TIME DELAY COMPENSATION IN NETWORKED CONTROL SYSTEM

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By

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DEDICATED

TO

MY FATHER SWAPAN KUMAR DAS,

MY MOTHER GEETA DAS

AND

MY WIFE ARATI DAS

NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

CERTIFICATE

This is to certify that the thesis entitled, **"TIME DELAY COMPENSATION SCHEMS IN NETWORKED CONTROL SYSTEM"** submitted by **Mr. MANAS KUMAR DAS** in partial fulfillment of the requirements for the award of Master of Technology Degree in **ELECTRICAL ENGINEERING** with specialization in **"CONTROL AND AUTOMATION"** at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

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DIFFERENT ACRONYMS USED

Acronyms	Description
NCS	Networked control system
MPC	Model Predictive Controller
LQR	Linear Quadratic Regulator
LQG	Linear Quadratic Gaussian
MIMO	Multi input multi output
CAN	Controller area network
DCS	Distributed control system
ADC	Analog to digital converter
DAC	Digital to analog converter
RTT	Round Trip Time
NTP	Network Time protocol
PTP	Precision Time Protocol
ML	Maximum Likelihood
COS	Change of state
MAC	Medium access control
CSMA	Carrier sense multiple access
CA	Collision avoidance
CD	Collision detection
HMM	Hidden Markov Model
LAN	Local Area Network

PC	Personal computer
UDP	User datagram Protocol
IP	Internet Protocol
GM	Gain Margin
PM	Phase Margin
dB	Decibel
QOP	Quality of performance
QOS	Quality of services
MATI	Maximum allowable transfer interval
RR	Round Robin
TOD	Try-once discard
MEF-TOD	Maximum error first try once discard
TDMA	Time division multiple access
LEF	Large error first
MUF	Maximum urgency first
LMI	Linear matrix inequalities
LTI	Linear time invariant

DIFFERENT SYMBOLS USED

Symbol	**Description**
τ^{sc}	Sensor to controller delay
τ^{ca}	Controller to actuator delay
τ^{c}	Computational delay
Π	Augmented system matrix in augmented state space model of NCS
Γ	Augmented input matrix in augmented state space model of NCS
Ξ	Augmented output matrix in augmented state space model of NCS
$\sum_k (z)$	Discrete time transfer function of Laguerre network
Ψ	Augmented system matrix used in augmented model for MPC
Φ	Augmented input matrix used in augmented model for MPC
Θ	Augmented output matrix used in augmented model for MPC
ξ	Lagerre network coefficient matrix
$\lvert X \rvert$	Indicates a row vector
$\lvert X \rvert^T$	Indicates a column vector
$\lvert x_i \rvert_{i=1\rightarrow n}$	Indicates a row vector with n elements
$\Delta u(k)$	Rate of control input

ABSTRACT

Networked control system is a special type of distributed control system where control loop is enclosed by communication medium. Networked Control System (NCS) suffers from the networked induced delay which may be induced in the forward path as well as in the feedback path. This delay is variable in nature. So if a controller is designed without considering the delays or considering the fixed delay then system performance will be degraded and in the worst case the system become unstable. To compensate the network induced variable transporting delay,a number of methods have been proposed in the literature such as robust control, Smith Predictor and Inteligent control theory. But there are few works reported in literature that employ Linear Quadratic Regulator (LQR) to compensate the networked induced delays.Firstly an LQR controller is designed to compensate the networked induced variable delay which is varied up to a maximum value. Then an LQG controller is designed to compensate the networked induced delay in noisy environment. Here the controller is the same controller used in LQR technique. Only difference between the standard LQR and the LQG controller said now is that it uses Kalman Filter to estimate the plant output using noisy measurement. Then an Model Predictive Controller (MPC) controller is designed using Laguerre network considering the constraints on control input and on the rate of control input. An integrator plant is considered for simulation where the above three controllers are applied. From the simulation result, it is observed that LQR gives a better step response but MPC has better disturbance rejection capacity. To validate the controllers in real-time, an experiment has been conducted in the Labrotory. In the experimental setup using one PC is considered as controller and other one is considered as plant. They are connected through an Ethernet network. From the real time experiment results it is seen that LQR exibits superior delay compensation performance..

***Key words*- LQR controller, Kalman filter, Laguerre network, UDP protocol, State observe, MPC controller**

1 CHAPTER 1- INTRODUCTION

1.1 A LOOK ON NETWORKED CONTROL SYSTEM

A networked control system is a system composed of physically distributed smart agents that can sense the environment, act on it, and communicate with one other through a communication network to achieve a common goal [7]. Or a networked control system can be defined as a special type of distributed control systems wherein the control loop is enclosed by some form of the communication network [8]. In the case of the point to point control system each component of the system (sensor, actuator, and controller) is connected through a dedicated wire [1]. But in case of MIMO system when there is an array of sensors and actuators it is not reliable and is not economical to use this point to point architecture because it increases the caballing cost and maintenance cost [2]. Also, such type of system is not flexible from the point of view of reconfigurability as it requires rewiring all the system components. Also, such type of system is stagnant from the point of view of reliability and interchangeability which is the main requirement of the modern control system [3]. Also, there is some situation like in missile tracking system, spacecraft system or in the hazardous area like nuclear power plant [4] where the point architecture can not be used. In such cases, the remote control technology is the only solution. Another thing is that this is the era of computer technology and embedded system. In every field, the computer is used and exchange of the information is done through the digital communication medium. Industrial automation system is a Hierarchical system where the base level is the field level and the top level is the information level. In field level, different type of sensors, actuators are there. Information level is the management level from where all decisions are made for plant operation. The intermediate level is the control level. This can be divided into three sublevels which are process sublevel, cell sublevel, and area sublevel. All levels communicate each other using digital communication medium [5]. In the industry, the digital controller is used as the cost of the digital controller is less than the analog counterpart and flexibility is better. Digital instrument more insensitive to the error due to noise than analog counterpart, Digital controller can implement more complex control algorithm. Accuracy of the digital system is more than analog counterpart [6]. All phenomena which are discussed up to this arise the need of using the digital communication medium for exchanging the data among the different component of a control system for reducing the cost and easy to implement the control algorithm. This develops the networked control system (NCS). The NCS becomes popular in distributed process control system ([9], [10], and [11]). There are so many potential applications of NCS such as factory automation, aircraft, manufacturing plant monitoring, tale-robotics, automobiles and military applications ([12], [13]). The control technology which is used for such type of system is different from conventional control theory. In the case of conventional control theory, it is assumed that there is proper synchronization among different components of the system and there is no time delay in sensing and actuation operations [14]. But NCS suffers from some unwanted phenomena like time delay, packet loss, jitter, multiple packet transmission which degrade the system performance and sometimes results in instability ([15], [16], [17] and [18]). To maintain the stability, gain of the controller should be reduced ([15], [16]). Depending on the network protocol, is used this delay may be deterministic or may be stochastic in nature. In case local area network protocol likes SAE token bus, PROFIBUS, IEEE 802.5, SAE token ring, MIL-STAD-1553B, this delay is deterministic nature. But random access local area networks like CAN and Ethernet yield stochastic time-delay [19]. The reason behind this is that the all real-time digital communication medium has finite bandwidth. Due to this data transmitted through this medium faced delay, traffic collision. And sometimes due to this traffic collision data is completely lost. The main reasons behind the time delays are computational time required by the digital device, network accessing time and transmission time. The main reasons behind the packet loss are traffic congestion, packet transmission failure, and excessive time delay [20]. Another thing is that if there is a delay in the system then the gain of the controller must be reduced ([21], [22]) to maintain the stability. Although the NCS have some disadvantage, it has several technical as well as economic advantages like low cost, easy maintenance and reliability, flexible system design, simple and fast implementation and easy of system diagnosis and maintenance [3]. The NCS reduce the system complexity when there are more sensors, actuators by eliminating the extra wiring with nominal investment. A large number of sensors and actuators can be installed with minimum cost [23] in case of NCS as the caballing cost reduces. So NCS have some technical problem and lots of technical and economic advantage. So if the network induced problems are compensated, it will serve the nation a lot. For a long time, research has been going on in this field ([18], [19]). The networked induced problems can be removed in two ways. Firstly an effective network protocol or scheduling method can be developed with which the utilization of network bandwidth is done in such a way such that the effects of network induced problems are reduced or it is completely removed. This is called the control of network. In this category, routing control, congestion control, efficient data communication and networking protocol are listed. Or a control algorithm can be developed which can compensate the network induced problem. This is called the control over network ([24], [25]). Now adays there are so many potential application of NCS in industry.

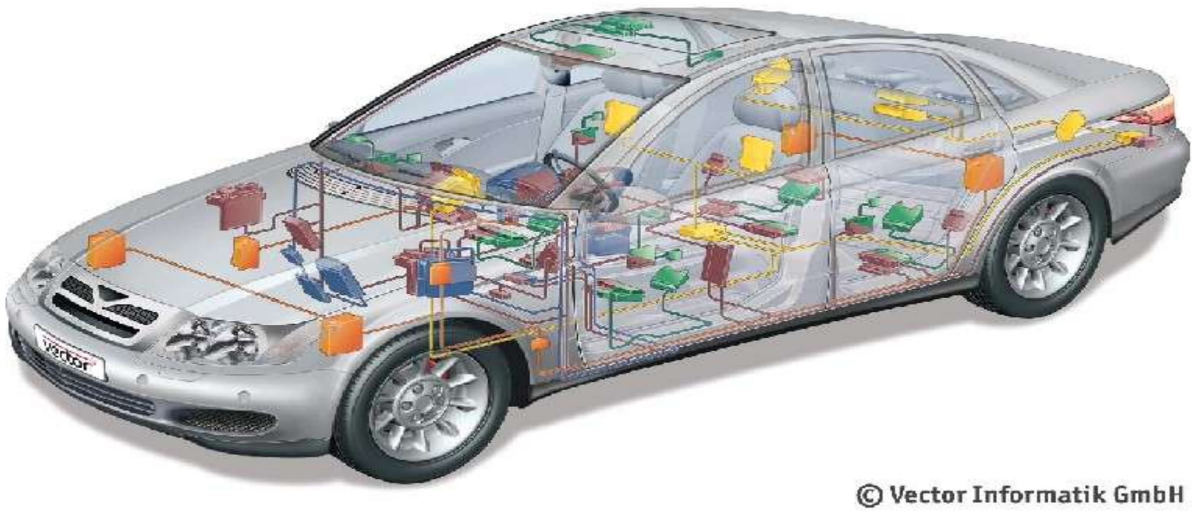


Figure1.1. NCS used in automobile [94]

Figure1.1 shows that shows that in a car all devices are connected through a common bus. As a result the wiring of the component reduces.

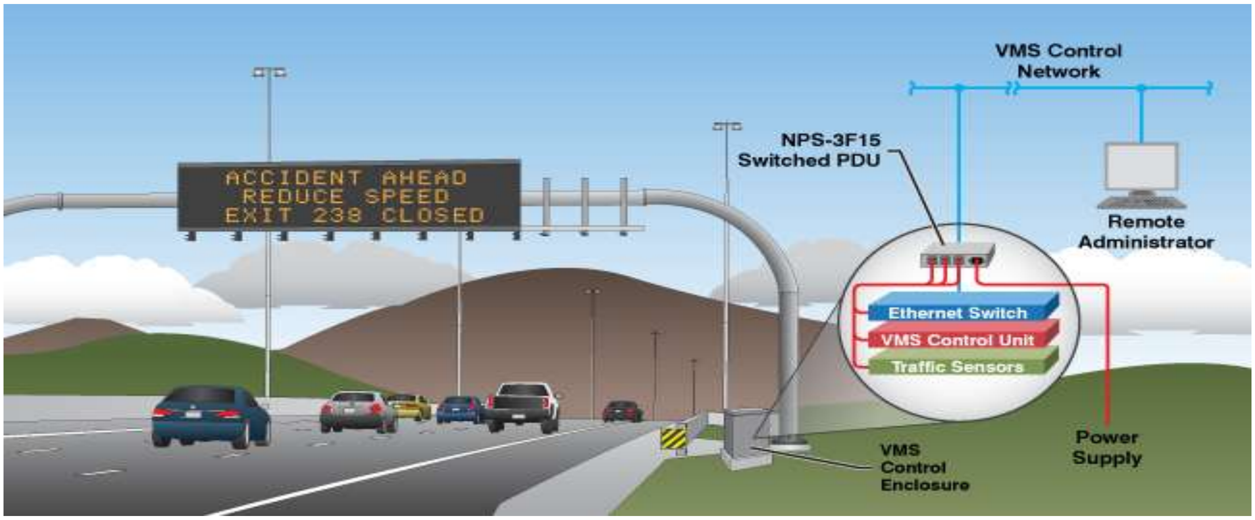


Figure1.2. NCS used to control the traffic in a highway. [96]

Figure1.2 shows that through the network a remote administrator can monitor the traffic in a highway and can diagnoses' the entire problem like movement of traffic, traffic jam etc.

1.2 INTRIGRATION OF COMMUNICATION NETWORK AND CONTROL SYSTEM

Networked control theory is an interdisiplinary diciplin where the knowledge of communication, control and networking are integrated to achive the goal of control. The networked control system is different from as usual control system where point to point architecture is used. In point to point architecture of control system, where individual cable is required to transmit the each information between two components of closed loop control system. The point point architecture is very much stragnent against the change in configuration because, for reconfiguration a large number of cabling is necessary which is very much time consuming and costly. NCS removes all problems associate with the point to point architecture of control system. But it suffers some problems like time delay and packet loss due to which NCS should be applied in time critical system with proper precaution. Due to advance in communication, networking and control theory, networked control system is applied in large scale in distributed control system (DCS).

1.2.1 Point to point control architecture

Figure1.3 shows the point to point architecture where for each sensor and actuator signal separate cable is necessary to transmit signal to the plant and controller. So if there are n number of sensor and n numbers actuators then 4n numbers of separate cables are necessary to transmit the signals. It increases the maitanance and installation cost. Due to this configuration this structure is stragnent against the reconfiguration which is one of the important requirement in modern control system. For reconfiguration, point to point architecture requires large time and large money.

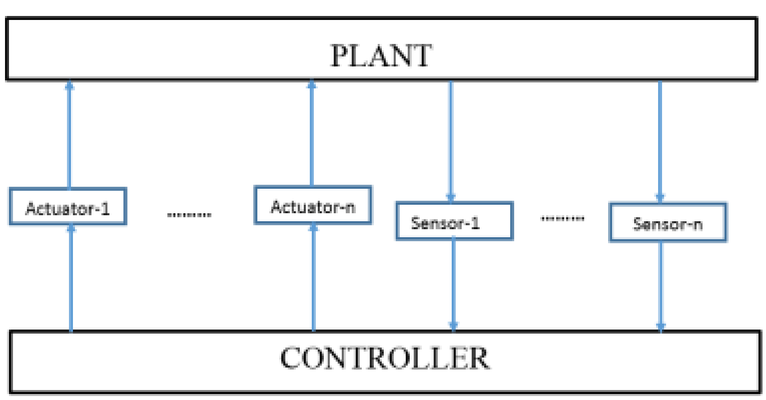


Figure1.3. Point to point architecture of control system

1.2.2 A prototype of Networked Control system

The basic networked control system is represented by the Figure1.4. From this figure it is seen that all sensor and all actuator exchange their signal through the network communication midium. Here all sensors are connected to the controller through a single network communication medium and all actuator are connected to the controller through a single network medium. So for NCS, no individual cable is required for exchanging each information as point to point architecture of control system.

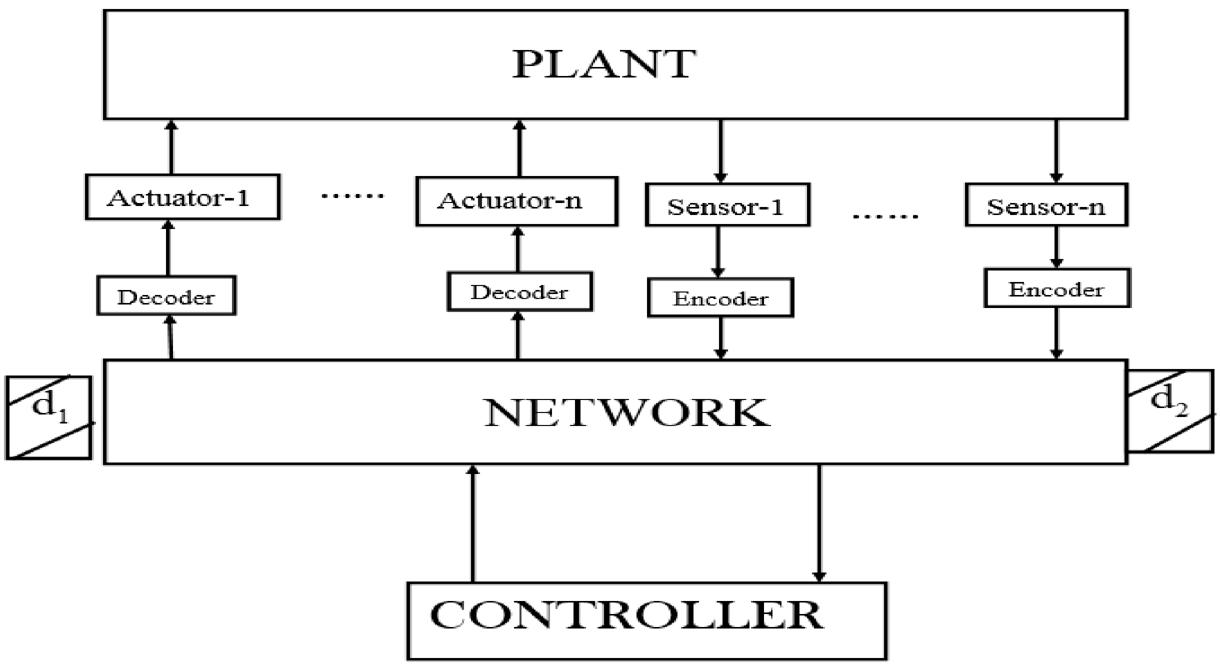


Figure1.4. Basic structure of NCS

But due to the finite bandwidth of the network medium, the signal passing through it suffers from unreliable behavior of the network medium. Here we have considered the network-induced delay. There are two sources of delay in an NCS. Delay can be induced in the feedback path which is denoted by τ^{sc}. Another delay source is the path from the controller to the actuator which is denoted by τ^{ca}. Another thing is to notice that generally all plants are continuous type, but here the control loop is enclosed by digital network medium. So the plant output must be discretized by ADC and a DAC must be used at the plant input to transform the digital control signal into the continuous signal as the plant is continuous. Due to which the NCS may suffer from quantization error which is a common problem in any quantized system. In NCS the connection point of the communication medium is called node. A node is active electronic device which is capable to send and receive the information from the communication channel.A node may be a source of information if it is a sensor or it may be recever of demand signal if it is an actuator. A node is called controller node if it runs a control algorithm. The node must have the capability of data coversion, encoding and decoding technique as NCS delas as digital control sytem.

1.3 TYPE OF NCS ARCHITECTURE

The type of networked of control of system is based on the system to be controlled and based on the requirement of control strategy by the client. For a small system where no need the information (controlling signal and actuation signal) to transmit to the remote place, direct configuration is used. But where remote control is required by the client besides the local control, hirarchical structure is used. Hirarchical structure is complicated and genaraly is used in the large organisation.

1.3.1 Direct structure of Networked Control system

Figure1.5 shows the direct structure of NCS for a simple system with one sensor and one transducer which excanging the information with the plant and controller through the networked medium. Here, there is no option to transmit the information to the remote place. This type of structure is generally prefarable for the small plant.

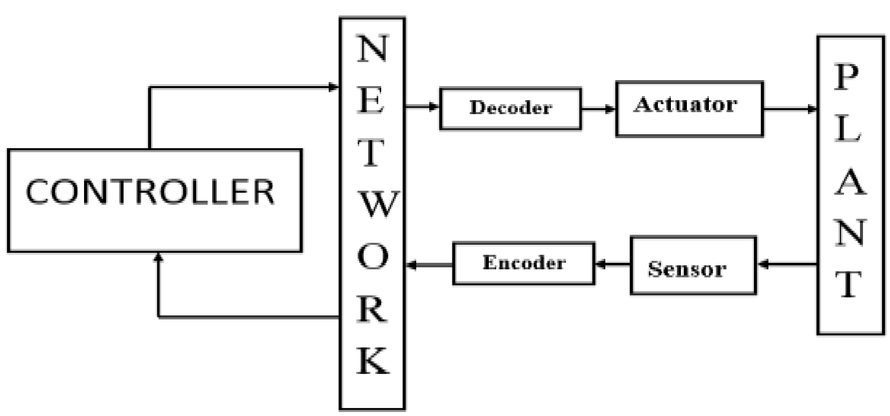


Figure1.5. Direct structure of NCS

1.3.2 Hirarchical structure of networked control system

Figure1.6 shows the hirarchical structure of networked control syste. The hirarchical structure is used in largeorganisation. From the figure it is seen that there is an option to transmit the information to remote place and there is an option to remote control. There is to option of control. Loccal control and remote control. Local controller controls the plant using the information available obtained by the filed sensor. But this controller can be trobolshoot from the remote place if there is a requirement of synchonisation among all operation performed in the other parts of the plant. The prority of the remote controller is first. If it gives the sisgnal to stop the operation, the operation of the local controller is ignored and operation must be stoped.

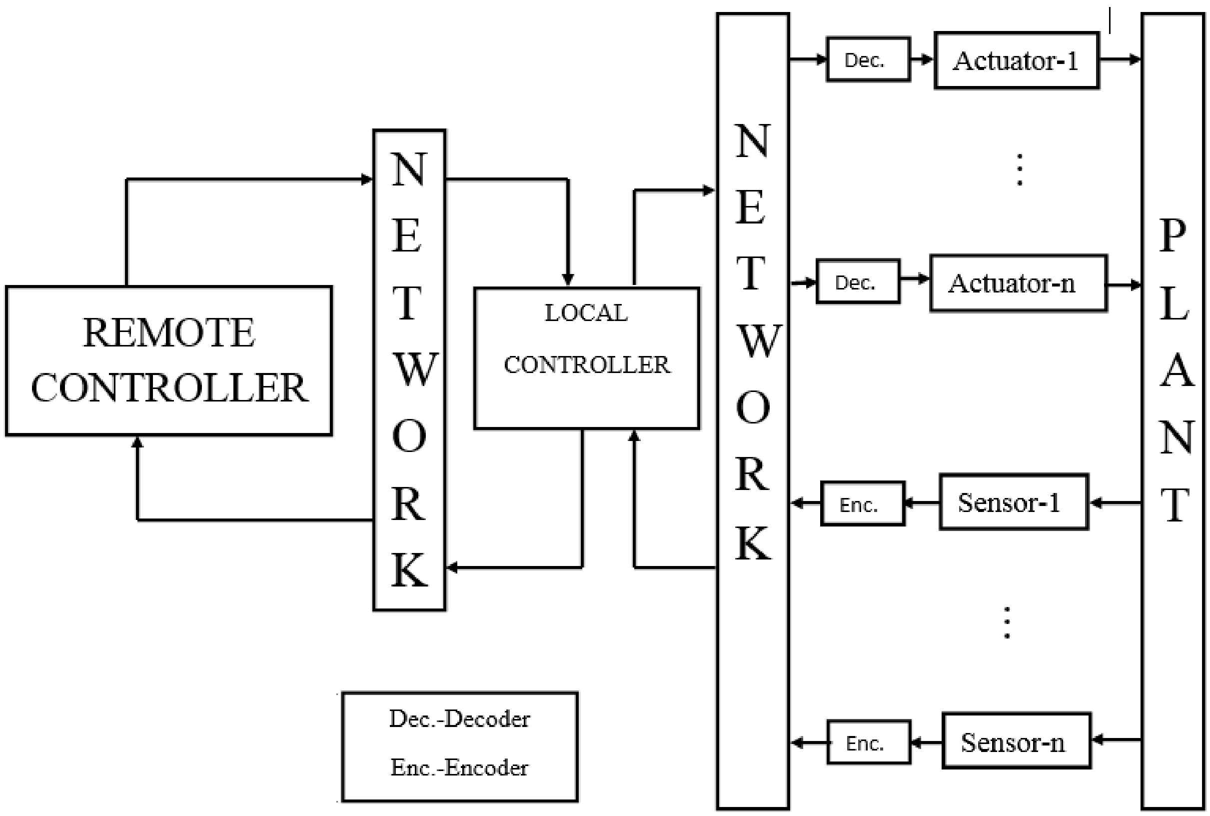


Figure1.6. Hirerchical structure of NCS

1.4 BASIC PROBLEMS IN NCS

Networked control system suffers from several problem due to its finite bandwidth. The main problems of NCS are time delay, packet loos and jitter, time varying sampling period and data quantization error, single packet versus multiple packet transmission ([26],[27]).

1.4.1 Networked induced delay

The main sources of networked induced delay are

(1) time delay induced between sensor and controller

(2) time delay induced between controller and actuator

(3) computational delay required by the controller

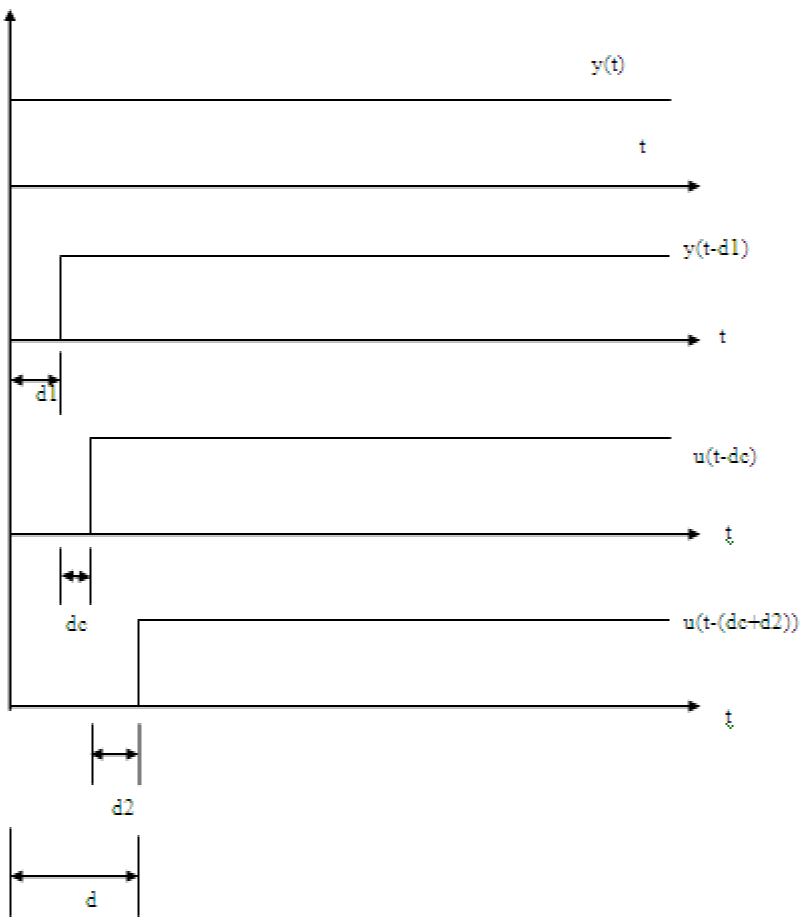


Figure1.7. Networked induced delay

Figure 1.7 shows the delay configuration in networked control system. y(k) is the plant output. y(k-d1) is the controller input.

where $\tau_1 = \frac{d_1}{T}$, d_1 is the delay induced between sensor and controller and T is the sampling period. u(k-dc) is the controller output.

where $\tau_c = \frac{d_c}{T}$, d_c is the computational time required by the controller.

u(k-(dc+d2)) is the plant input.

Where $\tau_2 = \frac{d_2}{T}$, d_2 is the delay induced between controller and actuator.

$\tau=\tau_1+\tau_c+\tau_2=\frac{d}{T}$ and $d=d_1+d_c+d_2$ is the total time delay induced in control loop.

The main resons of networked induced delays are computational delay which is considered negligible, networke accessing delay and tranmission delay.

The maximum transmission interval between two successive transmission is must be less than the maximum limit of time duration for maintaining the stability of the system. This is called Maximum Allowable Transfer Interval (MATI). The closed loop sytem will be stable if the following theorem is satisfied.

Theorem-1(Theorem-2, [91]): If there is p number of sensor nodes which are operating using Try Once Discard (TOD) or static scheduling methods and $\lambda_1=\lambda_{min}(P)$ and $\lambda_2=\lambda_{max}(P)$, then the MATI must be satisfied the following relation to maintain the globally exponentially stability.

$$\tau<\min\{\frac{\ln(2)}{p\|A\|},\frac{1}{8\|A\|(\sqrt{\lambda_1}/\lambda_2+1)\sum_{i=1}^{p} i},\frac{1}{16\lambda_2\sqrt{\lambda_1}/\lambda_2\|A\|^2(\sqrt{\lambda_1}/\lambda_2+1)\sum_{i=1}^{p} i}\}$$

Where P is a positive definite matrix is the solution of the following Lyapunov equation.

$$A_{cl11}{}^T P+PA_{cl11}=-I$$

A_{cl11} is thec closed loop system matix of the following closed loop system equation.

$$\dot{x}(t)=A_{cl11}x(t)$$

where $x(t)=[x_p(t),x_c(t)]^T$, $x_p(t)$ is the plant state vector and $x_c(t)$ is the controller state vector.

Now if the netwok is computed as error which is the difference between the output of the plant and input of the controller and this error is augmented with the state vector x(t) then new augmented state vector is obtained as $z(t)=[x^T(t),e^T(t)]^T$ and closed loop sytem is represented by the following equation.

$$\dot{z}(t)=Az(t)$$

The matrix A can be partitioned as follows.

$$A=\begin{pmatrix} A_{cl11} & A_{cl12} \\ A_{cl12} & A_{cl22} \end{pmatrix}$$

1.4.2 Packet loss and packet disorder

Genarally comunication medium is degital in nature. But real time plant is continious in nature. So before transmitting the plant output, it must be discretized. In NCS data is transmitted as packet.

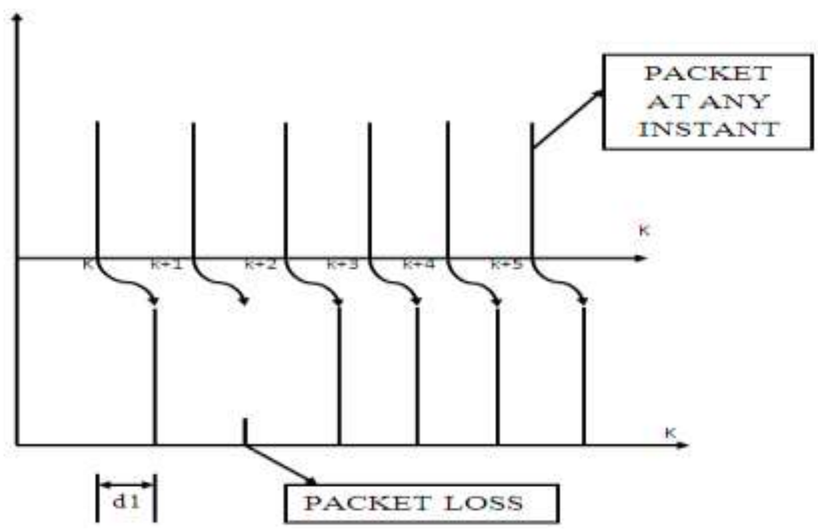


Figure1.8. Packet losses in NCS

Figure 1.8 shows the data packet transmission from plant output to the controller input. From the figure it is seen that at k+1 instant data packet is lost. The main reasons of packet loss and disorder are network trafic congestion, node failure and an excessivly long transmission delay which can be considered as packet losses. The packet disorder problem is arised if the networked induced delay is more than one sampling period. In most of the network protocol has retransmission facility if packet losses occure but this is valuable for the limited time duration. After that the packet loos occurred. In some networked protocol there is no retransmission mechanism which may be good for real time clsosed loop feedback system as the controller alaways receives the updated data every time. Generaly closed loop control system can tolarate packet loss upto a certain bound after that the closedv loop control sytem performance may degaded or it may becomes unstable. To maintain the stability there is a lower bound of the data transmission rate after which the closed loop sytem becomes unstable. The data rate theorem states that for a liner time invarient (LTI) system having the poles $s_1, s_2, ..., s_n$ in the right half plane ,the quantized feedback control law can stabilize the if the data rate R_d in the closed feedback loop path satisfies the following relation.

$$R_d > \log_2 e \sum \Re(s_i)$$

From this relation it can be said that for the large magnitude, a large data required to make the sytem is stable.

1.4.3 Jitter

Jitter is defined as the false variation in the duration of a time interval. The main resons of jitter are clock drift, scheduling, branching in the code and use of certain computer hardware like cache memory. Jitter distorts the control signal and degrads the performance of the system and may cause instability.

1.4.4 Time varying sampling intervals

If there are multiple sensor nodes and actuator nodes then multiple packets to be transmitted to the controller through the same network medium. Then the transmission interval between two successive transmission varied and it seems to be time varying. At this situation performance and stability of the closed loop system to be compromised.

1.4.5 Data quantization error

As the network medium is digital in nature, digital controller is used in networked control system. So plant output must be quantized before transmitting to the controller through network medium. As the data is quantized, there must be quantization error which may be reduced by increasing the number of bits used in quantization.

1.4.6 Single packet vessus Multiple-packet transmission

In single packet transmission sensors or actuator data are lumped together and then transmitted at the same time. But in case of multiple packet transmission a sensor or actuator data are beaked and transmitted in separate packets at different time instant. One reason of multiple packet transmission is that packet switched network can only support limited information in a single packet. Due to this a large data is broken into multiple packets and then transmitted in packet switched network. Other reason of multiple packet transmission is that the sensors or the actuators can be installed at different place in the plant due to which it may not be possible to pack all information in a single packet.

1.5 TIME DELAY ESTIMATION PROCEDURE IN NCS

The estimation of time delay induced in the closed loop is the first step to modeling the networked control systyem. The basic time delay estimation procedure is round trip time (RTT) delay estimation [28]. Round Trip Time delay is the time required for a signal to transmit from a specific source to the specific destination and then back to the source again. The source is basically a computer which send the signal abd destination is a remote computer which recevies the signal transmitted from the source computer. On the internet, RTT to and from an IP address can be estimated by pinging the address. The Round Trip Time is depends on the following parameters.

(1)the distance between source computer and destination computer

(2) source's internet conection's data transfer rate

(3) the number of nodes between source and destination

(4) types of tranmission medium used (copper, optical fiber, sattelite)

(5)external interference

(6) the tottal trafic on the network to which destination computer is connected

(7) the speed of intermediate nodes

But to achieve the higher accuracy in time delay estimation, the measurement with some compensation for offset is required. Network Time Protocol (NTP) [29] and Precision Time

Protocol (PTP, IEEE 1588) ([30], [31]) estimate round trip time delay with high accuracy. NTP has an accuracy in the range of sub-millisecond and PTP has the accuracy in the range of sub-microsecond. To estimate the synchronization time between two computers these two protocols exchange the message with accurate time stamping and then estimate the propagation time. They also estimate the offset between the clocks and take the action for compensation the offset. The time delay between signals recevied at two separated sensor can be estimated using Maximum Likelihood (ML) method ([32], [33] and [34]). The ML estimator is designed as a pair of reciver prefilter which is followed by a cross correlator. The time magnitude for which correlator achieves the maximum value is the estimation of time delay. The maximum networked induced delay can be calculated using network calculas theory ([35],[36] and [37]).

1.6 NETWORK SCHEDULING METHOD

Scheduling method is a technique to prioritize the permission of different nodes for accessing the network in an NCS in some optimal way to guarantee the Quality of Services (QOS) of the network [92]. The controller is designed with considering the network. A typical scheduling method adopted in NCS can be represented by Figure1.9.

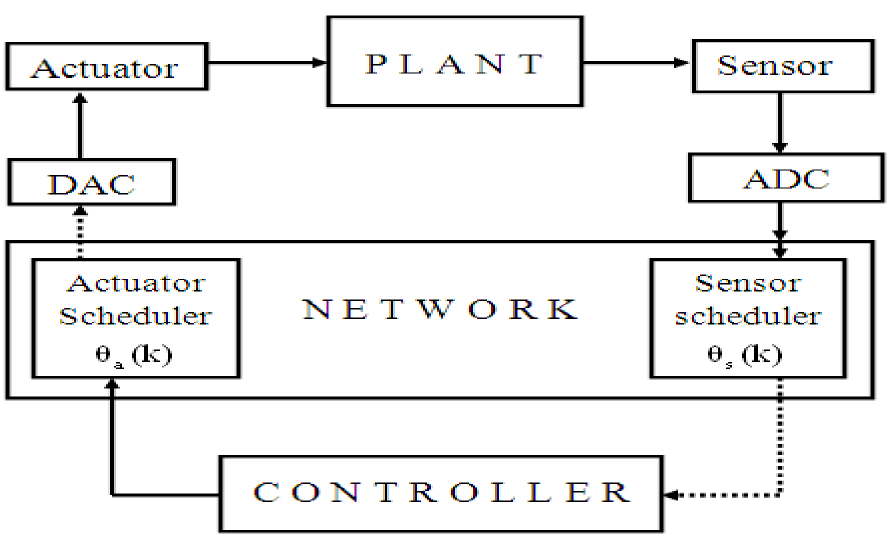


Figure1.9. Nentwork scheduling methods in networked control system

Where $\theta_s(K)$ is the sensor scheduler and $\theta_a(k)$ is the actuator scheduler. The schedulers are basically binary matrices which have zerors everywhere except some entries which is equal to one in the diagonal. There are two catagories of scheduling algorithms: open loop scheduling algorithm and closed loop scheduling algorithm. In open loop scheduling algorith, scheduling does not depends on the plant states. Roun Robin (RR) scheduling algorithm is an example of open loop sceheduling algorithm which may be used with TDMA or Token bus like deterministic protocol. In case of closed loop scheduling, scheduling depends on the plant states. In closed loop scheduling process, plant feedback is used to genarate the error and then the communication scheduling policy is implemented in such way such that the eroor is minimised. Maximum error first try once discard (MEF-TOD) is an example of closed loop scheduling methodes. This scheduling policy can be used in CAN like protocols which allows the bitwise arbitration (CSMA/ BA). Another example of the closed loop scheduling methods is Large error first (LEF) which scheduls the network according to the state distance fronm the equilibrium point. Here a Master-Slave strategy is used where master nodes scans the states of all slave nodes and takes the decision that which node should have prority. The message collision can be avoided using this scheduling algorithm as the prorities are assigned globally. Another scheduling algorithm is used to maximize the delay bound which is Linear Matix Inequality (LMI based. Maximum Urgency First (MUF) is another feedback based networked scheduler where scheduling based on the weigheted measure of the states of the process but scheduler is directly connected to each node using a separate network.

1.7 SOME IMPORTANT NETWORK USED IN NCS

There are two types of network- data network and control network. The data network can handle large data packets, high data rates, infrequent brusty transmission and not having hard real time constraints. The control network can handle countless small but frequent packet transmission among large number of nodes and can meet the time cretical requirment. The control network is more suitable for time critical application [38]. The main problem of networked control system is that it used the network for data transmission having finite bandwidth which is affected by sevaral parameters like sampling rate and network length, the number of elements that require synchonous operation and protocol used to control the data transmission [39]. Mainly three types of medium access control are used for control networks: random access having prioritization for collision avoidance (for example, control area network), random access having retransmission facilities when collisions occur (for example, Ethernet and most wireless mechanisms) and time division multiplexing (for example, tocken - passing). For operating control network, it must be specified that which type of message connection is used. Mainly three type of connections are used: polling, change of state (COS)/cyclic and strob. In case of polling, the master device transmits a message to the polled device and expect update information from that device. The device responds only after receving the poll message. In case of COS, the device send the message if the status of the device changes or it may send the message periodically (cyclic). In case of strobe connection, the master device transmits a strobed message to a group of devices all devices send their current status to the master device. In this case it is assumed that the all device sample the new information at the same time. The common used connection in industry are poll and strob [40]. The most widely used sublayer protocol for control networks are medium access control (MAC). This protocol satisfy the time critical and real time response over the network. It is also responsible to maintain the quality and reliability of communication between the network nodes [41]. The common type of networks used in industry are Ethernet, DeviceNet and ControlNet. To resolving the contention on the communication medium, Ethernet uses carrier sense multiple access (CSMA) with collision avoidance (CA) or collision detection (CD) mechanisms. There are three types of Ethernet networks: hub-based Ethernet which is used in office environment, switched Ethernet which is mainly used for automation in industry, wireless Ethernet. The main advantage of Ethernet network is tha it has low medium access overhead due to which it does not induce almost no delay if the network load is low [42]. It uses a simple algorithm for controlling the network. The common data rate standard for Ethernet is 10 Mbps (for example TCP/ Modbus). It also can support high data transmission rate as 100 Mbps or 1 Gbps. The main application of Ethernet is data network [43]. The main disadvantage of Ethernet is that it is a nondeterministic protocol and there is no option for message prioritization. If the network loads is high, message collision becomes a major problem in Ethernet network and time delay may become unbounded [42]. There are two ways to acomplish the time division multiplexing network: master-slave network and token passing network. In case of master-slave network, a single master polls a number of slaves and slave can send data over the network if there is a request from master. As a result it is free from data collision because the data transmission is scheduled in a deterministic manner. In case of token-passing network, there are multiple masters. Only that node will be allowed to send the message if it has token. After sending the message or if the maximum token holding time is over, this node will pass the token to the next logical node on the network. If a node has no data to send then it only passes the token to the neighbor node. In this case, data colliosion does not occurred as at a time only one node is allowed to send message. In token passing network, a linear, multidrop, segmented or tree-shaped topology is supported [42]. In token bus network, nodes are arranged into a ring logically and each node knows the address of the previous node and next node in the ring. The examples of master-slave networks are ASI, Bitbus and Interbus-S. The common examples of token passing networks are Profibus and ControlNet. The token bus protocol has excellent throughput and efficient at high network loads [41]. Another advantage of token passing network is that it allows adding or removing node from network dynamically. The main disadvantage of the token passing network is that if there are a large number of nodes in network, a large amount of network time is used for token passing when network load is small. CAN-Based network is a serial communication protocol which has good perfomance in time critical industrial application. The CAN protocol uses a CSMA/ arbitration on message prority medium access method. This protocol is message oriented and has a specific prority to arbitrate the access of the bus if there is simultaneous tranmission. For synchronization of the transmission of a bit stream, the start bit is used as identifier. In arbitration, logic zero identifier is dominant over a logic one identifier. When a node wants to transmit a message, it must be wait until bus becomes free and the it send the identifier of its message bit by bit. If two nodes want to transmit message simultaniously, the they start to send message simultanously and the listen to the network. The node will loss the right of accessing the bus if it receives a bit which is different from the one it sends out. CAN is one type of deterministic protocol which is optimal for short messages. As the higher priority messages alaways the permission to access the medium during arbitration, the higher priority messages have the guaranteed transmiision delay. The main disadvantage of CAN is that it has low data rate (500 Kbps) and it does not support fragmentation of data with the size more than 8 bytes. CAN networke is not suitable for tranmission large size data messages.

1.8 SOME IMPORTANT APPLICATION OF NCS

Now the application filed of NCS are large. The main application of NCs are

(1) Space craft and settalite control system

(2) Network robots

(3) Automobile industry

(4) Power system

(5) Military application

(6) Factory automation

(7) Traffic control system

1.9 LITRATURE REVIEW ON AVAILABLE METHOD TO COMPENSATE THE NETWORKED INDUCED DELAY

As the NCS is a limited communication system due to finite bandwidth shared network is used to close the control loop. Due to this NCS suffers from the problems like time delay, packet losses, jitter etc. This delay may be infinitely long if packet dropout occur and non-deterministic in nature. Due to this it is difficult to model the networked induced delay. The methods used to compensate the networked induced delay are developed on the augmentation, queuing and probability theory, perturbation theory, scheduling and nonlinear control theory. The all techniques used to compensate the networked induced delay can be grouped into three classes.

1. Control methods: In this category, for a given network a controller is designed considering the networked induced uncertainty and non-deterministic behavior to guarantee the Quality of Performance of the system (QOP).

2. Scheduling methods: In this category a controller is designed for a network free system and then a scheduling algorithm is designed to minimize the network's effects to guarantee the network Quality of Services (QOS).

3. Scheduling and controller co- design methods: In this category for a given plant and network an optimal scheduling method is designed to guarantee the Quality of Services (QOS) and simultaneously a controller is designed considering the network constraints to guarantee the Quality of Performances(QOP) .

Here some litaratures which explained the methodes which is used to compensate the networked induced dealy are reviewed.

In [44], a discrete time augmented model methodology is proposed to control a linear plant over a periodic delay network. An augmented state space model is developed where the state vector consists of plant state, delayed plant output, the controller state, and delayed controller output. In ([45], [46]) a queuing methodology is proposed for deterministic delay compensation where an observer is used to estimate plant state and a predictor is used to compute predictive control based on past output measurements. In [47], another queuing methodology is proposed for random delays where probabilistic information along with the number of packets in a queue is used to improve the state prediction. Using this methodology, any type of control law from the available various control algorithms can be used to compensate the networked induced delays. In ([48]), an optimal stochastic control methodology is proposed to control an NCS with the random delay where the effects of random delay are considered as Linear- Quadratic-Gaussian (LQG) problem. In ([49], [50]), network delay effects in an NCS is formulated as the vanishing perturbation of a continuous-time system assuming there is no observation noise. In this methodology, plant and controller are nonlinear, but linear control theory can be used for analysis and derivations. In [51], a sampling scheduling methodology is proposed to appropriately select the sampling period such that the networked induced delay does not significantly affect the control system performance if the multiple NCSs work on a periodic delay network and all NCS's components are known in advance. Also in this method it must be ensured that the delay is less than the sampling period. In [52], a controller is designed in the frequency domain using robust control theory. In this method, it is not required the information of the distribution of the delay in advance and the network delays are modeled as multiplicative perturbation. Here delays are assumed as bounded. In [53], fuzzy logic modulation methodology is proposed for NCS with linear plant and a modulated PI controller is used to compensate the networked induced delay effects. Here the PI controller gains are updated externally at the controller output based on the system output error due to the networked induced delay without redesigned the controller or without interruption of the system. In [54], an event based methodology is proposed to control a robotic manipulator over the internet where the system motion is used as reference. For example, for a robotic manipulator, the distance traveled by the end effectors is considered as motion reference function. In this case, the motion reference function must be a non-decreasing function to maintain the system stability. In ([55], [56]), an end-user adaptation methodology is proposed where the controller parameter is adapted according to the current traffic condition or the current network Quality-of-Services.

1.10 MOTIVATION TO DESIGN THE CONTROLLER FOR NCS

NCS has several technical as well as economic advantages like low cost, easy maintenance and reliability, flexible system design, simple and fast implementation and easy of system diagnosis and maintenance. The NCS reduce the system complexity when there are more sensors, actuators by eliminating the extra wiring with nominal investment. We can easily install a large number of sensors and actuators with minimum cost. There are some applications like, satellite control, space craft control where we must use the NCS. But NCS suffers from some unwanted phenomena like time delay, packet loses, jitter, data quantization error, multiple sampling period due to which it degrades the closed loop system performance and in the worst case the closed loop system may become unstable. Many well-known methods are developed to eliminate the adverse effect of quantization and constant loop delay in control system. But these methods are not suitable for NCS because the phenomena caused by the NCS are stochastic or variable in nature. Considering the constant delay, the control technology cannot perform well in NCS. For that, the controller has to be designed considering the stochastic or variable delay. To evaluate this view, in this thesis an LQR, an LQG-like and a MPC controller is designed considering the networked induced delay is variable in nature and it varies up to a maximum value.

1.11 CONTRIBUTION OF THE THESIS

(1) Gives an outlook of networked control system

(2) Developed a new augmented model for NCS considering long variable networked induced variable delay which is considered as plant input delay and much greater than the sampling period.

(3) Study the real time communication procedure between two PCs which are connected through an Ethernet network using UDP protocol.

(3) Design an LQR controller to compensate the networked induced variable delay.

(5)Analyze the stability of the closed loop system when LQR controller is used to compensate the networked induced delay.

(6) Design an LQG controller to compensate the networked induced variable long delay in noisy environment.

(7) Analyze the stability of the closed loop system when the LQG controller is used to compensate the networked induced delay in noisy environment.

(8) Design a MPC controller using Laguerre network to compensate the networked induced variable delay.

(9) Analyze the stability of the closed loop system when MPC controller is used to compensate the networked induced delay.

(10) A comparative study is done among the three controllers based on step response, time domain performance and frequency domain performance.

(11) Study the Laguerre network, Kalman filter and full order state observer.

1.12 THESIS LAYOUT

Chapter 1: Gives an overview expalnation of NCS

Chapter 2: Represents the augmentated model of NCS

Chapter 3: Expalined the communication procedure between two PCs using UDP protocol

Chappter 4: Design procedure of LQR controller based on augmented model is expalined and simulation results of an Integrator palant using MAT LAB software and results obtained in real time experiment are given.

Chapter 5: A method to compensate the networked induced long variable delay in noisy environment is explained and an integrator plant is simulated using MAT LAB software to so the effectiveness the LQG controller.

Chapter 6: Design procedure of MPC controller based on augmented model is expalined to compensate the networked induced long variable delay.

Chapter 7: A comperison is made among the three controller based on closed loop setep response and the values of time domain parameter and frequency domain paramete of closed loop system.

Chapter 8: The thesis is concluded.

Chapter 9: a suggestion for future scope of work

2 CHAPTER 2- AUGMENTED MODEL OF NCS

2.1 INTRODUCTION

To design the controller for any system first requirement is the model of the system to be controlled. In networked control system, as the information exchanges through the network, time delay induced in the closed loop path. So it makes the overall system a time delay system. At early stage of NCS research when it was difficult to obtain the random distribution characteristics of delay, the random delay is modeled as constant delay by using a buffer at the controller and actuator node ([57],[58]). The size of the buffer is equal to the maximum delay induced by the network. The main problem of this model is that it treats all delay as the maximum delay of buffer size. But the network induced delay is stochastic in nature due network load, network congestion and nodes competition. So the constant delay model is not appropriate for network control system. In 1998, Nilsson et al. designed an LQG controller based on mutually independent stochastic delay model where each delay is considered as a mutually independent stochastic variable and a stochastic function describes it's distribution [59]. But stochastic delay is not always mutually independent. Sometimes it is seen that there are some probabilistic dependency relationships among the delays, such as Markov chain and Bernoulli distribution. In [60] the sensor to controller delay and controller to actuator delay are summed up to obtain a single delay which is governed by Markov chain [60]. The networked induced delay is stochastic in nature due to many stochastic factor like network load, nodes competition and network congestion. This all factor can be considered in network modelling as netwok state which is hidden variable. When the network is modeled using Markov chain considering network sate, it is called hidden Markov chain model because the network state cannot be observed directly but it can be estimated from network delay. In Markov chain model the current delay is governed by previous delay. But in case of Hidden Markov Model (HMM), the current delay is governed by current network state. The HMM was first developed by Nilsson [48]. He considered the network load as network state. He considered three state: "L" for low network load, "M" for medium network load and "H" for high network load. The transition between different state is modeled as a Markov chain and at every state a delay distribution model is used for delay which was considered as HMM. In [61], a switched linear system model is developed considering both packet loss and networked induced delay. In [62], anautoregressive (AR) prediction model is developed to represent the time delayed and lost sensor data. In [63], a augmented statespace model is designed for long time delay where augmented state vector is consists of original state and delayed input vector $u(k-d), u(k-(d+1)) \ldots\ldots u(k-1)$. In [64] and [65], an augmented state space model is proposed same as [63] for networked control system. But here the plant is discretized considering the networked induced delay. Actually they have considered that the plant is a delayed plant with including the networked induced delay. But it is not the actual case. In actual case the discretized output is transmitted to the controller and during the transmission the delay is induced. Same is happned to the control signal also. So in actual case plant output and control input is delayed. But plant may not be internally delayed due to this networked induced delay. So here an augmentation model is proposed where the delay is considered after the discretizing the plant. The total closed loop delay is considered as plant input delay. Then an new augmentation model is developed for NCS.

2.2 AUGMENTED MODEL OF NCS

Let the continuous linear time invariant system is represented by the following state space equation.

$$\begin{aligned} \dot{x}(t) &= A\,x(t) + B\,u(t) \\ y(t) &= C\,x(t) \end{aligned} \tag{2.1}$$

Where, x(t)- state vector, u(t)- system input, y(t)- system output, A-system matrix, B- input matrix, C- system output matrix.

Now discretize the plant considering the sampling time T.

Let the discretize the state space equation is given by

$$\begin{aligned} x(k+1) &= A_d\,x(k) + B_d\,u(k) \\ y(k) &= C_d\,x(k) \end{aligned} \tag{2.2}$$

Where, and

Assume the network-induced delay is bounded by a maximum value as follows

$$0 < d \leq d_{max} \tag{2.3}$$

$$d = d_1 + d_2 \tag{2.4}$$

It is also assumed that the network-induced delay is greater than the sampling period i.e. $d > T$ and the delay is the integer multiple of the sampling period.

Delay time can be sampled as follows.

$\tau = \frac{d}{T}$, where τ is an integer value.

Now consider that input is delayed by d second. Here we use the augmentation technique to model the plant. The model is as follows.

$$\begin{pmatrix} x(k+1) \\ u(k-(\tau-1)) \\ u(k-(\tau-2)) \\ \vdots \\ u(k-1) \\ u(k) \end{pmatrix} = \begin{pmatrix} A_d & B_d & 0 & 0 & \dots & 0 \\ 0 & 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & 0 & \dots & 1 \\ 0 & 0 & 0 & 0 & \dots & 0 \end{pmatrix} \begin{pmatrix} x(k) \\ u(k-\tau) \\ u(k-(\tau-1)) \\ \vdots \\ u(k-2) \\ u(k-1) \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix} u(k) \tag{2.5}$$

$$y(k) = [C_d \ 0 \ 0 \ 0 \ \dots\dots \ 0] \begin{pmatrix} x(k) \\ u(k-\tau) \\ u(k-(\tau-1)) \\ \vdots \\ u(k-2) \\ u(k-1) \end{pmatrix}$$

$$\begin{aligned} z(k+1) &= \Pi z(k) + \Gamma u(k) \\ y(k) &= \Xi z(k) \end{aligned} \tag{2.6}$$

Where $z(k) = \begin{bmatrix} x(k) & u(k-\tau) & u(k-(\tau-1)) & \dots & u(k-2) & u(k-1) \end{bmatrix}^T$ is the augmented state vector

$\Pi = \begin{pmatrix} A_d & B_d & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & 0 & \dots & 0 \\ 0 & 0 & 1 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \dots & 1 \\ 0 & 0 & 0 & 0 & \dots & 0 \end{pmatrix}$ is the augmented system matrix, $\Gamma = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix}$ is the augmented input matrix and $\Xi = [C_d \quad 0 \quad 0 \quad 0 \quad \cdots \quad 0]$ is the augmented output matrix.

Using this augmented model we can design any type of state feedback controller which is easy to design.

2.3 CHAPTER SUMMARY

From this chapter, the idea about the differents modeling method of NCS is obtained. In this chapter a new augmented model of NCS is derived where it is assumed that the palnt is discrete one and all delay is considered as input delay. The augmented sate vector consists of actual plant sate and all posible delayed input upto possible maximum delay may induced in closed loop path.

3 CHAPTER 3- COMMUNICATION PROCEDURE BETWEEN TWO PCs USING UDP PROTOCOL

3.1 INTRODUCTION

For real time experiment, two PCs are taken which are connected over a Local Area Network (LAN) [66]. The medium of the connection is Ethernet. One PC is considered as controller and in other PC a subsystem of the plant intends to control is built using MAT LAB Simulink software. To exchange the data between two PCs, User datagram Protocol (UDP) of MATLAB software is used. The closed loop communication is considered to establish the closed loop control. For that both PCs have the capability of data sending and data receiving. So it is a two way communication or duplex type communication.

3.2 USER DATAGRAM PROTOCOL (UDP)

It is a simple communication protocol with minimum of protocol mechanism [67]. It is used to make the availability of a datagram mode for the packet switched computer communication in an interconnected set of computer networks environment, assuming that the Internet Protocol (IP) is behaved as the underlying protocol. It does not support any handshaking dialogue and for which it provides an unreliable communication. It gives no guarantee of the delivery of message and duplicate protection. It does not give surety of the secure communication. If the application needs the security in communication then this protocol must be used with additional protocol mechanism which will be responsible for security in communication. Although the UDP has many disadvantages it is used in NCS because it has the faster rate of the data transmission.

3.3 STRUCTURE OF UDP PACKETS AND UDP HEADER

UDP packets consist of two fields: UDP header and data. A general structure of UDP packets is shown in figure below. The length of the UDP header is 8 bytes and the length of the data field varies between 0 and 65527 bytes.

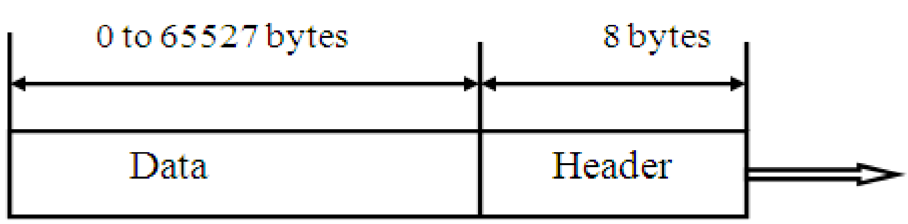


Figure3.1 UDP packet format

The UDP header has four fields. The size of each field is two bytes. A general structure of UDP header is shown in Figure3.1.

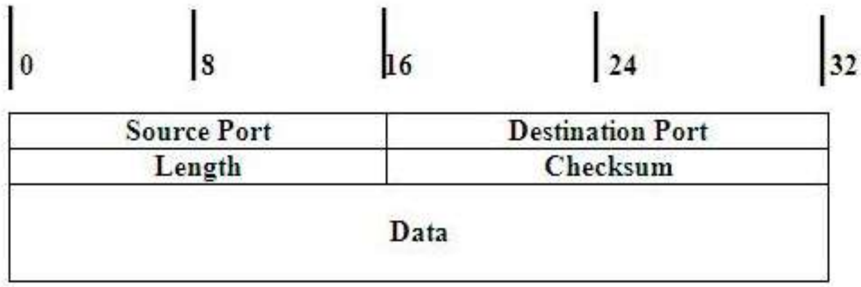


Figure3.2. Header format of UDP packet

The source port is a 16 bit port number of the sender from which UDP massage is to be sent. Destination port is the 16 bit port number of the receiver where the UDP massage is to be sent. Checksum is an error checking and correction procedure over the entire datagram. This field is also 16 bit. Data is the encapsulated message to be sent and length is the length of entire datagram which contains of both header and data fields.

3.4 CLOSED LOOP COMMUNICATION PROCEDURE BETWEEN TWO COMPUTERS

The total procedure to make the closed communication between two PCs can be explained according to the following steps.

3.4.1 Basic setup to make closed loop communication between two PCs

The basic set up to make the closed loop communication between two PCs is given below in Figure.3.3.

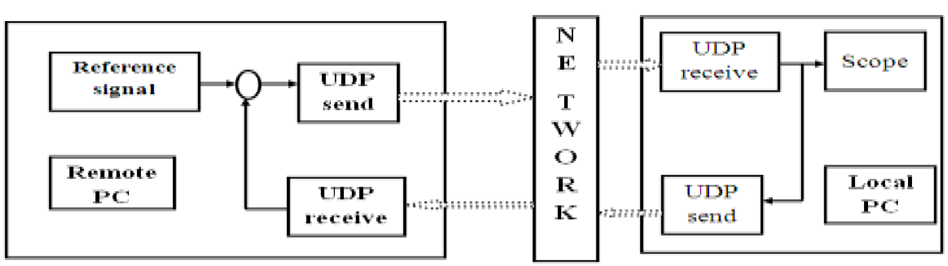


Figure3.3. Setup for closed loop communication between to PCs using UDP protocol

Before starting the real time experiment real time kernel in MATLAB should be installed using the command 'rtwintgt –install' which is shown in Figure3.4.

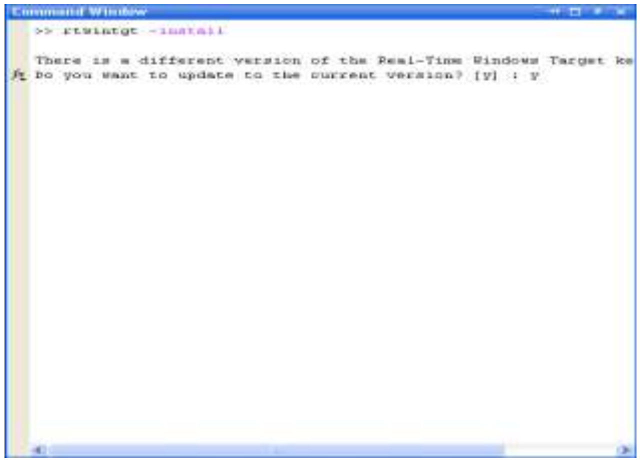


Figure3.4. Installation of real time Kernel in MATLAB software

3.4.2 Setting of remote PC

Consider Figure3.3. There are two embedded MATLAB Simulink block UDP send and UDP receive in remote PC. These blocks ask for the IP address of the receiving computer. So both the blocks contain the IP of the local PC. In the real time experiment, the local PC is used as plant. Figure3.5 shows the set up for the UDP send block and UDP receive block, where the IP address is the address of local PC (Plant) is used in the real time experiment as plant.

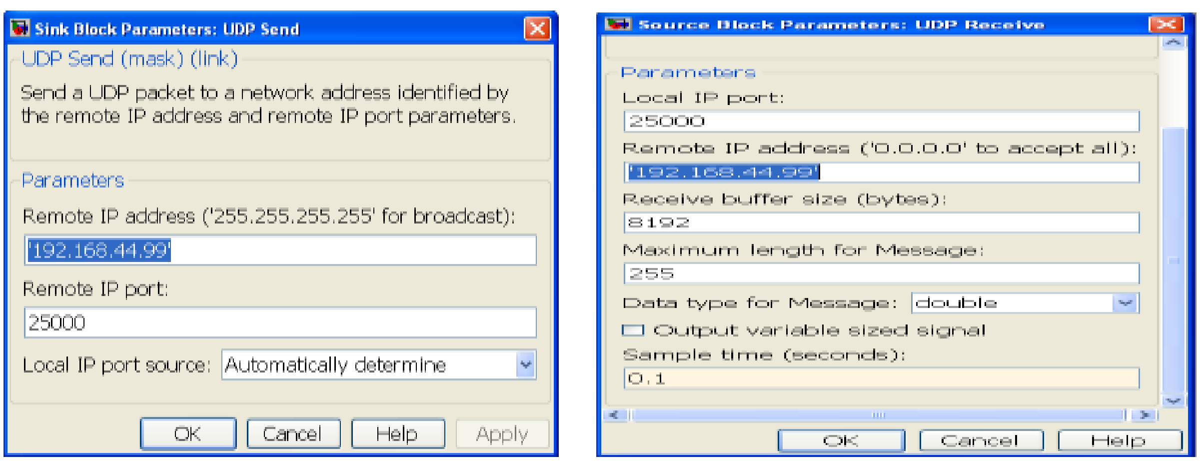


Figure3.5. Setting of UDP send and UDP receive in remote PC

3.4.3 Setting of local PC

In case of local PC, which is designed as plant in real time experiment contain the UDP send block and UDP receive block. In this case this block contains the IP address of remote PC which is designed as controller in real time experiment. Figure3.6. Shows the setting of UDP send and UDP receive block for real time experiment.

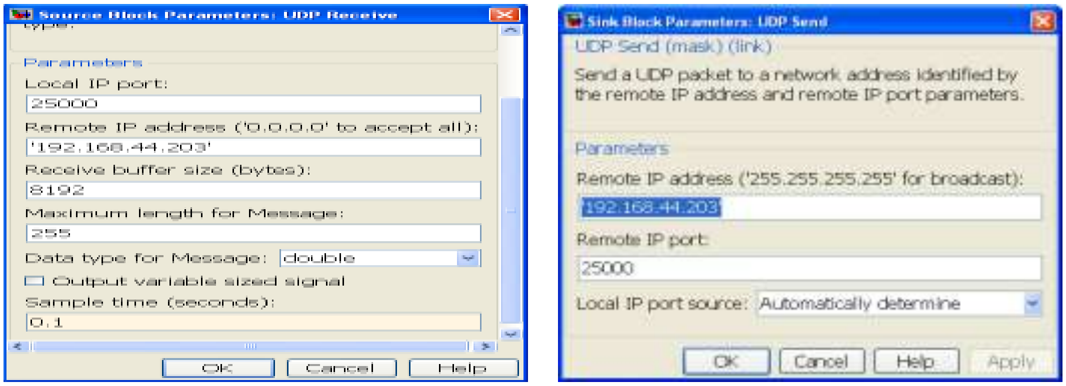


Figure3.6. Settings of UDP send and UDP receive in local PC

3.5 EXPERIMENTAL SETUP FOR REAL TIME EXPERIMENT

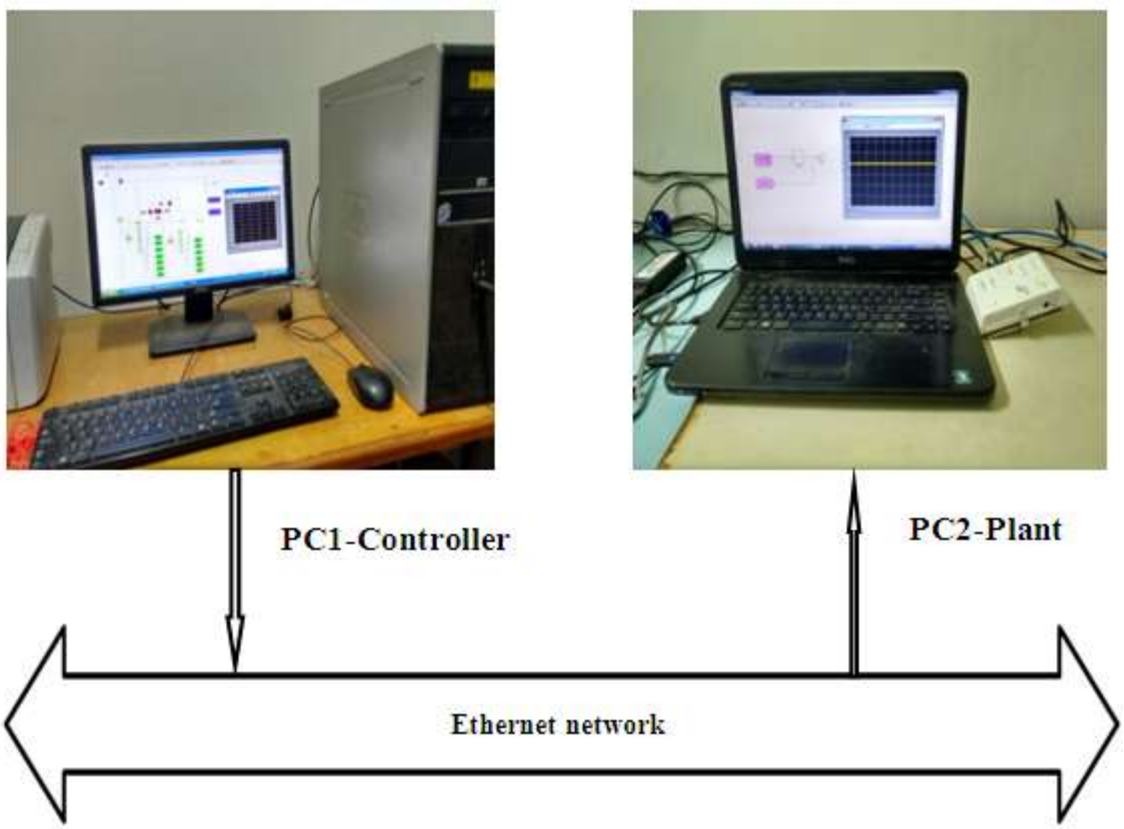
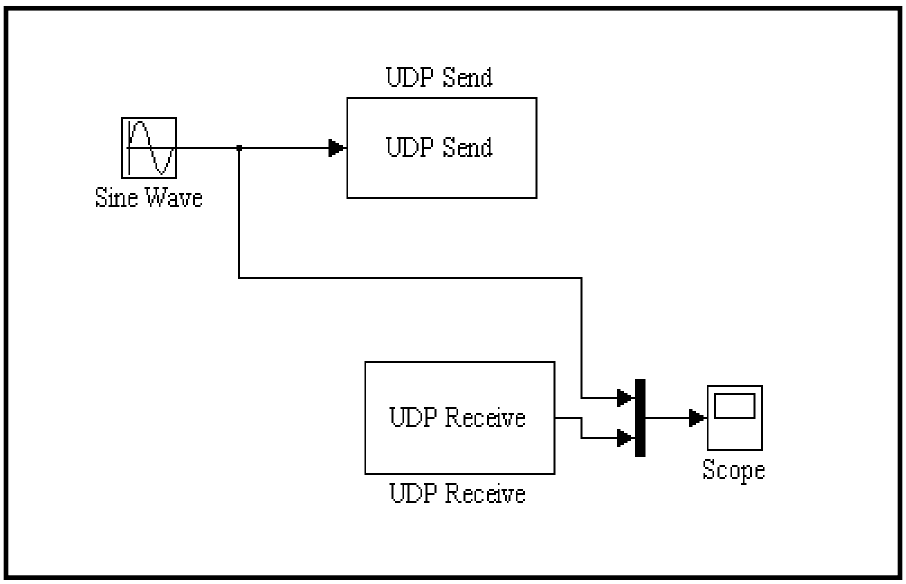


Figure3.7.Experimental setup for real time experiment

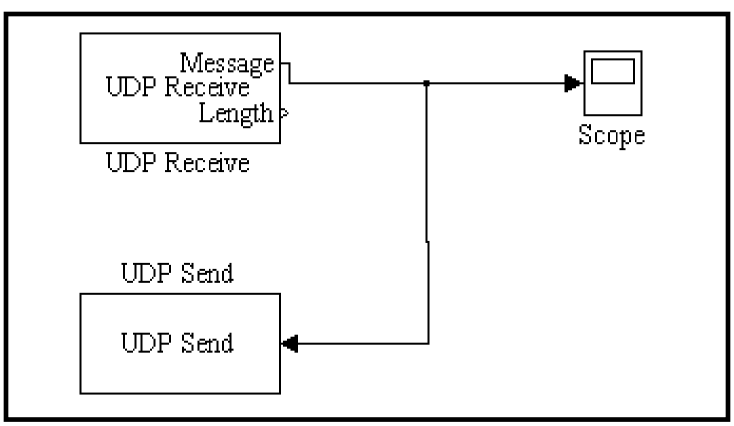
Figure3.7 shows the real time experiment setup where two PCs are connected though an Ethernet network. PC1 is used as controller and PC2 is used as plant. In PC2, a subsystem of the plant is modeled using MATLAB software.

3.6 TIME DELAY ESTIMATION USING RTT TECHNIQUE

The estimation of Round Trip Time for a signal for transmitting from the remote computer to the local computer and the back to the remote computer is done by using following simulink model.



a) Model in remote PC for closed loop communication



b) Model in local PC for closed loop communication

Figure3.8. Process of closed loop communication between two PCs using UDP protocol

Consider Figure3.8, where Figure (a) represents the remote PC and Figure (b) represents the local PC. From remote PC, a sinusoidal signa is sent to the local PC and the receive signal of local PC is sent back to the remote PC. In remote PC, the sending signal and the receving signal is comparedd which is shown ic scope.

Following this procedure we have estimated the round trip time between two PCs which are used as controller and plant in the real time experiment. The two PCs are placed in two different room and connected through Ethernet network.

The IP address of remote PC is 192.168.44.203 and the IP address of local PC is 192.168.44.195.

The display of the scope in remote PC is shown in Figure3.7

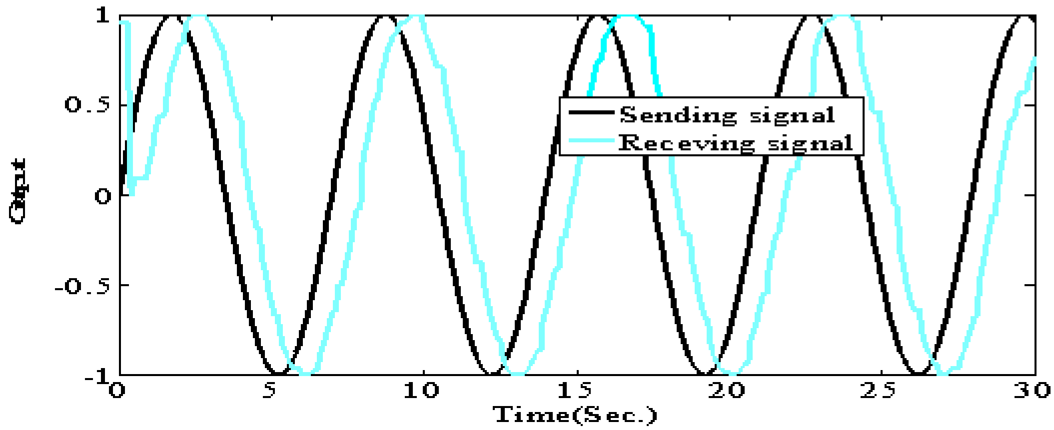


Figure3.9. Calculation of Round Trip Time between two PCs connected through Ethernet network

From Figure3.9, it is seen that the round trip time delay between two PCs is approximately 1 sec second.

The controller is designed based on the estimated maximum round trip delay. But the controller works efficiently if the actual induced delay is less than the maximum estimated delay which is used to design the controller. So over approximation will give the better result. It means if we have estimated the delay which is greater than the actual delay, controller will give the better result.

3.7 CHAPTER SUMMARY

In this chapter, properties of UDP protocol are presented. Then the closed loop communication procedure between two PCs using the UDP protocol in MATLAB software is discussed. At last, estimation procedure of round trip time is explained using real time experiment.

4 CHAPTER 4- DESIGN OF OUTPUT FEEDBACK LINEAR QUADRATIC REGULATOR TO COMPENSATE LONG VARIABLE NETWORKED INDUCED DELAY

4.1 INTRODUCTION

Optimality is a one of the main requirement of any system. For example, for financial system of an organization, the expenditure should be minimised. For a transpoting system the distance travelled by a car should be maximised using specific amount of fuel. So the optimisation (maximisation or minimisation) of it's ouput or input is one of the main targets for any system. In control theory, to optimised the control input or system output optimal control theory is used which is developed based on calculas of variation. The optimal control law is derived using Pontryagin's minimum principal (necessary condition) or can be solved using Hamilton-Jacob-Bellman equation. The main optimal controllers are Linear Quadratic Regulator (LQR), Linear quadratic Gaussian (LQG) controller. To compesate the networked induced delay, a number of methods are developed using Smith predictor, Predictive control technique, robust control technique, fuzzy logic and model predictive control technique. But there are few works reported in literature that employ Linear Quadratic Regulator (LQR) to compensate the networked induced delays.In [64], an LQR-output feedback controller is designed based on augmented state space model where state vector consists of actual state and delayed state vector. Here it is assumed that the delay is induced between sensor and controller. In [68], an adaptive regulator based on LQR approach is designed to compensate the networked induced variable delay. The gain of the controller is varied according the delay induced in channel. But delay is considered less than sampling period. In [69], a LQR controller is designed based on a delayed state variable model for networked control system with variable delay which is considered less than sampling period.

Here an LQR output feedback controller is developed for augmented plant. The output of the plant is estimated using full order state observer. This estimated output is used for the feedback to the controller. We have simulated an integrator plant using MATLAB software. From the simulation result, it is seen that the output of the integrator plant is stable and the output of the plant perfectly tracks the step reference input.

4.2 DESIGN OF LQR CONTROLLER TO COMPENSATE THE NETWORKED INDUCED VARIABLE DELAY

Here we have designed an LQR output feedback controller [70]. The plant output is estimated using full order state observer as it is delay by the feedback path delay. The estimation is done based on the available delayed output. Here we have considered there is delay in both feedback path and forward path. Now we are interested to design an LQR estimated output feedback controller for the augmented system represented by the equation (2.2) which will minimize the the following cost function.

$$J(k) = \frac{1}{2}\sum_{k=0}^{\infty} [y^T(k) Q y(k) + u^T(k) R u(k)]$$

$$= \frac{1}{2}\sum_{k=0}^{\infty} [Z^T(k) \Xi^T \Xi Z(k) + u^T(k) R u(k)] \qquad (4.1)$$

Where, Q is a positive semidefinite matrix and R is the positive definite matrix. The initial value for Q can be taken as $\Xi^T \Xi$ which iwill be better choice for reference tracking.

Then the optimal control input can be obtained as

$$u(k) = r(k) - \sum_{j=1}^{n} K_j \hat{C}_{dj} \hat{x}(j) - \sum_{i=1}^{\tau} K_{i+n} u(k-(\tau+1-i))$$

$$= r(k) - \sum_{j=1}^{n} K_j Y_e(j) - \sum_{i=1}^{\tau} K_{i+n} u(k-(\tau+1-i))$$

$$= r(k) - K_n Y_e(k) - \sum_{i=1}^{\tau} K_{i+n} u(k-(\tau+1-i)) \qquad (4.2)$$

Where, $\hat{x}$ is the estimated state of the full state observer. $k = [K_n \; K_d]$,the gain matrix is a row vector of dimension 1 x (n+d). $Y_e(j)$ is the full state observer output.

Gain matrix can be obtained as

$$K = [R + \Gamma^T P(k+1) \Gamma]^{-1} \Gamma^T P(k+1) \Pi \qquad (4.3)$$

Where P is the solution of following differential matrix Riccati equation.

$$P = G^T [P(k+1) - P(k+1)\Gamma(\Gamma^T P(k+1)\Gamma + R)^{-1}\Gamma^T P(k+1)]\Pi + Q \qquad (4.4)$$

If $k \to \infty$, then P(k+1)=P(k)=P, a constant value.

The augmented closed loop system is given by

$$z(k+1) = (\Pi - \Gamma KC) z(k)$$
$$z(k+1) = A_{cl} z(k) \qquad (4.5)$$

where $A_{cl} = (\Pi - \Gamma KC)$

The complete closed loop system is shown in figure below.

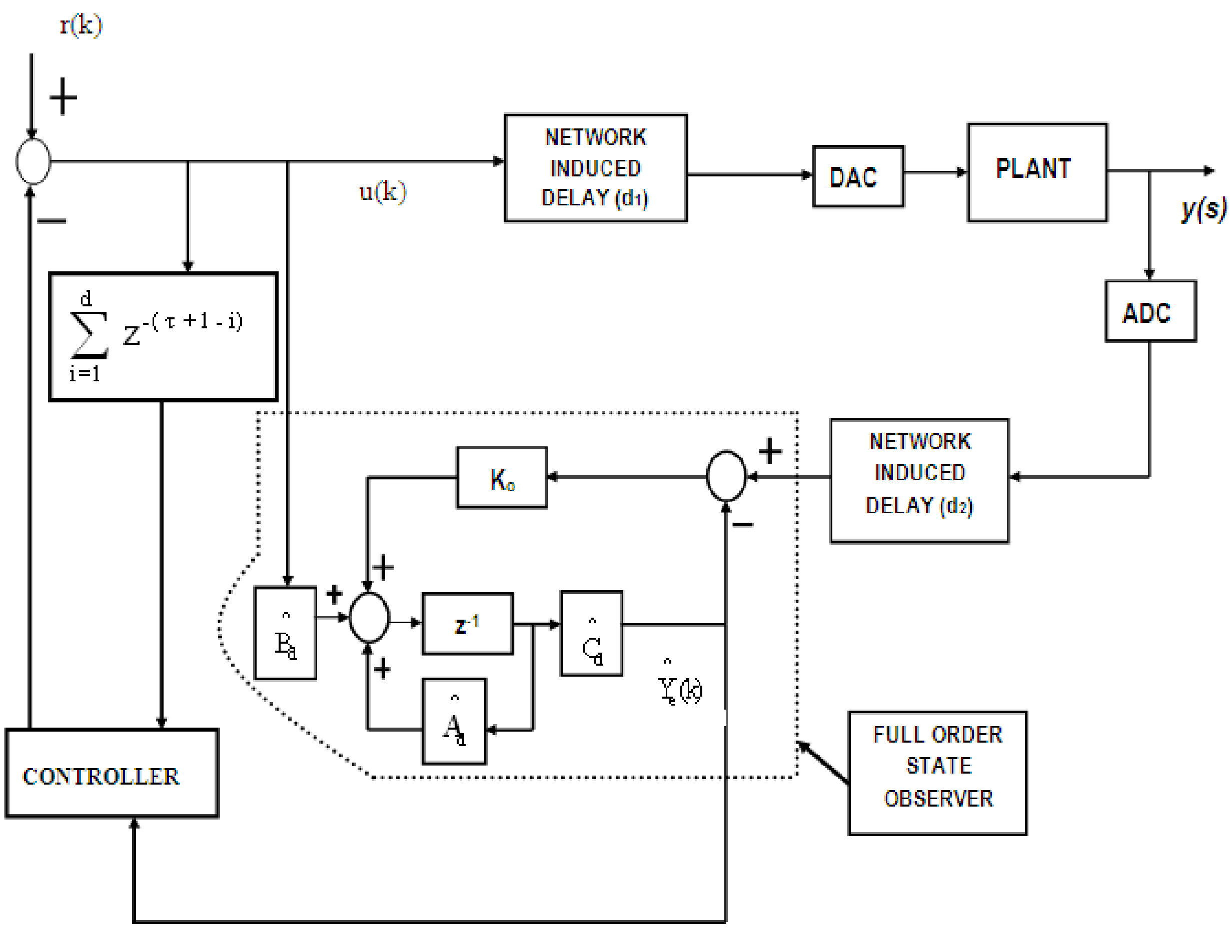


Figure4.1. Closed loop system with LQR controller

r(k)-reference input, y(k)-system output, Gp(s)- plant, $\hat{A}_d$ -Estimated system matrix, $\hat{B}_d$ - Estimated input matrix, $\hat{C}_d$ -Estimated output matrix, Gc(z)-discretized controller, d_1- networked induced delay in forward path, d_2-networked induced delay in feedback path, Ko-Observer gain, Y_e-output of full order state observer.

4.3 CALCULATION OF OBSERVER GAIN

The full order state observer can be represented by the following equation

$$\begin{aligned} \hat{x}(k+1) &= \hat{A}_d \hat{x}(k) + \hat{B}_d u(k) + K_o(y(k-\tau_2)-Y_e(k)) \\ Y_e(k) &= \hat{C}_d \hat{x}(k) \end{aligned} \tag{4.6}$$

Now consider $\hat{A}_d = A_d$, $\hat{B}_d = B_d$ and $\hat{C}_d = C_d$.

To find out the optimal gain of the observer we have used the LQR design technique ([71], [72]).To obtain the optimal gain of the observer, we replace (A_d, B_d) by (A^T, C^T) in LQR design technique. To obtain the gain, we can solve the following equations.

$$A_d P_o + P_o A_d^T + Q_o - P_o C_d^T R_o^{-1} C_d P_o = 0 \tag{4.7}$$

$$K_o = P_o C_d^T R_o^{-1} \tag{4.8}$$

Where, K_o is the observer gain. Qo and Ro are the observer design matrices and Po is the auxiliary matrix. Equation (4.7) is called the observer algebraic Riccati equation.

4.4 ANALYSIS OF CLOSED LOOP SYSTEM WITH FULL ORDER STATE OBSERVER AND LQR CONTROLLER

From equation (2.2) and equation (4.2), the following state space equation can be obtained.

$$x(k+1) = A_d x(k) + B_d r(k) - B_d Y_e(k) - B_d \sum_{i=1}^{d} K_{i+n} u(k-(\tau+1-i))$$

$$\begin{aligned} &= A_d x(k) + B_d r(k) - B_d Y_e(k) - B_d u_d(k) \\ &= A_d x(k) + B_d r(k) - B_d C_d \hat{x}(k) - B_d u_d(k) \end{aligned} \tag{4.9}$$

where $u_d(k) = \sum_{i=1}^{d} K_{i+n} u(k-(\tau+1-i))$

Putting the value $\hat{x}(k)=x(k)-\tilde{x}(k)$ in equation (4.9)

$$\begin{aligned} x(k+1) &= A_d x(k) + B_d r(k) - B_d C_d x(k) + B_d C_d \tilde{x}(k) - B_d u_d(k) \\ &= B_d C_d \tilde{x}(k) + (A_d - B_d C_d) x(k) + B_d r(k) - B_d u_d(k) \end{aligned} \tag{4.10}$$

To analysis the closed system considers Figure4.2. From this figure it is seen that up to d_2 instant there is only observer output. After d_2 both outputs are appeared.

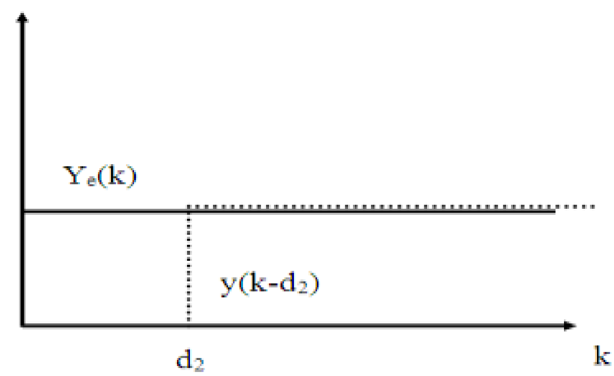


Figure4.2. Synchronization between system output and observer output

Case1: Up to the time instant d_2

Up to d_2, this equation (4.6) can be written as follows.

$$\begin{aligned} \hat{x}(k+1) &= \hat{A}_d \hat{x}(k) + \hat{B}_d u(k) - K_o Y_e(k) \\ &= \hat{A}_d \hat{x}(k) + \hat{B}_d u(k) - K_o C_d \hat{x}(k) \\ &= (\hat{A}_d - K_o C_d) \hat{x}(k) + \hat{B}_d u(k) \end{aligned} \tag{4.11}$$

Subtracting the equation (4.9) from the equation (2.2) the following relation is obtained.

$$\begin{aligned} \tilde{x}(k+1) &= A_d \tilde{x}(k) + K_o C_d x(k) - K_o C_d \tilde{x}(k) \\ &= (A_d - K_o C_d) \tilde{x}(k) + K_o C_d x(k) \end{aligned} \tag{4.12}$$

From the equation (4.10) and equation (4.12), the augmented closed loop state space equation can be written as follows.

$$\begin{pmatrix} \tilde{x}(k+1) \\ x(k+1) \end{pmatrix} = \begin{pmatrix} (A_d\text{-}K_oC_d) & K_oC_d \\ B_dC_d & (A_d\text{-}B_dC_d) \end{pmatrix} \begin{pmatrix} \tilde{x}(k) \\ x(k) \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ B_d & \text{-}B_d \end{pmatrix} \begin{pmatrix} r(k) \\ u_d(k) \end{pmatrix} \tag{4.13}$$

Case-2: after the time instant d_2

After the time instant observer dynamics is given by the equation (4.6).

Subtracting the equation (4.6) from (2.2), the following error equation is obtained.

$$\tilde{x}(k+1)=(A_d\text{-}K_oC_d)\,\tilde{x}(k) \tag{4.14}$$

From equation (4.10) and equation (4.14), the augmented closed loop state space equation cab be written as

$$\begin{pmatrix} \tilde{x}(k+1) \\ x(k+1) \end{pmatrix} = \begin{pmatrix} (A_d\text{-}K_oC_d) & 0 \\ B_dC_d & (A_d\text{-}B_dC_d) \end{pmatrix} \begin{pmatrix} \tilde{x}(k) \\ x(k) \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ B_d & \text{-}B_d \end{pmatrix} \begin{pmatrix} r(k) \\ u_d(k) \end{pmatrix} \tag{4.15}$$

4.5 STABILITY ANALYSIS OF CLOSED LOOP SYSTEM USING LQR CONTROLLER AND FULL ORDER STATE OBSERVER

The stability of the closed loop system is analyzed in two steps.

Step1: stability of closed loop augmented system

For stabilizing the closed loop system, the Eigen values of the matrix $(\Pi\text{-}\Gamma KC)$ should be within the unit circle.

We can also check the Eigen values of the augmented closed loop system matrices from the equation (4.15) and from equation (4.13) for after time instant d_2 and after time instant d_2 respectively.

After time instant d_2 Eigen values of the closed loop system can be obtained from the following equation.

$$\left(\lambda I\text{-}\begin{pmatrix} (A_d\text{-}K_oC_d) & 0 \\ B_dC_d & (A_d\text{-}B_dC_d) \end{pmatrix}\right)=0 \tag{4.17}$$

From the equation (4.17), the following relations can be obtained.

$$[\lambda I-(A_d-K_oC_d)]=0 \tag{4.18}$$

$$[\lambda I-(A_d-B_dC_d)]=0 \tag{4.19}$$

Before the time instant d_2 Eigen values of the closed loop system can be obtained from the following equation.

$$\left(\lambda I-\begin{pmatrix}(A_d-K_oC_d) & K_oC_d \\ B_dC_d & (A_d-B_dC_d)\end{pmatrix}\right)=0 \tag{4.20}$$

For stability, the roots of the equations (4.18), (4.19) and (4.20) should be within the unit circle.

Step2: Lyapunov stability criterion for asymptotic stability of the augmented closed loop system

The stability of the closed loop system is ensured if there exists a positive definite matrix P such that the following Lyapunov function is satisfied.

$$V(z(k),k)=z^T(k)Pz(k) \tag{4.21}$$

$$V(z(k+1),k+1)=z^T(k+1)Pz(k+1) \tag{4.22}$$

The closed loop system will be stable if the following criterion is satisfied.

$$\begin{aligned}\Delta V(z(k),k)&=V(z(k+1),k+1)-V(z(k),k)\\&=z^T(k+1)Pz(k+1)-z^T(k)Pz(k)\\&= z^T(k)A_{cl}{}^TPA_{cl}z(k)-z^T(k)Pz(k)\\&=z^T(k)(A_{cl}{}^TPA_{cl}-P)z(k)\end{aligned} \tag{4.23}$$

As $V(z(k),k)$ is chosen as positive definite, $\Delta V(z(k),k)$ must be negative definite.

From equation (4.23), the following relation is obtained.

$$\Delta V(z(k),k)= -z^T(k)Qz(k)$$

$$A_{cl}^TPA_{cl}-P=-Q \tag{4.24}$$

The matrix Q is to be chosen a positive definite matrix. Matrix P must be positive definite matrix for necessary and sufficient condition for the asymptotic stability of the equilibrium sate Z(k) =0

4.6 SIMULATION OF AN INTEGRATOR PLANT USING LQR CONTROLLER

For the simulation, an integrator is taken as plant. It is considered that there is a variable delay of maximum value 0.6 second in the forward path. There is also a variable delay in the feedback path of estimated maximum value of 0.6 seconds. The plant is discretized at a sampling rate of 0.1 second.

The continuous time state space equation of the integrator is obtained as follows.

$$\begin{aligned} \dot{x}(t) &= u(t) \\ y(t) &= x(t) \end{aligned} \tag{4.25}$$

The discrete time state space equation can be obtained as follows.

$$\begin{aligned} x(k+1) &= x(k)+0.1u(k) \\ y(k) &= x(k) \end{aligned} \tag{4.26}$$

The observer gain is obtained as 0.1.considering R_o=9 and Q_o=0.1.

The augmented state space matrices can be obtained as follows.

$$\Pi=\begin{pmatrix} A_d & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$\Gamma=[0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1]^T$

$\Xi=[1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$

The controller gain is obtained as

K= [0.9952, 0.0995, 0.0995, 0.0995, 0.0995, 0.0995, 0.0995, 0.0995, 0.0995, 0.0995, 0.0995, 0.0995, 0.0995]

Considering R=1 and $Q=\Xi^{T}\Xi$

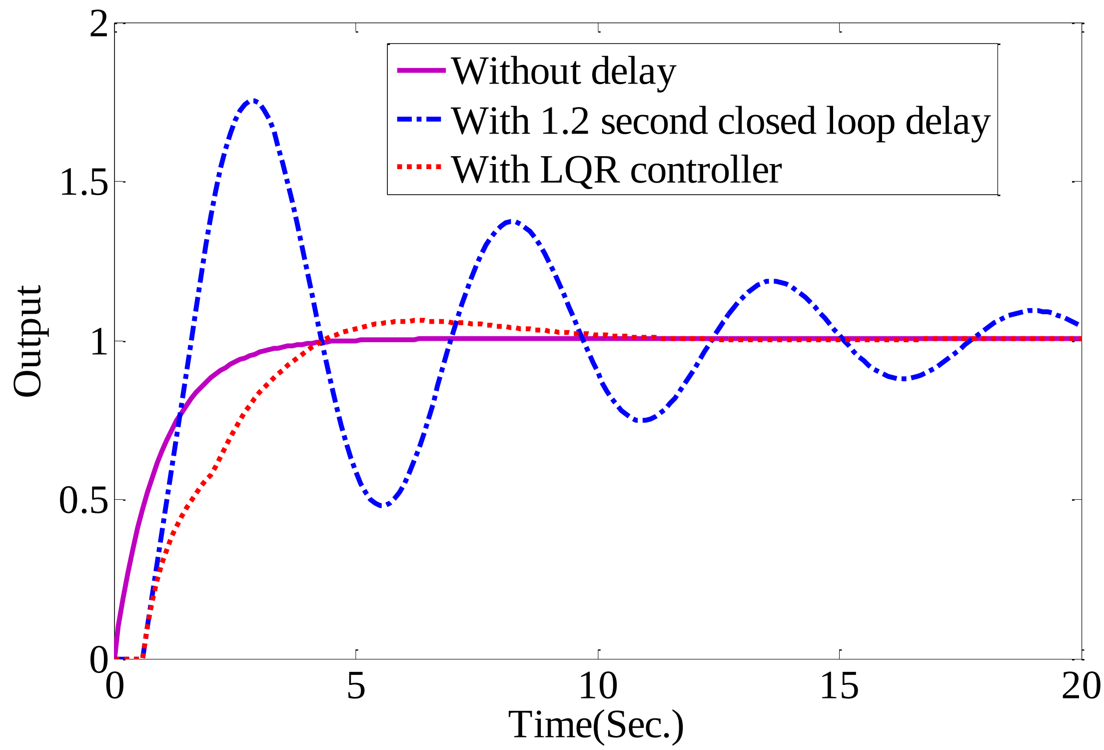


Figure4.3. Step response using LQR controller

Figure4.3 shows that if there is no delay in closed loop path the output is stable. But if there is a closed loop delay of 1.2 seconds the system becomes unstable. The step response of the system becomes stable when LQR controller is used. From the figure, it is observed that the output tracks the input after forward path delay and the output is stable. From the table4.1 it is seen that with 1.2 seconds closed loop delay the maximum overshoot increases to 43.3% from 0%. The Phase Margin (PM) is reduced to 59.4 degree from 174 degree. So it indicates that the delay reduces the stability margin of the system. Also delay increases the settling time of the system. It also reduces the gain Margin of the system from 25.6 dB to 11 dB. But it reduces the rise time from 2.1 seconds to 1.23 seconds. With LQR controller The PM increases from 59.4 degree to 138 degree and Maximum overshoot reduces to 5.65% from 43.3%. So it stabilizes the system.

Table4.1: Values of Time domain parameter and Frequency domain parameter for Figure4.3

	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
System without delay	2.1	3.73	0	174	25.6
System with delay (1.2 seconds)	1.23	14.8	43.3	59.4	11
System with LQR controller	3.4	9.33	5.65	138	10.6

4.7 DIFFERENT CASE STUDIES BASED ON DIFFERENT VARIATION OF FORWARD PATH AND FEEDBACK PATH DELAY

Here we have design the controller depends on the estimated maximum value of the forward path and feedback path delay. So in case of the variable transport delay this delay will be varied. Sometimes this delay may be zero, less than the estimated value or greater than the estimated value. It may be happened that at a time either only one delay is varying or both delay are varying simultaneously.

Case-1: Forward path delay is varied but the feedback path delay is constant

Here the effects of the variation in the forward path delay are shown through simulation of the integrator plant. But, in this case, it is assumed that the feedback path delay is not varied.

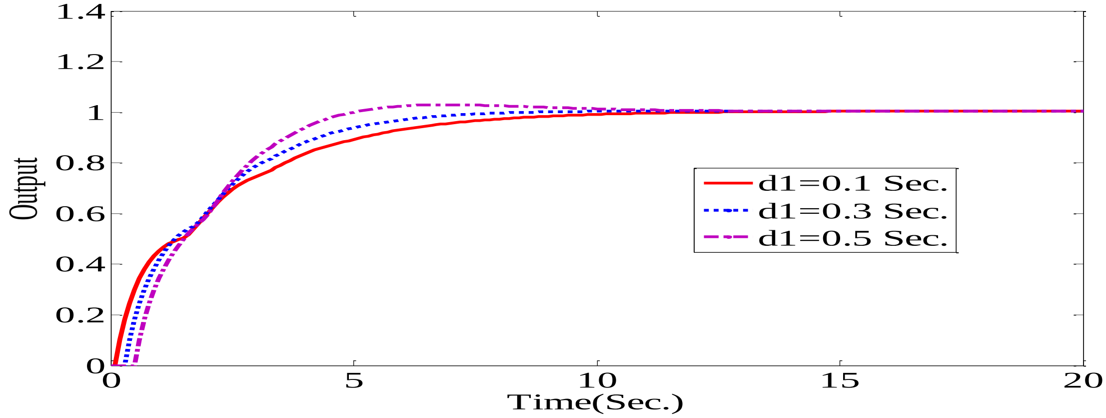


Figure4.4. Step response when the forward path delay is less than the estimated maximum delay

Table4.2: Values of time domain parameters and frequency domain parameter for figure4.4.

Forward path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.1	3.69	5.89	0	174	20.1
0.3	3.25	4.91	1.29	170	15.1
0.5	2.91	8.85	3.87	153	10.7

Figure4.4 shows the output response when the forward path delay is varied but always less than the estimated delay. From the response, it is seen that the output is stable and perfectly tracks the Reference input. From the table4.2 it is seen that the PM and GM reduces with increasing the delay and also maximum overshoot increases with increasing the forward path delay. The settling time increases but the rise time reduces with increasing the forward path delay. But the system is stable if the forward path delay is varied but always less than the estimated one.

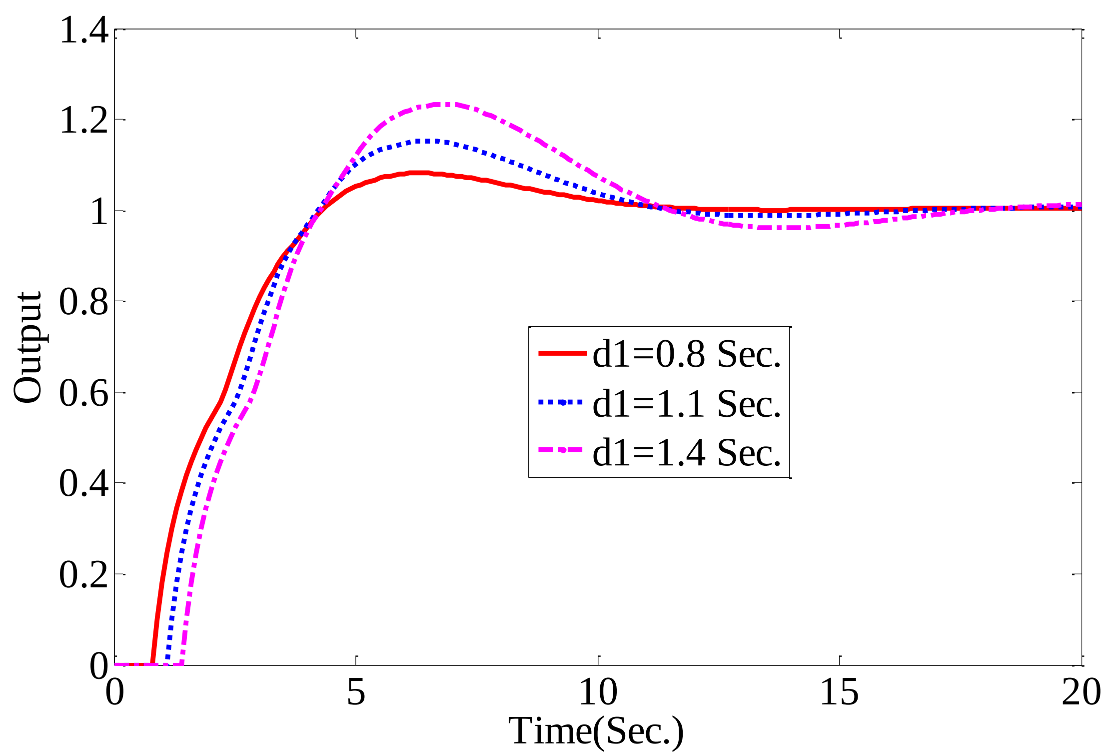


Figure4.5. Step response of the system when the forward path delay is greater than the estimated delay

Table4.3: Values of time domain parameters and frequency domain parameter for figure4.5.

Forward path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.8	2.56	9.91	9.89	115	11.7
1.1	2.36	14.8	17.3	85.9	12.4
1.4	2.28	17	25.5	62.5	10.9

Figure4.5 shows the step response of the system when the forward path delay is greater than the estimated delay. From the response, it is seen that the overshoot of the output response is increases with increasing the delay. When the forward path delay is 1.4 sec. (estimation error is 130%), overshoot is 24%. From the Table4.3 it is observed that the GM and PM reduce with increasing the forward path delay. The settling time increases but the rise time reduces if the forward path delay is varied but always greater than the estimated one. Also the overshoot increases with increasing the forward path delay. But from Figure4.5 and Table 4.3 it can be said that the system remain stable with the controller designed for 0.6 seconds forward path delay when the forward path delay increases up to 1.4 seconds.

Case-2: Feedback path delay is varied but the forward path delay is fixed

The feedback path delay is compensated using a predictor and full order estimator system. In the predictor, we have used an estimated model of the feedback path delay. So if there is an estimation error the performance of the system will be affected. How the variation of the feedback path delay affected the output response is shown by the simulation which is discussed in this section. But here it is assumed that the forward path delay is not varied.

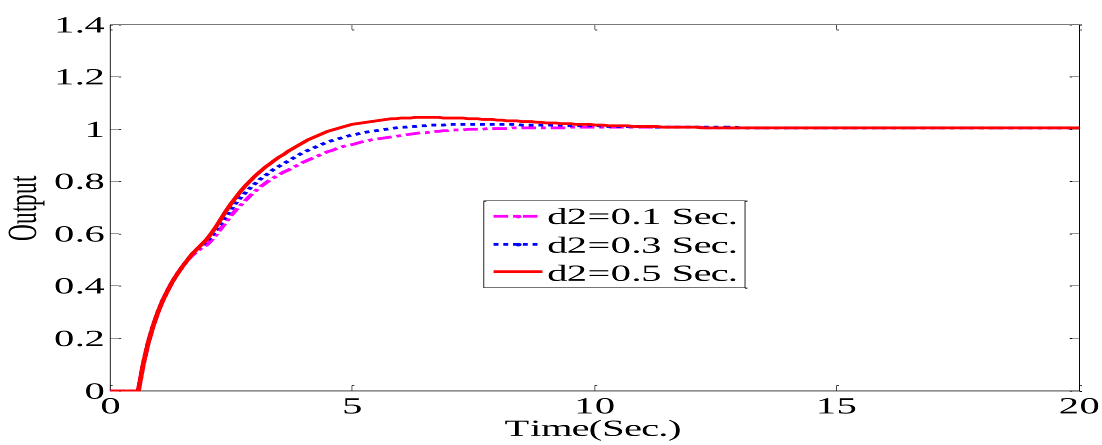


Figure4.6. Step response when the feedback path delay is less than the estimated delay.

Table4.4: Values of time domain parameters and frequency domain parameter for figure4.6.

Forward path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.1	3.69	6.39	1.01	172	10.1
0.3	3.25	5.21	1.29	168	10.5
0.5	2.91	8.95	3.84	151	10.7

From Figure4.6, it is seen that the output response remain stable if the feedback path delay is varied but always less than the estimated one. The output response is stable and tracks the reference input perfectly. From the Table4.4, it is observed that there is not significant change in GM. But the PM reduces and overshoot and settling time increases with increasing the feedback path delay. The rise time reduces with increasing the delay. But from the Figure4.6 and from the Table 4.4 it can be said that the closed loop system remains stable if the feedback path delay is varied but always less than the estimated one.

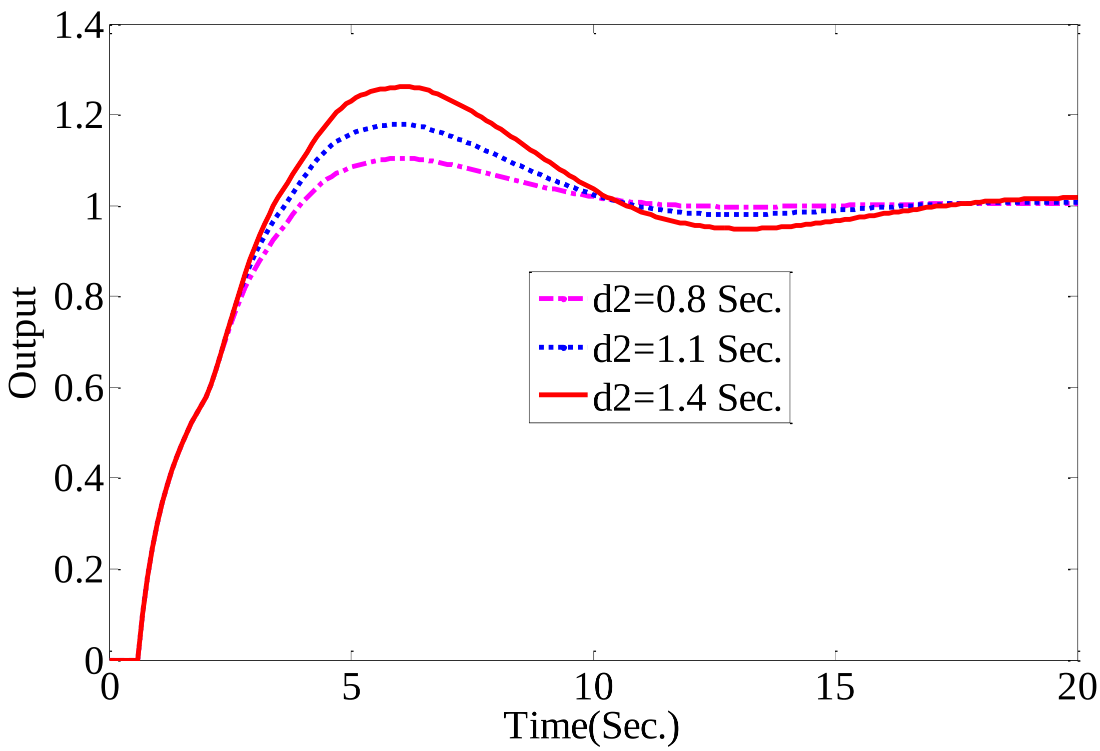


Figure4.7. Step response when the feedback path delay is greater than the estimated value.

Table4.5: Values of time domain parameters and frequency domain parameter for figure4.7.

Forward path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.8	2.56	9.71	9.89	120	10.2
1.1	2.36	14.3	17.3	103	9.36
1.4	2.28	16.2	25.5	90.5	9.06

Figure4.7 shows that the overshoot increases as the actual feedback path delay is greater than the estimated delay. When the actual feedback path delay is 1.4 seconds (Estimation error is 130%), the overshoot is 25.5%. from the Table4.5, it is observed that the PM decreases and settling time increases as the actual feedback path delay(d_2) increases and it is greater than the estimated one. But there is no significance change in rise time and GM with increasing in the feedback path delay which is greater than the estimated one.

Case-3: Simultanious feedback and forward path delays are varied

It may be happened that the delays in the both paths are varied. In this section we will discuss, what happned, if the both delays are varied simultaniously.

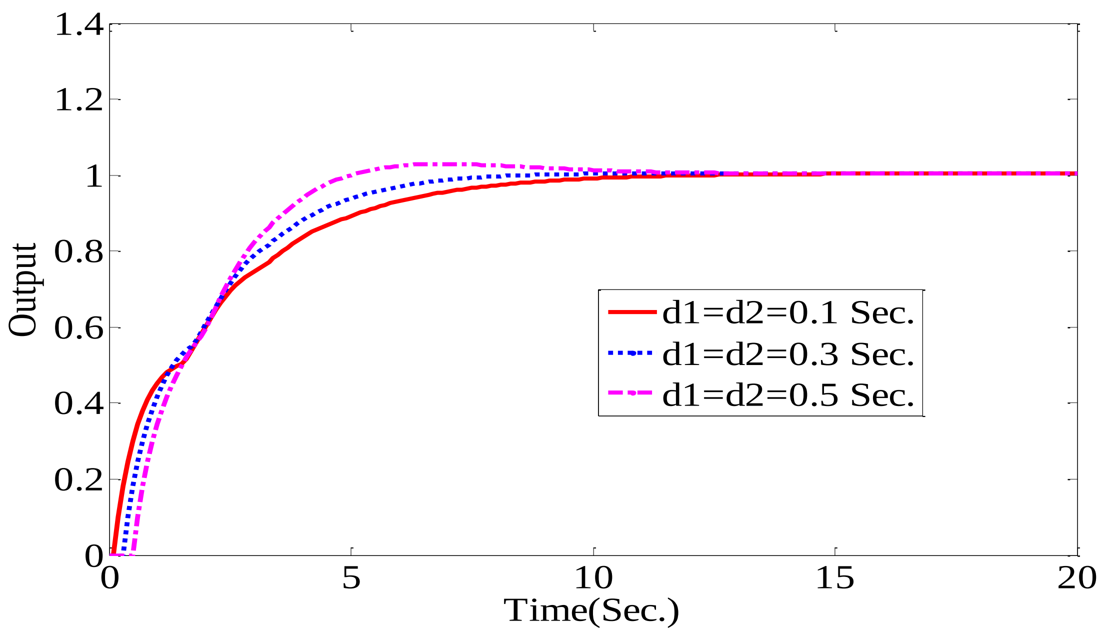


Figure4.8. Step response when the both delays are varied but always less than estimated one

From Figure4.8, it is observed that the system output remains stable if the feedback path delay and forward path delay varied simultaneously but always less than the estimated one. There is no significant overshot in the step response.

Table4.6: Values of time domain parameters and frequency domain parameter for figure4.8.

Forward path delay (Sec.)	Feedback path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.1	0.1	5.05	9.06	0	175	20.1
0.3	0.3	3.93	6.78	0	174	15
0.5	0.5	3.07	8.05	2.41	164	10.8

From the Table4.6, it is seen that the GM reduces significantly if the both forward and feedback path delay are varied but always less than the estimated one. But there is no significant change in PM. Rise time and settling time decreases with increasing the both delays but they are less than the estimated one.

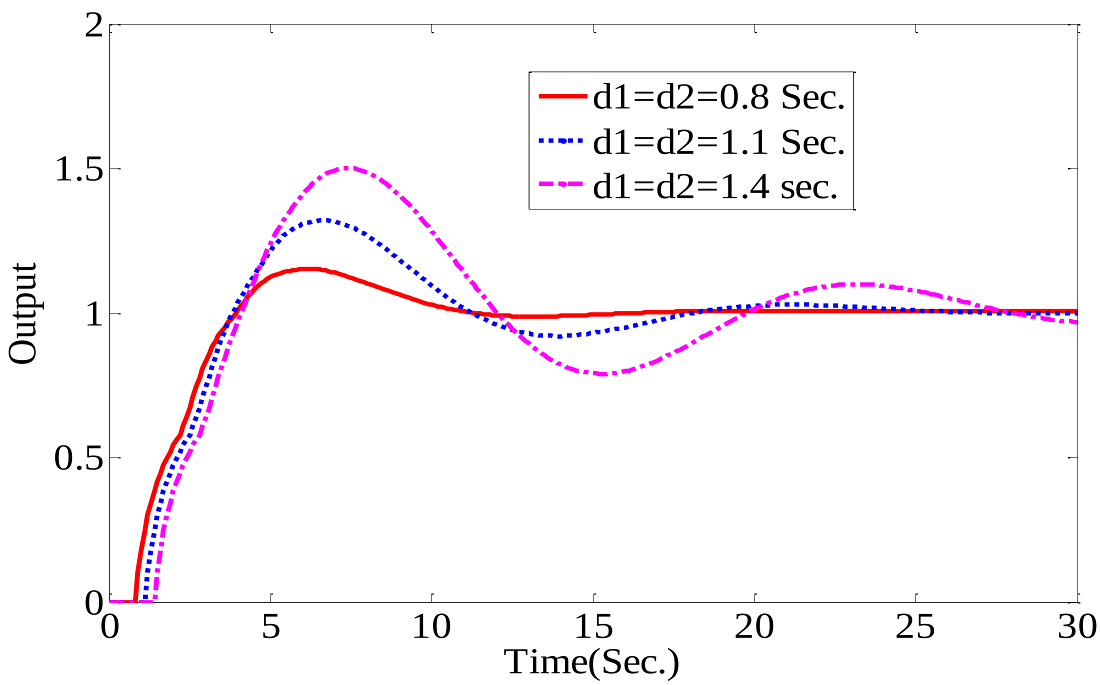


Figure4.9. Step response when the both delays are varied but always greater than estimated one

From Figure4.9, it is seen that the overshoot increases with increasing the both delays simultaneously and system becomes unstable in extreme case if the both delays are greater than the estimated one.

Table4.7: Values of time domain parameters and frequency domain parameter for figure4.9.

Forward path delay (Sec.)	Feedback path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.8	0.8	2.44	10.1	14.7	101	11.5
1.1	1.1	2.27	22.3	31.1	66.7	12.6
1.4	1.4	2.27	33.9	49.1	43.6	12.3

From the Table4.7, it is seen that PM reduces significantly as the both delays increases and both delays are greater the estimated one. There is no significant change in GM. But the overshoot increases significantly (49.6%) as there is an estimation error 130% in both delay estimation. There is no significant change in rise time but the settling time increases significantly as the both delays varied and they are greater than the estimated one.

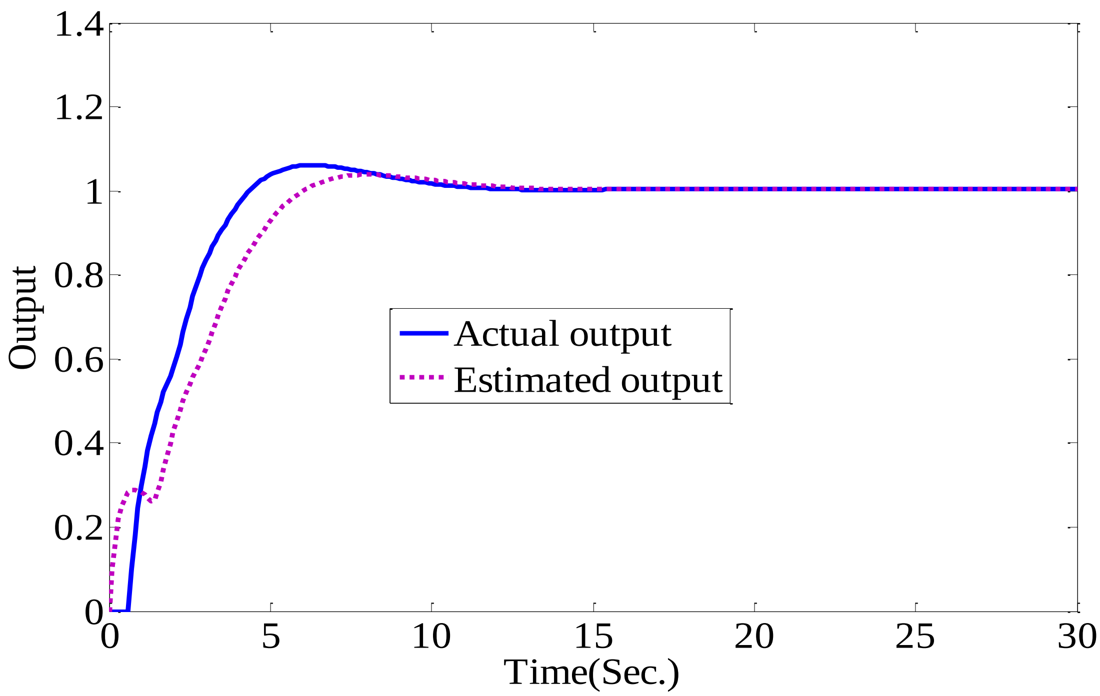


Figure4.10. Output of the estimator

From Figure4.10, it is seen that the full order observer estimates the system output properly and it removes the feedback path delay induced in the system output by the network.

4.8 STABILITY OF THE CLOSED LOOP SYSTEM WITH INTEGRATOR PLANT

The Eigen value of the original plant is 1.Eigen values of augmented closed loop system matrix are given by 0.9049, 0.0558, 0.0490 $\pm$ 0.0265i, 0.0304 $\pm$ 0.0462i, 0.0050 $\pm$ 0.0544i, -0.0207$\pm$ 0.0497i,-0.0406 $\pm$ 0.0341i, -0.0509 $\pm$ 0.0120i. All Eigen values are within the unit circle so the closed loop system is stable.

From the equation (4.18), (4.19) and (4.20), Eigen values are 0.9, 0.9 and 0.8 respectively.

Then the equation (4.24) is solved using the following MAT LAB code considering the Q is an identity matrix.

P= dlyap(A_{cl}, Q)

The P matrix is obtained as follows.

$$\begin{pmatrix}
18.5814 & -5.8933 & -6.4115 & -6.8681 & -7.2694 & -7.6208 & -7.9272 & -8.1933 & -8.4228 & -8.6196 & -8.7869 & -8.9275 & -9.0442 \\
-5.8933 & 17.8653 & 5.1820 & 4.5667 & 4.0127 & 3.5138 & 3.0646 & 2.6601 & 2.2958 & 1.9678 & 1.6724 & 1.4064 & 1.1669 \\
-6.4115 & 5.1820 & 16.8653 & 5.1820 & 4.5667 & 4.0127 & 3.5138 & 3.0646 & 2.6601 & 2.2958 & 1.9678 & 1.6724 & 1.4064 \\
-6.8681 & 4.5667 & 5.1820 & 15.8653 & 5.1820 & 4.5667 & 4.0127 & 3.5138 & 3.0646 & 2.6601 & 2.2958 & 1.9678 & 1.6724 \\
-7.2694 & 4.0127 & 4.5667 & 5.1820 & 14.8653 & 5.1820 & 4.5667 & 4.0127 & 3.5138 & 3.0646 & 2.6601 & 2.2958 & 1.9678 \\
-7.6208 & 3.5138 & 4.0127 & 4.5667 & 5.1820 & 13.8653 & 5.1820 & 4.5667 & 4.0127 & 3.5138 & 3.0646 & 2.6601 & 2.2958 \\
-7.9272 & 3.0646 & 3.5138 & 4.0127 & 4.5667 & 5.1820 & 12.8653 & 5.1820 & 4.5667 & 4.0127 & 3.5138 & 3.0646 & 2.6601 \\
-8.1933 & 2.6601 & 3.0646 & 3.5138 & 4.0127 & 4.5667 & 5.1820 & 11.8653 & 5.1820 & 4.5667 & 4.0127 & 3.5138 & 3.0646 \\
-8.4228 & 2.2958 & 2.6601 & 3.0646 & 3.5138 & 4.0127 & 4.5667 & 5.1820 & 10.8653 & 5.1820 & 4.5667 & 4.0127 & 3.5138 \\
-8.6196 & 1.9678 & 2.2958 & 2.6601 & 3.0646 & 3.5138 & 4.0127 & 4.5667 & 5.1820 & 9.8653 & 5.1820 & 4.5667 & 4.0127 \\
-8.7869 & 1.6724 & 1.9678 & 2.2958 & 2.6601 & 3.0646 & 3.5138 & 4.0127 & 4.5667 & 5.1820 & 8.8653 & 5.1820 & 4.5667 \\
-8.9275 & 1.4064 & 1.6724 & 1.9678 & 2.2958 & 2.6601 & 3.0646 & 3.5138 & 4.0127 & 4.5667 & 5.1820 & 7.8653 & 5.1820 \\
-9.0442 & 1.1669 & 1.4064 & 1.6724 & 1.9678 & 2.2958 & 2.6601 & 3.0646 & 3.5138 & 4.0127 & 4.5667 & 5.1820 & 6.8653
\end{pmatrix}$$

det(P) = 3.5633 X 10^{11}>0

So there exists a positive definite matrix (P) which satisfies the equation (4.24) which proves that the augmented closed loop system is stable.

The Bode plot, Nyquist plot and Pole-Zero maps are obtained for closed loop system after linearizing the closed loop system in using MATLAB software the closed loop system considering that there is 0.6 forward path delay and 0.6 seconds feedback path delay.

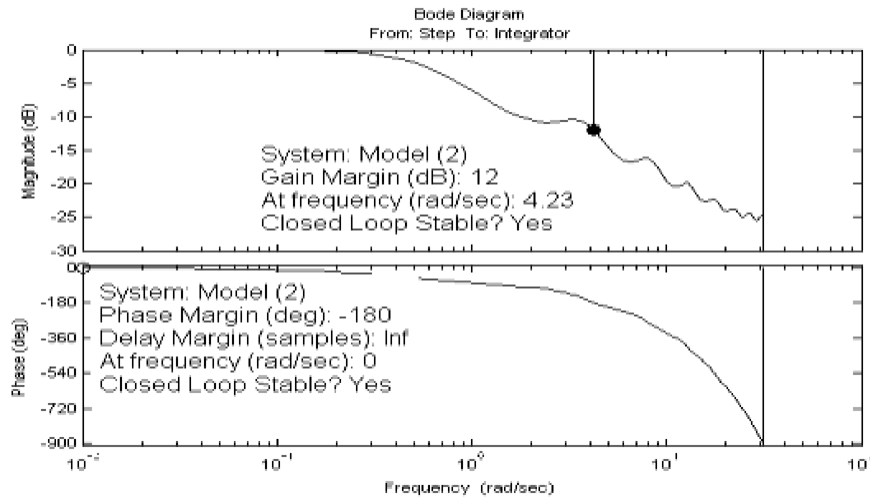


Figure4.11. Bode Magnitude and Phase plot for closed loop system

Figure4.11 shows the Bode Magnitude and Phase plot for the closed loop system. From the plot it is seen that the GM of the closed loop system is 12 dB and Phase margin of the closed loop system is -180 degree and closed loop system is stable.

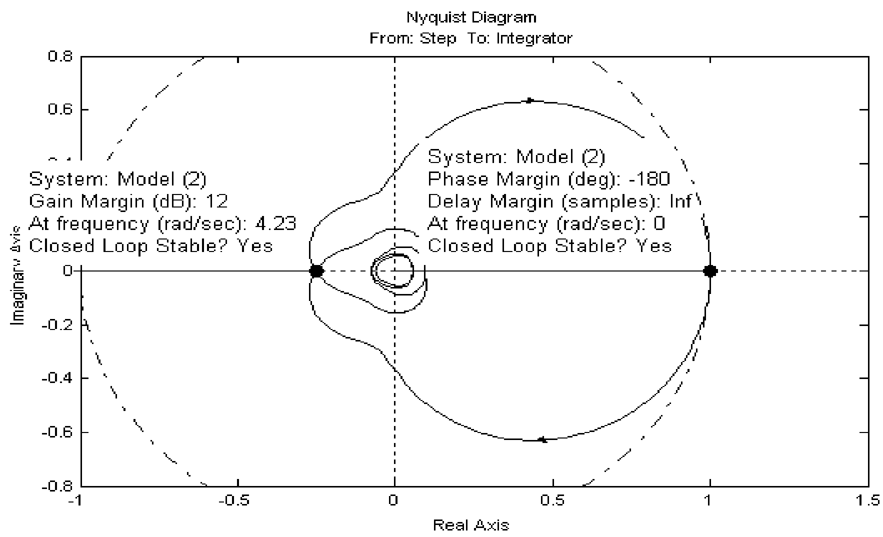


Figure4.11. Nyquist plot for closed loop system

Figure4.11 shows the Nyquist plot for the closed loop system. From this plot it is seen that the closed loop system is stable and GM is 12 dB and PM is -180 degree.

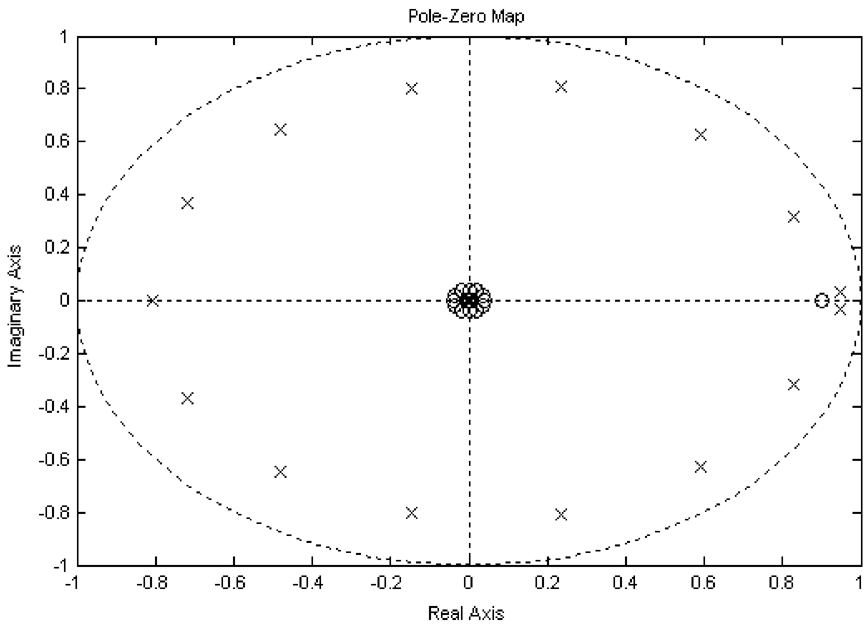


Figure4.13. Pole-Zero maps for closed loop system

Figure4.13 shows that the all poles and Zeros of the closed loop system are within the unit circle. So the closed loop system is stable with LQR controller designed based on augmented model.

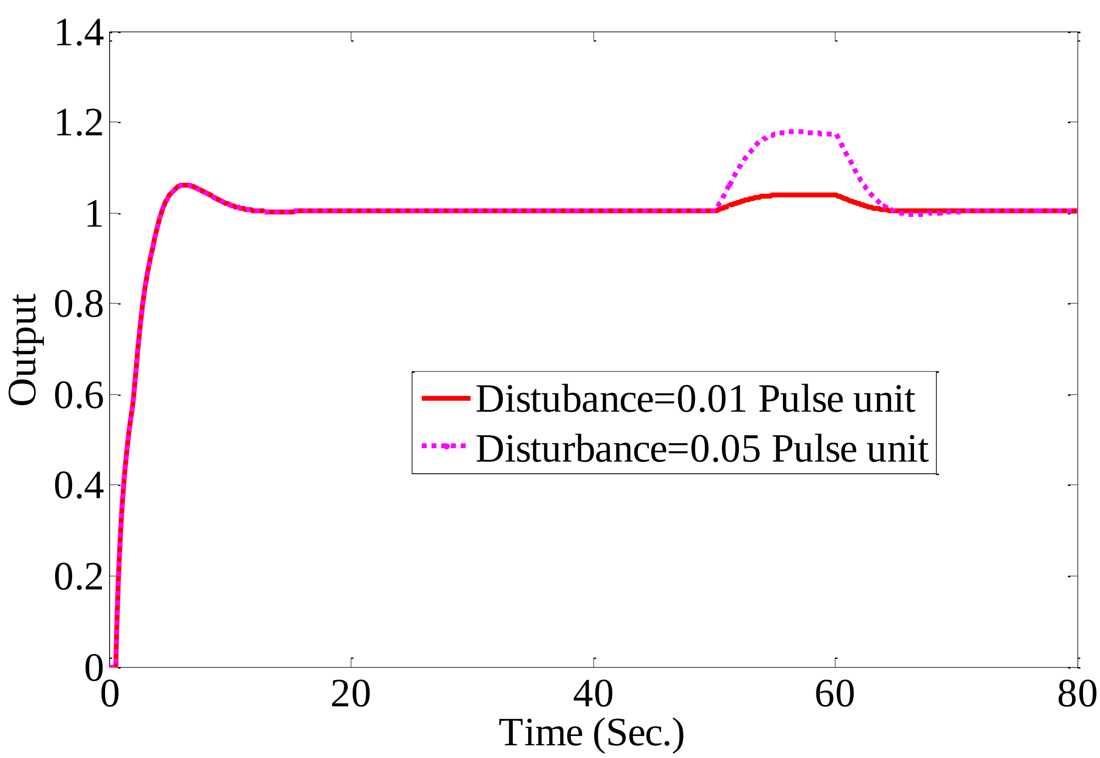


Figure4.14. Effect of disturbance

Figure4.14 shows that the closed loop system can tolerate the external disturbance. The disturbance of magnitude 0.01 and 0.05 are introduced during the time duration 50 seconds to 60 seconds. From Figure it is seen that the output does not becomes unbounded due to external disturbance.

4.9 REAL TIME EXPERIMENT

For real time experiment, the setup explained in chapter-3. The round trip time is estimated as 0.1 seconds. But we have designed the controller which can work up to the maximum delay considered at the time of design which is 1.2 seconds in the case. So redesign is not necessary. If delay exceeds 1.2 seconds then controller must be redesigned. So we can use same controller gain which is used in simulation. The plant is a simple integrator of which a subsystem is made in local PC (Plant).

The IP address of remote PC is 192.168.44.155

The IP address of local PC is 192.168.230.133

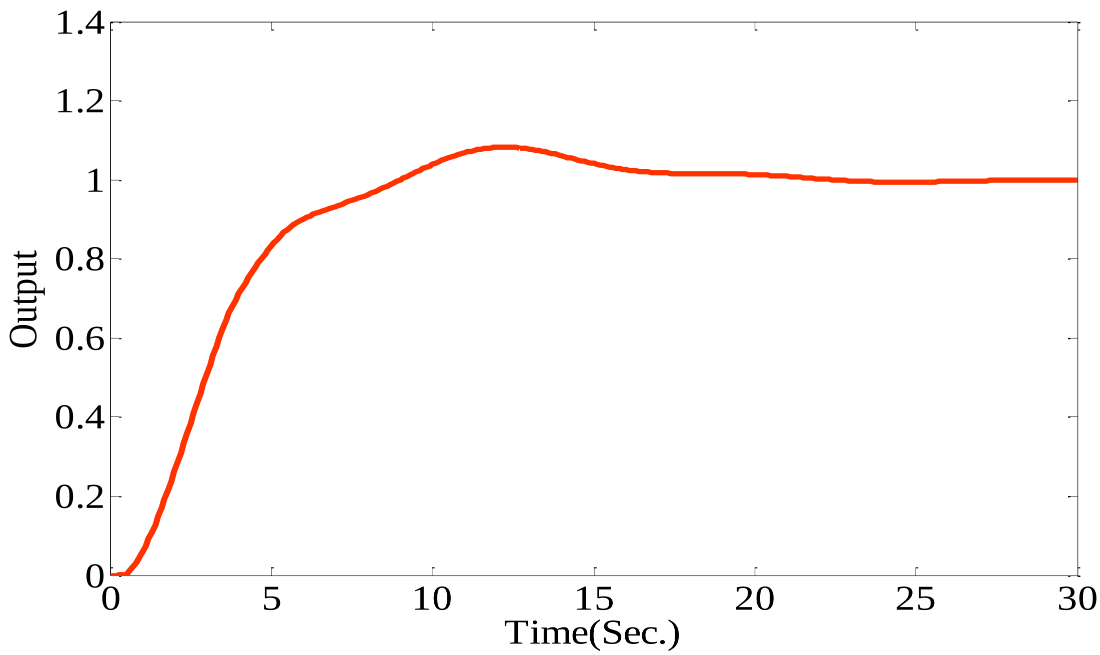


Figure4.16. Step response obtained in real time experiment

From figure4.16, it is seen that the designed LQR controller gives a stable step response in real time experiment. So the LQR controller is efficient in real time.

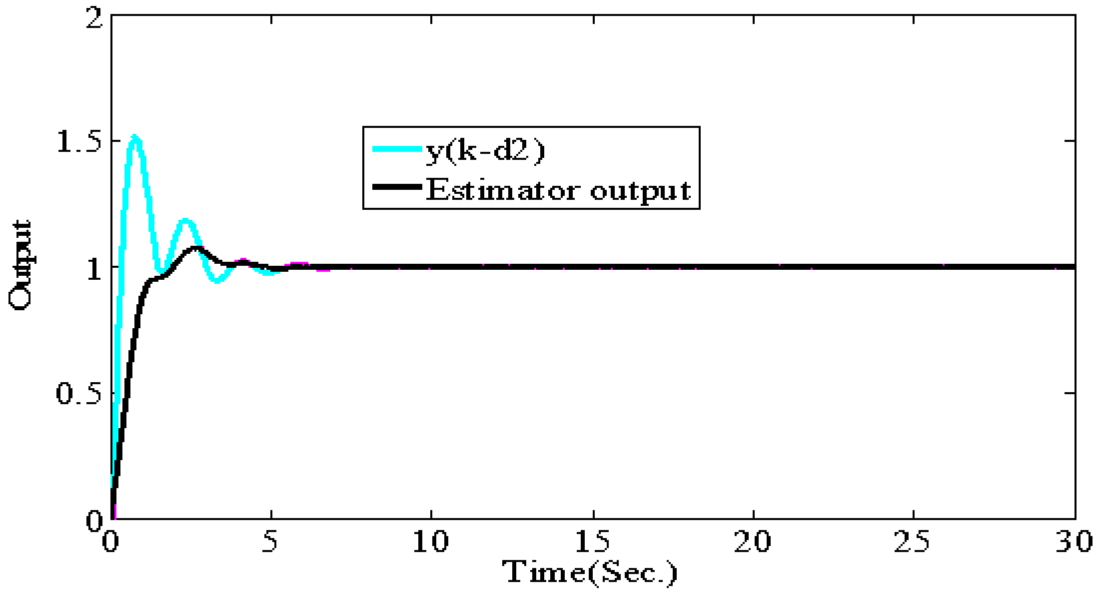


Figure4.17. Output of the state observer obtained in real time experiment

From Figure4.17, it is seen that the full order state observer can estimate the system output in real time experiment. It reduces the extreme overshoot due to the feedback path delay.

4.10 CHAPTER SUMMARY

In this chapter an LQR controller is designed based on the augmented model derived in chapter-2 to compensate the networked induced variable delay. The different cases of forward and feedback path delays are studied to prove the effectiveness the designed LQR controller to compensate the variable networked induced delays. It is seen that if the feedback path delay alone or forward path delay alone or both feedback and forward path delay simultaneously are varied the closed loop system is stable and the output has very less overshoot if they are less than the estimated one. But the overshoot increases if the delays are greater than the estimated one. The closed loop system can tolerate 130% estimation error in delay estimation. Then stability of the closed loop system is analyzed based on the augmentation model and using Lyapunov criterion. The real time experiment is conducted using the same LQR controller which is used in simulation. From the real time experiment result it is seen that the designed LQR controller is effective.

5 CHAPTER 5- DESIGN OF LQG CONTROLLER TO COMPENSATE THE NETWORKED INDUCED LONG VARIABLE DELAY IN NOISY ENVIRONMENT

5.1 INTRODUCTION

In practical cases there must be some interference noise at the plant input and sometimes the measurement is also noisy. In case of LQR, it is considered that there is no noise at the plant input and the measurement system is noise free. It sometimes does not meet the actual situation. So Linear Quadratic Regulator is designed where the actual plant output is estimated from noisy measurement using Kalman filter. To compensate the networked induced delay in noisy environment, approximately no work is done. Very small work is done to compensate the packet loss problem in noisy environment. In [73], a Linear Quadratic Gaussian (LQG) control problem is proposed where it is assumed that the data loses occurred according to the Bernoulli process. In [74], another LQG control problem is proposed considering the packet losses occurred between sensor and controller and between the latter and actuator. In this paper it is shown that the LQG controller is a linear function of the state and there exist critical probabilities of successful delivery of data packets. In [75], based on separation principle, another LQG control problem is proposed for control over packet dropping links. The problem is decomposed into a standard LQR sate feedback controller with optimal encoder-decoder designed for propagation and the information across the communication channel.

5.2 DESIGN OF LQG CONTROLLER TO COMPENSATE THE NETWORKED INDUCED VARIABLE DELAY IN NOISY ENVIRONMENT

The controller is considered here is same as the controller designed in chapter-4. So the controller is the LQR controller which is designed for the augmented system represented by the equation (2.2). But in chapter-4, only a full order observer is used to estimate the output of the plant as it is deterministic environment. But in this case we estimate the output in noisy environment. So the Kalman filter is used to estimate the plant output using noisy measurement.

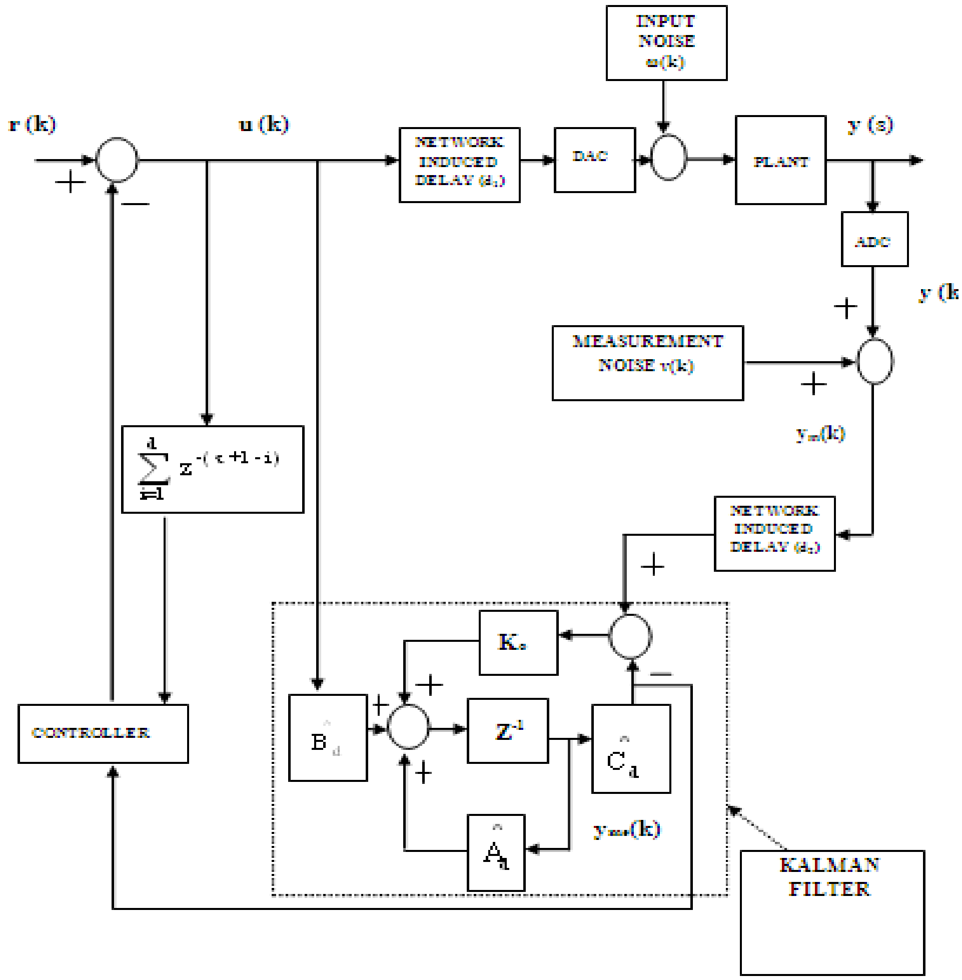


Figure5.1. Closed loop system with LQG controller

5.3 CALCULATION OF KALMAN FILTER GAIN

Here we have considered the noise model of the plant. Means plant has noisy input and measurement is noisy. The noisy model is represented by the equation (12) and the following measurement equation.

$y_m(t)=y(t)+B_v v(t)$

$y_m(t)=Cx(t)+B_v v(t)$ (5.1)

Let the discrete time state space equation of the noisy model is given by the following equations.

$x(k+1)=A_d x(k)+B_d u(k)+B_{\omega d}\omega(k)$ (5.2)

$$y_m(k)=C_d x(k)+B_{vd} v(k) \tag{5.3}$$

Where v(k) and ω(k) are the measurement and input zero mean white Gaussian noise respectively. The covariance matrix $Q=[\omega(k)^T\omega(k)]$ and $R=[v(k)^T v(k)]$.

The dynamics of the Kalman filter is given by the following equation.

$$\begin{aligned} \hat{x}_e(k+1) &= \hat{A}_d\,\hat{x}_e(k)+\hat{B}_d\,u(k)+K_k[y_m(k-\tau_2)-y_{me}(k)] \\ y_{me}(k) &= \hat{C}_d\,\hat{x}_e(k) \end{aligned} \tag{5.4}$$

From the noisy measurement, to estimate the output of the plant we use Kalman Filter. The optimal Kalman gain is obtained from [76].

$$K_k=P_{k(-)}\hat{C}_d^T[C_d P_{k(-)}\hat{C}_d^T+R_k]^{-1} \tag{5.5}$$

Error covariance extrapolation is given by the following equation.

$$P_{k(-)}=A_{d(k-1)}P_{(k-1)}(+)A^T{}_{d(k-1)}+Q_{k-1} \tag{5.6}$$

Error covariance update is given by the following equation.

$$P_{k(+)}=[I-K_k C_d]P_{k(-)} \tag{5.7}$$

5.4 ANALYSIS OF CLOSED LOOP SYSTEM INCLUDING THE LQG CONTROLLER AND KALMAN FILTER

The control input is given by the following equation.

$$u(k)= r(k) - K_n Y_e(k) - \sum_{i=1}^{\tau} K_{i+n}\, u(k-(\tau+1-i)) \tag{5.8}$$

$$\begin{aligned} x(k+1) &= A_d x(k)+B_d[\, r(k) - K_n Y_e(k) - \sum_{i=1}^{\tau} K_{i+n}\, u(k-(\tau+1-i))]+B_{\omega d}\omega(k) \\ &= A_d x(k) - B_d K_n C_d x_e(k) +B_d r(k)- B_d[\sum_{i=1}^{\tau} K_{i+n}\, u(k-(\tau+1-i))]+B_{\omega d}\omega(k) \qquad (5.9) \\ &= A_d x(k) - B_d K_n C_d x_e(k) +B_d r(k)- B_d u_d(k)+B_{\omega d}\omega(k) \end{aligned}$$

The estimation error is given by the following equation.

$$\tilde{x}_e(k)=x(k)-x_e(k) \tag{5.10}$$

From equation (5.9), the following relation can be written.

$$\begin{aligned} x(k+1) &= A_d x(k) - B_d K_n C_d x_e(k) + B_d r(k) - B_d u_d(k) + B_{\omega d}\omega(k) \\ &= A_d x(k) - B_d K_n C_d x(k) + B_d K_n C_d \tilde{x}_e(k) + B_d r(k) - B_d u_d(k) + B_{\omega d}\omega(k) \\ &= (A_d - B_d K_n C_d)x(k) + B_d K_n C_d \tilde{x}_e(k) + B_d r(k) - B_d u_d(k) + B_{\omega d}\omega(k) \end{aligned} \tag{5.11}$$

Case1: up to d_2 instant

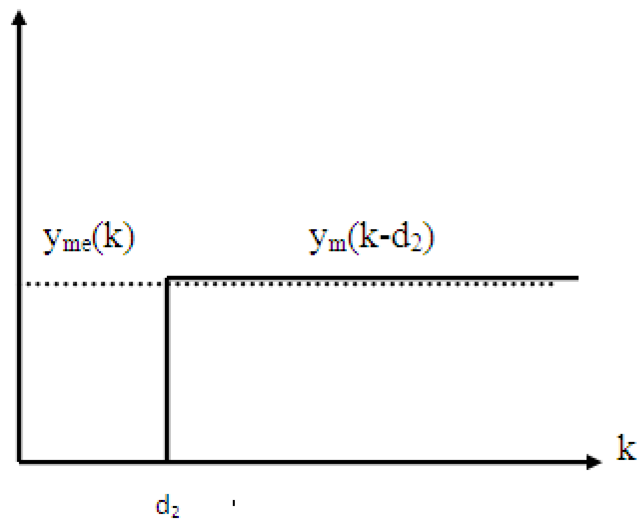


Figure5.2. Synchronization between in system output and observer output

Before d_2 instant there is only estimator output. So up to d_2 instant the estimator dynamics can be written as follows.

$$\begin{aligned} \hat{x}_e(k+1) &= \hat{A}_d \hat{x}_e(k) + \hat{B}_d u(k) - K_k y_{me}(k) \\ &= \hat{A}_d \hat{x}_e(k) + \hat{B}_d u(k) - K_k \hat{C}_d \hat{x}_e(k) \\ &= \hat{A}_d \hat{x}_e(k) - K_k \hat{C}_d x(k) + K_k \hat{C}_d \tilde{x}_e(k) + \hat{B}_d u(k) \end{aligned} \tag{5.12}$$

Subtracting the equation (5.12) from the equation (5.2), the following relation can be written.

$$\tilde{x}_e(k+1) = K_k \hat{C}_d x(k) + (A_d - K_k \hat{C}_d)\tilde{x}_e(k) + B_{\omega d}\omega(k) \tag{5.13}$$

From the equation (5.11) and from the equation (5.13), the following augmented state space equation can be written for the closed loop system.

$$\begin{pmatrix} x(k+1) \\ \tilde{x}_e(k+1) \end{pmatrix} = \begin{pmatrix} (A_d - B_d K_n C_d) & B_d K_n C_d \\ K_k C_d & (A_d - K_k C_d) \end{pmatrix} \begin{pmatrix} x(k) \\ \tilde{x}_e(k) \end{pmatrix} + \begin{pmatrix} B_d & -B_d \\ 0 & 0 \end{pmatrix} \begin{pmatrix} r(k) \\ u_d(k) \end{pmatrix} + \begin{pmatrix} B_{\omega d} \\ 0 \end{pmatrix} \omega(k) \quad (5.14)$$

Case2: After d_2 instant

The following relation can be written.

$$\hat{x}_e(k+1) = \hat{A}_d \hat{x}_e(k) + \hat{B}_d u(k) + K_k [y_m(k) - y_{me}(k)] \quad (5.15)$$

Let us consider $\hat{A}_d = A_d$, $\hat{B}_d = B_d$ and $\hat{C}_d = C_d$

$$\hat{x}_e(k+1) = A_d \hat{x}_e(k) + B_d u(k) + K_k C_d \tilde{x}_e(k) + v(k) \quad (5.16)$$

Subtract the equation (5.16) from the equation (5.2), the following relation can be written.

$$\tilde{x}_e(k+1) = (A_d - K_k C_d)\tilde{x}_e(k) + B_\omega \omega(k) - v(k) \quad (5.17)$$

For closed loop system, following augmented state space model can be formed using the equation (5.11) and the equation (5.17).

$$\begin{pmatrix} x(k+1) \\ \tilde{x}_e(k+1) \end{pmatrix} = \begin{pmatrix} (A_d - B_d K_n C_d) & B_d K_n C_d \\ 0 & (A_d - K_k C_d) \end{pmatrix} \begin{pmatrix} x(k) \\ \tilde{x}_e(k) \end{pmatrix} + \begin{pmatrix} B_d & -B_d \\ 0 & 0 \end{pmatrix} \begin{pmatrix} r(k) \\ u_d(k) \end{pmatrix} + \begin{pmatrix} B_{\omega d} & 0 \\ B_{\omega d} & -1 \end{pmatrix} \begin{pmatrix} \omega(k) \\ v(k) \end{pmatrix}$$

(5.18)

5.5 STABILITY ANALYSIS OF THE CLOSED LOOP SYSTEM CONSISTS OF NETWORK, PLANT, CONTROLLER AND KALMAN FILTER

The stability of the closed loop system depends on the stability of the augmented closed loop system and on the stability of the Kalman filter. Here the stability condition for the augmented closed loop system and the stability condition of the Kalman filter are explained.

5.5.1 Stability of closed loop system

The stability of the closed loop system can be analyzed following the same procedure of chapter-4.The Eigen values of the augmented closed loop system including estimator are obtained from the following equation.

$$\left(\lambda I-\begin{pmatrix}(A_d-B_d\ K_n C_d) & B_d\ K_n C_d\\ K_k C_d & (A_d-K_k C_d)\end{pmatrix}\right)=0 \qquad (5.19)$$

$$\left(\lambda I-\begin{pmatrix}(A_d-B_d\ K_n C_d) & B_d\ K_n C_d\\ 0 & (A_d-K_k C_d)\end{pmatrix}\right)=0 \qquad (5.20)$$

From the equation (5.20), following relation can be written.

$$[\lambda I-(A_d-B_d\ K_n C_d)]=0 \qquad (5.21)$$

$$[\lambda I-(A_d-K_k C_d)]=0 \qquad (5.22)$$

For stability the Eigen values obtained from equations (5.19), (5.21) and (5.22) should be within the unit circle.

5.5.2 Stability of the Kalman filter:

The dynamic stability of any system is depends of the behavior of the state variable. Sometimes it is found that the mean squared error of the estimator is bounded but the system is unstable. Neglecting the measurement output the Kalman filter equation can be written as follows.

$$\begin{aligned}\hat{x}_e(k) &= \hat{A}_d\,\hat{x}_e(k-1)+\hat{B}_d\,u(k-1)-K_k\,\hat{C}_d\,\hat{x}_e(k-1)\\ &=(\hat{A}_d-K_k\,\hat{C}_d)\,\hat{x}_e(k-1)+\hat{B}_d\,u(k-1)\end{aligned} \qquad (5.23)$$

The filter will be called asymptotically stable if the following relation is satisfied.

$$\lim_{k\to\infty}\left\|\hat{x}_e(k)\right\|=0 \qquad (5.24)$$

The relation given by the equation (5.24) should be satisfied irrespective to the initial condition. The estimator will be asymptotically stable if the system model is controllable and observable.

5.6 SIMULATION OF AN INTEGRATOR PLANT USING MAT LAB SOFTWARE

For the simulation, an integrator is considered same as LQR technique. It is also considered that there is a variable delay of maximum value 0.6 second in the forward path. There is also a delay in the feedback path of estimated value 0.6 seconds same as before. The plant is discretized at a sampling rate of 0.1 second.

The continuous time state space equation of the integrator is obtained as follows.

$$\begin{aligned} \dot{x}(t) &= u(t) \\ y(t) &= x(t) \end{aligned} \tag{4.27}$$

The discrete time state space equation can be obtained as follows.

$$\begin{aligned} x(k+1) &= x(k)+0.1u(k) \\ y(k) &= x(k) \end{aligned} \tag{4.28}$$

Input noise covariance=0.002

Measurement noise covariance=0.02.

Using this parameter, the Kalman gain is calculated as 0.0298.

To check the effectiveness, at first, the integrator plant is simulated in closed loop configuration without considering any delay in closed loop path. Then 0.6 sec. delay is introduced in each path and there are also input noise and measurement noise with covariance mentioned above. The simulation result is shown below.

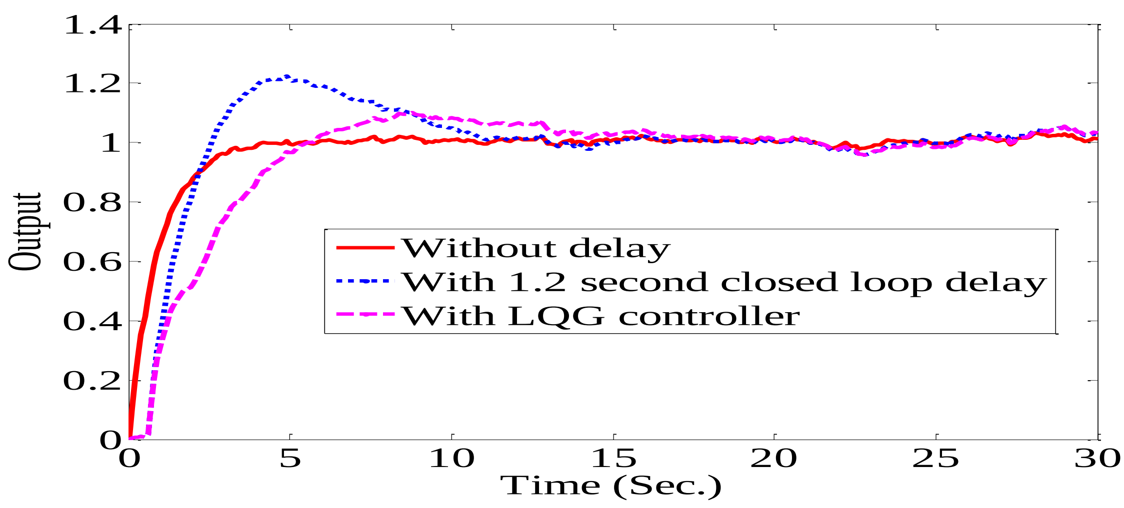


Figure5.3. Step response obtained using LQG controller

From Figure5.3, it is seen that the without delay there is no overshoot in step response. If a closed loop delay of value 1.2 seconds is introduced than there is 30% overshoot in the step response. So delay makes the system unstable. The LQG controller makes the overshoot 9% from 30%. So this controller increases the stability of the system.

Table5.1: Values of time domain parameters and frequency domain parameter for figure5.3.

	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
System without delay	2.1	3.73	0	174	25.6
System with delay (1.2 seconds)	1.52	16	30.2	82	7.4
System with LQG like controller	4.04	17.4	8.67	130	9.18

From Table5.1, it is seen that the delay reduces the PM from 174 degree to 82 degree and also reduces the GM from 25.6 dB to 7.4 dB. So it can be said that the delay significantly reduces the system satbility. Due to the delay of 1.2 seconds the overshhot increses from 0% to 30% and it increses the settling time from 3.73 seconds to 16 seconds and reduces the system rise time from 2.1 seconds to 1.52 seconds. Using the LQG controller the PM is significantly increased from 82 degree to 130 degree. It also reduces the overshoot from 30.2% to 8.67%. so it can be said that the LQG controller increases the system stability significantly.

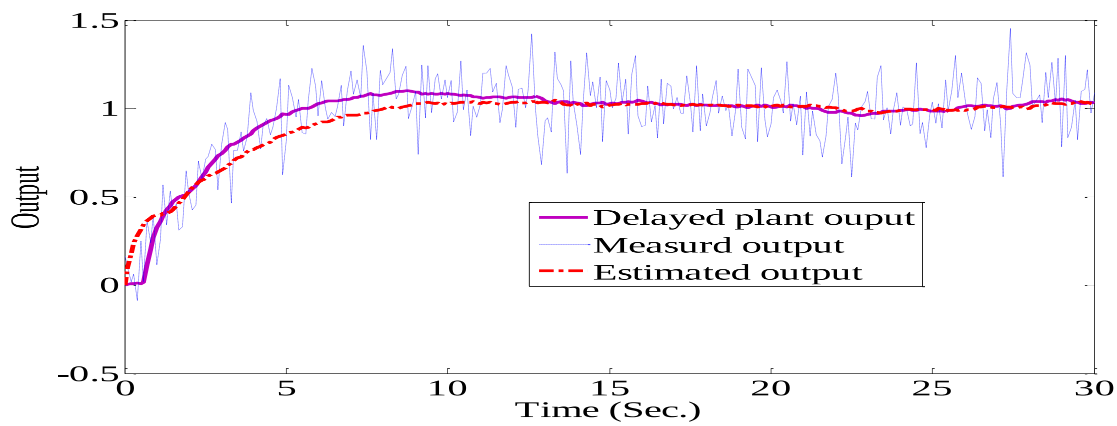


Figure5.4. Estimation of plant output using Kalman filter

From Figure5.4, it is seen that Kalman filter perfectly estimates the plant output using noisy measurement. The output of Kalman filter is free from the feedback path delay.

5.7 STABILITY ANALYSIS OF THE INTEGRATOR PLANT IN CLOSED LOOP SYSTEM USING LQG CONTROLLER

The stability analysis of the closed loop system using LQG controller can be carried out using the same procedure as LQR controller. The Eigen values of the augmented closed loop system considering the delayed input are the same as LQR as the controller gains used here are the same as LQR controller. The Eigen values of the augmented closed loop system are 0.9049, 0.0558, 0.0490 ± 0.0265i, 0.0304 ± 0.0462i, 0.0050 ± 0.0544i, -0.0207± 0.0497i,-0.0406 ± 0.0341i, -0.0509 ± 0.0120i. All Eigen values are within the unit circle. So the augmented closed loop system is stable.

The Eigen values obtained from the equation (5.19), (5.21) and (5.22) are 0.8730, 0.90 and 0.9702. These are within unit circle. So the closed loop system is stable.

The Bode plot, Nyquist plot and Pole/Zeros maps are obtained after linearizing the closed loop system considering the closed loop delay 1.2 seconds using the MAT LAB software.

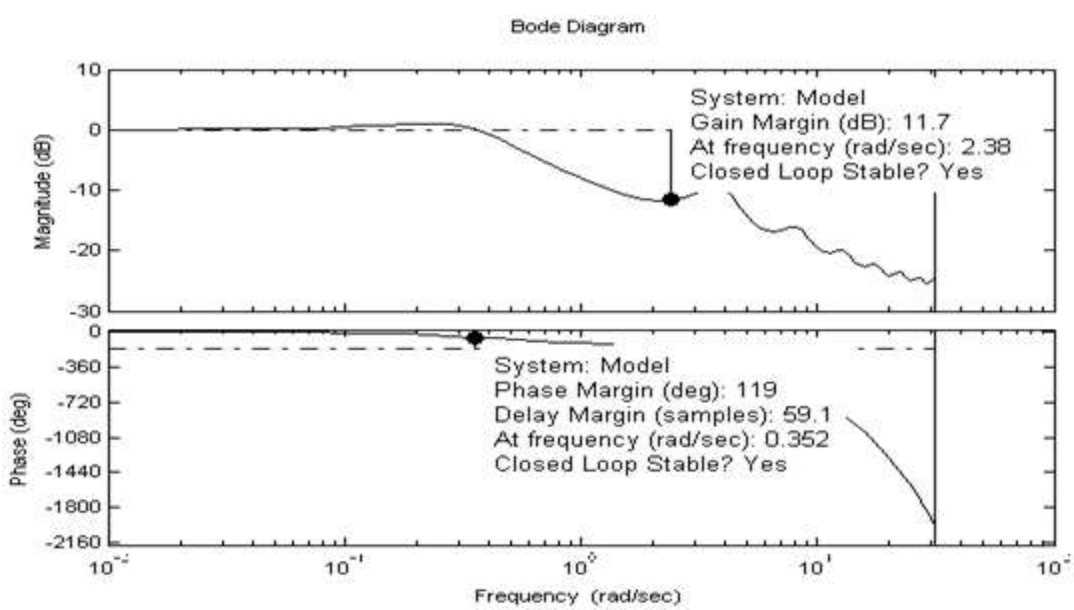


Figure5.8. Bode plot obtained using LQG controller for closed loop system

From Figure5.8, it is seen that the GM 11.7 dB and PM is 119 degree. The closed loop system is stable

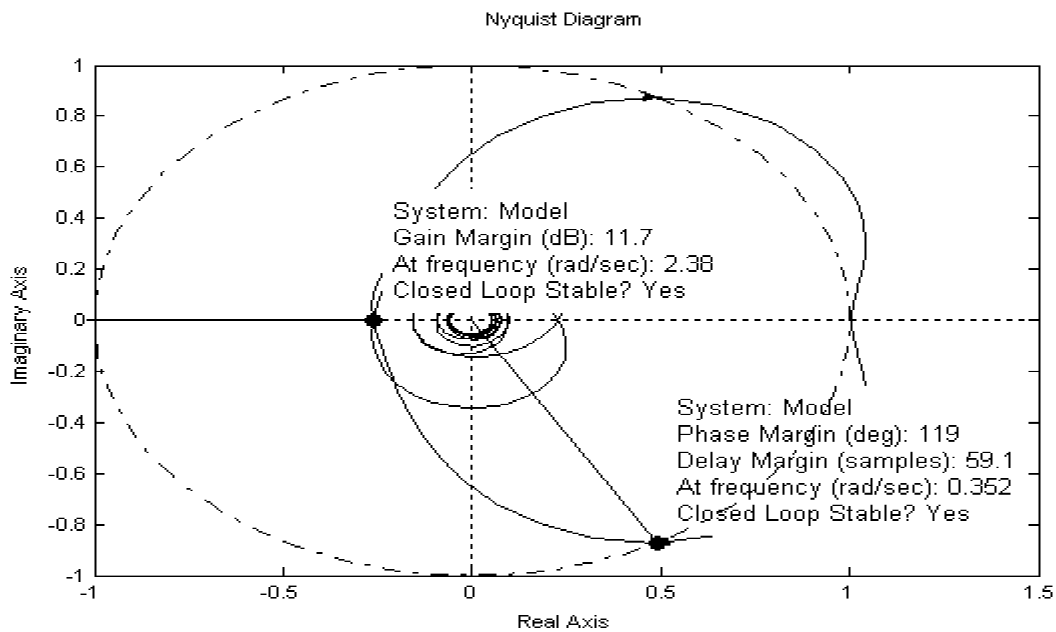


Figure5.9. Nyquist plot obtained using LQG controller for closed loop system

Figure5.9 shows the Nyquist plot for the closed loop system. From this plot that the Nyquist couture does not encircle the (-1, 0) point and GM is 11.7 dB and PM is 119 degrees. So the system is stable.

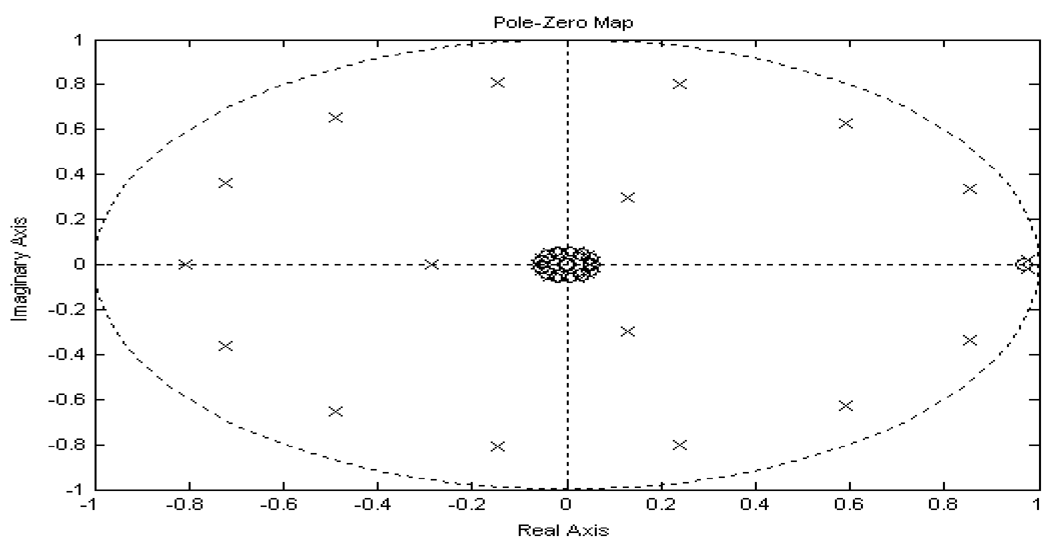


Figure5.10. Pole-Zero maps obtained using LQG controller for closed loop system

Figure5.10 shows the pole/zero maps for the closed loop system and from this plot it is seen that the all pole and zeros are within the unit circle. So the closed loop system is stable.

5.8 REAL TIME EXPERIMENT

For real time experiment the same setup as chapter- is used with same network parameter. Same network parameter means same IP address, same networked induced delay.

For real time experiment the same controller model is used in remote computer as chapter-4 except the full order state observer is replaced by optimal Kalman filter as the noisy environment is considered. In real time experiment, the controller gain and Kalman filter gain are considered as the same as simulation.

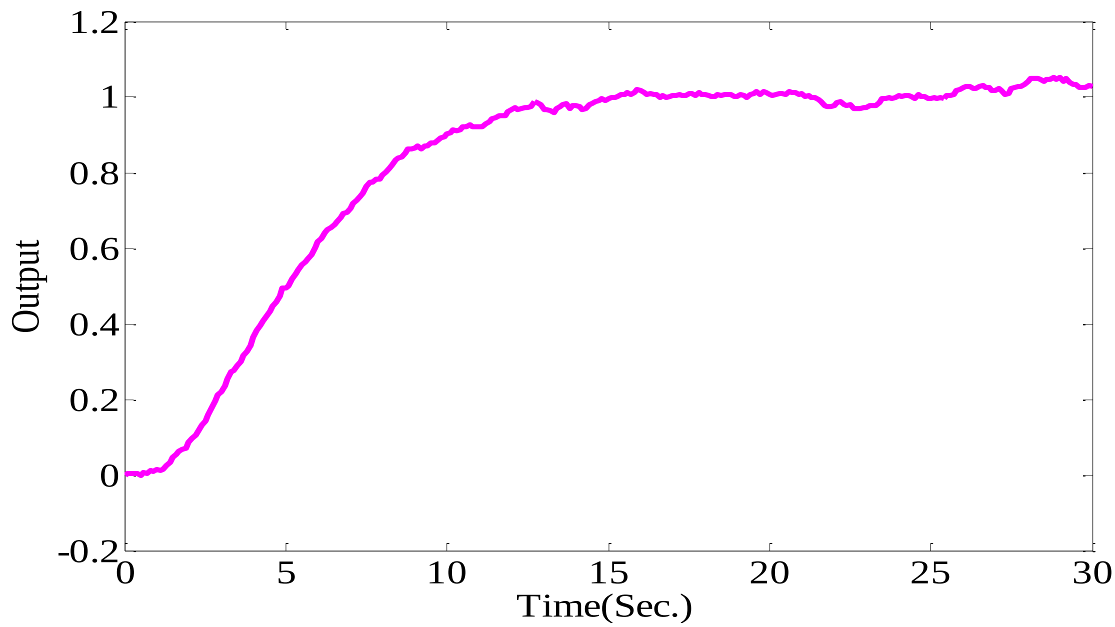


Figure5.6. Step response in real time experiment

Figure5.6 shows that in real time experiment a stable output is obtained using the LQG controller.

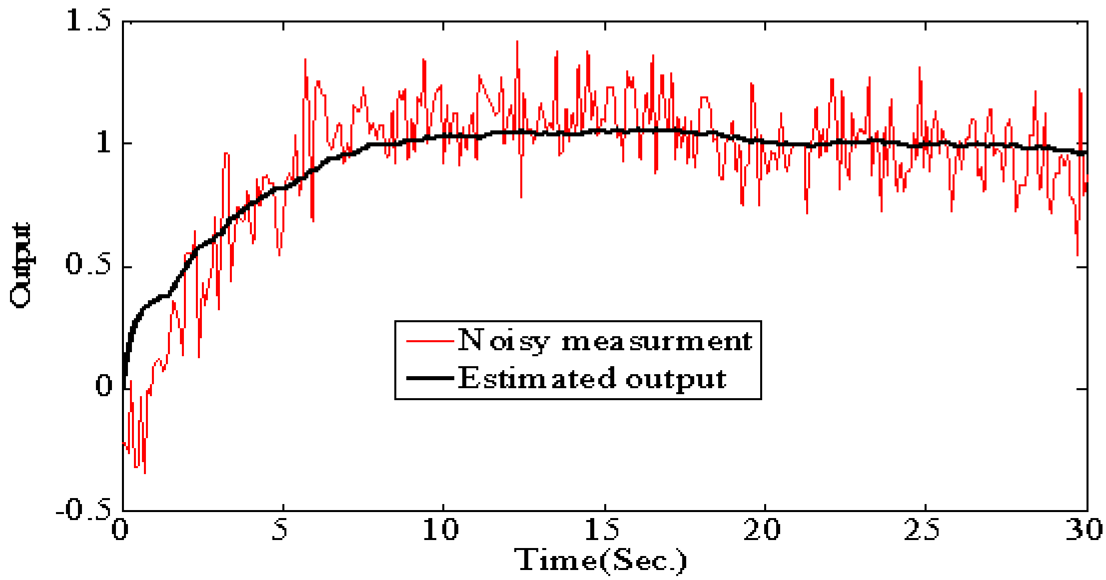


Figure5.7. Estimation of the plant output in real time

From Figure5.7 shows that the Kalman filter estimates the plant output using the noisy measurement in real time.

5.9 CHAPTER SUMMARY

In this chapter a LQG controller is designed to compensate the networked induced variable delay in noisy environment. Then the stability of the closed loop system is analyzed. An integrator plant is simulated using the designed LGG controller and using the same controller a real time experiment is conducted where a PC is considered as controller and another PC is considered as plant. The closed loop delay between two PCs is 1.1 seconds approximately is estimated using RTT technique. From the simulation result and from real time experiment it is seen that the designed LQG controller compensates the networked induced variable delay effectively in noisy environment.

6 CHAPTER 6-DESIGN OF OFFLINE MODEL PREDICTIVE CONTROLLER USING LAGUERRE NETWORK TO COMPENSATE LONG VARIABLE NETWORKED INDUCED DELAY

6.1 INTRODUCTION

To compensate the networked induced delay, a number of methods have been developed by researcher using Smith Predictor [77], LQG control theory ([78], [79]), LQR control theory [80], robust control theory [81], adaptive control theory [82], and Fuzzy logic [83]. But in all cases, input constraints which are basically the physical limitation (for example valve saturation and power limitation) of the system are neglected. Model Predictive Control (MPC) is an effective control technology which can accommodate the constraints on inputs effectively. MPC has prediction capability. So it can effectively compensate the time delay [84]. In [85], a MPC strategy is proposed for NCS with data packet dropout at sensor to controller path and the asymptotical stability condition is established considering that the control horizon is always greater than the maximum continuous packet dropout number. In [86], a networked decentralized MPC is developed for a complex process to improve the global control performances using an independent agent to exchange the reduced set of information through a local area network. In [87], a novel distributed MPC is designed to improve the performance of a class of large scale system entirely considering the idea that a local MPC control each subsystem and exchange a reduced set of information with each other through network. The performance index of each local MPC considers the neighbors' information with its own information. In [88], a MPC is developed for NCs structure with the sensor installed remotely from the plant. An offline MPC based gain scheduling strategy is used to compensate the network constraints actively. In [89], stability and optimality condition is established based on Lyapunov considering the projected receding horizon costs is lower and upper bounded by constraint MPC with the buffer used at the actuator to compensate the occurrence of data transmission error due to NCS.

6.2 MODEL FORMULATION FOR MPC

$$z(k)=\Pi z(k-1)+\Pi u(k-1) \tag{6.1}$$

Subtracting the equation (6.1) from equation (2.2), we obtain

$$\Delta z(k+1)=z(k+1)-z(k)$$

$$\Delta z(k+1)=\Pi\Delta z(k)+\Gamma\Delta u(k) \tag{6.2}$$

$$y_u(k+1)-y_u(k)=\Xi[z(k+1-z(k)]$$
$$=\Xi\Pi\Delta z(k)+\Xi\Gamma\Delta u(k)$$

$$y_u(k+1)=\Xi\Pi\Delta z(k)+y_u(k)+\Xi\Gamma\Delta u(k) \qquad (6.3)$$

Now using equation (6.2) and equation (6.3) we obtain the following augmented state space equation.

$$\begin{pmatrix}\Delta z(k+1)\\ y_u(k+1)\end{pmatrix}=\begin{pmatrix}\Pi & 0\\ \Xi\Pi & 1\end{pmatrix}\begin{pmatrix}\Delta z(k)\\ y_u(k)\end{pmatrix}+\begin{pmatrix}\Gamma\\ \Xi\Gamma\end{pmatrix}\Delta u(k)$$
$$y_u(k)=[0\ 1]\begin{pmatrix}\Delta z(k)\\ y_u(k)\end{pmatrix}$$

$$\begin{aligned}x_p(k+1)&=\Psi x_p(k)+\Phi\Delta u(k)\\ y_p(k)&=\Theta x_p(k)\end{aligned} \qquad (6.4)$$

where $x_p(k)=\begin{pmatrix}\Delta z(k)\\ y_u(k)\end{pmatrix}, y_p(k)=y_u(k)$

$$\Psi=\begin{pmatrix}\Pi & 0\\ \Xi\Pi & 1\end{pmatrix},\ \Phi=\begin{pmatrix}\Gamma\\ \Xi\Gamma\end{pmatrix},\ \Theta=[0\ 1]$$

The state can be predicted at N_p instant as follows.

$$x_p(k+N_p|k)=\Psi^{N_p}x(k)+\sum_{i=1}^{N_c}\Psi^{N_p-i}\Phi\Delta u(k+i-1) \qquad (6.5)$$

The output can be predicted at N_p instant as follows.

$$y_p(k+N_p|k)=\Theta\Psi^{N_p}x(k)+\Theta\sum_{i=1}^{N_c}\Psi^{N_p-i}\Phi\Delta u(k+i-1) \qquad (6.6)$$

Where N_p is the prediction horizon and N_c is the control horizon.

The main problem with MPC is that it gives heavy computational load. In the case of complicated process dynamics, rapid sampling and requirement of best closed loop performance require a good approximation of control trajectory ΔU which results in requirement of a long control horizon. All these result in heavy computational load. We can get a better approximation using Laguerre network.

6.3 LAGUERRE NETWORK:

Laguerre network is orthonormal in nature ([22], [23]). In frequency domain this orthonormality can be represented by the following relation.

— 1 (6.7)

— 0, if (6.8)

The main application of Laguerre Network is in system identification.

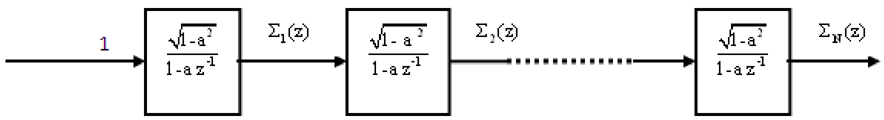


Figure6.1. A basic discrete time Laguerre network

The Z-transform of the Laguerre network is given by the following equations.

$$\Sigma_1(z)=\frac{\sqrt{1-b^2}}{1-bz^{-1}} \tag{6.9}$$

$$\Sigma_1(z)=\frac{\sqrt{1-b^2}}{1-bz^{-1}}\frac{z^{-1}-b}{1-bz^{-1}}$$

$$\vdots$$

$$\vdots$$

$$\Sigma_1(z)=\frac{\sqrt{1-b^2}}{1-bz^{-1}}\frac{(z^{-1}-b)^{N-1}}{1-bz^{-1}} \tag{6.10}$$

where b is the pole of the network and $0 \le b < 1$ for stability of the network and N is the number of terms to capture the impulse of the system.

The equation (6.9) to (6.10) can be written as

$$\Sigma_k(z)=\Sigma_{k-1}(z)\frac{z^{-1}-b}{1-bz^{-1}} \tag{6.11}$$

Lets $v_1(k), v_2(k),..........,v_N(k)$ are the inverse Z transform of $\Sigma_1(z,b), \Sigma_2(z,b),............,\Sigma_N(z,b)$ respectively.

Consider the vector $V(k)=[v_1(k), v_2(k),..........,v_N(k)]^T$

Then equation (6.11) can be written as

$$V(k+1)=A_L V(k) \tag{6.12}$$

Where A_L is a NxN matrix which is a function of b and $\alpha=(1-b^2)$. The initial condition is given by

$$V(0)^T=\sqrt{\alpha}[1 \ -b \ b^2..........(-1)^{N-1}b^{N-1}] \tag{6.13}$$

$$A_L=\begin{pmatrix} b & 0 & 0 & 0 & 0 & ..... & 0 \\ \alpha & b & 0 & 0 & 0 & ..... & 0 \\ -b\alpha & \alpha & b & 0 & 0 & ..... & 0 \\ b^2\alpha & -b\alpha & \alpha & b & 0 & ..... & 0 \\ \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\ (-b)^{N-2}\alpha & (-b)^{N-3}\alpha & (-b)^{N-4}\alpha & (-b)^{N-5}\alpha & ..... & \alpha & b \end{pmatrix}_{NxN}$$

6.4 PREDICTION OF OUTPUT AND STATE USING LAGUERRE NETWORK

Laguerre network can capture the impulse response of a system more effective and more quickly. The basic idea is that at time instant n consider the control trajectory $\Delta u(k), \Delta u(k+1), \Delta u(k+2)....\Delta u(k+n)$ are the impulse response of a stable dynamic system. To capture the dynamic response, a set of Laguerre functions $v_1(n), v_2(n),..........v_N(n)$ with a set of Laguerre coefficients $c_1(k)\ c_2(k).....c_N(k)$ which can be determined from the design process are used.

Then control trajectory can be represented by the following equation.

$$\Delta u(k+n)=\sum_{j=1}^{N} c_j(k)v_j(n) \tag{6.14}$$

The equation (6.14) can be written as

$$\Delta u(k+n)=V(n)^T\xi \tag{6.15}$$

where $\xi=[c_1(k)\ c_2(k)....c_N(k)]^T, V(n)=[v_1(n)\ v_2(n)....v_N(n)]^T$ N is terms used to capture the impulse response. So we will use N instead of N_c and n is the future sampling instant. If b=0, then N= N_c. Term 'b' is the pole of Laguerre network.

When Laguerre network is used to capture the response, then the prediction of the sate variable at sampling instant n can be obtained as

$$\begin{aligned}
x_p(k+1|k)&=\Psi x(k)+\Phi V(1)^T\xi \\
x_p(k+2|k)&=\Psi x(k+1)+\Phi V(2)^T\xi \\
&=\Psi^2 x(k)+\Psi\Phi V(1)^T\xi+\Phi V(2)^T\xi
\end{aligned} \tag{6.16}$$

$$\vdots$$

$$\begin{aligned}
x_p(k+n|k)=&\Psi^n x(k)+\Psi^{n-1}\Phi V(1)^T\xi \\
&+\Psi^{n-2}\Phi V(2)^T\xi+..........+\Phi V(n)^T\xi
\end{aligned} \tag{6.17}$$

Then the equations from (6.16) to (6.17) can be written as compact form as follows

$$x_p(k+n|k)=\Psi^n x(k)+\sum_{i=1}^{n}\Psi^{n-i}\Phi V(i)^T\xi \tag{6.18}$$

Then the predicted output can be written as follows for time instant n.

$$y_p(k+n|k)=\Theta\Psi^n x(k)+\sum_{i=1}^{n}\Theta\Psi^{n-i}\Phi V(i)^T\xi \tag{6.19}$$

6.5 DERIVATION OF MPC CONTROL SIGNAL TO COMPENSATE THE VARIABLE DELAY

The objective is to design an optimal control law which minimizes the following cost function.

$$J=\sum_{n=1}^{N_p}[x_p(k+n|k)^T Q x_p(k+n|k)+\xi^T R\xi] \tag{6.20}$$

where $Q\geq 0$, $R>0$ and $Q=\Theta^T\Theta$

The equation (6.19) can be written as

$$x_p(k+n|k)=\Psi^n x(k)+M(n)^T\xi \tag{6.21}$$

where $M(n)^T=\sum_{i=1}^{n}\Psi^{n-i}\Phi V(i)^T$

From equation (6.20) and equation (6.21) we obtain

$$\begin{aligned}J=&\xi^T(\sum_{n=1}^{N_p}M(n)QM(n)^T+R)\xi+2\xi^T(\sum_{n=1}^{N_p}M(n)Q\Psi^n)x_p(k)\\&+\sum_{n=1}^{N_p}x_p(k)^T(\Psi^T)^nQ\Psi^nx_p(k)\end{aligned} \tag{6.22}$$

To obtain the control law take the first derivative of the equation (6.22) with respect to ξ.

$$\xi=-(\sum_{n=1}^{N_p}M(n)QM(n)^T+R)^{-1}(\sum_{n=1}^{N_p}M(n)Q\Psi^n)x_p(k)=-\Lambda^{-1}\Xi x_p(k) \tag{6.23}$$

where $\Lambda=(\sum_{n=1}^{N_p}M(n)QM(n)^T+R)$, $\Xi=(\sum_{n=1}^{N_p}M(n)Q\Psi^n)$

6.6 RECEDING HORIZON CONTROL FOR NCS

The receding horizon control law obtained as

$$\Delta u(k)=V(0)^T\xi \tag{6.24}$$

Where for a given N and a

$$V(0)^T=\sqrt{(1-b)^2}[1\ -b\ b^2\ -b^3........(-1)^{N-1}b^{N-1}] \tag{6.25}$$

The control law can be written as

$$\Delta u(k)=-K_{mpc}x_p(k) \tag{6.26}$$

where $K_{mpc}=V(0)^T(\sum_{n=1}^{N_p}M(n)QM(n)^T+R)^{-1}(\sum_{n=1}^{N_p}M(n)Q\Psi^n)$ (6.27)

Now look at the state vector $x_p(k)$.

$$x_p(k)=\begin{pmatrix}\Delta z(k)\\ e(k)\end{pmatrix}=\begin{pmatrix}\Delta x(k)\\ \Delta u(k-\tau)\\ \Delta u(k-(\tau-1))\\ \vdots\\ \Delta u(k-2)\\ \Delta u(k-1)\\ e(k)\end{pmatrix}$$

$$e(k)=y_p(k)-r(k) \tag{6.28}$$

There are three parts in gain matrix. The first part will be multiplied with difference of state, second part will be multiplied with the difference of delayed control signal and third part will be multiplied with the plant output.

So the gain matrix can be written as follows for better understanding.

$$K_{mpc}=[|k_i|_{i=1\to n},|k_{n+i}|_{i=1\to\tau},k_{n+\tau+1}] \tag{6.29}$$

where $|\;|$ indicates that the element is a row vector and $|\;|^T$ indicates that it is a column vector. Subscript number indicates the position of the element in the vector.

6.7 SOLUTION OF MPC GAIN CONSIDERING CONSTRAINTS USING QUADRATIC PROGRAMMING

$$\begin{aligned} &u^{min}(k)\le u(k)\le u^{max}(k)\\ &\Delta u^{min}(k)\le \Delta u(k)\le \Delta u^{max}\end{aligned} \tag{6.30}$$

The constraints given by the equation (6.30) can write in compact form.

$$L\Delta U\le\gamma \tag{6.31}$$

where $L=\begin{pmatrix}L_1\\ L_2\end{pmatrix}$, $\gamma=\begin{pmatrix}\gamma_1\\ \gamma_2\end{pmatrix}$, $L_1=\begin{pmatrix}-\sum_{i=1}^{n-1}L(i)^T\\ \sum_{i=1}^{n-1}L(i)^T\end{pmatrix}$, $L_2=\begin{pmatrix}-L^T(n)\\ L^T(n)\end{pmatrix}$ $\gamma_1=\begin{pmatrix}-U^{min}+u(k-1)\\ U^{max}-u(k-1)\end{pmatrix}$, $\gamma_2=\begin{pmatrix}-\Delta U^{min}\\ \Delta U^{max}\end{pmatrix}$

To optimize the control solution with the constraints given by equation (6.31), the following cost function is to be minimized subject to the constraint. This is called quadratic programming.

$$J_1=\xi^T\Lambda\xi+2\xi^T\Xi x_p(k) \tag{6.32}$$

The overall closed loop system can be represented by the following block diagram.

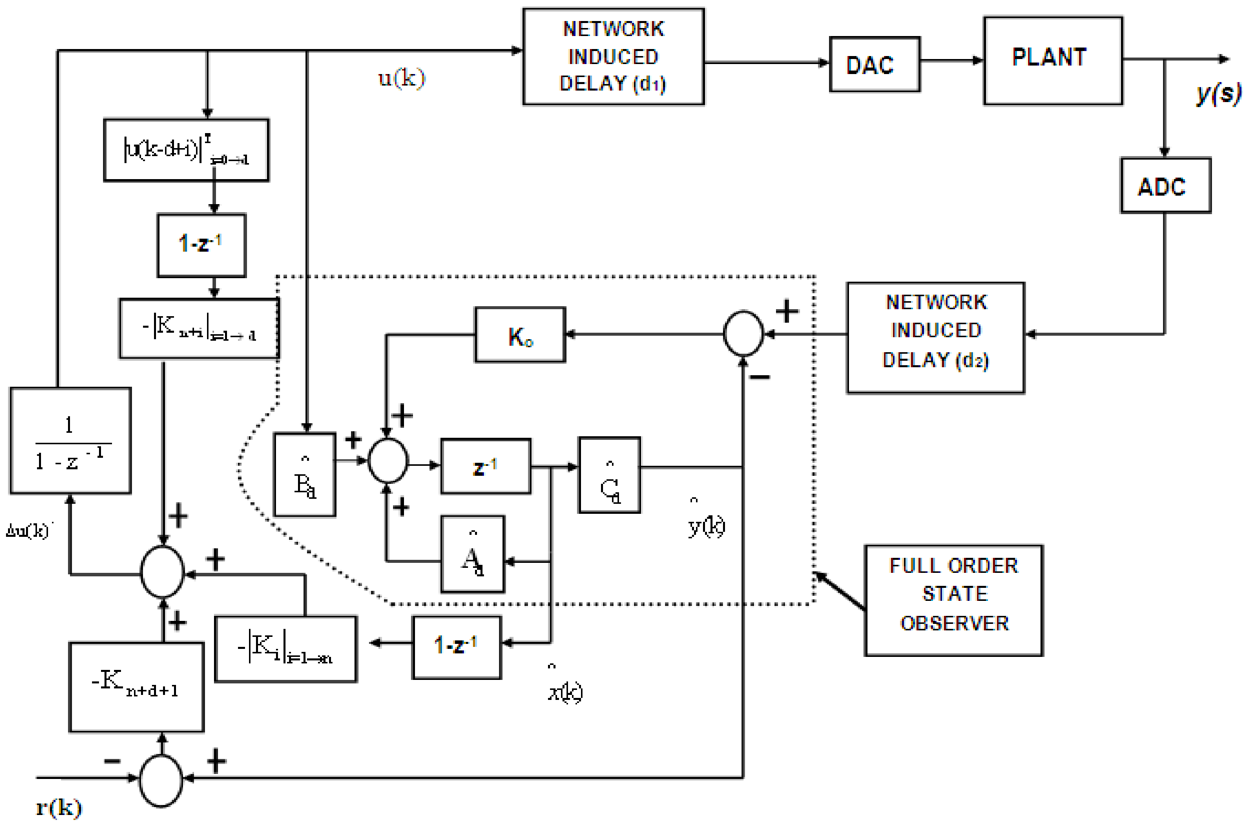


Figure6.2. Closed loop system using MPC controller

The control signal is computed as follows.

$$\Delta u(k)=-|k_i|_{i=1\to n}\,\Delta\hat{x}(k)^T-|k_{n+i}|_{i=1\to\tau}\,|\Delta u(k-\tau+i)|^T_{i=0\to(\tau-1)}-k_{n+\tau+1}(\hat{y}(k)-r(k)) \tag{6.33}$$

6.8 COMPUTATION OF OBSERVER GAIN

The dynamics of the state observer can be written as

$$\hat{x}(k+1)=\hat{A}_d\,\hat{x}(k)+\hat{B}_d\,u(k)+K_o(y(k)-\hat{y}(k)) \tag{6.34}$$

The observer gain can be calculated replacing (A_d, B_d) by (A_d^T, C_d^T) based on LQR technique. The observer gain can be obtained as

$$K_o = P_o C_d^T R_o^{-1} \tag{6.35}$$

where P_o is obtained by solving the following Riccati equation.

$$A_d P_o + P_o A_d^T + Q_o - P_o C_d^T R_o^{-1} C_d P_o = 0 \tag{6.36}$$

6.9 ANALYSIS OF THE CLOSED LOOP SYSTEM USING MPC CONTROLLER

The control input is given by the following relation.

$$u(k)=-\left|K_i\right|_{i=1\to n}\hat{x}(k)^T-\left|K_{n+i}\right|_{i=1\to\tau}\left|u(k-d+i)\right|_{i=0\to(\tau-1)}^T-K_{n+\tau+1}\frac{(\hat{y}(k)-r(k))}{1-z^{-1}} \tag{6.37}$$

The discrete sequence equivalent to $\frac{1}{1-z^{-1}}$ is given by [1, -1, 1, -1……..] which can be written as $(-1)^{k+2}$.

Then the control signal can be written as follows.

$$u(k)=-\left|K_i\right|_{i=1\to n}\hat{x}(k)^T-\left|K_{n+i}\right|_{i=1\to\tau}\left|u(k-d+i)\right|_{i=0\to(\tau-1)}^T-K_{n+\tau+1}(-1)^{k+2}(\hat{y}(k)-r(k)) \tag{6.38}$$

$$\begin{aligned}
x(k+1)&=A_dx(k)+B_d[-\left|K_i\right|_{i=1\to n}\hat{x}(k)-\left|K_{n+i}\right|_{i=1\to\tau}\left|u(k-\tau+i)\right|_{i=0\to(\tau-1)}^T-K_{n+\tau+1}(-1)^{k+2}(\hat{y}(k)-r(k))]\\
&=A_dx(k)-B_d\left|K_i\right|_{i=1\to n}\hat{x}(k)-B_d\left|K_{n+i}\right|_{i=1\to\tau}\left|u(k-d+i)\right|_{i=0\to(\tau-1)}^T-(-1)^{k+2}B_dK_{n+\tau+1}C_d\hat{x}(k)+(-1)^{k+2}B_dK_{n+\tau+1}r(k)\\
&=A_dx(k)-(B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d)\hat{x}(k)-B_du_d(k)+(-1)^{k+2}B_dK_{n+\tau+1}r(k)
\end{aligned} \tag{6.39}$$

Now consider $\tilde{x}(k)=x(k)-\hat{x}(k)$

From the equation (6.39), the following relation can be written.

$$
\begin{aligned}
x(k+1)&=A_d x(k)-(B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d)\hat{x}(k)-B_du_d(k)+(-1)^{k+2}B_dK_{n+\tau+1}r(k)\\
&=A_d x(k)-(B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d)x(k)\\
&\quad-(B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d)\tilde{x}(k)-B_du_d(k)+(-1)^{k+2}B_dK_{n+\tau+1}r(k)\\
&=(A_d-B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d)x(k)\\
&\quad-(B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d)\tilde{x}(k)-B_du_d(k)+(-1)^{k+2}B_dK_{n+\tau+1}r(k)
\end{aligned} \tag{6.40}
$$

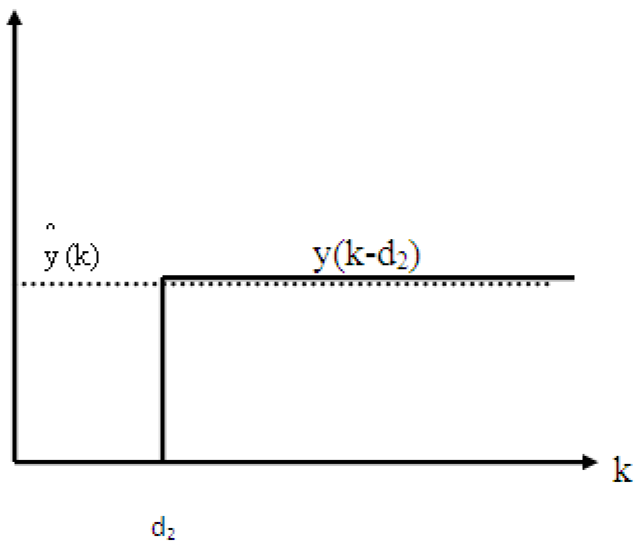


Figure6.3 Synchronization between system output and observer output

Case1: Up to time instant d_2

The observer dynamics is given by the following equation.

$$
\begin{aligned}
\hat{x}(k+1)&=\hat{A}_d\hat{x}(k)+\hat{B}_d u(k)-K_o\hat{y}(k)\\
&=\hat{A}_d\hat{x}(k)+\hat{B}_d u(k)-K_o\hat{C}_d\hat{x}(k)\\
&=\hat{A}_d\hat{x}(k)+\hat{B}_d u(k)-K_o\hat{C}_d x(k)+K_o\hat{C}_d\tilde{x}(k)
\end{aligned} \tag{6.41}
$$

Now subtracting the equation (6.41) from the equation (2.2), the following error equation is obtained.

$$\tilde{x}(k+1)=(A_d-K_o\hat{C}_d)\tilde{x}(k)+K_o\hat{C}_d x(k) \tag{6.42}$$

Then the augmented state space equation for closed loop system with state observer is written by the following state space equation.

$$\begin{pmatrix} x(k+1) \\ \tilde{x}(k+1) \end{pmatrix} = \begin{pmatrix} (A_d - B_d \left|K_i\right|_{i=1\to n} + (-1)^{k+2} B_d K_{n+\tau+1} C_d) & -(B_d \left|K_i\right|_{i=1\to n} + (-1)^{k+2} B_d K_{n+\tau+1} C_d) \\ K_o C_d & (A_d - K_o C_d) \end{pmatrix} \begin{pmatrix} x(k) \\ \tilde{x}(k) \end{pmatrix} + \begin{pmatrix} -B_d & (-1)^{k+2} B_d K_{n+\tau+1} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} u_d(k) \\ r(k) \end{pmatrix} \tag{6.43}$$

Case2: After the time instant d_2

The observer dynamics is given by the following equation.

$$\begin{aligned} \hat{x}(k+1) &= \hat{A}_d \hat{x}(k) + \hat{B}_d u(k) + K_o (y(k) - \hat{y}(k)) \\ &= \hat{A}_d \hat{x}(k) + \hat{B}_d u(k) + K_o \hat{C}_d \tilde{x}(k) \end{aligned} \tag{6.44}$$

Now subtract the equation (6.44) from the equation (2.2), the following relation can be written.

$$\begin{aligned} \tilde{x}(k+1) &= \hat{A}_d \hat{x}(k) + \hat{B}_d u(k) + K_o (y(k) - \hat{y}(k)) \\ &= (\hat{A}_d - K_o \hat{C}_d) \tilde{x}(k) \end{aligned} \tag{6.45}$$

From equation (6.40) and equation (6.45), following augmented state space equation can be written.

$$\begin{pmatrix} x(k+1) \\ \tilde{x}(k+1) \end{pmatrix} = \begin{pmatrix} (A_d - B_d \left|K_i\right|_{i=1\to n} + (-1)^{k+2} B_d K_{n+\tau+1} C_d) & -(B_d \left|K_i\right|_{i=1\to n} + (-1)^{k+2} B_d K_{n+\tau+1} C_d) \\ 0 & (\hat{A}_d - K_o \hat{C}_d) \end{pmatrix} \begin{pmatrix} x(k) \\ \tilde{x}(k) \end{pmatrix} + \begin{pmatrix} -B_d & (-1)^{k+2} B_d K_{n+\tau+1} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} u_d(k) \\ r(k) \end{pmatrix} \tag{6.46}$$

6.10 STABILITY ANALYSIS OF CLOSED LOOP SYSTEM WITH MPC CONTROLLER

Stability of the closed loop system can be analyzed in two steps.

Step1: Stability analysis considering constraints on terminal state

The closed loop system will be stable if the Eigen values of the matrix $(\Psi\text{-}\Phi K_{mpc})$ should be within unit circle.

The closed loop system will be stable if the Eigen values obtained from the following equations are remaining within unit circle.

$$\left(\lambda I\text{-}\begin{pmatrix} (A_d\text{-}B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d) & -(B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d) \\ K_oC_d & (A_d\text{-}K_oC_d) \end{pmatrix}\right)=0 \qquad (6.47)$$

$$\left(\lambda I\text{-}\begin{pmatrix} (A_d\text{-}B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d) & -(B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d) \\ 0 & (\hat{A}_d\text{-}K_o\hat{C}_d) \end{pmatrix}\right)=0 \qquad (6.48)$$

From equation (6.48), the following relation is obtained.

$$[\lambda I\text{-}(A_d\text{-}B_d\left|K_i\right|_{i=1\to n}+(-1)^{k+2}B_dK_{n+\tau+1}C_d)]=0 \qquad (6.49)$$

$$[\lambda I\text{-}(\hat{A}_d\text{-}K_o\hat{C}_d)]=0 \qquad (6.50)$$

The closed loop system will be stable if the Eigen values obtained from the equations (6.47), (6.49) and (6.50) are within the unit circle.

Step2: Stability analysis using Lyapunov function considering constraints on terminal state

The principle of receding horizon control is that at current sampling instant (k) the future control trajectory will be solved subject to constraints and among the all future control signal, only the first control signal will be used. At next sampling instant (k+1), same operation will be repeated. But when constraints are subjected, the control law will be nonlinear. So stability properties of linear time invariant system cannot be applied. But in certain condition the stability of the closed loop system can be established.

The closed loop stability can be established considering the following equality constraint on the terminal state.

$$x_p(k+N_p|k)=0 \tag{6.52}$$

Theorem 1 [94]: Assume that

(1) The terminal state $x_p(k+N_p|k)$ of the receding horizon problem subjects to the constraint $x_p(k+N_p|k)=0$. Where $x_p(k+N_p|k)$ is the terminal state corresponding to control sequence $\Delta u(k+N_p|k)=V(N_p)^T\xi$

(2) At each sampling instant, there exists a solution η such that the cost function J is minimized subject to the inequality constraints and terminal equality constraints $x_p(k+N_p|k)=0$

Subject to the assumptions, the closed loop model predictive controls is asymptotically stable.

Proof: Consider the following cost function for Receding horizon control.

$$J=\sum_{n=1}^{N_p} x_p(k+n|k)^T Q\, x_p(k+n|k)+\sum_{n=0}^{N_p-1}\Delta u(k+n)^T R\Delta u(k+n) \tag{6.53}$$

Choose the Lyapunov function L(x (k), k) as follows

$$L(x_p(k),k)=\sum_{n=1}^{N_p} x_p(k+n|k)^T Q\, x_p(k+n|k)+\sum_{n=0}^{N_p-1}\Delta u(k+n)^T R\Delta u(k+n) \tag{6.54}$$

where $x_p(k+n|k)=\Psi^n x_p(k)+\sum_{i=1}^{n}\Psi^{n-i}\Phi V(n)^T\xi^k$ (6.55)

$$\Delta u(k+n)=V(n)^T\xi^k \tag{6.56}$$

ξ^k is the parameter vector obtained at time k, considering the both inequality and equality constraints. Assumption (2) ensures the existence of ξ^k.

At time k+1, Lyapunov function will be

$$L(x_p(k+1),k+1)=\sum_{n=1}^{N_p} x_p(k+1+n\,|k+1)^T Q\, x_p(k+1+n\,|k+1) + \sum_{n=0}^{N_p-1} \Delta u(k+1+n)^T R \Delta u(k+1+n) \qquad (6.57)$$

where

$$x_p(k+1+n\,|k)=\Psi^n x_p(k+1)+\sum_{i=1}^{n} \Psi^{n-i}\Phi V(i)^T \xi^{k+1} \qquad (6.58)$$

ξ^{k+1} is the parameter vector solution at k+1

$$\Delta u(k+1+n)=V(n)^T\xi^{k+1} \qquad (6.59)$$

Now consider that the all constraints are satisfied at time k and a feasible solution of ξ^{k+1}(not optimal) obtained as ξ^k for the receding horizon. $x_p(k+1)$ is the one step ahead of x(k) is given by the following equation.

$$x_p(k+1)=\Psi x_p(k)+\Phi\Delta u(k) \qquad (6.60)$$

One step ahead feasible control sequence is given by

$$V(1)^T\xi^k,\ V(2)^T\xi^k, ..., V(N_p-1)^T\xi^k \qquad (6.61)$$

Consider another function $\tilde{L}(x_p(k+1),\ k+1)$ which is similar to $L(x_p(k+1),k+1)$ except controls sequence is given by (6.61).

As ξ^{k+1} is not optimal, the following inequality can be written.

$$L(x_p(k+1),k+1) \le \tilde{L}(x_p(k+1),\ k+1) \qquad (6.62)$$

Subtract $L(x_p(k),k)$ from both side of the equation (6.62)

$$L(x_p(k+1),k+1)-L(x_p(k),k) \le \tilde{L}(x_p(k+1),\ k+1)-L(x_p(k),k) \qquad (6.63)$$

$$\tilde{L}(x_p(k+1), k+1)-L(x_p(k),k)=x_p(k+n|k)^T Qx_p(k+n|k) \\ -x_p(k+1|k)^T Qx_p(k+1|k) \\ -\Delta u(k)^T R\Delta u(k) \tag{6.64}$$

Using the equation (6.52), the following relation can be written.

$$\tilde{L}(x_p(k+1), k+1)-L(x_p(k),k)=-x_p(k+1|k)^T Qx_p(k+1|k) \\ -\Delta u(k)^T R\Delta u(k) \tag{6.65}$$

From the equation (6.63) and equation (6.65), the following relation is obtained.

$$L(x_p(k+1),k+1)-L(x_p(k),k) \le -x_p(k+1|k)^T Qx_p(k+1|k) \\ -\Delta u(k)^T R\Delta u(k) \tag{6.66}$$

From the relation (6.66), it can be said that the predictive control is asymptotically stable.

6.11 SIMULATION OF AN INTEGRATOR PLANT USING MPC CONTROLLER

For the simulation, an integrator is taken same as before. There is a variable delay of maximum value 0.6 second in the forward path. There is also a delay in the feedback path of estimated value 0.6 seconds. The plant is discretized at a sampling rate of 0.1 second.

The continuous time state space equation of the integrator is obtained as follows.

$$\dot{x}(t) = u(t) \\ y(t) = x(t) \tag{4.67}$$

The discrete time state space equation can be obtained as follows.

$$x(k+1) = x(k)+0.1u(k) \\ y(k) = x(k) \tag{4.68}$$

The augmented state space matrices are obtained as follows.

$$\Psi=\begin{pmatrix} A_d & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\Phi=[0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 1\ \ 0]^T$$

$$\Theta=[0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 1]$$

The controller gain is obtained as follows.

K_{mpc}= [5.1030, 0.5103, 0.4961, 0.4820, 0.4678, 0.4536, 0.4395, 0.4253, 0.4111, 0.3970, 0.3828, 0.3686, 0.3545, 0.1417]

Simulation is done for the same plant using same parameter as previous and using following constraints.

$$\begin{aligned} -0.3 &\le u(k) \le 0.2 \\ -0.1 &\le \Delta u(k) \le 0.1 \end{aligned} \tag{4.69}$$

The observer gain can be obtained as 0.1.considering R_o=9 and Q_o=0.1.

For Laguerre network, the pole is taken at a=0.7 and N=1. The prediction horizon N_p=46.

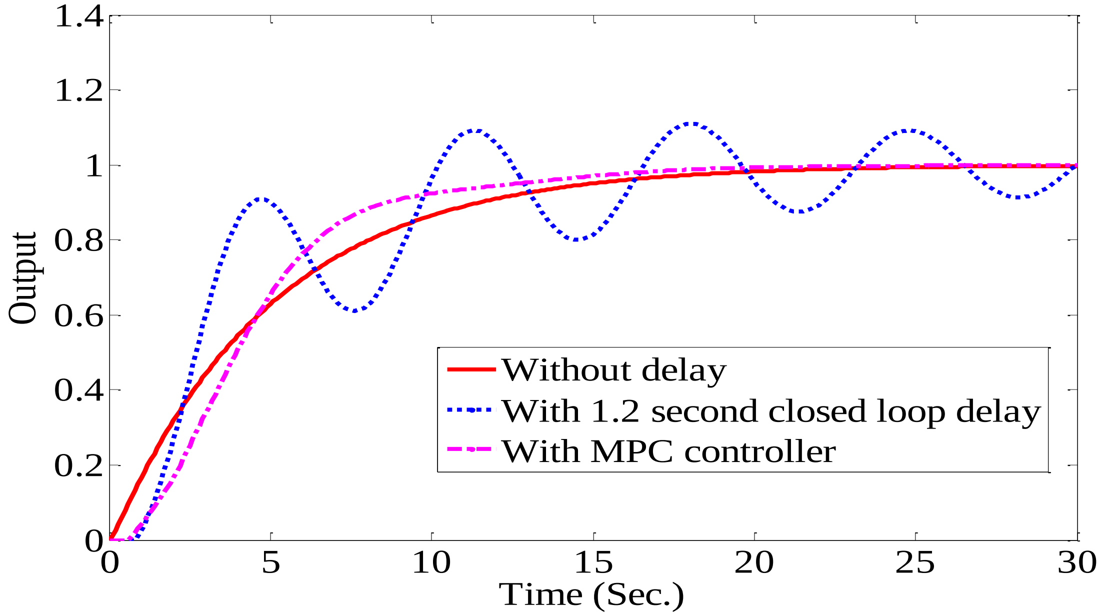


Figure6.4. Step response obtained using MPC controller

Table6.1: Values of time domain parameters and frequency domain parameter for figure6.4.

	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
System without delay	10.9	19.5	0	-180	49.5
System with delay (1.2 seconds)	3.05	59.1	11	Closed loop system is unstable	
System with MPC controller	7.12	16.4	0	-180	23.7

Figure6.4 shows that without delay, the system is stable. But the system becomes unsatble if there is a closed loop delay of 1.2 seconds. Using MPC controller designed here, the system becomes satble and tracks the sytem input with zero steady state error.

From the Table6.1, it is seen that MPC controller designed for compensating the networked induced variable delay imprves system transient response and it also makes the system stable with the closed loop delay of 1.2 seconds.

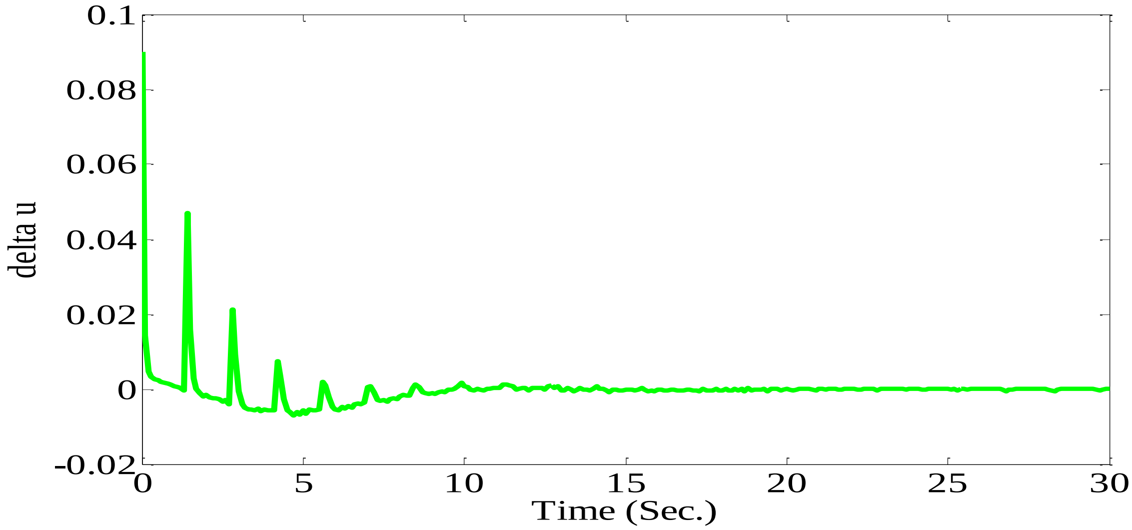


Figure6.5. Rate of control input

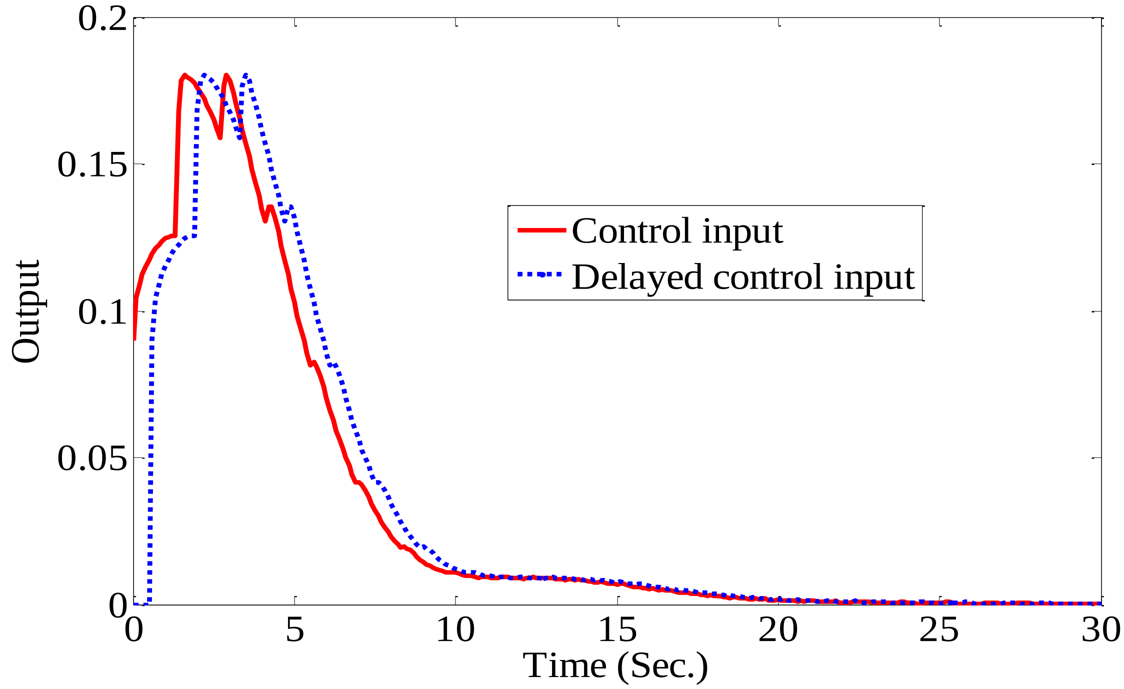


Figure6.6. Control input

Figure6.5 shows the rate of control input and Figure6.6 shows the control input. From these figure, it is seen that the imposed constraints on the control input and rate of control input are given by equation (6.29) are maintained.

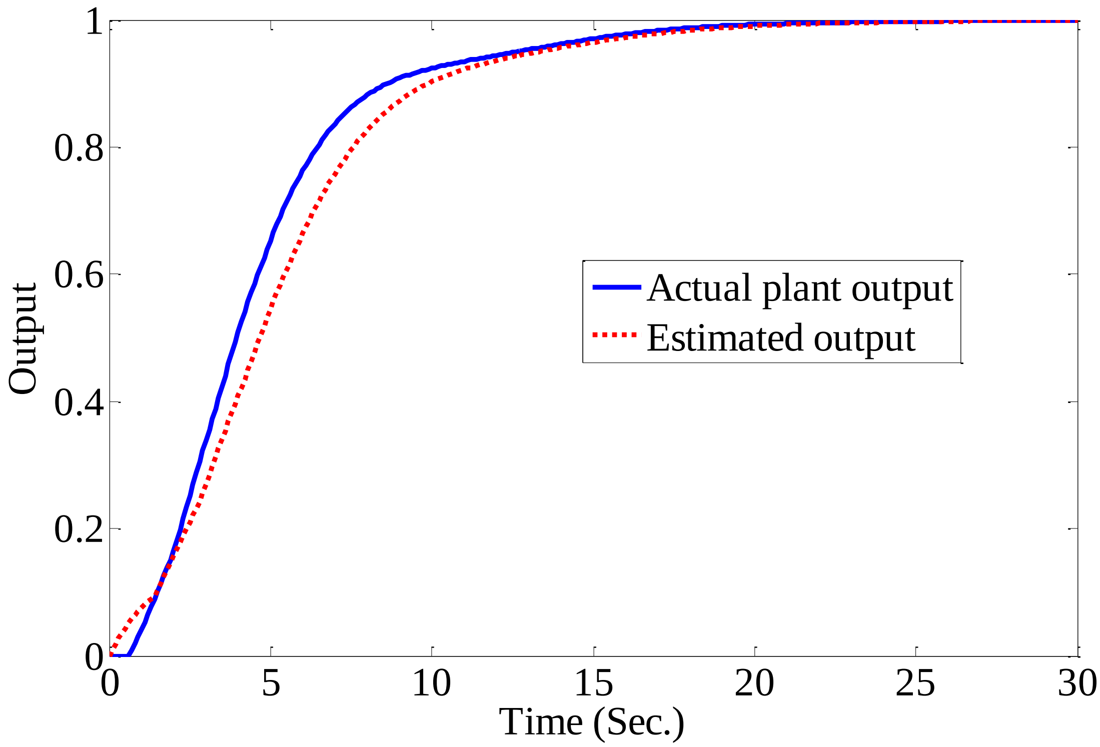


Figure6.7. State observer output

Figure6.7 shows that the state observer perfectly estimates the sytem output using delayed system output and the estimated output is free from the elay induced by network.

6.12 DIFFERENT CASE STUDIES BASED ON DIFFERENT STATUS OF DELAYS

The MPC controller is designed considering the maximum induced delay in the forward path and feedback path. But in practical cas it is not fixed. Sometimes it reaches to the maximum value. Sometimes it is less than the estimeted one and sometimes it may be happned that it becomes larger than the estimated one if the network states changes. It may be happned some new node is added to the network or some othe interference is arrived in the network. So the sate of the network may changed from estimated one. So it should checked the capability of the controller to compensate the networked induced delay which is greater than the estimated one considering some unknown chages may happned in the network sate which makes the networked induced delay greater than the estimated one. But the controller gain is same for all cases as the calculated considering the estimated maximum delay.

In this section different cases are studied considering different situation of networked induced delays.

Case1: Only forward path delay is varied but the feedback path delay is fixed

Figure6.8 shows the step response obtained considering that the forward path delay is varied but the feedback path delay is not varied. But it is assumed that the forward path delay is allaways less than the estimated one.

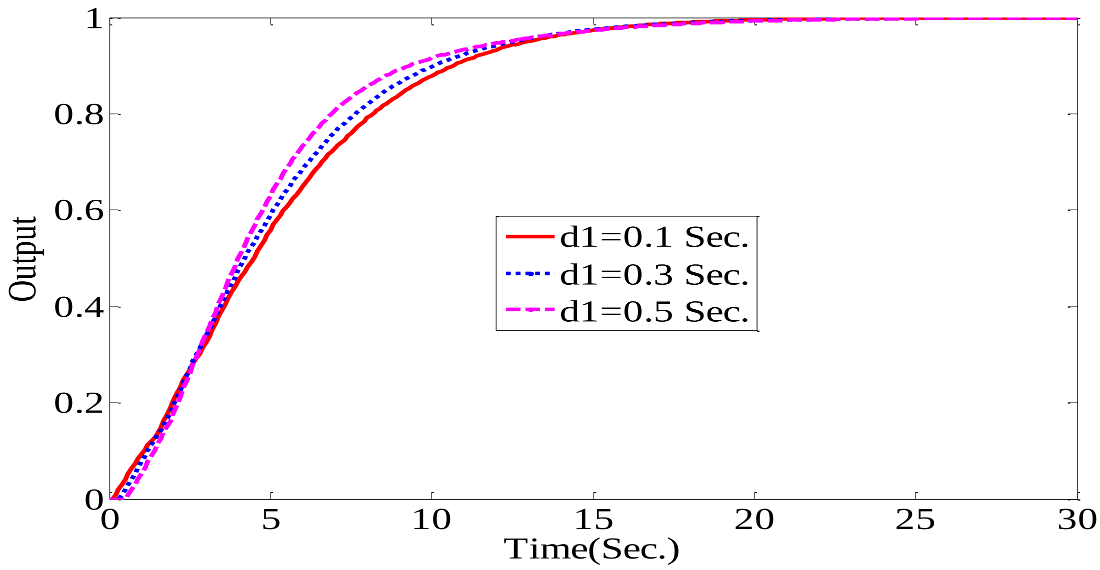


Figure6.8. Step response when the forward path delay is less than the estimated maximum delay

Table6.2: Values of time domain parameters and frequency domain parameter for figure6.8.

Forward path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.1	7.91	14.2	0	-180	30.3
0.3	7.37	14.6	0	-180	26.6
0.5	6.64	15.2	0	-	30.3

Figure6.8 shows that the step respons is stable if the forward path delay is varied and alaways less than the estimated one. The response hase 0% overshoot and zero steady state error. From Table6.2, it is seen that the rise time is reduces and settling time increases as the delay increases.

But there is no significant change in GM and PM. Ultimately the closed loop system is stable if the forward path delay is varied and alaways less than the estimated one.

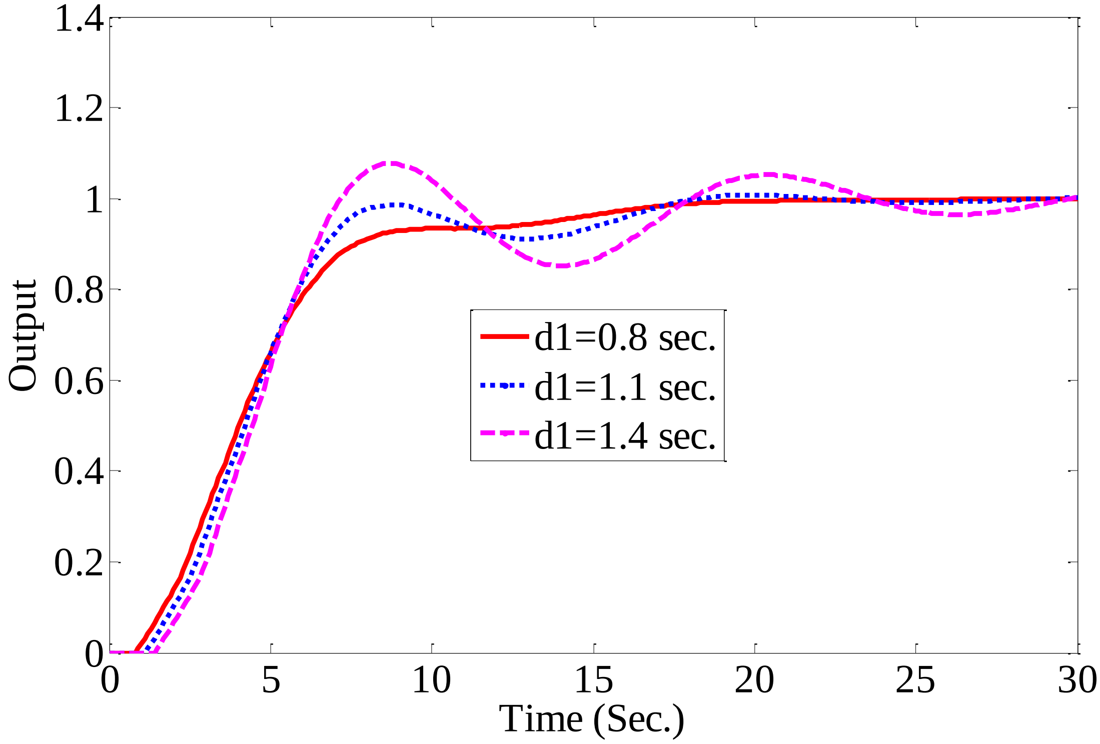


Figure6.9. Step response when the forward path delay is greater than the estimated maximum delay

Table6.3: Values of time domain parameters and frequency domain parameter for figure6.9.

Forward path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.8	5.96	16.7	0	-180	14.2
1.1	4.72	17	0.762	-180	6.91
1.4	4.13	28.3	7.71	8.81	1

Figure6.9 shows the step response when the forward path delay is varied but alaways greater than the estimated one. From the plot it is seen that the overshoot increases as the forward path delay increases. From the table6.3, it is seen that the PM and GM decreases as the forward path delay increases. So the ssytem stability reduces. When the estimation error is 130% (1.4 secod) then the overshoot becomes 7.71% , GM becomes 1 dB, Pm becomes 8.81 degree, settling time

becomes 28.3 seconds and rise time becomes 4.13 seconds. But the closed loop system is stable. So the closed loop system can tolarate 130% estimation error.

Case2: Only feedback path is varied but forward path is not varied

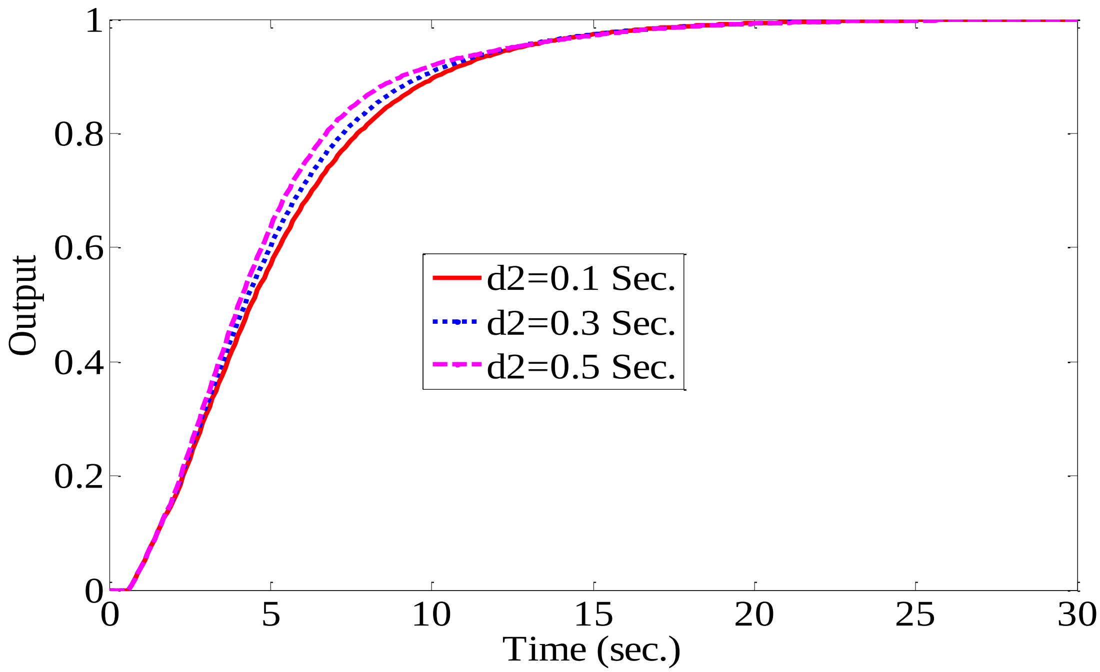


Figure6.10. Step response when the feedback path delay is less than the estimated maximum delay

Table6.4: Values of time domain parameters and frequency domain parameter for figure6.10.

Feedback path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.1	8.66	16.1	0	-	29.4
0.3	8.19	16.2	0	-180	27.9
0.5	7.58	16.4	0	-180	25.3

Figure6.10 shows that the step response is stable if the feedback path delay varies but always less than the estimated one. The system output perfectly tracks the system input with the 0% overshoot and zero steady state error. From Table6.4 it is seen that there is no significant changes in time domain parameters and frequency domain parameters.

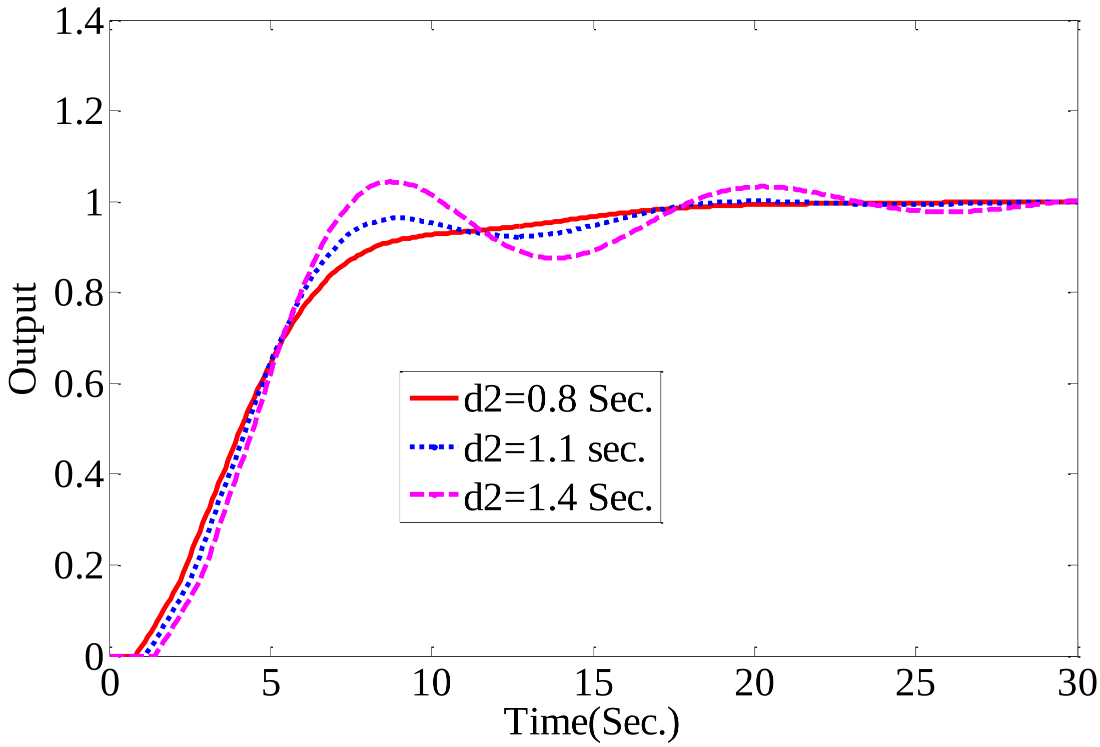


Figure6.11. Step response when the feedback path delay is greater than the estimated maximum delay

Table6.5: Values of time domain parameters and frequency domain parameter for figure6.11.

Feedback path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.8	5.96	16.5	0	-180	20
1.1	4.72	16.5	0.762	-180	14
1.4	4.13	27.5	7.71	34.8	7.86

Figure6.11shows the step response of the closed loop system is stable when the feedback path delay varies and always greater than the estimated one. From Table6.5, it is seen that the GM and PM reduces as the feedback path delay increases. The rise time reduces and settling time increases as the feedback path delay increases. The overshoot becomes 7.71% when there is an estimation error of 130% (1.4 seconds). But the system is stable. So the closed loop system can tolerate as large as 130% feedback path estimation error.

Case3: Simultaneously forward and feedback path delay are varied

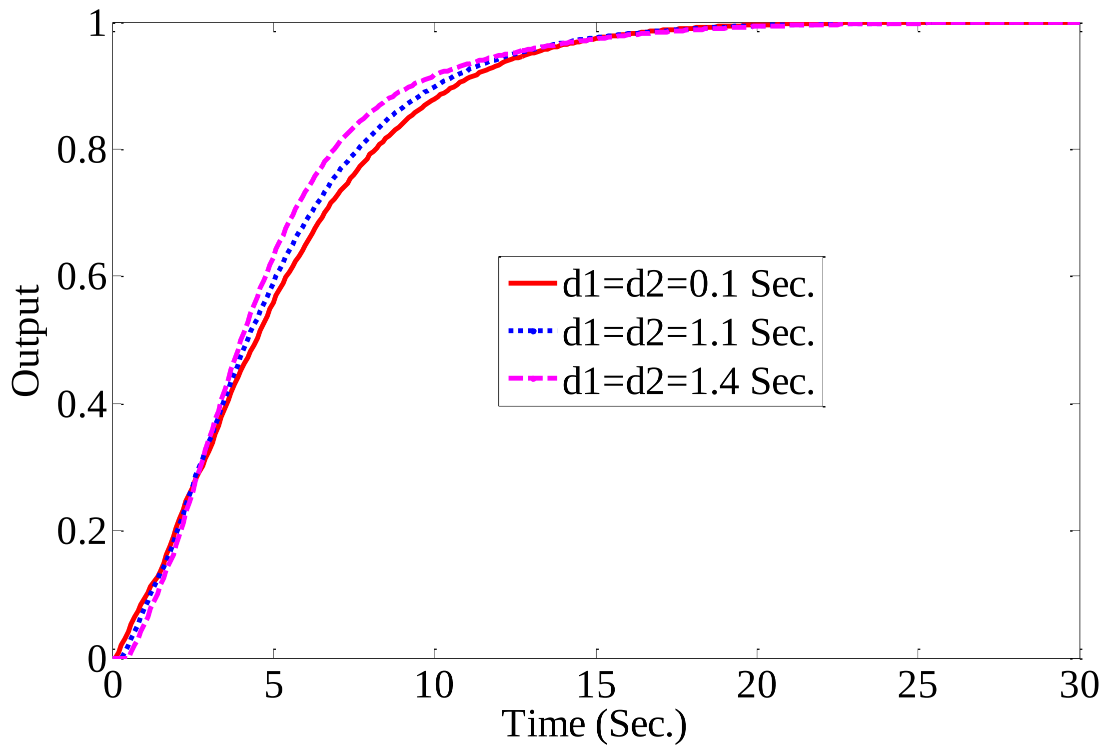


Figure6.12. Step response when forward and feedback path delay is less than the estimated maximum delay

Table6.6: Values of time domain parameters and frequency domain parameter for figure6.12.

Forward path delay (Sec.)	Feedback path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.1	0.1	9.58	15.9	0	-180	28.3
0.3	0.3	8.87	15.8	0	-180	24.7
0.5	0.5	7.91	16.2	0	-	30.7

Figure6.12 shows that the step response when the both feedback and forward path delays varies but alaways less than the estimated one. The system response is stable and output perfectly tracks the input withn zero steady state error and there is no overshoot. From Table6.6, it is seen that the there are no significant chages in time domain parameter and in the frequency domain paramete except the rise time reduces as the delay increases and settling time increses.

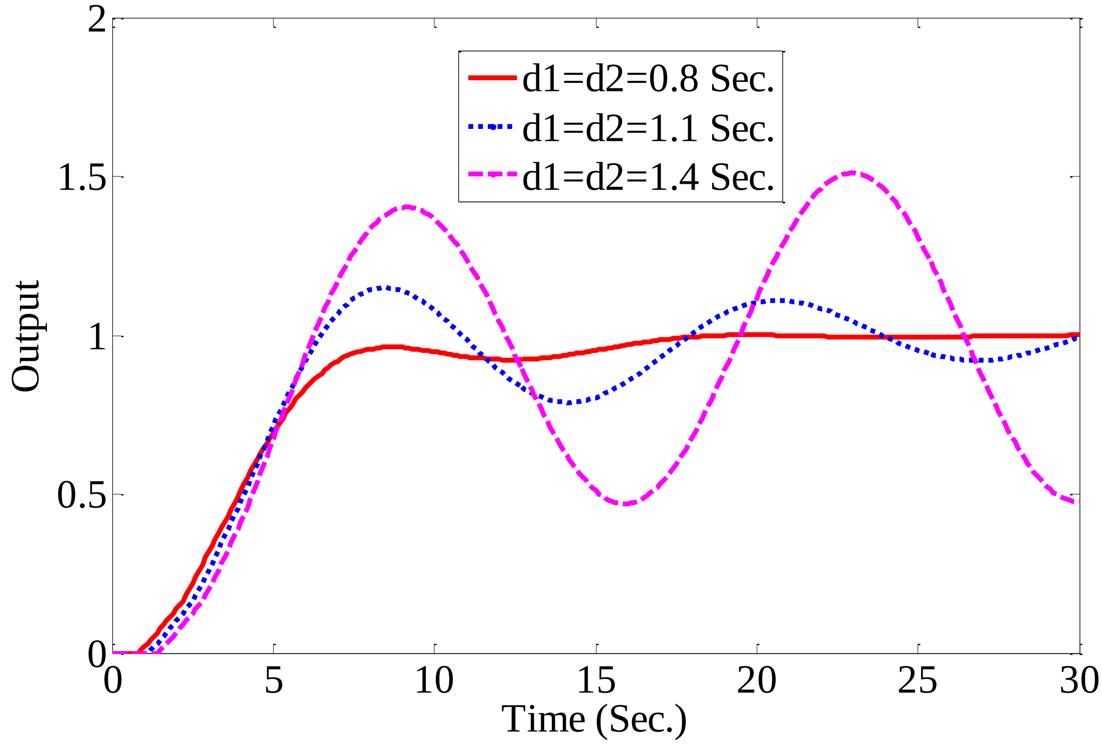


Figure6.13. Step response when forward and feedback path delay is greater than the estimated maximum delay

Table6.7: Values of time domain parameters and frequency domain parameter for figure6.13.

Forward path delay (Sec.)	Feedback path delay (Sec.)	Rise time (Sec.)	Settling time (Sec.)	Maximum overshoot (%)	Phase margin (Degree)	Gain margin (dB)
0.8	0.8	5.05	16.7	0.0696	-180	11.4
1.1	1.1	3.91	46.4	15	closed loop system becomes unstable	
1.4	1.4	closed loop system becomes unstable				

Figure6.13 shows that the closed loop step response when the both feedback and forward path delays varies but always greater than the estimated one. From Figure6.13 and Table6.7, it is seen that the system remain stable for 0.8 seconds but it becomes unstable when the delay becomes 1.1 seconds in both paths.

6.13 STABILITY ANALYSIS OF CLOSED LOOP CONTROL OF INTEGRATOR PLANT

Eigen values of the augmented closed loop systems are -0.0603 ± 0.0152i, -0.0457 ± 0.0419i, -0.0202 ± 0.0583i, 0.0099 ± 0.0601i, 0.0363 ± 0.0472i, 0.0520 ± 0.0244i, 0.0559, 0.9514, 0.7082

So the all Eigen values of the closed loop system are within the unit circle. So the system is stable.

From equation (6.46), Eigen value is 0.9.

From equation (6.43), Eigen values are 0.5062 when $(-1)^{k+2}=1$ and 0.5034 when $(-1)^{k+2}=-1$

From equation (6.45), Eigen values are 0.5042 when $(-1)^{k+2}=1$ and 0.4758 when $(-1)^{k+2}=-1$

All Eigen values are within the unit circle. So the closed loop system is stable.

Then the Bode plot, Nyquist plot and pole/ Zero maps are obtained by linearizing the closed loop system considering the 1.2 seconds closed loop delay.

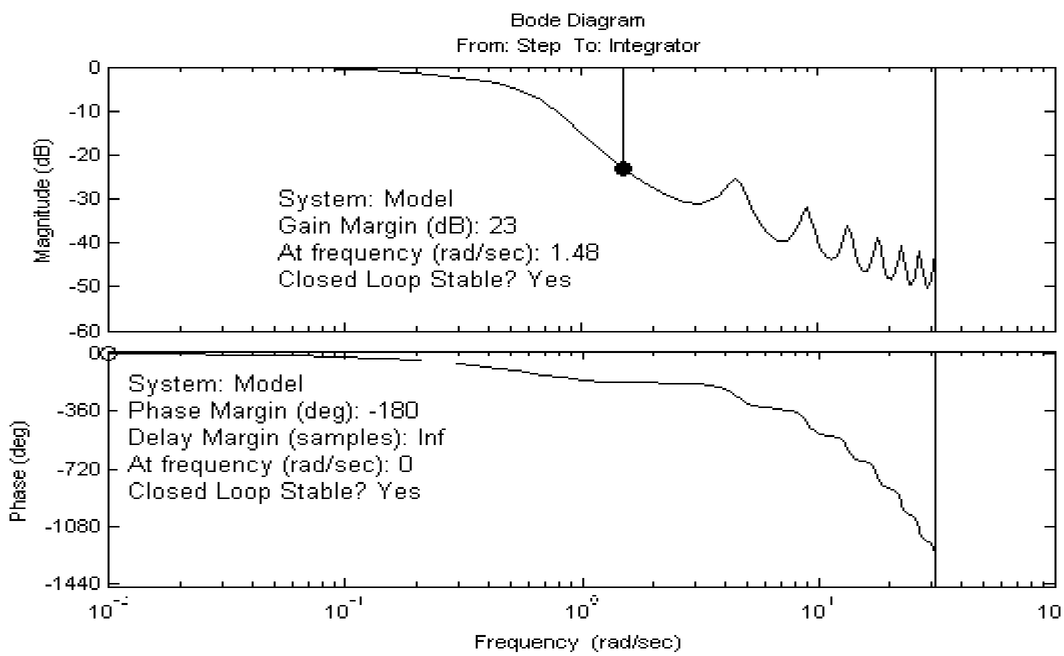


Figure6.14. Bode plot using MPC controller for closed loop system

Figure6.14 shows the Bode plot for the closed loop system obtained by linearizing using MAT LAB software considering 1.2 seconds closed loop delay. From the Bode plot it is seen that the closed loop system is stable and GM is 23 dB and PM is -180.

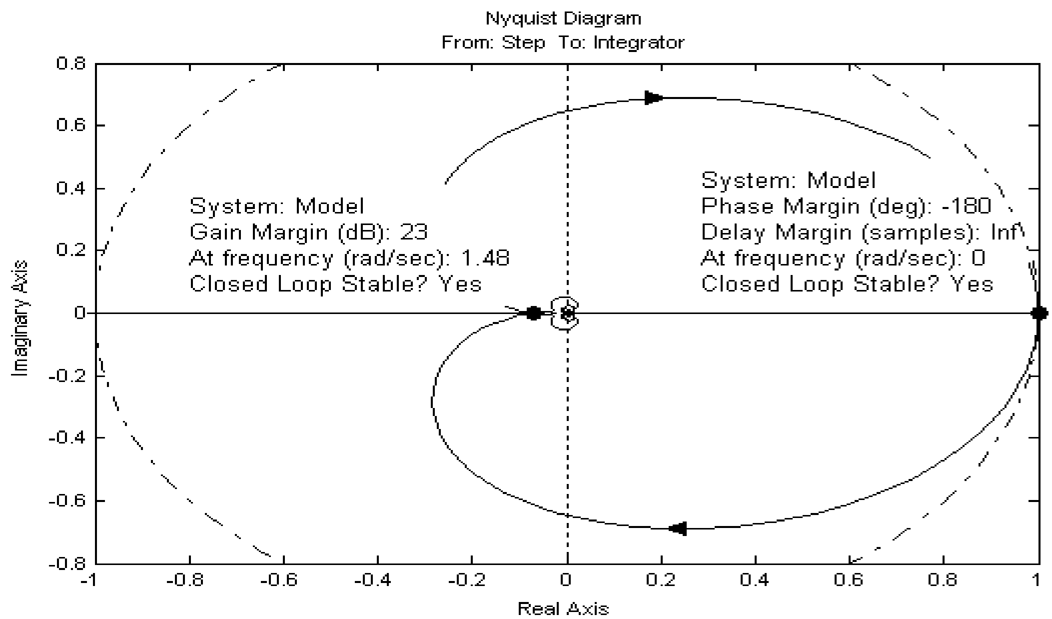


Figure6.15. Nyquist plot using MPC controller for closed loop system

Figure6.15 shows the Nyquist plot for closed loop system. From the plot it is seen that the Nyquist contour does not encircle the (-1, 0) point so the closed loop system is stable.

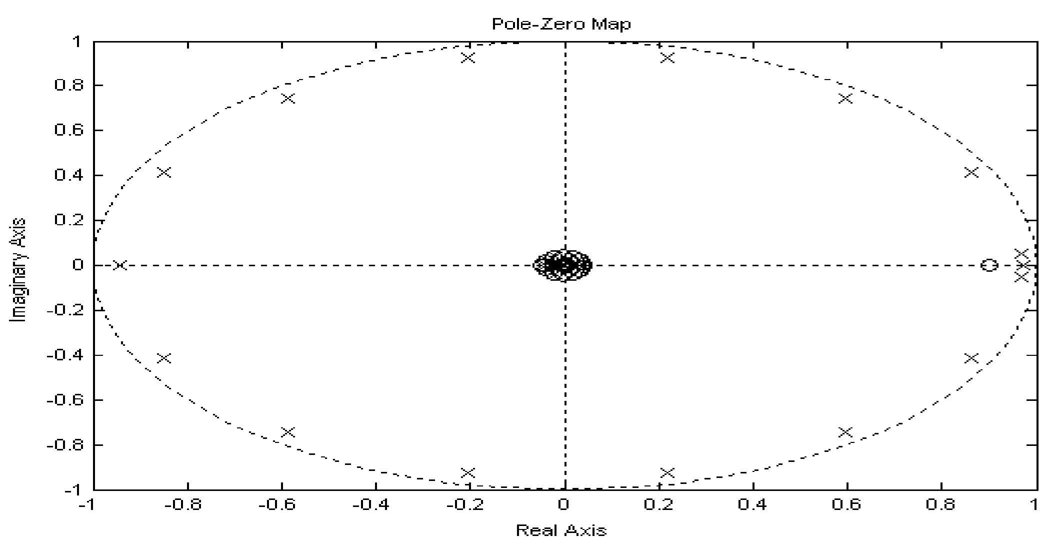


Figure6.16. Pole-Zero maps using MPC controller for closed loop system

Figure6.16 shows the pole-zero maps for the closed loop system. From the plot it is seen that all the poles and zeros are within the unit circle. So the closed loop system is stable.

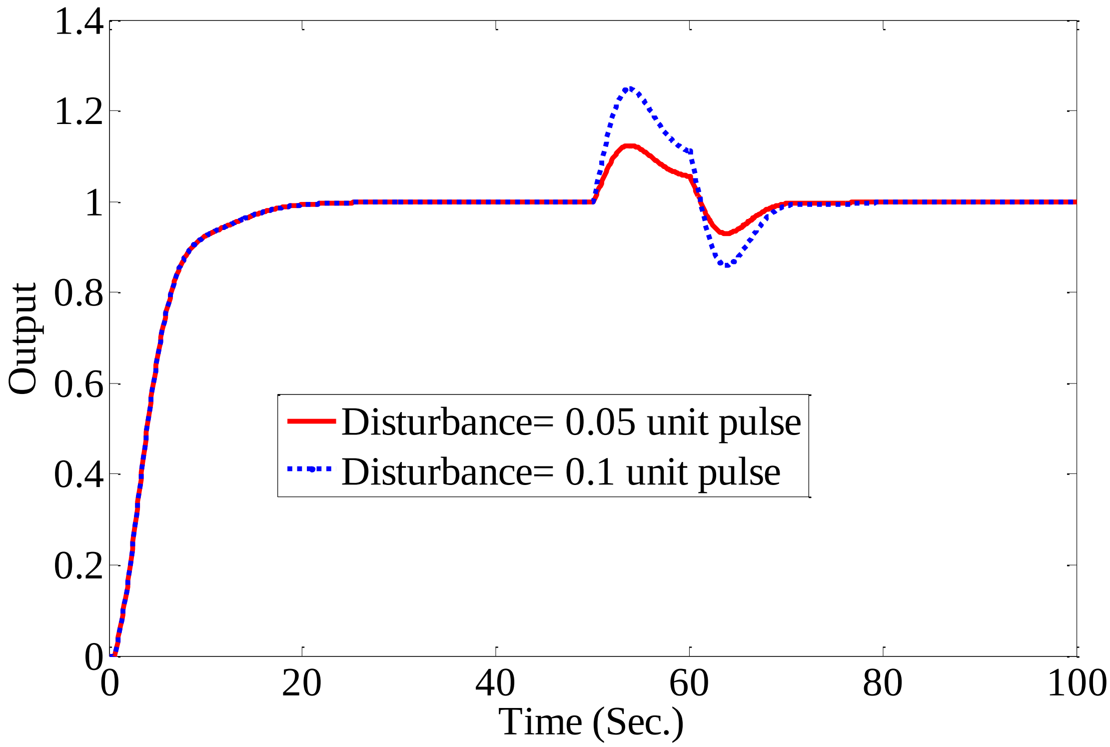


Figure6.17. Disturbance rejection using MPC controller

Figure6.17 shows the effects of external disturbance on the closed loop system. The disturbances of magnitude 0.05 and 0.1 are imposed for the time duration from 50 seconds to 60 seconds. From the response it is seen that the step response is bounded if there is an external disturbance.

6.14 REAL TIME EXPERIMENT

For real time experiment, the same setup of network is used like LQR and LQG like controller. The same controller gain and same observer gain is used as used in simulation. Because the controller is designed for 1.2 second closed loop delay and the real time closed loop delay is estimated as 1.1 seconds approximately. So the same controller can be used as designed for simulation.

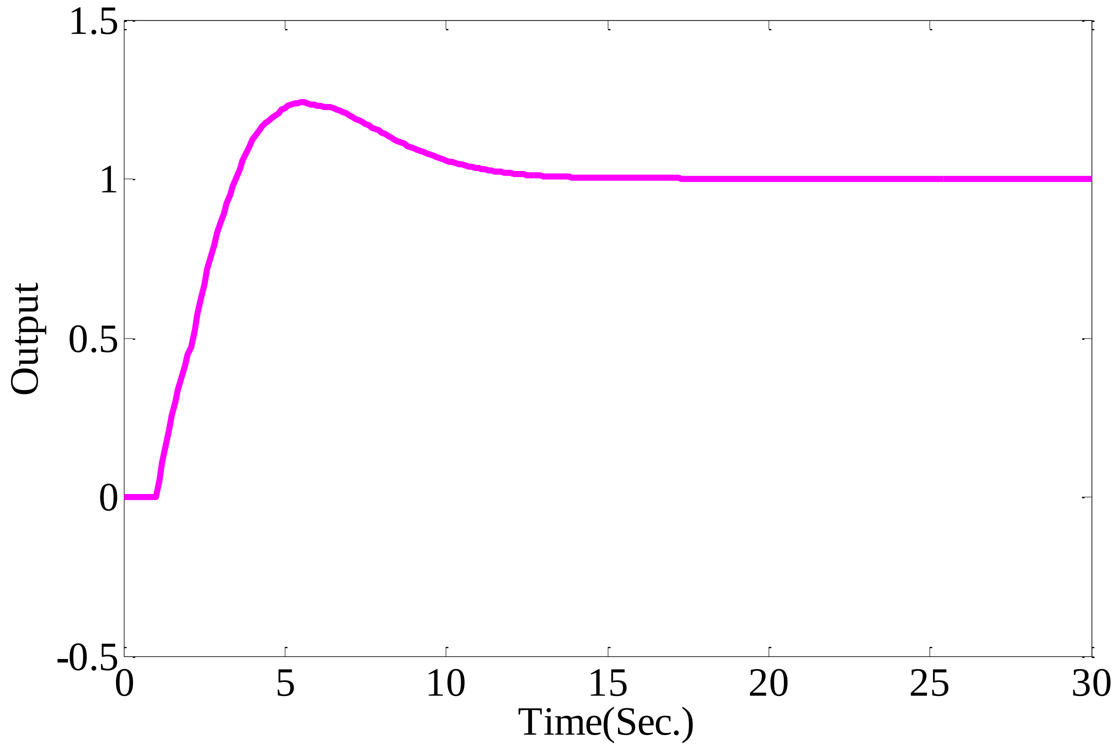


Figure6.18. Step response using MPC controller

Figure6.18 shows the step response obtained in real time experiment. From the response it is seen that the step response is stable except it has some initial delay which is equal to the forward path delay.

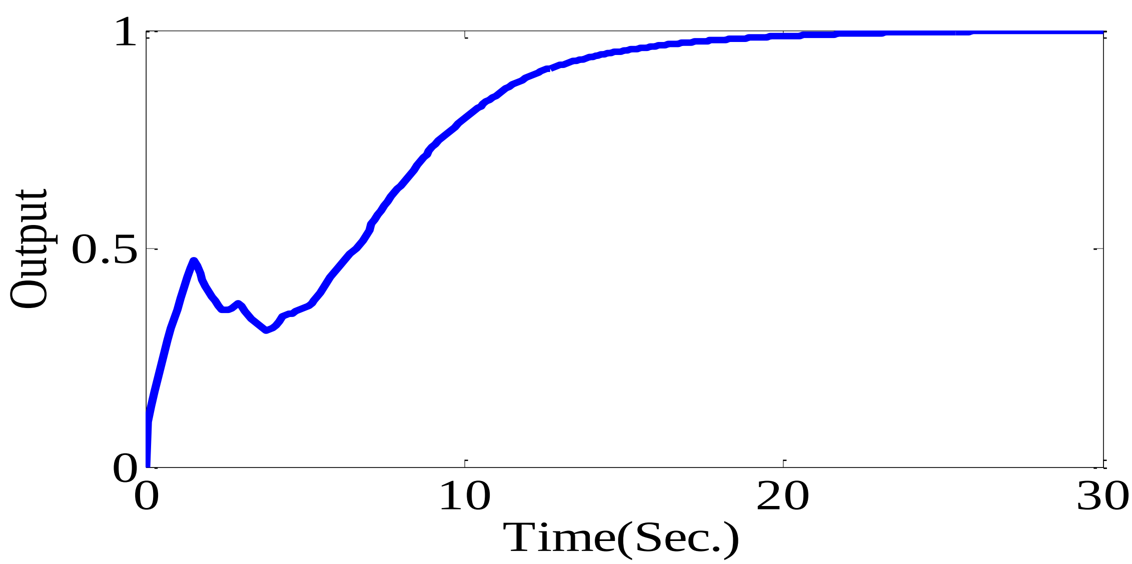


Figure6.19. Sate observer output obtained in real time experiment

Figure6.19 shows the estimeted output in real time experiment. From the response it is seen that initially it increses and the it has tendency to decreasing due to the feedback path delay. But ultimately it estimates the system output with approximately zero estimation error.

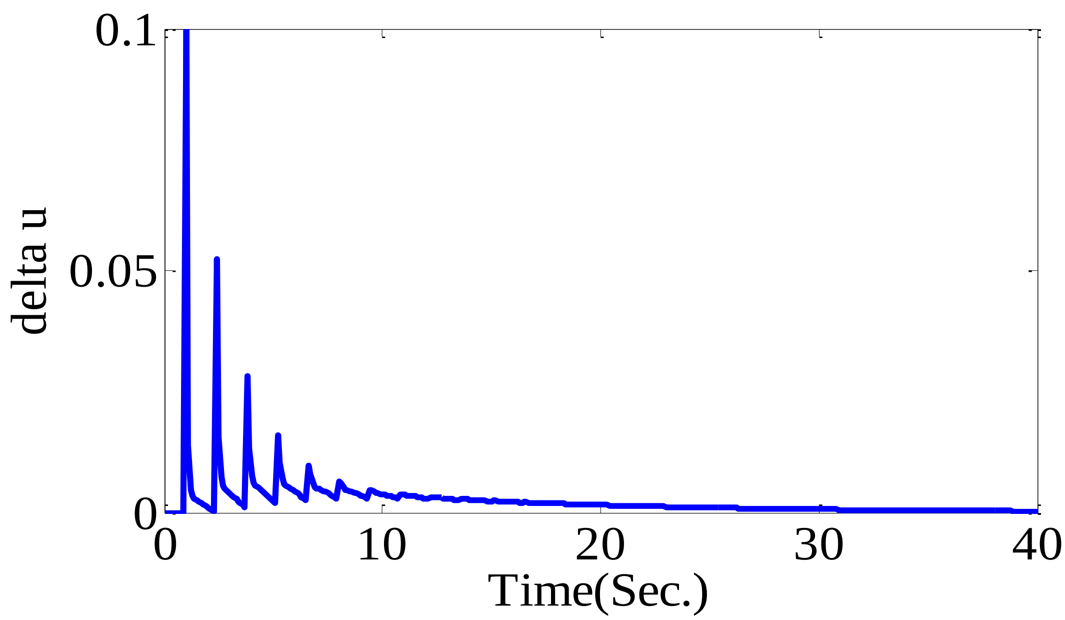


Figure6.20. Rate of control input obtained in real time experiment

Figure6.20 shows the rate of control input in real time which is identical to the result obtained in simulation and it maintain the constraints considered at the time of design.

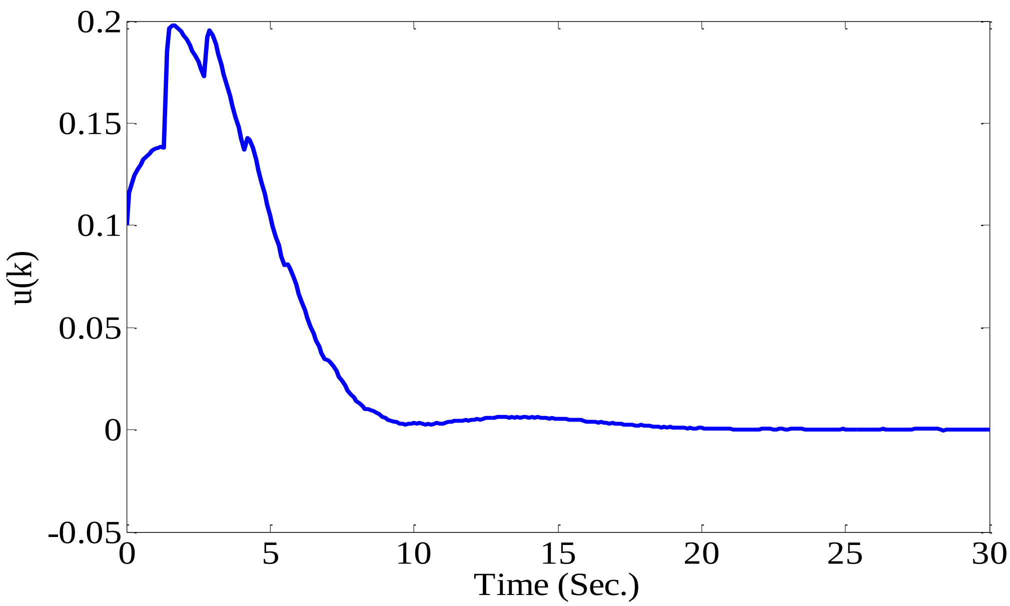


Figure6.21. Control input obtained in real time experiment

6.15 CHAPTER SUMMARY

In this chapter, an MPC controller is designed using Laguerre network for networked induced variable delay considering the constraints on rate of control input and on the control input. Then the stability of the closed loop system is analyzed. Then an integrator plant is simulated using g MAT LAB software. The real time experiment is conducted using the same controller as used in simulation. From the simulation result and from the real time experiment result it is seen that the MPC controller can compensate the networked induced variable delay.

7 CHAPTER 7- COMPERISON AMONG LQR, LQG-LIKE AND MPC CONTROLLERS

Although the working condition of the three controllers are not same, a comparison is presented based on the step response and different time domain and frequency domain parameter's values and closed loop pole location. In case of LQR controller only networked induced delay is considered and in case of LQG like controller, networked induced delay and plant input noise and measurement noise are considered. In case of MPC controller, there are constraints on the control input and on the rate of control input. Each controller can compensate the networked induced variable delay with their working condition.

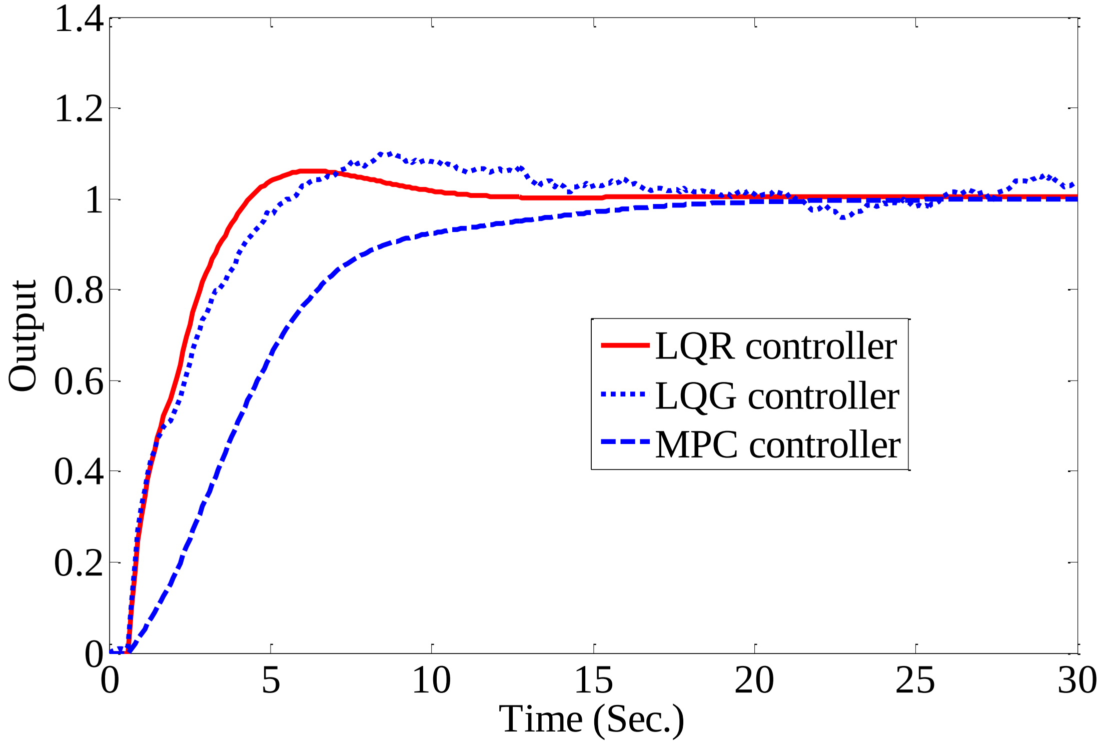


Figure.7.1. Comparison of step responses of three controllers

From Figure7.1, it is seen that LQR controller gives the better step response. The response is first from the MPC and LQG like controller. MPC gives slowest response. But all controller gives stable response. LQG like controller gives the step response with some overshoot.

Table7.1 Comparison among the three controllers based on time domain and frequency domain parameter and location of Eigen values of augmented closed loop system

Controller	Settling time (Sec.)	Rise time (Sec.)	Maximum overshoot (%)	Phase margin (degree)	Gain margin (dB)	Eigen values of closed loop augmented state space system	Working parameters
LQR	5.21	3.20	0.783	-180	12	0.9049, 0.0558, 0.0490 ± 0.0265i, 0.0304 ± 0.0462i, 0.0050 ± 0.0544i, -0.0207 ± 0.0497i, -0.0406 ± 0.0341i, -0.0509 ± 0.0120i.	Delay (τ)=1.2 sec.
LQG like controller	16.2	3.35	12.2	119	11.7	Same as LQR	Delay (τ) =1.2 sec. Input noise covariance (Q)= 0.002 Measurement noise covariance (R)=0.02
MPC	15.4	6.17	0	-180	23	-0.0603 ± 0.0152i -0.0457 ± 0.0419i -0.0202 ± 0.0583i 0.0099 ±0.0601i 0.0363 ± 0.0472i 0.0520 ± 0.0244i 0.0559 0.9514 0.7082	Delay (τ) =1.2 sec. $-0.3 \le u(k) \le 0.2$ $-0.1 \le \Delta u(k) \le 0.1$

From Table7.1, it is seen that the settling and rise time of the closed loop system are minimum with LQR controller with small overshoot. The rise time of the LQG like controller is same as LQR controller but it has largest settling time (16.2 seconds) and it has highest overshoot (12.2%). The rise time of the closed loop system with MPC controller is largest among the three controllers. The MPC controller gives a step response with 0% overshoot and zero steady state error. MPC controller gives highest GM with closed loop system. The location of Eigen values is identical for all controllers.

From the above discussion it can be said that the LQR controller has better delay compensating performance.

8 CHAPTER 8- CONCLUSIONS

Three controllers are designed to compensate the networked induced long variable delay in different working condition. LQR controller is designed considering the only networked induced delay which varies up to a maximum value. Then a LQG-like controller is designed to compensate the network induced variable long delay considering the plant has noisy input and measurement is noisy. Then an MPC controller is designed using Laguerre network considering that there is minimum and maximum limit on the rate of control input and on the control input. The Laguerre network reduced the computation burden of the normal MPC controller. To check the effectiveness of the designed controllers an integrator plant is simulated using MAT LAB software. Then the same controller used in real time experiment. The real time experiment is conducted using two PCs where one PC which is called remote PC is considered as controller and other PC which is called local PC is considered as plant. The two PCs are connected through an Ethernet network and to established communication between two PCs, UDP protocol is used. The round trip time between two PCs is estimated as 1.1 seconds using RTT techniques. The controller is designed considering the maximum estimated delay at any time instant. But the controller can work for variable delay. From the simulation result it is seen that the closed loop system is stable if the delay varies but always less than the estimated one. But it may happens that the networked state may change to other than which was at the time of delay estimation. Assume that due to change in network sate delay becomes greater than the estimated one. So we should check the tolerance of the closed loop system with the designed controller if the actual delay becomes greater than the estimated one. From the simulation result it is seen that the LQR and MPC controller both can tolerate 130% estimation error in forward path delay or in feedback path delay but at a time only one delay is varied but other delay is not varied at least it is not greater than the estimated one. LQR controller can tolerate 130% maximum positive variation in both delays simultaneously. But MPC controller can tolerate 30% maximum positive variation in both delays simultaneously. From the simulation result it is seen that the LQR controller gives better time domain response but MPC controller gives better frequency response. But one thing have to keep in mind that the working condition of the all controller are different For example LQR controller is designed considering that there is only networked induced delay but in case of LQG-like controller it is considered that the plant has noisy input and measurement is noisy. In this noisy environment if LQR controller is used than the step response gives an initial undershoot which is not acceptable for any system. So it can be concluded that although the three controllers are compared in the chapter-7, they are not comparable if working condition is considered.

9 CHAPTER 9- SUGESTION ABOUT FUTURE SCOPE OF WORK

Here the real time experiment is done considering the subsystem of the pant which is made using MATLAB software in local PC. So here plant is virtual. Only network is real. In future, the real time experiment would be done considering the both plant and network are real. Here all control algorithms are used to control a simple integrator. In future algorithm can be applied to other complicated system like MIMO system and nonlinear system.

APPENDIX-I

SIMULINK MODEL USED FOR LQR CONTROLLER:

➢ ***Simulink model used to simulate the integrator plant***

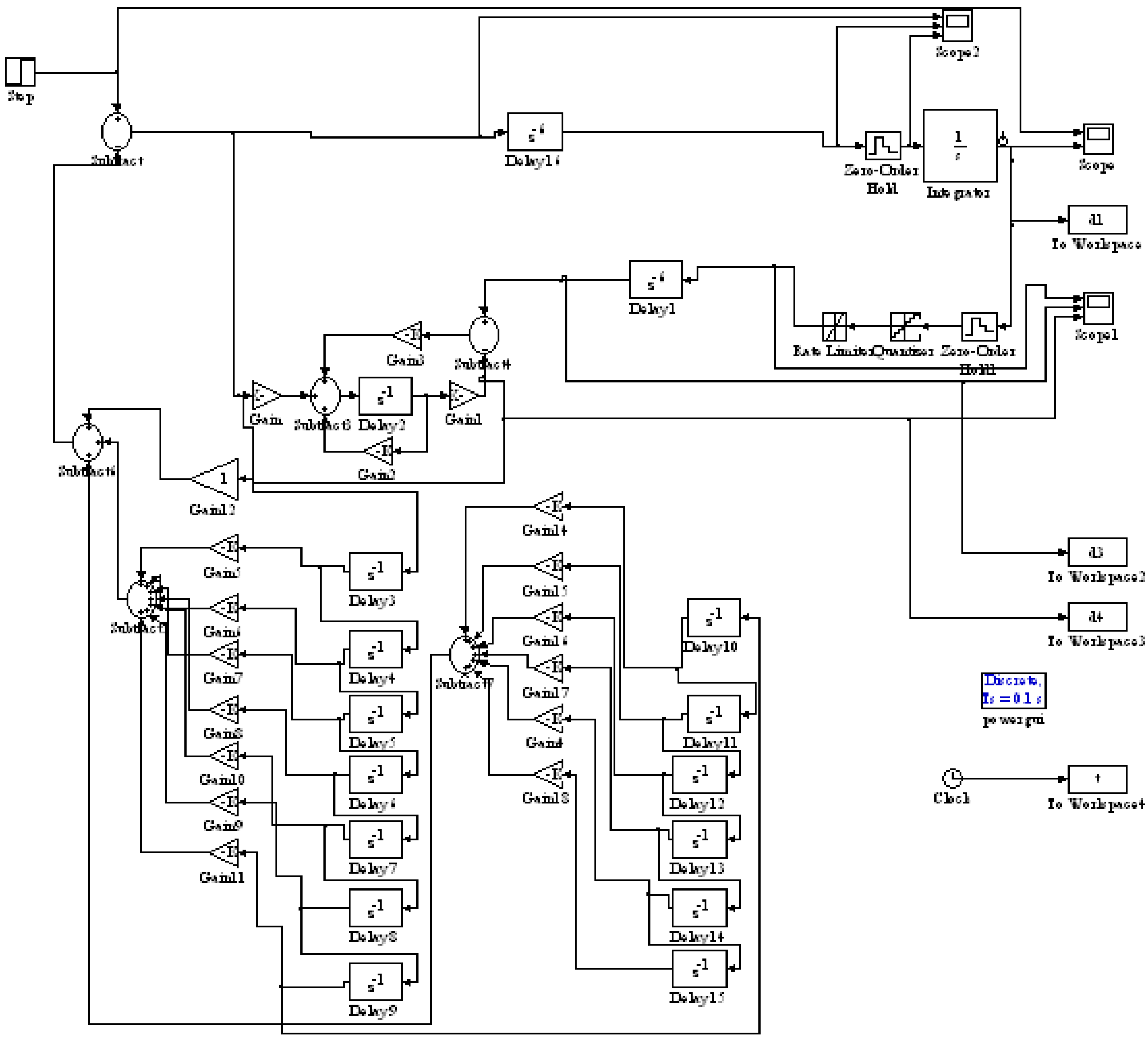


Figure1. MATLAB Simulink model used in LQR technique

➢ *Simulink model used for real time experiment*

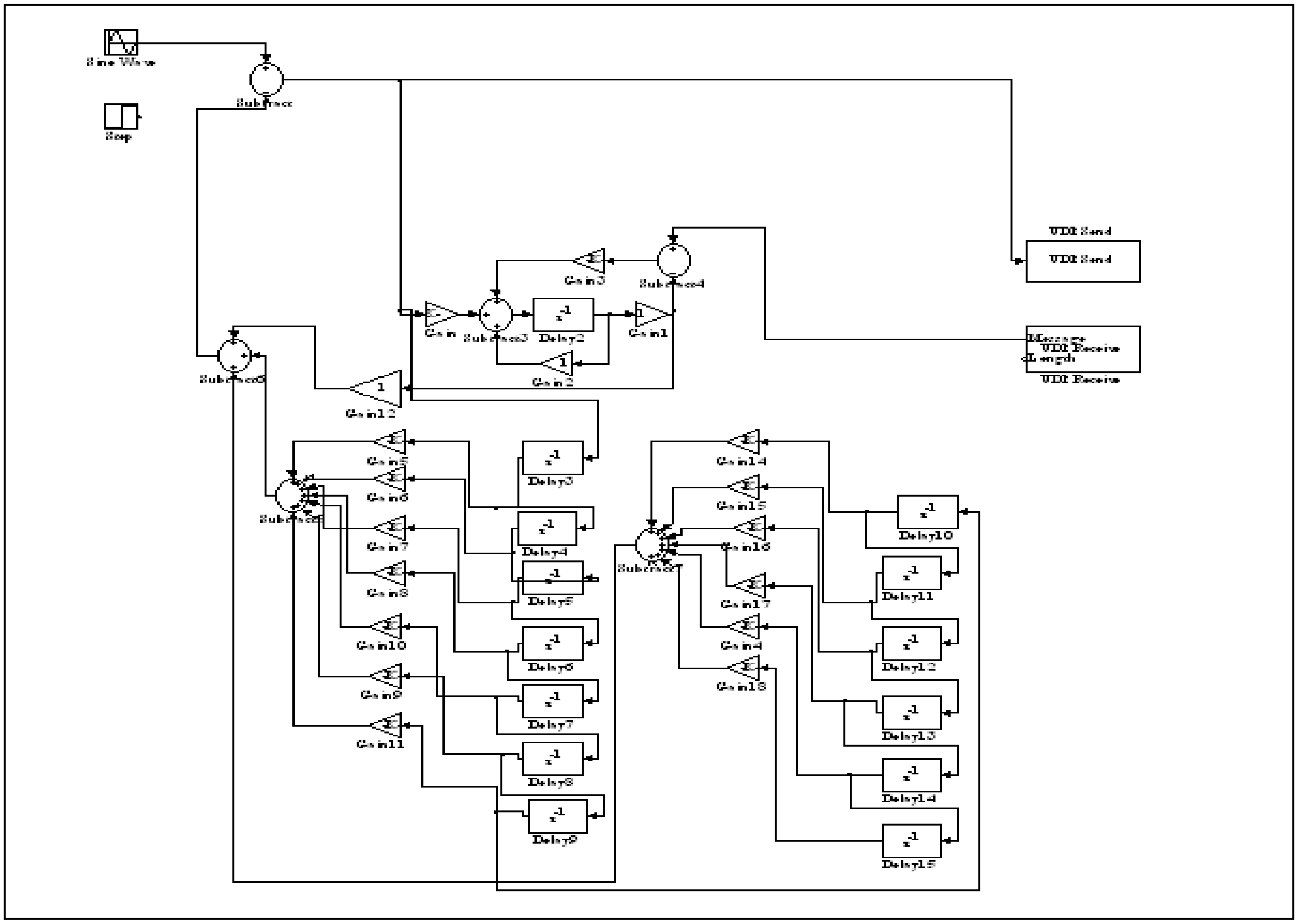


Figure2. Simulink model used in remote PC as controller

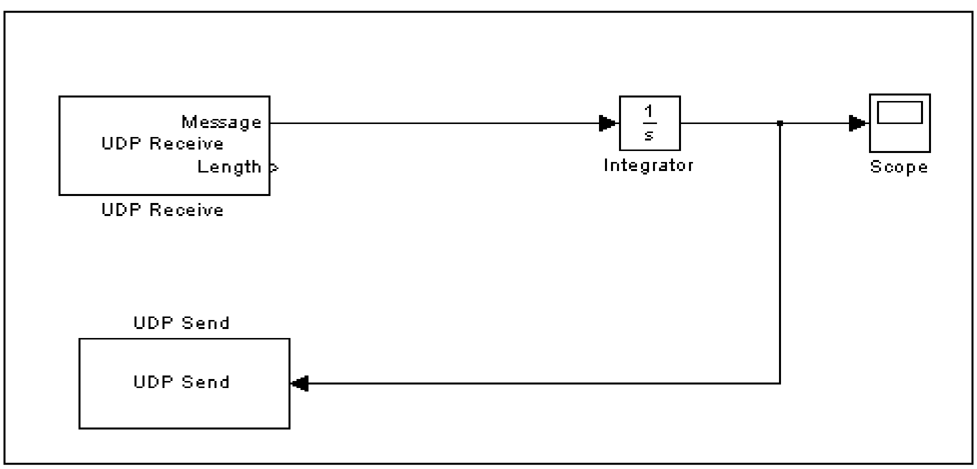


Figure3. Simulink model used in local PC as plant

APPENDIX-II

SIMULINK MODEL USED FOR LQG LIKE CONTROLLER:

➢ ***Simulink model used to simulate the integrator plant***

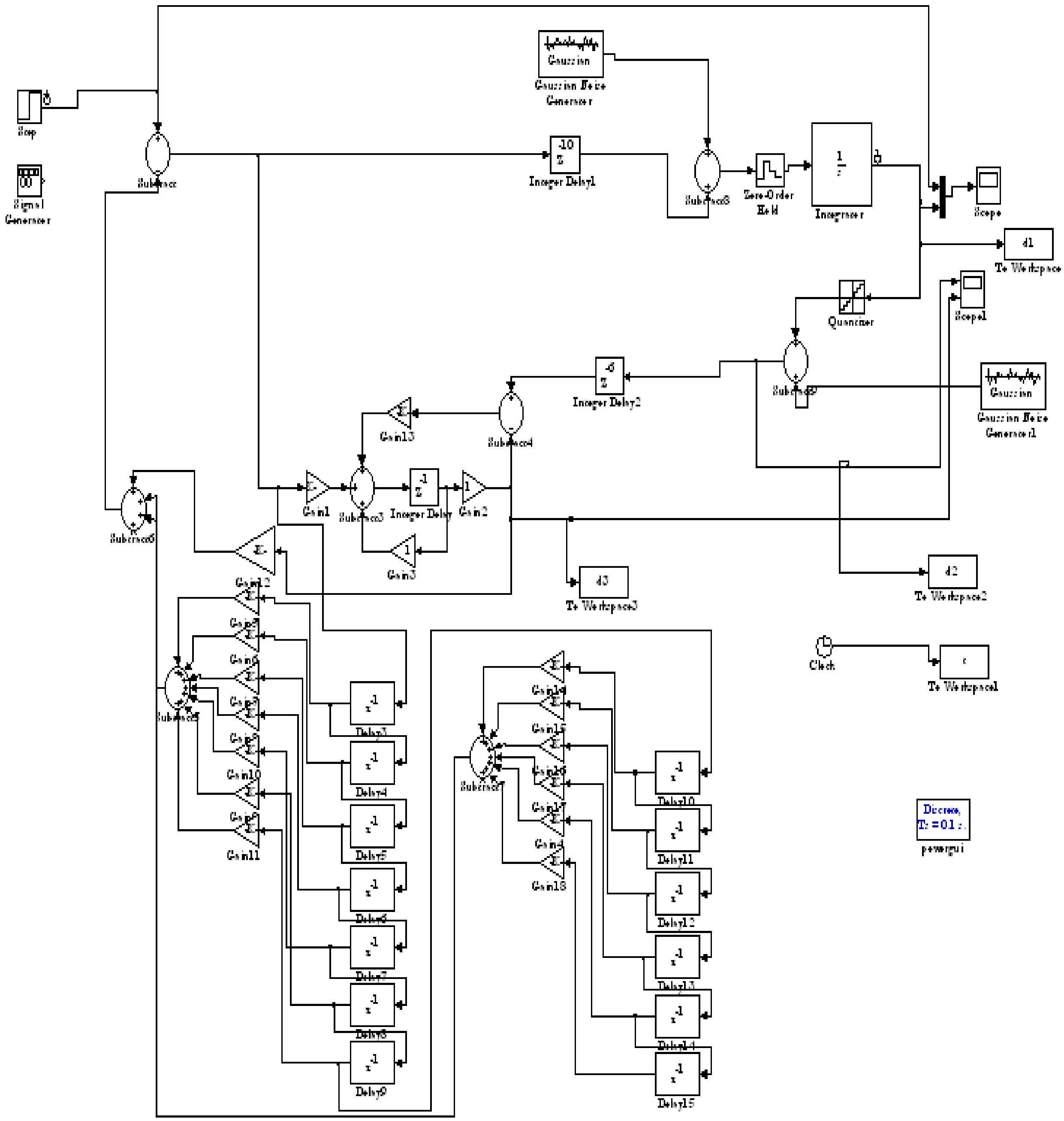


Figure1. MATLAB Simulink model used for LQG-like controller

➢ ***Simulink model used for real time experiment***

In remote PC same model is used as LQR controller for real time experiment except insatead of full oreder state observer Kalman filter is used to estimate the system output using noisy measuremet.

The model used in local PC for real time experiment is shown in Figure.1

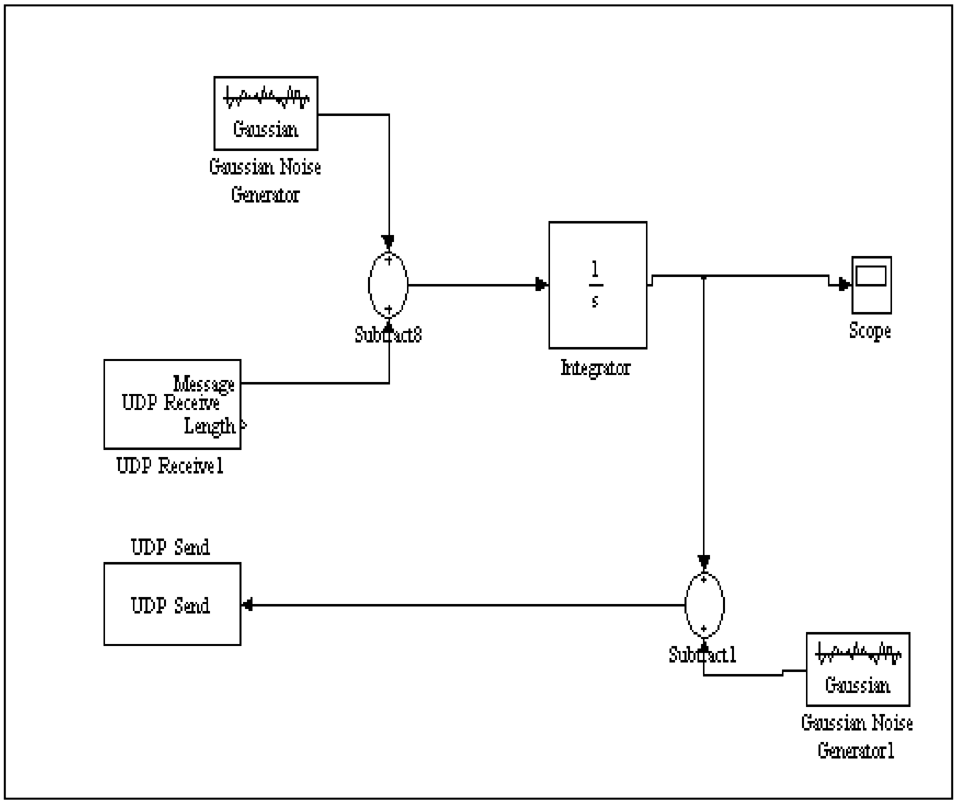


Figure1. Model used in local PC (Plant)

APPENDIX-III

SIMULINK MODEL USED FOR MPC CONTROLLER:

➢ ***Simulink model used to simulate the integrator plant***

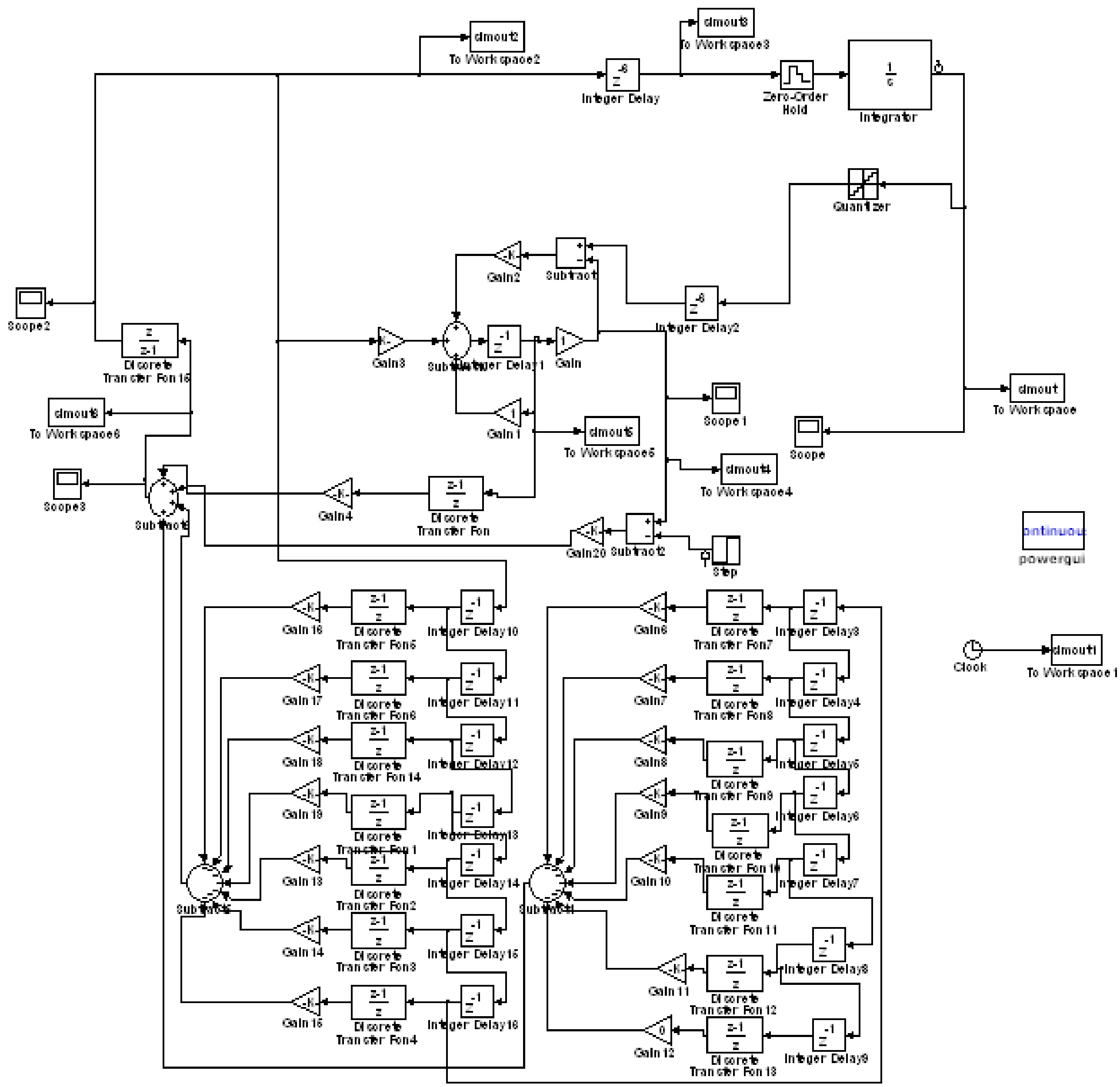


Figure1. Simulink model used to compensate the networked induced delay using MPC controller

➢ ***Simulink model used for real time experiment***

The model used in local PC is same as the model used in real time simulation used in LQR technique.

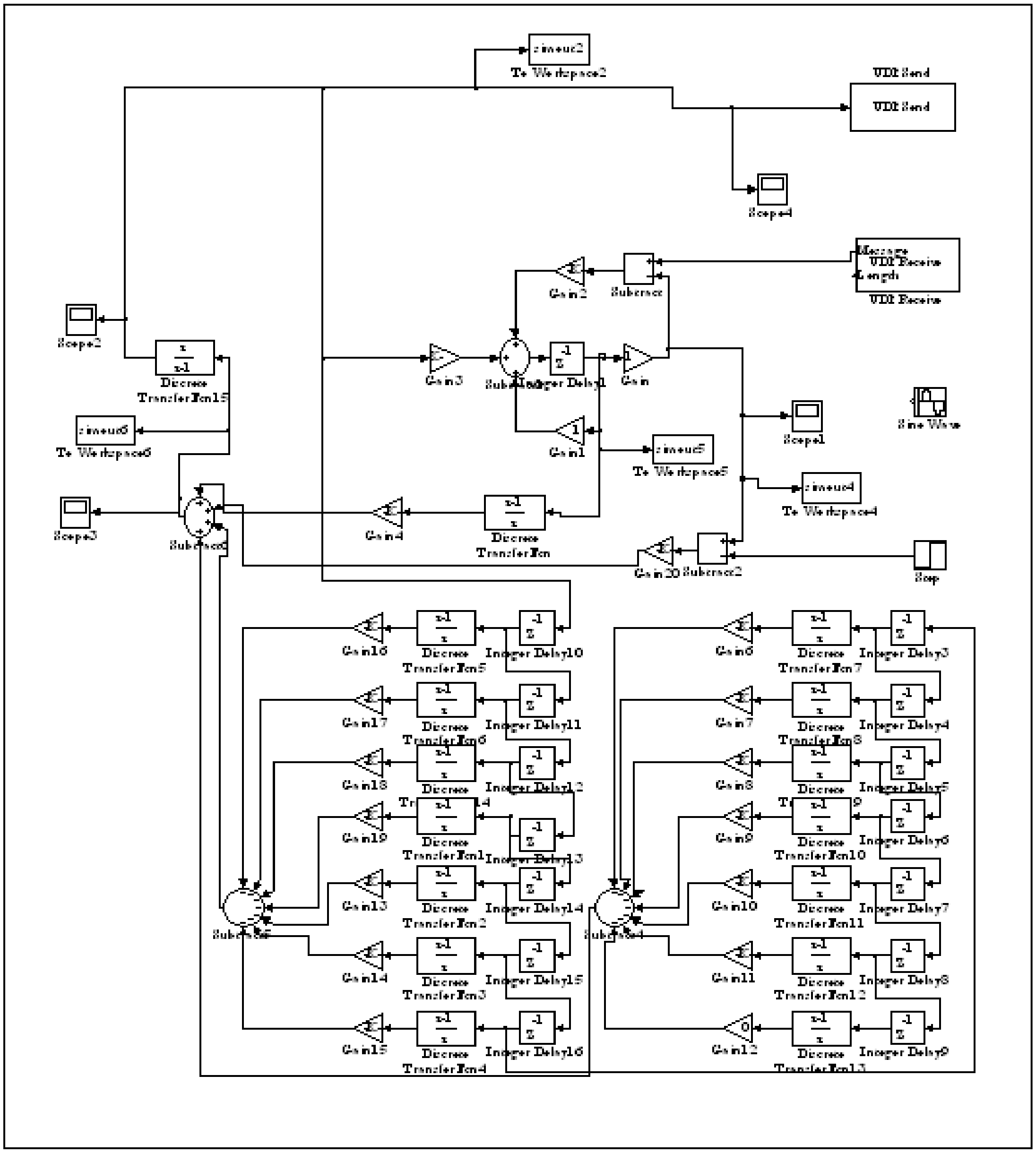


Figure2. Model used in remote PC used as MPC controller

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