A STUDY ON STATE PREDICTIVE CONTROLLERS FOR NETWORKED CONTROL SYSTEM

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In

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CERTIFICATE

This is to certify that the thesis entitled, **“A Study on State Predictive Controllers for Networked Control System”** submitted by **Aman Jain** to National Institute of Technology, Rourkela in partial fulfilment of the requirements for the award of **Bachelor of Technology & Master of Technology (Dual Degree)** in **Electrical engineering** with specialization in **“Control and Automation”** is an authentic record of research work carried out by him in the **Department of Electrical Engineering** under my supervision and guidance.

I believe that this thesis is based on candidate’s own work and the matter embodied in the thesis has not submitted elsewhere for a degree/diploma. In my opinion the thesis is of standard required for the award of Dual Degree in Control and Automation. To the best of my belief he bears a good moral conduct and decent behaviour.

Date:

Place:

Dr.Sandip Ghosh

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Abstract

When different control components of a closed loop control system are connected through a common network channel then the resulting control system is a Networked Control System. This spatially distributed system has several advantages like reduced system wiring, easy fault detection and maintenance capability. Unfortunately the introduction of communication channel results in several disadvantages like network induced delays and packet dropouts leading to loss of synchronism in the control system. The network induced imperfections causes system instability and complexity for the control engineers to design a suitable controller in order to compensate their effect on closed loop control system. In addition to the complexity in design the network induced imperfections should be measured, analysed by incorporating them in the closed loop control system.

The project investigates the problem of network induced time delays in a networked control system by studying the behaviour of network induced time delay in a control system controlled by Linear Quadratic controller or a Pole placement controller using the states obtained from discrete Kalman filter state estimation, which estimates the current state in the presence of state and output noises. Further a control augmentation method is used by incorporating network induced delay in the plant model control vector. The time delayed control vector creates difficulty in designing the controller which is solved by time shifting approach. Further a state predictor is designed by using plant model transition matrix to predict the future states from present and past values of control vector and state estimate. Hence an optimal predictive controller is designed wherein the Linear Quadratic or pole placement controller uses the predictive state obtained from the state predictor to compensate the effect of network induced time delay and improve the control system performance.

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List of Abbreviations and Notations

NCSS	Networked Control Systems
UAV'S	Unmanned Aerial Vehicles
P2P	Point-To-Point
LTI	Linear Time Invariant
τ_{sc}	Sensor To Controller Delay
τ_{ca}	Controller To Actuator Delay
LQR	Linear Quadratic Regulator
ω_d	Desired Natural Frequency
ρ	Damping Ratio
T	Sampling Period
k	Number of samples
τ_T	Total Delay
τ_c	Critical Delay
k_f	Final Time
J	Performance Criterion
$\hat{x}(k)$	Estimated State
$\hat{x}(k+\tau)$	Estimated Predicted State
$\varphi(k)$	State Transition Matrix

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Chapter-1

Introduction

1.1 Introduction to Networked Control System

A Networked control system is an integration of communication system and closed loop control systems wherein different control components of plant and controller exchange data through a commonly shared network channel. Basically the control signal to the actuator and the feedback measurement signal from the sensor node is communicated through the shared communication channel. In real life we have plant and its control components like sensor, actuators situated far away from the controller and we require control and feedback signal to be transmitted over a suitable real time network as shown in Fig.1.1

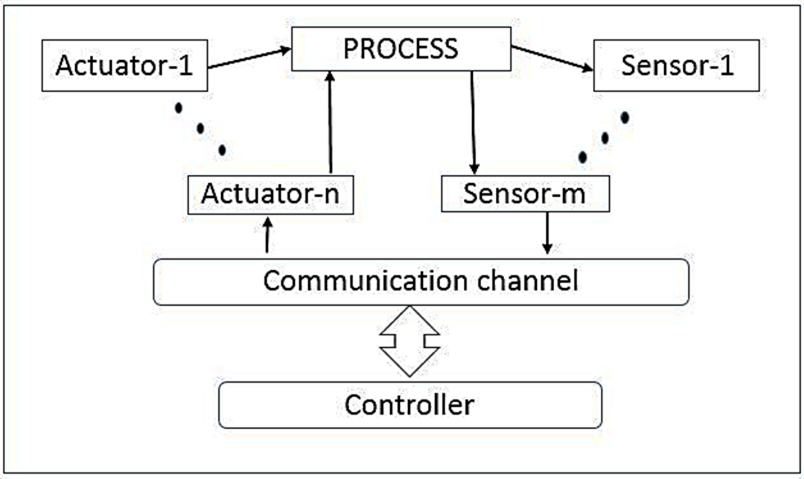

Fig.1.1 A Networked Control System

The study of NCS basically overlaps two areas Information Systems and closed loop control (feedback control).Information systems have been studied for decades in the field of computer science having a fundamental function of transmitting the information without whether the information has arrived or not, the time at which it has arrived, and the confirmation from the recipient regarding the receipt of the information. In closed loop control systems the confirmation regarding the information has arrived, the time at which it arrived are critical. Due to its wide range of applications in automation factories, hazardous industries, advanced spacecraft, military applications, and unmanned aerial vehicles (UAV's) has received interest in this field of research. The interdisciplinary nature of NCS upon integrating the information systems and feedback control systems raised several questions regarding the behaviour of network over quality of system's overall operations. Several limitations arises upon introducing network like network induced delays, bandwidth limitations, packet disorder etc. Limited computational capacity of controller effects network stability and its reliability are some of the different researchable areas which possess a big challenge. These network induced imperfections not only destabilise the system but also degrade the control system performance.

The research in the field of NCS focusses upon two major subjects which are the controller design and communication protocol. The assumptions used in traditional control theories like non delayed measurement, synchronized actuation and control must be considered and revaluated before applying the traditional control theory to NCS. This project work mainly focusses on how to overcome the influence the real time network have over networked control system by investigating the limitation of network induced delays i.e. the critical time delay of the system and to find a convenient control strategy by developing a predictive controller which could compensate the effect of network induced time delays. The project uses control augmentation approach to model the delays by incorporating them into the plant model control vector. A shifting approach is used for developing the algorithm of controller as the time delay in the control vector creates complexity in design. Further, the plant model transition matrix is used to develop a state predictor algorithm which uses the present and past values of control vector and the state estimates obtained from Kalman filter in the presence of state and output noises. The predicted state is used by the optimal or pole placement controller to perform a control action. The method adopted is simple and is applicable to the time delays that are greater than the sampling period.

1.2 Background

NCS background consists of communication between plant components and controller. Now-a-days data network systems have data transmitted in the form of binary digits from one place to another in a series of 0s and 1s.The binary information is transmitted in the form of packets having formatting and address information in addition to the data. They have a form consisting of header which contains error checking and address information, data consists of actual information that needs to be transmitted and the trailer which has error checking, to determine if the byte is received or not and message management information.

Several transmission systems like simplex transmission which is unidirectional transmission, half duplex which is bidirectional transmission which allows in only one direction at a given time and full duplex which allows in both the directions at the same time. Additionally, synchronous timed transmission in order to confirm when a transmission will begin and end, asynchronous transmission which mark the beginning and end of messages. Synchronous transmission is faster but it can introduce problems in timing between two remote machines whereas asynchronous transmission is economic and simpler, hence widely used.

1.2.1 Traditional Point-To-Point (P2P) Architecture

Traditionally networked control system employs P2P architecture scheme as shown in Figure 1.2 which consists of centralized closed controller with its respective sensors and actuators connected point to point for the calculation of control signals.

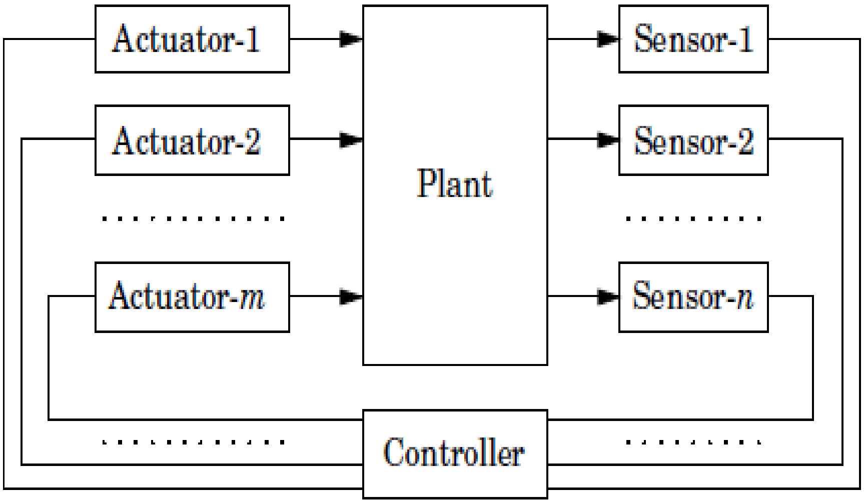

Fig. 1.2. Point-to-Point Architecture

It results in huge complexity in wiring and connections, the volume, weight keeps on increasing with increase in number of connected devices. Moreover the above scheme results in problem in system maintenance, diagnosis and reconfiguration. To overcome these problems due to centralized control NCS research area has received a considerable amount of focus.

1.2.2 NCS Configurations

Basically two types of NCS configuration are there namely level one and level two configuration. Level one configuration is further classified as direct and hierarchical structure. Most commonly used structure is direct structure which consists of controller and a plant with its sensors and actuators which are connected through a common network channel as shown in Fig.1.3.It shows for a particular sensor and actuator, whereas there can be many present in the practical application. The present work is based on the direct structure classification of level one configuration.

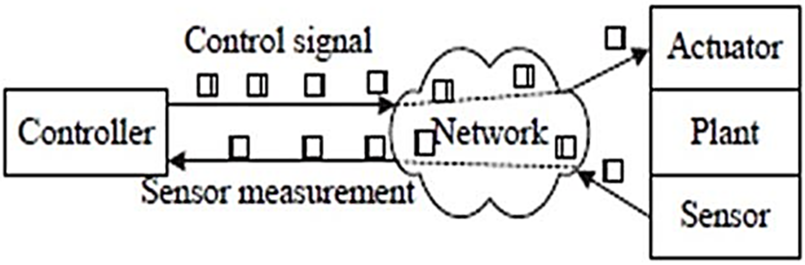

Fig. 1.3. Direct structure of NCS

Another form of level one configuration is hierarchical structure which comprises of a global controller and a remote local controller which forms a local closed loop control, whereas direct structure consists of a single controller as shown in Figure 1.4.

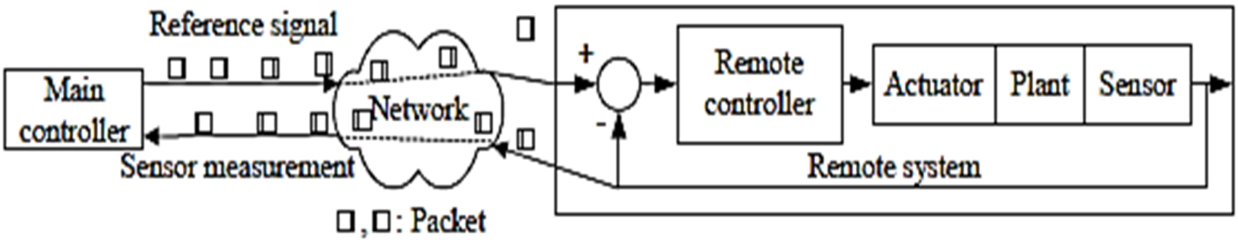

Fig. 1.4. Hierarchical structure of NCS

In hierarchical structure the global controller calculates and send the reference signal in a packet through a network channel. The remotely located local closed loop control processes the reference signal to perform local closed loop control and returns a feedback signal from the sensor to the global controller which perform the global closed loop control.

1.2.3 NCS Applications

Networked control system has wide variety of applications, some of them being listed below.

- Factory automation.
- Hazardous industries.
- Automobiles.
- Unmanned aerial vehicles (UAVs).
- Remote surgery.
- Remote Diagnostics, tele-operation, tele-robotics.
- Haptics collaboration over the internet.

1.3 Challenges Faced By NCS

Introduction of network in the closed loop control system creates several network induced limitations in synchronizing the actuator and control signal. It adversely affects the system performance by degrading it and can also destabilise the system. These topic discusses several network induced constraints like band limited channel, time delays and sampling time, packet losses and network induced delays.

1.3.1 Band Limited Network

Sharing of band limited digital network is a basic challenge for NCS. Mostly in digital communication networks data is carried in a finite amount per unit time which poses several limitations over NCS. The data is carried in small units called packets and it takes similar amount of network resources for sending a single bit or multiple bits. There is a minimum bit rate which is required to stabilize a LTI system. To ensure stability average bit rate is measured i.e. how infrequent feedback information is required. The data rate theorem serves as a breakthrough in determining the data rate requirement to ensure a stable system.

1.3.2 Sampling and Time Delay

To transmit a continuous time data through a digital communication network the signal need to be sampled and encoded to send it over the network as shown in Figure 1.5.Further, this data on the receiver end is decoded. The time taken in sampling, decoding at the receiver is varying in the sense that it usually takes time for a shared network channel to accept data, further transmission delay which is the time taken for data transit due to network congestion and its quality.

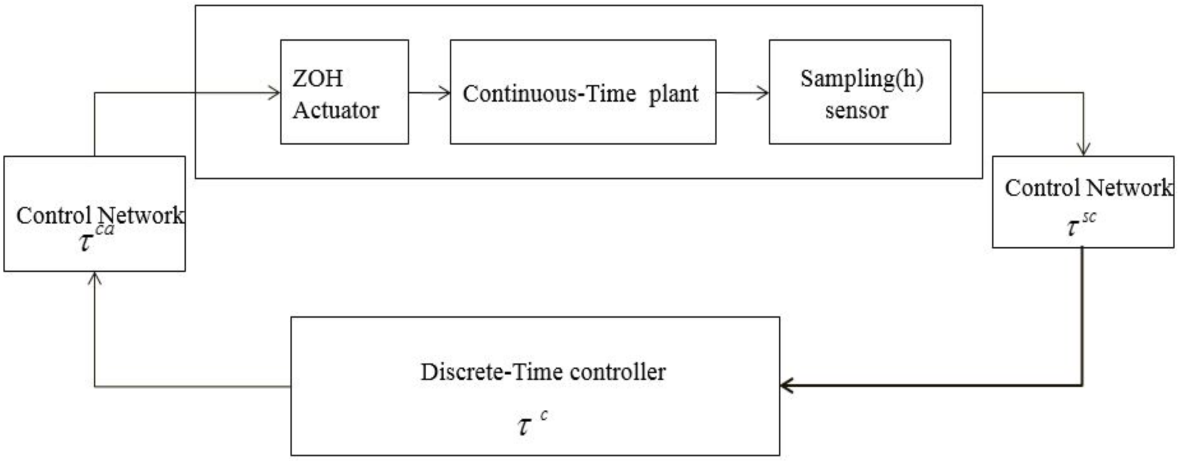

Fig. 1.5. A networked control system

The controller processing delay which is the amount of time required by the controller for the calculation of control signal, the network induced delays which occur when sensors, actuators, and controllers exchange data packet across the communication network i.e. from sensor to controller (τ_{sc}) and controller to actuator (τ_{ca}).This thesis work mainly focusses on the network induced delays and their critical values for which controller achieve desired performance specifications.

1.3.3 Packet Losses and Disorder

Packet dropout means the packets not only suffer from the network delay but also may be lost completely. In NCS this usually occurs due to improper network scheduling, node failures and data packet collisions. An excessive long propagation delay of a packet can also be viewed as a packet loss. Transmit retry mechanism is also available to overcome this problem but is available for limited time and the packet is dropped after that time. The packet disorder phenomena, which means that the indices of the packets transmitted over networks are mixed, can happen if the network induced delays are more than one sampling or transmission interval.

The limited feedback information caused by packet transmission delays and packet losses both of them occurs due to the sharing and competition of the transmission medium, and bring difficulties for analysis and design of NCSs. Both the information transmission delay and packet loss may result in the randomly missing output measurements at the controller node.

1.4 Literature Review

Networked control system (NCS) has become a widespread area of research, hence literature is reviewed on NCS. Practically plant and controller are situated far away from each other, the control and output signal are transmitted through common media. Network induced constraints should be considered while designing the controller these constraints are mainly the network induced delays, packet mismatch and losses, sensor node failure etc. Suitable methodologies to cope up with the network induced delays are suggested [1]. The major challenges faced by NCS are time delays which consists of network induced delays which occur when different control components exchange data packet across the communication network i.e. from sensor to controller (τ^{sc}) and controller to actuator (τ^{ca}),controller processing delay which is the time taken by the controller to compute the control signal, natural delay of plant, packet dropouts due to sensor node failure, packet disorder phenomenon which occur the indices of the packets transmitted over networks are mixed, can happen if the network induced delays are more than one sampling interval. Network control system causes network imperfections like bandwidth limitations, communication protocol type which also degrade the control system performance and its stability [2].

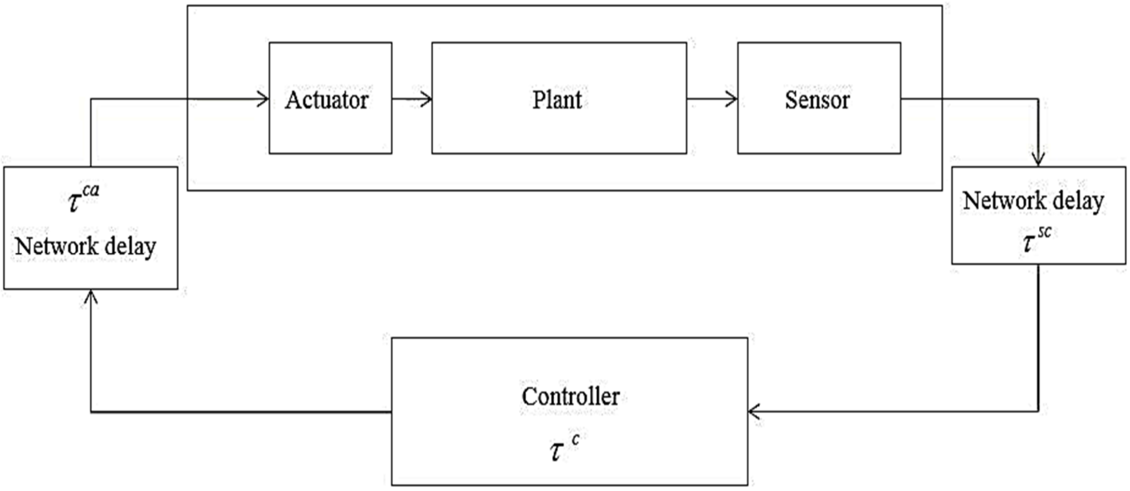

Fig. 1.6. A Basic Network Control System

The limited feedback information caused by transmission delays and packet loss both of them are due to the sharing and competition of the transmission medium, and bring difficulties for analysis and design of NCS. Both the information transmission delay and packet loss may result in randomly missing output measurements at the controller node, as shown in Figure 1.6.
Control system with wireless network have several applications and is an emerging field of research and the simulations can be performed with the help of special network tools like True time simulator [3].Suitable predictive algorithm need to be developed to design predictive controller which can compensate the effect of network induced delay [4]. Several other control algorithms for network delays prediction and estimation for NCS are discussed in [5], [6].A deterministic controller has a disadvantage that it cannot accurately measure the state variables in the presence of state and output noise so a state estimator is needed to accurately measure the current state like Kalman filter. State estimation using Kalman filtering incorporated with mixed uncertainties of network delays, packet losses and missing output is also studied in [7].The optimal state estimation scheme and LQR controller design for Networked Control System is proposed by Nilsson et al [8].To design an predictive controller algorithm the time delay model can be augmented into the control vector of the plant model where the delay is only between controller to actuator delay [9].In order to study the impact of time delay on Networked control system a continuous time plant is considered [10].The optimal controller can be designed by calculating the optimal control signal following the steps given in [11].A closed-loop proportional-integral (PI) control system with forward and backward delays is shown in the Figure 1.7

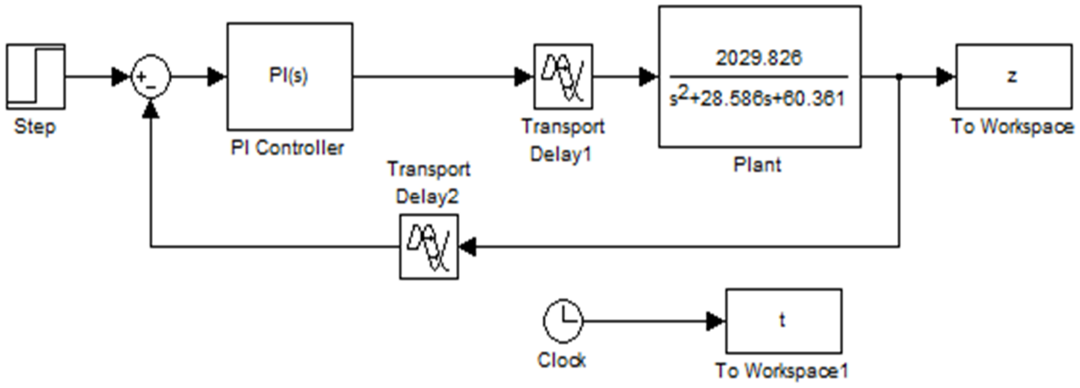

Fig.1.7 Closed loop control with forward and backward delay

Where Plant model is second order and is given by [10],

$$G(s) = \frac{2029.826}{s^2 + 28.586s + 60.36} \tag{1.1}$$

Proportional-Integral Controller is given by,

$$PI(s) = K_p + \frac{K_i}{s} \tag{1.2}$$

Where, the gains are obtained from tuning given by, $K_p = 0.0201$ & $K_i = 0.113$

$Assumption: \ \tau^{ca} = \tau^{sc}$

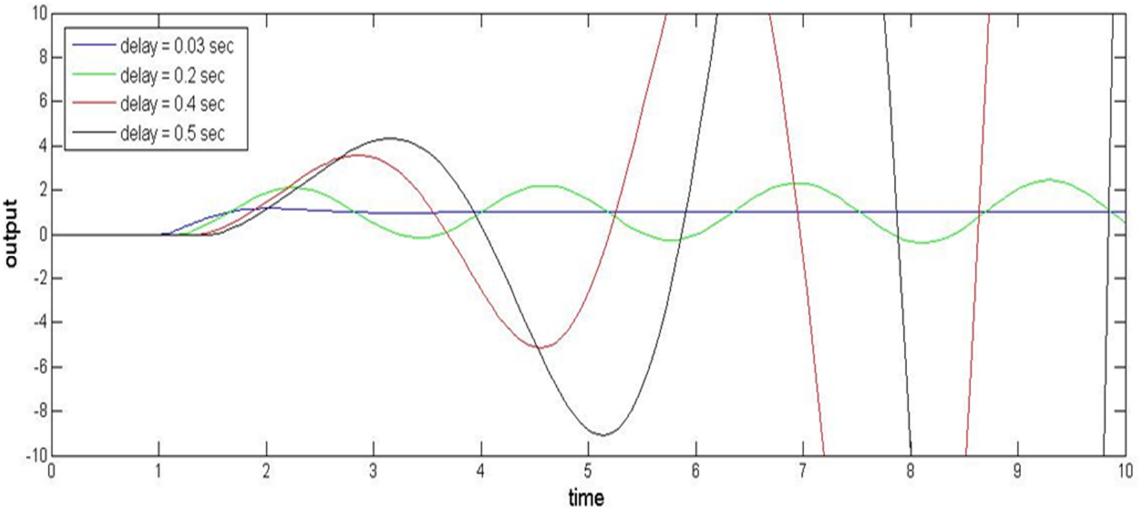

Fig.1.8 Control system performance analysis by varying delay from 0.03 to 0.5 sec

The network induced delays (forward and backward assumed to be equal) are varied from 0.03 to 0.5 sec and their respective step responses are shown in Figure 1.8. It is observed that as the delay is increased gradually the system overall performance degrades and causes instability. Settling time, percentage overshoot increases i.e. the response becomes more oscillatory (i.e. lower damping ratio).This simulation helps us in understanding the adverse effects of network delays, hence we must take into consideration the network induced delays while applying the traditional control theory in NCSs research.

1.5 Motivation

The Networked control system have several important and valuable industrial applications in automation factories, chemical process plants, power plants, refineries, advanced airplanes, remote surgery as it improves the production of process by operating the plants efficiently and effectively by transmitting information reliably via wireless or digital network connections. Many other advantages include reduced system wiring, ease of fault detection, diagnosis and maintenance. It leads to extensive commercial savings when it comes to multi controller projects where control action can be sent from one point using centralized controller which attracts the interest of control engineers to measure, analyse network induced imperfections. The networked control possess a big challenge due to the bandwidth limitations and unavoidable network induced delays caused by different communication protocol type. These network induced delays are mainly considered between controller and actuator and between sensor and controller. In order to analyse the effect of network induced delay over the control system performance and stability, it is necessary to study the behaviour and characterize the networked induced limitations which motivates a control engineer to develop robust predictive controller algorithm which could compensate the effect of network induced imperfections and improves control system reliability and stability. To compensate the time delay there are several schemes available like PID controller, Fuzzy controller, Smith predictor. This project uses a Linear Quadratic and Pole placement control strategy which uses the predicted states obtained from the state predictor which is based on the model transition matrix of the plant. The current states are obtained from Kalman filter state estimation in the presence of state and measurement noise because the deterministic controller cannot not accurately measure the state variables in the presence of state and measurement noise.

1.6 Thesis Deliverables

The project aims at utilising and combining different researchable fields, developing theoretical methods and achieving a desired overall goal. The project focusses on the following objectives.

1. Simulation of discrete Kalman filter algorithm with the help of Matlab & Simulink for the estimation of states of considered plant model in the presence of state and output noises and verify its functionality.

2. Design of pole placement controller which uses state obtained from the discrete Kalman filter state estimation to perform control action to control the plant under consideration which is free from any network induced delays.
3. Incorporating network induced delays between controller to actuator and between sensor to controller and investigating their impact such as critical delays on closed loop control designed not to cope with the time delays.
4. Incorporating the delay from controller to actuator or total delay which is sum of delays between controller to actuator and between sensors to controller in control vector of plant model using the control augmentation approach. Shifting the period in order to simplify the complexity created by control augmentation and designing Linear Quadratic controller.
5. Designing a state predictor based on plant model transition matrix to calculate future states from the present and past values of state estimate and control vector. Further using the future state obtained from state predictor to perform predictive control action and verify the functionality of designed optimal predictive controller.

1.7 Thesis Organization

- **Chapter -1** introduces Networked control systems and their different aspects like its literature review, different challenges faced, motivation and objectives for this thesis work.

- **Chapter-2** is based on Kalman filter state estimation and its simulation in Simulink Matlab software. It confirms the functionality of Kalman filter which is further required in the estimation of current state while designing the predictive controller.

- **Chapter-3** studies the influence of network induced delays over pole placement controller which is not designed to cope up with the delays. It helps in understanding the basic requirement in designing the predictive controller.

- **Chapter-4** develops an optimal predictive controller which performs the control action based on the predicted states obtained from a state predictor which is based on model transition matrix of plant model.

- **Chapter-5** discusses the conclusion of the thesis work and its scope for future development.

Chapter-2

KALMAN FILTER STATE ESTIMATION

2.1 Kalman Filter

The deterministic controller from the control theory cannot exactly measure the state variables. The filter is a set of equations which form a recursive algorithm to determine the state variables in the sense that the mean of the square error between the estimated and real state is minimum. The controller requires that the current state of plant is known perfectly even in the presence of process and measurement noise and thus a state estimator is needed for this discrete Kalman filter state estimation algorithm [9] is used and is given as,

Model Equations:

$$x(k+1) = Ax(k) + Bu(k) + w(k) \tag{2.1}$$

$$y(k) = Cx(k) + v(k) \tag{2.2}$$

The variables $w(k)\ and\ v(k)$ represents the state and output noise that are independent, have zero mean and have the normal probability distributions given by,

$$w(k) \sim N(0, R_w)$$

$$v(k) \sim N(0, R_v)$$

Initial Points are assumed to be given by:

$$\hat{x}(0|0) = \hat{x}_0\ and\ P(0|0) = P_0$$

Kalman Gain can be written as,

$$K(k+1) = P(k+1|k)C^T[R_v + CP(k+1|k)C^T]^{-1} \tag{2.3}$$

Measurement Update:

$$\hat{x}(k+1|k+1) = \hat{x}(k+1|k) + K(k+1)[y(k+1) - C\hat{x}(k+1|k)] \tag{2.4}$$

$$P(k+1|k+1) = P(k+1|k) - K(k+1)CP(k+1|k) \tag{2.5}$$

Time Update:

$$\hat{x}(k+1|k) = A\hat{x}(k|k) + H\ u(k) \tag{2.6}$$

$$P(k+1|k) = A\ P(k|k)A^T + R_w \tag{2.7}$$

2.2 Simulation of Discrete Kalman Filter State Estimation

The Kalman filter algorithm is simulated in the Simulink Matlab software and is shown in Figure 1.8.

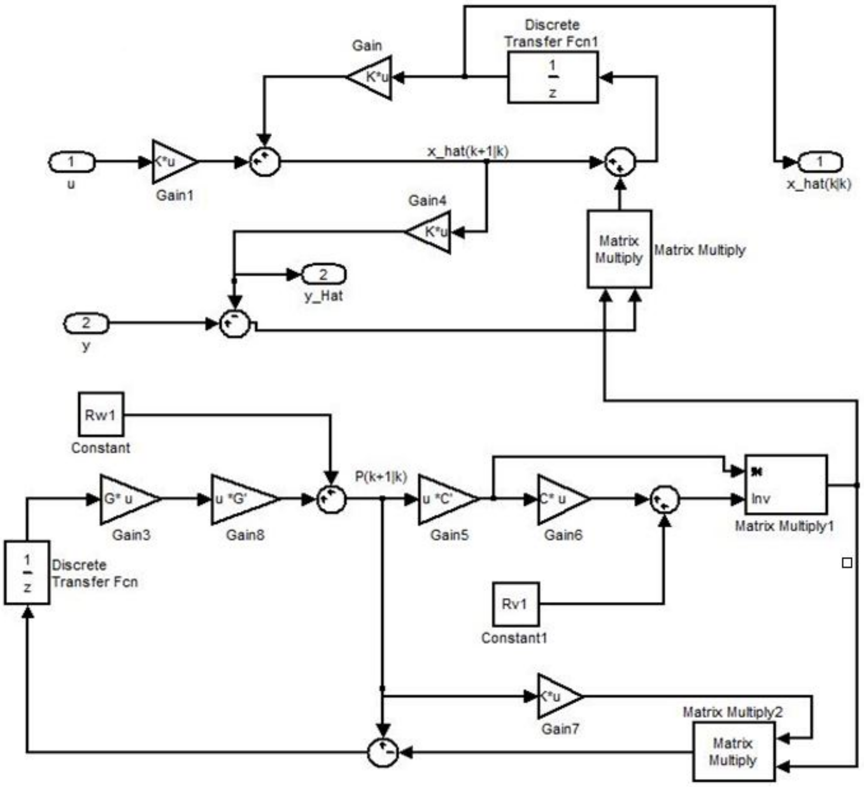

Fig. 2.1 Kalman Filter subsystem

The Random process model (Appendix II) given by the above equations is also simulated in Matlab Simulink software and is shown in Figure 2.2.

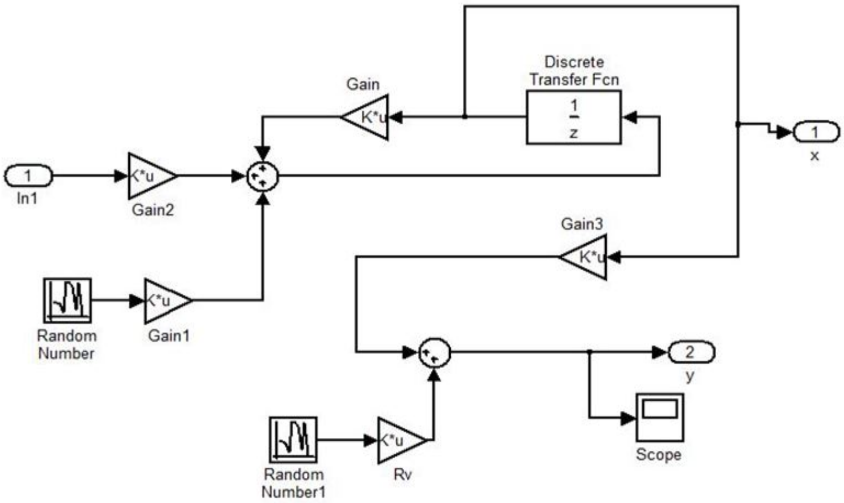

Fig. 2.2 Random process subsystem

The Random process model subsystem and the Kalman Filter subsystem are integrated as shown in Figure 2.3. The purpose of this procedure is to verify the functionality of the filter and confirm that it tracks the response of the open loop discrete plant under consideration.

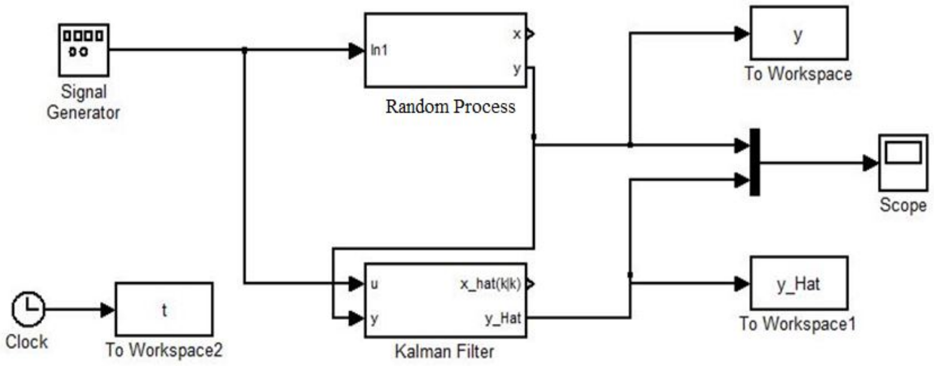

Fig. 2.3. Model of Kalman Filter state estimation

2.3 Results and Discussions of Discrete Kalman Filter State Estimation

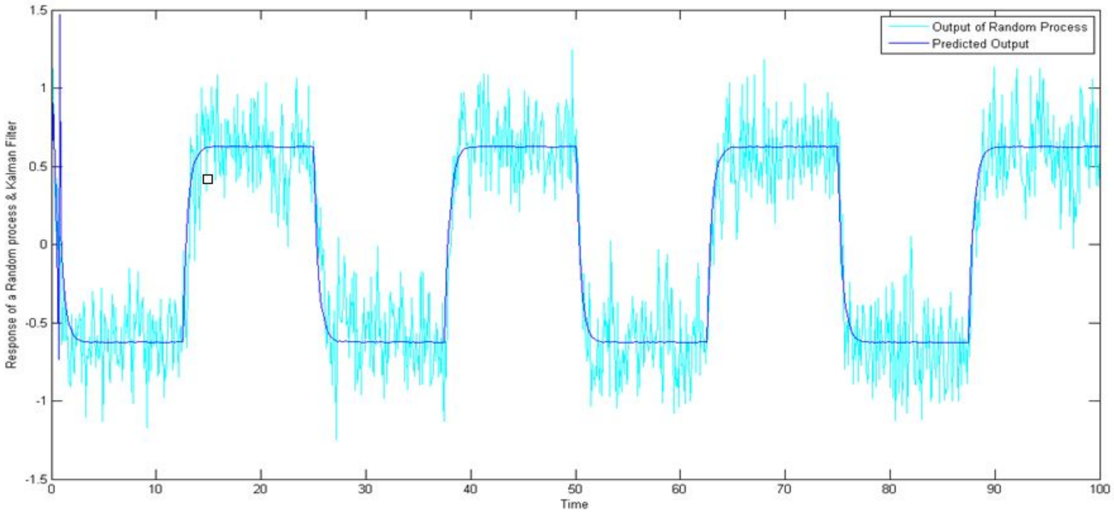

Fig. 2.4 Response of Random process & Kalman filter

The output of random process influenced by stochastic noises and the predicted output of Kalman filter are plotted and it is observed that it accurately tracks the output of the random process and its functionality is confirmed as shown in Figure 2.4. Now the Kalman filter can be further used with some suitable controller which requires the state estimates of a plant in presence of state and output noises. The Kalman filter used in this thesis work is used to estimate the current state accurately.

Chapter-3

STUDY OF POLE PLACEMENT CONTROLLER WITH NETWORK INDUCED TIME DELAYS

3.1 Pole Placement Controller and Discrete Kalman Filter Closed Loop Control for System without Network Delay

The general approach is to consider a plant model with stochastic process and measurement noises which is to be controlled by using a pole placement controller based on state estimates obtained by a discrete Kalman filter designed for the known characteristics of the state and output noises. The state space form of plant model is:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{3.1}$$

The pole placement controller has the form given by,

$$u(t) = Rr(t) - Lx(t) \quad \text{, where L} = [l_1\, l_2] \tag{3.2}$$

Determinant for closed loop control is:

$$\Delta_c(s) = |sI - A - BL| = 0 \tag{3.3}$$

The closed loop characteristic equation (3.3) is compared with the desired closed loop characteristic equation given by,

$$\Delta_d(s) = s^2 + 2\rho\omega_d s + \omega_d^2 \tag{3.4}$$

Where ω_d *and* ρ are calculated based on the desired percentage overshoot (< 10%) and settling time (< 5sec) to achieve this and to calculate the controller gain a Matlab code is written for that (Appendix 1) and the gain matrix L is calculated as L= [0.5531 0.0104]. In order to convert the desired continuous poles to desired discrete pole, the following conversion equation is used. $z = e^{p*T}$, T is the sampling period. Pole placement control law in discrete time is given by,

$$u(k) = Rr(k) - L\,\hat{x}(k) \tag{3.5}$$

3.2 Simulation of the Closed Loop System with Pole Placement Controller - No Network Induced Time Delay

The Pole Placement controller, the random process [9] and the Kalman filter are integrated Fig.3.1 without considering the network induced delay in the closed loop control system. The input signal used is generated by pulse generator having following specifications.

- Amplitude = 1
- Period = 10 sec (500 samples)

- Pulse width = 5 sec (250 samples)

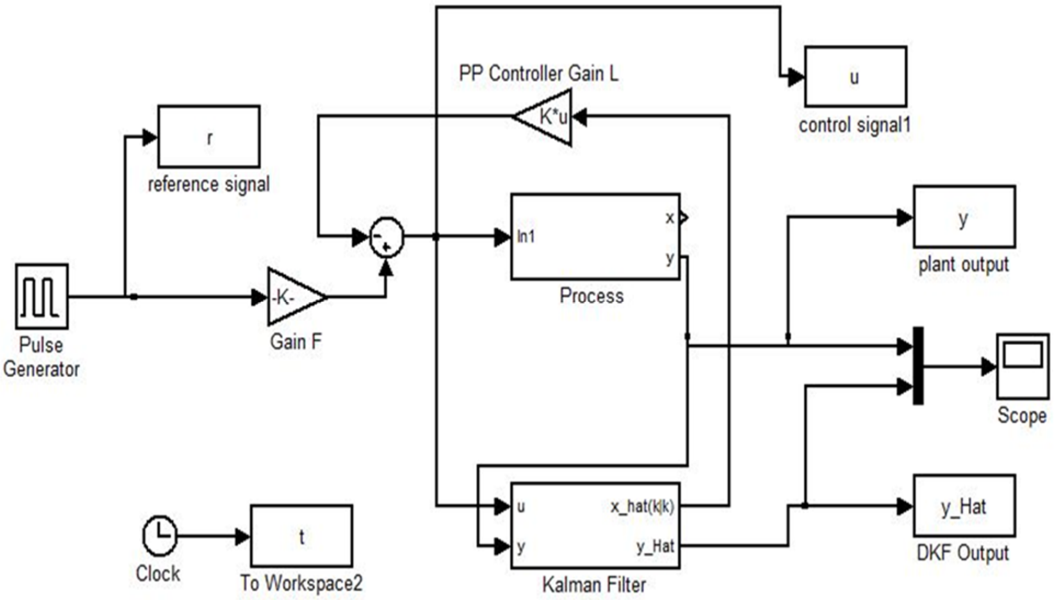

Fig 3.1 Simulink Block diagram of the closed loop system with Pole Placement controller - no Network Induced Time Delay

3.3 Results and Discussions of Closed Loop System with Pole Placement Controller - No Network Induced Time Delay

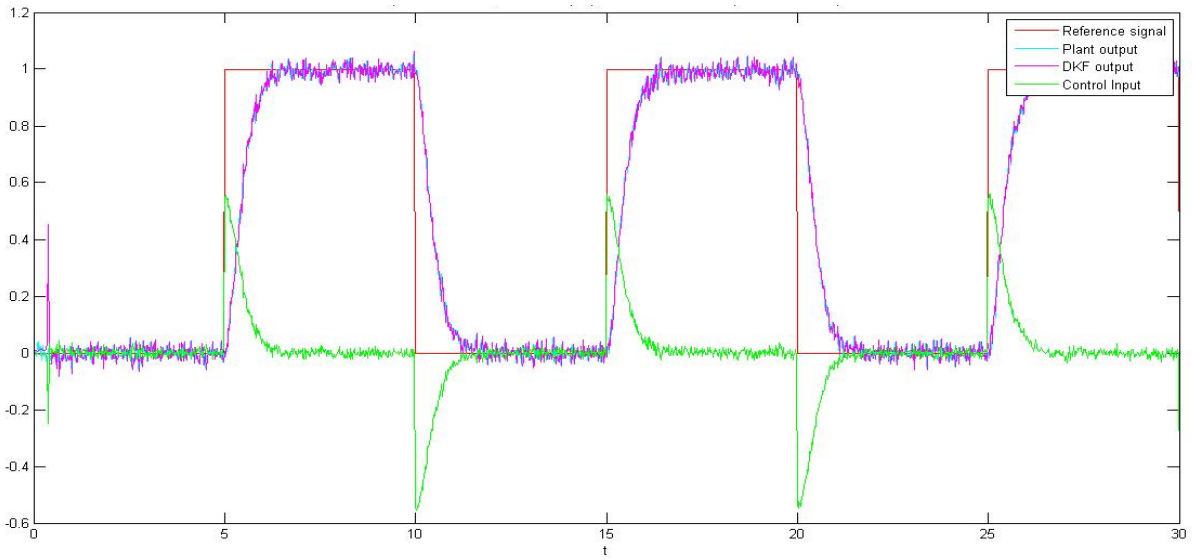

Fig 3.2 Outputs of the Plant, Controller (PP), DKF and Reference (Pulse Generator)

- The simulation is performed with the designed controller without paying much attention to network induced delays and the behavior is observed.
- X-axis data represents the discrete time which is considered as k*T where, k has initial value zero and represents number of samples and T represents the sampling period.
- The network induced delays (discrete) are specified in terms of number of samples.
- Y-axis data represents the magnitude of plant output, DKF output, reference input and control input.
- Delays are measured starting at time 5 sec (250 samples).

The results shows the following performance measures:

Performance Measure	**Pole-Placement Controller**
Rise time	1.1 sec
Percentage overshoot	0%
Settling time	1.4 sec
Steady state error	0.55%

Table 3.1 Performance measure of response

3.4 Pole Placement Controller and Discrete Kalman Filter For System with Constant Time Delay Behaviour

This simulation procedure is almost similar to the previous simulation (Figure3.1) except for the fact that the Pole Placement controller, the random process and the Kalman Filter are integrated incorporating the network induced delay between controller and actuator and between the sensor and the controller as shown in Figure 3.3. The input used in this simulation procedure has the similar specification as compared to the previous simulation with the same sampling period as 0.02 sec.

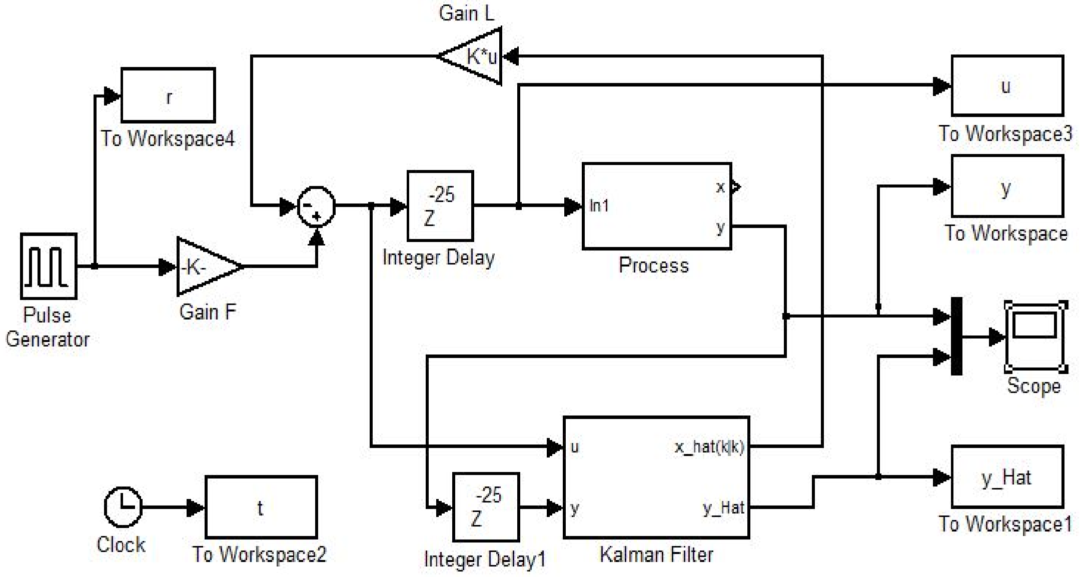

Fig. 3.3 Simulink block diagram of the closed loop system with PP Controller -constant network induced time delay (τ^{sc}, τ^{ca})

Total Delay (τ_T)	τ_{ca} (samples)	τ_{sc} (samples)	τ_T (samples)	τ_T (seconds)
τ_T=2*T	1	1	2	0.04
τ_T >T	5	5	10	0.2
$\tau_T = \tau_c$	18	15	33	0.66
$\tau_T > \tau_c$	25	25	50	1

Table 3.2 Delays under consideration

The four considered case of delay values given in Table 3.2 are used in all the simulation in this thesis work where τ_c denote the critical time period that determines the stability of plant.

The purpose of this simulation is to study the influence of the network induced delays over the pole placement controller, which is not designed to cope up with the network delays.

3.5 Results and Discussions of Closed Loop System with Pole Placement Controller Incorporating Network Induced Time Delay

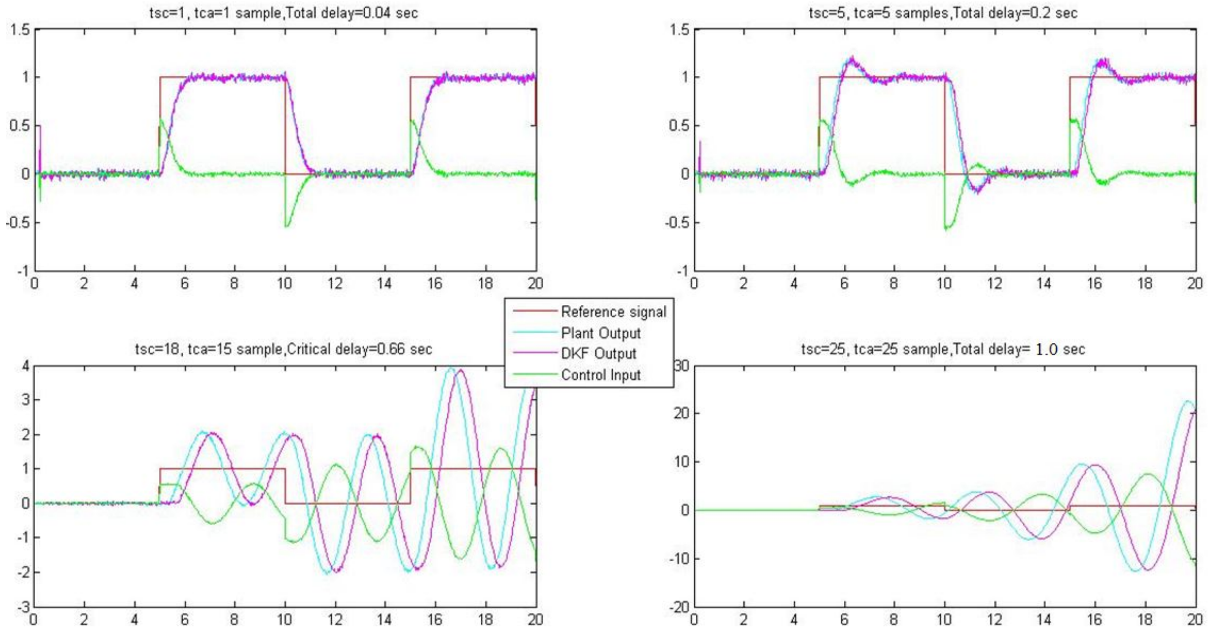

Fig 3.4 Outputs of the Plant, Controller, DKF and Pulse generator - constant NITD (τ^{sc}, τ^{ca})

- The simulation output is shown in Figure 3.4 which consists of four sub-plots, each one representing the response of the closed loop system for different values of delays under consideration as shown in table 3.2
- Several conclusion are drawn based on the above simulations, the critical delay for the system under consideration is found to be 33 samples at 0.66 seconds. When the delay is increased further the system becomes unstable.
- The discrete Kalman filter output is delayed by period τ_T and it tracks the measurement output with a delay period of τ^{sc}.
- The control action is produced depending on the delayed state of the system and is not produced according to the state estimate at moment thereby degrading the quality of control system.
- The following simulations helps us to conclude that the control action must be produced depending on the predicted state and we require a state predictor which is given in the next chapter.

Chapter-4

Optimal Predictive Controller Design

4.1 Optimal Predictive Controller Design

The major challenge is to design a robust predictive controller for NCS that can face the amount of uncertainties introduced by network. The purpose of this chapter is to study and simulate the optimal predictive controller design in order to compensate the effect of delay by performing a suitable predictive control action. Linear quadratic based optimal tracking reference control is used for designing the predictive control algorithm. The problem is to determine the control signal u (k) from $k = 0 \; to \; k_f - 1$, that minimises the performance given by

$$J = \frac{1}{2}[Cx(k_f) - y(k_f)]^T F[Cx(k_f) - y(k_f)] +$$

$$+\frac{1}{2}\sum_{k=0}^{k_f-1}\{[\,Cx(k_f) - y(k_f)]^T Q[Cx(k_f) - y(k_f)] \; + u^T(k)Ru(k)\} \tag{4.1}$$

The time delay between the controller and actuator or both time delays τ^{sc}, τ^{ca} are assumed to be augmented in the control vector of the plant model given by

$$x(k+1) = Ax(k) + B\,u(k-\tau), x\,(0) = x_0 \tag{4.2}$$

$$y(k) = Cx(k) \tag{4.3}$$

The introduced time delay in control vector creates problem in designing, this problem is further solved by introducing a new control vector given by

$$m(k) = u(k-\tau) \tag{4.4}$$

Substituting $m\,(k)$ in performance criterion J we have

$$J = \frac{1}{2}[Cx(k_f) - y(k_f)]^T F[Cx(k_f) - y(k_f)] +$$

$$+\frac{1}{2}\sum_{k=0}^{k_f-1}\{[\,Cx(k_f) - y(k_f)]^T Q[Cx(k_f) - y(k_f)] \; + m^T(k+\tau)Rm(k+\tau)\}$$

$$= \frac{1}{2}[Cx(k_f) - y(k_f)]^T F[Cx(k_f) - y(k_f)] + \frac{1}{2}\sum_{k=0}^{\tau-1}\{[\,Cx(k_f) - y(k_f)]^T Q[Cx(k_f - y(k_f)$$

$$+\frac{1}{2}\sum_{k=\tau}^{k_f-1}\{[\,Cx(k_f) - y(k_f)]^T Q[Cx(k_f) - y(k_f)] + m^T(k)Rm(k)\} \tag{4.5}$$

The performance criterion J is independent from control signal during the time period $[0, \tau - 1]$ and it can be omitted in our design analysis. This means that the design can be done for the period $[\tau, k_f - 1]$ with a new system having initial point at k= τ which can be shifted to the time $k = 0$.

The design problem is now changed to finding a new closed loop optimal trajectory $m(k)$,which minimizes the criterion J given by

$$J = \frac{1}{2}[Cx(k_f) - y(k_f)]^T F[Cx(k_f) - y(k_f)] +$$

$$+\tfrac{1}{2}\textstyle\sum_{k=\tau}^{k_f-1}\{[\,Cx\ - y(k_f)]^T Q[Cx(k_f) - y(k_f)] + m^T(k)Rm(k)\} \tag{4.6}$$

Satisfying the plant equations,

$$x(k+1) = Ax(k) + B\,m(k), x\,(k = \tau) = x(\tau) \tag{4.7}$$

$$y(k) = Cx(k). \tag{4.8}$$

The methodology used to solve the above problem are the steps given in Naidu, 2003.The solution is given by

$$m(k) = -L(k).\hat{x}(k)\ \ , k = [\,\tau, k_{f-1}] \tag{4.9}$$

where L=$R^{-1}B^T A^{-T}[P - Q]$ can be considered as constant for long optimisation period and constant model matrices .The expression can be seen from Naidu,2003. Shifting the period back to k = 0 from k =τ.

We have, $u\,(k) = m\,(k + \ \tau) = -L(k)\,\hat{x}(k+\tau)$ (4.10)

Now, the controller design requires prediction of state $\hat{x}(k)$ i.e. $\hat{x}(k+\tau)$.For this state transition matrix $\varphi(k)$ can be used which when multiplied with initial state $\hat{x}(k)$ to make the state $\hat{x}(k+\tau)$, the expression is given by

$$\begin{aligned}\hat{x}(k+\tau) &= \varphi(\tau)\hat{x}(k) + \textstyle\sum_{n=k}^{k+\tau-1}\varphi(k+\tau-n)\,Bm(n)\\ &= \varphi(\tau)\hat{x}(k) + \textstyle\sum_{n=k-\tau}^{k-1}\varphi(k-n)\,Bm(n+\tau)\\ &= \varphi(\tau)\hat{x}(k) + \textstyle\sum_{n=k-\tau}^{k-1}\varphi(k-n)\,Bu(n), m(n+\tau) = u(n)\end{aligned} \tag{4.11}$$

$$x(k) = \varphi(k)x(0) \tag{4.12}$$

Substituting k=0 in above equation we have ,$\varphi(0) = I$

For homogenous equation free from input we have,

$$x(k+1) = Ax(k) \qquad (4.13)$$

Substituting value of $x(k)$ from equation 3 in equation 4 we have,

$$\varphi(k+1)x(0) = A\varphi(k)x(0) \qquad (4.14)$$

$$\varphi(k+1) = A\varphi(k) \qquad (4.15)$$

Taking z transform both sides and using $\varphi(0) = I, \varphi(k)$ can be solved as A^k. (4.16)

From equation 4.11 and equation 4.16, we can write the predicted state as,

$$\hat{x}(\mathrm{k}+\tau) = A^{\tau}\,\hat{x}(k) + \sum_{n=k-\tau}^{k-1} A^{k-n}\; Bu(n) \qquad (4.17)$$

The closed loop control is given by,

$$u(k) = -L\left\{\hat{x}(\mathrm{k}+\tau) = A^{\tau}\,\hat{x}(k) + \sum_{n=k-\tau}^{k-1} A^{k-n}\; Bu(n)\right\} \qquad (4.18)$$

The control law derived is optimal in the sense that it minimizes the performance criterion, it is also predictive control because the future state is predicted from available present and past values of state and control signals. After obtaining a suitable predictive control action the design is simulated as shown in Figure 4.1.

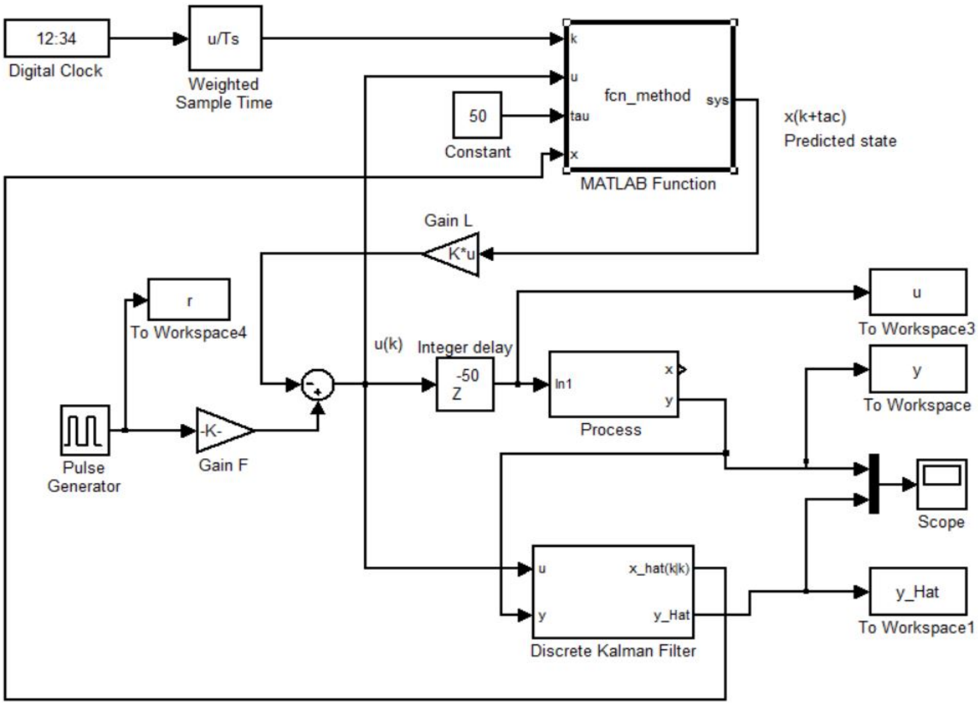

Fig. 4.1 Simulink Block Diagram of Predictive Controller

In this simulation proposed predictive control method is presented. The state predictor is implemented in Matlab Simulink and along with the Random process, Controller and Discrete Kalman filter. The similar delay values are considered as in Table 3.2.The control action is based on the predicted states and not on the delayed state values. The delay considered here is only between controller to actuator. The method shows that the controller is robust and works with the network delays that are much greater than the sampling period.

4.2 Simulation Results for Optimal Predictive Controller Design:

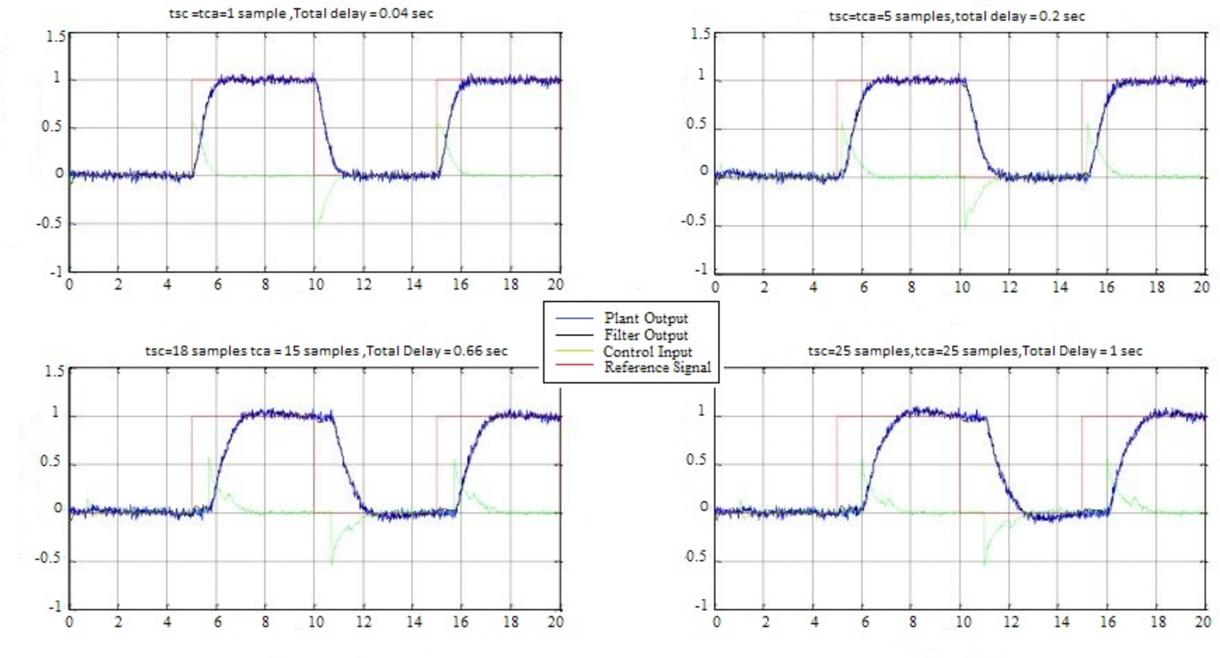

Fig 4.2 .Outputs of the Plant, Predictive Controller, Kalman filter and Pulse generator with delay (τ^{sc}, τ^{ca})

- From the above simulations we observe that controller is robust and there is no overshoot for the considered case of delays given in Table 3.2.
- The plant is initially delayed by the similar delay value but it become stable after that and no oscillations are observed at all.
- The control input is based on predictive control action and is not delayed.
- The observations confirms that the predicted controller is robust and works with the network induced delay between the controller and actuator which are much greater than the sampling period.

Chapter-5

Conclusion and Future Scope

5.1 Conclusion

For the problem concerning with limitations and constraints introduced by network mainly the network induced delays are studied by incorporating them into the control loop where the states are estimated by Kalman filter in the presence of state and output noises, several important conclusions are drawn like the critical delays for the plant for which the controller will guarantee stability and performance measures of the response are calculated. Further it is observed that the control action performed depends on the delayed state and thereby degrade the quality of control system therefore, the control action need to be determined depending on the predicted state .Hence a state predictive controller is designed based on the plant under consideration by incorporating the time delay in the control vector of the plant model. Further the predictive control is obtained and its functionality is confirmed .A state predictor approach based on transition model matrix of the plant is used to calculate the predicted value of state which is required in developing the optimal predictive control action. The developed method is simple and is also not computationally heavy.

5.2 Future Scope

- The predictive controller designed is based on the network induced delays only between controller and actuator. The delay is modelled in the control vector of the plant model as it becomes simpler from the point of view of controller design and discrete Kalman filter. The future work can be done by incorporating the delay between sensor and controller which can be considered in Kalman filter equations.

- In this thesis work the delays considered are assumed to be known at every moment k but the communication delays are statistical in nature and they can have different values and can appear at different moments. So future work can be done on the modelling of delays which are statistical in nature.

- Network induces constraints such as packet losses which are a result of network induced time delays can be modelled and their behaviour can be studied.

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APPENDIX –I

Matlab Code for a given process model and calculating Pole Placement controller gain matrix L:

```
A = [1 0.1; 0 0.85];
B = [0.005; 0.1];
C = [1 0];
D = 0;

% State and Measurement noise coefficients

Rw = 0.001;
Rv = 0.02;
x0 = [0;0];

% For Kalman filter, we use the same model
A1 = A;
B1 = B;
C1 = C;
D1 = D;
Rw1 = diag([0;1]);
Rv1 = 1;
x0 = [0;0]; %but with different initial state estimate
P0 = eye(2);

% The controller is designed by using Pole Placement Method via State Space
PO = 10; % Desired Percentage Overshoot
Ts = 5; % Desired Settling Time
zeta = abs(log(PO/100))/sqrt(((pi()^2)+(log(PO/100)^2))); % Damping Ratio
Wd =(4/Ts*zeta)*(sqrt(1-zeta^2)); %  damped natural frequency
h= 0.02; % Sampling time
po = [1 (2*zeta*Wd) (Wd^2)];
rt = roots(po);
j = imag(rt(1,1));
p = [-4-j*i -4+j*i];
z1 = exp(p(1,1)*h);
z2 = exp(p(1,2)*h);
pz = [z1 z2];
K = place (A,B,pz)  % Gain matrix using Pole Placement
```

APPENDIX – II

Plant model parameters for simulation of Figure 2.3 are given by are,
Sampling period h=0.1;
A= [0.8 0.1; 0 0.2];
B= [0; 1];
C= [1 0];
R_w= [0.001 0; 0 0.001];
R_v=0.05;

Kalman Filter parameters for simulation of Figure 2.3 are given by,

A= [0.8 0.1; 0 0.2];
B= [0; 1];
C= [1 0];
P_0= [100 0; 0 100];
R_{w1}=R_w
R_{v1}=0.5;

Plant model parameters for simulation of Figure 3.1 are given by [9] are,
Sampling period h=0.02;
A= [1 0.1; 0 0.85];
B= [0.005; 0.1];
C= [1 0];
R_w=0.001;
R_v=0.02;

Kalman Filter parameters for simulation of Figure 3.1 are given by [9] are,

A= [1 0.1; 0 0.85];
B= [0.005; 0.1];
C= [1 0];
P0=eye (2);
R_{w1}=diag ([0; 1]);
R_{v1}=2;