programs to get concurrent calculations within one CPU. The transmission protocol UDP is applied to communicate the data between the controller and the plant. In order to know the instant of data-sent, time-stamps are added to every data packet. To make the time unique for both sides of the controller and the plant, clock synchronization problem is to be considered. The data structure of list served as buffers is introduced for the program to search for the data of the right instance.

2.1 Application system

In this thesis, Master-Slave structure (M-S) is considered, where Master corresponds to the controller/observer and Slave corresponds to the plant. As in many such systems, the Slave is a low energy consumption system with a limited computation power, so the work of the Slave PC is simplified and the control and observation complexity is concentrated on the Master. In our experimental bench test, the plant is a robot Miabot of the company Merlin Systems Corp. Ltd. Together with a PC, it serves as the Slave.

This structure also makes our theory and application easier to adapt to sensor and actuator networks, where the sensors usually do not have powerful capability of calculation. The main features of the system refer to Fig.2.

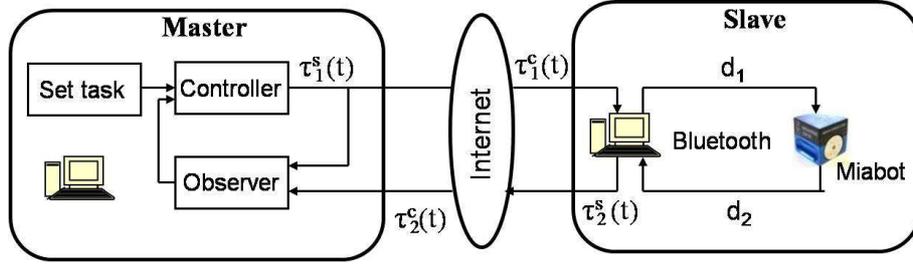


Figure 2.1: Structure of the global system

The transmission protocol UDP (User Data Protocol) is applied to communicate the data between Master and Slave. Here, UDP is preferred to TCP: Although TCP protocol provides reliable transmissions of data packets, acknowledges of receipt have to be made between the two sides, and this can degrade the communication capacity. In addition, the outdated packets are not necessary to be remitted for the control system. However, in our control strategy, the packet loss problem is considered as well as communication delays.

In order to simplify the observer design, the first part of this work (except Chapter 5) considers that a buffer (corresponding to a waiting strategy as described in Chapter 1) is added in the M-S communication. This ensures that the observer “knows” when the control will be applied. In contrast, on the side of the Master, the measurement information is applied to the observer as soon as it is received. In this way, the time-delay $\delta_{con}(t)$ is known, while the one $\delta_{obs}(t)$ is variable.

1. The real remote system, including Master, Slave and network, must involve some data sampling. However, following [Seuret A. *et al.* 2005; Fridman E. *et al.* 2004b], this phenomenon is equivalent to a time-varying, discontinuous delay. If the packets exchange between the Master and the Slave is of high speed, then it constitutes a disturbance that should be considered in the stabilization design [Yu M. *et al.* 2004]. It is supposed that there is a known T (maximum sampling period) so that $\tau_i^s(t) \leq T, i = 1, 2$.
2. Both Master and Slave computers dates are synchronized before the system works. To this end, the NTP (Network Time Protocol) [Mills D.L. 1995] is used on both sides

according to the same pool time server. By this way, whenever the Master or the Slave receives the data including the time-stamp, it knows the instant t_k of data sending out and the transmission delay $\tau_i^c(t_k), i = 1, 2$. As explained in the previous chapter, although the Internet communication delay is unbounded it is reasonable to assume a bound value since, if the time-delay surpasses the bound value, the packet can be treated as lost.

3. If some packet p_{t_k} containing the sample at t_k is lost, or arrives later than the packet $p_{t_{k+1}}$, then the Master only considers the most recent data (*i.e.*, those from $p_{t_{k+1}}$). Assuming that the maximum number of successive packets that can be lost is N , then the resulting additional delay is NT at most. The same lines also holds for the control packets. So, the total delay can be represented as $\delta_{con}(t) = \tau_1^c(t) + \tau_1^s(t) + NT$ and $\delta_{obs}(t) = \tau_2^c(t) + \tau_2^s(t) + NT$, which can be treated as a variable but bounded one.

2.2 Data communication through the Internet

2.2.1 Transmission and receipt of the control data

The k^{th} data packet sent by the Master to Slave includes the control $u(t_{m,k})$ together with the time-stamp indicating when the packet is sent out. At the time $t_{s,k}$ when the Slave receives the data, it can calculate the delay thanks to the time-stamp. The control u , sent out by the Master at time $t_{m,k}$, is received by the Slave at time $t_{s,k} > t_{m,k}$. As the protocol Bluetooth is used for the communication between the Slave PC and the Miabot, this time-delay has to be taken into account. To simplify the problem and concentrate on the main delay from the Internet, this local delay is considered as a constant one, defined as $d_i, i = 1, 2$ (this is, d_1 from Slave PC to Miabot, d_2 from Miabot to Slave PC).

The control will be injected to the Miabot only at the pre-defined ‘‘target time’’ $t_{m,k}^{target} = t_{m,k} + h_{1M}$, which includes the time-delay d_1 . The corresponding waiting time h_{1M} is depicted on Fig.2.2. This is realistic because the transmission delay is assumed to be bounded by a known value h_{1M} . By this way, the Master will know the time $t_{m,k} + h_{1M}$ when this control $u(t_{m,k})$ will be injected at the Slave input. This waiting strategy will be applied all azlong the Chapters 3 and 4, but avoided in the last Chapter 5.

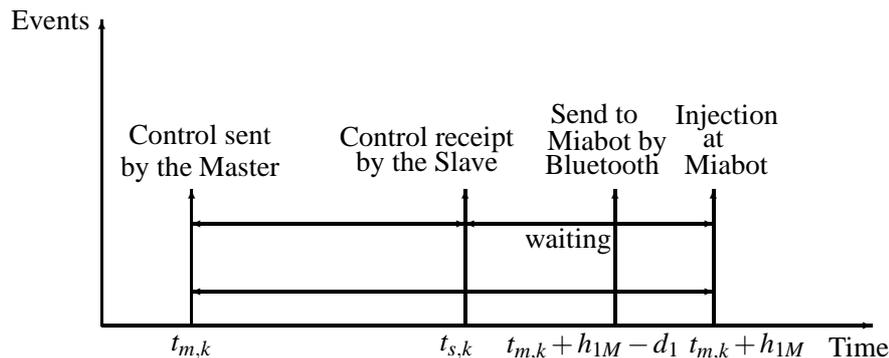


Figure 2.2: Control data processing

2.2.2 Control experiments over Internet

In order to show the influence of networks on the control system performance and to test our control strategies, control experiments over Internet will be performed. This allows real Internet traffic to be involved in the feedback loop. The experimental platform is depicted in Fig.2.3. In the experimental setup, the two computers are separated from 40 kilometers away,

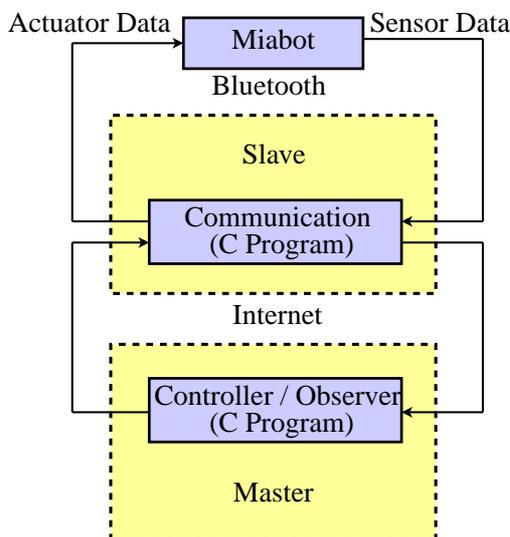


Figure 2.3: Experimental setup.

and communicate over Internet by UDP sockets. They work under the operating system Fedora 7 (a Linux version).

2.2.3 Clock synchronization between the Master and the Slave

The time-stamping method needs the Master and Slave internal clocks to be synchronized. For this purpose, two ways can be applied. One is by hardware synchronization: If the Slave plant already has a GPS for other operations, the Master can be equipped with another GPS device so to synchronize its clock on the same reference [Seuret A. *et al.* 2006]. However, a software solution can be cheaper and more flexible. Another way is to use software synchronization, *i.e.*, the synchronization signals are sent over the communication network. Several schemes for synchronization are available in the literature, see [Christian F. & Fetzer C. 1994; Schedl A.V. 1996; Van Oorschot J. 1993]. Among the algorithms designed for special application areas, the protocol NTP (Network Time Protocol) is used for clock synchronization on Internet [Mills D.L. 1995]. In addition to the clocks offset, there can be a drift and we have to make synchronization from time to time.

Our solution is to directly adapt the strategy of NTP in our program to calculate the time differences.

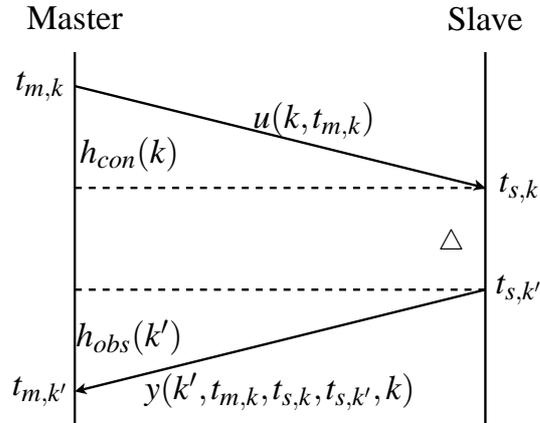


Figure 2.4: Packets communication between the M/S

As shown in Fig.2.4, here k is the sequential number of the packets sent from the Master and k' is the number sent back from the Slave. $h_{con}(k)$ and $h_{obs}(k')$ refer to the respective delays of the communication on Internet. To be able to solve the problem, we assume some symmetry, as it is done in NTP, *i.e.* that $h_{con}(k) = h_{obs}(k')$. If θ denotes the time clock difference between Master and Slave (to be estimated), and Δ the time taken by Slave to apply the command and get the output measurements, then:

$$\begin{aligned}\theta &= (t_{s,k'} - t_{m,k'} - t_{m,k} + t_{s,k})/2, \\ h_{con}(k) &= h_{obs}(k') = (t_{m,k'} - t_{m,k} - t_{s,k'} + t_{s,k})/2.\end{aligned}\tag{2.1}$$

That is to say, under the symmetry assumption, according to the equation (2.1), the time clock difference between the M/S and the time delay of the Internet can be measured every time the Master receives a packet. When the difference of clock θ is got, we re-synchronize the Master and the Slave.

2.3 Program with multiple tasks

Both of the programs, Master and Slave, have to fulfil multiple tasks concurrently. For instance, the Master's task has to be divided at least into the observer and the controller ones, with much more computation load to be reserved to the observer. Based on the Linux operating system, several techniques can be applied to achieve concurrence among different tasks with one Central Processing Unit (CPU). A computer program is sequentially executed in the form of a process, which has five fundamental parts: code ("text"), data, stack, file I/O, and signal tables. Two kinds of processes exist in the system: "Heavy-weight processes" (HWPs) and "light weight processes" (LWPs). HWPs have a significant amount of overhead when switching: All the tables have to be flushed from the processor for each task switch. Also, the only way to achieve shared information between HWPs is through pipes and "shared memory". If a HWP spawns a child HWP, the only part that is shared is the text. LWPs share most resources, so switching among the different LWP becomes more efficient. In the following part, the two different HWPs techniques will be recalled and then the multi-thread technique applied in our system will be introduced.

2.3.1 Sockets for inter-process communication

The most instinctive method is to create a program for each task and to use communication channels between these programs. A Unix domain socket or IPC socket (Inter-Process Communication socket) is a data communication endpoint that is similar to an Internet socket, but does not use a network protocol for communication. It is used in POSIX operating systems for inter-process communication [Stevens W.R. 1992].

Unix domain connections appear as byte streams, much like network connections, but all

data remain within the local computer. UNIX domain sockets use the file system as address name space, *i.e.*, they are referenced by processes as *inodes* (a file descriptor) in the file system. This allows two distinct processes to open the same socket in order to communicate. However, the actual communication (the data exchange) does not use the file system, but buffers in kernel memory. In addition to sending data, processes can send file descriptors across a Unix domain socket connection using the *sendmsg()* and *recvmsg()* system calls.

The socket is created by calling the following function:

```
int socket(int domain, int type, int protocol).
```

There are two choices for the parameter *domain*: *AF_UNIX* is used for the local inter-process communication; *AF_INET* is used for the communication through the Internet with the protocol TCP/IP. The latter will be used for the communication between the Master and the Slave. The parameter of type is to identify the communication type, *SOCK_STREAM* refers to a stream socket, *SOCK_DGRAM* refers to datagram sockets and *SOCK_RAW* is based on low layers for developing of new protocols.

Dividing the complicated task into several programs is easy for programming and the logical function of each program is clear, but this method is not suitable for the case with big quantity and high frequency of data exchanges, as CPU takes much time to change the working environment for the different programs.

2.3.2 Multiple hierarchical processes

In order to share the common used resource and improve the CPU efficiency, in Linux, the command *fork* can be used to dynamically create a child process of a program, while the child process inherits the node descriptor tables of its parent process. The system command is as follows:

```
pid_t fork(void).
```

The child process is an exact copy of its parent calling process but with its own unique process ID. The data spaces of the two processes are different. Then, the data exchange will be carried out by the mechanism of inter-process message communication [Stevens W.R. 1992]. As the child process has the same data structure as the one of its calling process, the change of the CPU working environment becomes faster.

2.3.3 Multiple threads technique

Threads are LWPs, and they reduce overhead by sharing fundamental parts. In this way, switching happens much more frequently and efficiently. Also, sharing information is not so “difficult” anymore: Everything can be shared.

In our case, this technique of multiple threads is used for both the Master and the Slave programs as the critical part of the program is focused on data calculation, and the data exchange among different tasks is of high frequency. In the following section, the function of each thread will be described.

2.4 Architecture of the computer programs

2.4.1 The structure of the Master

In order to implement the model for the remote control system, four-thread program is designed to fulfill the functions of Controller and Observer of Fig.2.

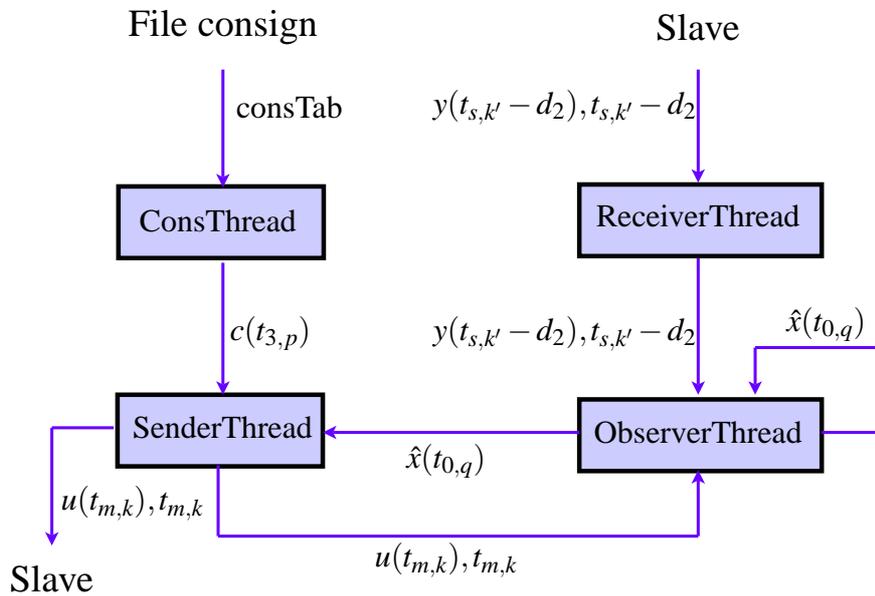


Figure 2.5: Structure of the Master

These four threads are parallel working, as shown in Fig.2.5. There are two buffers, $list_U$ and $list_X$, which respectively keep the data sent out from the Master and the data of the esti-

mated state of the process. The most recent calculated data is inserted at the beginning of the lists so that it is easier to find the right data we need and delete the useless ones.

(a) ConsThread gets the consign $c(t)$ (it is the position where the user wants the mobile to arrive) from a file given by the user. In this way, the user can freely change the task. The time period T_3 for this thread to work continuously is also set by the user, *e.g.* 8 seconds, which is the half of the period of the pulse generator we use as signal $c(t)$ for the experimentation.

(b) SenderThread gets the different consign ($c(t_{3,p})$) every time period of ConsThread. Then it calculates the control data to send out according to the following, proportional state feedback equation (see also equation (5.9) in the next chapter):

$$u(t_{m,k}) = K(\hat{x}(t_{0,q}) - c(t_{3,p})). \quad (2.2)$$

The most recent $\hat{x}(t_{0,q})$ can be found at the beginning of the *list_X*; then, the data of command together with the system time is sent out to the slave through the socket. While, at the same time it is inserted into the *list_U* for the ObserverThread to use. In order to adjust the $u(t)$ with the value of $x(t)$ which is the estimated state of the motor, the time period of this thread should be chosen much smaller than that of ConsThread, here 0.1 second is applied.

(c) ReceiverThread is a event-driven thread. As there is measurement data arrived from the Slave, it first checks whether there is packet loss. As the time period for the Slave to send out the data is so small, possible packets lost are considered in the computation of the resulting time delay. Then, according to the time-stamp, the most recent data is sent to the thread of ObserverThread.

(d) ObserverThread is the most important part of the program. It mainly serves as the Observer in the system model. The main task is to calculate an asymptotic estimate of the present position and speed of the motor. The corresponding equation will be given by equation (3.40) in the next chapter, based on a Luenberger-like structure with time-delays. To work this out, it is needed to find out the command u which has been applied to the slave system and the estimated motor position at the time when the information is sent out from the slave.

As it is illustrated in Fig.2.6, in order to determine $\hat{y}(t_{s,k'})$, it is necessary to find in the *list_X* the closer state estimation \hat{x} with regard to the date $t_{s,k'}$. And we can get the control data u in the *list_U* with the time-stamp of time h_{1M} before. So, according to the equation (3.40), the reconstructed state can be obtained. As we can see from the Fig.2.6, in order to find the state $\hat{x}(t_{0,q})$ at the time nearly to $t_{s,k'}$, the time period of this thread should be small enough. We choose here 0.02 second. As the obtained results will show, it is sufficient.

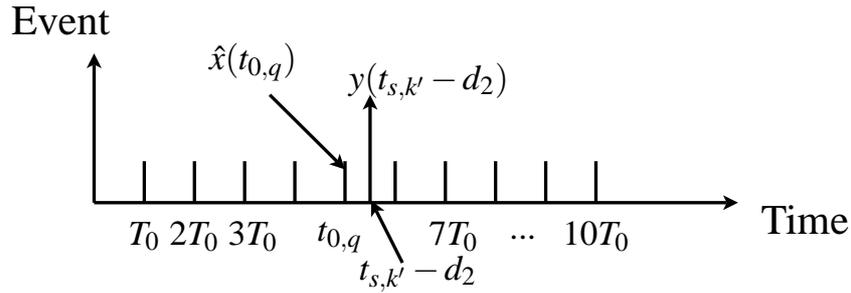


Figure 2.6: Packet Sequences

2.4.2 The structure of the Slave

The Slave must not need power computation abilities, and its role is limited to ensure the communication between the Master and the Miabot. As we can see from Fig.2.7, its program is divided into two threads: ReceiveThread and SendThread. As we need to apply the control data with the time delay of h_{1M} after the time-stamp, a *list_Y* is used to stock the control data temporarily.

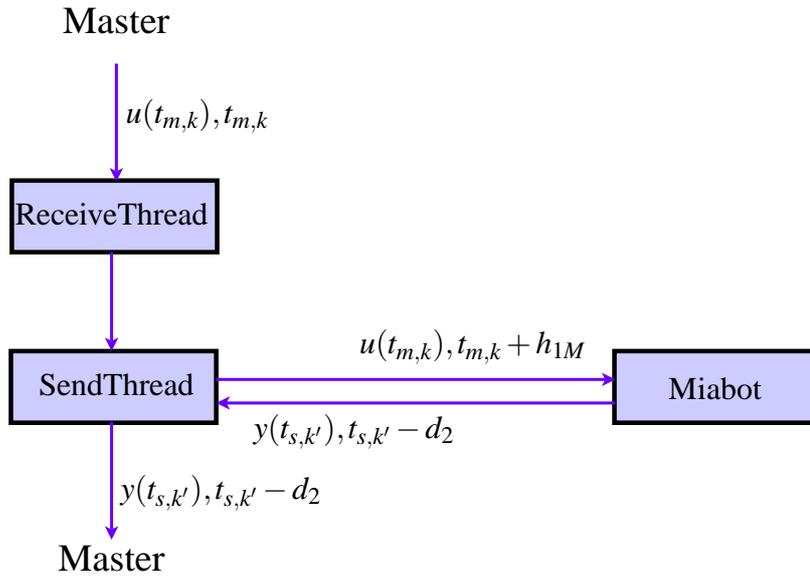


Figure 2.7: Structure of the Slave

(a) ReceiveThread is an event-driven thread which is activated by the control data arrived from the Master. The control data is inserted into the proper position of the list *list_Y* according to its time-stamp. If the time-stamp is before the oldest data of the list, that means there is disorder of the packets through Internet, then the data is discarded. If there are possible packets

lost, they are also considered in the computation of the resulting time delay.

(b) SendThread includes a function to get the real position of the Miabot. Considering the character of the mobile, we choose a time period T_2 for this thread equal to 0.1 second. At each cycle, it looks for the control data to be applied in *list_Y* and, then, sends it to the Miabot by the port of Bluetooth. The position sensor data of the Miabot is then sent to the Master.

2.5 Conclusion

This chapter was devoted to a technical presentation of the principles and programs used for the computer implementation of our experimental platform of the NCS. It mainly includes a clock synchronization algorithm, and the different threads applied in the computer programs to enhance the performance of the system.. The sequence of the data communication also was depicted.

Now, the following chapters can concentrate on different ways of designing the observer and control law to be realized by the threads.

Chapter 3

Output feedback stabilization

Our work is devoted to the problem of output stabilization of systems with time delay. In this area, more interests are focused on improving the closed-loop stability regions, using feedback laws [Bernstein D.S. 1987; Scherer C. *et al.* 1997]. Some classical theory as the Popov approach can be extended to discrete-time delay systems [Ionescu V. *et al.* 1998; Niculescu S.-I. 2001; Ivanescu D. *et al.* 1999], while for differential equations with delay [Kolmanovskii V.B. & Myshkis A. 1999], the condition becomes very complicated. Smith-type controllers [Niculescu S.-I. & Annaswamy A.M. 2003] can also be used for delay systems but, most often, are limited to constant delays. Some other results are dealing with dynamic output feedback controller [Diong B.M. & Medanic J.V. 1992; Briat C. *et al.* 2008; Scherer C.W. & Emre Köse I. 2007], but generally remain difficult to be designed.

The Lyapunov method remains a basic tool for stability analysis of systems with delays. Asymptotic stability can be checked if one can find a positive definite function whose derivative along solutions of the system is negative definite [Kolmanovskii V.B. & Myshkis A. 1999]. Extensions of the classical, quadratic functions have been particularly studied in the framework of LTI delay systems. The Lyapunov-Razumikhin Functions (LRF) approach has been deeply investigated for delay-independent stability problems due to its simplicity to handle with. However, the more general Lyapunov-Krasovskii Functionals (LKF) appeared to provide sharper results. They led (and still lead) to more and more sophisticated constructions of generalized quadratic functions, involving sums of iterated integrals of quadratic terms over various time intervals [Gu K. *et al.* 2003; Kolmanovskii V.B. & Myshkis A. 1999; Niculescu S.-I. 2001; Richard J.-P. 2003]. Other results [Seuret A. 2006] concern positive definite functions (or functionals) whose derivative along solutions of the system is piecewise negative definite, which

allows for dealing with non monotonically decreasing functions [Kruszewski A. 2006].

Our aim is to achieve the output exponential stabilization of our closed-loop NCS. In this chapter, LKF are considered in order to design a observer-based state feedback controller. Then, to enhance the system performance, exponential stability is also concerned.

3.1 Stability condition for the linear time-delay system

In this section, the stability conditions for general linear, interval time-delay systems are to be analyzed by the method of LKF, which is based on the resolution of LMI.

As an introduction, consider a system with constant time-delay [Richard J.-P. 2003; Seuret A. 2006]:

$$\begin{cases} \dot{x}(t) = Ax(t) + A_1x(t - \tau), \\ x(t_0 + \theta) = \phi(\theta), \quad \theta \in [-\tau, 0], \end{cases} \quad (3.1)$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$ are respectively the state and control vectors. ϕ represents the initial condition function. The $n \times n$ matrices A and A_1 are supposed to be known and constant.

By considering a simple extension of the classical, quadratic Lyapunov functions:

$$V(t, x_t) = x^T(t)Px(t) + \int_{t-\tau}^t x^T(s)Sx(s)ds, \quad (3.2)$$

one obtains sufficient LMI conditions: (3.1) is asymptotically stable for any constant $\tau \geq 0$ if there exist positive symmetric matrices P, S verifying:

$$\begin{bmatrix} A^T P + PA + S & PA_1 \\ A_1^T P & -S \end{bmatrix} < 0. \quad (3.3)$$

Now, for our NCS problem, the question is to extend such a criterion to variable delays laying in some interval with a non zero low bound: $\tau = \tau(t) \in [h_1, h_2]$, $h_1 \geq 0$. In particular, using $h_1 > 0$ corresponds to our situation since the network does impose a delay. This so called *nonsmall delay* condition should help for improving the maximum admissible bound h_2 .

3.1.1 A new result for the asymptotic stability of interval time-delay systems

Consider the system:

$$\dot{x}(t) = Ax(t) + A_1x(t - \tau(t)), \quad (3.4)$$

with the initial condition:

$$x(t_0 + \theta) = \phi(\theta), \quad \dot{x}(t_0 + \theta) = \dot{\phi}(\theta), \quad \theta \in [-h_2, 0], \quad (3.5)$$

where $\tau(t) \in [h_1, h_2]$, $h_1 \geq 0$. The delay is assumed to be fast-varying (with no special restriction on its derivative). The initial condition is supposed to be piecewise-continuous with bounded jumps, and continuously differentiable on each continuity subinterval.

Consider the following Lyapunov functional:

$$\begin{aligned} V(t, x_t, \dot{x}_t) &= x^T(t)Px(t) + \int_{t-h_1}^t x^T(s)Sx(s)ds \\ &+ h_1 \int_{-h_1}^0 \int_{t+\theta}^t \dot{x}^T(s)R\dot{x}(s)dsd\theta \\ &+ \int_{t-h_2}^t x^T(s)S_a x(s)ds + (h_2 - h_1) \int_{-h_2}^{-h_1} \int_{t+\theta}^t \dot{x}^T(s)R_a \dot{x}(s)dsd\theta \end{aligned} \quad (3.6)$$

where $P > 0$ and $R, R_a, S, S_a \geq 0$.

This functional constitutes a generalization of some other ones, since we note that the Lyapunov functional of the form (3.6) was recently introduced in [He Y. *et al.* 2007], whereas this functional with $S = 0$ was introduced earlier in [Fridman E. 2006].

Theorem 1 *Suppose that there exist $n \times n$ -matrices $P > 0, R > 0, S > 0, R_a > 0, S_a > 0, P_2, P_3, Y_1$ and Y_2 such that the LMI (3.7) with notations (3.8) is feasible. Then system (3.4) is asymptotically stable for all fast-varying delays in $0 \leq h_1 \leq \tau(t) \leq h_2$.*

$$\Phi = \begin{bmatrix} \Phi_{11} & \Phi_{12} & R + P_2^T A_1 - Y_1^T & Y_1^T & Y_1^T - P_2^T A_1 & Y_1^T \\ * & \Phi_{22} & P_3^T A_1 - Y_2^T & Y_2^T & Y_2^T - P_3^T A_1 & Y_2^T \\ * & * & -(S + R) & 0 & 0 & 0 \\ * & * & * & -S_a & 0 & 0 \\ * & * & * & * & -R_a & 0 \\ * & * & * & * & * & -R_a \end{bmatrix} < 0, \quad (3.7)$$

$$\begin{aligned} \Phi_{11} &= A^T P_2 + P_2^T A + S + S_a - R, \\ \Phi_{12} &= P - P_2^T + A^T P_3, \quad \Phi_{22} = -P_3 - P_3^T + h_1^2 R + (h_2 - h_1)^2 R_a. \end{aligned} \quad (3.8)$$

Proof: Differentiating V , one finds:

$$\begin{aligned} \dot{V}(t, x_t, \dot{x}_t) &\leq 2x^T(t)P\dot{x}(t) + \dot{x}^T(t)(h_1^2 R + (h_2 - h_1)^2 R_a)\dot{x}(t) \\ &- h_1 \int_{t-h_1}^t \dot{x}^T(s)R\dot{x}(s)ds \\ &- (h_2 - h_1) \int_{t-h_2}^{t-h_1} \dot{x}^T(s)R_a \dot{x}(s)ds + x^T(t)(S + S_a)x(t) \\ &- x^T(t - h_1)Sx(t - h_1) - x^T(t - h_2)S_a x(t - h_2). \end{aligned} \quad (3.9)$$

Following [He Y. *et al.* 2007], we employ the representation

$$\begin{aligned} & -(h_2 - h_1) \int_{t-h_2}^{t-h_1} \dot{x}^T(s) R_a \dot{x}(s) ds = -(h_2 - h_1) \int_{t-h_2}^{t-\tau(t)} \dot{x}^T(s) R_a \dot{x}(s) ds \\ & -(h_2 - h_1) \int_{t-\tau(t)}^{t-h_1} \dot{x}^T(s) R_a \dot{x}(s) ds \end{aligned} \quad (3.10)$$

and apply the Jensen's inequality ([Gu K. *et al.* 2003])

$$\begin{aligned} \int_{t-h_1}^t \dot{x}^T(s) R \dot{x}(s) ds & \geq \frac{1}{h_1} \int_{t-h_1}^t \dot{x}^T(s) ds R \int_{t-h_1}^t \dot{x}(s) ds, \\ \int_{t-\tau(t)}^{t-h_1} \dot{x}^T(s) R_a \dot{x}(s) ds & \geq \frac{1}{h_2-h_1} \int_{t-\tau(t)}^{t-h_1} \dot{x}^T(s) ds R_a \int_{t-\tau(t)}^{t-h_1} \dot{x}(s) ds, \\ \int_{t-h_2}^{t-\tau(t)} \dot{x}^T(s) R_a \dot{x}(s) ds & \geq \frac{1}{h_2-h_1} \int_{t-h_2}^{t-\tau(t)} \dot{x}^T(s) ds R_a \int_{t-h_2}^{t-\tau(t)} \dot{x}(s) ds. \end{aligned} \quad (3.11)$$

Then, denoting

$$v_1 = \int_{t-\tau(t)}^{t-h_1} \dot{x}(s) ds, \quad v_2 = \int_{t-h_2}^{t-\tau(t)} \dot{x}(s) ds,$$

we obtain

$$\begin{aligned} \dot{V}(t, x^t, \dot{x}^t) & \leq x^T(t) P \dot{x}(t) + \dot{x}^T(t) (h_1^2 R + (h_2 - h_1)^2 R_a) \dot{x}(t) \\ & - [x(t) - x(t - h_1)]^T R [x(t) - x(t - h_1)] \\ & - v_1^T R_a v_1 - v_2^T R_a v_2 \\ & + x^T(t) (S + S_a) x(t) - x^T(t - h_1) S x(t - h_1) \\ & - x^T(t - h_2) S_a x(t - h_2). \end{aligned} \quad (3.12)$$

We use further the descriptor method [Fridman E. & Shaked U. 2001], where, for some $n \times n$ -matrices P_2, P_3 , the right-hand side of the expression:

$$0 = 2[x^T(t) P_2^T + \dot{x}^T(t) P_3^T] [Ax(t) + A_1 x(t - h_1) - A_1 v_1 - \dot{x}(t)], \quad (3.13)$$

is added into the right-hand side of (3.12). We also add free weighting matrices of [He Y. *et al.* 2004]:

$$0 = 2[x^T(t) Y_1^T + \dot{x}^T(t) Y_2^T] [x(t - h_2) + v_1 + v_2 - x(t - h_1)], \quad (3.14)$$

Setting $\eta(t) = \text{col}\{x(t), \dot{x}(t), x(t - h_1), x(t - h_2), v_1, v_2\}$, we obtain that:

$$\dot{V}(t, x^t, \dot{x}^t) \leq \eta^T(t) \Phi \eta(t) < 0, \quad (3.15)$$

if the LMI 3.7, with notation given in 3.8, is feasible. This concludes the proof of Theorem 1.

3.1.2 Numerical examples

To show the efficiency of our result, in this section we use the same two numerical examples as in [He Y. *et al.* 2004].

Example 1. Consider the system (3.4) with

$$A = \begin{bmatrix} -2 & 0 \\ 0 & -0.9 \end{bmatrix}, \quad A_1 = \begin{bmatrix} -1 & 0 \\ -1 & -1 \end{bmatrix}. \quad (3.16)$$

As listed in the table of Fig.3.1, when $h_1 = 0$, our result recovers the best result of the literature [Park P.G. & Ko. J.W. 2007] for this example. The obtained improvement is more sensible for $h_1 > 0$, in which case the comparison with the methods of [Jiang X. & Han Q. L. 2005] and [He Y. *et al.* 2007] shows the merits of Theorem 1. Finally note that, as expected, considering a “non-small delay” enlarges the value of maximum upper-bound of the admissible time-delay.

Method	h_1	0	1	2	3	4
[Jiang X. & Han Q. L. 2005]	h_2	1.01	1.64	2.39	3.20	4.06
[He Y. <i>et al.</i> 2007]	h_2	1.34	1.74	2.43	3.22	4.07
[Park P.G. & Ko. J.W. 2007]	h_2	1.86	-	-	-	-
Our Theorem 1	h_2	1.86	2.06	2.61	3.31	4.09

Figure 3.1: Allowable upper bound of h_2 with given over bound h_1

Example 2. Consider the system (3.4) with:

$$A = \begin{bmatrix} 0 & 1 \\ -1 & -2 \end{bmatrix}, \quad A_1 = \begin{bmatrix} 0 & 0 \\ -1 & 1 \end{bmatrix}. \quad (3.17)$$

In the table of Fig.3.2, for given lower bounds h_1 of the variable time-delay, the corresponding maximum values of upper bounds h_2 are given by considering different methods. Here again, the comparison shows that our result is less conservative.

Method	h_1	0	0.3	0.5	0.8	1	2
[Jiang X. & Han Q. L. 2005]	h_2	0.67	0.91	1.07	1.33	1.50	2.39
[He Y. <i>et al.</i> 2007]	h_2	0.77	0.94	1.09	1.34	1.51	2.40
Our Theorem 1	h_2	1.06	1.24	1.38	1.6	1.75	2.58

Figure 3.2: Allowable upper bound of h_2 with given h_1

3.2 Exponential stability of interval time-delay systems

Consider the time-delay system of equation (3.4). Let $\alpha > 0$ be some positive, constant, real number. According to [Kolmanovskii V. & Myshkis A. 1992], the system is said to exponentially stable with the decay rate α , or α -stable [Niculescu S.-I. *et al.* 1998], if there exists a scalar $F \geq 1$ such that the solution $x(t; t_0, \phi)$ satisfies:

$$\|x(t; t_0, \phi)\| \leq F \|\phi\|_C e^{-\alpha(t-t_0)}, \quad (3.18)$$

where $\|x(\cdot)\|$ is the norm of vector and $\|\phi\|_C$ the associated function uniform norm.

Two methods are considered here: 1) State transformation with polytopic method and 2) exponential LKF. The former method is much easier since Theorem 1 can be almost directly applied after some changes of state variables. The latter one has to consider more analysis techniques and it is based on some bound of \dot{V} .

3.2.1 Polytopic method

In order to guarantee some α -stability performance, one applies the transformation $x_\alpha(t) = e^{\alpha t} x(t)$, $\alpha > 0$. Then, if $\|x_\alpha(t)\|$ is proved to decrease, equation (3.18) holds.

Through this transformation, the system is rewritten as:

$$\dot{x}_\alpha(t) = (A + \alpha I)x_\alpha(t) + e^{\alpha\tau(t)} A_1 x_\alpha(t - \tau(t)). \quad (3.19)$$

Since $e^{\alpha h_1} \leq e^{\alpha\tau(t)} \leq e^{\alpha h_2}$, we can rewrite the equation (3.19) in the following polytopic form:

$$\begin{aligned} \dot{x}_\alpha(t) = & (A + \alpha I)x_\alpha(t) + \lambda_1(t) e^{\alpha h_1} A_1 x_\alpha(t - \tau(t)) \\ & + \lambda_2(t) e^{\alpha h_2} A_1 x_\alpha(t - \tau(t)). \end{aligned} \quad (3.20)$$

for $i=1,2$, $\lambda_i(t) \geq 0$, $\sum_{i=1}^2 \lambda_i(t) = 1$.

Adapting Theorem (1) for the system (3.4) leads to the LMI:

$$\Phi_i = \begin{bmatrix} \Phi_{11} & \Phi_{12} & R + e^{\alpha h_i} P_2^T A_1 - Y_1^T & Y_1^T & Y_1^T - e^{\alpha h_i} P_2^T A_1 & Y_1^T \\ * & \Phi_{22} & e^{\alpha h_i} P_3^T A_1 - Y_2^T & Y_2^T & Y_2^T - e^{\alpha h_i} P_3^T A_1 & Y_2^T \\ * & * & -(S+R) & 0 & 0 & 0 \\ * & * & * & -S_a & 0 & 0 \\ * & * & * & * & -R_a & 0 \\ * & * & * & * & * & -R_a \end{bmatrix} < 0, \quad (3.21)$$

where:

$$\begin{aligned}\Phi_{11} &= (A + \alpha I)^T P_2 + P_2^T (A + \alpha I) + S + S_a - R, \\ \Phi_{12} &= P - P_2^T + (A + \alpha I)^T P_3, \quad \Phi_{22} = -P_3 - P_3^T + h_1^2 R + (h_2 - h_1)^2 R_a.\end{aligned}\quad (3.22)$$

Thus, the following result is obtained.

Theorem 2 *Suppose that there exist $n \times n$ -matrices $P > 0, R > 0, S > 0, R_a > 0, S_a > 0, P_2, P_3, Y_1$ and Y_2 such that the LMI (3.21) ($i = 1, 2$) with notations (3.22) is feasible. Then, system (3.4) is exponentially stable with a decay rate α for all fast-varying delays $h_1 \leq \tau(t) \leq h_2$.*

3.2.2 Exponential LKFs

Consider the same system as shown in equation (3.4). Here, we propose to extend a recent result by E. Fridman [Fridman E. & Yury Orlov 2009] to the case of $h_1 > 0$ by adapting the following Lyapunov functional:

$$\begin{aligned}V(t, x_t, \dot{x}_t) &= x^T(t) P x(t) + \int_{t-h_1}^t e^{2\alpha(s-t)} x^T(s) S x(s) ds \\ &+ h_1 \int_{-h_1}^0 \int_{t+\theta}^t e^{2\alpha(s-t)} \dot{x}^T(s) R \dot{x}(s) ds d\theta \\ &+ \int_{t-h_2}^t e^{2\alpha(s-t)} x^T(s) S_a x(s) ds \\ &+ (h_2 - h_1) \int_{-h_2}^{-h_1} \int_{t+\theta}^t e^{2\alpha(s-t)} \dot{x}^T(s) R_a \dot{x}(s) ds d\theta,\end{aligned}\quad (3.23)$$

where $P > 0$ and $R, Q, S \geq 0$.

We note that, for $\alpha = 0$, the LKF of the form (3.23) was recently introduced in [He Y. *et al.* 2007], whereas this functional with $S = 0, \alpha = 0$ was introduced earlier in [Fridman E. 2006] and, for $\alpha > 0, h_1 = 0$, in [Sun X-M. *et al.* 2006].

The following condition along the trajectories of (3.4):

$$\dot{V}(t, x_t, \dot{x}_t) + 2\alpha V(t, x_t, \dot{x}_t) \leq 0 \quad (3.24)$$

implies:

$$V(t, x_t, \dot{x}_t) \leq e^{-2\alpha(t-t_0)} V(t_0, x_{t_0}, \dot{x}_{t_0}) \quad \forall t_0 \in \mathbb{R}. \quad (3.25)$$

The latter implies exponential stability of (3.4) since

$$x^T(t) P x(t) \leq V(t, x_t, \dot{x}_t) \leq e^{-2\alpha(t-t_0)} V(t_0, x_{t_0}, \dot{x}_{t_0}) \leq e^{-2\alpha(t-t_0)} V(t_0, x_{t_0}, \dot{x}_{t_0})|_{\alpha=0}.$$

Differentiating V , we find:

$$\begin{aligned}
 & \dot{V}(t, x_t, \dot{x}_t) + 2\alpha V(t, x_t, \dot{x}_t) \\
 & \leq 2x^T(t)P\dot{x}(t) + 2\alpha x^T(t)Px(t) + \dot{x}^T(t)(h_1^2R + (h_2 - h_1)^2R_a)\dot{x}(t) \\
 & \quad - h_1 e^{-2\alpha h_1} \int_{t-h_1}^t \dot{x}^T(s)R\dot{x}(s)ds \\
 & \quad - (h_2 - h_1) e^{-2\alpha(h_2-h_1)} \int_{t-h_2}^{t-h_1} \dot{x}^T(s)R_a\dot{x}(s)ds + x^T(t)(S + S_a)x(t) \\
 & \quad - x^T(t-h_1)Sx(t-h_1)e^{-2\alpha h_1} - x^T(t-h_2)S_ax(t-h_2)e^{-2\alpha h_2}.
 \end{aligned} \tag{3.26}$$

Following [He Y. *et al.* 2007], we employ the representation:

$$\begin{aligned}
 & -(h_2 - h_1) \int_{t-h_2}^{t-h_1} \dot{x}^T(s)R_a\dot{x}(s)ds = -(h_2 - h_1) \int_{t-h_2}^{t-\tau(t)} \dot{x}^T(s)R_a\dot{x}(s)ds \\
 & -(h_2 - h_1) \int_{t-\tau(t)}^{t-h_1} \dot{x}^T(s)R_a\dot{x}(s)ds
 \end{aligned} \tag{3.27}$$

and apply the Jensen's inequality [Gu K. *et al.* 2003]:

$$\begin{aligned}
 & \int_{t-h_1}^t \dot{x}^T(s)R\dot{x}(s)ds \geq \frac{1}{h_1} \int_{t-h_1}^t \dot{x}^T(s)ds R \int_{t-h_1}^t \dot{x}(s)ds, \\
 & \int_{t-\tau(t)}^{t-h_1} \dot{x}^T(s)R_a\dot{x}(s)ds \geq \frac{1}{h_2-h_1} \int_{t-\tau(t)}^{t-h_1} \dot{x}^T(s)ds R_a \int_{t-\tau(t)}^t \dot{x}(s)ds, \\
 & \int_{t-h_2}^{t-\tau(t)} \dot{x}^T(s)R_a\dot{x}(s)ds \geq \frac{1}{h_2-h_1} \int_{t-h_2}^{t-\tau(t)} \dot{x}^T(s)ds R_a \int_{t-h_2}^{t-\tau(t)} \dot{x}(s)ds.
 \end{aligned} \tag{3.28}$$

Then, following [Gouaisbaut F. & Peaucelle D. 2006], we obtain:

$$\begin{aligned}
 & \dot{V}(t, x^t, \dot{x}^t) + 2\alpha V(t, x^t, \dot{x}^t) \\
 & \leq x^T(t)P\dot{x}(t) + 2\alpha x^T(t)Px(t) + \dot{x}^T(t)(h_1^2R + (h_2 - h_1)^2R_a)\dot{x}(t) \\
 & \quad - [x(t) - x(t-h_1)]^T R [x(t) - x(t-h_1)] e^{-2\alpha h_1} \\
 & \quad - [x(t-h_1) - x(t-\tau(t))]^T R_a [x(t-h_1) - x(t-\tau(t))] e^{-2\alpha(h_2-h_1)} \\
 & \quad - [x(t-\tau(t)) - x(t-h_2)]^T R_a [x(t-\tau(t)) - x(t-h_2)] e^{-2\alpha(h_2-h_1)} \\
 & \quad + x^T(t)(S + S_a)x(t) - x^T(t-h_1)Sx(t-h_1)e^{-2\alpha h_1} \\
 & \quad - x^T(t-h_2)S_ax(t-h_2)e^{-2\alpha h_2}.
 \end{aligned} \tag{3.29}$$

We use further the descriptor method [Fridman E. 2006], where the right-hand side of the expression:

$$0 = 2[x^T(t)P_2^T + \dot{x}^T(t)P_3^T][Ax(t) + A_1x(t-\tau(t)) - \dot{x}(t)], \tag{3.30}$$

with some $n \times n$ -matrices P_2, P_3 is added into the right-hand side of (3.29).

Setting $\eta_a(t) = \text{col}\{x(t), \dot{x}(t), x(t-h_1), x(t-\tau(t)), x(t-h_2)\}$, we obtain that:

$$\dot{V}(t, x^t, \dot{x}^t) + 2\alpha V(t, x_t, \dot{x}_t) \leq \eta^T(t)\Phi\eta(t) \leq 0, \tag{3.31}$$

if the following LMI holds:

$$\Phi = \begin{bmatrix} \Phi_{11} & \Phi_{12} & Re^{-2\alpha h_1} & P_2^T A_1 & 0 \\ * & \Phi_{22} & 0 & P_3^T A_1 & 0 \\ * & * & -(S+R)e^{-2\alpha h_1} - R_a e^{-2\alpha(h_2-h_1)} & R_a e^{-2\alpha(h_2-h_1)} & 0 \\ * & * & * & -2R_a e^{-2\alpha(h_2-h_1)} & R_a e^{-2\alpha(h_2-h_1)} \\ * & * & * & * & -S_a e^{-2\alpha h_2} - R_a e^{-2\alpha(h_2-h_1)} \end{bmatrix} \leq 0 \quad (3.32)$$

where

$$\begin{aligned} \Phi_{11} &= A^T P_2 + P_2^T A + 2\alpha P + S + S_a - R e^{-2\alpha h_1}, \\ \Phi_{12} &= P - P_2^T + A^T P_3, \quad \Phi_{22} = -P_3 - P_3^T + h_1^2 R + (h_2 - h_1)^2 R_a. \end{aligned} \quad (3.33)$$

Thus, the following result is obtained.

Theorem 3 Given $\alpha > 0$, let there exist $n \times n$ -matrices $P > 0, R > 0, S > 0, R_a > 0, S_a > 0, P_2$ and P_3 such that the LMI (3.32) with notations given in (3.33) is feasible. Then, system (3.4) is exponentially stable with a decay rate α for all fast-varying delays $h_1 \leq \tau(t) \leq h_2$ and the following bounding property is verified:

$$x^T(t) P x(t) \leq e^{-2\alpha(t-t_0)} V(t_0, \phi, \dot{\phi}). \quad (3.34)$$

3.3 Output feedback stabilization of a NCS with remote observer

As mentioned in the previous chapter, our closed-loop system is based on the Master-Slave structure, the observer-based controller being implemented in the Master side. The stability conditions for general linear systems with time-delay will be, first, applied to the design of observer and controller separately, thanks to a separation principle. Then, the global stability will also be considered.

3.3.1 Description of the closed-loop system

Recall the schema of the closed-loop control system as Fig.3.3, including an observer-based remote controller.

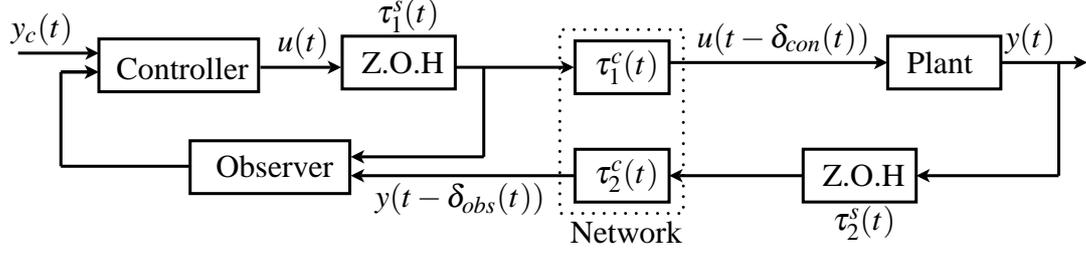


Figure 3.3: Features of the NCS

Consider the plant as a linear system. It is described by the following form:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t - \delta_{con}(t)), \\ y(t) = Cx(t), \end{cases} \quad (3.35)$$

where $\delta_{con}(t) \in [h_1, h_2]$, $\dot{\delta}_{con}(t) \leq 1$, $h_1 > 0$, and with the initial condition:

$$x(t_0 + \theta) = \phi(\theta), \quad \dot{x}(t_0 + \theta) = \dot{\phi}(\theta), \quad \theta \in [-h_{max}, 0]. \quad (3.36)$$

. This allows for using our Theorems 2 or 3 with interval time-delays, with the aim of guarantying the following closed-loop performance: The exponential stability with the rate α must be achieved whatever the delay variation. Here, the following state feedback and observer will be considered:

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t - \hat{\delta}_{con}(t)) + L(y(t - \delta_{obs}(t)) - \hat{y}(t - \delta_{obs}(t))), \\ \hat{y}(t) = C\hat{x}(t), \\ u(t) = K\hat{x}(t) + ky_c, \end{cases} \quad (3.37)$$

where the measurement channel delay $\delta_{obs}(t)$ verifies $\delta_{obs}(t) \in [h_1, h_2]$, $h_1 > 0$. y_c is the desired set point (as this value changes only after a satisfied long period, here it is considered constant) and k a gain ensuring an unitary static gain for the closed loop.

A main difficulty is to determine the gains K and L for the state feedback control so to guaranty the exponential stability of the Slave's motion despite the time-varying delays $\delta_{con}(t)$ and $\delta_{obs}(t)$.

The estimation error $e(t) = x(t) - \hat{x}(t)$ is given by:

$$\dot{e}(t) = Ae(t) + BK(\hat{x}(t - \delta_{con}(t)) - \hat{x}(t - \hat{\delta}_{con})) - LCe(t - \delta_{obs}(t)). \quad (3.38)$$

From the equation (3.38), the difficulty lies on the fact that the control delay is not known to the observer, *i.e.*, the time of control application to the plant is unknown. To resolve this

problem, in the side of the slave, a packet buffer (“waiting strategy”) is implemented as in [Seuret A. *et al.* 2006]. When the plant receives a control packet, it will not execute the control until some “target time” indicated in the packet, as defined in 2.2.1. That is to say, we enlarge the control delay to the upper bound of the interval time-delay. Here, it equals to h_2 . In this way, the observer “knows” at which moment the control is applied to the controlled object, *i.e.* $\hat{\delta}_{con}(t) = \delta_{con}(t)$. This waiting strategy decreases the system performance but brings about the separation principle for the design of the observer and the controller. By this way, the gains K and L can be calculated from LMI conditions. While for the time-delay from the Master to the Slave, thanks to the time-stamp in every packet, this one is “known” as the Master receives packets. So, the measurement can be directly used (without packet buffer).

Rewrite the equation (3.38), the following observation error equation can be obtained:

$$\dot{e}(t) = Ae(t) - LCe(t - \delta_{obs}(t)). \quad (3.39)$$

Note that the error system does not depend on u nor x . This ensures that the separation principle is applicable and allows for reducing the study of the closed-loop dynamic to two smaller stabilization problems: The observer design and the controller design.

3.3.2 Observer design

Applying the separation principle, re-write the equation (3.37) leads to:

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t - \delta_{con}(t)) + L(y(t - \delta_{obs}(t)) - \hat{y}(t - \delta_{obs}(t))), \\ \hat{y}(t) = C\hat{x}(t), \end{cases} \quad (3.40)$$

with $\delta_{obs}(t), \delta_{con}(t) \in [h_1, h_2]$.

Taking the equation (3.39) and applying Theorem (3), we choose $P_3 = \varepsilon P_2$, where ε is parameter to be adapted so to obtain the best result, and $W = P_2^T L$.

Define the following LMI:

$$\begin{aligned} \Phi = & \\ & \begin{bmatrix} \Phi_{11} & \Phi_{12} & Re^{-2\alpha h_1} & WC & 0 \\ * & \Phi_{22} & 0 & \varepsilon WC & 0 \\ * & * & -(S+R)e^{-2\alpha h_1} - R_a e^{-2\alpha(h_2-h_1)} & R_a e^{-2\alpha(h_2-h_1)} & 0 \\ * & * & * & -2R_a e^{-2\alpha(h_2-h_1)} & R_a e^{-2\alpha(h_2-h_1)} \\ * & * & * & * & -S_a e^{-2\alpha h_2} - R_a e^{-2\alpha(h_2-h_1)} \end{bmatrix} \\ & \leq 0 \end{aligned} \quad (3.41)$$

with:

$$\begin{aligned}\Phi_{11} &= A^T P_2 + P_2^T A + 2\alpha P + S + S_a - R e^{-2\alpha h_1}, \\ \Phi_{12} &= P - P_2^T + \varepsilon A^T P_2, \quad \Phi_{22} = -\varepsilon P_2 - \varepsilon P_2^T + h_1^2 R + (h_2 - h_1)^2 R_a.\end{aligned}\quad (3.42)$$

Thus, we get the following Lemma concerning the observer part.

Lemma 1 *If for some positive scalars α and ε , there exist $n \times n$ -matrices $P > 0, R > 0, S > 0, R_a > 0, S_a > 0, P_2$ such that the LMI (3.41) with notations given in (3.42) is feasible, then the gain:*

$$L = (P_2^T)^{-1} W, \quad (3.43)$$

makes the vector $\hat{x}(t)$ of observer (3.40) converge exponentially to the vector $x(t)$ of equation (3.35), with a decay rate α for any variable output delay $\delta_{obs}(t) \in [h_1, h_2]$.

3.3.3 Control design

We first consider a controller $u = Kx$, *i.e.* the ideal situation $e(t) = 0, x(t) = \hat{x}(t)$ and:

$$\dot{x}(t) = Ax(t) + BKx(t - \delta_{con}(t)). \quad (3.44)$$

In order to apply Theorem (3), we multiply (3.32) by $\text{diag}\{P_2^{-T}, P_2^{-T}, P_2^{-T}, P_2^{-T}, P_2^{-T}\}$ at the left side, and by $\text{diag}\{P_2^{-1}, P_2^{-1}, P_2^{-1}, P_2^{-1}, P_2^{-1}\}$ at the right side respectively. In addition, we choose $P_3 = \varepsilon P_2$ and $M = KP_2$ leads to the following result.

Define the following LMI:

$$\begin{aligned}\Phi &= \\ &\begin{bmatrix} \Phi_{11} & \Phi_{12} & R e^{-2\alpha h_1} & BM & 0 \\ * & \Phi_{22} & 0 & \varepsilon BM & 0 \\ * & * & -(S+R)e^{-2\alpha h_1} - R_a e^{-2\alpha(h_2-h_1)} & R_a e^{-2\alpha(h_2-h_1)} & 0 \\ * & * & * & -2R_a e^{-2\alpha(h_2-h_1)} & R_a e^{-2\alpha(h_2-h_1)} \\ * & * & * & * & -S_a e^{-2\alpha h_2} - R_a e^{-2\alpha(h_2-h_1)} \end{bmatrix} \\ &\leq 0\end{aligned}\quad (3.45)$$

with:

$$\begin{aligned}\Phi_{11} &= P_2^T A^T + A P_2 + 2\alpha P + S + S_a - R e^{-2\alpha h_1}, \\ \Phi_{12} &= P - P_2 + \varepsilon P_2^T A^T, \quad \Phi_{22} = -\varepsilon P_2 - \varepsilon P_2^T + h_1^2 R + (h_2 - h_1)^2 R_a.\end{aligned}\quad (3.46)$$

Thus, we get the following Lemma concerning the controller part.

Lemma 2 *If for some positive scalars α and ε , there exist $n \times n$ -matrices $P > 0, R > 0, S > 0, R_a > 0, S_a > 0, P_2$ such that the LMI (3.45) with notations given in (3.46) is feasible, then, the gain:*

$$K = MP_2^{-1}, \quad (3.47)$$

exponentially stabilizes the system (3.44) with the decay rate α for all the delays $\delta_{con}(t) \in [h_1, h_2]$.

Note that ε is an important variable when verifying the conditions LMI. A simple query loop algorithm may be considered to search for the best value of ε .

3.3.4 Global stability of the remote system

The global networked control system is as follows:

$$\begin{cases} \dot{x}(t) = Ax(t) + BKx(t - \delta_{con}(t)) - BKe(t - \delta_{con}(t)), \\ \dot{e}(t) = Ae(t) - LCe(t - \delta_{obs}(t)). \end{cases} \quad (3.48)$$

Considering to use $\xi(t) = col\{x(t), e(t)\}$, then we get the equation:

$$\dot{\xi}(t) = \bar{A}_0 \bar{e}(t) + \bar{A}_1 \bar{e}(t - \delta_{con}(t)) + \bar{A}_2 \bar{e}(t - \delta_{obs}(t)) \quad (3.49)$$

$$\text{for } \bar{A}_0 = \begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix}, \bar{A}_1 = \begin{bmatrix} -BK & BK \\ 0 & 0 \end{bmatrix}, \bar{A}_2 = \begin{bmatrix} 0 & 0 \\ 0 & -LC \end{bmatrix}.$$

This is under the block-triangular form, which diagonal subsystems have been proven to be exponentially stable in Lemma 1 and 2. Then the whole system is α -stable with the smallest α computed from Lemma 1 and 2.

3.4 Results and analysis

After identification of the Miabot, we get the model of the following form:

$$\begin{cases} \dot{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & -10 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0.024 \end{bmatrix} u(t - \delta_{con}(t)), \\ y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t). \end{cases} \quad (3.50)$$

where the state $x(t)$ comprises the position and the speed of the Miabot.

Every one minute, we have tested the RTT (round-trip-time) between the two PCs in the daytime and nighttime, by using the protocol ICMP (Internet Control Message). The result is depicted in Fig.3.4. The red curve is the time-delay in the daytime and the blue one is in the nighttime. According to Fig.3.4, for the total 1000 samples, more than 95% round-trip-times(RTT) are less than 60ms. From these tests, an evaluation of the maximal time delay is obtained. So, considering the characteristics of Internet, Bluetooth transmission delays and the time delay for applying the strategy combined with the sampling time, we have taken the value $h_1 = 0.01sec$ and $h_2 = 0.1sec$.

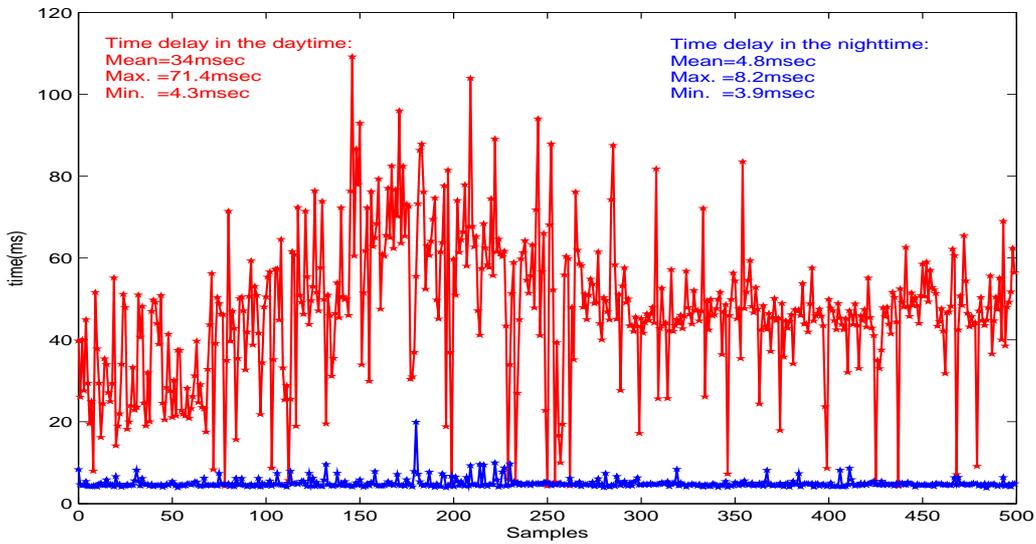


Figure 3.4: The RTT in the daytime and night between the two PCs by Internet (40km away).

3.4.1 Results obtained when neglecting the network effects

As it is known that time-delays can cause instability in a closed-loop control system. In this part, we will show in our NCS, if the network effects were neglected, what would happen. So, we remove the time-delay in the equation (3.50), then the system is a LTI system described as follows:

$$\begin{cases} \dot{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & -10 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0.024 \end{bmatrix} u(t), \\ y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t). \end{cases} \quad (3.51)$$

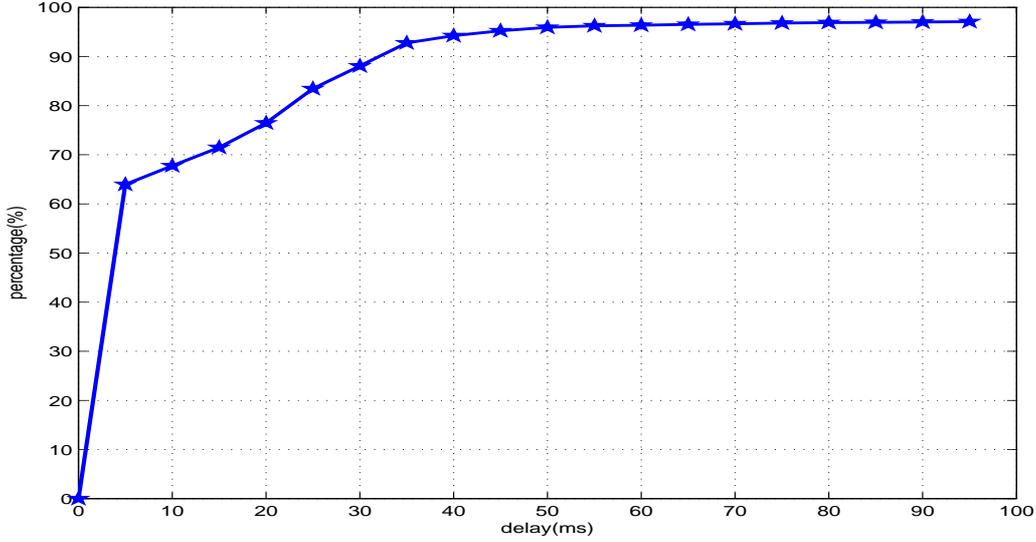


Figure 3.5: The percentage of the RTT in different time delay ranges.

Then a pole placement observer-based controller is designed for the closed-loop system. Considering the mechanic character of the Miabot, the poles are given as $[-1; -15]$ and $[-2; -20]$ respectively for the controller and the observer. Then the gains are calculated:

$$K = \begin{bmatrix} -750 & -300 \end{bmatrix}. \quad (3.52)$$

$$L = \begin{bmatrix} 12 \\ -80 \end{bmatrix}. \quad (3.53)$$

With these gain values, the real time experiment leads to the unstable phenomenon in Fig. 3.6. As we can see, the method of robust pole placement technique is useful to achieve given poles, however, as no time-delay is considered in this method, stability cannot be ensured in the NCS.

3.4.2 Design of the observer and controller gains

According to Lemma 1 and 2, the gains L and K have to be computed in such a way they α -stabilize the global Master-Slave-Observer system despite the variable delays $\delta_{con}(t)$ and $\delta_{obs}(t)$. We get $\alpha = 3$ if the gain L is chosen as:

$$L = \begin{bmatrix} 0.92 \\ 0.01 \end{bmatrix}. \quad (3.54)$$

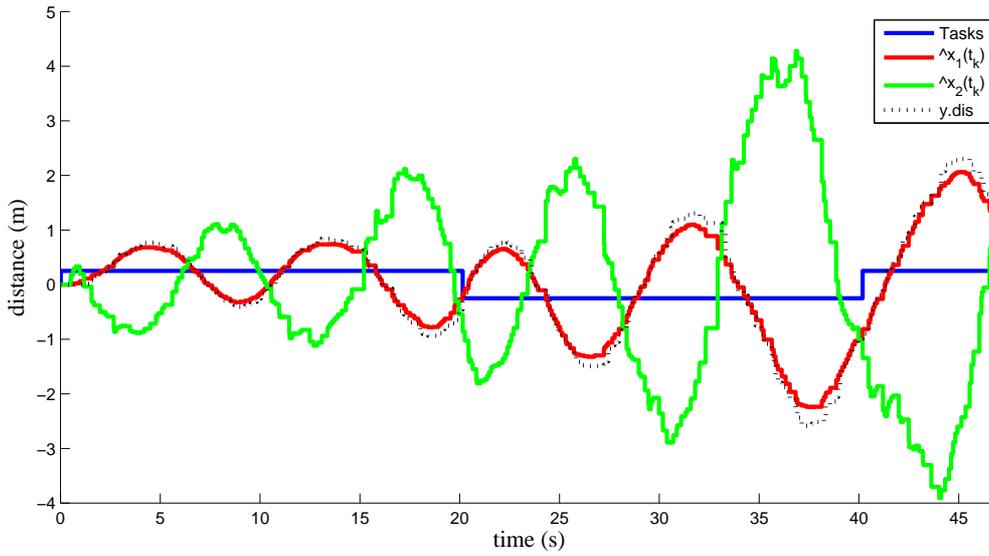


Figure 3.6: The result by neglecting the network effects.

and the gain K is chosen as:

$$K = \begin{bmatrix} -459 & -46 \end{bmatrix}. \quad (3.55)$$

3.4.3 Results of the centralized experiment

By experimenting the Master-Slave program on a same computer, 0.1 second was chosen as the maximum time delay h_2 which includes sampling and transmission delays. The result is shown in Fig.3.7, in which the blue curve represents the consign tasks; the black dot line correspond to the real Miabot output (the motor position); the red (position) and green (speed) represent motor estimated state. Fig.3.8 represents the sampled control data send to Slave.

In this first experiment, the system clock is unique, so the situation is totally in accordance with the theory and the results are similar to the simulation ones.

From the graph Fig.3.8, we can see that the time instance of the consign being implemented has a little delay in accordance with h_2 .

Because the maximal speed of the Miabot is $4m/sec$, the command value corresponding is 2000. But, in order to guaranty the linear character of the Miabot, we make the command not surpass 1000 as showed in Fig. 3.8.

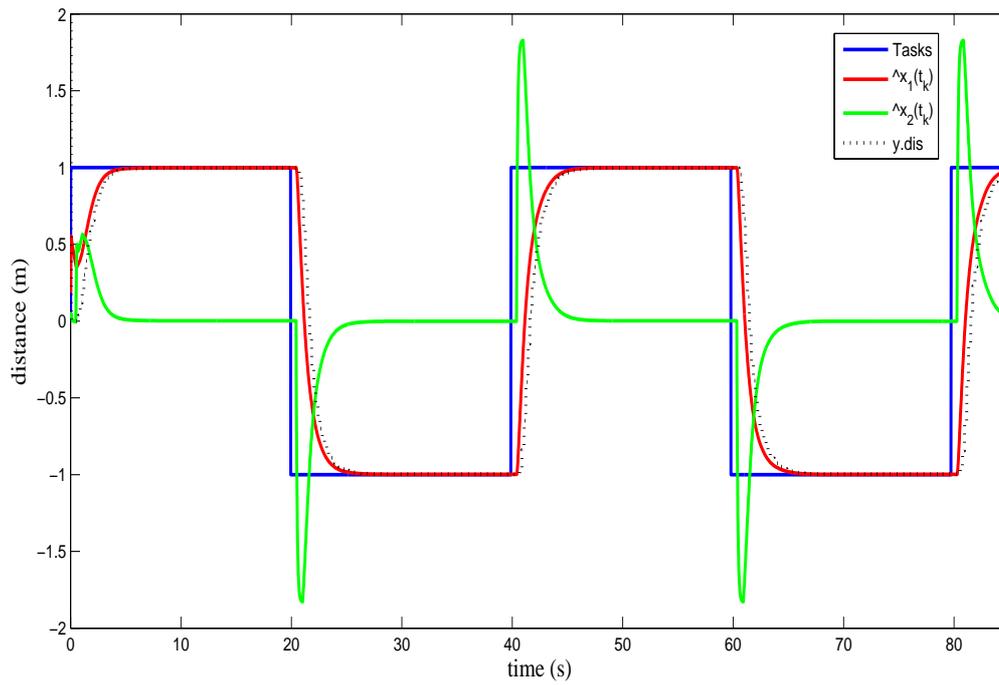


Figure 3.7: Results of experiment without network

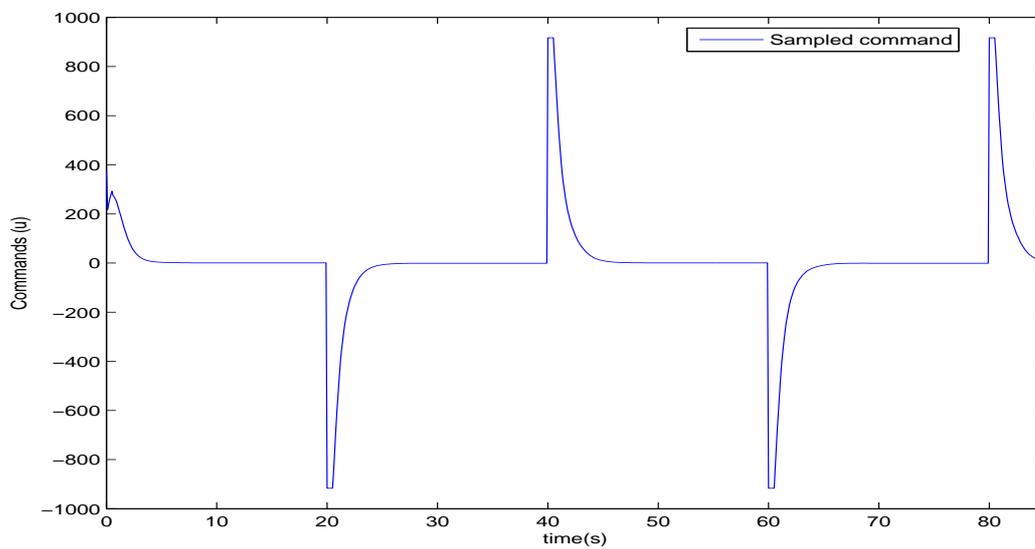


Figure 3.8: The corresponding Slave control of the experiment

3.4.4 Result of the remote experiment *via* Internet

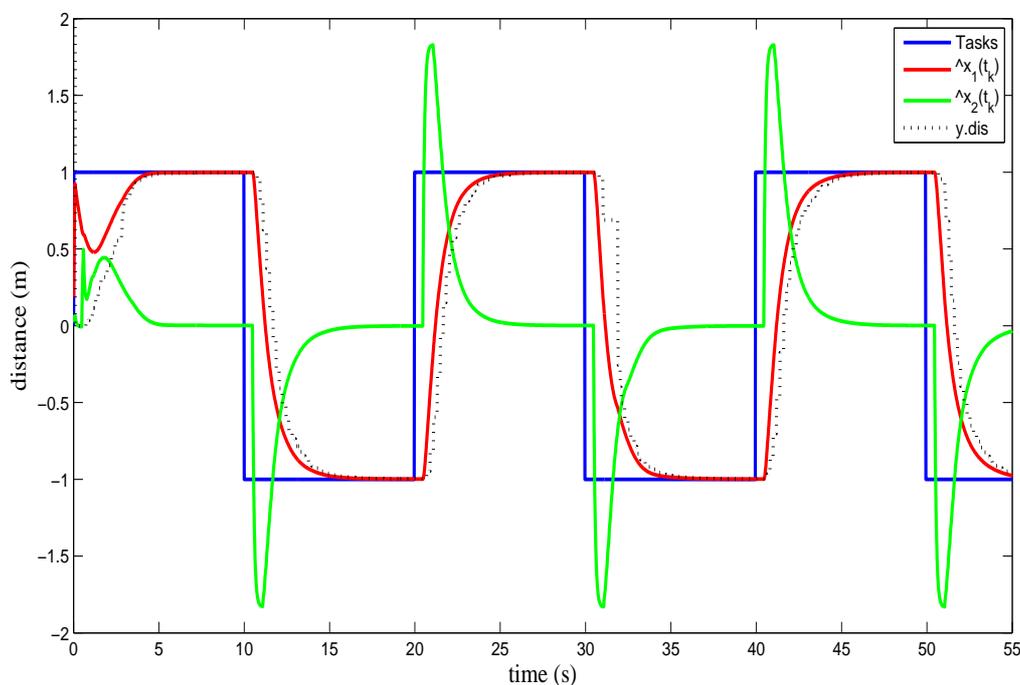


Figure 3.9: Results of remote experiment

The experiment is now done on two computers separated from about 40 kilometers away, the communication time-delay (RTT) is showed in the Fig. 3.4. We first synchronized the clocks of the two computers by the NTP (Network Time Protocol). We choose the same time pool server, *europa.pool.ntp.org*. Note that, for the problem of clock synchronization between the two PCs, two methods can be applied. One is to use the protocol NTP, *i.e.* before running the program, two PCs are synchronized. But after running a long time, we can not guarantee the perfect same time in the two PCs. So, the second method is adapted, the time clock difference is calculated in the program and it is taken account into the time-delay.

Then, the Master program runs on the remote computer with an advanced computing capability, the Slave program on the local one which also communicates with the Miabot by the port of Bluetooth as depicted on Fig.3.9, we get almost the same characteristics as these results with centralized experiment. Note that all the data in the figure is obtained from the Master, so the data of the real position of the Miabot (curve black) lags behind the estimated one, due to the time delays of Internet and Bluetooth. Our remote observer does work as a predictor.

3.5 Conclusion

Exponential stability is obtained and the experimental results confirm the theory. Both the local and distant experiments confirm the theory and the Miabot follows the given instructions.

To be adapted to more general situation of the Internet, we can augment h_2 while diminishing the value of α . When α is fixed as 0, we get the largest allowable time delay: h_2 should be no more than 1.9sec. This theoretically proved bound represents the Internet which is tolerated for the stabilization of the system.

From now, two possible limitations still remain:

1. In the present form, the delay interval, and the upper bound h_2 in particular, is fixed once for all. However, as shown on Fig.3.4, the delay may stay small during some period (at least, nighttime), while the controller keeps on working with gains adapted to big delay. The aim of the next chapter (Chapter 4) will be to adapt the gains to the estimated QoS of the network.
2. Our solution needs a “waiting strategy” to be implemented at the Slave side. This makes the computation of the gains easier, but may decrease the achievable speed performance since it maximizes one of the delays (the actuator channel). The theory to be developed in the last chapter (Chapter 5) will overcome this constraint by obtaining event-driven solutions in both the actuator and measurement channels.

Chapter 4

Stabilization of a remote system: a QoS dependent controller

In the case of the stabilization through Internet, time-delays present a strong jitter. It means that the controller has to be designed for a large delay interval. This leads to poor performance when the delay belongs to a smaller interval than the one for which it is originally designed. Whereas, in different periods of time, the average values of time-delay show big differences due to the communication quality of Internet, for example when comparing the daytime and the nighttime.

Considering different Qualities of Service (QoS) of the network, a switching controller is proposed. As previously, stability and speed performances are ensured despite the dynamic variations of the network, *via* the exponential stabilization. Moreover, here, the QoS is estimated by measuring the communication delays and the controller gains switch in consequence. Since this RTT estimation cannot be instantaneous, this additional delay of the switching instants is also taken into account.

Switched systems are dynamical hybrid systems consisting of a family of continuous-time subsystems (also called the “modes”) and a logical rule that orchestrates the switching between them [Liberzon D. 2003; Hirche S. *et al.* 2006]. It is known that the stability of the subsystems themselves is not sufficient for the stability of the overall system.

The theoretical proofs we use are, here again, related to Lyapunov-Krasovskii functionals (LKF), which approach is generally less conservative than the Lyapunov-Razumikhin functions technique. Moreover, to deal with delay-dependent stability problems, the LKFs condition is

attractive owing to the structural advantage, exposing the delay information more easily when obtaining the stability criterion.

Single and multiple Lyapunov function analysis methods are the most frequently applied in the stabilization of the whole, switched system. For systems with delays, they consist in the research of:

- a single (or “common”) LKF for all modes, so to obtain *uniform* stability [Jiang W.-J. *et al.* 2008; Sun Y.G. & Wang L. 2006; Lee J.-W. & Dullerud G.E. 2006, 2007],
- or different LKFs, one for each mode, with a minimum dwell time to guaranty the global stability for the whole system.

When the system mainly needs stability and the performance is not a critical condition, the former method can be used. As a common LKF is used for every subsystem, the condition is relatively simple and arbitrary switching can be realized among all the subsystems. However, for this first method, there are two deficiencies: One is that the common LKF cannot always be found, another is that even if a common LKF can be found, the performances will be limited.

Concerning the second approach, different LKFs can be applied to obtain the best performance for each subsystem, whereas, before the next switch, a minimum dwell time has to be considered to guarantee the global stability. This alternative, dwell-time based switching was introduced in [Hespanha J.P. & Morse A.S. 1999] in the case of a system without delay. It was extended to systems with delay in [Chen C.-C. *et al.* 2006; Yan P. & Özbay H. 2008] but, in these references, the delay was supposed to be constant.

In this chapter, aiming at the exponential stabilization of our NCS, we introduce a study of switched systems with non-small and fast-varying delays. This framework corresponds better to our problem. Here, the switches are voluntarily introduced at the control side, and their logical rule is decided according to the network QoS. This last is moreover estimated by measuring the communication delays. The switching controller gains are adapted in consequence.

Our assumptions on the delays are not very constraining:

- The transmission delays are variable and asymmetric, which means that the control channel delay $h_1(t)$ (from Master to Slave, shortly, M-to-S), and the return, measurement channel delay (S-to-M) $h_2(t)$, normally satisfy $h_1(t) \neq h_2(t)$.

- The resulting delays in both channels (with our notations, $\delta_{con}(t)$ and δ_{obs}) are bounded and belong to some interval $[h_m, h_M] = [h_1, h_3]$
- This interval is separated into two zones, $[h_1, h_2]$ for “small” delays, and $[h_2, h_3]$ for “big” delays. We assume that both $\delta_{con}(t)$ and δ_{obs} belong to the same zone.
- In the following, these two delay zones will correspond to the two “modes” of the switched controller.

Moreover, all the results can be straightforwardly extended to more than two modes, and with different zones for the control delay and the observation delay. However, in this case the computations become more cumbersome. For sake of clarity, and since our experiments were successful with the above hypothesis, we preferred not to develop the more general case.

In the following part, a deeper analysis of the communication delays is provided (in particular, we discuss the question of their estimation). Then, some result involving a switching controller and the use of a common LKF is given. A last part presents technical improvements based on the minimum dwell time. At each step, experiments are conducted.

4.1 Time-delay effect on the performance of systems

The delay sizes take very different values, especially if one compares the periods of rush hour and idle time. The Fig.4.1 shows the round-trip-time measured every one minute during a week between Lille and Lens (the places of our experiment, separated from 40km). It is clear that when the network is busy in the daytime the time-delay is much bigger than in the night-time. The difference weekdays/weekend is also perceptible. The maximum delay value (here, denoted by h_{max}) is used for the controller design, which means it has an influence on the performance of the system. To get an idea of this influence, Fig.4.2 and Fig.4.3 show the best step response we can obtain for a linear system with different values of h_{max} (in the corresponding computations, the minimum value h_{min} was equal to 0). We can see that, when the maximum time-delay h_{max} is smaller, the stability can be obtained with the greater value of α , *i.e.* the better performance can be got. On the contrary, the bigger the value of the maximum time-delay, the smaller the value of α , *i.e.* the performance becomes worse even if the real situation of the network is not so perturbing. This motivates the application of a gain scheduling strategy for the control system, with adaptation to the network quality of service (QoS). Two modes

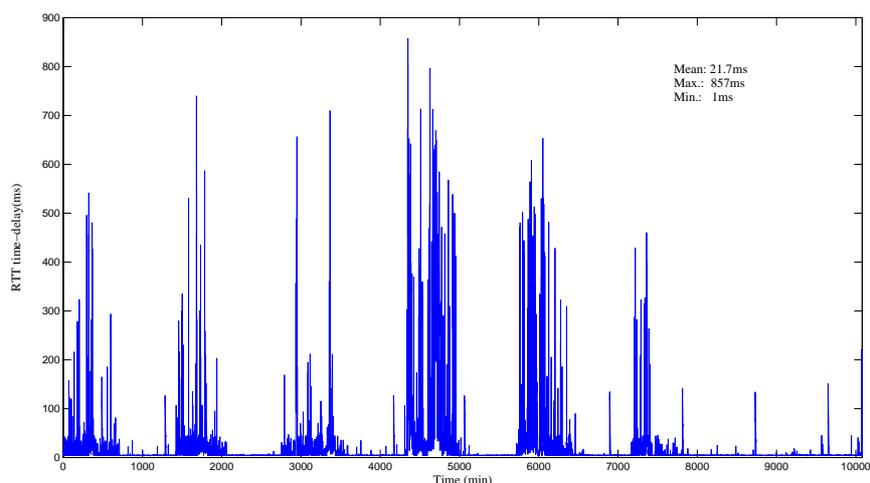


Figure 4.1: The time-delays via Internet during a week.

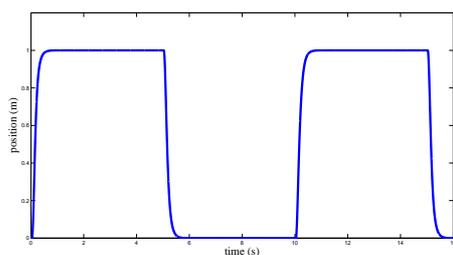


Figure 4.2: $h_{max} = 0.05s$, $\alpha = 8.74$

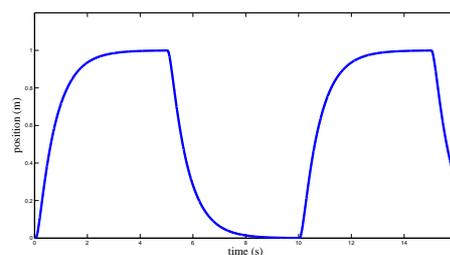


Figure 4.3: $h_{max} = 0.5s$, $\alpha = 0.96$

(small/big delay) will be considered in this work, but it can be extended to more modes.

4.2 A switched controller with arbitrary switches and a common LKF

This part develops a common L-K functional so to ensure exponential stability for the switched system. The global stability is also proved. Firstly the conditions for asymptotic stability are proved; Secondly, by using the polytopic method, exponential stability can be attained. The common LKF guarantees the property for arbitrary switching, which means that whenever the switch happens, the system stays stable. So, it is acceptable that the QoS of the network is assumed to be measured in real time (*i.e.*, without delay). Of course, because of the delayed

QoS measurement, there will be an effect of buffer changes at the switching point but the uniform system stability will be guaranteed. This phenomenon will be also analyzed in the following experimental results.

Considering the control problem as in the part (3.3.1). The controller switches according to the value of the delay. One mode represents the controller when the delay is small: $\delta(t) \in [h_1, h_2]$. The other mode appears when the delay is higher: $\delta(t) \in [h_2, h_3]$, $h_1 = h_{min}$ and $h_3 = h_{max}$.

Since a delay $\delta(t)$ is either in $[h_1, h_2]$ or in $[h_2, h_3]$, one naturally introduces $\chi : \mathbb{R} \rightarrow \{0, 1\}$, the characteristic function of $[h_1, h_2]$, defined by:

$$\chi_{[h_1, h_2]}(s) = \begin{cases} 1, & \text{if } s \in [h_1, h_2] \\ 0, & \text{otherwise.} \end{cases} \quad (4.1)$$

The characteristic function of $[h_2, h_3]$ is $1 - \chi$. Note that we assume $\chi(\delta_{con}(t)) = \chi(\delta_{obs}(t))$.

Now, considering the control problem (3.35) in the part (3.3.1), the stabilization problems of observer and controller with this 2-modes gain switching strategy can be rewritten as follows:

$$\begin{aligned} 1) \quad \dot{x}(t) &= Ax(t) + \chi_{[h_1, h_2]}(\delta_{con}(t))BK_1x(t - \delta_{con}(t)) + (1 - \chi_{[h_1, h_2]}(\delta_{con}(t)))BK_2x(t - \delta_{con}(t)), \\ & \quad (4.2) \\ 2) \quad \dot{e}(t) &= Ae(t) - \chi_{[h_1, h_2]}(\delta_{obs}(t))L_1Ce(t - \delta_{obs}(t)) - (1 - \chi_{[h_1, h_2]}(\delta_{obs}(t)))L_2Ce(t - \delta_{obs}(t)). \\ & \quad (4.3) \end{aligned}$$

4.2.1 Asymptotic stability of switched systems

Consider the switched system

$$\dot{x}(t) = Ax(t) + \chi_{[h_1, h_2]}(\tau)A_1x(t - \tau(t)) + (1 - \chi_{[h_1, h_2]}(\tau))A_2x(t - \tau(t)), \quad (4.4)$$

where the delays $\tau \in [h_1, h_2] \cup [h_2, h_3]$ are assumed to be fast-varying within these bounds.

Consider the following LKF:

$$\begin{aligned} V(t, x_t, \dot{x}_t) &= x^T(t)Px(t) + \sum_{i=0}^2 \int_{t-h_{i+1}}^t x^T(s)S_i x(s)ds \\ &+ \sum_{i=0}^2 (h_{i+1} - h_i) \int_{-h_{i+1}}^{-h_i} \int_{t+\theta}^t \dot{x}^T(s)R_i \dot{x}(s)dsd\theta, \end{aligned} \quad (4.5)$$

where $h_0 = 0$, $P > 0$ and $R_i, S_i \geq 0$.

Differentiating V , we find:

$$\begin{aligned}\dot{V}(t, x_t, \dot{x}_t) &\leq 2x^T(t)P\dot{x}(t) + \dot{x}^T(t) \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_i \dot{x}(t) \\ &- \sum_{i=0}^2 (h_{i+1} - h_i) \int_{t-h_{i+1}}^{t-h_i} \dot{x}^T(s) R_i \dot{x}(s) ds + x^T(t) \sum_{i=0}^2 S_i x(t) \\ &- \sum_{i=0}^2 x^T(t-h_i) S_i x(t-h_i).\end{aligned}\quad (4.6)$$

We start with the case of $\chi = 1$, *i.e.* of $\tau \in [h_1, h_2]$. We employ the representation:

$$\begin{aligned}-(h_{j+1} - h_j) \int_{t-h_{j+1}}^{t-h_j} \dot{x}^T(s) R_1 \dot{x}(s) ds &= -(h_{j+1} - h_j) \int_{t-h_{j+1}}^{t-\tau(t)} \dot{x}^T(s) R_j \dot{x}(s) ds \\ &-(h_{j+1} - h_j) \int_{t-\tau(t)}^{t-h_j} \dot{x}^T(s) R_j \dot{x}(s) ds,\end{aligned}\quad (4.7)$$

and apply the Jensen's inequality [Gu K. *et al.* 2003]

$$\begin{aligned}\int_{t-h_{i+1}}^{t-h_i} \dot{x}^T(s) R_i \dot{x}(s) ds &\geq \frac{1}{h_i - h_{i+1}} \int_{t-h_{i+1}}^{t-h_i} \dot{x}^T(s) ds R_i \int_{t-h_{i+1}}^{t-h_i} \dot{x}(s) ds, \\ \int_{t-\tau(t)}^{t-h_j} \dot{x}^T(s) R_j \dot{x}(s) ds &\geq \frac{1}{h_{j+1} - h_j} \int_{t-\tau(t)}^{t-h_j} \dot{x}^T(s) ds R_j \int_{t-\tau(t)}^{t-h_j} \dot{x}(s) ds, \\ \int_{t-h_{j+1}}^{t-\tau(t)} \dot{x}^T(s) R_j \dot{x}(s) ds &\geq \frac{1}{h_{j+1} - h_j} \int_{t-h_{j+1}}^{t-\tau(t)} \dot{x}^T(s) ds R_j \int_{t-h_{j+1}}^{t-\tau(t)} \dot{x}(s) ds,\end{aligned}\quad (4.8)$$

where $j = 1, i = 0, 2$. Then, denoting:

$$v_{j1} = \int_{t-\tau(t)}^{t-h_j} \dot{x}(s) ds, \quad v_{j2} = \int_{t-h_{j+1}}^{t-\tau(t)} \dot{x}(s) ds, \quad (4.9)$$

we obtain:

$$\begin{aligned}\dot{V}(t, x_t, \dot{x}_t) &\leq x^T(t)P\dot{x}(t) + \dot{x}^T(t) \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_i \dot{x}(t) \\ &+ \sum_{i=0}^2 x^T(t) S_i x(t) - \sum_{i=0}^2 x^T(t-h_{i+1}) S_i x(t-h_{i+1}) \\ &- [x(t) - x(t-h_1)]^T R_0 [x(t) - x(t-h_1)] \\ &- [x(t-h_2) - x(t-h_3)]^T R_2 [x(t-h_2) - x(t-h_3)] \\ &- v_{11}^T R_1 v_{11} - v_{12}^T R_1 v_{12}.\end{aligned}\quad (4.10)$$

We use further the descriptor method [Fridman E. & Shaked U. 2001] where, for some $n \times n$ -matrices P_2, P_3 , the right-hand side of the expression:

$$0 = 2[x^T(t)P_2^T + \dot{x}^T(t)P_3^T][Ax(t) + A_j x(t-h_j) - A_j v_{j1} - \dot{x}(t)], \quad (4.11)$$

is added into the right-hand side of (4.53). We also add free weighting matrices of [He Y. *et al.* 2004]:

$$0 = 2[x^T(t)Y_{j1}^T + \dot{x}^T(t)Y_{j2}^T][x(t-h_{j+1}) + v_{j1} + v_{j2} - x(t-h_j)]. \quad (4.12)$$

Setting $\eta_j(t) = \text{col}\{x(t), \dot{x}(t), x(t-h_1), x(t-h_2), v_{j1}, v_{j2}, x(t-h_3)\}$, we obtain that:

$$\dot{V}(t, x_t, \dot{x}_t) \leq \eta_1^T(t) \Phi|_{\chi=1} \eta_1(t) < 0, \quad (4.13)$$

if the LMI:

$$\Phi|_{\chi=1} = \begin{bmatrix} \Phi_{11} & \Phi_{12} & R_0 + P_2^T A_1 - Y_{11}^T & Y_{11}^T & Y_{11}^T - P_2^T A_1 & Y_{11}^T & 0 \\ * & \Phi_{22} & P_3^T A_1 - Y_{12}^T & Y_{12}^T & Y_{12}^T - P_3^T A_1 & Y_{12}^T & 0 \\ * & * & -(S_0 + R_0) & 0 & 0 & 0 & 0 \\ * & * & * & -(S_1 + R_2) & 0 & 0 & R_2 \\ * & * & * & * & -R_1 & 0 & 0 \\ * & * & * & * & * & -R_1 & 0 \\ * & * & * & * & * & * & -(S_2 + R_2) \end{bmatrix} < 0 \quad (4.14)$$

holds, where:

$$\begin{aligned} \Phi_{11} &= A^T P_2 + P_2^T A + \sum_{i=0}^2 S_i - R_0, \\ \Phi_{12} &= P - P_2^T + A^T P_3, \quad \Phi_{22} = -P_3 - P_3^T + \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_i. \end{aligned} \quad (4.15)$$

For $\chi = 0$, *i.e.* for $\tau \in [h_2, h_3]$, applying the same arguments and representation with $j = 2$ and $i = 0, 1$ we obtain:

$$\begin{aligned} \dot{V}(t, x_t, \dot{x}_t) &\leq x^T(t) P \dot{x}(t) + \dot{x}^T(t) \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_i \dot{x}(t) \\ &+ \sum_{i=0}^2 x^T(t) S_i x(t) - \sum_{i=0}^2 x^T(t - h_i) S_i x(t - h_i) \\ &- [x(t) - x(t - h_1)]^T R_0 [x(t) - x(t - h_1)] \\ &- [x(t - h_2) - x(t - h_1)]^T R_1 [x(t - h_2) - x(t - h_1)] \\ &- v_{21}^T R_2 v_{21} - v_{22}^T R_2 v_{22}, \end{aligned} \quad (4.16)$$

and arrive to the following property, that the inequality:

$$\dot{V}(t, x_t, \dot{x}_t) \leq \eta_2^T(t) \Phi|_{\chi=0} \eta_2(t) < 0, \quad (4.17)$$

is satisfied if the LMI holds:

$$\Phi|_{\chi=0} = \begin{bmatrix} \Phi_{11} & \Phi_{12} & R_0 & P_2^T A_2 - Y_{21}^T & Y_{21}^T - P_2^T A_2 & Y_{21}^T & Y_{21}^T \\ * & \Phi_{22} & 0 & P_3^T A_2 - Y_{22}^T & Y_{22}^T - P_3^T A_2 & Y_{22}^T & Y_{22}^T \\ * & * & -(S_0 + R_0 + R_1) & R_1 & 0 & 0 & 0 \\ * & * & * & -(S_1 + R_1) & 0 & 0 & 0 \\ * & * & * & * & -R_2 & 0 & 0 \\ * & * & * & * & * & -R_2 & 0 \\ * & * & * & * & * & * & -S_2 \end{bmatrix} < 0 \quad (4.18)$$

Then , along the trajectories of the switched system (4.4), one has:

$$\dot{V}(t, x^t, \dot{x}^t) \leq \chi(\tau)\eta_1^T(t)\Phi|_{\chi=1}\eta_1(t) + (1 - \chi(\tau))\eta_2^T(t)\Phi|_{\chi=0}\eta_2(t) < 0. \quad (4.19)$$

Thus, the following result is obtained.

Theorem 4 *Let there exist $n \times n$ -matrices $P > 0, R_i > 0, S_i > 0, i = 0, 1, 2, P_2, P_3, Y_{j1}$ and $Y_{j2}, j = 1, 2$ such that the LMIs (4.14), (4.18) with notations given in (4.15) are feasible. Then system (4.4) is asymptotically stable for all fast-varying delays $\tau_j \in [h_j, h_{j+1}], j = 1, 2$.*

4.2.2 Exponential stability of the switched systems

For a real $\alpha > 0$, the system (4.4) is said to be α -stable [Niculescu S.-I. *et al.* 1998], or exponentially stable [Kolmanovskii V. & Myshkis A. 1992] with the rate α , if there exists a scalar $F \geq 1$ such that the solution $x(t; t_0, \phi)$ satisfies:

$$\|x(t; t_0, \phi)\| \leq F \|\phi\|_{\mathcal{C}} e^{-\alpha(t-t_0)}, \quad (4.20)$$

where $\|x(\cdot)\|$ is the norm of vector and $\|\phi\|_{\mathcal{C}}$ the associated uniform norm of function ϕ (see Notations).

In [Seuret A. 2006], the α - stability of (non switched) systems with variable delays was studied by means of a transformed variable $x_\alpha(t) = e^{\alpha t}x(t)$. Following this idea and substituting this new variable $x_\alpha(t)$ in (4.4) leads to:

$$\begin{aligned} \dot{x}_\alpha(t) = & (A + \alpha I)x_\alpha(t) + \chi_{[h_1, h_2]}(\tau)e^{\alpha\tau}A_1x_\alpha(t - \tau(t)) \\ & + (1 - \chi_{[h_1, h_2]}(\tau))e^{\alpha\tau}A_2x_\alpha(t - \tau(t)). \end{aligned} \quad (4.21)$$

Lemma 3 *Given an $\alpha > 0$, if the system (4.21) can be proved to be asymptotically stable, then the system (4.4) is exponentially stable with the rate α .*

Considering the case $\chi = 1$, and since $e^{\alpha h_1} \leq e^{\alpha\tau(t)} \leq e^{\alpha h_2}$, we can rewrite the equation (4.21) in the following polytopic form:

$$\begin{aligned} \dot{x}_\alpha(t) = & \sum_{i=1}^2 \lambda_i(t) \{ (A + \alpha I)x_\alpha(t) + e^{\alpha h_1} A_1 x_\alpha(t - \tau(t)) \\ & + e^{\alpha h_2} A_2 x_\alpha(t - \tau(t)) \}, \end{aligned} \quad (4.22)$$

for $i=1,2, \lambda_i(t) \geq 0, \sum_{i=1}^2 \lambda_i(t) = 1$.

The case $\chi = 0$ can be rewritten in the same way. Applying Theorem 4 to these transformed systems allows for studying the α -stability of the original system.

4.2.3 Exponential stabilization of the controller and observer parts, separately

Applying the Theorem 4 and Lemma 3 with some matrix manipulations (bijective transformations and congruences), the following result for the state feedback controller design is obtained:

Lemma 4 *Given some scalars $\alpha > 0$ and $\varepsilon_i > 0$, if there exists $n \times n$ matrices $0 < P$, S_k , R_k ($k = 0, 1, 2$), and matrices P_2 , Y_{11} , Y_{12} , Y_{21} , Y_{22} , M_i , $i = 1, 2$ with appropriate dimensions, such that the following LMI (4.23) and (4.24) hold, then the closed loop given in (4.2) with $K_i = M_i P_2^{-1}$ is α -stable for each of the two modes.*

$$\Phi_{con1} = \begin{bmatrix} \Phi_{11} & \Phi_{12} & R_0 + \beta_{ij} B M_i - Y_{11}^T & Y_{11}^T & Y_{11}^T - \beta_{ij} B M_i & Y_{11}^T & 0 \\ * & \Phi_{22} & \varepsilon_i \beta_{ij} B M_i - Y_{12}^T & Y_{12}^T & Y_{12}^T - \varepsilon_i \beta_{ij} B M_i & Y_{12}^T & 0 \\ * & * & -(S_0 + R_0) & 0 & 0 & 0 & 0 \\ * & * & * & -(S_1 + R_2) & 0 & 0 & R_2 \\ * & * & * & * & -R_1 & 0 & 0 \\ * & * & * & * & * & -R_1 & 0 \\ * & * & * & * & * & * & -(S_2 + R_2) \end{bmatrix} < 0 \quad (4.23)$$

for $i = 1, j = 1, 2$;

$$\Phi_{con2} = \begin{bmatrix} \Phi_{11} & \Phi_{12} & R_0 & \beta_{ij} B M_i - Y_{21}^T & Y_{21}^T - \beta_{ij} B M_i & Y_{21}^T & Y_{21}^T \\ * & \Phi_{22} & 0 & \varepsilon_i \beta_{ij} B M_i - Y_{22}^T & Y_{22}^T - \varepsilon_i \beta_{ij} B M_i & Y_{22}^T & Y_{22}^T \\ * & * & -(S_0 + R_0 + R_1) & R_1 & 0 & 0 & 0 \\ * & * & * & -(S_1 + R_1) & 0 & 0 & 0 \\ * & * & * & * & -R_2 & 0 & 0 \\ * & * & * & * & * & -R_2 & 0 \\ * & * & * & * & * & * & -S_2 \end{bmatrix} < 0 \quad (4.24)$$

for $i = 2, j = 1, 2$ and with notations:

$$\begin{aligned} \Phi_{11} &= P_2(A + \alpha I)^T + (A + \alpha I)P_2^T + \sum_{k=0}^2 S_k - R_0, \\ \Phi_{12} &= P - P_2^T + \varepsilon_i P_2(A + \alpha I)^T, \\ \Phi_{22} &= -\varepsilon_i P_2 - \varepsilon_i P_2^T + \sum_{k=0}^2 (h_{k+1} - h_k)^2 R_k, \end{aligned} \quad (4.25)$$

$$\begin{aligned}\beta_{11} &= e^{\alpha h_1}, & \beta_{12} &= e^{\alpha h_2}, \\ \beta_{21} &= e^{\alpha h_2}, & \beta_{22} &= e^{\alpha h_3}.\end{aligned}\quad (4.26)$$

$$K_i = M_i(P_2)^{-1}, i = 1, 2; \quad (4.27)$$

In the sequel, the above LMI condition ensuring the exponential stabilization of the system considering the delay $\delta_{con} \in [h_i, h_{i+1}], i = 1, 2$ will be noted:

$$LMI_{con}(P_1, P_2, \varepsilon_i, S_l, R_l, M_i, h_i, h_{i+1}, \alpha), l = 0, 1, 2. \quad (4.28)$$

The observer design result is given in the same way, as follows.

Lemma 5 *Given some scalars $\alpha > 0$ and $\varepsilon_i > 0$, if there exist $n \times n$ matrices $0 < P, S_k, R_k (k = 0, 1, 2)$, and matrices $P_2, Y_{11}, Y_{12}, Y_{21}, Y_{22}, W_i, i = 1, 2$, with appropriate dimensions, such that the following LMI (4.29) and (4.30) hold, then the observation error given in (4.3) with $L_i = P_2^{-T} W_i$ is α -stable for each of the two modes.*

$$\Phi_{obs1} = \begin{bmatrix} \Phi_{11} & \Phi_{12} & R_0 + \beta_{ij} W_i C - Y_{11}^T & Y_{11}^T & Y_{11}^T - \beta_{ij} W_i C & Y_{11}^T & 0 \\ * & \Phi_{22} & \varepsilon_i \beta_{ij} W_i C - Y_{12}^T & Y_{12}^T & Y_{12}^T - \varepsilon_i \beta_{ij} W_i C & Y_{12}^T & 0 \\ * & * & -(S_0 + R_0) & 0 & 0 & 0 & 0 \\ * & * & * & -(S_1 + R_2) & 0 & 0 & R_2 \\ * & * & * & * & -R_1 & 0 & 0 \\ * & * & * & * & * & -R_1 & 0 \\ * & * & * & * & * & * & -(S_2 + R_2) \end{bmatrix} < 0 \quad (4.29)$$

for $i = 1, j = 1, 2;$

$$\Phi_{obs2} = \begin{bmatrix} \Phi_{11} & \Phi_{12} & R_0 & \beta_{ij} W_i C - Y_{21}^T & Y_{21}^T - \beta_{ij} W_i C & Y_{21}^T & Y_{21}^T \\ * & \Phi_{22} & 0 & \varepsilon_i \beta_{ij} W_i C - Y_{22}^T & Y_{22}^T - \varepsilon_i \beta_{ij} W_i C & Y_{22}^T & Y_{22}^T \\ * & * & -(S_0 + R_0 + R_1) & R_1 & 0 & 0 & 0 \\ * & * & * & -(S_1 + R_1) & 0 & 0 & 0 \\ * & * & * & * & -R_2 & 0 & 0 \\ * & * & * & * & * & -R_2 & 0 \\ * & * & * & * & * & * & -S_2 \end{bmatrix} < 0 \quad (4.30)$$

for $i = 2, j = 1, 2$,

with β_{ij} ($i, j=1, 2$) defined by (4.26) and:

$$\begin{aligned}\Phi_{11} &= (A + \alpha I)^T P_2 + P_2^T (A + \alpha I) + \sum_{k=0}^2 S_k - R_0, \\ \Phi_{12} &= P - P_2^T + \varepsilon_i (A + \alpha I)^T P_2, \\ \Phi_{22} &= -\varepsilon_i P_2 - \varepsilon_i P_2^T + \sum_{k=0}^2 (h_{k+1} - h_k)^2 R_k.\end{aligned}\tag{4.31}$$

In the sequel, the above LMI condition ensuring the exponential stability of an observer considering the delay $\delta_{obs} \in [h_i, h_{i+1}]$, $i = 1, 2$ will be noted:

$$LMI_{obs}(P_1, P_2, \varepsilon_i, S_l, R_l, W_i, h_i, h_{i+1}, \alpha), l = 0, 1, 2.\tag{4.32}$$

4.2.4 Exponential stabilization of the global NCS (controller+observer)

The dynamic global networked control system is as follows [Seuret A. *et al.* 2006] for $i = 1, 2$:

$$\begin{cases} \dot{x}(t) = Ax(t) + BK_i x(t - \delta_{con}^i(t)) - BK_i e(t - \delta_{con}^i(t)), \\ \dot{e}(t) = Ae(t) - L_i C e(t - \delta_{obs}^i(t)). \end{cases}\tag{4.33}$$

Considering to use $\zeta(t) = col\{x(t), e(t)\}$, then we get the equation:

$$\dot{\zeta}(t) = \bar{A}_0 \zeta(t) + \bar{A}_{1i} \zeta(t - \delta_{con}^i(t)) + \bar{A}_{2i} \zeta(t - \delta_{obs}^i(t))\tag{4.34}$$

for $\bar{A}_0 = \begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix}$, $\bar{A}_{1i} = \begin{bmatrix} BK_i & -BK_i \\ 0 & 0 \end{bmatrix}$, $\bar{A}_{2i} = \begin{bmatrix} 0 & 0 \\ 0 & -L_i C \end{bmatrix}$. These matrices are under the block-triangular form. Thus, if the diagonal subsystems can be proven to be exponentially stable by Lemma 4 and 5, then the whole system is α -stable with the smallest α computed from Lemma 4 and 5.

4.2.5 Performance enhancement

In Lemma 4 and 5, the value of α was same for both of the modes. This is rather conservative, specially for the mode of small time-delay. In order to reach higher value of the convergence rate α , the design strategy is now divided into two parts with reference to Fig.4.4. The first one ensures the *uniform* stability of the switching closed loop by finding a common Lyapunov-Krasovskii functional for all gains. The second part guarantees some performance rates α_i for the mode i when the delay $\delta_{con}^i(t), \delta_{obs}^i(t) \in [h_i, h_{i+1}]$. The obtained performance indexes are

expected to be better than considering only one mode, as it was done previously in Chapter 3. With the notations 4.28 and 4.32, the conditions ensuring the first part are given by:

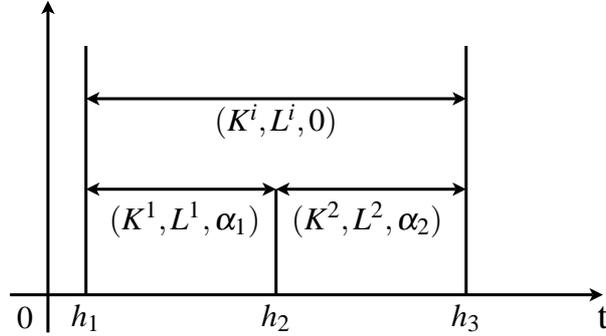


Figure 4.4: Uniform/exponential stability of the system, depending on the delay situation

- 1) $LMI_{con}(P_1^c, \dots, R_i^c, M_i, h_1, h_3, \alpha = 0), \forall i \in \{1, 2\},$
- 2) $LMI_{obs}(P_1^o, \dots, R_i^o, W_i, h_1, h_3, \alpha = 0), \forall i \in \{1, 2\}.$

The second part is guaranteed by:

- 3) $LMI_{con}(P_{1i}^c, P_2^c, \varepsilon_i^c, S_{li}^c, \dots, R_{li}^c, M_i, h_i, h_{i+1}, \alpha_i^c), \forall i \in \{1, 2\}$
- 4) $LMI_{obs}(P_{1i}^o, P_2^o, \varepsilon_i^o, S_{li}^o, \dots, R_{li}^o, W_i, h_i, h_{i+1}, \alpha_i^o), \forall i \in \{1, 2\}.$

Solving the problems 1) and 3) simultaneously achieves the state feedback design. Thanks to the choice of a common matrix P_2^c for 1) and 3), the design problem becomes linear (with the condition that the value of ε_i is first chosen and fixed). This allows for using standard LMI solvers [Boyd S. *et al.* 1994]. The same remark can be done for the observer part. It is only needed to solve 2) and 4). Thanks to the separation principle, the problems 1 & 3 and 2 & 4 can be solved independently.

The choice of these common matrices induces some conservatism but allows keeping the problem solving independent on the algorithm chosen. Only the scalars ε_i have to be chosen.

4.2.6 Experimental results

4.2.6.1 Parameters of the system

As shown in the Fig.4.1, the Round-trip-times between the two PCs have been continuously tested by the protocol ICMP (Internet Control Message) during a week and the average value

is 21.7ms. The minimum and maximum RTT were 1ms and 857ms, respectively. From these tests, considering also the Bluetooth transmission delays and the sampling delays, we take the value 0.5sec as the maximum time-delay. If the time-delay is bigger than this value, the packet is treated as lost.

As previously, the same maximum time-delay values are chosen for the controller and the observer, for sake of the simplification of the switching strategy. Considering two zones of delay with $[h1, h2] = [0.01, 0.09]$ and $[h2, h3] = [0.09, 0.5]$. It means that the gains switch when the delay crosses the value of 0.09sec. According to the part (4.2.5) and Lemma (4), (5), the maximum exponential rate ensuring the global stability are: $\alpha_1^c = \alpha_1^o = 3.1$ and $\alpha_2^c = \alpha_2^o = 1$.

The gains K_i and L_i ($i = 1, 2$) are:

$$\begin{bmatrix} L_1 & L_2 \end{bmatrix} = \begin{bmatrix} -3.02 & -1.37 \\ -0.27 & -0.36 \end{bmatrix}, \begin{bmatrix} K_1 \\ K_2 \end{bmatrix} = \begin{bmatrix} -1311 & -129 \\ -682 & -68 \end{bmatrix}. \quad (4.35)$$

4.2.6.2 Results of the remote experiment

The result is shown in Fig.4.5, in which the dash-dotted line represents the set values, this is the angle that we want the Miabot's motor to achieve; The dashed-line and straight-line represent respectively the estimated angle the real angle of the robot.

Fig.4.6 illustrates the corresponding switched control signals from Master to Slave. The straight-line curve is the real control while the dashed line and the dots are the controls calculated respectively for the two modes. We can see the switch points according to the values of time-delay.

Fig.4.7 depicts the variable time-delays, which comprise the time-delay of sampling and communication of Bluetooth (we consider it as constant time-delay, here we take the value of 40ms).

On Fig.4.5, one can notice three kinds of step responses. The first one corresponds to the case where the control switches a lot during the response. In that case, only the global stability is guaranteed denoted as $\alpha \geq 0$. During the second step, only the second mode is active, *i.e.* only the gains K_2 and L_2 are active ($\alpha = 1$). In this case, performances are guaranteed. In the last kind of response, only the first mode is active because the delays are small. In that case, the performances are still better ($\alpha = 3.1$): the response time is smaller and the damping is greater.

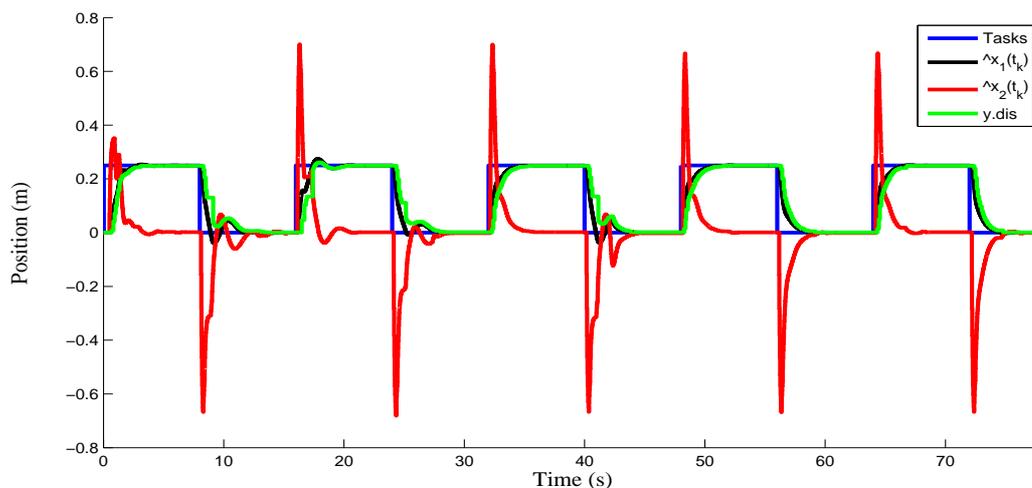


Figure 4.5: Results of the remote experiment

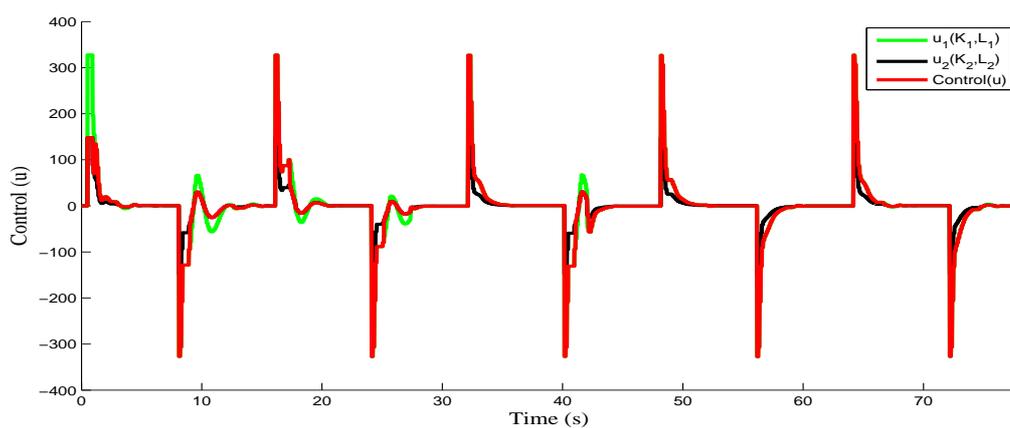


Figure 4.6: The corresponding switched control

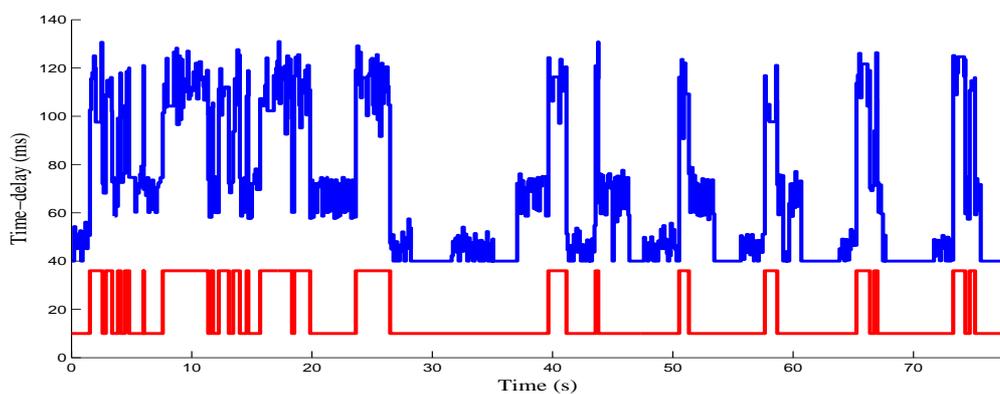


Figure 4.7: The corresponding variable delays

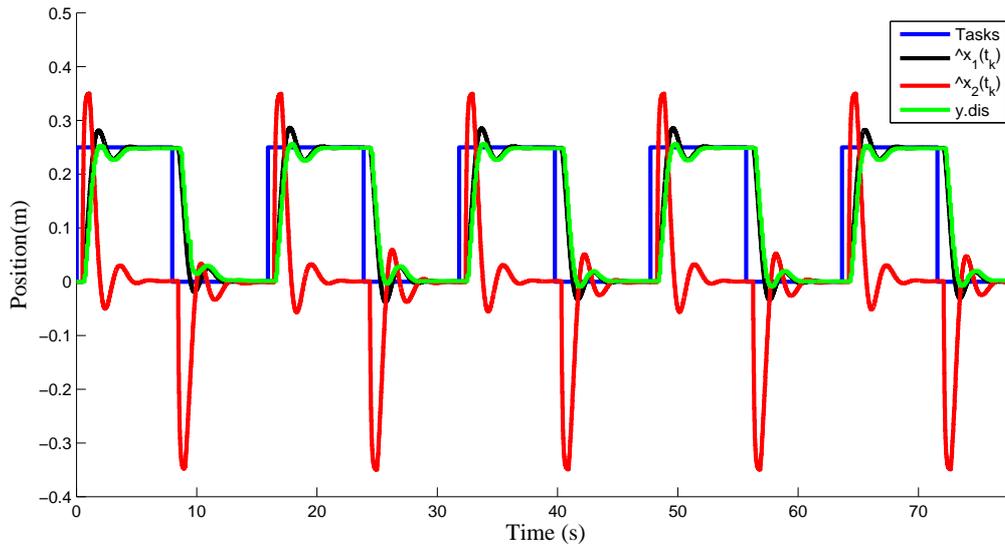


Figure 4.8: The results of system without switching

As it is clearly shown in Fig.4.5, the global stability of the closed loop is maintained despite that the assumption real time measurement of the time-delay is satisfied (in practice the QoS is measured after a RTT).

4.2.7 Conclusion

In addition to some theoretical results, our experimental platform illustrates the results of our switched control strategy.

The experimental results confirm the theory:

1. The exponential stability is obtained in both the time-delay zones and the *uniform* stability is guaranteed whatever the mode switches.
2. The experimental performances are shown to be better when considering two modes of time delay instead of one. To be convinced, one can compare the experimental results under the same network communication quality but without switching strategy, given in Fig.4.8 and corresponding to the achievable rate $\alpha = 0.96$ (note that, for the comparison purpose, this figure was obtained by replaying the same sequence of Internet delays).

4.3 A switched controller with multiple LKF and minimum dwell time

As it was explained in the introduction of this chapter, two strategies are often considered in switched systems analysis. The common LKF method (as developed in the previous section) guarantees the stability of the system with arbitrary switching, but suffers from conservatism. The second strategy is adapted to slower switching frequencies: Multiple LKF are used under the additional hypothesis that the switching logic respects some minimum dwell time. Such use of multiple LKFs reduces the conservatism since it permits each of the modes to behave in a completely different way. In most cases, this reduction allows for getting better performances or robustness. In our NCS case, such strategy (minimum dwell time) can be considered since the controller can artificially increase the delay and force the global switching system to be in the "big delay mode".

Since the modes do not share the same LKF, the fact that the QoS is measured after a RTT will bring some problems. To illustrate these problems, we first consider only the control part: Consider the following system:

$$\dot{x}(t) = Ax(t) + Bu(t - \tau(t)) \quad (4.36)$$

The switching controller to be considered is:

$$u(t) = \begin{cases} K_1x(t), \tau(t - RTT(t)) \in [h_1, h_2]; \\ K_2x(t), \tau(t - RTT(t)) \in [h_2, h_3]; \end{cases} \quad (4.37)$$

Now consider that the delay is small for a long period. The closed loop is then described by the following model:

$$\dot{x}(t) = Ax(t) + BK_1x(t - \tau(t)), \tau(t) \in [h_1, h_2]; \quad (4.38)$$

which stability and performances will be ensured by a LKF. after some time, the delay becomes big, the time that controller detect that the QoS has changed, the closed loop is described by:

$$\dot{x}(t) = Ax(t) + BK_2x(t - \tau(t)), \tau(t) \in [h_2, h_3]; \quad (4.39)$$

which stability is not guaranteed.

The second problem encountered concerns the change of buffer size. To illustrate the problem consider the following system with a input delay:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t - \tau(t)), \\ y = Cx(t) \end{cases} \quad (4.40)$$

with its linear observer:

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t - \hat{\tau}(t)) + L(y(t) - \hat{y}(t)), \\ \hat{y} = C\hat{x}(t) \end{cases} \quad (4.41)$$

since the QoS is measured after a RTT, the delay $\hat{\tau}(t)$ equals $\tau(t)$ only when there are no buffer size switches. When a switch occurs, the separation principle is lost for a while and the error equation is disturbed by the control signal of the system:

$$\begin{cases} \dot{e}(t) = Ae(t) - LCe(t) + B(u(t - \tau(t)) - u(t - \hat{\tau}(t))), \\ y = Cx(t) \end{cases} \quad (4.42)$$

Since these periods of instability are limited (the maximum RTT), ensuring a minimum dwell-time on the stable modes ensures the global stability. The only switching time that the controller can enlarge is when the delay goes from a big value to a smaller one. In fact, this is easily done by artificially enlarging the delay to meet the required dwell-time.

In order to guarantee some performances, the control and the observer gains are designed by considering the following model for $i = 1, 2$:

$$\begin{cases} \dot{x}(t) = Ax(t) + \chi(\tau)(BK_1x(t - \delta_{con}^1(t)) - BK_1e(t - \delta_{con}^1(t))) + \\ \quad (1 - \chi(\tau))(BK_2x(t - \delta_{con}^2(t)) - BK_2e(t - \delta_{con}^2(t))), \\ \dot{e}(t) = Ae(t) - \chi(\tau)L_1Ce(t - \delta_{obs}^1(t)) - (1 - \chi(\tau))L_2Ce(t - \delta_{obs}^2(t)). \end{cases} \quad (4.43)$$

Considering to use $\zeta(t) = col\{x(t), e(t)\}$, then we get the equation:

$$\begin{aligned} \dot{\zeta}(t) = & \bar{A}_0\zeta(t) + \chi(\tau)(\bar{A}_{11}\zeta(t - \delta_{con}^1(t)) + \bar{A}_{12}\zeta(t - \delta_{obs}^1(t))) + \\ & (1 - \chi(\tau))(\bar{A}_{21}\zeta(t - \delta_{con}^2(t)) + \bar{A}_{22}\zeta(t - \delta_{obs}^2(t))). \end{aligned} \quad (4.44)$$

for $\bar{A}_0 = \begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix}$, $\bar{A}_{i1} = \begin{bmatrix} BK_i & -BK_i \\ 0 & 0 \end{bmatrix}$, $\bar{A}_{i2} = \begin{bmatrix} 0 & 0 \\ 0 & -L_iC \end{bmatrix}$, with $i = 1, 2$ corresponding to the two switching modes. The following sections brings conditions for the gains design and some dwell-time conditions for the global stability.

4.3.1 Performance guarantee

4.3.1.1 Exponential stability of switched delay systems

Consider the switched system as (4.4). Hereafter, different LKF are applied with a minimum dwell time ensuring the stability when the closed loop go from the big delay mode to the small

delay mode. This minimum dwell time is achieved on the closed loop by artificially increasing the communication delay so that $\delta(t) \in [h_{min}^2, h_{max}^2]$.

Not using a common LKF reduces the conservatism, as each mode can have a completely different behavior. This reduction permits, in most cases, to get better performances or robustness. The stability analysis is performed by using a pair of LKFs for each mode (small delay, big delay). In order to make the LKFs comparable, their structures are chosen as follows:

$$V_j(t, x_t, \dot{x}_t) = x^T(t)P_{1j}x(t) + \sum_{i=0}^2 \int_{t-h_{i+1}}^{t-h_i} e^{2\alpha_j(s-t)} x^T(s) S_{ij} x(s) ds + \sum_{i=0}^2 (h_{i+1} - h_i) \int_{-h_{i+1}}^{-h_i} \int_{t+\theta}^t e^{2\alpha_j(s-t)} \dot{x}^T(s) R_{ij} \dot{x}(s) ds d\theta, \quad (4.45)$$

where j represents the mode, and $h_0 = 0$.

These LKFs consider the delay over the two zones. Without lack of generality, they can be used to analyze the system when the delay stays in one of the two intervals, *i.e.* when staying in one mode. Note that if $R_{2j} = 0$ and $S_{2j} = 0$, then the previous LKFs (4.45) are recovered for a time-delay $\tau(t) \in [h_1, h_2]$.

The following condition along the trajectories of (4.4):

$$\dot{V}_j(t, x_t, \dot{x}_t) + 2\alpha_j V_j(t, x_t, \dot{x}_t) \leq 0, \quad (4.46)$$

implies:

$$V_j(t, x_t, \dot{x}_t) \leq e^{-2\alpha_j(t-t_0)} V_j(t, x_{t_0}, \dot{x}_{t_0}) \quad \forall t_0 \in \mathbb{R}. \quad (4.47)$$

The latter implies exponential stability of (4.4) since:

$$x^T(t)P_j x(t) \leq V_j(t, x_t, \dot{x}_t) \leq e^{-2\alpha_j(t-t_0)} V_j(t, x_{t_0}, \dot{x}_{t_0}) \leq e^{-2\alpha_j(t-t_0)} V_j(t, x_{t_0}, \dot{x}_{t_0})|_{\alpha_j=0}.$$

Theorem 5 Given $\alpha_j > 0$, $j = 1, 2$, if there exist $n \times n$ -matrices $P_j > 0$, $R_{ij} > 0$, $S_{ij} > 0$, $i = 0, 1, 2$, P_{2j} , P_{3j} , Y_{1j} and Y_{2j} such that the following LMIs (4.48) and (4.49), with notations (4.50), are feasible, then the switched delay system (4.4) is exponentially stable in the j^{th} mode with the rate α_j respectively for all fast-varying delays $\tau \in [h_j, h_{j+1}]$:

$$\Phi|_{\chi=1} = \begin{bmatrix} \Phi_{111} & \Phi_{121} & \tilde{R}_{01} + P_{21}^T A_1 - Y_{11}^T & Y_{11}^T & [Y_{11}^T - P_{21}^T A_1] & Y_{11}^T & 0 \\ * & \Phi_{221} & P_{31}^T A_1 - Y_{21}^T & Y_{21}^T & [Y_{21}^T - P_{31}^T A_1] & Y_{21}^T & 0 \\ * & * & \hat{S}_{11} - (\tilde{S}_{01} + \tilde{R}_{01}) & 0 & 0 & 0 & 0 \\ * & * & * & \hat{S}_{21} - (\tilde{S}_{11} + \tilde{R}_{21}) & 0 & 0 & \tilde{R}_{21} \\ * & * & * & * & -\tilde{R}_{11} & 0 & 0 \\ * & * & * & * & * & -\tilde{R}_{11} & 0 \\ * & * & * & * & * & * & -(\tilde{S}_{21} + \tilde{R}_{21}) \end{bmatrix} < 0, \quad (4.48)$$

$$\Phi|_{\chi=0} = \begin{bmatrix} \Phi_{112} & \Phi_{122} & \tilde{R}_{02} & P_{22}^T A_2 - Y_{12}^T & [Y_{12}^T - P_{22}^T A_2] & Y_{12}^T & Y_{12}^T \\ * & \Phi_{222} & 0 & P_{32}^T A_2 - Y_{22}^T & [Y_{22}^T - P_{32}^T A_2] & Y_{22}^T & Y_{22}^T \\ * & * & \hat{S}_{12} - (\tilde{S}_{02} + \tilde{R}_{02} + \tilde{R}_{12}) & \tilde{R}_{12} & 0 & 0 & 0 \\ * & * & * & \hat{S}_{22} - (\tilde{S}_{12} + \tilde{R}_{12}) & 0 & 0 & 0 \\ * & * & * & * & -\tilde{R}_{22} & 0 & 0 \\ * & * & * & * & * & -\tilde{R}_{22} & 0 \\ * & * & * & * & * & * & -\tilde{S}_{22} \end{bmatrix} < 0, \quad (4.49)$$

where:

$$\begin{aligned} \tilde{R}_{ij} &= e^{-2\alpha_j(h_{i+1})} R_{ij}, \\ \tilde{S}_{ij} &= e^{-2\alpha_j h_{i+1}} S_{ij}, \\ \hat{S}_{ij} &= e^{-2\alpha_j h_i} S_{ij}, \\ \Phi_{11j} &= A^T P_{2j} + P_{2j}^T A + S_{0j} - e^{-2\alpha_j h_1} R_{0j} + 2\alpha_j P_j, \\ \Phi_{12j} &= P_j - P_{2j}^T + A^T P_{3j}, \quad \Phi_{22j} = -P_{3j} - P_{3j}^T + \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_{ij}. \end{aligned} \quad (4.50)$$

Proof: Computing (4.46) with the multiple LKFs (4.45) gives:

$$\begin{aligned} \dot{V}_j(t, x_t, \dot{x}_t) + 2\alpha_j V_j(t, x_t, \dot{x}_t) &\leq 2x^T(t) P_j \dot{x}(t) + 2\alpha_j x^T(t) P_j x(t) \\ &+ \dot{x}^T(t) [\sum_{i=0}^2 (h_{i+1} - h_i)^2 R_{ij}] \dot{x}(t) - \sum_{i=0}^2 (h_{i+1} - h_i) e^{-2\alpha_j(h_{i+1})} \int_{t-h_{i+1}}^{t-h_i} \dot{x}^T(s) R_{ij} \dot{x}(s) ds + \\ &\sum_{i=0}^2 x(t-h_i)^T e^{-2\alpha_j h_i} S_{ij} x(t-h_i) - \sum_{i=0}^2 e^{-2\alpha_j h_{i+1}} x^T(t-h_{i+1}) S_{ij} x(t-h_{i+1}). \end{aligned} \quad (4.51)$$

1) We start with the case of $\chi = 1$, which means $\tau \in [h_1, h_2]$, $i = 0, 2$, $j = 1$. Note that:

$$\int_{t-h_{i+1}}^{t-h_i} \dot{x}^T(s) R_{ij} \dot{x}(s) ds = \int_{t-h_{i+1}}^{t-\tau(t)} \dot{x}^T(s) R_{ij} \dot{x}(s) ds + \int_{t-\tau(t)}^{t-h_i} \dot{x}^T(s) R_{ij} \dot{x}(s) ds.$$

Applying the Jensen's inequality [Gu K. *et al.* 2003] for $i = 0, 2$ gives:

$$\begin{aligned} \int_{t-h_{i+1}}^{t-\tau(t)} \dot{x}^T(s) R_{ij} \dot{x}(s) ds &\geq \frac{1}{h_{i+1}-h_i} \int_{t-h_{i+1}}^{t-\tau(t)} \dot{x}^T(s) ds R_{ij} \int_{t-h_{i+1}}^{t-\tau(t)} \dot{x}(s) ds, \\ \int_{t-\tau(t)}^{t-h_i} \dot{x}^T(s) R_{ij} \dot{x}(s) ds &\geq \frac{1}{h_{i+1}-h_i} \int_{t-\tau(t)}^{t-h_i} \dot{x}^T(s) ds R_{ij} \int_{t-\tau(t)}^{t-h_i} \dot{x}(s) ds. \end{aligned} \quad (4.52)$$

Then, denoting $v_{j1} = \int_{t-\tau(t)}^{t-h_1} \dot{x}(s) ds$, $v_{j2} = \int_{t-h_2}^{t-\tau(t)} \dot{x}(s) ds$, where $j = 1$, we obtain:

$$\begin{aligned} \dot{V}_1(t, x_t, \dot{x}_t) + 2\alpha_1 V_1(t, x_t, \dot{x}_t) &\leq 2x^T(t) P_1 \dot{x}(t) + 2\alpha_1 x^T(t) P_1 x(t) \\ &+ \dot{x}^T(t) \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_{ij} \dot{x}(t) + \sum_{i=0}^2 e^{-2\alpha_1 h_i} x^T(t-h_i) S_{ij} x(t-h_i) \\ &- \sum_{i=0}^2 e^{-2\alpha_1 h_{i+1}} x^T(t-h_{i+1}) S_{ij} x(t-h_{i+1}) - [x(t) - x(t-h_1)]^T e^{-2\alpha_1 h_1} R_{0j} [x(t) - x(t-h_1)] \\ &- [x(t-h_2) - x(t-h_3)]^T e^{-2\alpha_1 h_3} R_{2j} [x(t-h_2) - x(t-h_3)] - v_{11}^T e^{-2\alpha_1 h_2} R_{1j} v_{11} - v_{12}^T e^{-2\alpha_1 h_2} R_{1j} v_{12}. \end{aligned} \quad (4.53)$$

We use further the descriptor method [Fridman E. 2001]. For some matrices P_{21}, P_{31} of the appropriate size, the following quantity:

$$0 = 2[x^T(t)P_{21}^T + \dot{x}^T(t)P_{31}^T][Ax(t) + A_1x(t-h_1) - A_1v_{11} - \dot{x}(t)], \quad (4.54)$$

is added to the right-hand side of (4.53). Following [He Y. *et al.* 2004], we also add free weighting matrices:

$$0 = 2[x^T(t)Y_{1j}^T + \dot{x}^T(t)Y_{2j}^T][-x(t-h_1) + x(t-h_2) + v_{11} + v_{12}]. \quad (4.55)$$

Setting $\eta_j(t) = \text{col}\{x(t), \dot{x}(t), x(t-h_1), x(t-h_2), x(t-h_3), v_{j1}, v_{j2}\}$, where $j = 1$, we obtain that the inequality:

$$\dot{V}_j(t, x_t, \dot{x}_t) + 2\alpha_j V_j(t, x_t, \dot{x}_t) \leq \eta_j^T(t) \Phi \eta_j(t) < 0, \quad (4.56)$$

is satisfied if the LMI (4.48) holds.

2) *Continuing with the case $\chi = 0$* , which means $\tau \in [h_2, h_3]$, by applying the same arguments and representation with $j = 2$ and $i = 0, 1$, we obtain:

$$\begin{aligned} \dot{V}_2(t, x_t, \dot{x}_t) + 2\alpha_2 V_2(t, x_t, \dot{x}_t) &\leq 2x^T(t)P_2\dot{x}(t) + 2\alpha_2 x^T(t)P_2x(t) \\ &+ \dot{x}^T(t) \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_{i2} \dot{x}(t) + \sum_{i=0}^2 x^T(t-h_i) \hat{S}_{i2} x(t-h_i) \\ &- \sum_{i=0}^2 x^T(t-h_{i+1}) \tilde{S}_{i2} x(t-h_{i+1}) - [x(t) - x(t-h_1)]^T \tilde{R}_{02} [x(t) - x(t-h_1)] \\ &- [x(t-h_2) - x(t-h_1)]^T \tilde{R}_{21} [x(t-h_2) - x(t-h_1)] - v_{j1}^T \tilde{R}_{22} v_{j1} - v_{j2}^T \tilde{R}_{22} v_{j2}. \end{aligned} \quad (4.57)$$

The equation (4.56) with $j = 2$ is then satisfied if the LMI (4.49) holds.

This concludes the proof of Theorem 5.

Note that Theorem 5 can also be easily applied to arbitrary switches by using the same LKF for both the switching modes, *i.e.*, fixing $\alpha_1 = \alpha_2 = \alpha, P_1 = P_2 = P, S_{i1} = S_{i2} = S_i, R_{i1} = R_{i2} = R_i, P_{21} = P_{22} = P_2, P_{31} = P_{32} = P_3, (i = 0, 1, 2)$. Then the following results can be obtained.

Corollary 1 *Given $\alpha > 0$, if there exist $n \times n$ -matrices $P > 0, R_i > 0, S_i > 0, i = 0, 1, 2, P_2, P_3, Y_{j1}$ and $Y_{j2}, j = 1, 2$ such that the LMIs (4.48), (4.49) with notations given in (4.50) are feasible, then the arbitrary switching delay system (4.4) is α -stable for all fast-varying delays $\tau \in [h_j, h_{j+1}], j = 1, 2$.*

4.3.1.2 Exponential stabilization of the controller and observer parts, separately

In this part, the output stabilization of a linear system with a switching controller is discussed. Considering the control problem as the equation (4.2) and (4.3) from Section (4.2), the prob-

lems can be solved by using Theorem 5 and some matrix manipulations (bijective transformations and congruences).

In a first step, we provide a “toolbox” of two lemmas that allow for checking the exponential stability, with some rate α , of the controller and, then, of the observer in each of the modes. In the sequel, these rates α will be different with regard to the mode (small/big delays). The global stabilization (with switched modes) will also be addressed further on. The first lemma, concerning the state feedback design, is as follows.

Following the same proof as in the previous section, one can get the followings theorems for the exponential stabilization in each of the modes (if there are no switches). The result for the state feedback design is given by the following result.

Lemma 6 *Given some scalars $\alpha_j > 0$ and $\varepsilon_j > 0$, $j = 1, 2$, if there exist some matrices $P_{1j} > 0$, $R_{ij} > 0$, $S_{ij} > 0$, P_{2j} , P_{3j} , Y_{ij} , and M_j such that the following LMIs (4.58) and (4.59) hold, then the closed loop (4.2) with $K_j = M_j P_{2j}^{-1}$ is exponentially stable with the rate α_j in the mode j (i.e., without mode switch):*

$$\Phi_{con1} = \begin{bmatrix} \Phi_{111} & \Phi_{121} & [\tilde{R}_{01} - BM_1 - Y_{11}^T] & Y_{11}^T & [Y_{11}^T + BM_1] & Y_{11}^T & 0 \\ * & \Phi_{221} & [-\varepsilon_1 BM_1 - Y_{21}^T] & Y_{21}^T & [Y_{21}^T + \varepsilon_1 BM_1] & Y_{21}^T & 0 \\ * & * & \hat{S}_{11} - \tilde{S}_{01} - \tilde{R}_{01} & 0 & 0 & 0 & 0 \\ * & * & * & \hat{S}_{21} - \tilde{S}_{11} - \tilde{R}_{21} & 0 & 0 & \tilde{R}_{21} \\ * & * & * & * & -\tilde{R}_{11} & 0 & 0 \\ * & * & * & * & * & -\tilde{R}_{11} & 0 \\ * & * & * & * & * & * & -\tilde{S}_{21} - \tilde{R}_{21} \end{bmatrix} < 0, \quad (4.58)$$

$$\Phi_{con2} = \begin{bmatrix} \Phi_{112} & \Phi_{122} & [-BM_2 - Y_{12}^T] & Y_{12}^T & [Y_{12}^T + BM_2] & Y_{12}^T & \tilde{R}_{02} \\ * & \Phi_{222} & [-\varepsilon_2 BM_2 - Y_{22}^T] & Y_{22}^T & [Y_{22}^T + \varepsilon_2 BM_2] & Y_{22}^T & 0 \\ * & * & \hat{S}_{22} - \tilde{S}_{12} - \tilde{R}_{12} & 0 & 0 & 0 & \tilde{R}_{12} \\ * & * & * & -\tilde{S}_{22} & 0 & 0 & 0 \\ * & * & * & * & -\tilde{R}_{22} & 0 & 0 \\ * & * & * & * & * & -\tilde{R}_{22} & 0 \\ * & * & * & * & * & * & \hat{S}_{12} - \tilde{S}_{02} - \tilde{R}_{02} - \tilde{R}_{12} \end{bmatrix} < 0, \quad (4.59)$$

with:

$$\begin{aligned} \tilde{R}_{ij} &= e^{-2\alpha_j h_{i+1}} R_{ij}, \\ \tilde{S}_{ij} &= e^{-2\alpha_j h_{i+1}} S_{ij}, \\ \hat{S}_{ij} &= e^{-2\alpha_j h_i} S_{ij}, \\ \Phi_{11j} &= AP_{2j} + P_{2j}^T A^T + S_{0j} - e^{-2\alpha_j h_1} R_{0j} + 2\alpha_j P_{1j}, \\ \Phi_{12j} &= P_{1j} - P_{2j} + \varepsilon_j P_{2j}^T A, \\ \Phi_{22j} &= -\varepsilon_j P_{2j} - \varepsilon_j P_{2j}^T + \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_{ij}. \end{aligned} \quad (4.60)$$

The observer design result is now given by the following lemma.

Lemma 7 *Given some scalars $\alpha_j > 0$ and $\varepsilon_j > 0$, $j = 1, 2$, if there exist some matrices $P_{1j} > 0$, $R_{ij} > 0$, $S_{ij} > 0$, P_{2j} , P_{3j} , Y_{ij} , and M_j such that the following LMIs (4.61) and (4.62) hold, then the observation error given in (4.3) with $L_j = P_{2j}^{-T} W_j$ is exponentially stable with a decay rate α_j in the mode j (i.e., without mode switch):*

$$\Phi_{obs1} = \begin{bmatrix} \Phi_{111} & \Phi_{121} & [\tilde{R}_{01} - W_1 C - Y_{11}^T] & Y_{11}^T & [Y_{11}^T + W_1 C] & Y_{11}^T & 0 \\ * & \Phi_{221} & [-\varepsilon_1 W_1 C - Y_{21}^T] & Y_{21}^T & [Y_{21}^T + \varepsilon_1 W_1 C] & Y_{21}^T & 0 \\ * & * & \hat{S}_{11} - \tilde{S}_{01} - \tilde{R}_{01} & 0 & 0 & 0 & 0 \\ * & * & * & \hat{S}_{21} - \tilde{S}_{11} - \tilde{R}_{21} & 0 & 0 & \tilde{R}_{21} \\ * & * & * & * & -\tilde{R}_{11} & 0 & 0 \\ * & * & * & * & * & -\tilde{R}_{11} & 0 \\ * & * & * & * & * & * & -\tilde{S}_{21} - \tilde{R}_{21} \end{bmatrix} < 0, \quad (4.61)$$

$$\Phi_{obs2} = \begin{bmatrix} \Phi_{112} & \Phi_{122} & [-W_2 C - Y_{12}^T] & Y_{12}^T & [Y_{12}^T + W_2 C] & Y_{12}^T & \tilde{R}_{02} \\ * & \Phi_{222} & [-\varepsilon_2 W_2 C - Y_{22}^T] & Y_{22}^T & [Y_{22}^T + \varepsilon_2 W_2 C] & Y_{22}^T & 0 \\ * & * & \hat{S}_{22} - \tilde{S}_{12} - \tilde{R}_{12} & 0 & 0 & 0 & \tilde{R}_{12} \\ * & * & * & -\tilde{S}_{22} & 0 & 0 & 0 \\ * & * & * & * & -\tilde{R}_{22} & 0 & 0 \\ * & * & * & * & * & -\tilde{R}_{22} & 0 \\ * & * & * & * & * & * & \hat{S}_{12} - \tilde{S}_{02} - \tilde{R}_{02} - \tilde{R}_{12} \end{bmatrix} < 0, \quad (4.62)$$

with:

$$\begin{aligned} \tilde{R}_{ij} &= e^{-2\alpha_j h_{i+1}} R_{ij}, \\ \tilde{S}_{ij} &= e^{-2\alpha_j h_{i+1}} S_{ij}, \\ \hat{S}_{ij} &= e^{-2\alpha_j h_i} S_{ij}, \\ \Phi_{11j} &= A^T P_{2j} + P_{2j}^T A + S_{0j} - e^{-2\alpha_j h_1} R_{0j} + 2\alpha_j P_{1j}, \\ \Phi_{12j} &= P_{1j} - P_{2j}^T + \varepsilon_j A^T P_{2j}, \\ \Phi_{22j} &= -\varepsilon P_{2j} - \varepsilon P_{2j}^T + \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_{ij}. \end{aligned} \quad (4.63)$$

4.3.2 Exponential stabilization of the global NCS (controller+observer) with minimum dwell time

4.3.2.1 Minimum dwell time for switched time-delay system with unstable switching modes

Consider a state feedback controller to stabilize the following linear time-delay system:

$$\dot{x}(t) = Ax(t) + Bu(t - \tau(t)), \quad (4.64)$$

with $\tau(t)$, a fast varying interval delay within the bounds $[h_{min}, h_{max}]$. We know that the stabilization is generally easier (we mean here, to guaranty a higher exponential rate) if the delay is small. So, the interval can be divided into several smaller ones in correspondence with the switched controller. To simplify the problem, here again two switching modes are considered, but it can be extended to more modes.

The switching controller to be considered is:

$$u(t) = \begin{cases} K_1x(t), \tau(t) \in [h_1, h_2]; \\ K_2x(t), \tau(t) \in [h_2, h_3]; \end{cases} \quad (4.65)$$

So, the closed-loop system can be written as follows:

$$\begin{aligned} \dot{x}(t) = & Ax(t) + \chi_{[h_1, h_2]}(\tau)BK_1x(t - \tau_1(t)) \\ & + (1 - \chi_{[h_1, h_2]}(\tau))BK_2x(t - \tau_2(t)), \end{aligned} \quad (4.66)$$

where $\tau_i \in [h_i, h_{i+1}]$, $i = 1, 2$ and where $\chi_{[h_1, h_2]} : R \rightarrow \{0, 1\}$ is the characteristic function of $[h_1, h_2]$:

$$\chi_{[h_1, h_2]}(s) = \begin{cases} 1, & \text{if } s \in [h_1, h_2], \\ 0, & \text{otherwise.} \end{cases} \quad (4.67)$$

For switching systems with variable time-delays, the switching signals can also be delayed. This is the case in our NCS, as explained in the beginning of Section 4.3. During this period, the controller lacks of the correct information on the delay zone, and the command is no longer correct. As illustrated in Fig.4.9, the system is supposed to switch at the moments t_1 and t_3 , but the switching signals can only be detected by the system after the period of time $(t_2 - t_1)$ and $(t_4 - t_3)$. Even if the system is stable in the two modes, the delayed signals can make the system unstable (wrong control gain). In order to make the global system stable, the values of the LKFs should be in the decreasing sequence as shown in Fig.4.9. The two-mode switching system with delayed switching signals can be modeled as a four-mode system, which is shown in Fig.4.10. Here, the two principle modes SS_1 and SS_2 are considered as exponential stable and the stability of the two modes SU_1 and SU_2 is not guaranteed since K_i is designed only for the mode i . The four switched modes can be modeled as follows:

$$\begin{aligned} SS_1 : \dot{x}(t) &= Ax(t) + BK_1x(t - \tau_1(t)), t \in [t_0, t_1]; \\ SU_1 : \dot{x}(t) &= Ax(t) + BK_1x(t - \tau_2(t)), t \in [t_1, t_2]; \\ SS_2 : \dot{x}(t) &= Ax(t) + BK_2x(t - \tau_2(t)), t \in [t_2, t_3]; \\ SU_2 : \dot{x}(t) &= Ax(t) + BK_2x(t - \tau_1(t)), t \in [t_3, t_4]; \end{aligned} \quad (4.68)$$

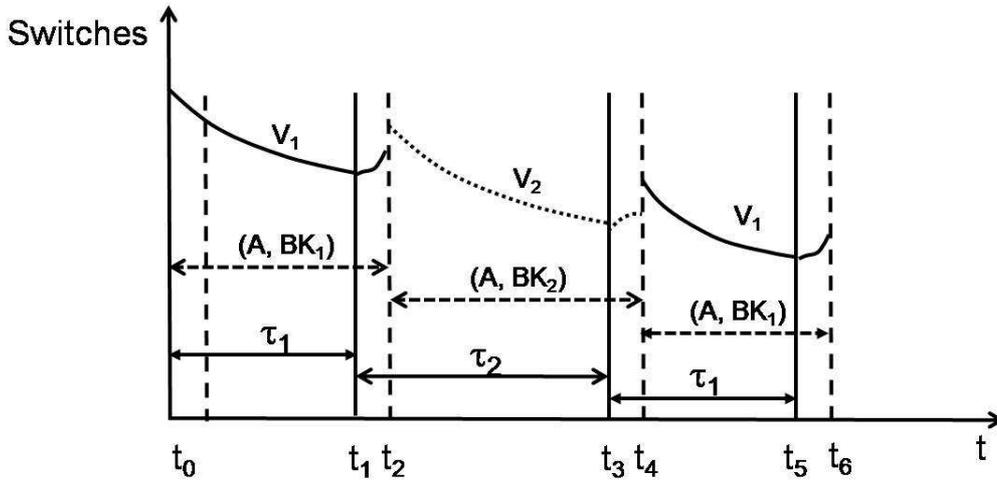


Figure 4.9: Minimum dwell time

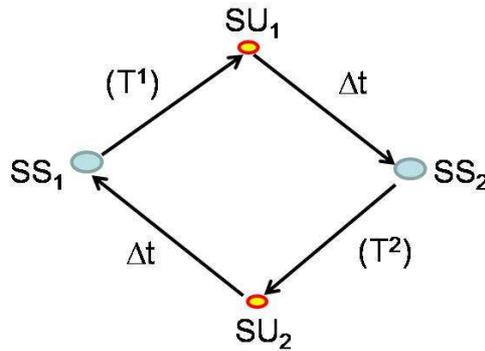


Figure 4.10: Switch among four modes.

The minimum dwell time for SS_1 and SS_2 has to be calculated to guarantee the decreasing sequence of the values at the switching instants for each stable mode. Decreasing sequence in Fig.4.68 implies that there exists a μ , the smaller positive real such that:

$$V_i(t, x_t, \dot{x}_t) \leq \mu V_j(t, x_t, \dot{x}_t), i, j \in \{1, 2\}. \quad (4.69)$$

This is implied by the following conditions:

$$\begin{aligned} P_i &\leq \mu P_j, \\ e^{-2\alpha_i h} S_{ki} &\leq \mu e^{-2\alpha_j h} S_{kj}, h \in [0, h_k], \\ e^{-2\alpha_i h} R_{ki} &\leq \mu e^{-2\alpha_j h} R_{kj}, h \in [0, h_k], \\ k &= 0, 1, 2, \end{aligned} \quad (4.70)$$

Here we give the analysis for the minimum dwell time calculation of SS_2 , the same method can be applied for the case of SS_1 .

So, the global stability problem can be solved by completing the following three smaller ones:

1. Exponential stabilization for each mode: Adapt Theorem 5, applying the bijective transformation to some matrices as shown in [Jiang W.-J. *et al.* 2008]. The maximum values of α_1 and α_2 , respectively representing the exponential decay rate of each mode, can be obtained according to the similar LMI conditions as (4.58) for $j = 1$, (4.59) for $j = 2$. Then, the two gains can be calculated as $K_j = M_j P_{2j}^{-1}$.
2. Calculation of the smaller positive μ according to the equations (4.69) and (4.70).
3. Exponential decay for the mode SU_1 : Apply Theorem 5 for the mode SU_1 with time-delay $\tau(t) \in [h_2, h_3]$, with K_1 calculated from (1). Here, the time-delay of switching signal is supposed to be constant, then the exponential value α'_1 can be calculated. If this mode is unstable, the value of α'_1 is negative, which will be taken into account in the calculation of the minimum dwell time for SS_2 .

Note that:

$$\begin{aligned} V_2(t_2, x_{t_2}, \dot{x}_{t_2}) &\leq \mu V_1(t_2, x_{t_2}, \dot{x}_{t_2}) \\ &\leq \mu e^{-2\alpha'_1(t_2-t_1)} V_1(t_1, x_{t_1}, \dot{x}_{t_1}) \\ &\leq \mu e^{-2\alpha'_1(t_2-t_1)-2\alpha_1(t_1-t_0)} V_1(t_0, x_{t_0}, \dot{x}_{t_0}). \end{aligned} \quad (4.71)$$

$\mu e^{-2\alpha'_1(t_2-t_1)-2\alpha_1(t_1-t_0)} \leq 1$ is sufficient to prove the stability when switching from SS_1 to SS_2 , shown in Fig.4.68. So, the minimum dwell time for SS_1 is:

$$t_1 - t_0 = \frac{\ln(\mu) - 2\alpha'_1(t_2 - t_1)}{2\alpha_1}. \quad (4.72)$$

The minimum dwell time for SS_2 can be calculated in the same way and its value is:

$$t_3 - t_2 = \frac{\ln(\mu) - 2\alpha'_2(t_4 - t_3)}{2\alpha_2}. \quad (4.73)$$

4.3.2.2 An illustration with simulation

Let us illustrate the technique of the previous section 4.3.2.1 on the linear model of our Miabot, recalled in equation (4.74):

$$\dot{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & -10 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0.024 \end{bmatrix} u(t - \tau(t)). \quad (4.74)$$

Consider a linear state feedback controller, *i.e.*, no switch is concerned. Applying the same LKF as equation (4.5) with $S_2 = 0$, $R_2 = 0$ and $\tau(t) \in [0.01, 0.4]$, the maximum exponential decay value of α is obtained as 0.88. While, considering two intervals of delay with $[0.01, 0.05[$ and $[0.05, 0.4]$, we can get better performance. With this control solution, the control gain switches when the delay crosses the value of 0.05sec. According to our approach, the decay rates ensuring the exponential stability in each of the modes are: $\alpha_1 = 1.1$, $\alpha_2 = 0.89$ and the maximum exponential values for SU_1 and SU_2 respectively are: $\alpha'_1 = -2.35$, $\alpha'_2 = 1.1$. That is to say, the mode SU_1 (without switch) may be unstable: A minimum dwell time has to be introduced.

The gains K_i ($i = 1, 2$) and μ are:

$$\begin{bmatrix} K_1 \\ K_2 \end{bmatrix} = \begin{bmatrix} -1639 & -164 \\ -742 & -74 \end{bmatrix}, \mu = 1.4. \quad (4.75)$$

Considering the estimation delay of the switching signal is 0.1sec, so the minimum dwell time for staying in the mode SS_1 before switching to the mode SS_2 can be achieved as 0.35sec and the one for stay in the mode of SS_2 is 0.06sec. In Fig.4.11, when the condition of minimum dwell time is satisfied, one can see that the guaranteed global stability is obtained. As we can

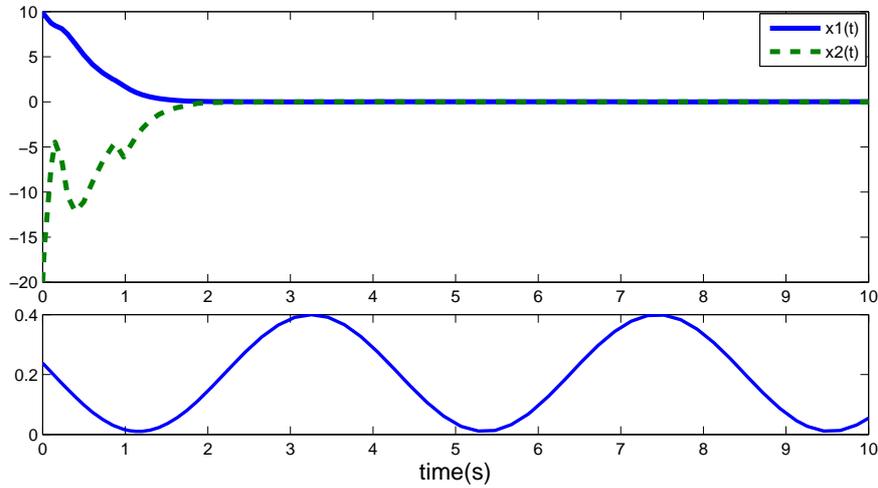


Figure 4.11: Solution of (4.74) for $\tau(t) = 0.19\sin(1.5t) + 0.21$.

find in the equations (4.72) and (4.73) that the values of dwell time depend on the value of the exponential decay rate, so we have to make a tradeoff between the bigger value of α and the

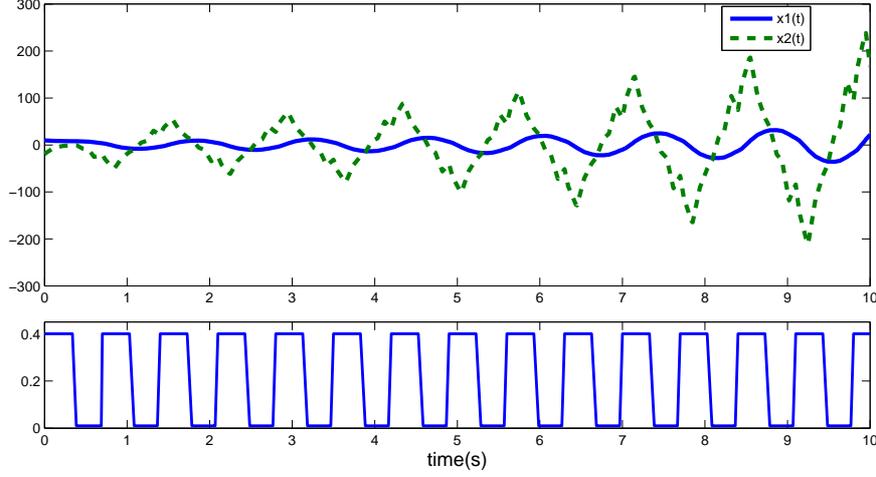


Figure 4.12: Solution of (4.74) for $\tau(t)$, a pulse signal.

smaller dwell time. For example, we can get $\alpha_1 = 3.8$ but with the dwell time for SS_2 equals 1.15sec. Fig.4.12 shows that when the dwell time in the mode SS_2 is not sufficient, the system may become unstable.

These new conditions can be also used to enlarge the interval of admissible delays. For example, considering a linear state feedback controller *i.e.* without QoS adaptation, the linear model 4.74 can be stabilized for delays in $[0.01, 1.26]$ (largest interval possible). By considering the delay intervals $[0.01, 1.2]$ and $[1.2, 2]$, one can find a switching controller with a decay rate of $\alpha = 0.1$ and a minimum dwell time of 3.38.

4.3.2.3 Exponential stability for switched systems with three time-delays

Let us start with a preliminary results extending the theory of the section (4.3.1.1) to a system with three time-delays as follows:

$$\dot{x}(t) = A_0x(t) + \chi(\tau)\left(\sum_{k=1}^3 A_{1k}x(t - \tau_{1k}(t))\right) + (1 - \chi(\tau))\left(\sum_{k=1}^3 A_{2k}x(t - \tau_{2k}(t))\right), \quad (4.76)$$

where $\tau_{1k} \in [h_1, h_2], \tau_{2k} \in [h_2, h_3], k = 1, 2, 3$ and where $\chi : \mathbb{R} \rightarrow \{0, 1\}$. Analyzing such a system with additional delay will be useful when dealing with the delayed estimation of the instants when the delay changes its zone. The following result can be obtained.

Lemma 8 Given $\alpha > 0$, if there exist matrices $P > 0$, $R_i > 0$, $S_i > 0$, $i = 0, 1, 2$, P_2, P_3 , Y_{j1} and Y_{j2} , $j = 1, 2$ with proper dimensions such that the following LMIs (4.77) and (4.78) with similar form of notations given in (4.50) are feasible, then system (4.76) is α -stable for all fast-varying delays $\tau_{1k} \in [h_1, h_2]$, $\tau_{2k} \in [h_2, h_3]$, $k = 1, 2, 3$:

$$\Phi|_{\chi=1} = \begin{bmatrix} \Phi_{11} & \Phi_{12} & \tilde{R}_0 + P_2^T A_{11} - Y_{11}^T & P_2^T A_{12} - Y_{11}^T & Y_{11}^T & Y_{11}^T - P_2^T A_{11} & Y_{11}^T & Y_{11}^T - P_2^T A_{12} & Y_{11}^T & Y_{11}^T - P_2^T A_{13} & Y_{11}^T \\ * & \Phi_{22} & P_3^T A_{11} - Y_{21}^T & P_3^T A_{12} - Y_{21}^T & Y_{21}^T & Y_{21}^T - P_3^T A_{11} & Y_{21}^T & Y_{21}^T - P_3^T A_{12} & Y_{21}^T & Y_{21}^T - P_3^T A_{13} & Y_{21}^T \\ * & * & \hat{S}_1 - \tilde{S}_0 - \tilde{R}_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & \hat{S}_2 - \tilde{S}_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & -\tilde{S}_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & -1/3\tilde{R}_1 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & -1/3\tilde{R}_1 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & * & -1/3\tilde{R}_1 & 0 & 0 & 0 \\ * & * & * & * & * & * & * & * & -1/3\tilde{R}_1 & 0 & 0 \\ * & * & * & * & * & * & * & * & * & -1/3\tilde{R}_1 & 0 \\ * & * & * & * & * & * & * & * & * & * & -1/3\tilde{R}_1 \end{bmatrix} < 0 \quad (4.77)$$

$$\Phi|_{\chi=0} = \begin{bmatrix} \Phi_{11} & \Phi_{12} & \tilde{R}_0 & [P_2^T A_{21} - Y_{12}^T] & Y_{12}^T & [Y_{12}^T - P_2^T A_{21}] & Y_{12}^T & [Y_{12}^T - P_2^T A_{22}] & Y_{12}^T & [Y_{12}^T - P_2^T A_{23}] & Y_{12}^T \\ * & \Phi_{22} & 0 & [P_3^T A_{21} - Y_{22}^T] & Y_{22}^T & [Y_{22}^T - P_3^T A_{21}] & Y_{22}^T & [Y_{22}^T - P_3^T A_{22}] & Y_{22}^T & [Y_{22}^T - P_3^T A_{23}] & Y_{22}^T \\ * & * & \hat{S}_1 - \tilde{S}_0 - \tilde{R}_0 - \tilde{R}_1 & \tilde{R}_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & \hat{S}_2 - \tilde{S}_1 - \tilde{R}_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & -\tilde{S}_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & -1/3\tilde{R}_2 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & -1/3\tilde{R}_2 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & * & -1/3\tilde{R}_2 & 0 & 0 & 0 \\ * & * & * & * & * & * & * & * & -1/3\tilde{R}_2 & 0 & 0 \\ * & * & * & * & * & * & * & * & * & -1/3\tilde{R}_2 & 0 \\ * & * & * & * & * & * & * & * & * & * & -1/3\tilde{R}_2 \end{bmatrix} < 0 \quad (4.78)$$

with:

$$\begin{aligned} \tilde{R}_i &= e^{-2\alpha h_{i+1}} R_i, \\ \tilde{S}_i &= e^{-2\alpha h_{i+1}} S_i, \\ \hat{S}_i &= e^{-2\alpha h_i} S_i, \\ \Phi_{11} &= A^T P_2 + P_2^T A + S_0 - e^{-2\alpha h_1} R_0 + 2\alpha P, \\ \Phi_{12} &= P - P_2^T + A^T P_3, \\ \Phi_{22} &= -P_3 - P_3^T + \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_i. \end{aligned} \quad (4.79)$$

Now, we can come back to the analysis of the delayed estimation problem. It is known that a bad switching sequence can make the closed loop unstable, even if the stability of the two, non-

switched modes is ensured by the two previous lemmas. In order to avoid such bad sequences, a minimum dwell time between the modes is computed here by using the exponential stability property.

Technically speaking, this minimum dwell time will be achieved at the “big-to-small” switching instants by artificially increasing the communication delay, in such a way that $\delta(t) \in [h_2, h_3]$. So, when the Master have detected that the time-delay enters the “big” mode, the controller should directly switch. But the time-delay augmentation can only be detected by the system after a period of time $t_2 - t_1$, which is at least a complete communication time-delay of the closed-loop. The delay of detection from big to small is comprised in the time period of $t_s - t_3$, which is taken into account within the minimum dwell time.

Here, the global stability of the system will be studied by using the method of [Liberzon D. 2003]. As depicted on Fig.4.13, the values of the switched LKF V at the switching instants in a given mode (1 or 2) form a strictly decreasing sequence. The two-mode switching system with delayed detection of time-delay and minimum dwell time can be modeled as a four-mode system, which is shown in Fig.4.14. The two principle modes SS_1 and SS_2 , with respectively two time-delays for controller and observer, are exponential stable and the stability of the two modes SU_1 and SU_2 , with respectively three time-delays (additional time-delay because of the wrong gains) cannot be proved.

As shown in Figure 4.13, we consider (without restriction) that the delay is small when $t \in [t_0, t_1]$ (good QoS) and big when $t \in [t_1, t_3]$ (poor QoS), then small after t_3 , and so on. The controller switching instants are denoted t_2 and t_s . Because the controller estimates the value of the time-delays after a whole round trip (at least), these switching instants are delayed with regard to the moments t_1 and t_3 when the QoS intervals change: $t_2 \in [t_1, t_3]$ and $t_s \geq t_3$. We will consider successively these two kinds of mode switches.

As in the interval of $[t_1, t_2]$, the LKF V_1 cannot be used for the big time-delay, we use V_3 to calculate the decay rate α_3 , which is possibly negative (*i.e.*, system is divergent over this interval). But in order to have the same gains K_1 and L_1 , the common P_2 will be applied in the LMI conditions.

By introducing $\zeta(t) = \text{col}\{x(t), e(t)\}$ and considering the global closed-loop system, rewrite the equations (4.2) and (4.3) for the two modes $SS_1 : t \in [t_0, t_1]$ and $SS_2 : t \in [t_2, t_3]$ as follows:

$$\frac{d}{dt}\zeta(t) = \bar{A}_0\zeta(t) + \bar{A}_{i1}\zeta(t - \delta_{con}^i(t)) + \bar{A}_{i2}\zeta(t - \delta_{obs}^i(t)), \quad (4.80)$$

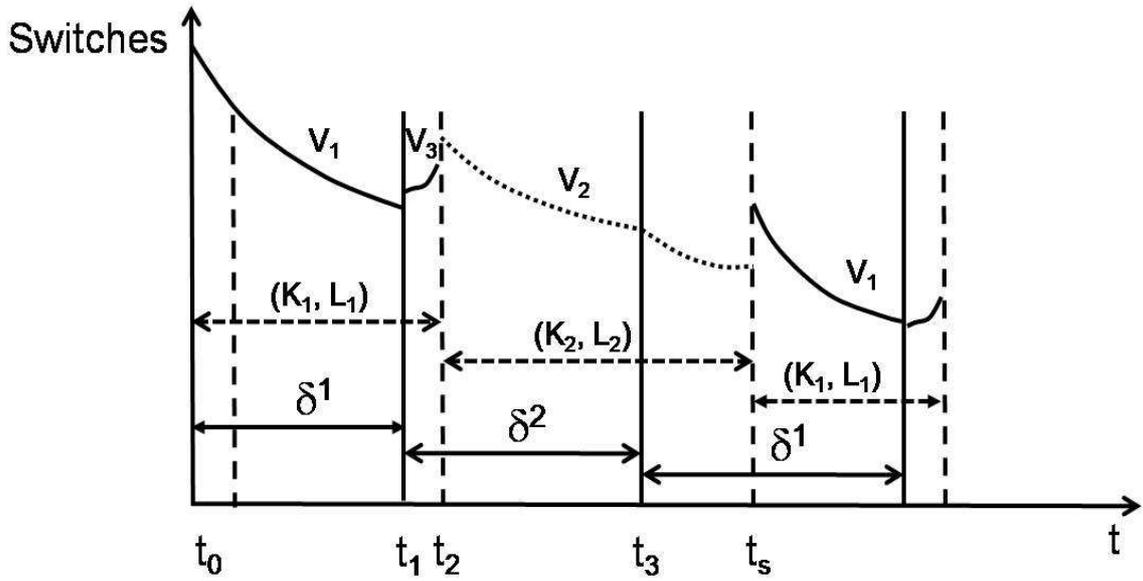


Figure 4.13: Minimum dwell time: Small delay from t_0 to t_1 , then big delay from t_1 to t_3 , switches at t_2 and t_s .

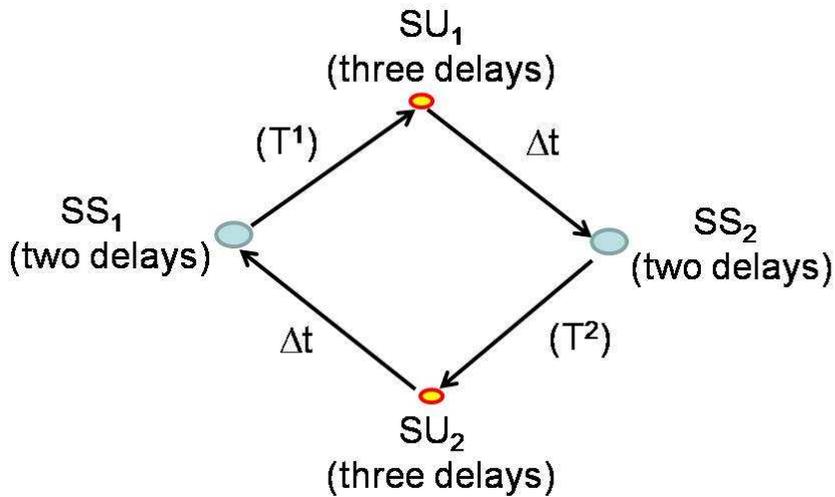


Figure 4.14: Switch among four modes.

with $\bar{A}_0 = \begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix}$, $\bar{A}_{i1} = \begin{bmatrix} BK_i & -BK_i \\ 0 & 0 \end{bmatrix}$ and $\bar{A}_{i2} = \begin{bmatrix} 0 & 0 \\ 0 & -L_i C \end{bmatrix}$.

The modes $SU_1 : t \in [t_1, t_2]$ can be modeled as follows:

$$\frac{d}{dt} \zeta(t) = \bar{A}_0 \zeta(t) + \bar{A}_1 \zeta(t - \delta_{con}^1(t)) + \bar{A}_2 \zeta(t - \delta_{con}^2(t)) + \bar{A}_3 \zeta(t - \delta_{obs}^2(t)), \quad (4.81)$$

$$\text{for } \bar{A}_0 = \begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix}, \bar{A}_1 = \begin{bmatrix} 0 & 0 \\ -BK_1 & 0 \end{bmatrix}, \bar{A}_2 = \begin{bmatrix} BK_1 & -BK_1 \\ BK_1 & -BK_1 \end{bmatrix}, \bar{A}_3 = \begin{bmatrix} 0 & 0 \\ 0 & -L_1C \end{bmatrix}.$$

In order to guarantee the global stability of the closed-loop system, the positive μ , as small as possible, has to be considered such that:

$$V_i(t, x_t, \dot{x}_t) \leq \mu V_j(t, x_t, \dot{x}_t), i, j \in \{1, 2, 3\}. \quad (4.82)$$

This leads to the following lemma.

Lemma 9 For the given moments t_0, t_1 , with the assumption of the fixed time-delay $t_2 - t_1$, the observer-based control can guarantee the global stability of the closed-loop system with the minimum dwell time from mode “big” to mode “small delay” defined by:

$$t_s - t_2 = \frac{\ln(\mu) - \alpha_3(t_2 - t_1) - \alpha_1(t_1 - t_0)}{\alpha_2}, \quad (4.83)$$

where $\alpha_i, (i \in \{1, 2, 3\})$ are the decay rates of SS_1, SS_2 and SU_1 .

Proof: To make the modes SS_1, SS_2 comparable to SU_1 , the equation (4.80) has to be extended to the system with three delays. The Lemma 8 can be applied with $A_{i3} = 0, i = 1, 2$.

Considering the mode of SU_1 , by extending Theorem 5, the following LMI can be obtained with the same matrix P for the LMI condition of SS_1 , with possible $\alpha_3 < 0$:

$$\Phi = \begin{bmatrix} \Phi_{11} & \Phi_{12} & \tilde{R}_0 + P_2^T \bar{A}_1 - Y_{11}^T & P_2^T \bar{A}_2 + P_2^T \bar{A}_3 - Y_{11}^T & 2Y_{11}^T & Y_{11}^T - P_2^T \bar{A}_1 & Y_{11}^T & Y_{11}^T - P_2^T \bar{A}_2 & Y_{11}^T & Y_{11}^T - P_2^T \bar{A}_3 & Y_{11}^T \\ * & \Phi_{22} & P_3^T \bar{A}_1 - Y_{21}^T & P_3^T \bar{A}_2 + P_3^T \bar{A}_3 - Y_{21}^T & 2Y_{21}^T & Y_{21}^T - P_3^T \bar{A}_1 & Y_{21}^T & Y_{21}^T - P_3^T \bar{A}_2 & Y_{21}^T & Y_{21}^T - P_3^T \bar{A}_3 & Y_{21}^T \\ * & * & \hat{S}_1 - \tilde{S}_0 - \tilde{R}_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & \hat{S}_2 - \tilde{S}_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & -\tilde{S}_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & -\tilde{R}_1 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & -\tilde{R}_1 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & * & -0.5\tilde{R}_2 & 0 & 0 & 0 \\ * & * & * & * & * & * & * & * & -0.5\tilde{R}_2 & 0 & 0 \\ * & * & * & * & * & * & * & * & * & -0.5\tilde{R}_2 & 0 \\ * & * & * & * & * & * & * & * & * & * & -0.5\tilde{R}_2 \end{bmatrix} < 0 \quad (4.84)$$

with:

$$\begin{aligned}
 \tilde{R}_i &= e^{-2\alpha h_{i+1}} R_i, \\
 \tilde{S}_i &= e^{-2\alpha h_{i+1}} S_i, \\
 \hat{S}_i &= e^{-2\alpha h_i} S_i, \\
 \Phi_{11} &= A^T P_2 + P_2^T A + S_0 - e^{-2\alpha h_1} R_0 + 2\alpha P, \\
 \Phi_{12} &= P - P_2^T + A^T P_3, \\
 \Phi_{22} &= -P_3 - P_3^T + \sum_{i=0}^2 (h_{i+1} - h_i)^2 R_i.
 \end{aligned} \tag{4.85}$$

The equation (4.82) is implied by the following conditions:

$$\begin{aligned}
 P_i &\leq \mu P_j, \\
 e^{-2\alpha_i h} S_{0i} &\leq \mu e^{-2\alpha_j h} S_{0j}, h \in [0, h_1], \\
 e^{-2\alpha_i h} S_{1i} &\leq \mu e^{-2\alpha_j h} S_{1j}, h \in [0, h_2], \\
 e^{-2\alpha_i h} S_{2i} &\leq \mu e^{-2\alpha_j h} S_{2j}, h \in [0, h_3], \\
 e^{-2\alpha_i h} R_{0i} &\leq \mu e^{-2\alpha_j h} R_{0j}, h \in [0, h_1], \\
 e^{-2\alpha_i h} R_{1i} &\leq \mu e^{-2\alpha_j h} R_{1j}, h \in [0, h_2], \\
 e^{-2\alpha_i h} R_{2i} &\leq \mu e^{-2\alpha_j h} R_{2j}, h \in [0, h_3],
 \end{aligned} \tag{4.86}$$

or by considering that $\alpha_1 > \alpha_2$ (here, α_1 refers to the mode with small time-delays and α_2 to the big ones):

$$\begin{aligned}
 P_2 &\leq \mu P_1, \\
 S_{02} &\leq \mu e^{-2(\alpha_1 - \alpha_0)h_1} S_{01}, S_{12} \leq \mu e^{-2(\alpha_1 - \alpha_0)h_2} S_{11}, \\
 S_{22} &\leq \mu e^{-2(\alpha_1 - \alpha_0)h_3} S_{21}, R_{02} \leq \mu e^{-2(\alpha_1 - \alpha_0)h_1} R_{01}, \\
 R_{12} &\leq \mu e^{-2(\alpha_1 - \alpha_0)h_2} R_{11}, R_{22} \leq \mu e^{-2(\alpha_1 - \alpha_0)h_3} R_{21}, \\
 P_1 &\leq \mu P_2, S_{01} \leq \mu S_{02}, S_{11} \leq \mu S_{12}, \\
 R_{01} &\leq \mu R_{02}, R_{11} \leq \mu R_{12}, R_{21} \leq \mu R_{22},
 \end{aligned} \tag{4.87}$$

If the above LMIs conditions are satisfied, one has:

$$V_1(t, x_t, \dot{x}_t) \leq e^{-2\alpha_1(t-t_0)} V_1(t_0, x_{t_0}, \dot{x}_{t_0}) \text{ for the mode of small time delay } SS_1.$$

$$V_2(t, x_t, \dot{x}_t) \leq e^{-2\alpha_2(t-t_0)} V_2(t_0, x_{t_0}, \dot{x}_{t_0}) \text{ for the mode of big time delay } SS_2.$$

$$V_3(t, x_t, \dot{x}_t) \leq e^{-2\alpha_3(t-t_0)} V_1(t_0, x_{t_0}, \dot{x}_{t_0}) \text{ for the mode } SU_1.$$

Note that:

$$\begin{aligned}
 V_1(t_s, x_{t_s}, \dot{x}_{t_s}) &\leq \mu V_2(t_s, x_{t_s}, \dot{x}_{t_s}) \\
 &\leq \mu e^{-2\alpha_2(t_s-t_2)} V_2(t_2, x_{t_2}, \dot{x}_{t_2}) \\
 &\leq \mu e^{-2\alpha_2(t_s-t_2)} \cdot e^{-2\alpha_3(t_2-t_1)} V_3(t_1, x_{t_1}, \dot{x}_{t_1}) \\
 &\leq \mu^2 e^{-2\alpha_2(t_s-t_2)-2\alpha_3(t_2-t_1)-2\alpha_1(t_1-t_0)} V_1(t_0, x_{t_0}, \dot{x}_{t_0}).
 \end{aligned} \tag{4.88}$$

The inequality $\mu^2 e^{-2\alpha_1(t_s-t_2)-2\alpha_3(t_2-t_1)-2\alpha_2(t_1-t_0)} \leq 1$ is sufficient to prove the stability of the model, which ends the proof.

4.3.3 Experimental study

For sake of the simplification of the switching strategy, the same maximum time-delay values are chosen for the controller and the observer. Considering two zones of delay with $[0.01, 0.08[$ and $[0.08, 0.5]$. It means that the gains switch when the delay crosses the value of $0.08sec$.

According to Lemma (6) and (7), the maximum exponential convergence rates ensuring the global stability are: $\alpha_1^c = 3.8$, $\alpha_1^o = 4.49$, $\alpha_2^c = \alpha_2^o = 0.72$. For the experimental application, in order to guaranty the linearity of the system, the following values of α are adapted: $\alpha_1^c = 2$, $\alpha_1^o = 2.5$, $\alpha_2^c = 0.6$ and $\alpha_2^o = 0.72$. The smaller value of exponential decay can be applied.

The gains K_i and L_i ($i = 1, 2$) are:

$$\begin{bmatrix} L_1 & L_2 \end{bmatrix} = \begin{bmatrix} -7.06 & -1.44 \\ 0.04 & -0.01 \end{bmatrix}, \begin{bmatrix} K_1 \\ K_2 \end{bmatrix} = \begin{bmatrix} -1485 & -461 \\ -99 & 1 \end{bmatrix}. \quad (4.89)$$

and $\alpha' = -3.9$, $\mu = 5.6 * 10^4$. Then, the minimum dwell time can be achieved.

The result is shown in Fig.4.15, in which the blue curve represents the set values; the green and red represent respectively the robot's estimated position and speed; the black corresponds to the real position (motor angle) of the Miabot. Fig.4.16 illustrates the corresponding switched control signals from Master to Slave. The red curve is the real control while the green and the black ones are the controls calculated respectively for the two subsystems. We can see the switch points according to the values of time-delay. Fig.4.17 depicts the variable time-delays and also the switching signals, which comprise the time-delay of sampling and communication of Bluetooth (we again consider this last as constant, here we take the value of 40ms).

On Fig.4.15, one can notice three kinds of step responses. The first one corresponds to the case when the time-delay is greater than 80ms, only the second subsystem is active, *i.e.* only the gains K_2 and L_2 are active. In this case, certain performances are guaranteed. During the second step, only the first mode is active because the delays are small. The performances are still better: The response time is smaller and the damping is greater. In the last kind of response, the control switches a lot during the response. In that case, only the global stability is guaranteed. Notice that at the moment $[42ms \ 45ms]$, the time-delay becomes small, but, because the dwell time in the second mode has not reached the minimum one, and in order to

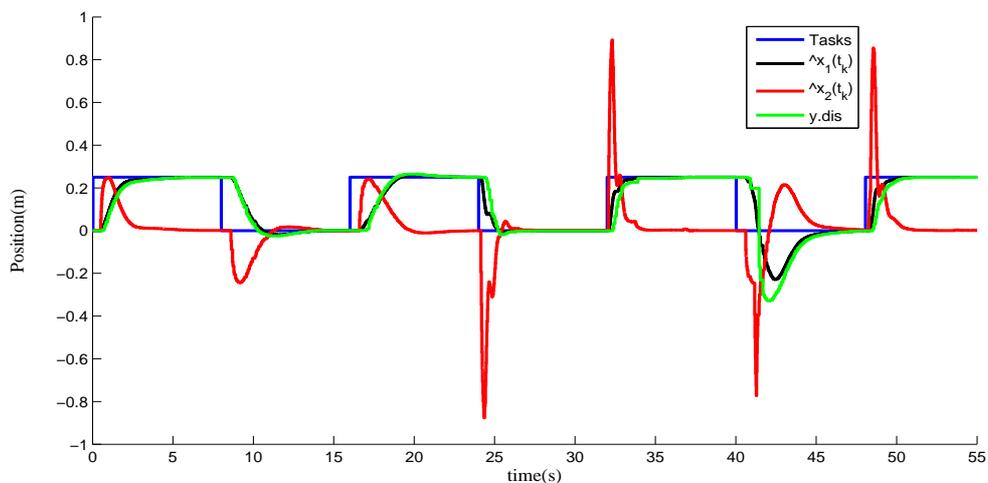


Figure 4.15: Results of the remote experiment

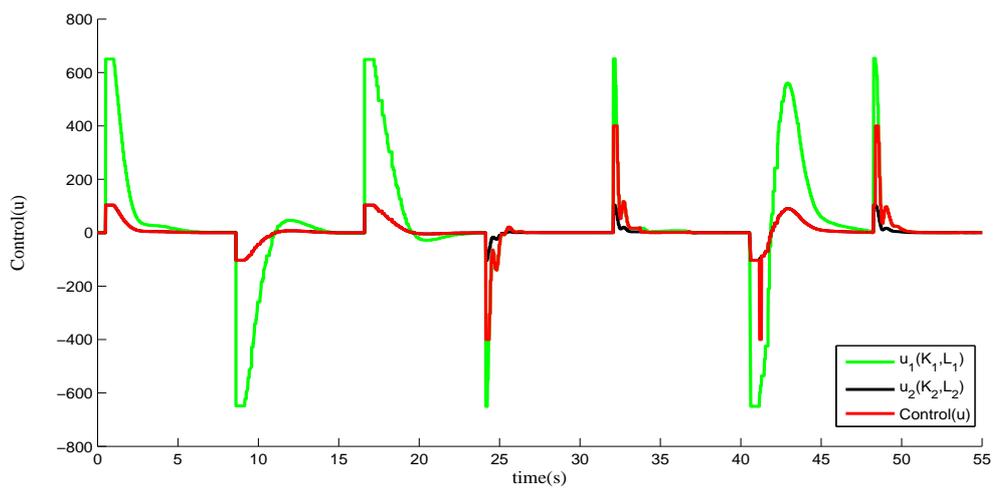
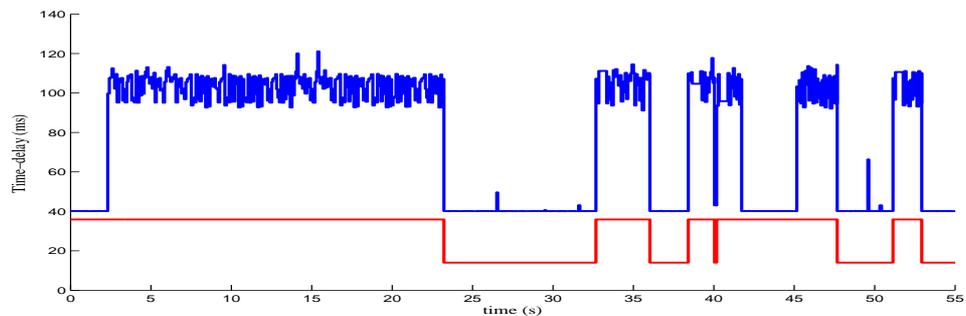


Figure 4.16: The corresponding switched control



86 Figure 4.17: The corresponding variable time-delays and signals of switching

guaranty the global stability, the system does not switch.

As it is clearly shown in Fig.4.15, the global stability of the closed loop is maintained despite the assumption that the time-delay of Bluetooth is treated as a constant one.

4.4 Conclusion

In this chapter the exponential stability analysis and control synthesis problems for continuous switched time-delay systems have been studied. Experimental measurements of time-delays of Internet show that the QoS of network greatly depends on the different periods of the day. So, a switching controller strategy was proposed in this chapter. In the first section, common LKF has been applied for all the switching modes so to guaranty the exponential stability with arbitrary switchings. To get different performances according to the QoS of network, polytopic method has been used to get exponential stability for each mode. In the second part, multiple exponential LKF were used for each mode, which allowed for reducing conservatism. Exponential stability is obtained for each mode and the global stability is guaranteed by a minimum dwell time. This method is suitable for the systems with slow frequency of switching. Experimental results are given for both methods and do confirm the theory.

Chapter 5

Fully event-driven control with packet dropouts consideration

In this chapter, fully event-driven mode is applied. In such a situation, there is no more packet buffer on the Slave's nor on the Master's sides. In comparison with the previous chapters, the removal of the control channel packet buffer allows for saving communication time, since no waiting strategy occurs.

However, the observer design has to be a bit more sophisticated, since the time when control is actually applied to the Slave process is not anymore known by the Master part which drives the observer. In particular, the packet loss problem in the control channel becomes critical, since it has to be considered as a controller failure. Because we use the UDP protocol, packet loss is frequent and must be dealt with.

In [Seuret A. & Richard J.-P. 2008], Seuret and Richard presented a way to compute a maximum number of the successive packets which can be lost in such a situation without breaking the stability guaranty. The work was considering a single interval of delays, without adaptation to the quality of service, and was illustrated by an academic example. Here, while keeping the same principles for the computation of the maximum number of lost packets, it is proposed two improve this result in two ways:

- an adaptation of the feedback loop to two different levels of QoS, obtained by switching the controller and observer gains;
- a concrete implementation of the resulting structure allows for checking the overall behavior of the event-driven solution.

The corresponding results were published in [Jiang W.-J. *et al.* 2009b].

The structure of the chapter is as follows: Firstly, the driving modes of nodes in the NCS (event-driven, time-driven) will be recalled. The control is applied to the Slave as soon as this latter receives it. In a second part, an analysis of the packet loss problem gives LMI conditions for finding the maximum number of lost packet admissible. In this case, the delay are modeled over a single interval as in [Seuret A. & Richard J.-P. 2008]. Then, a third part proposes a switching controller taking into consideration the available QoS. Throughout the chapter, the stability condition as well as arbitrary switching condition are analyzed by means of the common LKF method, as depicted in Chapter 4, Section 4.2. At the end of this chapter, the experimental results are given.

5.1 Driving modes of nodes in NCS

Driving modes of nodes in NCS have a close connection with the networked-induced delays. To ensure the performance of the NCS, it is necessary to choose the driving mode. The modes can be divided into two categories: time-driven nodes and event-driven nodes [Wei L. *et al.* 2007].

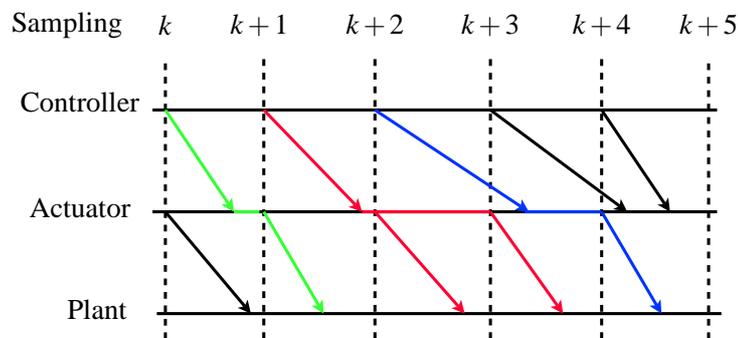


Figure 5.1: The diagram of time-driven controller

In Fig.5.1, the controller is time-driven with a time period of T . For this mode, clock synchronization should be considered before the installation of the system. Time-driven mode means that the controller calculates the control signals based on the sampling clock and sends out the command to the plant at each time instance of kT . For the plant, it also actuates the command according to the sampling clock. As showed in the previous chapters, for the control channel, a packet buffer can be used at the side of the slave, in such a way time-driven mode is

applied and makes the observer realizable.

Under the time-driven mode, controller may bring some problems, such as message rejection or vacant sampling. The plant actuator is time-driven and executes the command at the fixed interval, so when there are two or more commands arriving within the sampling period, only the “newest” data can be used. Such kind of phenomenon is named as “message rejection”. This occurrence is depicted in Fig.5.1, in the sampling period of $[k+4, k+5]$ when two controls are accepted. When the actuator do not receive the command packet from the controller within a sampling period, it only uses the old command, so “vacant sampling” occurs. Such as in Fig.5.1, it occurs in the sampling period of $[k+3, k+4]$, there is no new control for the plant.

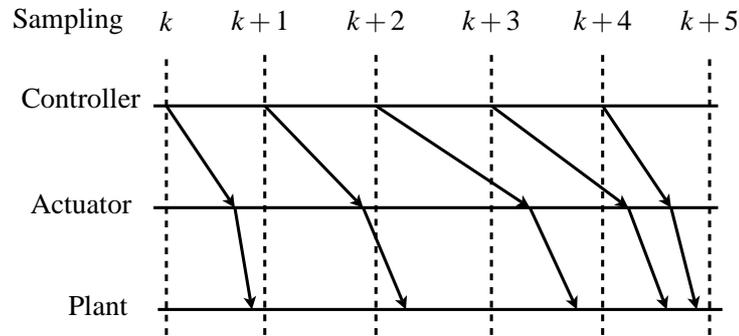


Figure 5.2: The diagram of event-driven controller

For the benefit of system performance, event-driven actuators are preferred to time-driven ones, in order to eliminate the extra waiting time for the next actuator sampling instance to arrive, before the new input signal can be updated. In fact, time-driven actuators can be considered as a special case, with “events” happening at regular sampling instants of event-driven actuators. In Fig.5.2, the actuator is event-driven, which means only the “newest” control will be applied to the plant. The control is immediately applied as soon as it is received by the actuator. In the view of system performance, as the actuator does not waste the time to wait for the sampling period, the control is more efficient. But due to the randomness of the network time-delays, the “newest” arriving packet is not necessary the most recently sent one. As every packet is sent out together with the time-stamp, according to the send out time, the outdated data will not be applied. In this case, it is possible that a control is holding an unchanged value for a time longer than the sampling period. In this means, it can be modeled as the packet loss problem.

In the following section, the conditions for time-driven controller is to be analyzed.

5.2 Maximum number of consecutive lost packets: The single delay interval case

First recall the closed-loop system as described in Chapter 3, the equation of the Slave is written as follows:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t - \delta_{con}(t)), \\ y(t) = Cx(t), \end{cases} \quad (5.1)$$

where $\delta_{con}(t)$ is unknown in the event-driven case.

The observer equation is:

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) - BK\hat{x}(t - \hat{\delta}_{con}(t)) + L(y(t - \delta_{obs}(t)) - \hat{y}(t - \delta_{obs}(t))), \\ \hat{y}(t) = C\hat{x}(t), \end{cases} \quad (5.2)$$

where $\hat{\delta}_{con}(t) \in [h_1, h_2]$.

In the case of event-driven mode, the time of control being applied is not known to the observer, *i.e.*, $\hat{\delta}_{con}(t)$ is unknown. Suppose that N consecutive packets are lost, then $\{\hat{\delta}_{con}(t) \text{ and } \delta_{obs}(t)\} \in [h_1, h_2 + NT]$, with T the sampling period. For sake of clarity, redefine $h_M = h_2 + NT$. To simplify the problem (and without loss of generality except some additional conservatism), we consider that if packet loss occurs, it occurs at both of the two communication channels. In order to make the observer realizable, two steps have to be considered.

- First, in order to calculate the gain of the observer, the same strategy as in Chapter 3 is applied, supposing a packet buffer at the side of the Slave which makes $\delta_{con}(t)$ “known”. By this way, the observer gain L is calculated.
- In a second step, the maximum packet loss is calculated with the stability conditions for the variable time-delay system.

In the following section, only the analysis for the second step is given.

Using the error vector $e(t) = x(t) - \hat{x}(t)$, the global system can be rewritten as:

$$\begin{cases} \dot{x}(t) = Ax(t) + BKx(t - \delta_{con}) - BKe(t - \delta_{con}); \\ \dot{e}(t) = Ae(t) - LCe(t - \delta_{obs}) + BK(x(t - \delta_{con}) - x(t - \hat{\delta}_{con}) - e(t - \delta_{con}) + e(t - \hat{\delta}_{con})). \end{cases} \quad (5.3)$$

Considering to use $\zeta(t) = \text{col}\{x(t), e(t)\}$, then we get the equation:

$$\dot{\zeta}(t) = \bar{A}_0\zeta(t) + \bar{A}_1\zeta(t - \delta_{obs}(t)) + \bar{A}_2\zeta(t - \delta_{con}(t)) + \bar{A}_3\zeta(t - \hat{\delta}_{con}(t)), \quad (5.4)$$

$$\text{in which } \bar{A}_0 = \begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix}, \bar{A}_1 = \begin{bmatrix} 0 & 0 \\ 0 & -LC \end{bmatrix}, \bar{A}_2 = \begin{bmatrix} BK & -BK \\ BK & -BK \end{bmatrix}, \bar{A}_3 = \begin{bmatrix} 0 & 0 \\ -BK & BK \end{bmatrix}.$$

So, the similar LMI condition can be found as (4.77) in Chapter 4 but with the guaranty of $\alpha' \geq 0$. When fixing $\alpha' = 0$, the upper bound of $\hat{\delta}_{con}$ can be found. In this way, the maximum number of packet loss without destabilizing the NCS system can be got.

5.3 Maximum number of consecutive lost packets for NCS with QoS switches

In this section, the result of maximum number of lost packets will be extended to the case of time-delays switching between “small” and “big” value intervals. Here, a common LKF is considered to assure an arbitrary switching. While, it can be easily adapted to the case of multiple LKF with minimum dwell time.

Consider the plant as a linear system. It is described by the following form:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t - \delta_{con}^i(t)), \\ y(t) = Cx(t), \end{cases} \quad (5.5)$$

where $i = 1, 2$, N_1 and N_2 refer to the maximum packets loss respectively for the two modes, $\delta_{con}^1(t) \in [h_1, h_{M_1}]$, $\delta_{con}^2(t) \in [h_2, h_{M_2}]$, $h_{M_1} \in [h_2, h_2 + N_1 T]$ and $h_{M_2} \in [h_3, h_3 + N_2 T]$. It is possible to define the average delay $\delta^i(h_i, h_{M_i}, N_i, T)$ and the maximal delay amplitude $\mu^i(h_i, h_{M_i}, N_i, T)$ as:

$$\begin{aligned} \delta^i(h_i, h_{M_i}, N_i, T) &= (h_{M_i} + N_i T + h_i)/2; \\ \mu^i(h_i, h_{M_i}, N_i, T) &= (h_{M_i} + N_i T - h_i)/2. \end{aligned} \quad (5.6)$$

For the sake of simplicity, in the following part, the shortened notation δ^i and μ^i will be used.

The common LKF with descriptor representation [Fridman E. 2001; Fridman E. & Shaked U. 2002] is adapted from [Seuret A. & Richard J.-P. 2008] with $\bar{x}(t) = \text{col}\{x(t), \dot{x}(t)\}$, $\bar{e}(t) = \text{col}\{e(t), \dot{e}(t)\}$ as follows:

$$\begin{aligned} V(t, x_t, \dot{x}_t) &= \bar{x}^T(t) E P_x \bar{x}(t) + \int_{-\delta^i}^0 \int_{t+\theta}^t \dot{x}^T(s) R_x \dot{x}(s) ds d\theta + \int_{t-\delta^i}^t x^T(s) S_x x(s) ds \\ &+ \int_{-\mu^i}^{\mu^i} \int_{t+\theta-\delta^i}^t \dot{x}^T(s) R_{xa} \dot{x}(s) ds d\theta + \int_{-\mu^i}^{\mu^i} \int_{t+\theta-\delta^i}^t \dot{x}^T(s) R_{xp} \dot{x}(s) ds d\theta \\ &+ \bar{e}^T(t) E P_e \bar{e}(t) + \int_{-\delta^i}^0 \int_{t+\theta}^t \dot{e}^T(s) R_e \dot{e}(s) ds d\theta + \int_{t-\delta^i}^t e^T(s) S_e e(s) ds \\ &+ \int_{-\mu^i}^{\mu^i} \int_{t+\theta-\delta^i}^t \dot{e}^T(s) R_{ea} \dot{e}(s) ds d\theta + \int_{-\mu^i}^{\mu^i} \int_{t+\theta-\delta^i}^t \dot{e}^T(s) (R_{ep} + R_{xe}) \dot{e}(s) ds d\theta, \end{aligned} \quad (5.7)$$

with $E = \text{diag}\{I_n, 0\}$, positive definite matrices $P_{q1}, S_q, R_{qa}, S_{xe}$ and R_{xe} for q presenting the subscript of the variables x and e and:

$$P_q = \begin{bmatrix} P_{q1} & 0 \\ P_{q2} & P_{q3} \end{bmatrix}. \quad (5.8)$$

This allows for using a polytopic formulation of the variable delays. In order to guaranty the closed-loop performance whatever the delay variation, the exponential stability with the rate α will be achieved. In other words, there must be a real $\kappa \geq 1$ so that the solution $x(t; t_0, \phi)$ starting at any time t_0 from any initial function ϕ satisfies: $\|x(t; t_0, \phi)\| \leq \kappa \|\phi\|_c e^{-\alpha(t-t_0)}$. This is achieved by using the following state feedback and observer:

$$u(t) = K_i \hat{x} + k y_c, \quad (5.9)$$

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t - \hat{\delta}_{con}^i(t)) + L_i(y(t - \delta_{obs}^i(t)) - \hat{y}(t - \delta_{obs}^i(t))), \\ \hat{y}(t) = C\hat{x}(t), \end{cases} \quad (5.10)$$

$i = 1, 2$ corresponding the two switching periods. $\hat{\delta}_{con}^1(t), \delta_{obs}^1(t) \in [h_1, h_{M_1}]$, $\hat{\delta}_{con}^2(t), \delta_{obs}^2(t) \in [h_2, h_{M_2}]$, $h_{M_1} \in [h_2, h_2 + N_1 T]$ and $h_{M_2} \in [h_3, h_3 + N_2 T]$. Here, y_c is the desired set point and k is a gain ensuring an unitary static gain for the closed loop.

Note that in the system, there are no more packet buffers, which means the Master is not supposed to know the time of packet applied. *The separation principle does not hold in this case.* To solve the problem, the control gains and the observer gains are computed *as if* there was the separation principle (Chapter 3 and 4) for some performances (guaranteed by the exponential convergence), *i.e.*, $\hat{\delta}_{con}^i(t) = \delta_{con}^i(t)$, which is resolved in Chapter 4. Then, the stability has to be checked for these values.

In the following part, the global stability of the system is checked by considering both observation and control problem for the given gains.

The maximum number of packet loss is considered for both of the switched modes, while the system stability is still guaranteed. In this case, $\hat{\delta}_{con}^i(t) \neq \delta_{con}^i(t)$ in the equation (5.10), *i.e.* $h_i + NT \leq \hat{\delta}_{con}^i(t) \leq h_{i+1} + NT$, $i = 1, 2$ corresponding to the two delay zones. By adapting the theorem [Seuret A. & Richard J.-P. 2008] for both modes, the maximum number of packet loss is obtained.

Theorem 6 *For given K_i and L_i ($i = 1, 2$), the global remote system is asymptotically stable if, for q representing the subscripts x or e , there exist positive definite matrices P_{q1}, S_q, R_{qa} ,*

S_{xe} , R_{xe} , and matrices of size $n \times n$: P_{q2}, P_{q3}, Z_{ql} for $l = 1, 2, 3$, $Y_{ql'}$ for $l' = 1, 2$, such that the following LMIs hold:

$$\begin{bmatrix} \Theta_x & P_x^T \begin{bmatrix} 0 \\ BK_i \end{bmatrix} - \begin{bmatrix} Y_{x1}^T \\ Y_{x2}^T \end{bmatrix} & \mu_i P_x^T \begin{bmatrix} 0 \\ BK_i \end{bmatrix} & P_x^T \begin{bmatrix} 0 \\ BK_i \end{bmatrix} & \mu_i P_x^T \begin{bmatrix} 0 \\ BK_i \end{bmatrix} \\ * & -S_x & 0 & 0 \\ * & * & -(\mu_i R_{xa}) & 0 \\ * & * & * & -S_{xe} \\ * & * & * & * & -\mu_i R_{xe} \end{bmatrix} < 0, \quad (5.11)$$

$$\begin{bmatrix} \Theta_e & P_e^T \begin{bmatrix} 0 \\ L_i C \end{bmatrix} - \begin{bmatrix} Y_{e1}^T \\ Y_{e2}^T \end{bmatrix} & \mu_i P_e^T \begin{bmatrix} 0 \\ L_i C \end{bmatrix} & P_e^T \begin{bmatrix} 0 \\ \beta_i BK_i \end{bmatrix} & \mu_i P_e^T \begin{bmatrix} 0 \\ \beta_i BK_i \end{bmatrix} \\ * & -S_e + S_{xe} & 0 & 0 \\ * & * & -(\mu_i R_{ea}) & 0 \\ * & * & * & -\beta_i R_{ep} \\ * & * & * & * & -\beta_i R_{xp} \end{bmatrix} < 0, \quad (5.12)$$

$$\begin{bmatrix} R_q & Y_{q1} & Y_{q2} \\ * & Z_{q1} & Z_{q2} \\ * & * & Z_{q3} \end{bmatrix} \geq 0, \quad (5.13)$$

where $q \in \{x, e\}$, $\beta_i = 2\mu_i$, $\mu_i = \sigma_{i+1} - \sigma_i + NT$, $\delta_i = \sigma_{i+1} + \sigma_i + NT$,

$$P_q = \begin{bmatrix} P_{q1} & 0 \\ P_{q2} & P_{q3} \end{bmatrix}, \quad \Theta_x = \Theta_x^n + \begin{bmatrix} 0 & 0 \\ 0 & 2\mu_i * R_{xp} \end{bmatrix}, \quad (5.14)$$

$$\Theta_e = \Theta_e^n + \begin{bmatrix} 0 & 0 \\ 0 & 2\mu_i * (R_{ep} + R_{xe}) \end{bmatrix}, \quad (5.15)$$

$$\Theta_q^n = P_q^T \begin{bmatrix} 0 & I \\ A & -I \end{bmatrix} + \begin{bmatrix} 0 & I \\ A & -I \end{bmatrix}^T P_q + \begin{bmatrix} S_q + Y_{q1} + Y_{q1}^T + \delta_i Z_{q1} & Y_{q2} + \delta_i Z_{q2} \\ * & \delta_i R_q + 2\mu_i R_{qa} + \delta_i Z_{q3} \end{bmatrix}. \quad (5.16)$$

5.4 Experimental results

Considering two zones of delay:

- $[0.01, 0.09[$ for the “small” ones (mode 1)

- $[0.09, 0.5]$ for the “big” ones (mode 2).

The gains switch when the delay crosses the value of 0.09_{sec} . The controller gains are computed using Theorem 3 and 4. Then, the global stability (observer + controller) is checked using Theorem 5. The maximum exponential rates of convergence ensuring the global stability are:

- $\alpha_1^c = \alpha_1^o = 3.1$ in the mode 1,
- $\alpha_2^c = \alpha_2^o = 1$ in mode 2.

The maximum numbers of lost packets for the two modes are 0 and 3, respectively, while the system stays stable. Note that when, coming from mode 1, the time-delay bypasses the upper bound of the small delay interval, the system switches to mode 2. So, packet losses only have to be considered for the mode 2 (“big delay”).

The gains K_i and L_i ($i = 1, 2$) are as the one found in Chapter 4.

The result is shown in Fig.5.3, in which the blue curve represents the set values; The green corresponds to the real position (motor angle) of the Miabot; The black and red represent respectively the robot’s estimated position and speed. Fig.5.4 illustrates the corresponding switched control signals from Master to Slave. The red curve is the real control while the green and the black ones are the controls calculated respectively for the two subsystems. We can see the switch points according to the values of time-delay. Fig.5.5 depicts the variable time-delays and, also, the switching signals.

On Fig.5.3, one can verify that, when the time-delay is smaller than $90ms$, the first mode is active. In this case, the system involves the gains K_1 and L_1 and is quickly stabilized. While when the time-delay becomes bigger than $90ms$, a lowest (but still exponential) performance is guaranteed. As it is clearly shown in Fig.5.3, the global stability of the closed loop is maintained. This experimental result is obtained despite the assumption that the time-delay of Bluetooth is treated as a constant one.

5.5 Conclusion

Packet loss problem has been considered in this chapter. As UDP is used for the packet communication, packet loss is unavoidable. In the previous chapters, it was treated as an additional

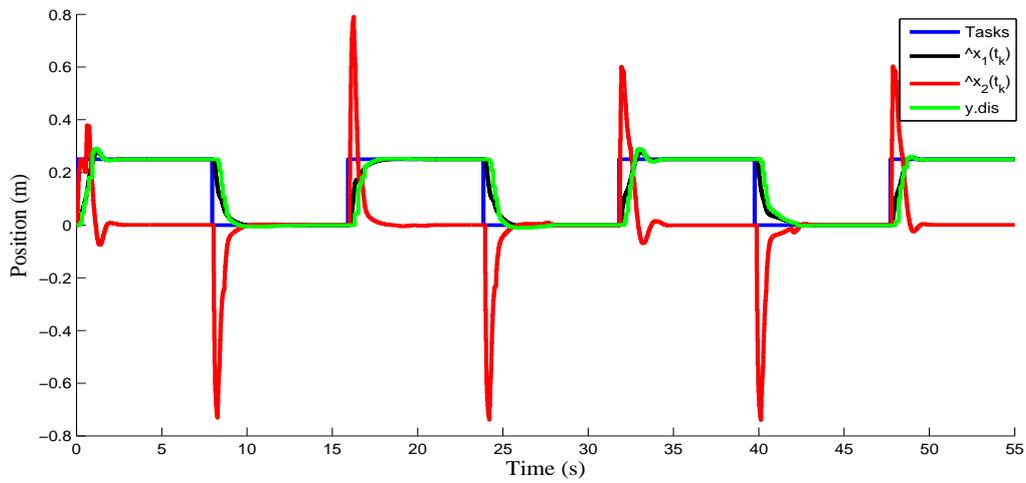


Figure 5.3: Results of remote experiment

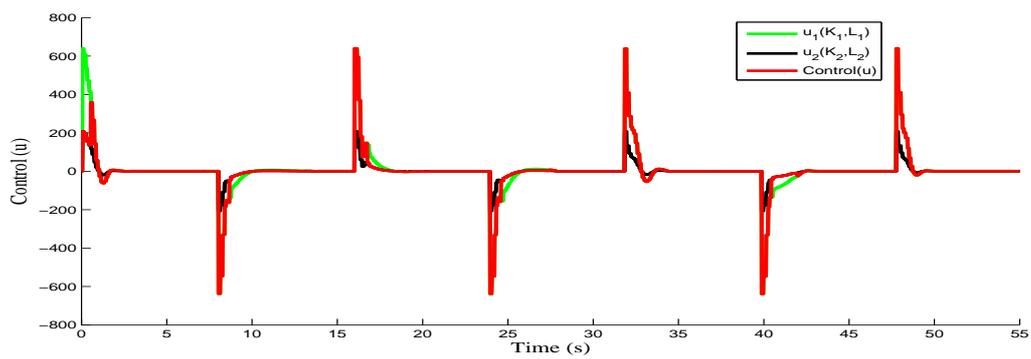
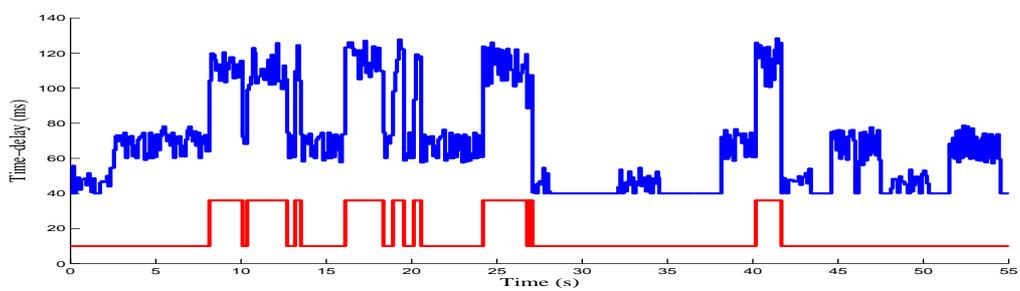


Figure 5.4: The corresponding switched control

Figure 5.5: The corresponding time-delay and switch signals (the characteristic function χ)

time-delay introduced to the closed-loop control system because the control channel was time-driven.

Since such a time-driven mode can slow down the network capacity, in this chapter we analyzed and implemented a fully event-driven mode. Such solution optimizes the use of the network capacity but can now suffer from the packet loss in the control channel. Thus, by using the LKF method, we have proposed a way to compute the maximum number of allowed consecutive lost packets. When the packet loss happens, the buffer in the side of the Slave is no longer useful. Generally speaking, it is more efficient than time-driven model as the control can now be directly applied as soon as received. For example, Comparing the result in Fig. 5.3 with Fig. 4.5 in chapter 4, we can see that the response time in the case without buffer is about 1 second and the latter is about 2 seconds for the big mode.

Conclusions and Perspectives

Conclusions

This PhD thesis is dedicated to the exponential output stabilization of linear NCS. The studied solution is based on a remote observer which is able to estimate the present state of the plant despite the various network induced delays. These last are present in both the control and the measurement channels.

Four main contributions can be noted:

- In Chapter 2 and 3, we design and implement a computer structure which realizes the remote, observer-based, state feedback controller. Although the main structure is inspired from the PhD works of Seuret [Seuret A. 2006; Seuret A. *et al.* 2006], various LKF improvement are original, as well as the concrete implementation. To make the observer know the moment of control application to the Slave, a buffer is used in the side of the slave, so the actuator node works in the time-driven model. As the observer uses the measurements from the Slave as soon as it receives, the sensor node is of event-driven model. The corresponding results are published in [Jiang W.-J. *et al.* 2009a].
- In Chapter 4, we enrich the previous mixed time/event-driven structure by adapting the controller to the available Quality of Service. The idea is to provide better performance when the network allows fast communications, and keep a basic performance when the network slows down. Considering different QoS of the network (here, two levels), a two-mode switching controller is proposed. As previously, stability and speed performances are ensured despite the jitter of the network. We develop two switching techniques:
 - one involves a common LKF and allows for an arbitrary switching rate,
 - another uses multiple LKF with a minimum dwell time and, thus, limited switching

rate.

If both methods have their advantages according to the system's needs, the second one presents better performance for each switching mode. Packet loss problem is also considered, which is treated as an additional delay introduced to the closed-loop control system.

In addition, the QoS is estimated by measuring the communication delays and the controller gains switch in consequence. Since this RTT estimation cannot be instantaneous, this additional delay of the switching instants is also taken into account. Note that this application motivated the development of new stability criteria for general switched time delay systems. The corresponding results are published in [Jiang W.-J. *et al.* 2009c] and could be easily generalized to more than two QoS levels.

- Since a time-driven mode can slow down the network capacity, in Chapter 5 we analyze and implemented a fully event-driven mode. Such solution optimizes the use of the network capacity but can suffer from the packet loss in the control channel. Thus, we propose a way to compute the maximum number of allowed consecutive lost packets. When the packet loss happens, the buffer in the side of the Slave is no longer useful. Generally speaking, it is more efficient than time-driven model as the control can now be directly applied as soon as received. With regard to the recent result [Seuret A. & Richard J.-P. 2008], this part provides a major contribution by developing a switched controller so to adapt the performance to the available QoS. The corresponding results are published in [Jiang W.-J. *et al.* 2009b].
- Last but not least, we designed and realized the implementation of all the above control strategies. Although theoretical results on NCS are many, experimental ones still remain far fewer. This was the first challenge and motivation in starting this work. So, all the theoretical results are verified on the experimental platform, which is composed of two PCs connected by the Internet, one serves as the Master and another PC together with a small mobile robot, Miabot, as the Slave. Multi-thread technique is applied in both of the two programs to enhance the performance of the system. The experimental results are given at the end of every chapter.

On the theoretical side, our research is principally focused on linear interval time-delay systems. The stability problems are treated in the framework of the Lyapunov-Krasovskii theory.

Polytopic method and exponential LKF method are explored to guarantee the fast convergence with a decay rate α . Then it is resolved in the form of LMI. In this context, we have shown the merits of the new LKF by comparing with the most recent research results. Various uses of time-delay dependent LKF allowed us to derive less conservative stability and control design criteria.

Perspectives

Several perspectives of the results developed in this thesis can be considered:

- In our work, the system is based on Master-Slave structure with only one Slave. The next step, we can consider use several slave systems, see Fig. 1. The difficulty lies on share strategy of the bandwidth, the computation power... For example, one can consider a strategy that allocates more bandwidth to the slave with the higher dynamic, or to the slave with the higher energy. The control law will include both of the Master-Slave and Slave-Slave interaction strategies.

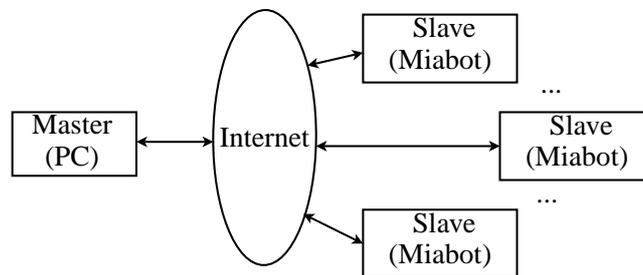


Figure 1: Multiple slaves (Miabot) in the systems

- In this thesis, only linear models of the plant are investigated and a way to extend it to nonlinear one has to be found. In practice, most physical systems are inherently nonlinear in nature (for instance, we had to limit the input voltage in the robot so to keep the model linear). Nonlinear equations are difficult to solve and the analysis of control law is difficult but feasible by certain method. Among the possible trends, two solutions seem to be available: The polytopic models can be considered, at least at the price of increased LMI dimensions [Cannon M. *et al.* 2003], or the feedback linearization as considered in [Estrada-García H.J. 2008] for inverted pendulums.

- In practice, the model parameters are not well known or are time varying. In the view of robust stability, the model of uncertain dynamical system can be further developed. We think it is possible to enlarge the results at the price of the LMI dimension.
- Concerning the QoS of the network, a switching system model with two modes is proposed in this thesis. To further enhance the system performance, the method of real time dynamic gains calculation can be considered. This could constitute a long-term research.

Résumé étendu en français

Introduction générale

Selon l'article de synthèse de Zampieri [Zampieri S. 2008] on peut distinguer trois types de contributions dans le cadre des Systèmes Commandés en réseau : l'amélioration de la Qualité de Service des réseaux (QoS), la commande par le réseau, et les systèmes multi-agents.

- Les études sur la qualité de service des réseaux ont pour objectifs de permettre au réseau de garantir les performances attendues par les applications synchronisées par son biais. Un autre objectif dans ce cadre consiste à permettre une utilisation efficace et équitable de ses ressources afin de minimiser l'apport continu de nouvelles ressources.
- La commande par le réseau consiste au développement d'applications robustes basées sur le concept de rétroaction. Dans le cadre de ces applications on suppose que le système de contrôle envoie des ordres de commande au système piloté par le biais de canaux de données non fiables. L'objectif est donc en contrôlant les données en retour du système commandé d'avoir une stratégie de commande permettant de faire face aux retards des paquets de commande ou à leur perte.
- Les systèmes multi-agents portent sur l'étude de la manière dont l'architecture de réseau et les interactions entre ses composants influent sur les objectifs de contrôle global par le réseau.

Dans ce travail, nous abordons la question de la commande par le réseau. Cela signifie que les systèmes commandés en réseau à prendre en considération sont du type système en boucle fermée composés de deux parties : une partie commande éloignée et une partie opérative échangeant en temps réel des données au travers de canaux de communication. Les signaux

sont échangés entre les composants du système sous la forme des paquets d'information émis à travers un réseau.

De manière plus précise, dans ce travail nous nous intéressons à la problématique de la stabilisation d'un système commandé au travers du réseau. C'est un problème complexe qui nécessite la mise en œuvre d'un observateur éloigné au sein de la partie commande. Un tel observateur a pour objectif la reconstruction de l'état du système l'aide de données de retour de position du système commandé. Notons que ces données subissent les retards induits par le réseau ce qui rend non applicables les approches traditionnelles de commande en centralisé.

Avec le développement des techniques de contrôle des systèmes, de l'informatique et des technologies réseaux, la commande des systèmes par le réseau devient une problématique de plus en plus populaire qui demande beaucoup de performances pour être résolue. Le contrôle temps réel au travers du réseau devient possible et a fait l'objet de plusieurs travaux : pour une vue générale sur les tendances de la commande en réseau, voir [Hespanha J.P. *et al.* 2007; Richard J.-P. & Divoux T. 2007; Tipsuwan Y. & Chow M.-Y. 2003; Zampieri S. 2008]. On peut également avoir une synthèse sur les protocoles et les réseaux dans le premier chapitre de [Witrant E. 2005]. Comme les approches traditionnelles de commande dans un contexte centralisé ne sont pas adaptées au contexte des systèmes commandés en réseau de nombreuses études sont en cours sur cette thématique.

Dans ce travail, une attention particulière sera portée au contrôle d'un système simple en boucle fermé constitué de deux parties communicantes. Comme il a été noté par Hespanha dans sa récente synthèse [Hespanha J.P. *et al.* 2007], ce type d'architecture en boucle fermé, bien que plus simple que les architectures à multiples boucles, elle peut prendre en compte différentes caractéristiques des systèmes commandés en réseau comme la limitation de la bande passante, les délais variables, la perte de paquets, les effets de l'échantillonnage ...

En raison de son faible coût et de sa flexibilité pour la reconfiguration, Internet est largement utilisé dans la commande des systèmes. Cependant, comme il est construit à l'aide de différentes architectures de réseaux hétérogènes, sa structure est très compliquée. La QoS varie selon la charge du réseau qui induit des délais variables et imprévisibles au fil du temps, ce qui est facteur d'instabilité dans le comportement des systèmes en réseau. Une des facteurs clés du contrôle d'applications temps réel au travers du réseau est la capacité à garantir des délais bornés entre émetteur et récepteur afin de réagir aux données avec la fréquence souhaitée. Par exemple, dans le contrôle en réseau d'une valve du circuit de refroidissement d'un réacteur

nucléaire, il est nécessaire de garantir que les commandes de positionnements arriveront aux bonnes dates afin d'obtenir la bonne commande. Dans le cas contraire, cela peut être critique pour la sécurité (dans ce cas, le coût du système de communication n'est plus un critère critique). Aussi, pour obtenir les meilleures performances du système, il est nécessaire de prendre en compte plusieurs stratégies tenant compte de la variation dans le temps des délais du réseau.

Préliminaires

Ce chapitre donne une vue générale des structures, questions et recherches récentes dans le domaine des systèmes commandés en réseau. Les problèmes existants tels que les délais variables, les paquets perdus et la QoS des réseaux ont été analysés de manière concise. Différentes sources de délais ont été définies pour la commande en boucle fermée de systèmes en réseau. Ces délais sont résumés par les notations δ_{con} et δ_{obs} comme illustrés par la Figure 1. Ils définissent respectivement la somme des délais entre le contrôleur et le système commandé d'une part et le délai inverse d'autre part.

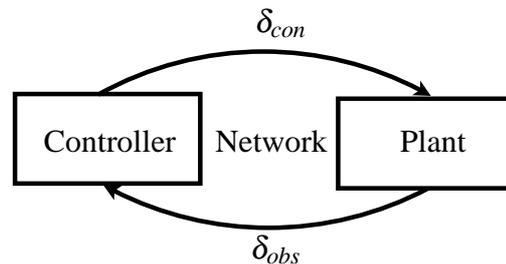


Figure 1: Délais entre le contrôleur et le système commandé

Dans ce chapitre, nous introduisons les principales hypothèses définissant le cadre de notre modélisation. Notre approche a pour but de garantir la stabilité des systèmes en réseau tout en optimisant leur performance. Dans ce cadre, du point de vue stabilité, la solution technique proposée consiste à rendre constant les retards en les maximisant.

Nos principales hypothèses sont les suivantes :

- *Essayer de garder les retards aussi petits que possibles et être capable de gérer leur gigue afin de maximiser les performances du système commandé global.*
- *Prendre en compte toutes variations rapides même sans disposer d'un modèle de ces*

variations. Pour cela, nous supposons que les retards varient à l'intérieur d'un intervalle qui devra être parfaitement défini.

- *Restreindre l'étude au cas des systèmes linéaires afin de pouvoir exploiter les méthodes de Lyapunov-Krasovskii et les outils LMI.*

Ainsi, seuls les systèmes linéaires avec des retards variant dans un intervalle temporel seront à considérer.

Pour finir, nous concluons en définissant le type de contrôle à implémenter.

D'une manière, on peut distinguer trois types de contrôleurs : les contrôleurs par retour statique de la sortie, les contrôleurs par retour dynamique de la sortie, et les contrôleurs par retour d'état basés sur un observateur. Le contrôleur par retour statique de la sortie est simple à construire mais ne peut être envisagé pour la commande des systèmes en réseau en raison de même de sa trop grande simplicité (Pas de consommation de ressource). Par contre le contrôleur par retour dynamique de la sortie correspond à un comportement en boucle fermée plus robuste mais sa conception est difficile. Dans notre cas, nous avons choisi la méthode du contrôleur par retour d'état avec observateur. Nous avons choisi un observateur de type Luenberger car c'est un bon compromis entre qualité des performances et difficulté de conception. D'autre part, l'utilisation d'un contrôleur basé sur la technique de l'observateur permet l'estimation à distance de l'état d'une variable qui peut être utilisé pour différentes applications, pas forcément la commande.

Dans les chapitres suivants, notre objectif est de proposer une méthode de contrôle robuste pour garantir la stabilité du système commandé en réseau et de proposer une stratégie d'adaptation des gains du contrôleur et de l'observateur en fonction de la QdS du réseau.

Implémentation du système de commande à distance

Le second chapitre focalise sur l'architecture du système d'expérimentation et sur les principales fonctions implémentées par les programmes. Comme notre théorie de la stabilité est basée sur un modèle continu, la période d'échantillonnage doit être très petite pour compenser les effets de la discrétisation. Aussi, la technique du multi-threading est appliquée pour accroître les performances du programme. Tous les paquets émis vers une destination sont datés par la source afin que le destinataire puisse savoir quand l'exploiter. Cela nous a obligé à mettre en

œuvre une technique pour la synchronisation des horloges de l'émetteur et du destinataire afin d'avoir une référence de temps unique. Dans ce cadre, la structure des programmes des deux côtés du système contrôlé (contrôleur et observateur) est expliquée par la fonction de chaque thread. En cas de pertes de paquets, le paquet reçu le plus récent est appliqué. Mais si le nombre de paquets consécutifs perdus dépasse le nombre maximal tolérable pour la stabilité du système, le contrôle place le système dans un mode de repli afin d'éviter tout danger potentiel.

Dans ce travail, nous avons mis en place une structure maître-esclave pour implémenter le système global. Le maître correspond au système de commande éloigné contrôleur/observateur et l'esclave correspond au système commandé. Comme c'est généralement le cas par exemple pour les systèmes mobiles ou de téléopération, nous supposons que l'Esclave est un système à faible consommation d'énergie avec des capacités de traitement limitées. Aussi, le traitement effectué par le PC Esclave est simplifié et la commande et la complexité de l'observation est concentrée sur le PC Maître. Dans notre application de test, le système commandé est un robot Miabot de la compagnie Merlin Systems Corp. Ltd. Avec le Miabot et son PC de commande constitue le système Esclave.

Cette structure permet également de rendre notre théorie facilement applicable aux applications de capteurs/actionneurs intelligents dans lesquelles les capteurs n'ont en général pas une forte capacité de calcul. Les principales caractéristiques du système global sont illustrées par la Figure 2.

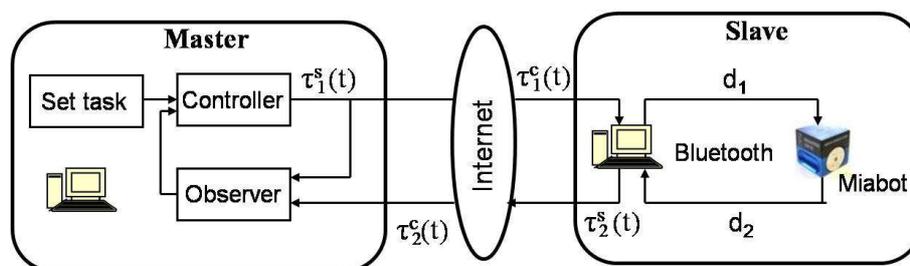


Figure 2: Architecture du système global

Le protocole de transmission UDP (User Data Protocol) est utilisé pour l'échange de données entre le Maître et l'Esclave. Bien que TCP (Transmission Control Protocol) fournisse des transmissions de paquets de données plus fiables nous avons privilégié UDP pour des questions de performances. En effet, TCP nécessite l'acquittement des échanges par les deux extrémités d'une communication entraînant un trafic utilisant de la bande passante et limitant la réactivité du système. Cela est donc préjudiciable aux performances du système. D'autre part, les pa-

quets hors délais ne doivent pas être réémis par le système de commande. Notons toutefois, que notre approche prend en compte les paquets perdus. Dans notre stratégie de contrôle, le problème de la perte de paquets est considéré comme un problème de retard.

Stabilisation par retour de la sortie

Dans le chapitre 3, les conditions de stabilité pour les systèmes à délais variables bornés par intervalles sont étudiées à l'aide de l'approche de Lyapunov-Krasovskii. Elles sont données sous la forme d'inégalités matricielles linéaires ou LMI (Linear Matrix Inequalities) qui rendent le problème simple à résoudre. La comparaison entre nos résultats et ceux des autres prouve la qualité de notre méthode. Les résultats ont été étendus à la stabilité exponentielle respectivement par la méthode polytopic et la méthode des fonctionnels de Lyapunov-Krasovskii. Le résultat théorique a été prouvé dans notre système commandé en réseau et des résultats expérimentaux sont également donnés à la fin du chapitre.

Les résultats sur la stabilisation par retour de sortie que nous avons développé dans ce chapitre, aussi bien que dans le chapitre 4, sont basés sur une stratégie événementielle du côté contrôleur et sur une stratégie contrôlée du côté du système commandé. Dans la stratégie contrôlée, le PC Esclave attend la date fixée par le contrôleur pour appliquer la commande. De cette manière, l'observateur peut prédire les instants où la commande est appliquée au système.

La stabilité exponentielle a été obtenue et des résultats expérimentaux confirment la théorie. Elle est caractérisée par le paramètre α qui mesure la performance du système et qui dépend du retard maximal définissant l'intervalle de variation des retards. Plus est α important, plus on obtient rapidement la stabilité. A la fois les expériences locales et distantes confirment la théorie et le robot Miabot a suivi les instructions qui lui ont été envoyées.

Pour être adapté à des situations plus générale d'Internet, nous pouvons augmenter la borne h_2 tout en diminuant la valeur de α . Quand α est fixé à 0, nous obtenons le retard maximal le plus grand. Nous avons montré que dans le cadre de notre expérimentation avec le Miabot, h_2 ne doit pas être supérieur à 1,9s. Cette borne théorique représente la QoS limite offerte par Internet permettant de garantir la stabilisation de notre système expérimental.

A ce stade, deux limitations restent possibles :

1. Dans cette étude, l'intervalle des retards et sa borne maximale h_2 en particulier sont fixés

une fois pour toute. Cependant, le retard peut rester faible pendant une longue période (par exemple la nuit), bien que le contrôleur continue de travailler avec des gains adaptés aux retards importants. L'objectif du chapitre suivant (chapitre 4) sera d'adapter les gains à la QoS estimées du réseau.

2. Notre solution nécessite d'implémenter une stratégie d'attente du côté de l'Esclave. Cela permet de faciliter le calcul des gains mais réduit la vitesse des performances réalisables car il maximise l'un des retards (le canal de l'actionneur). La théorie développée dans le dernier chapitre (chapitre 5), résoudra cette contrainte en mettant en œuvre une approche événementielle aussi bien côté contrôleur que côté système commandé.

Stabilisation du système distant : un contrôleur dépendant de la QoS

Dans le cas de stabilisation par Internet, les retards présentent une forte gigue. Le contrôleur doit être conçu pour gérer des intervalles de retards importants. Cela entraîne l'obtention de performances médiocres lorsque les retards mesurés appartiennent en fait à un intervalle beaucoup plus faible que celui pris en compte dans la modélisation. En effet, la mesure des retards sur Internet montrent des fortes variations selon les périodes de mesures. Par exemple, on constate en général de fortes variations entre le jour et la nuit.

Compte tenu de la Qualité de Service (QoS) variable du réseau, nous proposons dans cette partie la conception d'un contrôleur prenant en compte l'état du réseau. Comme précédemment, la stabilité et les performances sont assurées en dépit des variations du réseau, par la technique de la stabilisation exponentielle. En outre, ici la QoS est estimée par la mesure des retards de communication et les gains des contrôleurs sont adaptés en conséquence. Comme l'estimation de ce RTT ne peut pas être instantanée, ce retard additionnel de l'instant de commutation est également pris en compte.

Les systèmes commutés sont des systèmes dynamiques hybrides constituant une famille de sous-systèmes (également appelés modes) et des règles logiques qui gèrent la commutation entre ces différents sous-systèmes [Liberzon D. 2003; Hirche S. *et al.* 2006]. Mais la stabilité des sous-systèmes n'est pas une condition suffisante pour garantir celle du système global.

Les preuves théoriques que nous avons utilisé ici, sont de nouveau basées sur des fonction-

nels de Lyapunov-Krasovskii (LKF) dont l'approche est généralement moins conservatrice que la technique des fonctions de Lyapunov- Razumikhin. D'autre part, pour résoudre les problèmes de stabilité dépendante des retards, les conditions LKF sont attractives car possédant l'avantage structurel de présenter plus simplement les informations de retard quand le critère de stabilité est obtenu.

Les méthodes d'étude de la stabilité basée sur une ou plusieurs fonctions de Lyapunov sont celles les plus fréquemment utilisées pour la stabilisation globale d'un système commuté. Pour les systèmes à retards, elles consistent en la recherche de :

- Une fonction LKF (commune) pour tous les modes pour garantir la stabilité *uniforme* [Jiang W.-J. *et al.* 2008; Sun Y.G. & Wang L. 2006; Lee J.-W. & Dullerud G.E. 2006, 2007],
- Ou différentes LKFs, une pour chaque modé, avec un temps de commutation minimal pour garantir la stabilité globale de l'ensemble du système.

Quand le système nécessite principalement de la stabilité et que la performance n'est pas une condition critique, la deuxième méthode peut être utilisée. Quand une fonction LKF commune est utilisée pour tous les modes, la condition de commutation est relativement simple et la commutation peut être effectuée entre tous les modes. Cependant, pour cette première méthode, il y a deux limites : la première est qu'il n'est pas toujours possible de trouver une telle fonction LKF commune et la deuxième limite est que même si elle est trouvée les performances restent limitées.

S'agissant de la deuxième approche, différentes LKFs peuvent être appliquées pour obtenir les meilleures performances pour chaque mode. Néanmoins avant chaque commutation, un temps de séjour de séjour minimal dans le mode courant doit être considéré pour garantir la stabilité globale. Cette solution, basée sur le temps de séjour minimal a été introduite dans [Hespanha J.P. & Morse A.S. 1999] dans le cas d'un système sans retard. Elle a été étendue à des systèmes avec retard dans [Chen C.-C. *et al.* 2006; Yan P. & Özbay H. 2008], mais dans ces travaux, le délai est supposé constant.

Dans ce chapitre, visant à la stabilisation exponentielle de nos NCS, nous présentons une étude des systèmes à commutation caractérisés par des retards non nuls et à fortes variations. Ce cadre correspond mieux à notre problème. Ici, la commutation est volontairement mise en œuvre par le contrôleur et la stratégie de commutation est décidée en fonction de la qualité de

service du réseau. Cette QdS est d'ailleurs estimée par la mesure des retards de communication. Les gains du contrôleur ont été adaptées en conséquence.

Nos hypothèses sur les délais ne sont pas très contraignantes :

- Les délais de transmission sont variables et asymétriques, ce qui signifie que le retard $h_1(t)$ du canal de contrôle (de maître à esclave ou M-à-E en raccourci), et le retard $h_2(t)$ du canal de retour (E-à-M) satisfont normalement $h_1(t) \neq h_2(t)$.
- Les retards des deux canaux (avec nos notations, $\delta_{con}(t)$ et δ_{obs}) sont bornés et appartiennent à un intervalle $[h_m, h_M] = [h_1, h_3]$.
- Cet intervalle est partagé en deux zones, $[h_1, h_2]$ pour les "petits" retards, et $[h_2, h_3]$ pour les "grands" retards. Nous supposons que les deux retards $\delta_{con}(t)$ et δ_{obs} appartiennent à la même zone.
- Dans la suite, ces deux zones de retard correspondent aux deux "modes" du contrôleur de commutation.

En outre, tous les résultats peuvent être simplement étendus à plus de deux modes, et avec des zones différentes pour le retard de contrôle et le retard d'observation. Toutefois, dans ce cas, les calculs deviennent plus complexes. Par souci de clarté, et comme nos expériences ont été réalisées avec succès dans le cadre d'hypothèses mentionnées ci-dessus, nous avons préféré ne pas développer le cas le plus général.

Dans la partie suivante, une analyse plus approfondie des retards de communication est réalisée (en particulier, nous discutons la question de leur estimation). Ensuite sont proposés certains résultats impliquant une commutation de contrôleur et l'utilisation d'une fonction LKF commune. Une dernière partie présente des améliorations techniques basées sur des temps de séjour minimum. A chaque étape, des expériences sont menées.

Système complètement événementiel avec prise en compte de la perte de paquets

Dans ce chapitre, une approche totalement événementielle est proposée. Dans ce cas il n'y a plus aucun buffer, ni du côté maître, ni du côté esclave. Par comparaison avec les résultats

obtenus dans les chapitres précédents, la suppression du buffer dans le sens maître-esclave permet d'accroître les performances globales du système dans la mesure où il n'y a plus de temps d'attente avant d'appliquer une commande reçue par l'esclave.

Cependant, ce type d'approche accroît également la complexité de l'observateur intégré dans le maître pour la génération des commandes. En effet, dans ce cas, le moment d'application de la commande par l'esclave n'est plus connu par l'observateur. Dans ce cadre, la perte de paquets de commande devient cruciale et peut être considérée comme une faute du contrôleur. Comme nous utilisons le protocole UDP, la perte de paquet est fréquente et doit être traitée.

Dans [Seuret A. & Richard J.-P. 2008], les auteurs ont proposé une méthode pour calculer un nombre maximal de paquets successifs qui peuvent être perdus dans une telle situation, sans rupture de la garantie de la stabilité. Le travail ne considérait pour les retards un unique intervalle de retards, sans adaptation à la qualité du service. Il a été illustré par un exemple académique. Ici, tout en gardant les mêmes principes pour le calcul du nombre maximal de paquets perdus, il est proposé d'améliorer ce résultat de deux manières :

- une adaptation de la boucle de rétroaction à deux niveaux distincts de qualité de service, obtenue par la commutation des gains du contrôleur et de l'observateur en fonction du mode ;
- une mise en œuvre concrète de la structure résultante a permis de vérifier le comportement complet de la solution totalement événementielle.

Ces résultats ont été publiés dans [Jiang W.-J. *et al.* 2009b].

La structure du chapitre est la suivante: Tout d'abord, les modes d'échange (événementiel ou périodique) des nœuds du système en réseau sont rappelés. La commande est appliquée à l'esclave, dès que ce dernier le reçoit. Dans une deuxième partie, une étude du problème de la perte de paquets permet d'obtenir les conditions LMI pour déterminer le nombre maximal de paquets pouvant être perdus tout en garantissant la stabilité du système. Dans ce cas, les retards sont modélisés sur un seul intervalle comme dans [Seuret A. & Richard J.-P. 2008]. Puis, une troisième partie propose un changement de contrôleur en prenant en considération la qualité de service disponible. Tout au long du chapitre, la stabilité ainsi que l'état de commutation arbitraires sont analysés par le biais de la méthode de fonction LKF commune, telle que décrite dans le chapitre 4. A la fin de ce chapitre, des résultats expérimentaux sont donnés.

Conclusion et perspectives

Cette thèse est consacrée à l'étude de la stabilisation exponentielle des systèmes commandés en réseau linéaires. La solution proposée est basée sur l'utilisation d'un observateur distant permettant d'estimer l'état actuel du système commandé, malgré les divers retards induits par le réseau. Ces derniers sont présents à la fois dans la communication maître-esclave et esclave-maître sans pour autant être du même ordre.

Contributions

Quatre contributions majeures peuvent être notées :

- Dans les chapitres 2 et 3, nous avons proposé et mis en œuvre une structure informatique qui réalise la commande par retour de sortie basée sur un observateur d'état. Bien que la structure soit inspirée des travaux de thèse de A. Seuret [Seuret A. 2006; Seuret A. *et al.* 2006], nous avons amélioré l'approche en proposant fonctionnels LFK originales et nous avons réalisé sa mise en œuvre. Ces résultats sont publiés dans [Jiang W.-J. *et al.* 2009a].
- Dans le chapitre 4, nous enrichir l'approche mixte événementielle/périodique précédente par l'adaptation de la structure du contrôleur en fonction de la qualité de service disponible. L'idée est de fournir une meilleure performance lorsque les retards de communication du réseau le et de conserver des performances acceptables lorsque la qualité du réseau se dégrade. Considérant différentes QdS du réseau (ici, deux niveaux), un contrôleur basé sur la commutation entre deux modes est proposé. Comme précédemment, la stabilité et les performances du système sont garanties en dépit de la gigue du réseau. Nous avons développé deux techniques de commutation :
 - L'une est basée sur une fonction de Lyapounov commune est permet des commutations selon un taux arbitraire,
 - Une autre utilise plusieurs fonction de Lyapounov est nécessite le respect d'un temps de séjour minimum dans le mode courant avant d'envisager la commutation dans un autre mode.
- Si les deux méthodes ont leurs avantages en fonction de besoins du système, la seconde présente de meilleures performances pour chaque changement de mode. Le problème de

perte de paquets est également pris en compte, ce qui est considéré comme un délai supplémentaire introduit par la boucle fermée de contrôle du système. En outre, la qualité de service est estimée par la mesure des retards de communication et les gains du contrôleur sont adaptés en fonction de mode. Comme cette estimation du RTT n'est pas instantanée, ce retard supplémentaire est également pris en compte. Notons que cette application a motivé le développement de nouveaux critères de stabilité pour le cas général des systèmes à retards commutés. Ces résultats ont été publiés dans [Jiang W.-J. *et al.* 2009c] et pourraient facilement être généralisé à plus de deux niveaux de QdS.

- Comme une approche basée sur l'introduction d'un buffer peut réduire les performances globales, dans le chapitre 5, avons étudié et mis en œuvre un événementiel. Cette solution permet d'optimiser l'utilisation de la capacité du réseau, mais peut souffrir de la perte de paquets dans le canal maître-esclave. Aussi, nous proposons une méthode de calcul du nombre maximum de paquets consécutifs perdus. Lorsque la perte de paquets se produit, la mémoire tampon côté esclave n'est plus utile. De manière générale, il est plus efficace lorsque la commande peut être directement appliquée dès réception. Par rapport aux récents résultats de [Seuret A. & Richard J.-P. 2008], cette partie offre une contribution majeure qui concerne l'adaptation du contrôleur aux performances de la qualité de service disponible. Ces résultats ont été publiés dans [Jiang W.-J. *et al.* 2009b].
- Enfin, nous avons conçu et réalisé la mise en œuvre de l'ensemble de ces stratégies de contrôle. Bien que les résultats théoriques sur la commande en réseau soient nombreux, il existe peu de mise en œuvre pratique. Cela a été le premier défi et la motivation de départ de ce travail. Ainsi, tous les résultats théoriques ont été vérifiés sur une plateforme expérimentale, composée de deux PC connectés par l'Internet, l'un servant de poste maître et l'autre poste, l'esclave, permettant le contrôle d'un robot mobile Miabot. La technique multi-thread est appliquée aux programmes des deux postes pour améliorer la performance du système. Ces résultats expérimentaux sont donnés à la fin de chaque chapitre.

Sur le plan théorique, notre recherche est principalement axée sur les systèmes à retards linéaires par intervalle. Les problèmes de stabilité sont traités dans le cadre de la théorie de Lyapunov-Krasovskii. La méthode Polytopic et la méthode exponentielle LKF sont utilisées pour garantir la convergence rapide avec un taux de . Ensuite, il est résolu sous la forme de LMI. Dans ce contexte, nous avons montré l'intérêt de la nouvelle LKF par comparaison avec

les plus récents résultats de recherche. Différentes utilisations de fonctions LKF dépendant de retards variables nous ont permis de proposer des critères moins conservatifs permettant de garantir la stabilité.

Perspectives

On peut développer plusieurs points concernant les résultats obtenus dans cette thèse :

- Dans notre travail, le système est basé sur la structure maître-esclave avec un seul esclave. Dans la prochaine étape, on peut envisager d'utiliser plusieurs esclaves.
- Dans cette thèse, seuls des modèles linéaires des systèmes commandés ont été étudiés. Il sera nécessaire d'étendre ce travail au cadre des systèmes non linéaires. Dans la pratique, la plupart des systèmes physiques sont intrinsèquement non-linéaire (par exemple, nous avons dû limiter la tension d'entrée dans le robot afin de maintenir la linéarité du comportement du système. Les équations non linéaires sont difficiles à résoudre et les lois de contrôle sont difficiles à obtenir, mais réalisable par certaines méthodes. Parmi les tendances, deux solutions semblent être disponibles : Les modèles polytopique peuvent être considérés, au moins au prix d'une augmentation des dimensions LMI [Cannon M. *et al.* 2003], ou de la linéarisation par rétroaction comme dans le cas des pendules inversés [Estrada-García H.J. 2008].
- Dans la pratique, les paramètres du modèle ne sont pas bien connus ou variable dans le temps. Dans le cadre de l'étude de la robustesse de la stabilité, un modèle de dynamique incertaine du système peut être développé. Nous pensons qu'il est possible d'élargir les résultats, au prix de la taille des conditions LMI.
- Concernant la qualité de service du réseau, un modèle de système à commutation avec deux modes est proposé dans cette thèse. Pour améliorer encore la performance du système, la méthode de calcul de gains dynamiques peut être envisagée. Cela pourrait constituer une perspective de recherche à long terme.

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