DESIGN AND DEVELOPMENT OF AN EFFICIENT MIDDLEWARE FOR NETWORKED CONTROL SYSTEMS

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THESIS

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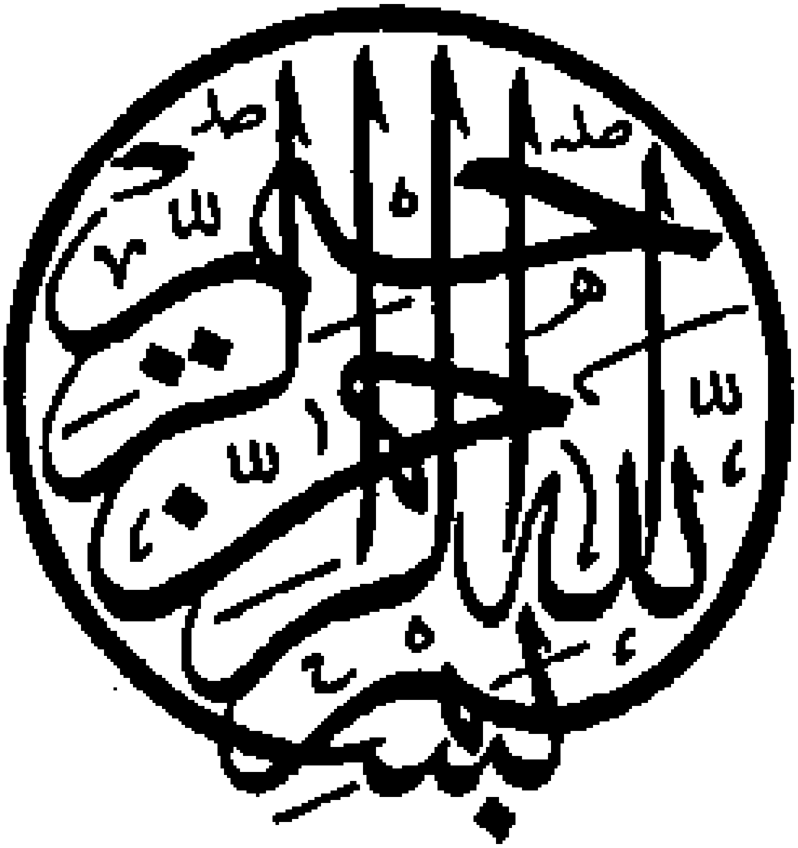
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Title of Thesis:

Design and Development of an Efficient Middleware for Networked Control System

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Dedicated to the love that Allah, His Prophet, my family and humanity at large share with each other.

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Praise be to Allah Almighty who led me to this phase of my learning. He has taught man which he did not know. It’s been His mercy and grace that I am able to complete this task.

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Last but not the least, my father’s patience and motivation, my mother’s prayers and my brothers’ belief in me have made me complete this thesis eventually and all my successes have been possible only because of their love, prayers and self-belief in me.

ABSTRACT

Feedback control systems are ubiquitous in both natural and engineered systems. Recent advancements in communication technologies have enabled control systems to transmit and receive control data over networks thus making systems more sophisticated and maneuverable. Control systems wherein the control loop is closed through real time networks are termed as Networked Control Systems (NCS).

Insertion of communication medium makes design and analysis of such systems complex. Communication networks induce random delays in the loop which deteriorate the performance of system and even destabilize the system in some cases.

In order to cater for the delay problem in NCS, we have proposed a design of a middleware device which will enable existing control technique to work in Networked environment. A simple DC motor control example has been considered for which a simple PI controller is designed to get desired performance. Once system is connected through network, delays deteriorate the performance of the system. Playback buffers have been used in typical multimedia application over internet to reduce variability in network delay and jitter. We have used the same concept of buffers in networked control system to eliminate randomness in the delay. Buffer is followed by a gain which is used to restore the performance of the system. This gain is found by first finding the maximum possible value of gain for which the system remains stable. Then a cost function is defined to find the best suitable value of gain.

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.

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LIST OF ABBREVIATIONS

NCS	Networked Control System
CAN	Controller Area Network
MATI	Maximum Allowable Transfer Interval
TOD	Try Once Discard
MEF	Maximum Error First
SMC	Sliding Mode Control
LAN	Local Area Network
RTT	Round Trip Time
MPC	Model Predictive Control
PI	Proportional Integral
PID	Proportional Integral Derivative
IAE	Integrated Absolute Error
MSE	Mean Squared Error

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Recent progress in communication, control and computation techniques has enabled the communication networks to offer sophisticated implementation of control systems. These control systems use communication networks to send and receive control data among sensors, actuators, controllers and plants. Ethernet, CAN, Profibus, Fieldbus, ATM and Internet are examples of such networks which transmit signals in a control system to make Networked Control Systems.

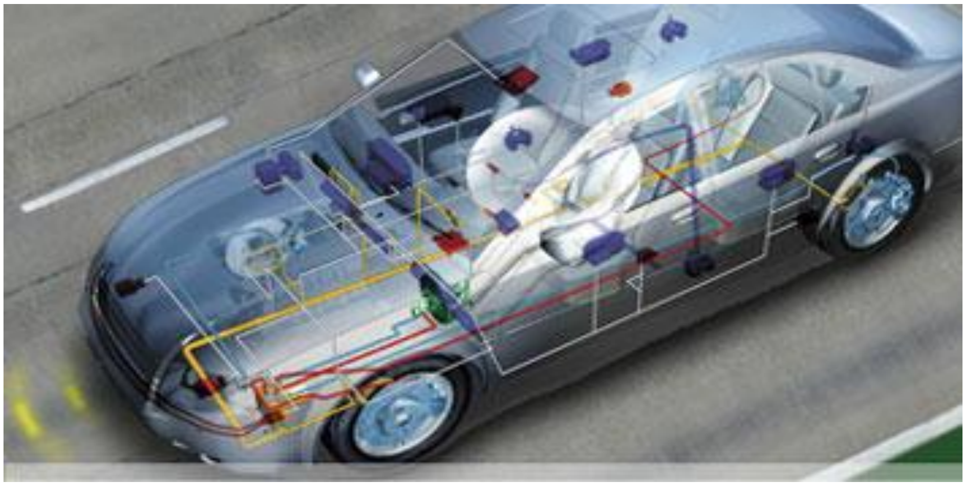

Figure 0-1 Control Network in Automobiles (Courtesy Robert Bosch GmBH)

Feedback Control Systems wherein the control loops are closed through real-time networks are called *Networked Control Systems (NCS)* or a *Networked Based Control System* [1].

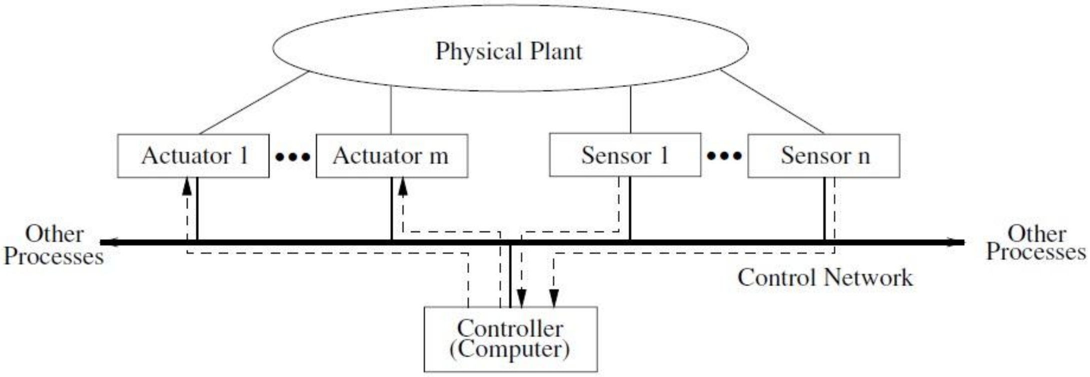

Figure 0-2 Typical Networked Control System [1]

In Networked Control systems, closed loop consists of actuators, sensors, plant and controllers where sensors and actuators have some computational power as well. Sensor nodes are used for measuring plant outputs and transmit these values to the controller through the network whereas actuator nodes are mainly responsible for receiving the control command from the controller through the network and apply these commands to the plant. Controller nodes have the task of computing control command from the plant outputs received from the sensors through the network and transmitting the control command to the actuator to be applied on the plant.

1.2 ADVANTAGES OF NCS

They have several benefits comparing with traditional point-to-point wired feedback control systems. Unlike traditional control systems with clumsy network of wires, which make them impractical, Networked Control Systems save space and offer easy maintenance and installation for complex systems. Modern communication technology can provide flexible and cost effective installation, maintenance, manipulation and expansion of Networked Control Systems. Application based on NCS can be easily maneuvered compared with application with wired connections; this makes NCS more acceptable in manufacturing factories. Moreover, only NCS has enabled us to operate and control systems remotely i.e. teleoperation.

1.3 APPLICATIONS

Due to these advantages, NCS have become widely used in factory automation, aircrafts, vehicles, robots, telesurgery and mobile teleoperation in space and hazardous places. The areas of application of NCS can be categorized in three groups: Complex systems, Remote Controlled systems and Large Scattered systems [2]. Complex systems are large scale systems which are formed by integration of several small scale systems. In such systems direct wiring will make the connections troublesome. Examples of complex systems are vehicles, robots and aircrafts. Remote controlled systems are particularly employed in places where moving can be inconvenient or hazardous e.g. Space, Nuclear & Chemical plants, offshore wind turbines or war zone. Remote controlled systems are finding its applications in distance learning laboratories as well. Systems where components are scattered in a wide area, are also difficult to be connected by direct wiring. Examples include manufacturing plants, chemical plants and aircrafts. Figure 1.3 is an example of networked process control system.

1.4 FUNDAMENTAL ISSUES

It is said that “there is no such thing as a free lunch”. Insertion of communication network in a control loop makes the analysis and design complex. In a traditional point to point control system information is instantaneously delivered from sensors to the controller and from the controller to the actuators whereas in a Networked Control System regardless of the network type several side effects will be introduced in the control loop. The following factors have been pointed out by various researchers affecting the performance of NCS:

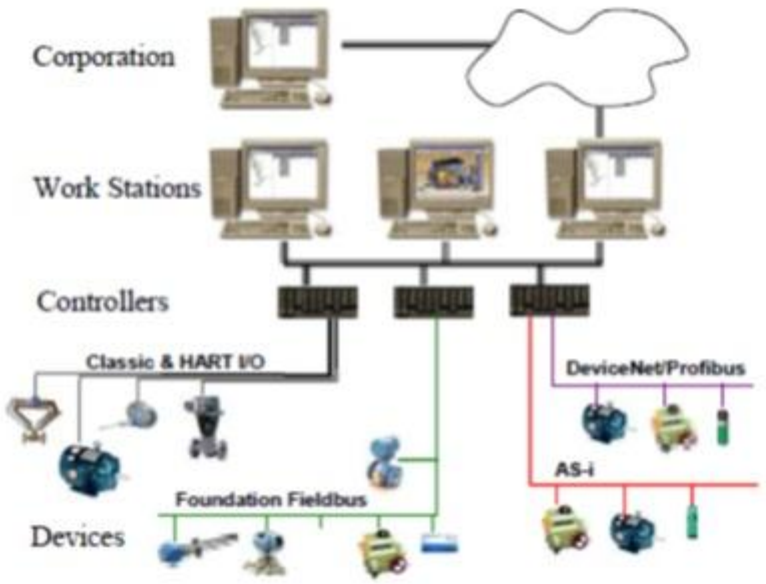

Figure 0-3 Example of Networked Process Control System

- Network induced time delay in the loop
- Packet drop outs and data loss in the network
- Multiple packet transmission
- Sampling rate constraints
- Network capacity for communication
- Disturbance introduced in the medium

Due to the limited communication bandwidth time delays are inevitable during information transmission which makes the conventional controller design ineffective. These delays are generally varying and in most cases stochastic in nature depending on the scheduling policy and network protocol. There are essentially three kinds of delay in a Networked control loop: Delay between sensor and controller nodes τ^{sc}, Computation delay in controller node τ^{c} and Transmission delay between controller and actuator nodes τ^{ca}. Sensor and Actuator nodes also have some computation delay expressed as τ^{s} and τ^{a} but these are constant and can be included in τ^{sc} and τ^{ca} respectively. These delays can be lumped together as total network induced delay $\tau = \tau^{sc} + \tau^{c} + \tau^{ca}$.

A network can be seen as a web of unreliable transmission paths, some packets may be lost in addition to the packets suffering from delay. Packet drop-out occurs when there is a node failure or message collision. Normally, in such cases, network retries to send the packets but they can retransmit within a limited time. Once this time has expired the packet is discarded. Most of the control systems tolerate a certain amount of data loss but beyond this limit system can become unstable.

Another important issue in networked control system is multiple packet transmission. In single packet transmission sensor or actuator data is lumped together in a single packet but this is practically not possible in most of the systems due to packet size constraints and distributed nature of sensors and actuators in a large systems. In these cases, data to be transmitted is broken into multiple packets and then transmitted over the communication medium. Due to network delay, all packets may not be received at the time of computation or may not receive few of the packets at all. This will lead to bad performance of NCS.

1.5 CURRENT RESEARCH AND FUTURE

Due to the flexibilities and advantages offered by Networked Control Systems, they have become ubiquitous. Wide applications of NCS are fueling high level of research in the area of Networked Control Systems analysis and design. “Panel on Future Directions of Control, Dynamics and Systems” has also recommended for increased research in aimed at the integration of Control, Computer Science & Communications viz. Networked Control Systems [3]. They have presented 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 summarizes current state of the art research in the area of NCS in. The papers presented are organized in three sections: First, Current State of Technology of NCS which discusses applications of NCS in Industrial Control, Large Irrigation Networks and UAVs. Next section

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

1.6 ORGANIZATION OF THE THESIS

The work presented in this thesis is divided into five chapters. Organization of the thesis and brief introduction of each chapter is as follows:

Chapter 1 – This chapter introduces the concept of Networked Control Systems, their advantages and issues that arise in these.

Chapter 2 – This chapter provides different techniques used to design NCS and brief review of the prominent work done by researchers.

Chapter 3 – This chapter is based on design issues, mathematical formulation of the problem and the proposed strategy.

Chapter 4 – This chapter presents the simulation results of the proposed technique for a DC motor speed control problem.

Chapter 5 – This chapter contains a discussion on results obtained and possible future work.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

It is said that “there is no such thing as free lunch”, everything comfort comes with a price. Similarly, due to insertion of communication medium, regardless of its type, control encounters a lot of problems e.g. delay, packet loss etc. Several researchers have addressed nature of these problems and their possible solutions. This chapter summarizes some important results concerning stability of networked controlled systems.

A Networked Control Systems utilizes a data network to receive plant information from sensors and send control data to actuators. Networks always have constraints and do not always transfer data reliably. Common major problems encountered, as discussed in section 1.4 are networked induced delays, data loss and synchronization problem in multiple packet transmission to name a few. These constraints 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:

- Designing of a good communication medium that can cope with the network constraints
- Designing of intelligent control methodologies that can tolerate these constraints

Several researchers have produced valuable results in both directions. In designing control methodologies robust to network constraints, again two directions can be followed.

- Design of controllers which can cater for network related issues and replace them with existing controllers.
- As replacement of existing controllers is a costly and inconvenient job in some cases, middleware can be designed that will enable existing controllers to handle the network related issues.

The next sections presents review of some previous work done in the field of networked control system.

2.2 REVIEW OF PREVIOUS WORK

The augmented state model is a significant method for analyzing and designing an NCS. Halevi and Ray [24] considered a continuous time plant and discrete time controller over a periodic delay network. They studied a clock driven controller with mis-synchronization between the plant and the controller. They augmented 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.

Nilsson [5] also analyzed NCS 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.

Walsh et al. [6] considered a continuous plant and a continuous controller. They introduced the notion of MATI (Maximum Allowable Transfer Interval) i.e. the interval between two successive messages to ensure absolute stability. They also introduces in the form of the TOD protocol, the concept of dynamically allocating network resources to those information sources with critical information. In TOD, the node with greatest weighted error from the last reported value wins the competition for network access; this scheduling technique is called Maximum Error First (MEF).

Zhang et al. [1] analyzed fundamental issues of network induced delay, packet dropout and multiple packet transmission in Networked Control Systems. They characterized the relation between sampling rate and network delay and discussed the stability of NCS using hybrid system stability analysis and using time domain solution. 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] proposed a new estimator, which along with actuator, was both event and time driven. In the proposed scheme, the current control signals in every sampling interval were received and delay was compensated.

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

Zhang and Hritsu-Varsakelis [9] designed a communication sequence to access the communication medium. They ignored the actuators and sensors that are not actively communicating with the plant and controller which significantly decreases the complexity of the joint controller/ communication design. An output feedback controller consisting of state observer followed by time varying feedback can be designed for such a communication sequence that exponentially stabilizes the NCS.

Onat and Parlakay [10] implemented the previously proposed idea of Model Based Predictive Network Control System on a non-real-time communication network; Ethernet. Real-Time Linux is used to guarantee real-time performance of the computer nodes.

In [11], authors focused on the use of play-back buffers to eliminate the variability in the loop delay in a Networked Control System. They explored the design issues for a smith predictor with a play-back buffer controlling a first order linear plant with loop delays given by both bounded interval and heavy tailed distribution. An analytical approximation method for finding optimal play back delay was presented.

As existing controllers has to be replaced in order to control a system over a data network, which is often costly and inconvenient, Tipsuwan and Chow [12], [13] introduced a methodology to enable existing controllers for networked control and teleoperation by use of a middleware. This middleware modifies the output of the controller with respect to the current network traffic conditions. Controller output modification is performed based on a gain scheduling algorithm. They presented 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.

Fei et al. [14] found that modeling the round trip time (RTT) in a network by a single statistical model is not adequate. Therefore two combined statistical distributions, Pareto distribution and generalized exponential distribution, are used to develop their model. An initial study of gain-scheduling controller design for NCS using the developed delay statistical model to adjust controller gain to compensate time delay is presented in their work.

2.3 CONCLUSION

Ample research papers have presented comprehensive survey and results on the stability and techniques on Networked Control Systems. Ge, Tian and Liu [15] summarized fundamental issues related to NCS and then related handling approaches and techniques. The most recent, Li and Wang [16] also summarized some recent developments relating to the issues in NCS and also discuss some problems. They divided the techniques into two implicitly interlaced approaches: (1) Control oriented communication design in NCS and (2) Controller design in NCS with regard to communication constraints. [17] and [18] also summarize issues and results on NCS. Most remarkable work in summarizing control methodologies in NCS has been done by Tipsuwan and

Chow [19] where they have categorized techniques according to the strategies applied.

Recently there have been great emphasize on use of multidisciplinary strategies to the design of networked control systems. In this regard Kiminao Kogiso of Systems and Control Lab, Nara Institute of Science & Technology have remarked use of reference governors in networked control systems whereas Alldredge, Branicky and Liberatore [11] proposed use of playback buffers in the design of NCS.

CHAPTER 3

SYSTEM DESCRIPTION

3.1 INTRODUCTION

Networked Control Systems will become ubiquitous in near future. They have various areas of application. Motor control has always remained an area of special consideration for researchers due to its simplicity in analysis and design and its variety of applications ranging from household to heavy industry.

3.2 SYSTEM DESCRIPTION

The dynamics of a linear system can be described by the generalized equations:

$$\dot{x} = f(x, u, px) \tag{3-1}$$

$$y = g(x, u, px) \tag{3-2}$$

Where

x are states

y is output

u is the input

px are the system parameters

A simple output feedback controller may be described generally as

$$u = h(y, \gamma pu) \qquad \text{3-3}$$

pu are controller parameter

γ is the gain which is used to change the parameters of controller

When the system is connected via communication network the performance of the system is affected by the network conditions. Let variable q defines the network condition, then in presence of network the system is defined as

$$\dot{x} = f(x, u, px, q) \qquad \text{3-4}$$

$$y = g(x, u, px) \qquad \text{3-5}$$

The existing control is no longer applicable to this system. One way to cater for network delays is to change the parameters of the controller internally by changing the internal gain values to satisfy the performance required i.e. designing a new controller.

Recent research [14] has shown that an external gain factor can always be extracted in almost all types of controllers, varying which directly influence the internal parameters of the controller. Hence we can describe our controller as

$$u = \beta h(y, pu) \qquad \text{3-6}$$

β is the external gain which can be used to vary the internal parameters of the controller.

It is observed that γ and β are linearly dependent satisfying the relationship

$$u = \beta h(y, pu) \cong h(y, \gamma pu) \qquad \text{3-7}$$

Hence we have control over controller parameters by simply adjusting the gain externally and without altering the internal structure of the controller itself.

Let G_P represents the transfer function of a second order linear system. A simple PI controller is designed to get the desired performance and let G_e be the transfer function of the controller such that,

$$G_P = \frac{k}{(T_1 s+1)(T_2 s+1)} \tag{3-8}$$

$$G_e = K_P + \frac{K_I}{s} \tag{3-9}$$

Where K_P and K_I are the proportional and integral gains respectively.

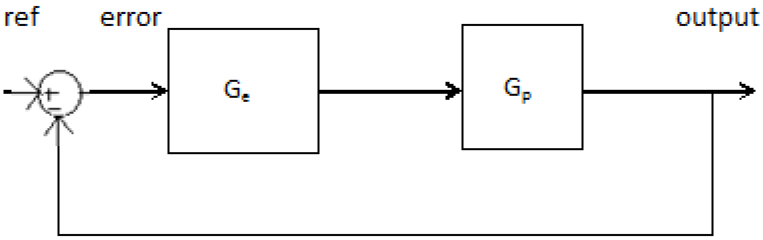

Figure 3-1 Closed Loop System in Normal Configuration

The closed loop transfer function can be described as:

$$G_s = \frac{G_P G_e}{1+G_P G_e} \tag{3-10}$$

Now controller and plant are connected through a network. Let τ_{CPD} and τ_{PCD} are the delays, which will be discussed further in the next section, from controller to plant and from plant to controller respectively and T be the combined delay or RTT then the plant may be described as:

$$G_P = \frac{k}{(T_1 s + 1)(T_2 s + 1)} e^{-Ts} \qquad \text{3-11}$$

Due to the network delays the existing control does not remain valid for the system and a new controller is designed to get the performance in this case. Let G_m be the transfer function of the modified controller.

$$G_m = K_P' + \frac{K_I'}{s} \qquad \text{3-12}$$

As we have said that an external gain factor can always be extracted from a controller varying which alters the internal structure of the controller. Let β be the external gain factor for this system such that

$$G_m = \beta * G_e \qquad \text{3-13}$$

$$G_m = \beta * \left(K_P + \frac{K_I}{s} \right) \qquad \text{3-14}$$

$$G_m = \beta * \left(\frac{K_P s + K_I}{s} \right) \qquad \text{3-15}$$

$$G_m = \beta * K_P \left(\frac{s + \frac{K_I}{K_P}}{s} \right) \qquad \text{3-16}$$

Comparing equations 3-11 and 3-12 returns $K_P' = \beta * K_P$ and $K_I' = \beta * K_I$. From equation 3-16 we see that analytically β adjusts both K_P and K_I while maintaining the ratio between the two.

Hence, in place of designing a whole new controller we can simply find a suitable gain factor which controls the performance of the system by enabling the existing control strategy. Now it is important to find the range of stable values of β.

3.3 NETWORK DELAYS

Insertion of network in control loop incurs delays that are random and unpredictable in nature. In the given work network is modeled as pure delay not taking other issues like multiple packet transmission etc. into account.

Block diagram of the system with network delays is as depicted in the figure below.

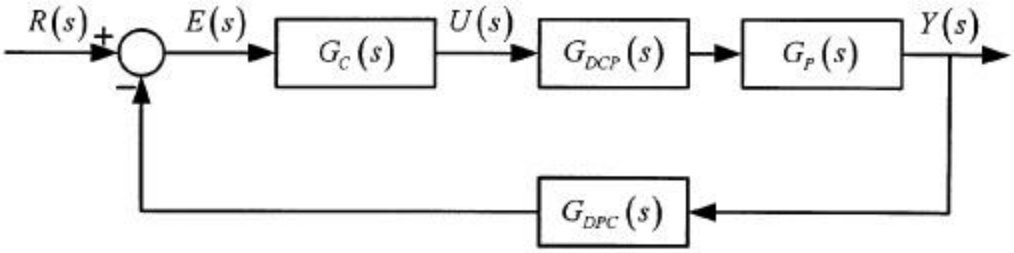

Figure 3-2 Block Diagram of the System with Network Delays [12]

Where $G_{DCP}(s)$ and $G_{DPC}(s)$ represents controller to plant and plant to controller delays transfer functions respectively.

Delay models $G_{DCP}(s)$ and $G_{DPC}(s)$ can be written analytically as

$$G_{DCP} = e^{-\tau_{CPD} s} \tag{3-17}$$

$$G_{DPC} = e^{-\tau_{PCD} s} \tag{3-18}$$

Where τ_{CPD} and τ_{PCD} are the delays from controller to plant and from plant to controller respectively. These delays are approximated using the following typical formulation:

$$G_D = e^{-\tau s} \cong \left(1 + \left(\frac{\tau s}{n}\right)\right)^{-n} \qquad 3\text{-}19$$

Where τ is the combined delay or RTT, which is sum of τ_{CPD} and τ_{PCD} in case of an event driven controller.

Network delays can take on any value from fractions of milliseconds to several minutes. Statistical measure of the RTT delays calculated from Advanced Diagnosis, Automation and Control (ADAC) Lab at North Carolina State University (NCSU) to various destinations are summarized in the following table [12]:

Table 3-1 Statistical Measure of RTT Delays in Seconds

Destination	Min Time	Max Time	Mean	Median
www.lib.ncsu.edu	0.000435	0.0862	0.000580	0.000471
www.visitnc.com	0.0166	0.7562	0.0326	0.0232
www.utexas.edu	0.0622	0.1187	0.0629	0.0627
www.ku.ac.th	0.0045	227.7095	0.3730	0.3150

The network delays can be modeled by various delay distributions. Tipsuwan et al modeled network delays using Poisson distribution whereas Fei et al used two different models Pareto distribution and Exponential distribution to model the network delays. Alldredge et al used beta distribution to model the network delays because of their simplicity and the fact that most of the delays in any network are close to the minimum delay while probability of occurrence of longer delays is very less, which is supported by beta distribution.

The probability distribution function (PDF) of the beta distribution is described as:

$$f(x)=\frac{\left(\frac{x-\tau_{\min}}{\tau_{\max}-\tau_{\min}}\right)^{\alpha-1}\left(1-\left(\frac{x-\tau_{\min}}{\tau_{\max}-\tau_{\min}}\right)\right)^{\beta-1}}{\left(\tau_{\max}-\tau_{\min}\right)\int_0^1 u^{\alpha-1}(1-u)^{\beta-1}\,du} \tag{3-20}$$

Where we are supposing that the delays in the network are bounded in an interval of $\left[\tau_{\min},\tau_{\max}\right]$. Parameters α and β are used to describe the behaviors of the distribution. For α=1 and β=1, the delays are uniformly distributed.

The following figures represent the distribution functions for various combinations of α and β.

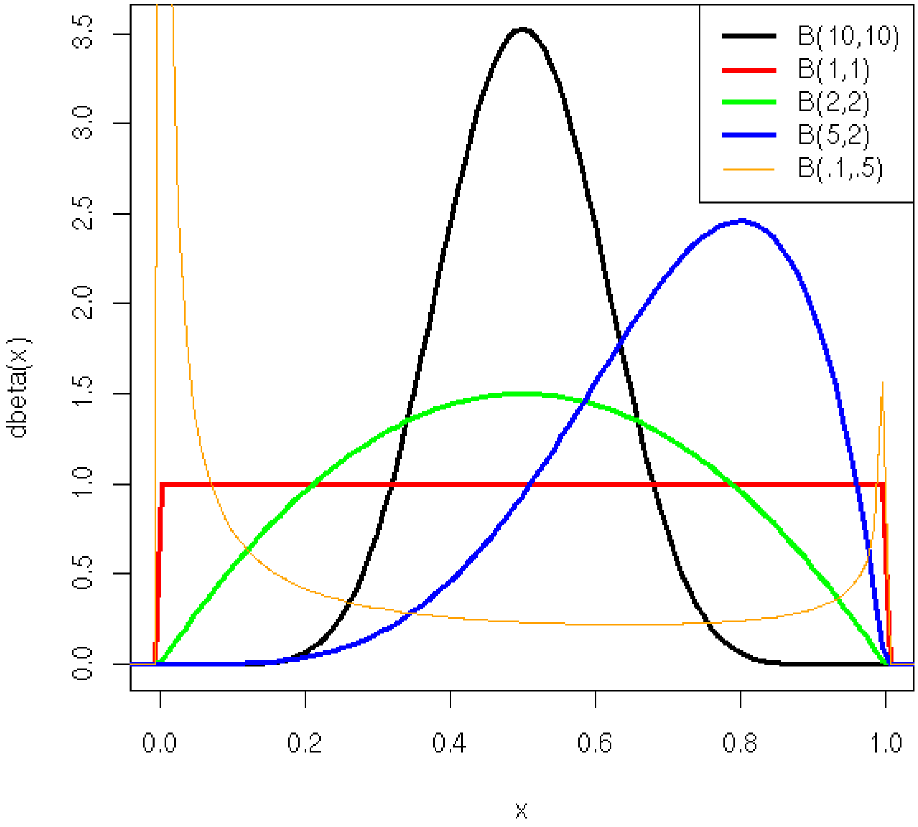

Figure 3-3 PDF of Beta Distribution for Different values of α and β

For α < β, the probability of occurrence of lower samples is more and for α > β, the probability of occurrence of higher samples is more whereas for α = β the distribution is bell shaped.

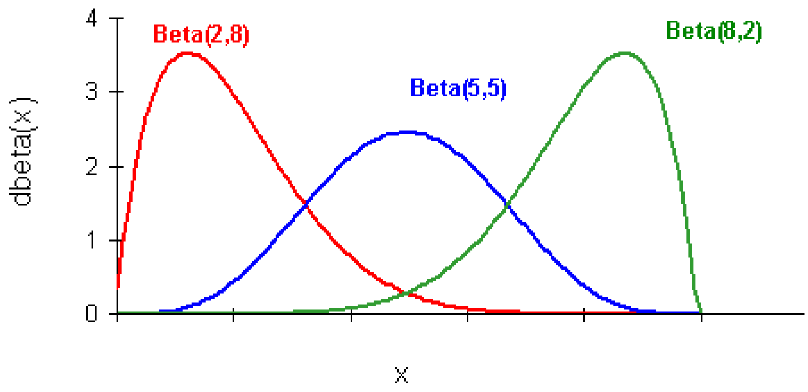

Figure 3-4 Relationship Between α and β in Beta Distribution (courtesy VOSE SOFTWARE)

For some fixed value of α=1, increasing β converts the distribution function from uniform distribution to an impulse at lowest sample or minimum delay in this case.

3.4 PROPOSED STRATEGY

In our proposed strategy we will device a mechanism in the form of a middleware that will enable the existing controller to cater for these unknown delays. Playback buffers are being used in video streaming to reduce delay jitter by storing the media packets before the playback [21]. Playback buffers have recently been used by researchers in Networked Control Systems [11, 20]. The only drawback of playback buffers is they incur end-to-end delays in the overall system. We will use a playback buffer to store command signal from the controller received over a communication network for a certain time and then apply calculated amount of gain to get desired performance from the plant. Figure 3-2 depicts the block diagram of the proposed system.

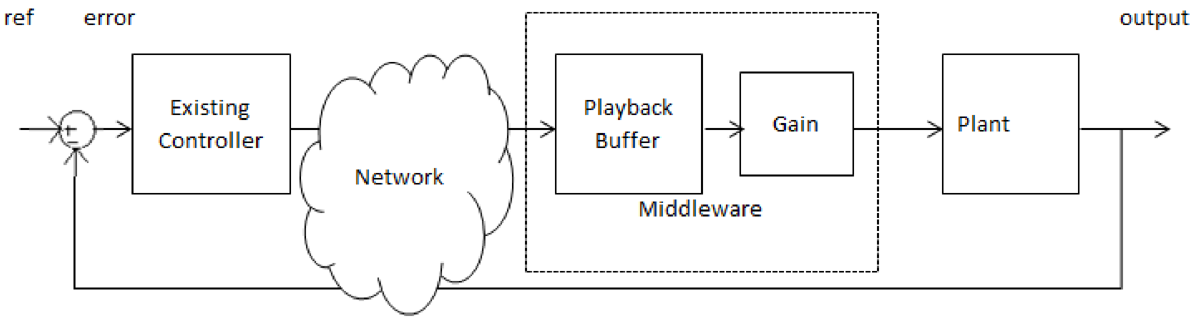

Figure 3-5 Block Diagram of the Proposed System

3.5 MIDDLEWARE

Middleware is the key component of the design. As replacing existing controllers with the ones specially designed for networked environment can be inconvenient, a middleware that will enables existing control strategy to work in networked environments can be more efficient. The proposed middleware has two essential elements: Buffer and Gain. Random delays in the network are fixed to a certain value by using buffer and then gain is tuned to get desired response.

3.5.1 PLAYBACK BUFFER

Playback buffers are typically used in multimedia application over network in order to reduce delay spikes and jitter occurred during streaming. They are used at the client host to compensate for variable delays in real time applications. Packets received are queued in the buffer and then applied after a certain period of time which removes variability in the delay. This delay is commonly referred as playback or playout delay. Choosing a playback delay is however a complex and important task. A too short playback delay treats packets to be lost even if those packets eventually arrive while the large playback delay may introduce an unacceptable delay. Liberatore [20] first proposed an algorithm to integrate playback buffers in networked control system. Later Alldredge et al [11] worked on design of playback buffers to remove the uncertainty. However in all those researches the emphasis was on designing a whole new controller.

Finding an optimal playback delay for networked control systems is an important and yet very critical task. A very large delay with effect the performance of the system and a too small delay will create issues in handling data thus destroying a lot of important information. A simple rule to find a playback delay may be to set it equal to the maximum delay occurring in the delay distribution but it may not be controlled by our proposed gain scheduling mechanism. Also we want the system to be easy to control hence a smaller delay is more preferable. In order to find the optimal playback delay for any arbitrary delay distribution we define upper bound for playback delay as the maximum delay that could be controlled by simply adjusting the external gain, let's define this as τ_{upper}. Then we define a cost function and try to minimize the function for various candidate playback delays.

Let J_{pb} be the cost function for a particular candidate playback delay τ_{pb}, such that:

$$J_{pb}(\tau_{pb}) = \sum_{i=1}^{N} w(\tau_i) J(\tau_i, \tau_{pb}) \qquad 3\text{-}21$$

Where $w(\tau_i)$ represents the probability of occurrence of the candidate is delay and $J(\tau_i, \tau_{pb})$, cost function, is the IAE associated with a loop delay τ_i against candidate playback delay τ_{pb}.

This cost function is evaluated for $0 < \tau_{pb} < \tau_{upper}$.

This cost function tends to find the delay which has the capability to cause most damage to the system performance.

The flowchart in figure 3-4 describes the steps involved in finding an optimal playback delay.

3.5.2 EXTERNAL GAIN

The open loop transfer function of the system with buffer and hold may be defined as:

$$G_P G_{BD} = G_P e^{-\tau_{PB} s} \tag{3-22}$$

The transfer function of the closed loop system with existing control in this case is described as:

$$G_S = \frac{G_P G_{BD} G_e}{1 + G_P G_{BD} G_e} \tag{3-23}$$

However this system does not fulfill the desired performance.

A new controller has to be designed to get the desired performance. Let G_m be the modified controller.

$$G_s = \frac{G_P G_{BD} G_m}{1 + G_P G_{BD} G_m} \tag{3-24}$$

As discussed in earlier section $G_m = \beta G_e$ we get the following transfer function

$$G_s = \frac{G_P G_{BD} \beta G_e}{1 + G_P G_{BD} \beta G_e} \tag{3-25}$$

That is by adjusting the value of gain only we can restore the performance of the system. Stability being the core issue in control system, we first need to find the range for which the system remains stable.

For a given systems, instead of just finding suitable gains for PID controller, some recent researches have focused on defining a range of stabilizing gains. Several important results have been presented on computation of all stabilizing P, PI, and PID controllers. Silva et al. [22] presented results on range of stable PID gains for single order time delayed systems of the form:

$$G = \frac{k}{(T_1 s + 1)} e^{-Ts} \qquad 3\text{-}26$$

For conditions k>0, T_1>0 and T>0, the range of stable proportional gain K_P can be found from:

$$-\frac{1}{k} < K_P < \frac{1}{k}\left[\frac{T_1}{T}\alpha\sin(\alpha) - \cos(\alpha)\right] \qquad 3\text{-}27$$

Where α is the solution of the equation

$$\tan(\alpha) = -\frac{T_1}{T_1 + T}\alpha \qquad 3\text{-}28$$

Based on the results Fei et al computed range of stable gains for a PI controller for a second order time delayed process represented by equation 3-10.

$$-\frac{1}{k} < K_P' < \frac{1}{kT^2}\left[(T_1T_2\alpha^2 - T^2)\cos(\alpha) + \left(T_1 + T_2\right)\alpha L\sin(\alpha)\right] \qquad 3\text{-}29$$

Where α is the solution of the equation

$$\tan(\alpha) = \frac{\left(T_1 + T_2\right)\alpha T}{T_1T_2\alpha^2 - T^2} \qquad 3\text{-}30$$

The stable range of β is then found from the following set of equations:

$$0 < \beta < \frac{1}{kK_PT^2}\left[(T_1T_2\alpha^2 - T^2)\cos(\alpha) + \left(T_1 + T_2\right)\alpha L\sin(\alpha)\right] \qquad 3\text{-}31$$

$$\tan(\alpha) = \frac{\left(T_1 + T_2\right)\alpha T}{T_1T_2\alpha^2 - T^2} \qquad 3\text{-}32$$

This can also be done by using root locus technique for the closed loop system including the delay and buffer hold.

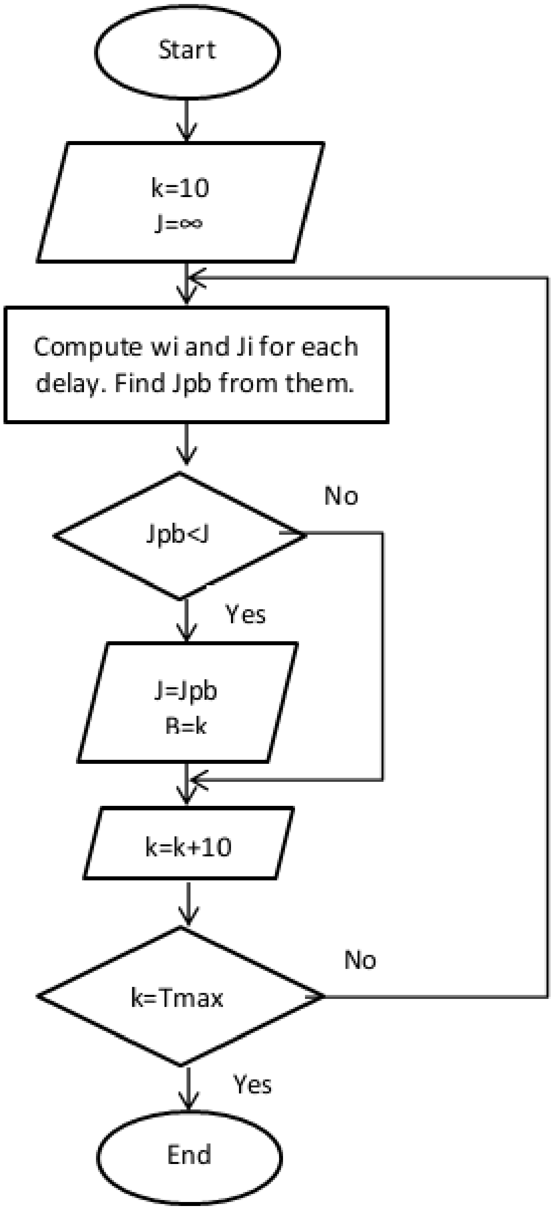

Figure 3-6 Flowchart for Finding Optimal Playback Delay

Our performance criterion relies mainly on rise time, settling time and overshoot of the system when a step input is applied. An efficient technique would be one which ensures minimum deviation from the desired performance criterion. A cost function can be defined here which involves all these system specification. Our performance is based on meeting design requirements in settling time, rise time, percentage overshoot and steady state error. Each one of this design requirement can be taken as a cost function and overall cost function is given as:

$$J_c = w_1 J_1 + w_2 J_2 + w_3 J_3 + w_4 J_4 \tag{3-33}$$

Where J_1 denotes rise time, J_2 settling time, J_3 overshoot and J_4 is steady state error, then:

$$J_1 = \begin{cases} t_r - t_{r_o} & \text{when } t_r > t_{r_o} \\ 0 & \text{when } t_r \le t_{r_o} \end{cases} \tag{3-34}$$

$$J_2 = \begin{cases} t_s - t_{s_o} & \text{when } t_s > t_{s_o} \\ 0 & \text{when } t_s \le t_{s_o} \end{cases} \tag{3-35}$$

$$J_3 = \begin{cases} OS - OS_o & \text{when } OS > OS_o \\ 0 & \text{when } OS \le OS_o \end{cases} \tag{3-36}$$

$$J_4 = \begin{cases} SSE - SSE_o & \text{when } SSE > SSE_o \\ 0 & \text{when } SSE \le SSE_o \end{cases} \tag{3-37}$$

Where w_1, w_2 w_3 and w_4 are the weighting functions. These weighting function are defined on the basis of importance of each parameter. Here nominal values are taken as the desired requirement.

In order to find the best possible value of gain, we first impose limits on gain values. This is done by finding the stable set of gain values i.e. gain values for which system remains stable. This can be done by simply drawing the root locus and observing the value of K at which it touches the imaginary axis. Once the stable set of gain is calculated we start simulating the cost function for various values of gain from the stable set and the one with minimum cost function is selected as optimal gain. The process flowchart is depicted in figure 3-3.

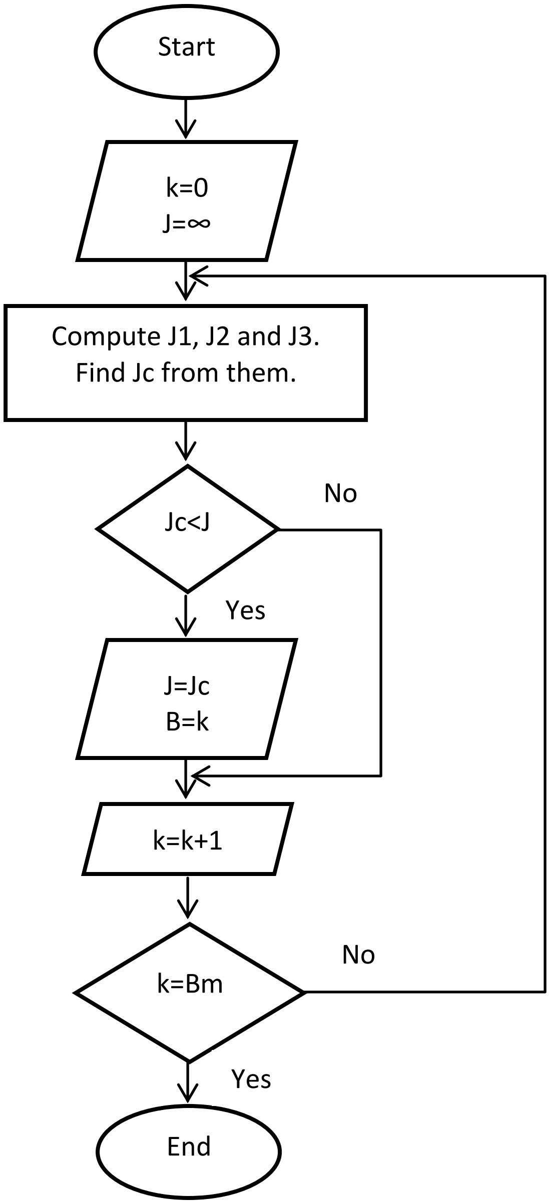

Figure 3-7 Flow Chart for Finding Optimal Gain

3.6 ASSUMPTIONS MADE ON THE SYSTEM

In networked environment the goal of designing is to maintain the performance of the system regardless of the network delays. The main objective of this thesis is to evaluate the performance restoration of the delayed system when we use proposed middleware. In order to carry out our research following assumptions are made about the system as made by other researchers [23]:

1. All control and measurement signals are transmitted in a single packet.
2. No packet loss or packet dropout occurs during the process.
3. Effects of disturbances and noise are neglected.
4. The sampling period of the system is assumed to be considerably smaller than the network delays.

The analysis and design are carried out in continuous domain for the sake of simplicity. However for implementation all systems are to be discretized. If our assumption of sampling period being smaller than the network delays holds, the same results will hold for discrete case.

3.7 CONCLUSION

Networked Control System has caught the attention of many researchers and considerable work has been done in the field. Some researchers have developed different gain scheduling algorithms to enable existing controllers to work in networked environment. Most of these are based on estimating network traffic for delays in the loop. Estimation and gain scheduling makes the system computationally less efficient. In our proposed strategy network delays are made fixed using buffer which eliminates need for traffic estimation and gain scheduling.

CHAPTER 4

SIMULATION RESULTS

4.1 INTRODUCTION

Analysis and design of control systems has been made very easy due to the development of modern simulation tools like MATLAB. Such tools give very deep insight into analysis of systems. This chapter describes the simulations and results of our proposed strategy in MATLAB environment.

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

4.2 SYSTEM MODEL

Here for the purpose of our experiments and simulations we are considering an example of simple DC motor speed control using PI controller over IP network. This model has been taken from [12] to make analysis and comparison easier in the later stages. A simple linear DC motor plant is used for simulations. Its linear equations in state space and transfer function are as follows:

$$\dot{x} = \begin{bmatrix} -\dfrac{R_a}{L_a} & -\dfrac{K_b}{L_a} \\ \dfrac{K}{J} & -\dfrac{f}{J} \end{bmatrix} x + \begin{bmatrix} \dfrac{1}{L_a} \\ 0 \end{bmatrix} u \tag{4-1}$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} x \qquad \text{4-2}$$

Where $x = \begin{bmatrix} i_a & \omega \end{bmatrix}^T$

Meaning and values of all motor parameters are mentioned in the table 4-1.

Plant dynamics are represented by the following transfer function

$$G_P(s) = \frac{2029.826}{(s+26.29)(s+2.296)} \qquad \text{4-3}$$

Table 4-1 Motor Parameters

Parameter	Description	Value
R_a	Armature Resistance	4.67
L_a	Armature Inductance	170e-3 H
J	Moment of Inertia	42.6e-6 Kg-m^2
f	Viscous Friction Coefficient	47.3e-6 N-m/rad/sec
K	Torque Constant	14.7e-6 N-m/A
K_b	Back EMF Constant	14.7e-6 V-sec/rad
i_a	Armature Current	--
ω	Rotational Speed	--

4.3 CONTROLLER DESIGN

The plant’s step response can be modified using control techniques to get desired performance. The design criteria for the plant under consideration, as set in the reference, are:

- Percentage Overshoot $\le 5\%$
- Settling Time $\le 0.309s$
- Rise Time $\le 0.117s$

PI controllers are easy to realize and implement. It is said that almost 90% of the controllers in Pulp and Paper Industry are of PI type. PI controllers have a general form of:

$$G_C(s) = K_P + \frac{K_I}{s} \tag{4-4}$$

Where K_P denotes the proportional gain and K_I integral gain.

The desired performance i.e. 5% overshoot and 0.309 sec settling time may be used to find the location of dominant second order pole pair using the general formulae:

$$\%O.S. = e^{-\pi\zeta/\sqrt{(1-\zeta^2)}} \tag{4-5}$$

$$T_s = \frac{4}{\zeta\omega_n} = \frac{4}{\sigma_d} \tag{4-6}$$

The desired pole location comes out to be $-12.7 \pm 13.3i$.

In order to attain this pole location we use SISOTOOL to find suitable values for compensator gains. A simple PI controller is tuned to get desired performance. Following gain values fulfill our design criteria:

K_P=0.1701

K_I=0.308

4.4 SIMULATION RESULTS

Model of the DC motor has been represented as a transfer function for which a PI controller is designed again as a transfer function. Step response of the system is then taken to investigate 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.

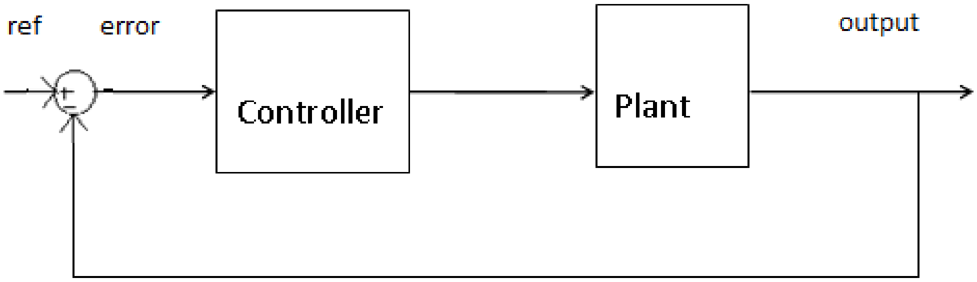

Figure 4-1 Close Loop System without Any Network

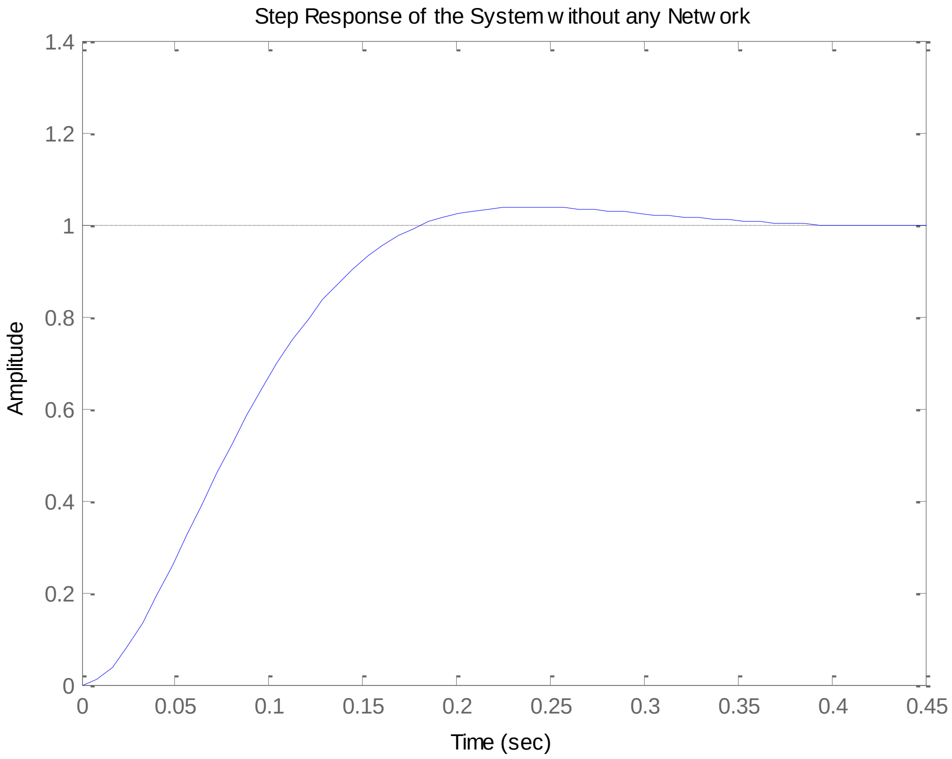

Figure 4-2 Response of the Closed Loop System without Network

Step response of the system is as follows:

```
>>stepinfo(Gs)
```

```
ans =

RiseTime: 0.1165

SettlingTime: 0.3092

SettlingMin: 0.9125

SettlingMax: 1.0385

Overshoot: 3.8474

Undershoot: 0

Peak: 1.0385

PeakTime: 0.2386
```

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 200 msec in our work because for 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 behavior of the system in presence of one such delay can be seen in figure 4-4.

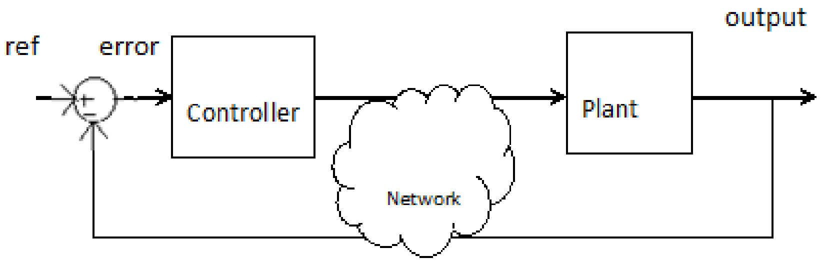

Figure 4-3 Closed Loop System in Presence of Network

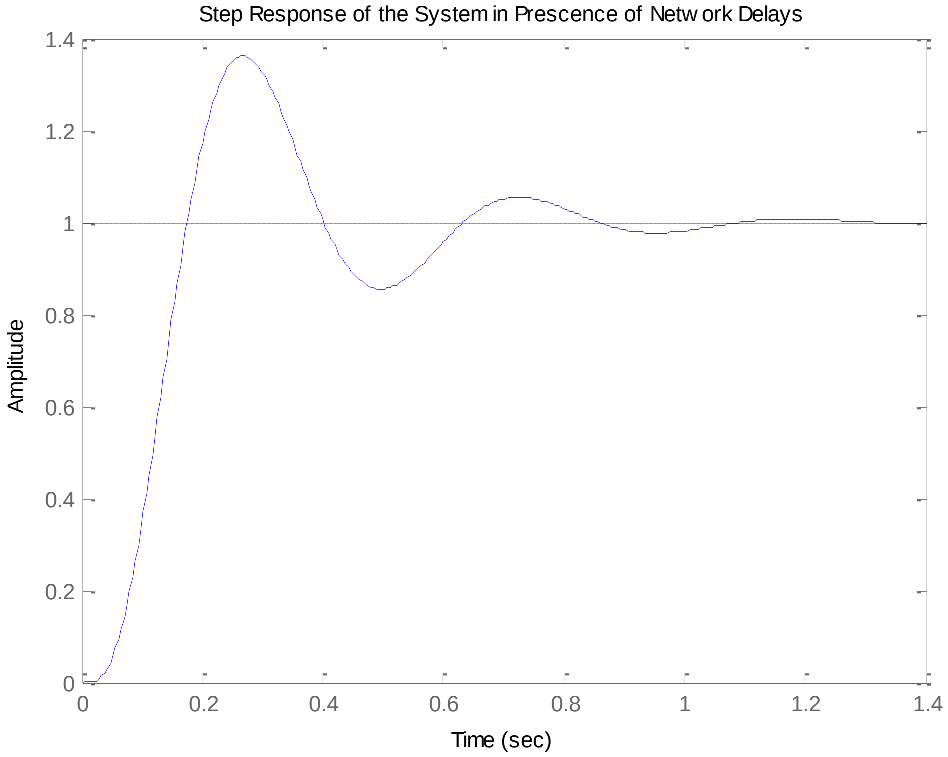

Figure 4-4 Response of the Closed Loop System in Presence of Network

Step response of the system in this case is as follows:

```
>>stepinfo(Gsn)

ans =

RiseTime: 0.1001

SettlingTime: 0.9884

SettlingMin: 0.8553

SettlingMax: 1.3614

Overshoot: 36.1352

Undershoot: 0
```

```
Peak: 1.3614
PeakTime: 0.2651
```

These delays are difficult to deal with due to their random nature. For this purpose, we have used a memory element or buffer which will store data in it and apply the most recent data periodically after every specific time instant. This fixes the overall delay to a deterministic value. The figure 4-6 shows the response of the system with a buffer.

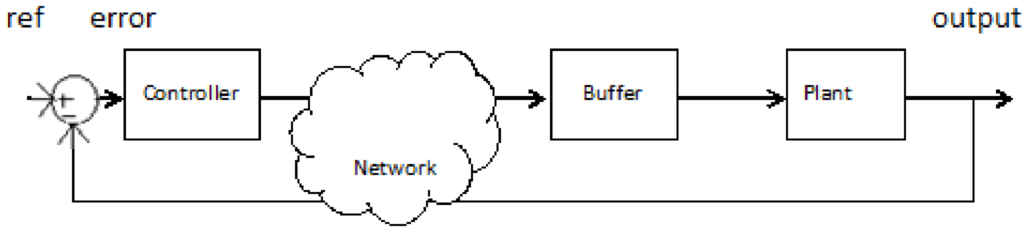

Figure 4-5 Closed Loop System with Buffer

The step response of the system with buffer is as follows:

```
>>stepinfo(Gsn_b)
ans =
RiseTime: 0.1165
SettlingTime: 2.9786
SettlingMin: 0.5690
SettlingMax: 1.6269
Overshoot: 62.6942
Undershoot: 0
Peak: 1.6269
PeakTime: 0.3432
```

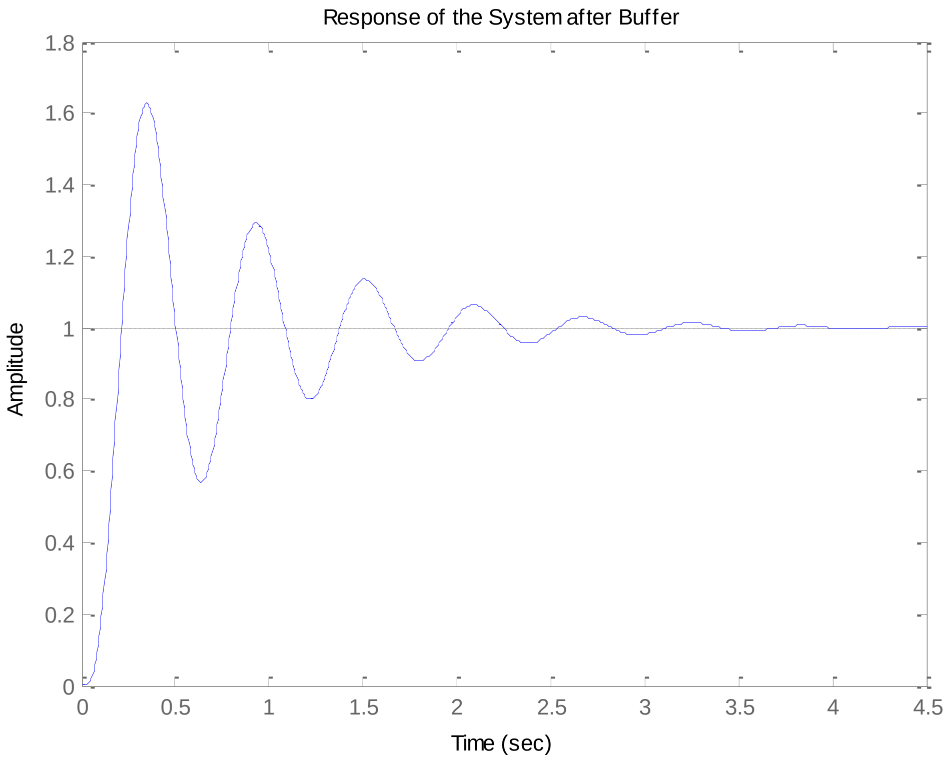

Figure 4-6 Response of Closed Loop System with Buffer

Now we are concerned with the stability and transient performance of the system. In order to restore the performance of the system we need a gain which would yield nearest to desired performance. This buffer and gain collectively makes our middleware.

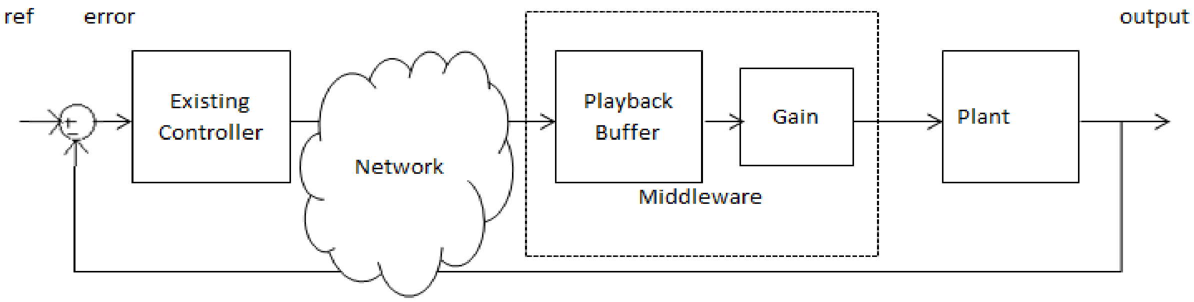

Figure 4-7 Closed Loop System with Proposed Middleware

The performance of the system with the proposed middleware is as below.

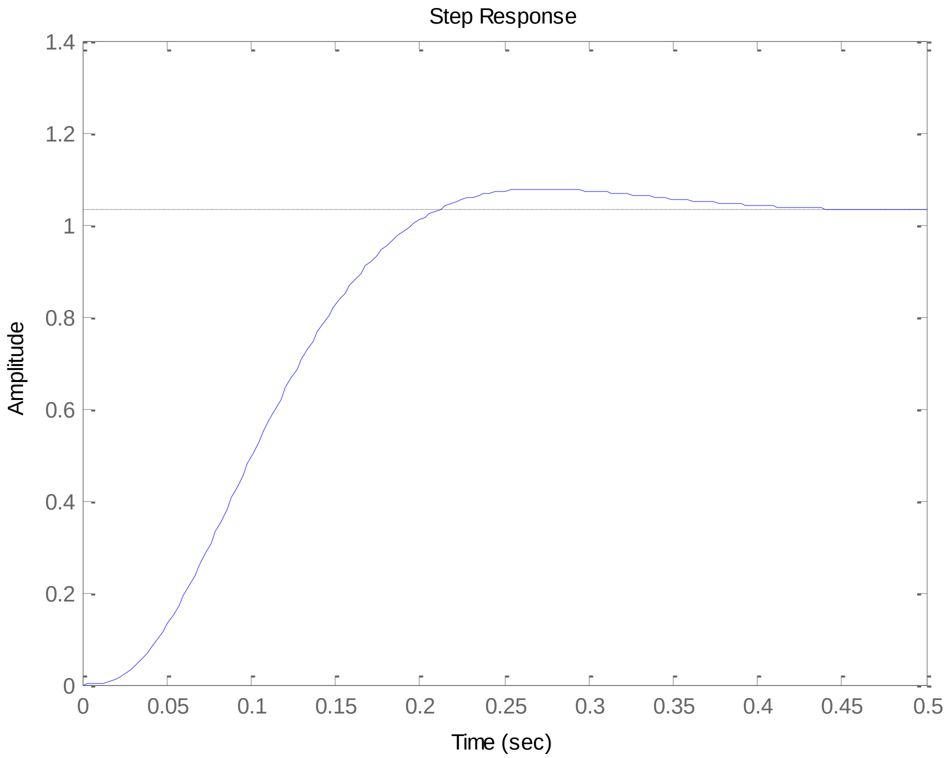

Figure 4-8 Response of the Closed Loop System with Proposed Middleware

The step response of the system with proposed middleware in presence of network delays is as follows:

```
>>stepinfo(Gsn_bg)

ans =

RiseTime: 0.1281

SettlingTime: 0.3544

SettlingMin: 0.9337

SettlingMax: 1.0775
```

Overshoot: 4.2299

Undershoot: 0

Peak: 1.0775

PeakTime: 0.2727

4.5 CONCLUSION

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.

CHAPTER 5

CONCLUSIONS

5.1 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 environment. The block diagram of the proposed system is shown in figure 5-1. This work can be extended for further improvements.

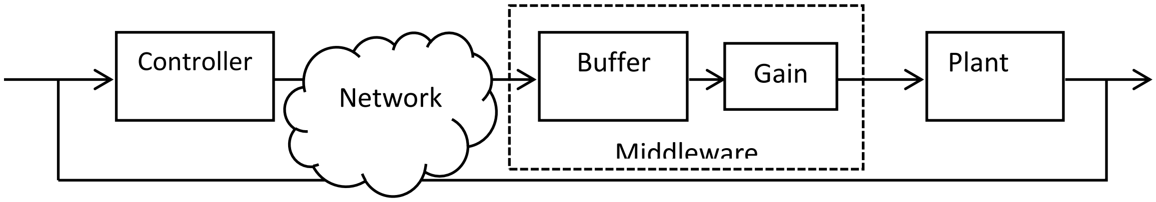

Figure 5-1 Block Diagram of Proposed Strategy

5.2 RESULTS

The proposed strategy was simulated over MATLAB. Plant behavior was simulated first and then a controller was applied to get certain performance parameters. The closed loop system followed the desired response when connected directly. Once we connect the controller through network, performance of the system deteriorates. Network related issues are kept limited to delays only for the sake of simplicity and other issues are not taken into account. Delays are approximated by their second order pade approximation. Proposed strategy is then applied to cope up with the network delays. Buffer delay is carefully chosen to handle most of the delays in the loop. The system thus resulted is stable and fulfills steady state error and is very near to the performance in terms of overshoot and settling time criteria as can be seen in the figure 5.2 where G_s is the closed loop system in absence of any network and G_f is the closed loop system in presence of network with proposed strategy.

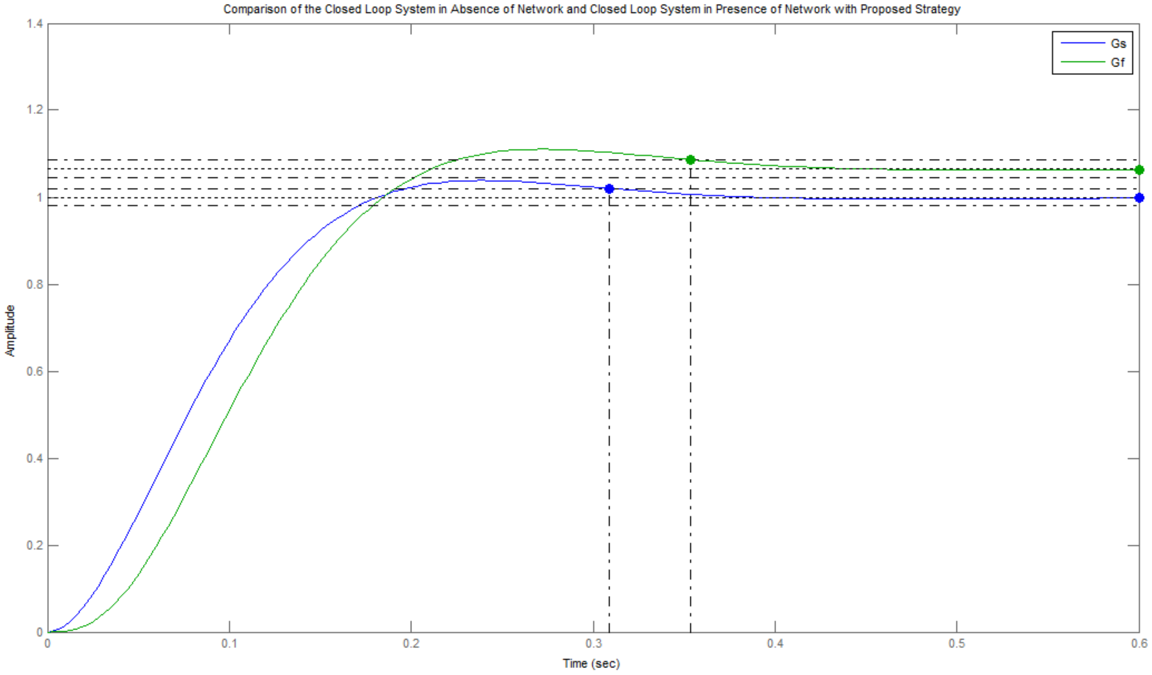

Figure 5-2 Comparison of the Closed Loop System in Absence of Network and in Presence of Network with Proposed Strategy

5.3 PROBLEMS

Control and Communication integrated design appears very interesting and offers very efficient solution to various problems. It is a complex 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 playback buffers and network issues due to limited knowledge of the field.

5.4 FUTURE WORK

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 design of playback buffer are also left and playback delay is assumed. This work may be taken as first investigating step and can be continued in future to:

- Include a more accurate and real network delay model
- Consider other network related issues e.g. multiple packet transmission
- A more efficient design using a model predictive control scheme
- Design a more realistic playback buffer taking into account its various parameters
- Implement the system practically

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