TO DESIGN AND DEVELOP AN EFFICIENT MIDDLEWARE FOR THE NETWORKED CONTROL SYSTEM

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Thesis Submitted in Partial Fulfillment of the requirements for

the Degree of Master of Science in Electrical Engineering

With Specialization in Control Systems

at

Department of Electronics & Power Engineering

Pakistan Navy Enginreeing College, Karachi

National University of Sciences & Technology, Islamabad, Pakistan

June 2013

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ACKNOWLEDGMENT

I would like to thank Dr. Attaullah Memon, my supervisor, for his many suggestions and constant support during this research. I am also thankful to Dr. Syed Sajjad Haider zaidi, Dr. Sameer Hashmat Qazi and Dr. Khwaja Bilal for their guidance through the early years of chaos and confusion.

Dr. Attaullah Memon expressed his interest in my work and supplied me with the preprints of some of his recent work, which gave me a better perspective on my own results. He shared with me his knowledge of stability analysis and provided me many useful references and friendly encouragement

Finally, I am grateful to my parents for their patience and love. Without them this work would never have come into existence (literally).

ABSTRACT

Due to the improvement of computing and communication technology, networked control systems may soon become extensive in many control applications. While the power of employing the communication network in the control loop absolutely provides many benefits, it also increment several challenges which need to be overcome to utilize the benefits.

Network Control Systems (NCS) are the control loop systems in which data is sent from sensors to actuators and from actuators to control unit using communication networks. Communication network causes the complexity in the design and analysis of such systems. Communication network induces random delays in the control loop which degrade the performance of the system and even destabilize the system in some cases. The problem of performance degradation that results due to such network delays are recovered by carefully designed compensators.

Network Control Systems have become key players in modern control systems. The issues like time delays and information loss are the challenges one faces while implementing these control systems. In order to cater the delay problem for NCS, a design of middleware has been proposed in this work which will enable the existing controller to work in the networked environment.

In this work, the regulation problem of the speed of DC motor is considered over a networked communication link. The network delays tend to disrupt the control effort of the controller. The challenge lies in compensating for the performance loss.

The control system is based on proportional integral (PI) controller combined with proportional derivative (PD) compensator to address the degradation in the transient performance. The proposed strategy shows that even in the presence of significant time delays, the control system gives satisfactory performance.

Time delays of the network are estimated through the use of a time delay observer. Time delay observer plays a key role when system has time varying delays. The work

of time delay observer/estimator is to estimate the current delay of the system by adaptively changing the gains of the PD compensator, so that the estimated network delay translates to appropriate values of proportional and derivative gains (Kp and Ki, respectively).

A Time Delay estimator with state feedback is proposed for DC motor speed control and is proven to be very effective through simulations.

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Chapter 1

Introduction

1.1 Introduction

Control loops that are closed over a communication network get more and more common as the hardware devices for network and network nodes become cheaper. A control system over a communication network communicating with sensors and actuators is called a distributed real-time control system. In distributed real-time control systems, data are sent and received by different kind and manufacturers of network nodes.

Networked control systems could possibly constitute the next logical step in the evolution of control, leading to the aggregation of control with communication and computing. Networked control systems are the closed loop systems in which information is sent from sensors to actuators and from actuators to control unit using communication link. They have several advantages over wired networks and finds application in many areas. Due to communication media system experiences various side effects. This chapter discus about advantages, applications and fundamental issues in NCS.

Network nodes such as sensor nodes, actuator nodes, and controller nodes that are of specific interest for distributed control. Process values are measured from Sensor nodes and transmit these over the communication network. New values for the process inputs over the communication network are received by actuator nodes and apply these on the process input. Process values from sensor nodes are read by controller nodes. Control signals are calculated and sent to the actuator nodes using a control algorithm. The system setup reduces cost of cabling and offers modularity and flexibility in system design with a common communication network. Some caution must be taken in case of distributed control which is a powerful setup. Communication networks inevitably introduce delays due to limited bandwidth and also due to overhead in the communicating nodes and in the network.

In many systems delays vary with the passage of time. From a control perspective the control system with varying delays will no longer be time invariant. This thesis addresses the problem of analysis and design of control systems when the communication delays are time varying.

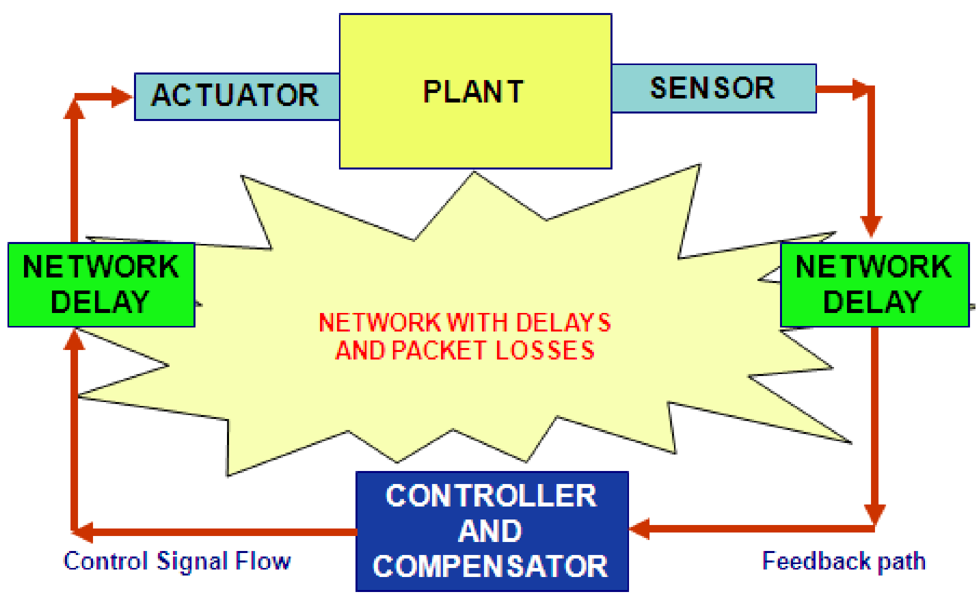

Figure 1.1: PI controller combined with PD compensator for variable delay NCS

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1.2 General Configuration of NCS

Networked control system comprises of interconnected components such as sensors, actuators, control unit and the system to be controlled in order to achieve the desired purpose, where sensor and actuator has computational power as well. In networked control systems plant outputs are measured from sensor nodes and the values are transmitted to the controller through the network whereas the control commands are received by the actuator nodes through the network and apply these commands to the plant. Networked control systems work in the presence of network delays to meet the design specifications of the control system.

The network can be shared with other control loops and other network resources.

Recent advancement in communication and control has enabled the communication to offer sophisticated implementation of control systems. The data is send and receive among sensors, actuators, control unit and plant in control systems through these communication networks. The examples of networks which transmit signals in a control system to make Network Control System are Ethernet, CAN, Profibus, Fieldbus, ATM and Internet.

1.3 Advantages of NCS

Due to the improvement of computing and communication technology, networked

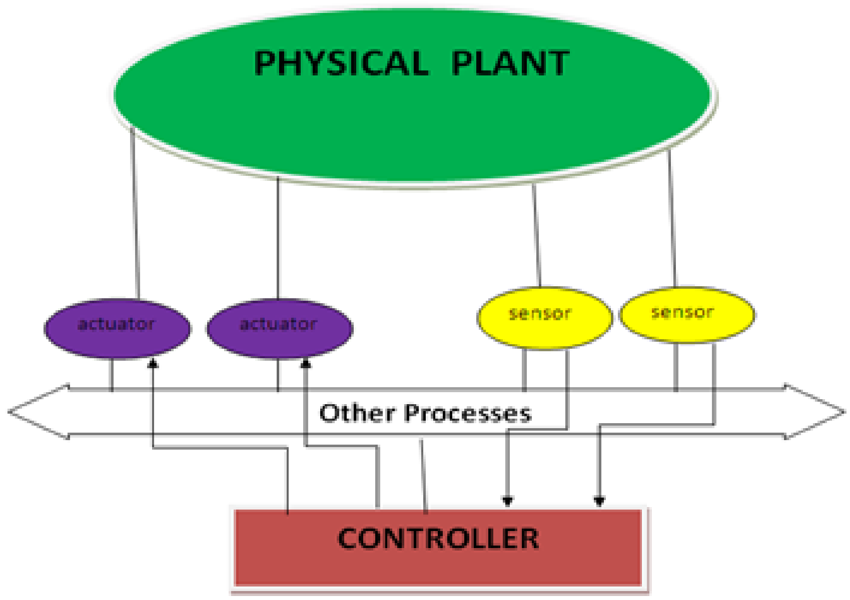

Figure 1.2: Typical network control system

control systems may soon become extensive in many control applications. While the power of employing the communication network in the control loop absolutely provides many benefits, it also increment several challenges which need to be overcome to utilize the benefits.

The main advantage of NCS is that it connects cyberspace to physical space and enable execution of several tasks from long distance. Network control systems reduce the complexity and overall cost in designing and implementing the control systems. Without major changes in the structure network control system can be easily upgraded by adding sensors, actuators and controllers with relatively low cost.

Network control system can be used to make intelligent decisions over large physical space by easily defusing the global information. Network control system offer easy maintenance and installation for the complex system. Flexible and cost effective installation, maintenance and expansion of network control system can be provided by modern communication technology

Due to flexibility of NCS over wired communication network they are more acceptable in manufacturing factories. The most important is that only NCS has enabled us to operate and control systems remotely i-e teleoperation.

1.4 Applications of NCS

There are numerous potential applications of NCS and they cover a wide range of industries such as: space and terrestrial exploration, access in hazardous environments, factory automation, remote diagnostics and troubleshooting, experimental facilities, domestic robots, aircraft, automobiles, manufacturing plant monitoring, nursing homes and tele-operations.

The application area of NCS can be categorized in three groups: Complex systems, Remote Controlled systems and Large Scattered systems. Complex systems are large scale systems which are obtained by integration of several small scale systems. Examples of complex systems are robots, vehicles and aircrafts. Remote controlled systems are particularly employed in places where moving can be inconvenient or risky e.g. Space, Nuclear and Chemical plants, offshore wind turbines or war zone.

Applications of Remote controlled systems find in distance learning laboratories as well. Remote control Systems also find its applications where components are scattered in a wide area and difficult to be connected by direct wiring. Examples of such systems include manufacturing plants, chemical plants and aircrafts. Figure 1.3 is an example of networked process control system which describes control of temperature, flow and filling level.

Efficiency, Flexibility and Reliability of large scale systems in modern industries can be improved by applications of network control system. NCS applications for remote control and monitoring reduce the time and cost installation, reconfiguration and maintenance.

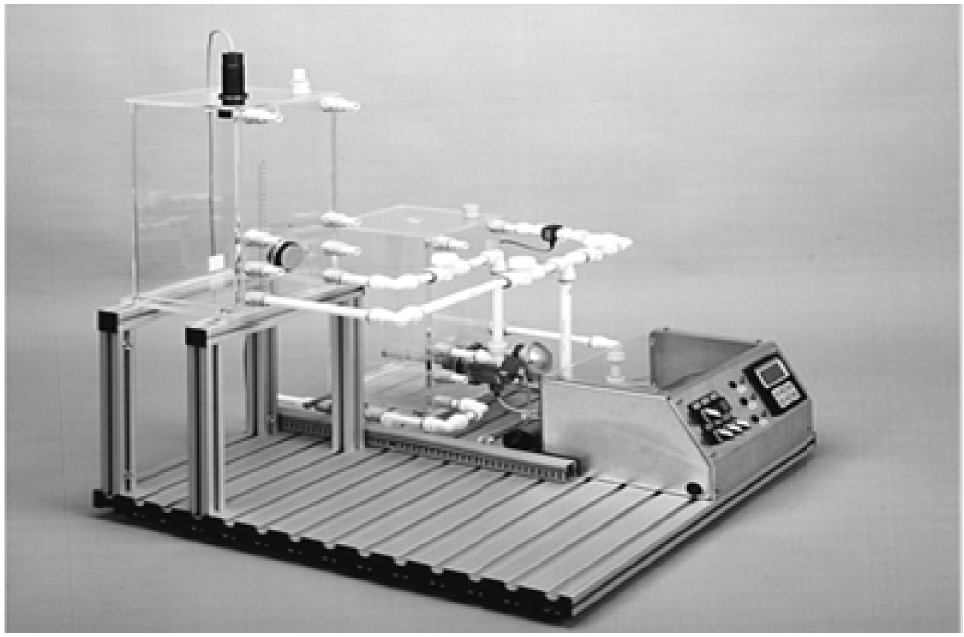

Figure 1.3: Network process control system (control temperature)

1.5 Fundamental Issues

Communication network causes the complexity in the design and analysis of network control systems. In traditional point to point network information is instantaneously delivered from sensor to control unit and from control unit to actuator whereas in network control system regardless of the type of network several side effects will be introduced in the control loop. Following are the major factors which are pointed by various researchers affecting the performance of network control system.

- Time delay in the control loop.
- Packet drop out and information loss in the network.
- Sampling rate constraints.
- Multiple packet transmission.
- Network capacity for communication.
- Disturbance induced in the medium.

1.6 Network Delays

In NCS, information transfers from the sensors to the controller and from controller to actuator are described by time-varying delays. While sending the information from sensor to controller four time consuming operations are involved: $\tau_{1,1}$- data acquisition and analog to digital conversion time; $\tau_{1,2}$- for data processing for network transmission at sensor level; $\tau_{1,3}$- for one way delay time between sensor node and controller node; $\tau_{1,4}$- for data processing and preparing for controller usage. Total time delay between moment of acquisition and the moment when data is ready to be used by the controller can be defined as $\tau_1 = \tau_{1,1} + \tau_{1,2} + \tau_{1,3} + \tau_{1,4}$

Sending data from controller to actuator also involves four time varying consuming operations: $\tau_{2,1}$- for data processing at the controller level; $\tau_{2,2}$- one way delay time between controller node and actuator node; $\tau_{2,3}$- for data processing at the actuator level; $\tau_{2,4}$- for digital to analog conversion. Thus total time which is used to transfer data from controller to actuator is $\tau_2 = \tau_{2,1} + \tau_{2,2} + \tau_{2,3} + \tau_{2,4}$

The time delay τ_1 can be measured by taking the difference between the time when control data is ready to be used by the controller t_2 (final) and the time taken by the sensor to acquire data t_1 (initial). Similarly, τ_2 can be measured by taking the difference between the time when command information is ready to be used by actuator t_2 (final) and the time it is computed by the controller t_1 (initial). Both time delays can be expressed in terms of sample rate h multiple as following:

$$T_k = (1 + [t_k(final) - t_k(initial)h^{-1}].h) \tag{1.1}$$

A network based on TCP/IP network relies on standard layer 3 transport. When the sample rate is less than 10 ms UDP can only be used for data transport because of its speed advantage compared to TCP. UDP is used as a transport protocol for transmitting data packets containing control information through the network. As UDP is not a connection oriented protocol, therefore three irregular situations can occur.

- S1: no information is received at receiver's end in one sample period. In this case latest information is used at a previous sample rate.
- S2: Two or more data packets are received at receiver's end in one time. Only the packet containing the latest information will be used.
- S3: A packet arrives in a sample period after another packet containing the newer information already arrived and was used in a previous sample period; In this case receiver rejects the packet.

Modeling of Network delays

In order to analyze control systems with network delays in the control loop we have to model these. The network delay is varying due to varying network load, scheduling policies in the network and the nodes, and due to network failures. We will use two models of the network delay

- Constant delay.
- Time varying delay.

To model the delay as being constant for all transfers is the simplest model of the network delay in the communication network. It can be a good model even if the network has time varying delays

In this work the worst case delay of 2500 sampling time is used in the analysis. One way to obtain constant delays is by introduction of timed buffers after each transfer. This method was suggested in Luck and RayH1990I. Control delay becomes longer than necessary is a drawback of this method. This can lead to decreased performance.

1.7 Current and Future work

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Network control systems have many applications and research direction for NCS in automobiles, smart homes, large manufacturing systems, intelligent highways and networked city services, and enterprise-wide supply and logistics chains. Special issue on the technology of Networked Control Systems [4] also dicusses current state of the art research in the area of NCS . The papers are organized in three sections: First, Current State of Technology of NCS which describes applications of NCS in Industrial Control, Large Irrigation Networks and UAVs.

Foundations of Networked Real-Time Systems provide an overview of Data rate constrained control, Control over lossy networks and recent results in NCS. Finally, in last and third section Wireless Networks- the Backbone of NCS present research in Wireless Networks. Various other researchers have presented different results which will be summarized in the coming chapter.

1.8 Focus of Research

The main focus of this research will be on the control engineering view on NCSs. From this point of view several research contributions can be found in literature. This research can be divided into three categories:

1.8.1 Modeling of NCS

Networked control systems analysis starts with an NCS model. To model an NCS numerous approaches have been adopted which are based on different parameters of interest. Mainly the discrete-time delayed system formulation and hybrid formulations have been used. Different models have been derived based on the delay assumptions, varying from models for constant delays from less than a sampling period. Also time varying network delays have been modeled .

1.8.2 Analysis of NCS

In NCS research Performance and stability analysis plays an important role. In this chapter, the induced network delay can degrade the performance and destablize the NCS. Also sampling issues as pointed out in this chapter play an important role. Issues like sample rate selection, sampling methods and network delay characteristics are transmitted in literature . In oder to analyze the stability of NCS Lyapunov stability theory and other techniques such as the Jury test have been used under different assumptions, using different models and different control techniques.

1.8.3 Control of NCS

The design of control strategies is another focus within the NCS research that can compensate for the network induced delays. The most common methods are LQG optimal control, state feedback control using a state observer , fuzzy logic control, robust control and control techniques for hybrid systems have been proposed.

The goal of this research is to explore the issues involved in the design of NCSs. No complicated control strategies are used. In the field of NCS research a lot of work has done which are based on more sophisticated control strategies, the goal of this thesis is to develop a control strategy that can compensate for the negative effects introduced by a network.

The reason for the use of this control strategy is that it can be easily implemented in an embedded setting. Furthermore the majority of industrial controllers consist of standard term PID controller because it is simple to implement and reliable for the majority of control problems. Moreover the use of feed-back control gives some surprising results.

1.9 Research Goals

The purpose of the research is to uncover the problems that arise in the control of networked systems and give a theoretical analysis of the effect of network parameters on the performance and stability of the controlled system.

The goal of this research can be summarized in the following main research question:

How would the use of communication network effect the control loop to stabilize the closed loop system and how can these effects be considered in order to design a control system with a communication network?

To go through this research question, the following questions need to be answered respectively:

- What are the problems in the control of networked systems?
- Which parameters are involved when a communication network is integrated into a control system?
- What is the effect of these parameters on the stability of the controlled system?
- Can a relevant design rules be formulated that can serve as a guideline in designing a networked control system?

In order to get these questions answered, the following approach has been followed. A thorough study has been performed to identify involved parameters and issues which arise in the control of networked systems. With the above cited information, a mathematical model has been derived to analyze the effect of parameters on the stability of a networked control system, under motivated assumptions, both analytically and using simulations.

Chapter 2

Literature Review

2.1 Literature Review

Due to communication medium, regardless of its type, control encounters a lot of problems e.g. time delays, information loss etc. Several researchers have addressed nature of these problems and their possible solutions. This chapter discus some important results concerning stability of networked controlled systems.

2.2 Fundamental Issues

In this thesis, a middleware important for the future of networked control systems is designed. It discusses the fundamental issues which need to be considered in the design and development of an appropriate middleware for networked control systems. It describes a middleware for networked control system which has been developed, and to illustrate how these issues can be addressed in the design of a middleware. Using a networked control system dc motor as an example, we demonstrate the powerful capabilities provided by middleware for a networked control system.

2.3 Concept of Middleware

Middleware is a computer software that provides services to software applications available from the operating system. Infact, middleware is not definitely part of an operating system, not a database management system, and neither is it part of one software application. Middleware provides an easier for the software developers to perform communication, so that they can focus on the specific purpose of their application.

The term middleware is commonly used for the software that enables communication and management of data in distributed applications. The middleware is a software layer that lies between the operating system and applications on each side of a distributed computing system in a network.

The middleware is somewhat consistent through the Service Availability Forum and commonly used in complex, embedded systems within telecom, defense and aerospace industries. Middleware is anything that helps developers to create networked applications. This includes the familiar kitchen sink.

2.4 Scope of the Thesis

The thesis comprises of five chapters.

Chapter 1 gives a brief discussion about advantages of NCS, applications of NCS, fundamental issues on the face of these networks such as time delay in the control loop, information loss in the network, sampling rate constraints, multiple packet transmission, network capacity for communication and disturbance in the medium. A part from just discussing the issues, this chapter also covers the solution to handle these issues.It also discuses the focus and goal of research. Network related issues are kept limited to delays only for the sake of simplicity while other issues are not taken into account.

In chapter 2, the review of some previous work done in the field of the Networked control systems will be discussed. Due to communication medium, regardless of its type, control encounters a lot of problems e.g. time delays, information loss etc. Several researchers have addressed nature of these problems and their possible solutions. This chapter also discuses some important results concerning stability of networked controlled systems.

In chapter 3, the stability of an NCS will be discussed analytically. A discrete time NCS model will be derived for this purpose that consists of several relevant parameters that were identified such as sample time and network delays. This discrete-time NCS model is used to analyze an NCS with two-dimensional plant dynamics. Simulations with a second-order plant will show the observed phenomena. A brief discussion about the obtained results is included at the end of this chapter.

A discrete-time NCS model will be derived in this chapter. First, studied the configuration and the next, a few assumptions on which the model is based are stated. At the end of this chapter, the derived discrete-time NCS model is used to analyze the performance and stability of a plant controlled over a network.

In Chapter 4, simulations and results will be discussed.For the verification and validation purposes,the proposed control scheme is simulated using simulink tool box of MATLAB.

Chapter 5 gives a brief discussion about the proposed strategy used for a particular case for the speed control of DC motor, results and problems.This chapter will discus the control problems that originates when control loops are closed over a communication network and the effect of network delays on the stability and performance.

Literature Review

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In simulation, middleware is generally used in the circumstances of the high level architecture (HLA) that handles many distributed simulations. Middleware is a layer of software that lies between the application code and the run-time infrastructure. Middleware generally consists of a library of functions, and enables a number of applications.

Wireless networking builder can use middleware to meet the challenges associated with wireless sensor network. Implementing a middleware application allows Wireless sensor network builders to integrate operating systems and hardware with the wide variety of various applications that are currently available.

A Networked Control System uses a data network to receive plant information from Sensor nodes and send control data to actuators. Networks do not always transfer data reliably. Common major problems, as discussed in section 1.4 are networked induced delays, information loss and synchronization problem in multiple data packet transmission to name a few. These factors affect the performance of networked control systems and even destabilize the system in some cases. These networked related issues can be address by the following two approaches:]

The next section discusses the review of some previous work done in the field of Networked control system.

2.8 Review of previous Research work

Nilsson [5] analyzed networked control system in discrete time domain. He modeled the network delays as constant, independently random and random but governed by an underlying Markov Chain. His proposed strategy Optimal Stochastic Control Methodology, as called by Tipsuwan, solved the effect of delay as LQG problem.

Halevi and Ray [4] considered the plant in continuous time domain and controller in discrete time domain over a periodic delay network. They deliberate a clock driven controller with mis-synchronization between the plant and the controller. They enlarged the system model to include past values of the plant input and output as additional states, in addition to current state vector of the plant and controller.

Zhang et al. [1] analyzed fundamental issues that one has to face while implementing Networked Control Systems such as network induced delay, packet dropout and multiple packet transmission. They developed the relation between sampling rate and network delay and use hybrid system stability analysis and time domain solution for the stability of NCS. They modeled an NCS with packet dropout and multiple packet transmission and determined the highest rate of data loss for the NCS to be stable.

Wang et al. [7] propounded a new estimator, which was event and time driven, along with actuator. In the intended scheme, delay was compensated by the current control signals in every sampling interval.

The work of [8], a new sliding mode controller (SMC) is proposed which is based on the predicted vectors of the system. The long time delays are compensated in time according to SMC

According to Zhang and Hritsu-Varsakelis [9], to access the communication medium a communication sequence was designed. The actuators and sensors were not considered because they were not communicating with the plant and controller which significantly reduced the complexity of the joint controller/ communication design. For exponential stability of networked control system, an output feedback controller consisting of state observer followed by time varying feedback could be designed for communication sequence.

Onat and Parlakay [10] carried out the previously suggested idea of Model Based Predictive Networked Control System on a non-real-time communication network; Ethernet. Real-Time Linux is employed to guarantee real-time performance of the computer nodes.

Replacement of existing controllers in order to control a system over a data network is costly and inconvenient, Tipsuwan and Chow [12], [13] introduced a middleware which is a methodology to enable existing controllers for networked control and teleoperation. This middleware mutated the output of the controller with respect to the current network traffic conditions. Controller output mutation is performed which is based on a gain scheduling algorithm. They offered case studies on the use of the proposed methodology for networked control system and teleoperation in the presence of IP network delays in these companion papers.

Nilsson[19] In this paper, two models for the network delays are developed. The first model is memoryless and assumes that the delays have a constant probability distribution function. One way to obtain constant delays is by addition of timed buffers after each transfer. By making these buffers larger than the worst case delay time the transfer time can be viewed as being constant. This method was suggested in Luck and RayH1990I. The imperfection with this method is that the control delay becomes longer than necessary. The probability distribution functions for the delays are given by an underlying Markov chain in second model. These models are well suited for design and analysis of distributed real-time control systems.

This paper contains several sub problems that are connected to this thesis. Some are extent to the theory developed, including sampling interval jitter and setups with multiple sensors and actuators. A problem that is related to the delay in measurements is the use of timeouts. They present and analyze a controller that uses a timeout for waiting on a new measurement. Time variations resulting from use of asynchronous loops are also studied[20]

This paper gives an introduction to the problem formulation. A brief discussion of networks for distributed control and clock synchronization is also presented. This paper concludes with a work related to this thesis. Clock synchronization is an area of research itself. The aim of clock synchronization is to deliver the internal clocks of two or more nodes corresponding values. Only software synchronization is considered in this paper i.e. the synchronization signals are directed over the communication network. However, hardware synchronization is also a possible, for instance, using special wiring just to assign a global clock signal in the system. Their first study of the problem with varying network delays is published in[21].

Due to its cost effective and flexible applications, the use of a data network in a control loop has gained increasing attentions in recent years. One of the major challenges in networked control system (NCS) is the network-induced delay effect in the control loop. Network delays cause the degradation in control system performance and destabilize the system in some cases. A significant stress has been on developing control methodologies to handle the network delay effect in NCS. This paper presents NCS control methodologies. A general view on NCS structures and description of network delays including characteristics and effects are also.

This paper has introduced the fundamental and modern control methodologies for NCS. Irrespective of the structure used, the system performance of NCS will degrade due to the existences of network delays in the control loop. In the worst case, by reducing the system stability region the network delays can destabilize the NCS. It is more difficult to handle random network delays in the loop than constant or periodic delays because there is no criterion to generally guarantee the stability of an NCS. Stability criteria are usually subject to specific methodologies and network protocols in networked control systems. In order to design an NCS with a networked control methodology, by the methodology under a selected network protocol, the designer has to understand an application whether it is feasible, acceptable, and reliable controlled. There are additional factors of concern including the size and distance of the application, and the price for the network protocol. The control methodologies described in this paper cover a huge variety of systems and protocols.

Chapter 3

Modeling and Stability Analysis

3.1 Modeling and Stability Analysis

In this chapter, the stability of an NCS will be discused analytically. A discrete time NCS model will be derived for this purpose that consists of several relevant parameters that were identified in the previous chapter such as sample time and network delays. This discrete-time NCS model is used to analyze an NCS with two-dimensional plant dynamics. Simulations with a second-order plant will show the observed phenomena . A brief discussion about the obtained results is included at the end of this chapter.

3.1.1 A Networked Control System Model

A discrete-time NCS model will be derived in this section. First, the studied configuration and the next, a few assumptions on which the model is based are stated. At the end of this section, the derived discrete-time NCS model is used to analyze the performance and stability of a plant controlled over a network.

Modeled NCS configuration

Consider the NCS schematic, given in Figure. 3.1. A continuous-time plant P is controlled by a controller C. The plant and the controller are interconnected via some kind of data network. The controller can be connected to the input and the output of P through the same network line or a different network line. The continuous time input of plant P is obtained via the zero order hold D/A conversion of the discrete time control signal which is computed by controller.

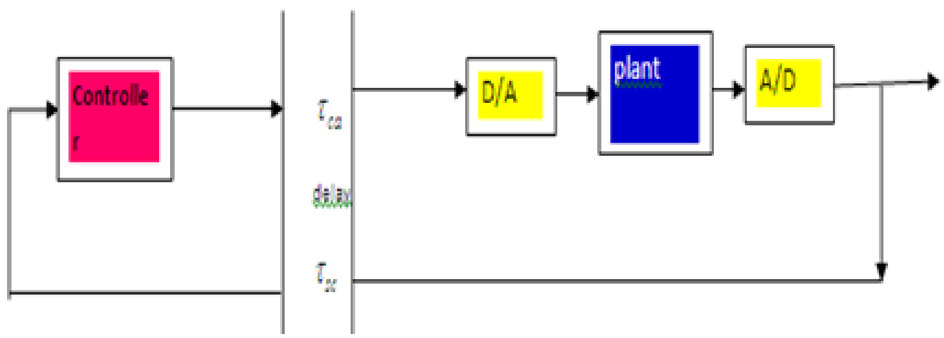

Figure 3.1: Schematic diagram for Networked Control System

3.1.2 Problem Statement

A case study of controlling the speed of DC motor is considered in work. An application to illustrate the use of PI controller is a DC motor speed control system over network delays. In order to analyze the causes of the system that destabilize and results in performance degardation in the presence of network delays, a PI controller along with PD compensator can be used. The problem can be formulated mathematically in a continuous time domain by first assuming the network delay constant, and then by taking the time varying delay.

3.1.3 DC Motor Model

In control systems, a DC motor is a common actuator. The electric circuit and free body diagram of the DC motor is shown in figure.3.2

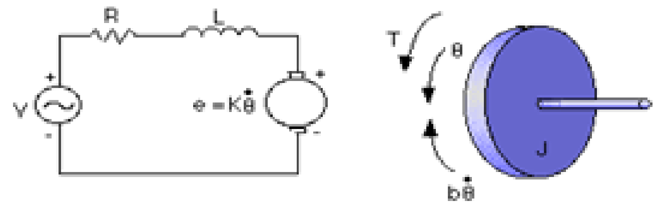

Figure 3.2: Block diagram of DC motor

The differential equations of the DC motor are:

$$J\ddot{\theta} + b\dot{\theta} = Ki \tag{3.1}$$

$$Ldi/dt + Ri = V - K\dot{\theta} \tag{3.2}$$

Taking the Laplace transform of the differential equation transfer function of the DC motor can be obtained.

$$s(Js + b)\theta(s) = KI(s) \tag{3.3}$$

$$(Ls + R)I(s) = V - Ks\theta(s) \tag{3.4}$$

Eliminating I(s) we get transfer function of dc motor which is described as:

$$\theta/V = K/(Js + b) + (Ls + R) + K^2 \tag{3.5}$$

The model of DC motor in state space form is

$$\text{d/dt} \begin{pmatrix} \dot{\theta} \\ i \end{pmatrix} = \begin{pmatrix} -b/J & K/J \\ -K/L & -R/L \end{pmatrix} \begin{pmatrix} \dot{\theta} \\ i \end{pmatrix} + \begin{pmatrix} 0 \\ 1/L \end{pmatrix}$$

3.2 Stability Analysis

3.2.1 Model assumption

The following assumptions are made for the derivation of the NCS model.

Assumption-1

The total network induced delay

$\tau_t = \tau_{sc} + \tau_{ca} < h.$

High sample rates increase the network load and as a results increase the network induced delays. Therefore it is sensible to choose a sample time such that the sample interval (h) is larger than the total network induced delay.

Assumption-2

The network induced delays τ_{sc} and τ_{ca} are constant.

This can always be obtained when a time-skew that is larger than the upper- bound of the delay is introduced between the sampling instant of the sensor and the actuator. Consequently, no assumption has to be made on the time-driven or the event-driven operation of the controller and the actuator. However, if a time driven actuator is considered, the moment of actuation is not necessarily the same as the sampling instant of the sensor

Assumption-3

No computational delay in the controller.

The computational delay of a controller is typically much smaller than the Network induced delays therefore it is not taken into account as a separate parameter. Furthermore, if one wishes to take into account the computational delay of the Controller, it can be included in τ_{ca}.

Assumption-4

No Data loss due to network transfers.

Therefore, by choosing an appropriate sample time, data loss can be minimized or even prevented under strict conditions.

3.2.2 The discrete time NCS model

The dynamics of the system to be controlled P which is a continuous-time for linear time-invariant system as in figure3.1.

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{3.6}$$

$$y(t) = Cx(t) \tag{3.7}$$

Where $x(t)$ is the continuous state of the system, $u(t)$ is the continuous control input, is the continuous output and A, B and C are system matrices of appropriate dimensions.

The discrete time model of the system, a standard result from digital control theory, is given by:

$$x(kh + h) = e^{Ah}x(kh) + \int_{kh}^{kh+h} e^{A(kh+h-\tau)}\, d\tau \tag{3.8}$$

$$y(kh) = Cx(kh) \tag{3.9}$$

here h is the sampling interval. In (10), $y(kh)$ is the sampled output at the sampling instant $t = kh$. $u(\tau)$ is the continuous time input of P over the sampling-interval $[kh, kh+h]$ .The continuous time input over the sampling interval $u(\tau)$ is piecewise constant due to the zero order hold D/A conversion of the delayed discrete control input $u(kh - \tau_t)$.

Under assumptions stated in the previous sub-section, the discrete control input that arrives at the actuator is given by:

According to assumption 1, the piecewise continuous control input $u(\tau)$ has two different values over the sampling interval as:

$$u(\tau) = -Kx(kh - \tau_t), u(\tau) = -Kx(kh) \tag{3.10}$$

then (3.8) becomes:

$$x(kh+h) = e^{Ah}x(kh) - \int_{kh}^{kh+\tau_t} e^{A(kh+h-\tau)}\, d\tau BKx(kh-h) \tag{3.11}$$

$- \int_{kh+\tau_t}^{kh+h} e^{A(kh+h-\tau)}\, d\tau BKx(kh)$

$$y(kh) = Cx(kh) \tag{3.12}$$

The variables in the integral are changed according to $\alpha = k + h - \tau$ the following form is obtained:

$$\phi = e^{Ah} \tag{3.13}$$

$$\alpha = k + h - \tau \tag{3.14}$$

$$x(kh+h) = \phi x(kh) - \varepsilon_0 x(kh) - \varepsilon_1 x(kh-h) \tag{3.15}$$

where $\phi = e^{Ah}$,$\varepsilon_0 = \int_0^{h-\tau_t} e^{A\alpha}\, d\alpha BK$ and
$\varepsilon_1 = \int_{h-\tau_t}^{h} e^{A\alpha}\, d\alpha BK$

$$\gamma(k+1) = \psi z(k) \tag{3.16}$$

$$\gamma = \begin{pmatrix} x(kh) \\ x(kh-h) \end{pmatrix},\ \psi = \begin{pmatrix} \phi - \epsilon_0 & \epsilon_1 \\ I & 0 \end{pmatrix}$$

The closed loop dynamics of an NCS with input feedback under the given assumptions can be formulated in state-space as:

$$\psi = \begin{pmatrix} \beta_0 - \Delta_0 & \beta_1 - \Delta_0 & \Delta_1 & 0 \\ \beta_2 - \Delta_0 & \beta_3 - \Delta_0 & 0 & -\Delta_1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}.$$

where $\Delta_0 = -BK\alpha_1 A^{-1}$, $\Delta_1 = -BK\alpha_2 A^{-1}$and
$\alpha_1 = e^{A(h-\tau_t)} - 1$, $\alpha_2 = e^{Ah} - e^{A(h-\tau_t)}$

In order to know the positive influence of certain amount of delay on the stability of controlled NCS ,an analysis of the eigen values of the closed loop matrix ψ can give more insight in the encounter phenomenon. In order for the system to be stable, the absolute value of the eigen values λ_i of closed loop matrix ψ have to lie inside the complex unit, $\lambda_i < 1$. Over a network, a system is controlled by a proportional input feedback controller $u = -Kx$, where K is given by $[K_1, K_2]$. In the continuous-time domain with no delay, the closed loop system can only be stabilized if $K_1 > 0$ upto $K_1 > 0$ of the order of 10 and $K_2 > 0$ of the order of 10^3. In discrete time domain with delay, the closed loop system can only be stabilized if $0 < K_1 < 0.35$ and $K_2 > 0$ of the order of 10^2. the stability region is obtained by calculating the eigenvalues, characterizing combinations of K_1 and τ_t.

$$K \geq C_0 B^T A^{-1} \tag{3.17}$$

$$K \geq C_1 B^T A^{-1} \tag{3.18}$$

$$K \geq C_2 B^T A^{-1} \tag{3.19}$$

$$K \geq 0 \tag{3.20}$$

A two dimensional continuous-time plant dynamics are simple and has more physical meaning, the discrete-time NCS model which becomes more complex. Eigenvalue analysis however proved to be helpful to analyze the stability of system in this case. Control loop delay is well known for degrading the performance of a control system and affect its stability. Furthermore, an increase of the sample time results in reducing the performance and smaller stability regions. The region of K for which the system is stable increases with increasing delay up to a certain delay value where the stable region is the largest.

Chapter 4

Simulations and Results

4.1 simulations and Results

For the verification and validation purposes, the proposed center scheme is simulated using Simulink Tool Box of MATLAB for the said purposes.

4.2 Introduction

In the analysis and design of control system MATLAB has been adopted for its simplicity and comprehensiveness by researchers. We have used MATLAB for analysis and design of our system. All fundamental blocks of the system are written in MATLAB editor and taken in transfer function form. Results are taken step by step by running the MATLAB code.

4.3 Simulations

DC motor Model has been represented as a transfer function and a PI controller is designed again as a transfer function. Step response of the system investigates its performance, which has returned desired performance. The following figures shows the block diagram and step response of the closed loop system when network delays are not taken into account.

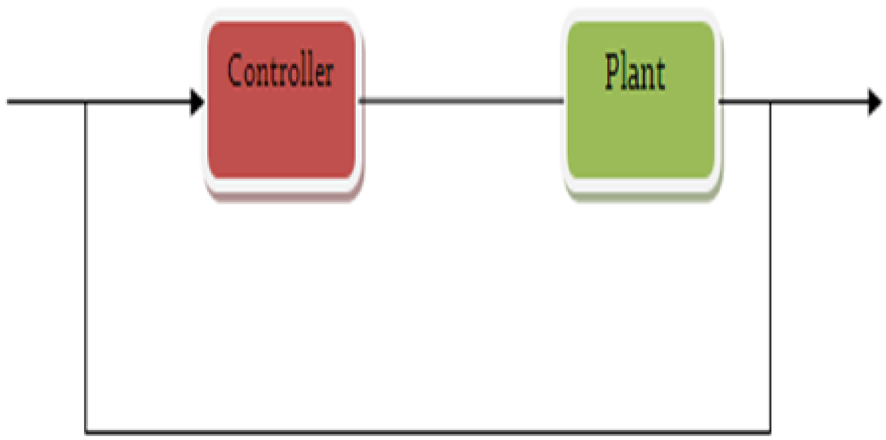

Figure 4.1: Block diagram of NCS without delays

4.4 Component based Motor Model:Open Loop System

A dynamic motor model was constructed using the mathematical representation of a DC motor. The open loop response is shown in figure 4.2. It can be observed that in response to step input, the motor speed does not even reach the final desired value.

4.5 PI Controller based Speed Control:

After observing the system performance for open loop configuration, the next logical step was to attempt a closed loop configuration; a PI controller based system was implemented. The system response is shown in Figure 4.3 The various parameters of PI controller are kp =40, ki = 50.

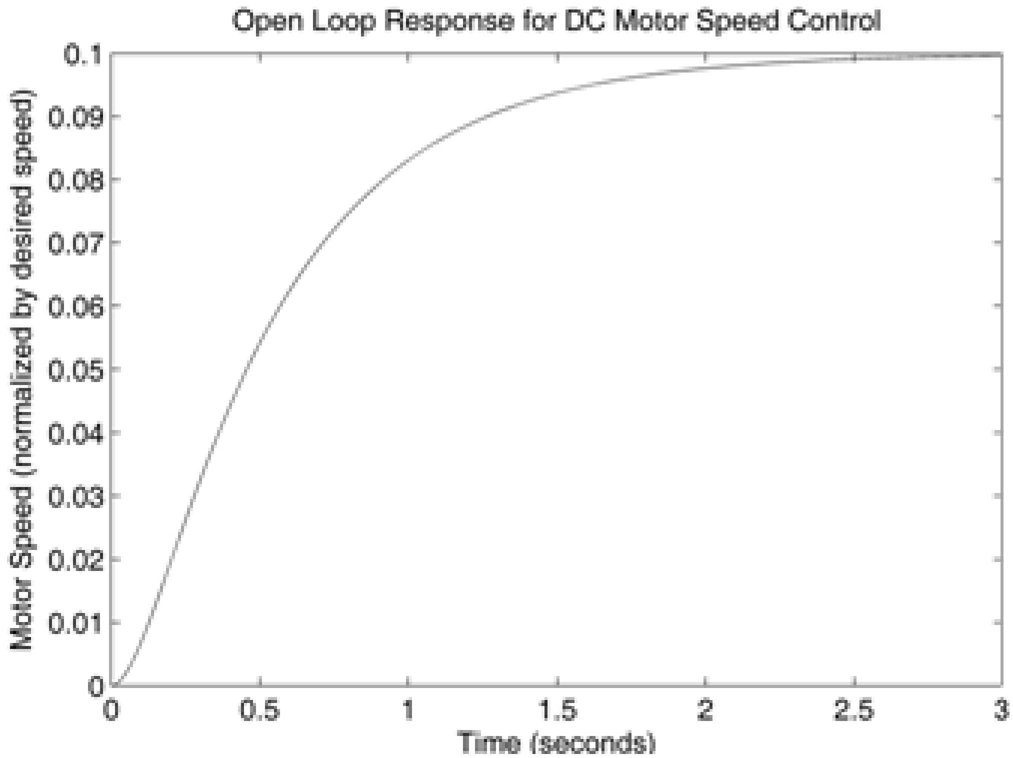

Figure 4.2: Open Loop Response of the System

4.6 PI Controller based Speed Control Sampled Data:

4.6.1 CASE-I (System Response without network delay):

So far, all the closed loop systems were in continuous time domain. However, for a network control system, the controller works in discrete-time domain. Therefore, simulations were modified to make it sampled data system. The plant is continuous time. Its output is converted from analog to digital by a zero-order hold device. The controller is discrete-time, whose output is converted from digital to analog by another zero-order hold device. The system response without network delay is shown in Figure 4.4, which is very close to Figure 4.3.

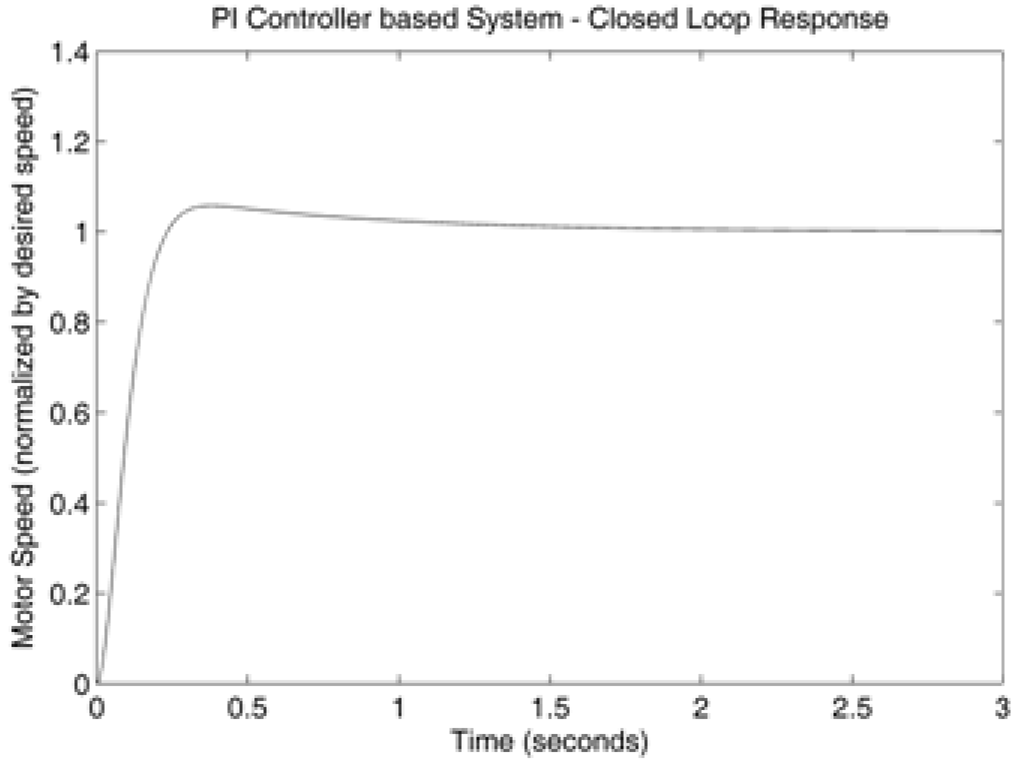

Figure 4.3: PI Controller based System - Closed Loop Response

4.6.2 CASE-II (System Response with network delay):

System performance is considerably deteriorated once a communication network is taken into account between controller and plant. In this work only network delays are considered for simplicity of analysis whereas all other network related issues are taken as ideal case. We have bounded delay to a maximum of 2500 sample time interval in our work because no system can be designed to cater for delays more than this limit. Insertion of delay in loop has modified the system block diagram which along with the behavior of system in the presence of one such delay can be seen as follows.

So far, all the closed loop systems were implemented without any network delay. However, network delays are inherent in NCS. The performance degradation is expected due to these delays. Therefore, simulations were modified to incorporate

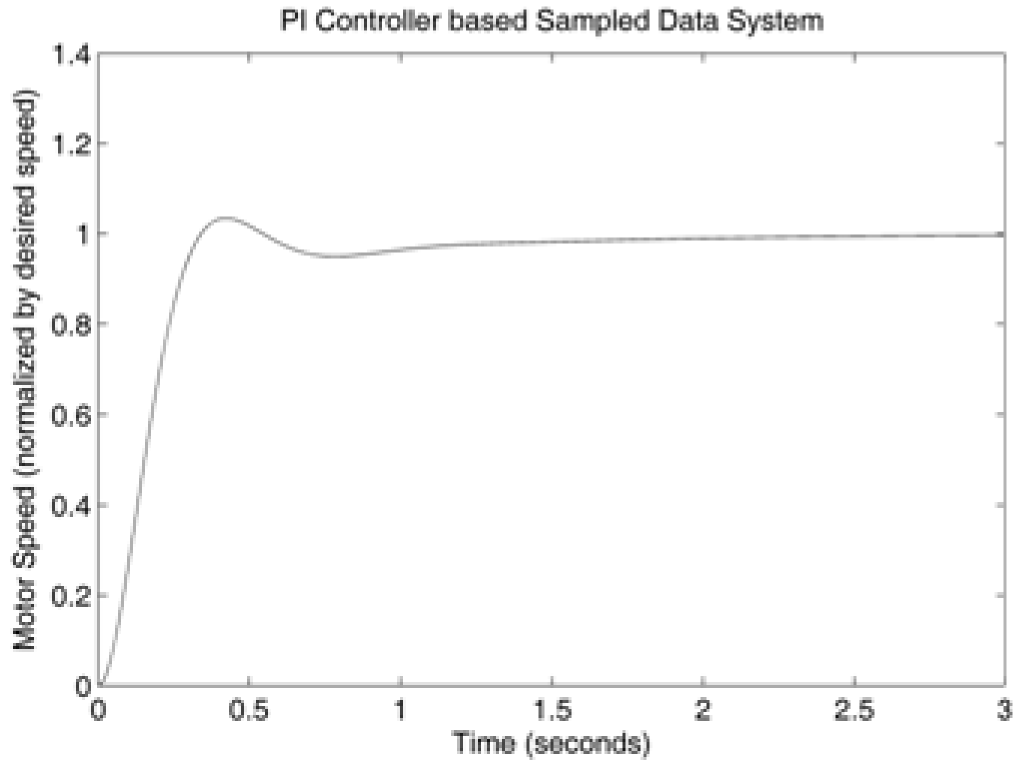

Figure 4.4: PI Controller based Sampled Data System- System Response

network delays. A fixed delay of 2500 sampling time units was included to mimic a network delay. The system response is shown in Figure 4. 6, which shows obvious degradation in performance.

4.7 PI controller combined with PD compensator for NCS:

We have observed in the previous subsection that system performance degraded in the presence of network delays. To recover the performance, we incorporate a PD compensator. The values of proportional and derivative gains were set at Kp = 0.3 and Kd = 100. The values were current obtained through empirically. However, in a full fledged NCS, the choice of Kp and Kd will be based on the value of estimated network delay. The system response is shown in Figure 4.7 , which shows significant

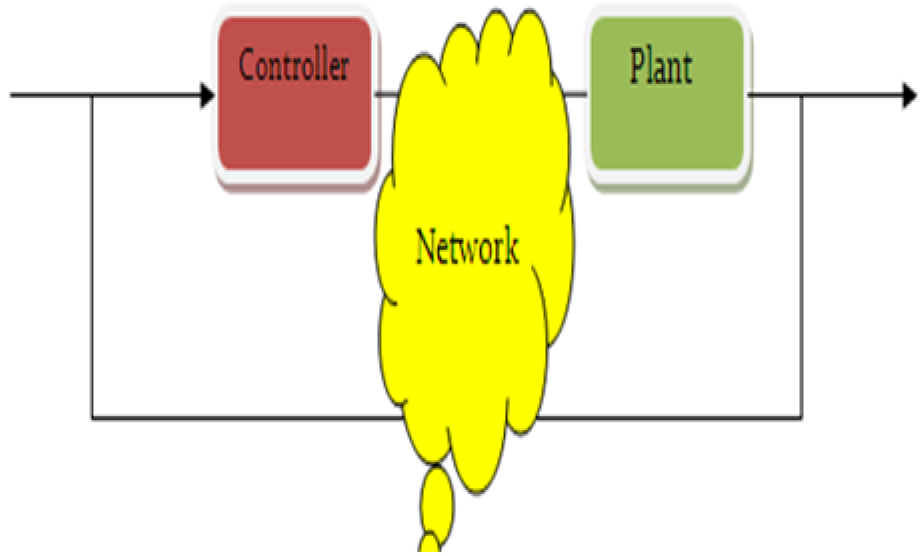

Figure 4.5: Block diagram of NCS System with Network Delays

recovery of performance.

A variable delay of sampling time units ranging from 1000 to 2500 was included to mimic a network delay. The system response is shown in Figure 4.6, which shows obvious degradation in performance. For variable network delay, the system response is shown in Figure 4.8 which is similar in performance as for fixed network delay.

4.8 NCS with delay Observer/Estimator

4.9 Discrete PI Controller:

It receives error signal input and processes it to generate a control signal using PI control philosophy. The input error signal is multiplied by proportional gain Kp. Simultaneously, the input error signal is integrated and multiplied by integrator gain Ki. The most appropriate values of these gains were established empirically. The outputs of both the gains are added together to generate the control signal which is output to Discrete PD Compensator.

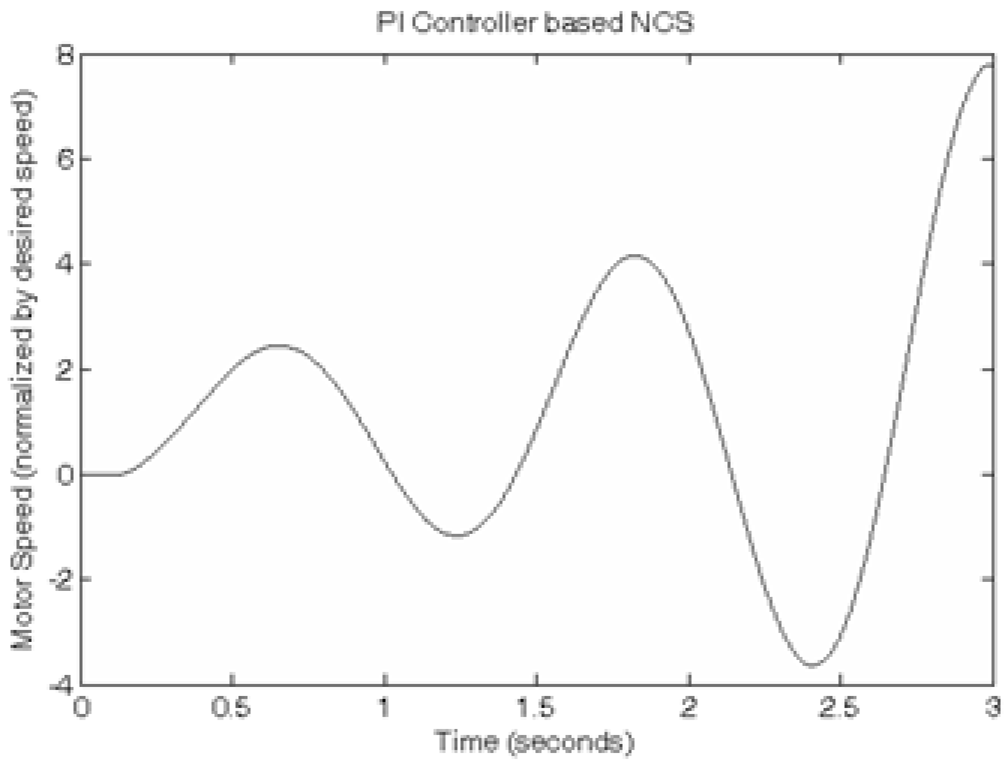

Figure 4.6: PI Controller based NCS - System Response

4.10 Discrete PD Compensator:

It works as an adaptive PD Compensator to compensate for network delays. It is called adaptive because the proportional and derivative gains are tuned at run time by a separate Gain Selector for PD Compensator . The PD Compensator receives control signal input from Discrete PI Controller and processes it to generate a compensator signal using PD control philosophy. The input control signal is multiplied by proportional gain obtained from Gain Selector for PD Compensator block. Simultaneously, the input control signal is differentiated and multiplied by derivative gain received from Gain Selector for PD Compensator block. The outputs of both the gains are added together to generate the compensator signal which is output to Network Packet Maker .

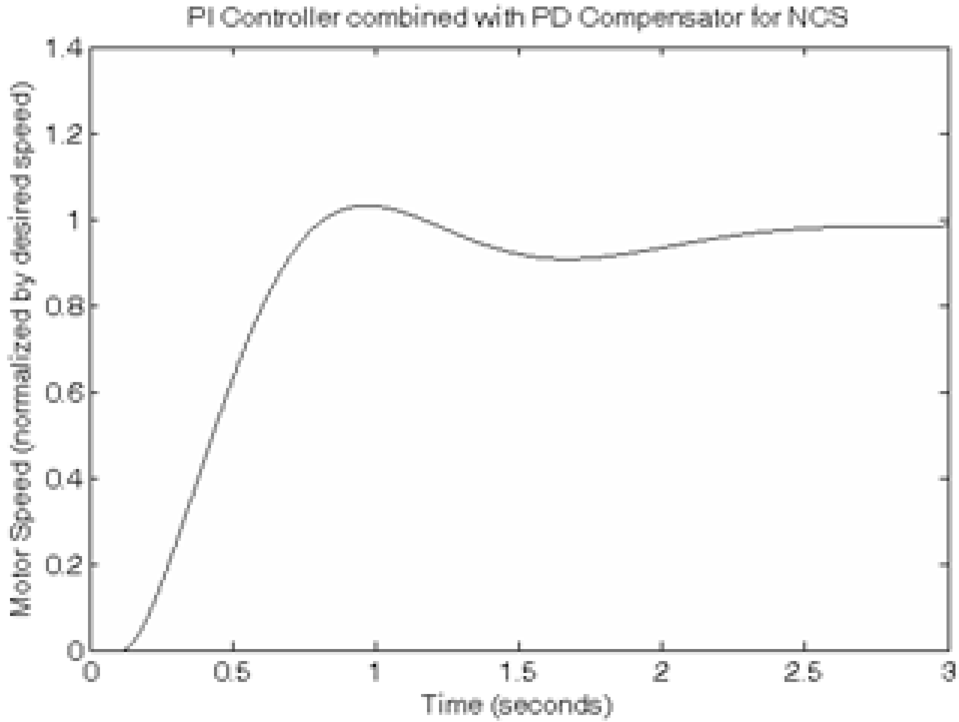

Figure 4.7: PI Controller combined with PD Compensator for Fixed Delay NCS System Response

4.11 Network Packet Maker:

It combines a) Packet number obtained from a packet counter, b) Packet originating time, c) Compensator signal. These three information bearing signals are combined into a single network packet and output to the network.

4.12 Delay Observer/Estimator:

Time delay observer play a key role when system have time varying delays .The work of time delay observer/estimator is to estimate the current delay of the system. The adaptation makes the PD compensator gains time varying so that the estimated network delay translate to appropriate values of proportional and derivative gains (Kp and Ki, respectively). The block diagram of delay observer based network control system for the speed control of DC motor is shown in figure 4.9

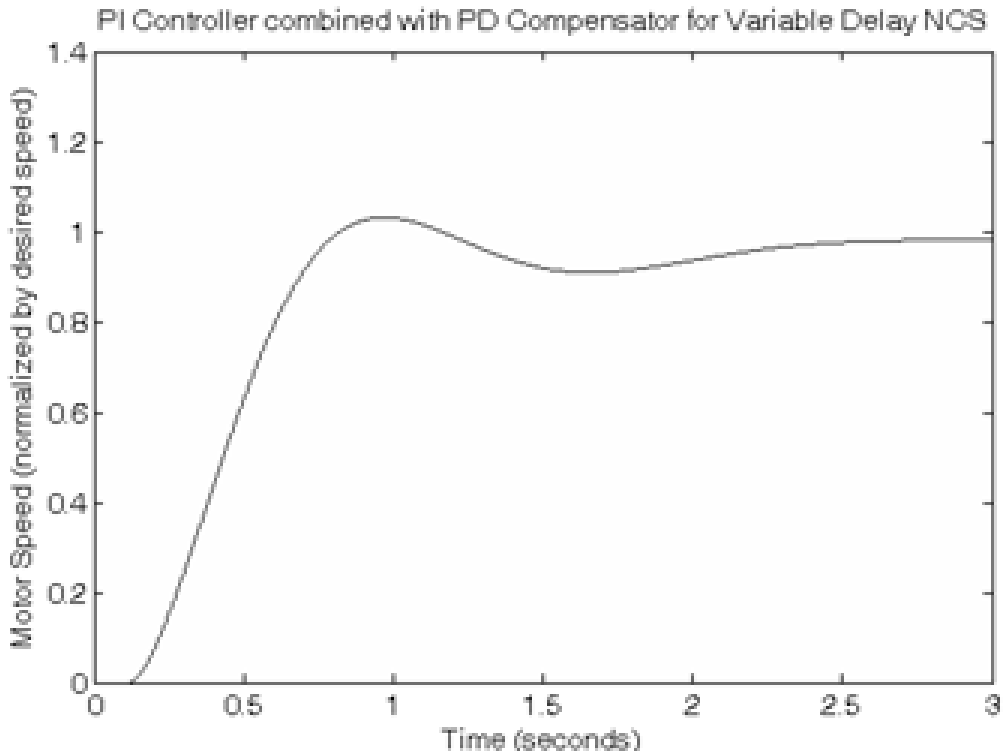

Figure 4.8: PI controller combined with PD compensator for variable delay NCS

The delay observer subtracts the network packet originating time from current simulation time to provide an estimate of the roundtrip time. The estimated roundtrip time depicts the forward and backward propagation delays being experienced in the network. The approach is simple yet powerful to provide a basis for choosing appropriate values of proportional gain Kp and derivative gain Kd, based on estimated roundtrip time.

4.13 Gain Selector for PD Compensator:

The gain selector block is fundamental to the implementation of adaptive Discrete PD Compensator block. The proportional gain Kp and derivative gain Kd are continuously tuned on the basis of current estimate of roundtrip network delay. It is emphasized that the mapping of estimated roundtrip network delay to the values of

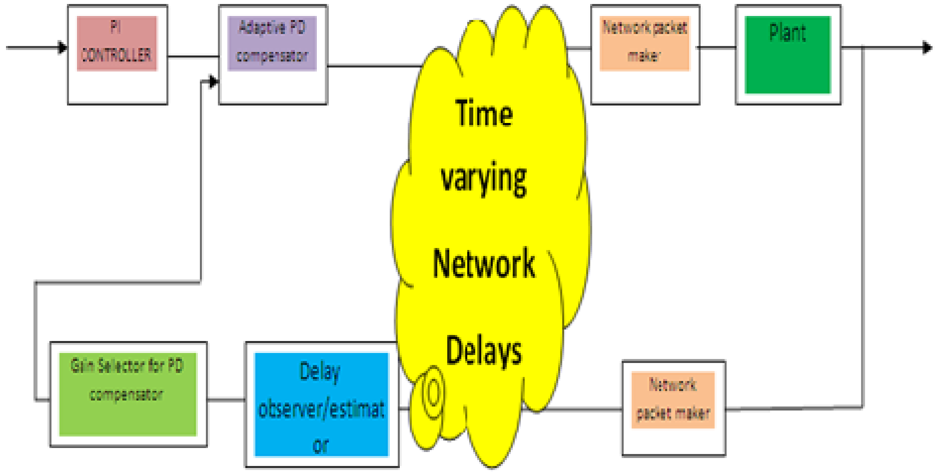

Figure 4.9: Block diagram of delayed observer based network control system for the speed control for DC motor

Kp and Kd is established empirically, as shown in the table given below. Further refinement of results is possible through in-depth, extensive experimentation.

Table 4.1: Estimated round trip network delay to the values of kp and kd

Round trip network delay(sec)	Proportional gain kp	Derivative gain kd
0 to 0.2	0.27	97
0.2 to 0.21	0.28	98
0.21 to 0.22	0.29	99
0.22 to 0.23	0.30	100
0.23 to 0.24	0.31	101
0.24 to 0.25	0.32	102

4.14 Conclusion

In this thesis, the idea of network control system has been demonstrated through computer simulations, for controlling the speed of a DC motor over a computer network. The network delays tend to disrupt the control action initiated by the controller. A proactive approach is to sense the network delay and work for its compensation, such

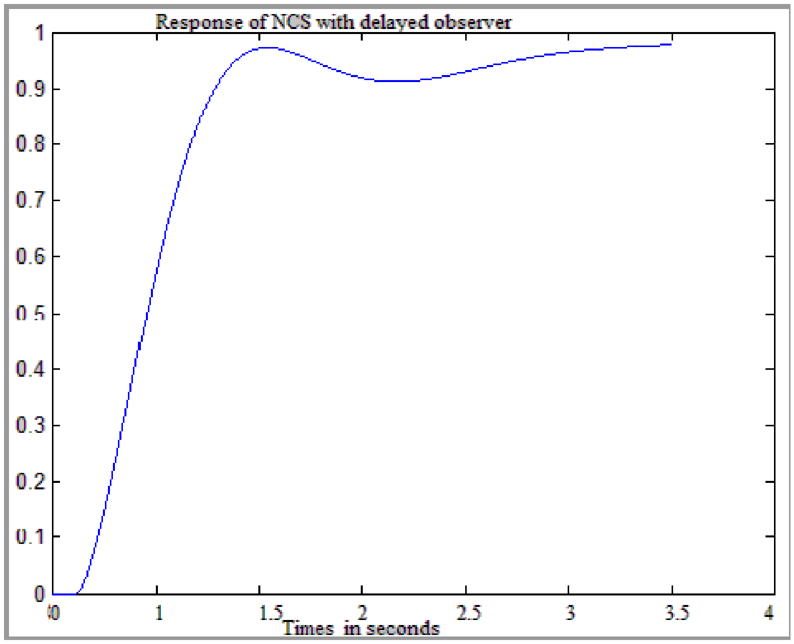

Figure 4.10: Delayed observer based closed loop response of NCS

that motor speed control specifications are met. The PI controller combined with a PD compensator satisfactorily achieves the design specifications. This is confirmed by the computer simulation results. A further extension is done which make the compensator adaptive. The adaptation makes the PD compensator gains time varying so that the estimated network delay translate to appropriate values of proportional and derivative gains (Kp and Ki, respectively).

Chapter 5

Conclusion

5.1 Conclusion

This thesis has presented a control problem that originates when control loops are closed over a communication network. Time delays are introduced by communication network in the control loop. These network induced time delays can have effect on system stability and performance.

The proposed strategy has shown satisfactory response as can be seen from the step response of the system with middleware and without middleware. Proposed strategy is computationally more efficient as it does not require any online estimation of the network traffic and scheduling of gain accordingly.

5.2 Introduction

No work is complete and accurate; there always is a room for improvement. We have proposed an idea and analyzed it by simulating in a MATLAB . The block diagram of the proposed system is shown in Figure 5.1. This work can be extended for further improvements.

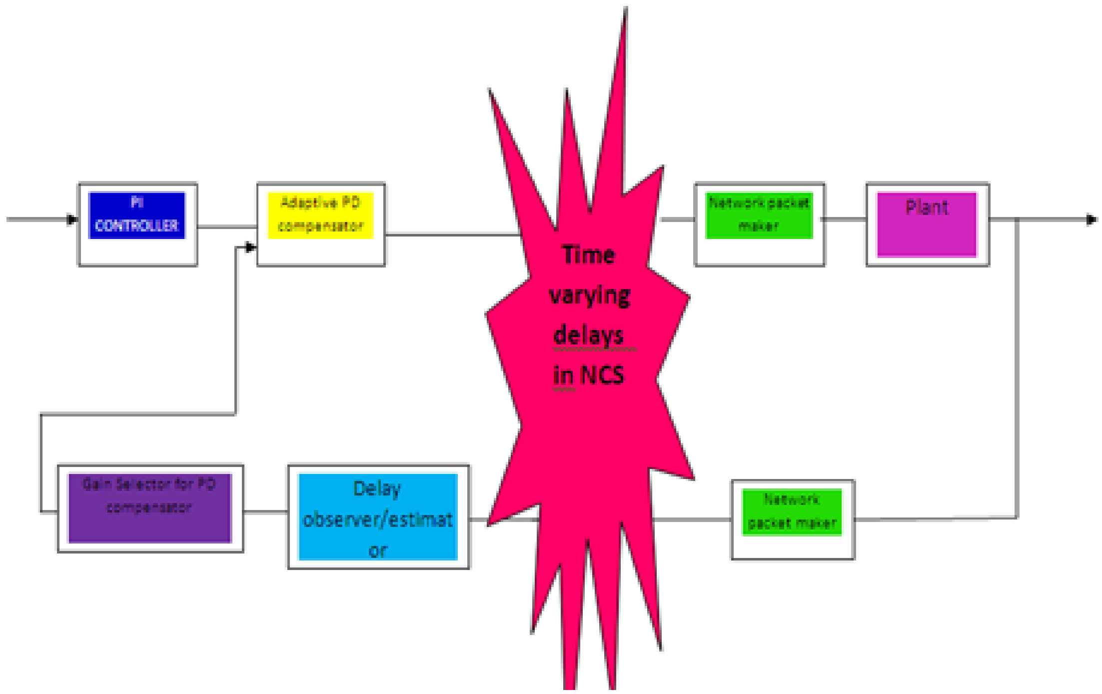

Figure 5.1: Block diagram of the proposed strategy

5.3 Results

Using the developed strategy in the thesis, distributed real-time control systems can be analyzed and controllers can be designed taking the network delays behavior into account. The results are nice abstraction of well known theory for sampled-data control. Engineers with background in sampled data control will identify the similarities with the case without delays.

The proposed strategy was simulated in MATLAB. First, plant behavior was simulated to get certain performance parameters and then a controller was applied. The desired response is obtained by closed loop system when connected directly. Performance of the system deteriorates, when we connect the controller through a network.

Network related issues are kept limited to delays only for the sake of simplicity while other issues are not taken into account. Proposed strategy is then applied to cater the network delays. The amount of delay varies from time to time to depict time varying nature of delays encountered in computer networks. The delay varies from 20 sampling times to 2500 sampling times, various step functions are used to switch from one delay to the other. The resulted system is stable and fulfills steady state error and overshoot criteria however the response of the overall system is slow.

5.4 Problems

Various interesting problems in the area of real-time control systems are still to be solved. Some of the problems not handled in this thesis are:

Throughout this thesis, we have assumed that the delay variation is less than a sampling interval. How can controllers be designed if the delay variations can be longer than a sampling interval?

One stimulus for keeping the network delay less than a sampling interval is that if we have a field bus, only one message can be on the network at each time.

If we have a larger delay than a sampling interval a measurement signal would be waiting for the sending of delayed signal. In this case maybe we should send measurement signal instead of delayed, and consider delayed signal as a vacant sample. However, in other network types we can think of messages reaching at destination in another order than the order of sending.

Control and Communication integrated design appears very interesting and offers very efficient solution to various problems. It is a difficult task to design such a system however as it needs deep intuition and proven knowledge in both fields. While restricting our work to control related performance criteria we have not gone into designing of NCS and network issues due to limited knowledge of the field.

5.5 Future Research

This work is assumed to investigate the applicability of the proposed strategy only. We have analyzed the proposed strategy for a very particular case and assumptions to see if the proposed strategy can result in a system which is stable and fulfills steady state and transient criteria. Most of the network related issues are not taken into account except for the delays in the loop. Details in the designing of NCS are also left and network delay is assumed. This work may be taken as first investigating step and can be continued in future to:

- By taking into account a more accurate and real network delay model.
- By taking other network related issues e.g. multiple packet transmission.
- By designing network control system taking into account its various parameters.
- By designing a system to cater for longer delays.
- By Implementing the system practically.

5.6 References

[1] P. Marti, M. Velasco, C. Lozoya, J.M. Fuertes, Clock Synchronization for Networked Control Systems Using Low-Cost Microcontrollers, Report: ESAII-RR-08-02, 2008.

[2] M. Schmidt, K. Schilling, Data combination mechanism in highly dis-tributed ground station networks, International Astronautical Congress, 2010.

[3] M. Nicolaos, N. Freris; S. Graham, P. Kumar, Fundamental limits on synchronizing clocks over networks,IEEE Transactions on Automatic Control, 2011

[4] N.M. Freris, H. Kowshik, P.R. Kumar, Fundamentals of Large Sensor Networks: Connectivity, Capacity, Clocks, and Computation, Pro-ceedings of the IEEE, vol.98, no.11, pp.1828-1846, 2010

[5] H.J. Choi, S. Jung, Neural network-based Smith predictor design for the time-delay in a tele-operated control system, Artificial Life and Robotics, Springer, 2009

[6] S.S. Hu, Q.X. Zhu, Stochastic optimal control and analysis of stability of networked control systems with long delay, Automatica, No. 39, pp. 1877-1884, 2003

[7] Y. Yang, Y. Wang, S.H. Yang, Design of a networked control system with random transmission delay and uncertain process parameters, International Journal of Systems Science, Vol. 39, No. 11, pp. 1065-1074, 2008.

[8] S.H. Yang, X. Chen, L.S. Tan, L. Yang, Time delay and data loss compensation for Internet-based process control systems, Transactions of the Institute of Measurement and Control, Vol. 27, pp. 103-118, 2005.

[9] O. Stefan, T. L. Dragomir, A. Codrean, I. Silea, Issues of Identifying, Estimating and Using Delay Times in Telecontrol Systems.

[10] Y. Tipsuwan and M.-Y. Chow, Control methodologies in networked control systems,Control Eng. Practice, vol. 11, no. 10, pp. 10991111,2003. Based on TCP/IP

Networks, IFAC-PapersOnLine http://www.ifac-papersonline.net/Detailed/45039.html, 2nd IFAC Symposium on Telematics Applications (2010),Timisoara, Romania, 2010.

[11] M.-Y. Chow and Y. Tipsuwan,Gain adaptation of networked DC motor controllers based on QoS variations,IEEE Trans. Ind. Electron., vol. 50, pp. 936943, Oct. 2003

[12] R. Luck and A. Ray, An observer-based compensator for distributed delays,Automatica, vol. 26, no. 5, pp. 903908, 1990.

[13] H. Chan and. zgner,Closed-loop control of systems over a com-munication network with queues,Int. J. Control, vol. 62, no. 3, pp.493510, 1995.

[14] G. C. Walsh, H. Ye, and L. G. Bushnell, Stability analysis of net-worked control systems,IEEE Trans. Contr. Syst. Technol., vol. 10, pp. 438446, May 2002

[15] J. Nilsson, B. Bernhardsson, and B. Wittenmark, Stochastic analysis and control of real-time systems with random time delays,Automatica, vol. 34, no. 1, pp. 5764, 1998.

[16] S. H. Hong,Scheduling algorithm of data sampling times in the inte-grated communication and control systems,IEEE Trans. Contr. Syst.Technol., vol. 3, pp. 225230, June 1995

[17] Y. Tipsuwan and M.-Y. Chow, Gain scheduler middleware: A method-ology to enable existing controllers for networked control and teleop-eration: PART I: Networked control, IEEE Transactions on Indust Electronics, Vol. 51, No. 6, 2004.

[18] P. Antsaklis and J. Baillieul, Special issue on networked control systems, IEEE Transactions on Automatic Control, vol. 49, no. 9, 2004.

[19] NILSSON,JH1996I: Analysis and design of real-time systems with random delays. Report ISRN LUTFD2/TFRT- -3215- -SE. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden.

[20] Nilsson, J.B.Bernhardsson, and B. Wittenmark h1997I: Some topics in real-time control. Submitted for conference publication

[21] Wittenmark, B.J.Nilsson, and M. Trngrenh1995I: Timing problems in real-time control systems. In Proceedings of the 1995 American Control Conference, Seattle, Washington.

[22] Handbook of Networkedand Embedded Control Systems Dimitrios Hristu-Varsakelis William S. Levine Editors Editorial Board Rajeev Alur, Karl-Erik Arz en, John Baillieul Tom Henzinger