PREDICTIVE CONTROLLER BASED DELAY COMPENSATION APPROACHES IN NETWORKED CONTROL SYSTEM

Thesis submitted in fulfillment for the requirement of the Degree of

Doctor of Philosophy

by

RATISH KUMAR

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY

WAKNAGHAT, SOLAN, H.P., INDIA
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TABLE OF CONTENTS

DECLARATION

I hereby declare that the work which is being presented in this thesis entitled **"Predictive Controller Based Delay Compensation Approaches In Networked Control System"** is in fulfillment of the requirement for the degree of Doctor of Philosophy in Electronics and Communication Engineering in the Department of Electronics and Communication Engineering of Jaypee University of Information Technology, Waknaghat, Solan, Himachal Pradesh, India is an authentic record of my work carried out under the supervision of **Prof. Rajiv Kumar and Prof. Madhav Ji Nigam**. I have not submitted this work elsewhere for any other degree or any other Institute/University.

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Date – 20 November 2021

CERTIFICATE

This is to certify that the work reported in this thesis entitled **“Predictive Controller Based Delay Compensation Approaches In Networked Control System”**, submitted by **Ratish Kumar** in fulfillment of the requirement for the award of the degree of Doctor of Philosophy in Electronics and Communication Engineering and submitted in the Department of Electronics and Communication Engineering of **Jaypee University of Information Technology**, HP, India, is a bonafide record of his original work carried out under our supervision.

The work presented in this thesis has not been submitted elsewhere for any other degree or diploma.

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Ratish Kumar

ABSTRACT

This is an application-oriented thesis with the aim of developing new algorithms to develop controller within the framework of NCS.

Science and Technology advancements contributed significantly to the robustness and efficiency of the Control System. The Fourth Industrial Revolution introduced a holistic approach to the control system. The concept of the control system in-coagulation with communication network transformed to Networked Control System (NCS). Hence, Networked Control System implies a feedback control system in which the controller and the plant, are located at geographically distant locations but, via a communication network or the Internet, share the control signals from the controller to the plant and feedback signals from the sensor to controller. This approach improves the proximity and approachability of NCS. Its applications include remote polyhouse monitoring, remotely controlled defense operations, teleoperation or telesurgery and unmanned aerial vehicles are few to name. These applications rely on quick actuator or control signal manipulation to get the expected outcomes. A significant delay in the processing may have catastrophic consequences.

In the literature, the problem of minimization of time delay is achieved through predictive approaches. The network induced delay is primarily; controller-to-actuator delay (τ_{ca}) and sensor-to-controller delay (τ_{sc}). When the controller directs a control signal to the plant through the network then the time taken by the control signal to reach the plant is termed as sensor-to-controller delay, the time taken by the plant to act accordingly to control signal is included in this delay. Whereas; the delay observed in receiving the feedback signal by the controller from the sensor through the network is termed as sensor-to-controller delay. It also includes the delay observed by the sensor to perceive the output from the plant. The maximum delay observed to stabilize the plant after receiving the control signal is called the deadtime. The deadtime influences the system's functionality and degrades the system's performance. Minimizing these delays helps to stabilize the system which enhances the performance of NCS and provides better service to consumers. Keeping the above consideration, an algorithm is proposed to design a model-based modified Smith Predictor Controller (SPC); used to further minimize the network-induced delay. A Smith Predictor Controller uses a predicted process model to anticipate future values of the output variable and deadtime estimations. The control calculations are based on a comparison of both, the

predicted model values with estimated deadtime values and the current actual values of the plant output.

In the proposed algorithm to modify Smith Predictor Controller; Markov Approach is used to predict the process model of the plant and the Kalman Estimation Technique is used for deadtime estimation. Using these two approaches, efforts have been made to minimize the network-induced delay by considering the realistic parameters to design and simulate NCS in MATLAB/Simulink 2020. The plant model so designed for simulation of NCS is considered as a state-space model of DC Motor with parameters as described in Appendix A. The network involved a Universal Datagram Protocol (UDP) [1] to set a communication network between controller-to-actuator and sensor-to-controller in NCS. For time-sensitive applications, UDP is considered as much faster, simpler, and efficient for broadcast and multicast types of network transmission. The Simulation Results of the proposed controller algorithm with respect to parameters constitute settling time, rise time, overshoot, slew rate, signal-to-error ratio (SER), IAE, ITAE, ISE, and ITSE are presented in Chapter 4 and 5. To evaluate performance improvement, these simulated findings are compared to current research [2].

NCS based applications can be categorized as time-sensitive and non-time-sensitive. Firstly, a time-sensitive application i.e., Evolution of Third Eye for Defense Covert Operations is designed [3]. It describes the controlling of the weapon from the base station. The weapon along with an excellent image quality camera, the system dynamics (i.e., actuation of weapon and rotary motion of the system) is mounted on one of the shoulders of the soldier and will continuously feedback the real-time images of the combat zone. Any suspicious movement received by the support team at the base station will send a control signal to the weapon actuator to neutralize the apprehensive activity.

The terrible phase of pandemic Covid-19 has brought humanity and technology closer. The second application involves a prototype design and development of a Smart Home Health mobile application to assist patients in-home/institutional isolation/quarantine and to patients living in remote areas, medical resources are scarce. This application also provides a networked control platform to regulate and direct home appliances such as light, air conditioners, fans home security cameras [4]. The application includes other facilities like Video call to Doctor, Medical Prescription, book a Medical Test in nearby laboratories, Medicines delivery from nearby medical stores, Book an Appointment with Doctor, Order meal as per Physician’s prescription, Book an Ambulance and social platforms such as Facebook, Instagram, etc. to communicate with family and friends.

In third application considered the polyhouse crops grown under a controlled environment in any season across the year. To improve the quality of the different crops in a polyhouse; an NCS based remotely controlled and monitored system is proposed to regulate various parameters such as temperature, moisture, CO_2 gas, light, use of fertilizers and water usage in the polyhouse. The outputs obtained from various sensors are recorded and analyzed by the farmers to decide the application of resources in the polyhouse. The daily recorded data can be used by agricultural scientists, researchers, research institutes/agencies to build a documentation process for crop production. This documentation will assist to improve efficiency and new techniques to grow crops in polyhouse.

In the end, it will only be appropriate to point out that the author foresees the emergence of new commercial software packages for the Networked Control System or a galaxy of a number of expert systems related to NCS.

LIST OF ACRONYMS

APV	Actual Process Variable
BSL	Blood Sugar Level
BT	Body Temperature
C(s)	Control signal from the controller
CDOB	Communication Disturbance Observer
CHD	Control Home Device
CM	Central Controller
COVID-19	Corona Virus Disease - 2019
CPS	Cyber-Physical Systems
DC	Direct Current
DHT	Distributed Hash Table
DHT 11	Digital Humidity Temperature Sensor
DMJLS	Discrete-time Markovian Jump Linear System
DNS	Domain Name System
DS	Doctor's Side
DSD	Diastolic blood pressure
EC	Edge Computing
FOPDT	First Order Pulse Dead Time
FTP	File Transfer Protocol
HD	Home Device
HDNM	home Device Network Management
HNA	Hierarchical Network Architecture
IAE	Integral Absolute Error
IMC	Internal Model Control
IOT	Internet of Things
IOT WF	Internet of Things World Forum
ISE	Integral Squared Error
ITAE	Integral Time Absolute Error
ITSE	Integral Time Squared Error
KMSPC	Kalman-Markov Approach Based Smith Predictor Controller

LMI	Linear Matrix Inequality
LQG	Linear Quadratic Gaussian
MIMO	Multiple-Input and Multiple-Output
MJLS	Markovian Jump Linear System
MJS	Markovian Jump System
MSPC	Markov Approach Based Smith Predictor Controller
NC	Network Connection
NCS	Networked Control Systems
ND	Network Disturbance
NN	Neural Network
P(s)	Variable Consists of Process
PD Controller	Proportional Derivative Controller
PI Controller	Proportional Integral Controller
PID Controller	Proportional Integral Derivative controller
PS	Patient's Side
RNN	Recurrent Neural Network
SBD	Systolic Blood pressure
SBL	Stability Boundary Locus
SER	Signal to Error Ratio
SMLR	Sparse Multivariate Linear Regression
SNA	Shared Network Architecture
SOPDT	Second Order Plus Dead Time
SPC	Smith Predictor Controller
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
WNCS	Wireless Networked Control System

LIST OF SYMBOLS

$x(k)$	State vector
s	State of the system
S	Set of states
R	Real Number
$n \times m$	Number of rows × Number of columns
$\tau(k)$	Total delay
τ_{max}	Maximum delay
τ_{sc}	Sensor-to-controller delay
τ_{ca}	Controller-to-actuator delay
τ_{ap}	Actuator-to-plant delay
τ_{pt}	Plant processing delay
τ_{ps}	Sensor delay
τ_{ct}	Computational delay
A	System matrix
B	Input matrix
C	Output matrix
D	Feed-forward matrix
K_p	Proportional gain
K_i	Integral gain
K_d	Differential gain
$e_r(t)$	Error signal
$\widetilde{e_r}(t)$	Expected error signal
$e^{-L_n s}$	Estimated deadtime
$e^{-L_p s}$	Disturbance in the plant
$C(s)$	Transfer function of controller
$G_n(s)$	Fast model of the plant
$P_n(s)$	Predicted process model of the plant
P_r	Transition probability
$P(s)$	Transfer function of the plant
$e_p(t)$	Estimated disturbance

$X(t)$	Reference control signal
$\hat{X}(t)$	Estimated output signal of the system
i,j	ith and jth state of the system
p_{ij}	Transition probability from i to j
$\alpha(t)$	Homogeneous Markov chain
Θ	Transition matrix
$y(t)$	Output of the plant
$u(t)$	Control input to the plant
K	Controller gain
$s_a(t+1)$	Future state of the system
F_n	state-transition matrix
v_n	Gaussian random state noise vector
Q_n	covariance matrix
H_n	measurement matrix
$p(x_n\|x_{n-1})$	Probability density function of state vector
$p(y_n\|x_n)$	Probability density function of measurement vector
$\mathcal{N}(*;m,P)$	Gaussian probability density function
m	Mean
$m_{n\|n}$	Gaussian posterior mean
$P_{n\|n}$	Gaussian posterior covariance
r	Proximity Estimation
θ	Polar angle
φ	azimuthal angle or the zenith angle
δ	Latitude
μ_i	Centroid intensity
k	Number of clusters
d	Euclidean distance or distance metric
c_k	Center position

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
Introduction

Origin of Control System is linked to Lego Blocks, Mechanical Components, and Control Measures that are used to regulate the system dynamics. Researchers have provided various optimum and precise control policies. With the development of communication networks, the idea of remote control gave rise to networked control systems (NCS). The Networked Control Systems are typical feedback control systems that are integrated to various nodes of communication networks [6].

1.1 Networked Control System

An NCS is a feedback control system that terminates feedback procedures by utilizing a real-time network to accomplish the process. The use of NCS is becoming extremely prevalent in almost every field of technology where devices can be managed and operated from a distant location, as has been observed [7]. To facilitate the integration of measurement information and control messages between the systems conveniently, NCS has assimilated a real-time communication network into the control loop. These systems tend to be spatially distributed and provide a variety of competitive advantages, including low capital costs, ease of service, improved system agility, and energy efficiency, among others [8]. The schematic of NCS is shown in Fig1.1.

Because of the numerous advantages offered by NCS applications, they are becoming increasingly popular in industrial robotics [9], operations management [10], agribusiness and farming [11], aerospace and aircraft [12], the healthcare industry [13], the digital economy (IoT) [14], and military operations [15]. NCS may be split into two types of structures; based on their architectural design such as Shared Network Architecture (SNA) and Hierarchical Network Architecture (HNA) [5].

In a shared or direct network design, the central controller (CM) is responsible for setting the control signal. Sensors and actuators are directly connected to the network, as shown in Fig. 1.2(a). In the later design method of the networked control system, the central controller is connected to the subsystems through a network, while the status or sensor measurements alter the regulated commands of the central controller. They are controlled by their subsystem controllers [16]. As shown in Fig. 1.2(b), these controllers get the setpoint from the central controller and attempt to fulfill the subsystem following that setpoint. As the sensor input is received, the subsystem controller generates a regulated signal based on the central controller's set point.

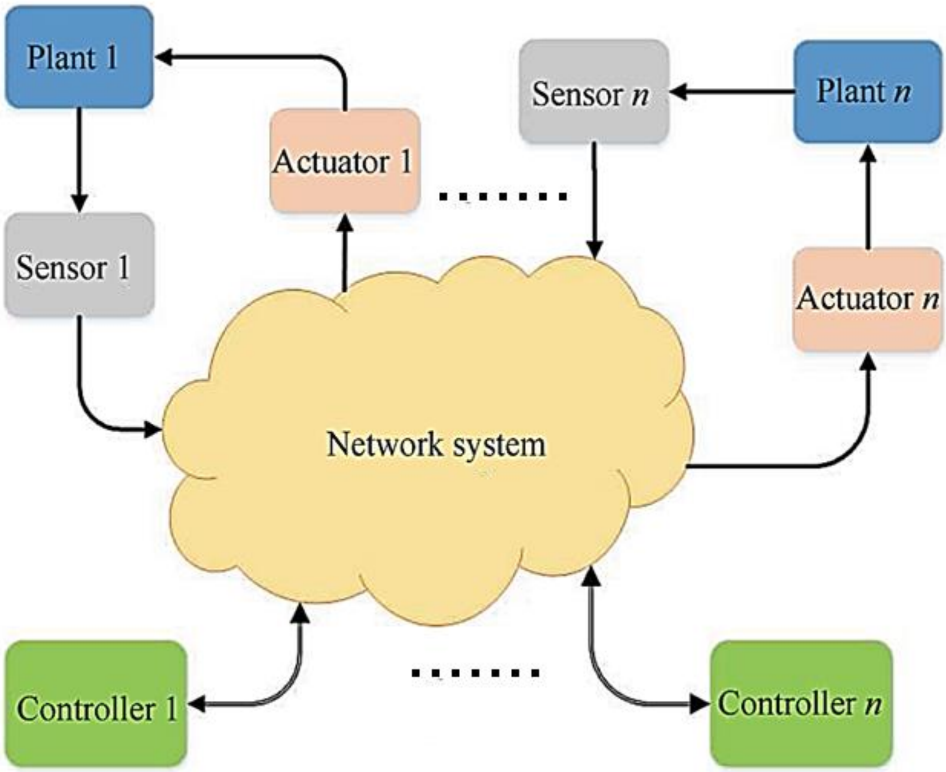


Figure 1.1 Basic Schematic of Networked Control System [5]

Control and communication components are regarded as completely separate entities in a hierarchical approach. This greatly simplifies the analysis and design of the whole system, and it is particularly useful for developing systems with high transmission bandwidth [17]. Traditionally, control theory has been concerned with the assessment of interlinked dynamical systems that are connected by perfect channels, however, communication theory has been concerned with the transmission of information through imperfect channels [18].

To model NCS, it is necessary to use a mix of these two frameworks. We may classify NCS applications into two major types, in terms of timed response urgency as described below:

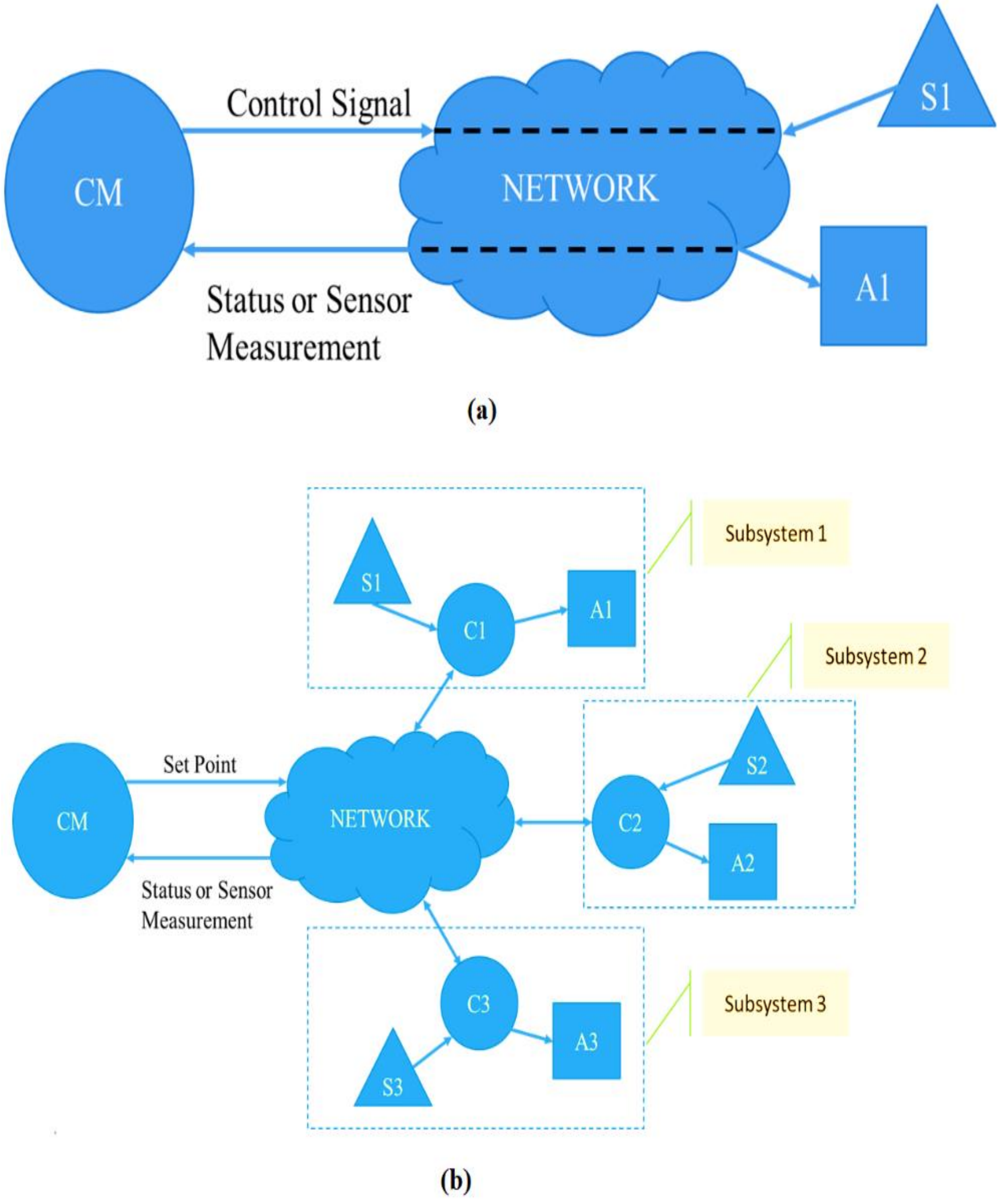


Figure 1.2: Schematic of NCS (a) Shared Structure (b) Hierarchical Structure

1. Time-sensitive applications are those which require immediate reaction to act upon. Covert operations, firefighting operations, underwater operations, medical crises, and automated highway driving and teleoperation are all examples of applications that rely on

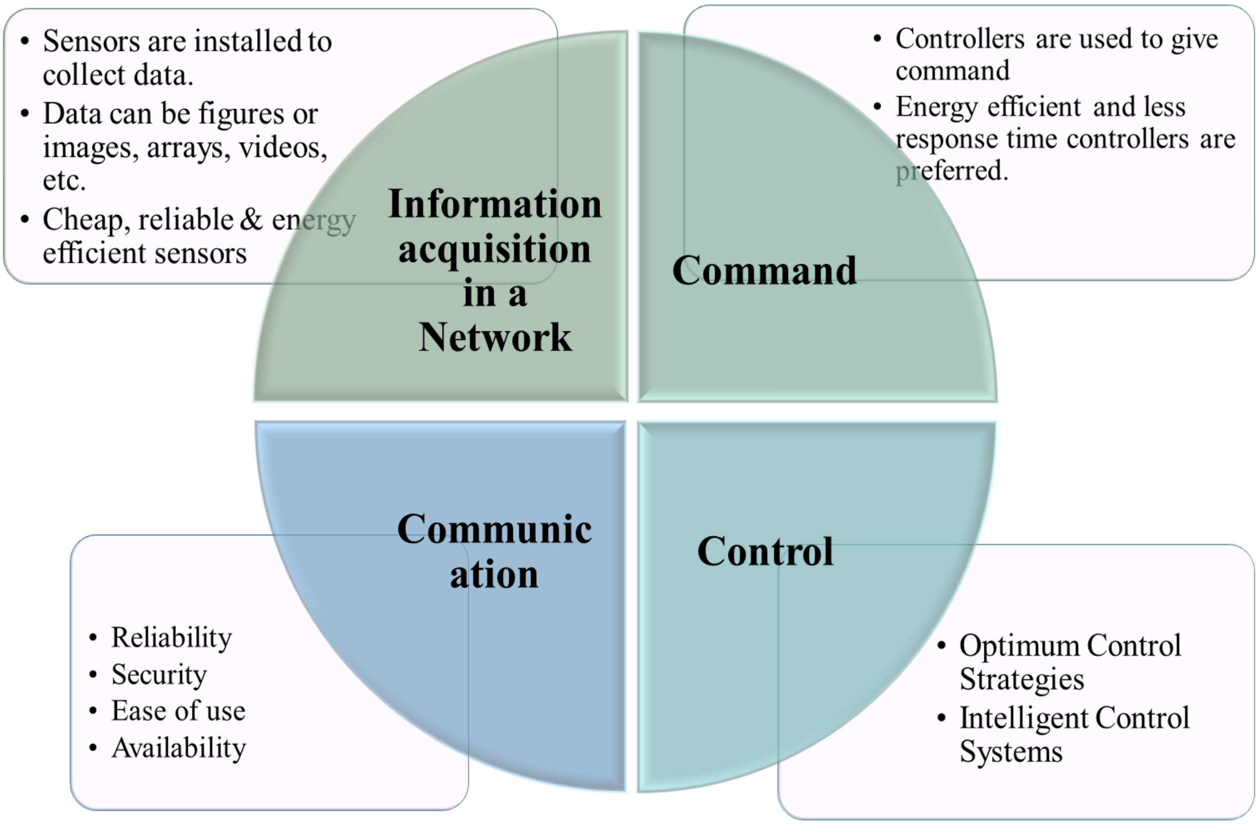
time-sensitive networked control system [19]. The prominence of time in such applications cannot be overstated; thus, If the delay period outweighs the admissible time limit, the plant or hardware may be ruined, or its performance may be compromised.

2. Time-insensitive applications do not require urgent control input signals to react upon any condition or situation [20]. Examples of such applications are polyhouse automation, information management, sensor information gathering, e-mail, FTP, and DNS, etc. are all examples of technologies, etc.

However, for both types of system applications, network dependability is a critical element to address. The availability of a consistent network ensures the efficacy of an NCS.

1.2 Components of Networked Control System

For any modality or arrangement to connect and configure various hardware and software play a key role in the implementation and become part of the system [21].



Information acquisition in a Network
Command
Communic ation
Control
• Sensors are installed to collect data.
• Data can be figures or images, arrays, videos, etc.
• Cheap, reliable & energy efficient sensors
• Controllers are used to give command
• Energy efficient and less response time controllers are preferred.
• Reliability
• Security
• Ease of use
• Availability
• Optimum Control Strategies
• Intelligent Control Systems

Figure 1.3: Components of NCS

To accomplish the requisite operation, the Networked Control System executes specific functions regardless of the layouts and methodologies employed for integrating and customizing the hardware and software assets in order to successfully complete the objective. It has to follow the four functions for a required task as elaborated in Fig. 1.3. to provide convenience to NCS designers so as to prove the functionality of the system [22].

1.3 Factors Affecting Networked Control System

NCS may be used to update traditional point-to-point wired control methods while also affording a number of notable improvements. However, the incorporation of network technology into feedback control loops makes modeling of NCS more complex to execute. Several challenges, as seen in Fig. 1.4, may be experienced [23]. Broadly, these are acknowledged as important variables that contribute to system performance deterioration and even the inability to maintain reliable operation. Various terms have been used in the literature to describe the challenges that networks offer, including network channel limitations, inadequate information, network-induced faults, network-induced phenomena, and network-induced restrictions are few examples to mention. The challenges are referred to as communication restrictions produced by networks, and they may include, but are not limited. Other network characteristics include time-varying topology, network channel fading, and random network throughput.

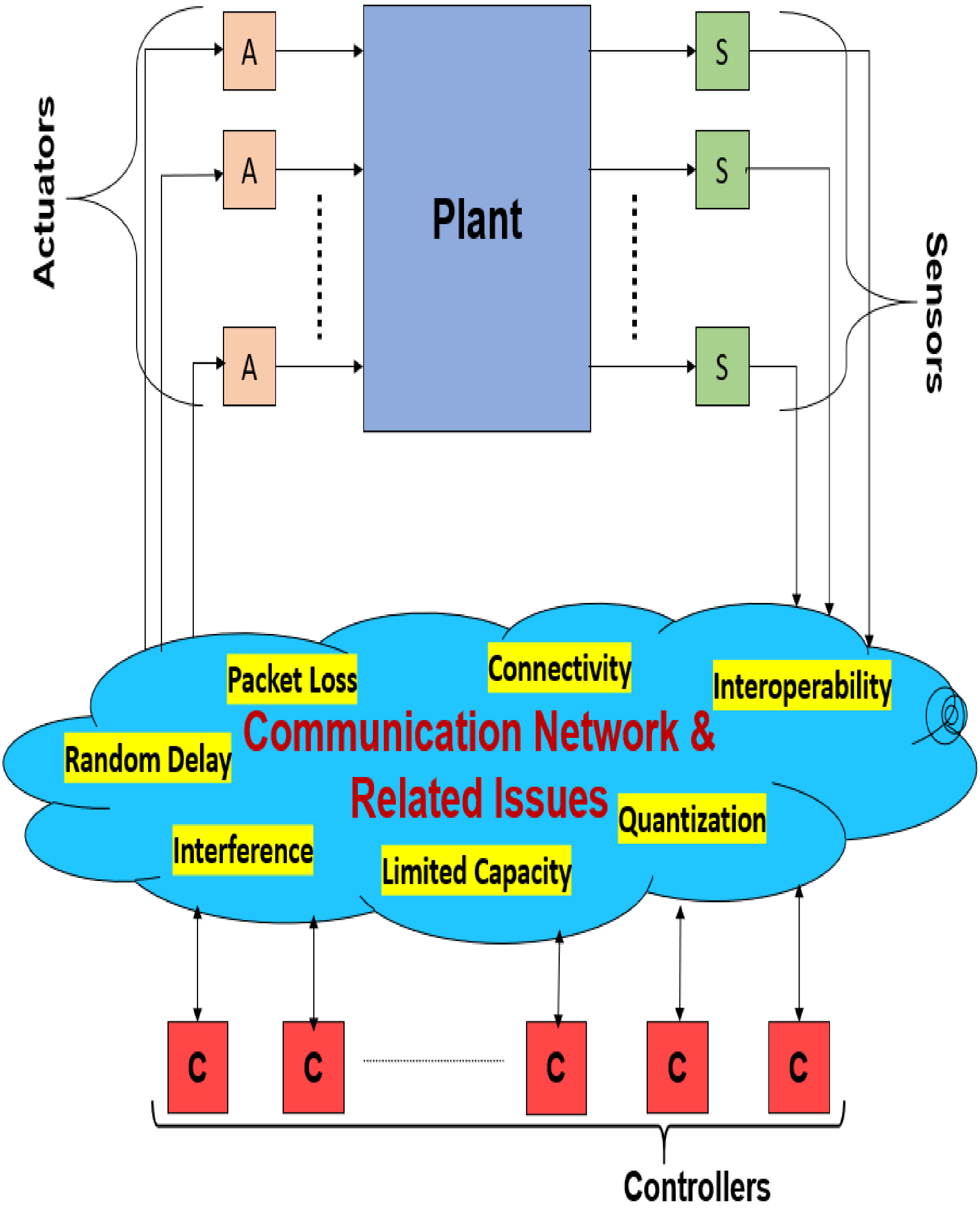


Figure 1.4: Issues Related to NCS

1.4 Delays in Networked Control System

It is possible to experience network-induced delay, particularly include sensor-to-controller (s-c) and controller-to-actuator (c-a) delays, when data is transmitted between linked sites via a network infrastructure, it can cause system performance and stability to be compromised [24]. It is possible for this delay to be continuous or time-varying based on the network features such as network load, topologies, and routing algorithms.

Network-induced time delays perform a significant role in the deprived performance of networked control systems and are one of the main reasons differentiating system instability [25]. The various kinds of delay in a networked control system can be illustrated through Fig.1.5. The control system state dynamics can be depicted using the state equation as:

$$x(k+1) = Ax(k) + Bu\big(k - \tau(k)\big) \tag{1.1}$$

where the state vector x(k), is $R^{n\times 1}$, input vector, u(k) is $R^{m\times 1}$, square matrix A & B have dimensions as $R^{n \times n}$ & $R^{n \times m}$ respectively. $\tau(k)$ is the total delay in the system that can be limited as τ_{max} such that $0 \le \tau(k) \le \tau_{max}$. Similarly, system output can be expressed as the combination of state variables and inputs as:

$$y(k) = Cx(k) + Du(k) \tag{1.2}$$

where, output vector y is $R^{p \times 1}$, output matrix C is $R^{p \times n,}$ and D is transmission matrix having dimensions $R^{p \times m}$. Here m, n, and p superscripts are showing the dimensions of the matrix in the dimensions of rows versus columns.

For a feedback loop of the networked control system, various delays emerge that affect the working of the system. These delays are related as:

$$\tau_{total} = \tau_{sc} + \tau_{ca} + \tau_{ap} + \tau_{pt} + \tau_{ps} + \tau_{ct} \tag{1.3}$$

the total delay τ_{total} is sum of $\tau_{sc}, \tau_{ca}, \tau_{ap}, \tau_{pt}, \tau_{ps}$ and τ_{ct} are defined as, delay in receiving the signal from feedback sensor over the network to controller, the time it takes for a control action to travel from the controller to the actuator over a network, delay in actuating the control signal at the actuator to plant, delay in evolving processing time at plant unit, delay in acquisition of sensor data by a sensor and the delay due to computational time taken by the controller to create a succession of control signals respectively. Primarily, the network-induced delay provokes the issue of packet dropout and bandwidth congestion leads to system instability.

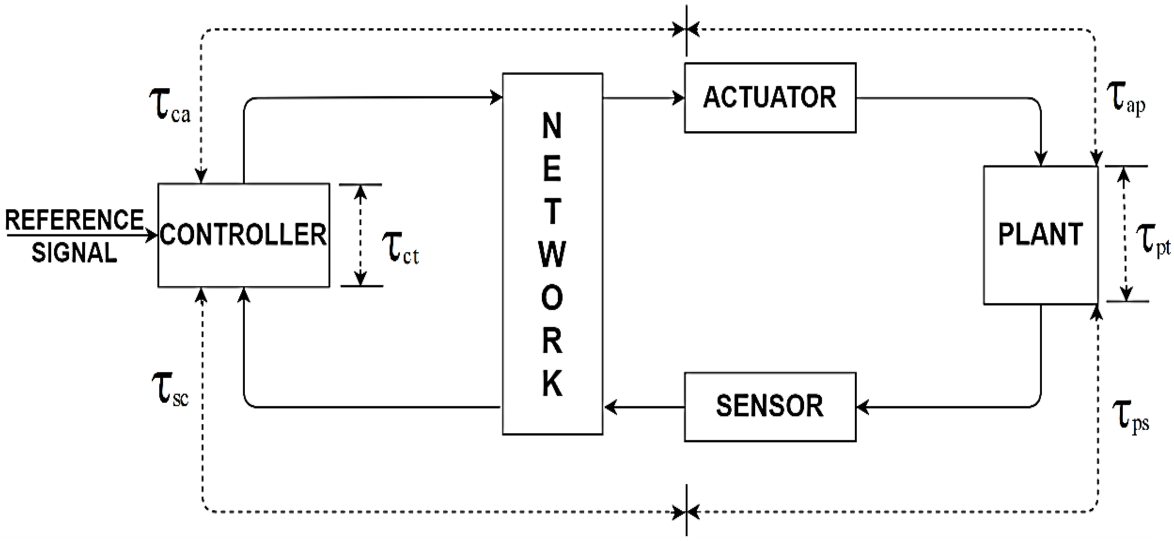


Figure 1.5: Types of Delays involved in NCS

Buffering, access congestion, computational delay, propagation ("transmission") delay, and network-induced delays all-cause information sharing in the feedback control loop to be delayed.

Time delay is a common event in real-world operations, and it has the potential to alter both information and control signals. Time delays in an NCS are largely formed of three types of delays, which are most commonly encountered are as follows:

- computational delays in system components, due to the restricted computing power or capability of digital technology, such as sensors, controllers, and actuators;
- network access delays, data is delivered across a network in packets, and standby network data packets might have to wait a long time before they can be dispatched, incurring network access delays. When a communication network is shared by several processes, this is especially true, and
- transmission delays in the network is due to a communication network's limited bandwidth, this type of delay may be caused by fluctuating network circumstances including network channel state information and routing traffic congestion [26].

In practical terms, the computational delays observed due to system components are often modest, and in certain cases, they may be non-existent. When network queues have access delays and when communication networks experience transmission delays, they are referred to as "network-induced delays," according to industry terminology. When modeling delays in NCS, some researchers have taken into account transmission delays, which they refer to as network-induced delays because network access delays are sometimes insignificant when compared to transmission delays in some cases. In a network framework, networked-induced delays might have random or deterministic features, constant or time-varying characteristics and be caused by a variety of applications using a range of distinct network technologies [27].

Whenever there are terminal outages or messaging clashes, network packet-dropout can occur in an NCS. Despite the fact that since most information systems are outfitted with a transmission-retry approach, but these can only resend signals for a finite period [28]. If this time limit has elapsed, the packets are no longer considered valid. It may also be advantageous to reject the prior, untransmitted message and transmit the new packet as soon as it is made available when dealing with real-time feedback control data, such as sensor readings and estimated control signals. As a result, the controller receives current information for control calculations on a consistent schedule.

1.5 Simulation Results of Networked Control System

PID controllers have long been the most widely used in operational industrial applications because of their clear and obvious physical meaning, their ease of tuning, and their robustness, to name just a few advantages. In [20], the strategies for designing PID controllers for the time-delay process were discussed, and the applications of PID in NCS were considered in [21]-[22]. Control loop feedback mechanisms such as PID controllers are frequently employed throughout industries [6]. Consider the characteristics parameters –

proportional (P), integral (I), and derivative (D) controls, as applied to the diagram below in Fig.1.6. A PID controller can have transfer function as:

$$\mathrm{C(s)} = \mathrm{K_P} + \frac{\mathrm{K}_i}{\mathrm{S}} + \mathrm{K_d S} \tag{1.4}$$

$$\mathrm{C(s)} = \frac{\mathrm{K_d S^2 + K_P S + K_i}}{\mathrm{S}} \tag{1.5}$$

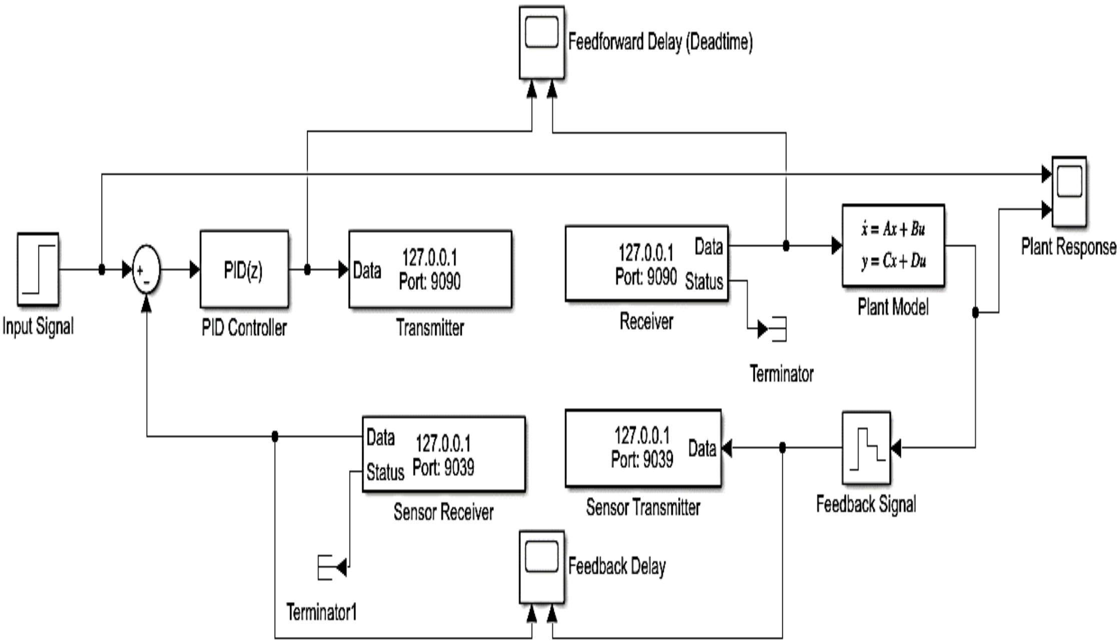


Figure 1.6: Simulink Block Diagram of Conventional PI, PD, and PID Controllers

$$\mathrm{u} = \mathrm{K_p} + \mathrm{K_i} \int \mathrm{edt} + \mathrm{K_d} \frac{\mathrm{de}}{\mathrm{dt}} \tag{1.6}$$

In Fig. 1.6 a networked control system is designed using UDP protocol to send control signal to regulate and command the dynamics of the DC motor over network using PID Controller with values as P = 1.50, I = 1.85 and D = 0.01, the input step function is set at T_{step} = 1sec, with Initial value equal to zero. As background research study to develop. To make the basis for a comparative research study the conventional PI, PD and PID controllers are simulated for the plant model with state space model as:

$$\mathrm{A} = \begin{bmatrix} -11 & -91 & -108.3 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \mathrm{B} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \mathrm{C} = \begin{bmatrix} 0 & 0 & 107 \end{bmatrix} \text{ and } \mathrm{D} = \begin{bmatrix} 0 \end{bmatrix}$$

PID controllers generally adopted in more than 95% of closed-loop industrial processes, owing to their accessibility. In time domain analysis of the plant the three major design parameters are rise time, overshoot and settling time. This study involves the design of above parameters for a plant using Networked Control System. The transfer function of the DC motor considered for the simulation is given as:

$$\frac{107}{s^3 + s^2 + 91s + 108.3} e^{-\tau s}$$

Here, τ defines the delay in the system, that ranges from 0.2 sec to 60 sec. To make a comparative study of the proposed controller the DC motor is cited from the reference [83].

The simulation of PI, PD, and PID controller is carried out in Simulink to study their values for the derived system. The parameters obtained are compared in Table 1.1.

The results so obtained show that the PID controller provides better percentage improvement as compared to the other two controllers in respect of rise-time which is 10.85%, settling time 28.9% and overshoot 53.2%. The signal to error ratio (SER) is improved by 1.7%. The feedforward delay and feedback delay show an improvement of 0.4% and 0.1% respectively. The transient response parameters are mentioned in Appendix A.

Table 1.1: Comparison of Controller Parameters

S.No.	**Parameters**	**Type of Controllers**			
		PI	**PD**	**PID**	**%ge Improvement of PID over others**
1.	Rise Time (in milli seconds)	397.67	307.593	440.84	No Improvement
2.	Overshoot (in %)	**2.646**	13.068 (Undershoot)	**1.505**	53.2%
3.	Settling Time (in seconds)	**0.69**	Infinite	**0.49**	28.9%
4.	Signal to Error Ratio (SER)	**6.757**	3.744	**6.872**	1.7%
5.	Feedback Delay (in milli seconds)	**97.25**	90.97	**97.12**	0.1%
6.	Feedforward Delay (in milli seconds)	**89.52**	83.27	**88.95**	0.4%

To observe the plant response a comparative analysis of PI, PD, and PID controllers are shown in Fig.1.7. It can be observed from the Fig.1.7 that the PID controller presented in the blue curve shows a better response curve as compared to the PI and PD controllers.

The settling time to achieve the steady-state response of the system increased by 90 seconds and rise time increase to 67.5 seconds when a deadtime of 60 seconds introduced in the system for PID controller. For a time-sensitive application such as a networked controlled Fire Extinguisher Robot with such a rise time and steady-state response parameters will collapse the system and will cause disaster. So, there is a need to design and develop controllers which show stability under such conditions.

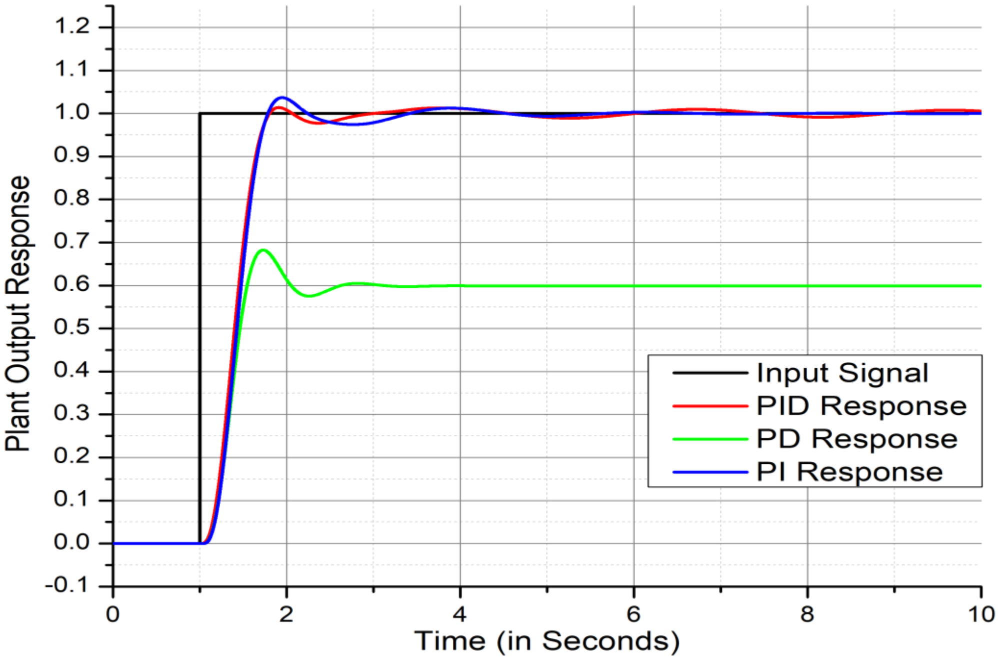


Figure 1.7: Plant Output Response Comparison of PI, PD, and PID Controllers

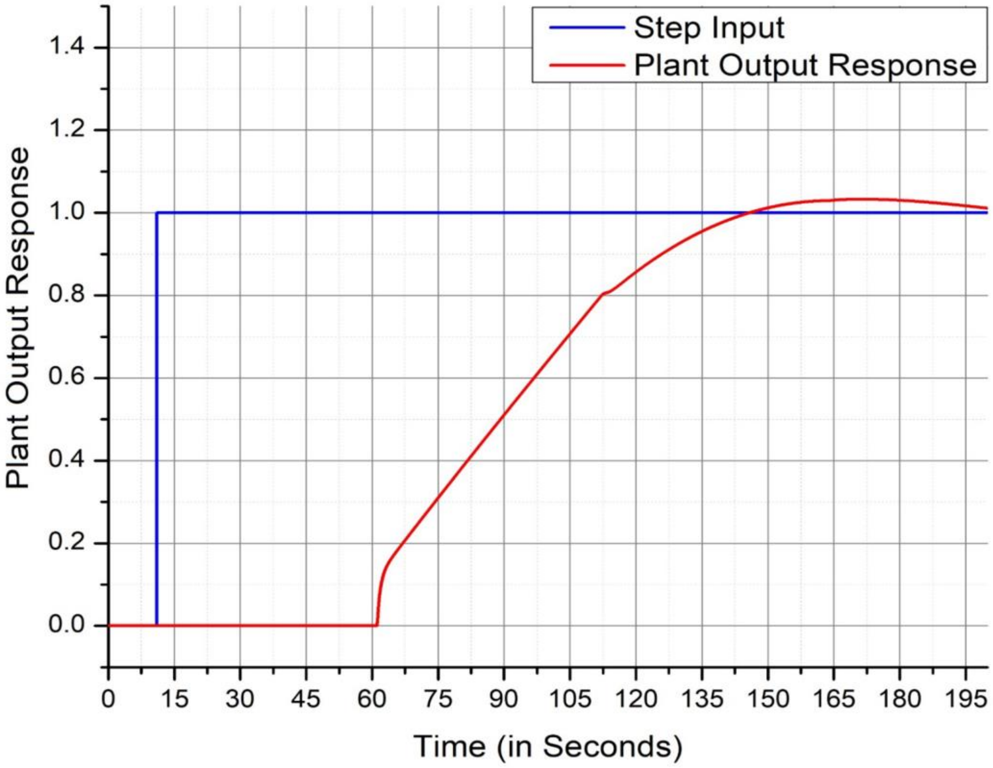


Figure 1.8: Sluggishness in Plant Output Response by PID Controller at Large Deadtime, t = 60sec

These simulations are carried out at a delay time of 0.1sec introduced in the system. It is observed that when a delay of 60 sec is introduced in the system, the PID controller shows sluggish behavior as shown in Fig.1.8. To improve the response at large delay time researchers carving about different methodologies to develop controllers that can eliminate such controller behavior.

1.6 Research Motivation

Technology is rapidly moving towards the innovative development of robotics to strengthen humanity for assistance during any natural calamity, space-underwater exploration, disaster rescue operations, defense, and industrial production. NCS not only provides a path to realize these applications but also strengthens the other technological evolutions such as Edge Computing (EC), Cyber-Physical Systems (CPS), and Internet of Things (IoT) [29]. With the increase in machine-to-machine connectivity and information sharing between these machines the utilization of channels is overburdened and their performance is affected by network-induced delays.

An effective networked control system demands that the control signal transmitted from the controller to the plant appears to arrive instantly and that feedback data arriving at the controller from a sensor also on the network occurs as promptly as possible so that the next control signal can be calculated. Because we can't guarantee a low network latency throughout this process. However, we can make a task go forward faster, both for the actuator to receive and interpret a control signal, and for sensors to check for feedback and provide a new control signal. To ensure the success of this procedure, the following conditions must be met:

- Understanding the plant's dynamics can help you to build a predictive model.
- It is possible to enhance efficiency and reliability by considering an expected delay in the system model.
- A comparison of predicted and actual plant outputs should be carried out to produce updated control signals for actual models.

In case of an extreme scenario, such as packet dropout or packet loss, above mentioned steps can be followed to achieve the desired operation. The input control signal sequence of this system can be anticipated with a short time delay. To meet time-sensitive applications, we need to increase the visibility of the data packets with low latency of the packets and maintain the optimum delay of these packets less than 200 milliseconds. The utmost objective is to improve the network's trustworthiness by finding methods to minimize network-induced delay via innovative modifications to the Smith Predictor Controller (SPC).

1.7 Research Objectives and Methodologies

The aim of this research is to minimize network-induced delay to the best of its ability via the design and development of a Controller that operates in accordance with network delay. For this, an innovative attempt has been made to modify the model-based Smith Predictor Controller which compensates for the large deadtime in NCS. The modifications are introduced in the Smith Predictor Controller by using Markov Approach and Kalman Estimation Technique. To predict the model of a plant that is being used in the working of Smith Predictor Controller, an algorithm is designed using Markov Approach whereas, the deadtime involved in the working of Smith Predictor Controller is estimated through Kalman Estimation Technique. Hence, a modified Smith Predictor Controller is proposed by incorporating these two methodologies in the working of Smith Predictor Controller to compensate large deadtime arise in NCS. The background study of research work related to various delays, their compensations, applications, and issues involved in NCS are simulated using MATLAB/Simulink2020 and findings are presented in Table 1.1, Fig.1.7 and Fig. 1.8.

The ultimate objective of this research is to design a modified Smith Predictor through successful completion of each of the objectives mentioned below:

1. To design an algorithm for the development of NCS using Smith Predictor Controller to compensate network-induced delay.
2. To develop an algorithm for inclusion of Markov approach in Smith Predictor Controller that works efficiently for NCS with reduced delay.
3. To study and design the Smith Predictor Controller using the Markov Approach and Kalman Filter that should work efficiently for any type of system.

This research focuses on the practical implementation of the designed algorithms and controller in real-world problems such as telesurgery operations, defense covert operations, automated vehicles controllers, etc. where time consideration is extremely important for the controller to react and control the operations. As an application part, the proposed methodology is implemented and simulation results are compared to verify the effectiveness of the proposed algorithms and design.

1.8 Thesis Organization

The thesis consists of the following chapters:

Chapter 1 introduces the Networked Control System, as well as the variables that influence its performance and stability. A brief of network-induced delay and its effects on NCS are described in this chapter. In the end, research motivation and research objectives along with methodologies are discussed.

Chapter 2 involves the research background and exhaustive literature review. In recent years, various researchers worked and evolved different techniques to minimize delay in NCS and improve the stability of the plant. The work of different authors is compared and analyzed. Further, research problem formulation followed by research objective is presented to fill the research gaps.

A comparison of the simulation study is presented in Chapter 3. The different available conventional controllers are compared with the Smith Predictor controller. This chapter contains the principle and the working of the Smith Predictor Controller. The parameters obtained from the simulation results are analyzed and compared.

Chapter 4 presents the principle and working of the Markov Approach applied in NCS. This chapter describes the working of the proposed model of the Markov approach to derive the plant model to be used as the predicted model in the Smith Predictor Controller. The simulation results using MATLAB/Simulink 2020 of the proposed model are obtained. The results so obtained are analyzed and compared with other authors [30]–[32].

In Chapter 5, an attempt is made to use the Kalman Estimation technique to estimate the randomness in Smith Predictor Controller used for NCS and results are quite encouraging. Further, the Markov Approach and Kalman Estimation technique are proposed and implemented in the Smith Predictor Controller for NCS. Using Markov Approach and Kalman State Estimation in Smith Predictor Controller; simulated results are obtained which have an edge over other researchers [18], [30]–[34].

Chapter 6 details out the solutions obtained using NCS for various applications such as Precision Agriculture, Third Eye Evolution, the Smart Health Home Mobile Application, and Teleoperation with reduced lag time. A prototype model of the Smart Health Home application is described here, as well as how it works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Since the end of the 20th century, it’s been a tremendous rise in technological advancements, thanks to developments in electronics, information, and telecommunication. Network Technologies have been steadily included in the control system throughout the same era, resulting in the rise of NCS [35]. Research on NCS is divided into two primary categories. The first is control of the network, which entails telecommunications and networking research in order to optimize networks for real-time NCS [36]. The second area of study is control over the network, which is concerned with the development of control techniques and control-system design for networks in order to reduce the negative impacts of network factors such as latencies, control signal failure and information loss [37].

Several advantages exist when comparing NCS to conventional point-to-point control schemes. These include concurrency, relatively low cost, quick expansion, inexpensive repair and commissioning, and high dependability, among others [38]. The Networked Control System (NCS) significantly aids the growth of modern industry. As a result of imprecise communication, node movement, foreign intervention, hacker attacks, and other factors, NCS also poses certain new difficulties to classic control regulations, which must be addressed. All of these concerns have the potential to invalidate existing control algorithms or worsen system performance, resulting in difficulties for academics as well as financial losses for businesses. Prior research on NCS has mostly focused on ways to mitigate for and overcome the negative consequences of above mentioned challenges [39].

2.2 Literature Survey

NCS is an example of a distributed sensing control system, in which the components are connected via wired or wireless networking. Recently, NCS has been employed in a variety of applications including cloud management, smart grid, big data, teleoperation, and defect detection, to name a few. [40] researched NCS modeling, with the result of coming up with various types of system issues. When delays and blackouts are in effect, standard stabilization techniques are unable to preserve systems. In the article, [41] the author examined time lag and looked at a remote-controlled system that needed a time delay to keep steady monitoring and control. Conventional computer control methods proved to be useless when dealing with variable network latency or transmission outages, as demonstrated in [42]. NCS may improve the progress of the current industry. In addition, network-induced delays, such as the delay from s-c and c-a, impair the system's performance and stability. This delay may last forever, fluctuate in length over time, or be randomized, depending on the network. In the article [43], the authors performed research to explore the changing latency issues, packet failures, and inconsistent data transfer intervals perceived in NCS. The propagation delays and transmission periods were modeled using a categorization of continuous random variables [44]. The author discussed how time-varying delays and data losses affect NCSs in his paper [45]. Latency and data packet dropout are challenging to model than networks altogether [46], discuss Schur technique to stabilize systems that are discrete/continuous unstable systems. The authors in [47] developed a novel switching linear framework for the network-induced delay and packet dropout in NCS and established the criterion for closed-loop NCS exponential stability. [48] proposed a compensation technique to deal with network latency and packet dropouts, developed a controller with random delay decomposition-based Lyapunov functional, put forward a novel way for dealing with random delays and controller design. The development of a sliding-mode predictive controller was needed to improve data throughput and availability in an electronic machine [49]. [50], proposes a modified controller using the linear quadratic regulator in coagulation with backstepping technique and PID controller to effectively control the dynamics of UAV.

Developing controllers that are dependable on a temporal lag may be challenging. If time-delayed teleoperation control solutions develop, new issues will arise, and this will need the revision of fundamental control ideas [51]. The studies [52]–[56] suggest that network latency and packet failure are the main causes of control deterioration and inconsistency and that they are the primary causes of control degradation and instability. Several ways to manage the issue have been given in the article, some of which may be found by looking at the many control strategies described in [57]–[60]. It's as though these network-induced time delays are passively presented by researchers for Networked Control System in [61]–[65]. The idea of pseudo partial derivative was implemented to a DC permanent magnet motor that had random delay and packet dropouts in the feedback and feedforward channels, as discussed in [66]–[68]. [69], [70] provides a thorough investigation of the techniques for predictive control, covering a substantial portion of the literature. Models are used extensively to assist teleoperation. In industrial, PI/PID controllers are extensively utilized. An IMC-based PID tuning method Methods for adjusting delayed outputs are known for time-delay techniques [71]. PID controllers utilize feedback linearization control. PID control widely use the two-degree-of-freedom method. In [72], to reduce the impact of variable delay in communications, communication disturbance observer (CDOB) and network disturbance (ND) have been proposed for NCS. There are also other schemes of delay compensation, such as optimal controller [73], Fuzzy controller [74], robust control [75], and sliding mode controller [76]. SBL is a common technique in literature [77]–[79] to carry out stability analysis and to define stability zones for closed-loop control systems using PI/PID controllers. For fractional-order derivative and integrator operators, a recently proposed integer order approximation technique utilizes SBL fitting. Then, uses the SBL fitting technique to compute model parameters in the Smith predictor setup, uses the IMC strategy to provide PID controller settings [80]. In [30], [81], the method employs traditional and adaptive Smith Predictors (SP) and is applied to NCS networks through wired connections (Ethernet). In the conventional Smith predictor, the employed induced time delay was random, but in the adaptive Smith predictor, the observed network delay was used to design the controller parameters.

Delay compensation schemes for wireless NCS are proposed in [82]–[84]. Internal mode and Smith predictor control are among the most popular process control methods, however, are suitable for unstable processes with time delay because of their inability to adjust quickly. Many other types of modified Smith predictor control schemes have lately been developed since the traditional SP control structure is comparable to the internal model control structure for time-delay processes [85]. [86] devised control technique for unstable systems with temporal delay, with two degrees of freedom, and based on the Smith predictor for both reference input tracking and load disturbance rejection. [87] proposed a two-degree-of-freedom control system, complete with a modified Smith predictor. The study found that the overall optimization (performance/robustness tradeoff) has made improvements as well as the process for adjusting the balance. [88] a dual feedback loop method has been developed to enhance process accuracy and reliability. Relying on the Smith Predictor Controller framework, a straightforward approach for creating a self-tuning controller for a first-order system was developed in [2]. [89] had done work where they used the quadratic infinite time integration to get the system performance index. The mentioned writers have achieved stability with increased complexity. The existence of time-delay processes is something prevalent in the industrial world. To manage the lengthy reaction times that come with the use of PID controllers, the tasks must have a sequential structure. Even if quicker settling time is yielded by raising proportional gain Kp, a new temporal response has been discovered in the process which shows an increase in instability [90]–[93]. As a result, several control methods are used to boost the performance of these operations [94]–[96]. The Smith Predictor control structure is a type of control structure that is widely used in operations that include a time delay, it is also called a model-based predictive controller [97]. This structure is made up of three parts: a plant with a time delay, a model with a time delay, and a proportional integral derivative controller. The FOPDT and SOPDT models are utilized in the structure to fine-tune the settings of the controller. The success of the Smith predictor is reliant on the degree to which the characteristics of these models and the characteristics of the plant transfer function are compatible with one another [98], [99]. Several techniques were developed to find the controller settings and compute the system variables. Recently, researchers have focused on the stability and stabilization of discrete-time Markovian jump systems.

Markovian Jump Systems (MJSs) is a type of hybrid system with finite operating modes. According to, a stabilizing controller must exist if two random delays are modeled as separate Markov chains[100]–[103]. According to [104], [105], a time-varying delayed MJS with extended state space is used to describe a closed-loop system with a time-varying delayed system state and mode signal. The Markov technique is used to describe packet errors in NCSs' control system design and stability. [106], [107] built Markovian jump linear system (MJLS) models using Lyapunov stability theory and LMI approach, which takes into account Markov delays. A system of networked control systems is more complicated, because of the presence of uncertainty from dropped data packets and various simulation settings as discussed in [108], [109]. To avoid delays and packet dropout, a networked predictive controller is suggested. A predictive control technique is designed to correct for the lag caused by the network and lost data [110], [111]. The tracking control of NCSs was investigated via a Markov chain model modeling random time delays, and the resulting model was proposed by [112]. [113] proposed the utilization of Pade-Approximation in the frequency domain to model random temporal delay to improve the performance of the system. Then, Kalman Estimation was implemented to get an estimate. [114] the study showed that unpredictable communication delays in NCSs make output feedback control more difficult to manage, and used a networked predictive control technique to counter the effect of these delays. For closed-loop systems, [115] showed that predictive control may be utilized to handle network latency issues and robustness. A discrete-time nonlinear networked system with a randomized delay was investigated for a step-tracking control problem in [116]. For their work, researchers implemented an asynchronous process for an entire class of NCs by subjecting them to random time delays in the discrete-time domain. Two Markov chains were utilized to model the delay durations of the sensor-to-controller and controller-to-actuator connections, and the closed-loop system was analyzed to evaluate its stability [117], [118]. A Kalman filter was utilized to assess the current plant states and provide predictions about future states, which were then put into motion using sliding-mode control, that scheduled the control sequences [119]. The predictive controller based on modeling of the plant and its dynamics was suggested by [120]. For teleoperation, a discrete linear quadratic Gaussian (LQG) controller with a time delay is suggested in [121]. In order to minimize the risk of numerical issues, teleoperation stability and open-loop response are maintained with restricted sample rate, reducing the computational load [122].

The paper [123] describes the research findings that introduced a novel MIMO (multiple-input and multiple-output) control method to address the delay of nonidentical components in the system and further proved that the new system could improve the existing system's detection sensitivity and stability. For system control using a Kalman filter works well in certain instances, especially when the controlled system isn't confident about its parameters and is often influenced by outside forces. Predictive control is very effective in handling complex systems, as is shown from research on the following studies: [124]–[128]. [129], [130] use a statistical technique to estimate time-delay for space teleoperation that comprises a multivariate linear regression model. This approach gives us an edge over previous strategies like sparse multivariate linear regression (SMLR) [131], and neural network (NN) [132] because it permits better administration of distant systems since time-delay is known in advance. Deep convolutional neural networks are used by [133]. [134] explored to detect the dynamics of a robot tool for bidirectional teleoperation. A combination of recurrent neural networks (RNNs) is used by [135] to simulate and forecast internet end-to-end latency delay. The paper [136], provides an enhanced RNN that can simulate the trajectory of manipulators. Using recursive least-squares filtering [137] was able to find the delay and target waypoints. An aerial vehicle may observe the user instructions while also estimating a waypoint. as described by [138], researchers utilize a similar method for predicting a ground vehicle's heading. A Taylor series expansion is used in their approach to mimic the heading of remote-controlled vehicles, which takes into account noise estimations [139]. In the case of a delay, the vehicle will not be off track. Human gaze points are being used in conjunction with exponential statistical models to aid in the movement of teleoperated robots by [140], [141]. A first-order gaze movement model is used to the empirical observations, along with a time lag, to anticipate specific target positions. These points function as time delay movement points [142]. [143], estimate what a person sees by including a movement simulation of the head and neck in addition to camera settings. An interesting technique that involves cameras capturing photos according to how the controllers move through space is utilized, and they predict future images based on the photographs that were taken presently using a linear model of motion [144].

2.3 Research Gaps

Based upon the literature review it is found that network-induced delay degrades the performance and stability of the system. And researchers are in search of new techniques to compensate for delay and its effect on the system. So, based on the literature survey following Research Gaps were evolved from the studies.

- The network-induced delay destabilizes the performance of the plant and degrades the efficiency of the system.
- The large deadtime time destabilizes the controller such that a distorted output response is received.
- In the Smith Predictor Controller, modeling the process model poses difficulties for researchers.
- Predictive models efficiently compensate for the delay, but the estimate of process models is laborious and necessitates simplicity.

The prediction of delay in a networked control system requires the model-based prediction of the plant model. Chapter 3 elucidates the principle and working of delay compensation through the Smith Predictor Controller.

2.4 Research Objectives

To fill the research gaps and to initiate our study in this direction we formulate the following objective which can fill the gaps to stabilize the system and improve the output efficiency.

Objective I

Design and Development of NCS using Smith Predictor Controller to Compensate Induced Delay.

Objective II

Design and Development of Markov Approach Based Smith Predictor Controller to Reduce Delay in NCS.

Objective III

Design and Development of Markov Approach and Kalman Filter-based Smith Predictor Controller to Reduce Delay in NCS.

Objective IV

Design, Development, and Implementation of Networked Control System Applications

CHAPTER 3

DESIGN AND DEVELOPMENT OF NETWORKED CONTROL SYSTEM WITH SMITH PREDICTOR CONTROLLER

3.1 Introduction

In a control system, dead time is a delay in the reaction to a control operation in the most basic sense. The deadtime appears as a result of the time lag between applying the control action and seeing its effect on the process variable. It is unified with settling time and is inherited in it. As mentioned in Fig. 3.1, settling time is the time a process takes to achieve the steady-state response, shown as $t_3 - t_1$ but the deadtime is represented as t_2-t_1.

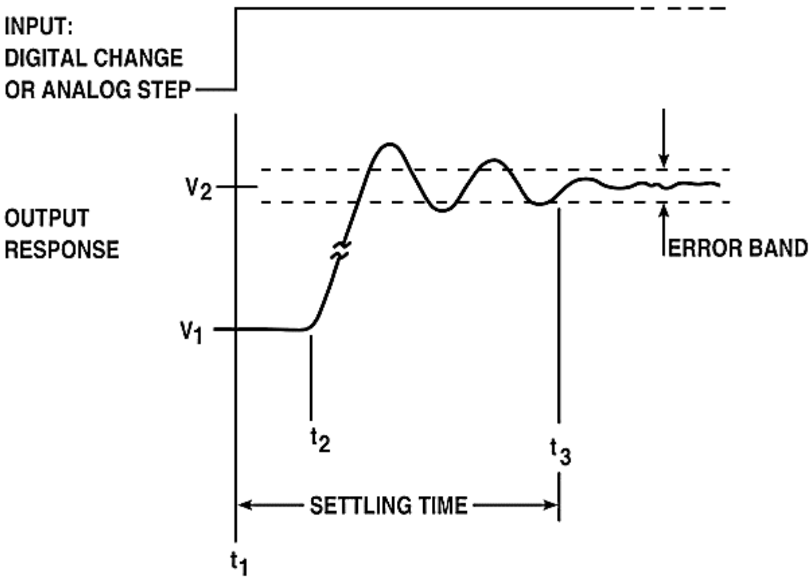


Figure 3.1: Deadtime involved in Plant Response

Deadtime (or 'idle time') is seen in many dynamic processes, whether in the manufacturing or general industry realms. Most process dynamics models, which are very essential, include dead time as a crucial factor when implementing tuning methods in the industry. The inclusion of dead time is common in many types of work, whether it is commercial or scientific, including any work that has financial or medical implications. Dead-time processes are difficult to regulate, which in turn makes it more challenging to evaluate and design controllers. Primarily three variables are responsible for dead time: (a) the time required to convey control signal or data (b) the effect of input control commands on output regulation over a period of time, and (c) the control action taken to correct an earlier situation. The inactive time of the system causes it to deviate even more from the initial position, perhaps resulting in instability.

3.2 Deadtime Compensation

In the industrial automation process and manufacturing precision, inertial controls through PID are implemented to control feedforward-feedback action, automatic adjustment, and other similar procedures. It has been examined using many approaches and several different techniques to see whether it is possible to figure out how to accurately measure the execution time of the control variables of a system with low-order processes. Tiny deadtime activities are easily controlled with PID controllers.

To regulate a deadtime process, one convenient technique of doing so is via the use of a predictor-based control structure, which may be implemented. As it is well known, PID controllers may be effectively utilized to govern operations with a good extent of efficacy, in specific circumstances when deadtime is quite low.

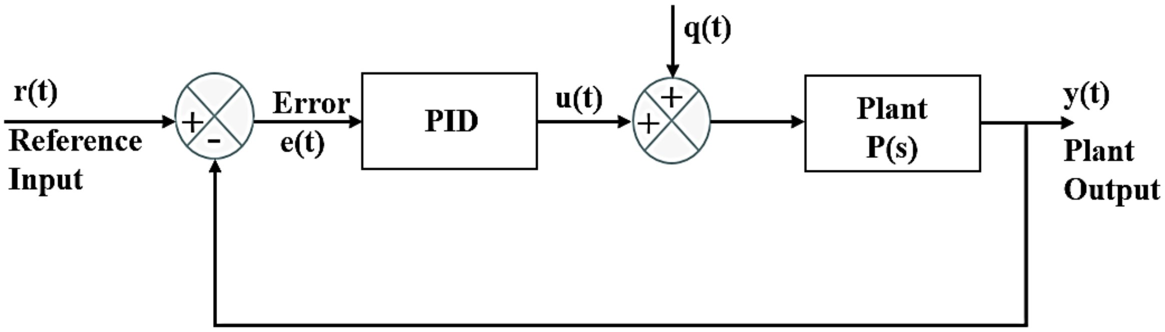


Figure 3.2: Plant control using PID Controller

In order to comprehend the significance of PID in regulating processes, it is essential to understand its use as a predictive controller. Suppose the control action u(t) of a PID controller is given as:

$$u(t) = K_p \left[e_r(t) + \frac{1}{T_i} \int_0^t e_r(\tau) d\tau + T_d \frac{de_r(t)}{dt} \right] \tag{3.1}$$

For each time step (t), to know about error signal the reference r(t) and output y(t) are subtracted from each other as follows: $e_r(t) = r(t) - y(t)$. K_p, T_i, and T_d measure the proportional gain, integral time and derivative time respectively. Consequently, the controller's transfer function is as follows:

$$C(s) = \frac{U(s)}{E(s)} = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{3.2}$$

The PD operation can be seen as a proportional estimate of the deviation in $t + T_d$, hence the prediction can be symbolized by, $\widehat{e_r}(t + T_d|t)$

$$u_{PD}(t) = K_c\left[e_r(t) + T_d\frac{de_r(t)}{dt}\right] \tag{3.3}$$

that is, $\widehat{e_r}(t + T_d|t)$ utilizes the series expansion of $e_r(t + T_d)$ to get to its conclusion.

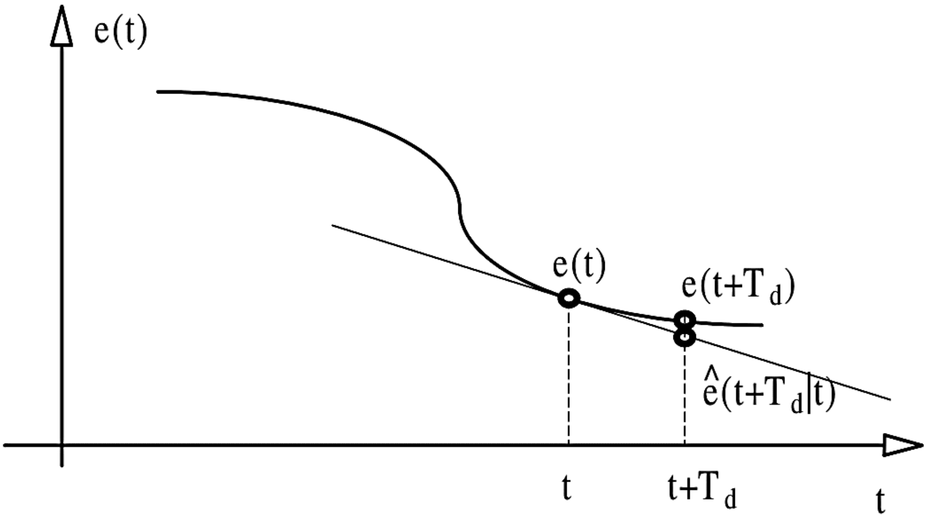


Figure 3.3: Linear prediction as a function of Derivative Action in PID Controller

The control algorithm for the PID operation can be understood using transfer function as:

$$C(s) = k_c\frac{(1+T_i s)}{T_i s}(T_d s + 1) \tag{3.4}$$

A deadtime process $P(s) = G(s)e^{-Ls}$ can be controlled using above mentioned transfer function. The solution equivalence of Fig. 3.2 can be observed in Fig. 3.3. As a result, the mathematical expression for input signal which is fed to the PI controller can be expressed as:

$$\tilde{e_r}(t) = r(t) + T_d\frac{dr(t)}{dt} - y(t) - T_d\frac{dy(t)}{dt} \tag{3.5}$$

which might be taken to represent the expected error as:

$$\tilde{e_r}(t) = \widehat{e_r}(t + T_d) = \hat{r}(t + T_d) \tag{3.6}$$

For a condition of deadtime, $(\mathrm{T_d} = \mathrm{L})$ the PI controller find prediction error at (t+L) if $\mathrm{e_r}$(t) shows a smooth operation in the interval (t, t + T_D), small deadtime may be achieved with the PI controller while operating in the presence of small error, $\widehat{e_r}(\mathrm{t} + \mathrm{T_d}) \cong \mathrm{e_r}(\mathrm{t} + \mathrm{T_d})$. The dominant time constant of the closed system, T_0, is considered to be significantly smaller as compared to L.

This interpretation emphasizes the significance of fine-tuning the PID controller for derivative operation for the existence of deadtime in the dynamic behavior. Equations (3.2), (3.4), and (3.5) yield formulations of the PID controller. To anticipate the future error, the PID controller relies on a linear prediction that is only acceptable for small deadtime and gradual fluctuations of the output signal; that is, it is dependent on the rapidity of the closed-loop response. Increasing the value of $\mathrm{T_D}$ may result in a deterioration of the closed-loop behaviour caused by an increase in the prediction error. Hence, PID controller are not acceptable for large deadtime compensation.

3.3 Principle of Smith Predictor Controller

For over 40 years, the Smith Predictor Controller (SPC) is a has attracted much interest for its precise control algorithm for substantial deadtime correction to ensure stable operations. However, its broad use is hindered by the need for complicated modelling, non-trivial adjustment, and inadequate knowledge. The use of PID controllers, on the other hand, is still widespread across the process industry. Relay feedback tests, that are becoming common in several computer-controlled operations, can be used to solve the SPC modelling challenge. A single relay feedback test may identify the modelling approach and variables based on shape information. It is convenient to begin controller optimization using the methodological framework. As an improved feature of a normal PID controller, the Smith Predictor Controller is presented in this study as a new form of controller. The tuning operation that shows a gradual transition between the SPC and PID controller is K_{sp}; such that for SPC it is unity and zero for PID controller.

When the process model estimate is closely aligned to the real plant, the SPC performs optimally. Later, the deadtime compensation is dramatically improved, the plant's reaction is enhanced, and the controller is reduced to the well-known PID controller. And because of this an SPC may support longer delay time operations and it is also commonly known as a deadtime compensator. Compared with other conventional controllers, the Smith Predictor

Controller exhibits better set point because it eradicates the induced delays caused by the closed-loop transfer function. Set-point is just a minor issue when it comes to improving system performance; the primary focus is on dealing with deadtime disturbance rejection and delay compensation, both of which are tracked in many different processes in control applications.

3.4 Design Methodology

The Smith Predictor approach, circumvented largely the time delay in the transfer function which thus links process performance to setpoint. Both the major controller and the predictive framework are represented in Fig. 3.4 of the Smith Predictor Controller framework. The principle or primary controller can be either PI, PID or any other higher-order controller.

The plant of the system is described as an Actual Process Variable (APV) that consists of process P(s) involved and disturbance, $e^{-L_p s}$ in the plant [145].

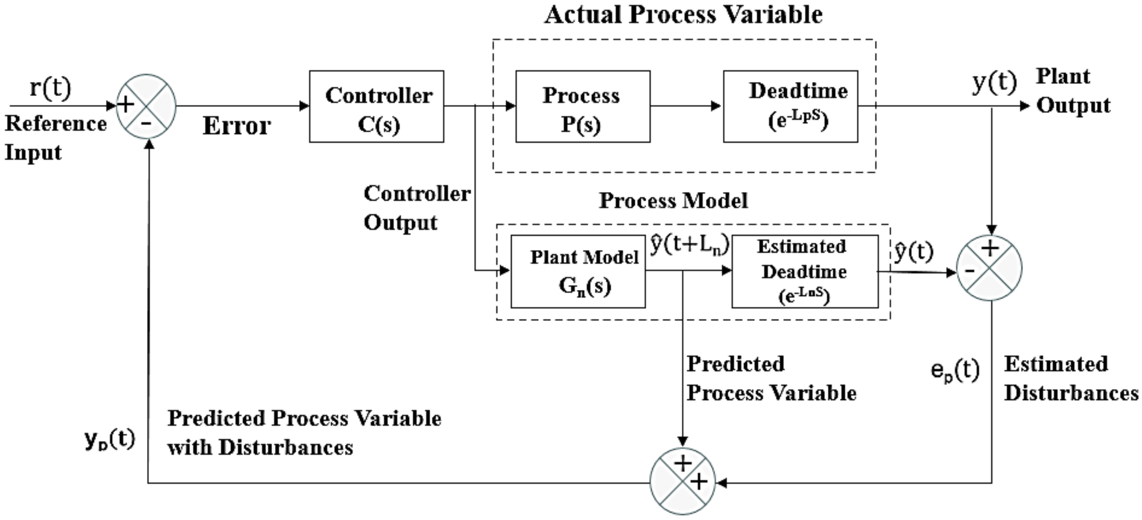


Figure 3.4: Conventional Smith Predictor Controller

The Predictive Process Model (PPM) is composed of an actual model or estimated model, $G_n(s)$ of the plant and estimated deadtime $e^{-L_n s}$ equivalent to actual deadtime or disturbance involved in the plant. So, the complete PPM predictor structure can be written as $P_n(s) = G_n(s)e^{-L_n s}$. The $G_n(s)$ is also called as ideal model or fast model of the plant. A control signal from the controller C(s) will parallelly actuate the actual process variable and process model of the plant. The plant output y(t) generated is subtracted from the estimated output $\hat{y}(t)$ of the process model to produce an estimated disturbance $e_p(t)$. As the plant model

$G_n(s)$ is the fast model actuated by control signal C(s) produces a predicted output or the open-loop prediction of the actual plant gets added to the estimated disturbance as a feedback signal to the controller.

This feedback signal is termed as a predicted process variable with disturbances ($y_p(t)$). The resultant transfer function of the model can be written as eq. 3.7

$$\frac{Y(s)}{R(s)} = \frac{C(s)P(s)e^{-L_p s}}{1+C(s)G_n(s)+C(s)\left[P(s)e^{-L_p s}-G_n(s)e^{-L_n s}\right]} \tag{3.7}$$

If modeling errors or disturbances are infinitesimally small such that can be ignored and the difference between disturbances (actual and estimated) are negligible then anticipated disturbance can be overlooked and the estimated output $y_p(t)$ would be deadtime exempted output of the plant. For such conditions, C(s) is calibrated as there is no deadtime in the system. Mathematically it can be mentioned as:

$$P(s) = G_n(s),$$
$$e^{-L_n s} = e^{-L_p s}$$

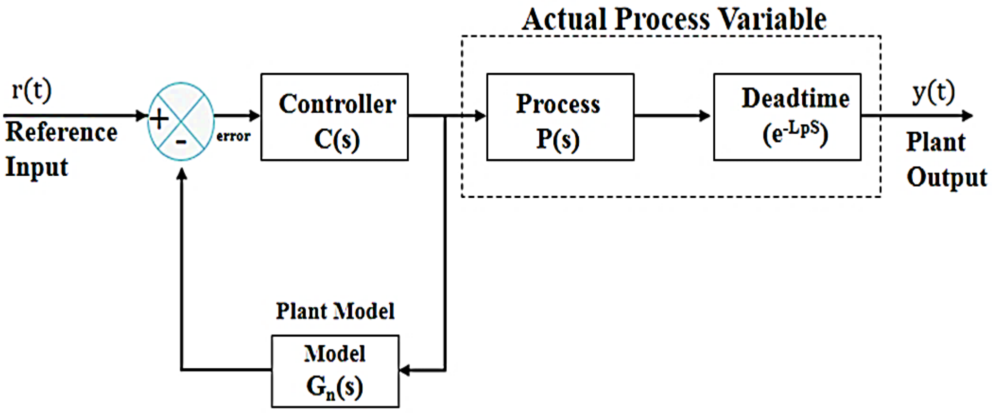


Figure 3.5: Ideal Smith predictor controller in case of perfect modeling

Considering these conditions in eq.3.7, will cancel out the third term in the denominator and can be written as,

$$\frac{Y(s)}{R(s)} = \frac{C(s)P(s)e^{-L_p s}}{1+C(s)G_n(s)} \tag{3.8}$$

As it can be seen in the eq.3.8 that Y(s) has a negative exponential growth rate, then Y(s) → 0 as t → ∞ will stabilize the system. The block diagram of ideal Smith Predictor Controller equivalent to eq. 3.8 can be seen in Fig. 3.5. It is an open-loop control structure such that the SPC will behave as PID controller to regulate the plant.

3.5 Simulation Results

3.5.1 Experimental Setup

Smith Predictor Controller is designed and simulated in MATLAB R2018b edition to assess the controller's performance. The Smith Predictor Controller designed to control DC motor over network using UDP protocol to send control signal is shown in Fig. 3.6. The input step function is set at T_{step} = 1sec, with Initial value equal to zero. The final value T_{final} = 5sec. While simulating a dynamic system, it is recommended to check for inconsistencies throughout the system's state variables for each time step to ensure that the system is functioning properly, using the concept of zero-crossing detection, in order to ensure that the system is operating efficiently. When modelling a dynamic system, it is required to use the zero-crossing detection approach to look for irregularities in the system's state vector at each sampling interval. To find a discontinuity in the current time step, just look for one that happens and take extra time steps before and after it. Because discontinuities generally signify substantial changes in a stochastic process, it is crucial to accurately mimic discontinuity points. Instead, the findings might lead to erroneous interpretations of the system's behavior. As a result, the system now has zero-error crossing detection enabled. For deadtime compensation, a Smith dead-time PI dynamic model in discrete domain is used by the SPC. For the Smith Predictor Controller to simulate the model, Proportional Gain, Kp = 5.01, Integral gain, Ki = 50.001, the control action upper limit i.e., the upper limit of the control action is set at 5.08. The Smith Predictor Controller is a model-based controller, so the transfer function defined to predict the model parameters are defined as num = [107]; den = [1 11 91 108.3] with sampling time, t_s = 0.4sec. The estimated delay introduced in the SPC varies from 0.2sec to 60sec, the performance metrics such as IAE, ITAE, ISE and ITSE for the designed Smith Predictor in regard to the Fig. 3.6 are mentioned and compared with other proposed designed controllers in Chapter 4, Table 4.3, Table 4.4, Table 4.5 and Table 4.6 . Table 3.1 includes several metrics such as Rise Time, Settling Time, Overshoot and other steady state response parameters to assess the efficiency of the developed SPC in contrast to PI, PD and PID. The NCS allows the τ_{sc} to be calculated and regulated by the controller during the implementation of the control scheme. The performance of τ_{ca}, on the other hand, can only be determined after the control algorithm has been executed.

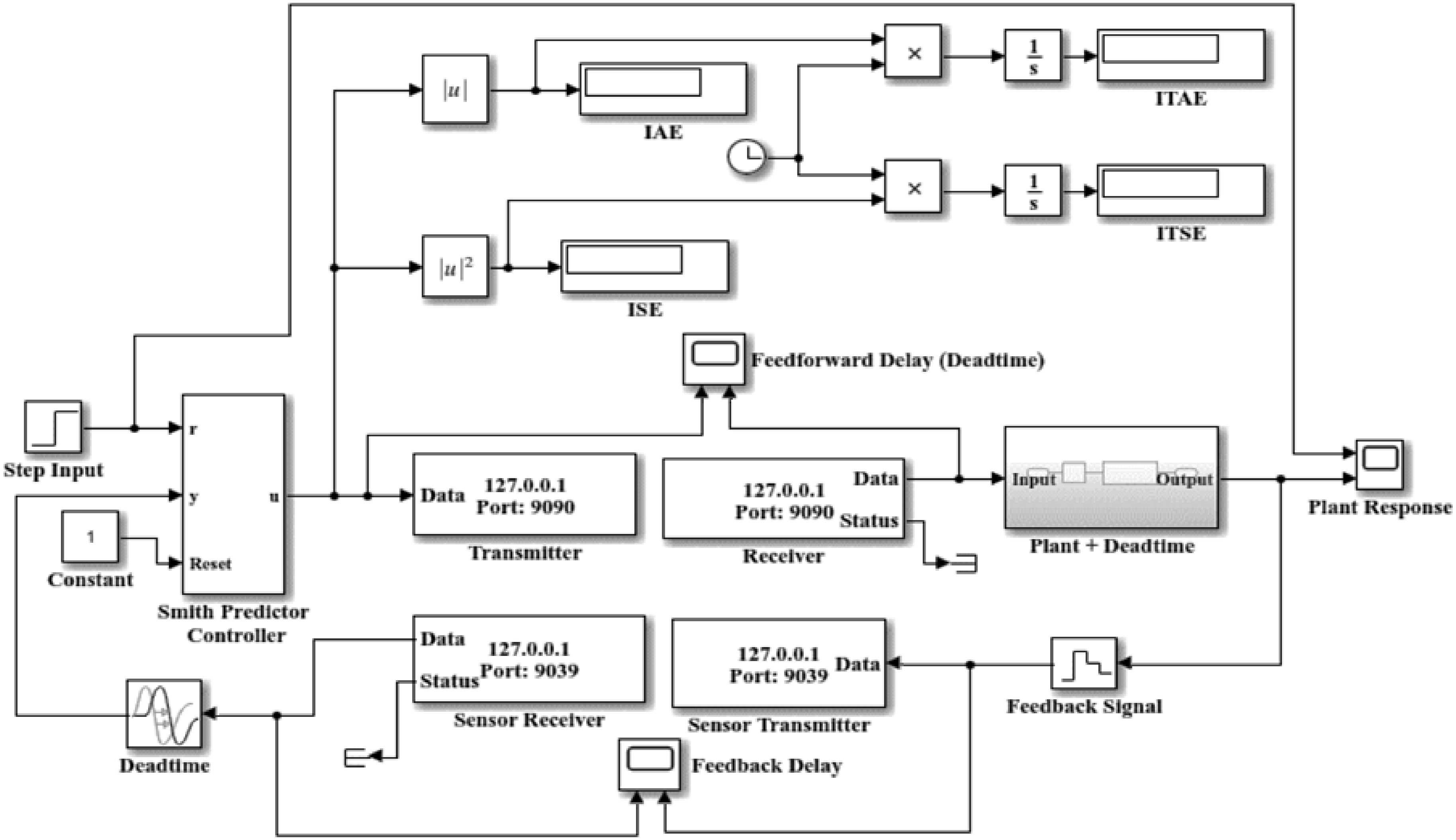


Figure 3.6: Simulink Block Diagram of Designed Smith Predictor Controller (SPC)

3.5.2 Performance Analysis

The transient and steady state response are recorded in the Table 3.1. The different results obtained after simulation are compared to analyse the performance improvement of each controller. The Smith Predictor Controllers shows trivial improvement in comparison to the different controllers simulated under similar conditions. Therefore, the objective of this comparison is not to show considerable improvements in performance but to show that the proposed controller can have similar performance when compared to a more advanced control technique.

Table 3.1: Comparison of Transient Response Parameters and Delay Parameters between PI, PD, PID Controllers

S.No.	**Parameters**	**Type of Controllers**				
		PI	**PD**	**PID**	**Smith Predictor**	**%ge Improvement of SPC over Others w.r.t PID Controller**
1.	Rise Time (in milli seconds)	397.67	307.593	440.84	377.86	4.91 %
2.	Overshoot (in %)	3.646	13.068	0.505	0.502	0.59 %
3.	Settling Time (in seconds)	0.69	infinite	0.49	0.38	22.44 %
4.	Signal to Error Ratio (SER)	6.757	3.744	6.872	6.893	0.30 %
5.	Feedback Delay (in milli seconds)	97.25	90.97	97.12	88.21	3.03 %
6.	Feedforward Delay (in milli seconds)	89.52	83.27	88.95	79.54	4.4 %

It is evident in the Table 3.1 that a slight improvement of 4.91 % in Rise Time when compared to other conventional controllers is observed, whereas a significant improvement of 22.44 % in Settling Time is observed, indicating that the controllers bring the system to steady-state 0.31 seconds faster when compared to the other controllers shown in this table. The feedback delay and the feedforward delay for the Smith Predictor Controller have been reduced by 3.03 % and 4.4%, respectively, compared to the previous version. Table 3.1 shows a very modest increase of 0.3 percent in the signal to error ratio (SER) for SPC when compared to the SER mentioned for other controllers in the table. The plant response for PI, PD, PID and SPC is compared and shown in Fig. 3.7. It has been shown that PD controller did not reach the required response whereas, the PI controller is showing peak overshoot of 3.646 while PID is representing

Table 3.2: Comparison of Results Obtained for Control Parameters

Reference	Control Approaches	Results Obtained				
		Rise Time (in Seconds)	**Slew Rate (per units of time)**	**Overshoot (in %)**	**Settling Time (in Seconds)**	**Signal to Error Ratio (SER)**
[30]	Adaptive Smith Predictor	0.054	72.152 /ksec	0.534	0.425	4.372
[34]	Smith Predictor	0.0187	63.12 /ksec	0.457	2.51	4.148
[33]	Improved Predictive Control Method	0.0016	89.142 /ksec	0.544	0.340	--------
[32]	Modified Smith Predictor	0.00271	----------	0.514	0.457	5.118
[31]	Markovian Jump Linear System	0.0047	----------	1.24	----------	6.041
[18]	Event Based Controller	0.0754	----------	0.98	----------	5.991
Designed Smith Predictor Controller	PID based Controller	0.377	40 /sec	0.502	0.380	6.893
Percentage Improvement		No Improvement	No Improvement	2.33 % w.r.t. [29]	10.58 % w.r.t. [39]	14.1 % w.r.t. [30]

an improvement of 0.505% and SPC is showing an improvement of 0.502%. There is only a difference of 0.003 in overshoot factor.

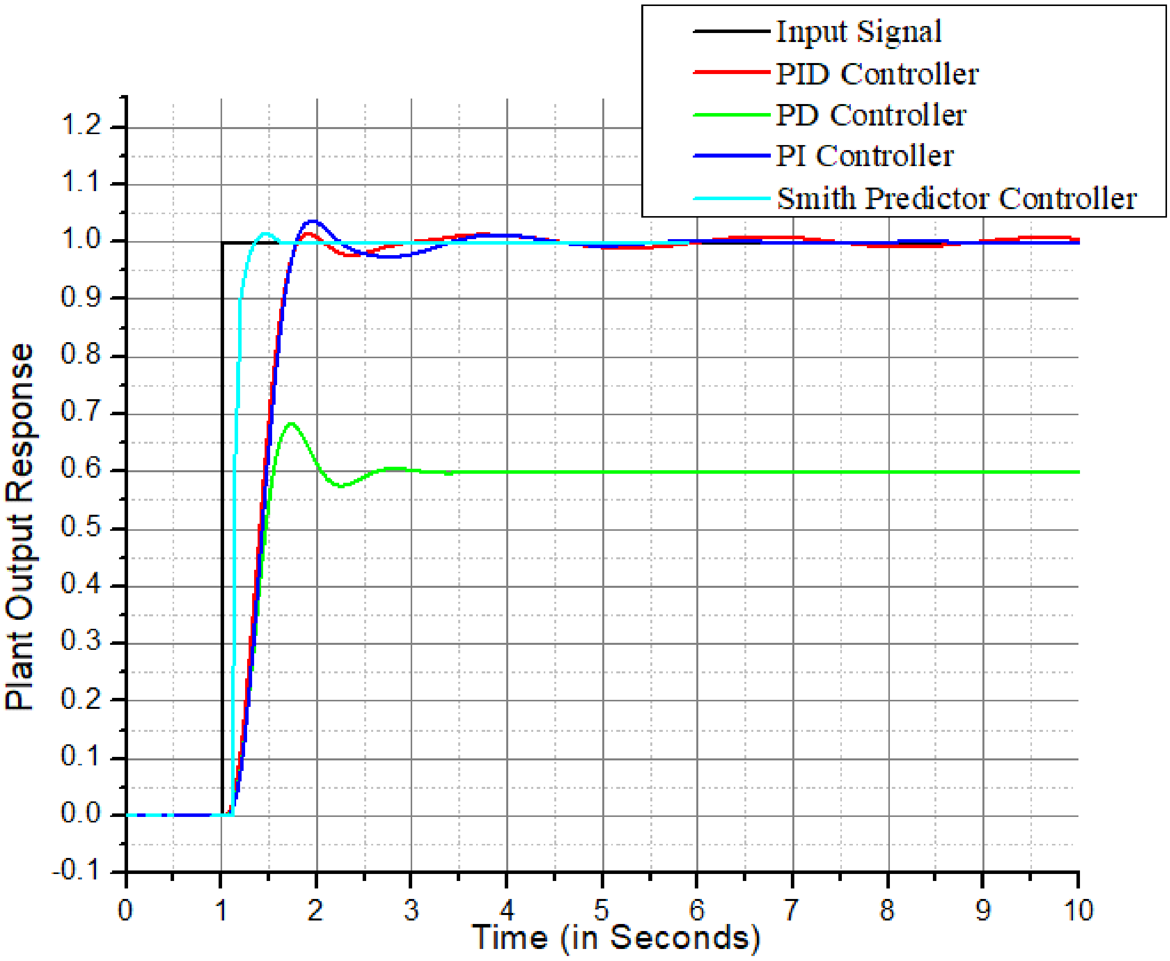


Figure 3.7: Output Response Comparison of PI, PD, PID Controllers with Smith Predictor Controller

The plant response of designed SPC is compared with the conventionally available PI, PD and PID controllers. It is evident from the Fig. 3.7 that the response of PI, PD and PID controllers is sluggish as compared to the response observed for designed SPC. Over the time number of authors have explored about the different configuration and structure of SPC and obtained transient and steady state response for their designed controllers. In Table 3.2 a comparison of control parameters for the proposed controllers with other authors mentioned in the literature is elucidated. These authors designed SPC using different approaches like Event Based approach, Adaptive SPC, Markovian Jump System and other Improved approaches. It can be observed from the comparison that the designed SPC shows 2.33% of improvement in Overshoot as compared to the SPC designed by author [39] in the year 2017.Whereas, the steady-state response obtained for the designed SPC is 10.58% improved settling time in comparison to [39].

Another performance parameter used in this literature is signal to error ratio (SER) defined as

$$\mathrm{SER} = \frac{\sum(\mathrm{X(t)})^2}{\sum(\mathrm{X(t)} - \hat{\mathrm{X}}(\mathrm{t}))^2} \tag{3.9}$$

Where, X(t) is the reference control signal and $\hat{\mathrm{X}}(\mathrm{t})$ is the output signal of the system. The values of SER for different authors are mentioned in Table 3.2, showing that 14.1% improvement in designed SPC such that the delay compensation is improved which in-turn mends the system performance compared to the other SP Controllers.

3.6 Conclusion

An NCS is created to govern the dynamics of a DC Motor in this chapter. Furthermore, Simulink is used to construct PD, PI, PID, and Smith Predictor Controllers to regulate the dynamics of a DC Motor using NCS. The controller parameters may be compared using the simulation research, as illustrated in Tables 3.1 and 3.2. The developed SPC has a notable improvement in settling time of 22.44% when compared to the PI, PD, and PID controllers, indicating that SPC can achieve steady state response 22.44 times faster than the other controllers shown in Table 3.1. The reduction of 4.91% in Rise Time indicates that the controller's transient responsiveness has been improved, which will result in the correction of feedback and feedforward delays. Feedback delay and feedforward delay both show significant improvement, with improvements of 3.03% and 4.4%, respectively. This demonstrates that SPC controllers are more resilient when compared to PI, PD, and PID controllers. During this analysis, the developed SPC for NCS for controlling the dynamics of a DC motor is further investigated, and it is discovered that the designed SPC achieves a significant improvement in SER and Settling Time when compared to other control approaches, with 14.1% and 10.58%, respectively, in SER and Settling Time. This reinforces the concept of utilizing SPC for long periods of time in conjunction with design and functioning adjustments.

CHAPTER 4

MARKOV APPROACH BASED SMITH PREDICTOR CONTROLLER FOR NETWORKED CONTROL SYSTEM

4.1 Introduction

One of the primary study areas for NCS is time delay, which has the potential to significantly reduce the system performance and eventually cause instability. The goal of the associated study is to determine how to explicitly include the time delay into the controller architecture. In NCS, the presence of a time delay may reduce its performance or perhaps lead it to become unstable. It is possible to represent the network-induced delays in NCS using the Markov chain, which is a discrete-time stochastic process. The Markov chain can not only represent the dependency between the current time-delay and the prior time-delay, but it can also characterize packet dropout, making it a useful way for describing time-delay in NCS, as well as other networks.

4.2 Markov Chain

To make an understanding of Markov Chain; We have a set of states, $\mathrm{S} = \{\mathrm{s}_1, \mathrm{s}_2, \ldots, \mathrm{s}_\mathrm{r}\}$. It is possible for the process to begin in one of these phases and progress through them in a sequential fashion. The term "step" refers to the number of movements made. The chain with its current state s_i, will move with a probability of p_{ij} to next state s_j. This probability of shifting is independent of previous states of the chain where it is currently residing. The probabilities p_{ji} and p_{ij} are called transition probabilities. The process can remain in the state it is in, and this occurs with probability p_{ii}. In this case, the starting state is specified by an initial probability distribution described on S. Typically, this is accomplished by designating a specific state as the beginning state. The time-delay τ_{sc} from sensor-to-controller and from controller-to-actuator τ_{ca} are modeled as two Markov chains. Both the temporal delays created in NCS and the closed-loop system that results from them are represented as Markovian Jump Linear Systems (MJLS), which are derived from the Markov process theory. MJLS is an example of linear system with randomly changing parameters, in which the significant steps are represented by the transitions of a Markov chain, and the attributes of the system are determined through randomness. It is possible that the Discrete-time

Markovian Jump Linear System (DMJLS) constitutes a substantial class of hybrid systems. These are prone to rapid structural changes as a result of a variety of events, including random component failures, unexpected disruptions, and environmental variables. Also, the changes in the interconnections between the subsystems are possible. A DMJLS is a specific type of hybrid systems that has discretized operation modes and develops like a linear system inside a fixed mode. The transitions among distinct modes are controlled by a discrete Markov chain. The state augmentation approach would be used to develop a structure of the plant's anticipated process model. Through this a time-delay compensation approach is implemented in the Smith Predictor Controller. It is important and required to establish a necessary and sufficient condition in order to carry out the stability analysis.

4.3 Prediction of Process Model through Markov Approach

Time delay has been identified as a significant performance barrier in the design of a Networked Control System (NCS). To alleviate the sluggish reaction time caused by the PI control action, the derivative action is used. Even with the use of a PID controller, it is difficult to regulate additional phase lag in processes owing to extended time delays, and this can lead to system instability.

The Smith predictor Controller, as depicted in Fig. 3.4, is composed of three parts: the primary controller C(s), which can be PID or any other higher order controller; the Actual Process Variable (APV) which is actual plant under consideration and the Predictive Process Model (PMM), which must have the same dynamics as the actual plant. The modelling of the PMM equivalent to APV is time-consuming and laborious because it necessitates the collection of information about transient elements that occur in the network during the operation of APV in order to represent the plant. As a result, the Markov Approach is employed to decrease the complexities associated with modelling PMM. The transfer function as predictive model of the Actual Process Variable (APV) is assumed to be $G_n(s)$ and estimated dead time in the process mentioned as $e^{-L_n s}$ as shown in Fig. 3.4. Such that, the PMM module of the proposed modified Smith predictor is given as $G_n(s)\ e^{-L_n s}$. Based upon the followed assumption the Markov Approach based proposed modified Smith Predictor Controller is as shown in Fig. 4.1.

As a result of the network's inherent randomness, there is always some degree of latency. s-c and c-a delays are two examples of feedforward and feedback delays. Control inputs are a function of feedback inputs; hence feedback delays are more essential. As a result of network delays, packet dropouts occur. To ensure early prediction of system state and control input, it is vital to adapt to these delays. Stabilization of the system can be achieved by optimising the simulated state, which can be represented by a Markov chain. Consider here that Markov chains is used to simulate a feedback channel with a delay of $\tau(t)$. So, to develop the delay in the state of the system Markov Chain can be employed. Such that for inclusion of delay in the state equation, the delay measured (observed) in one cycle will impact the delay measured (observed) in the next cycle, or we may say that the previous state of delay will affect the present delay. As a result, a homogeneous Markov chain may be used to describe $\tau(t)$.

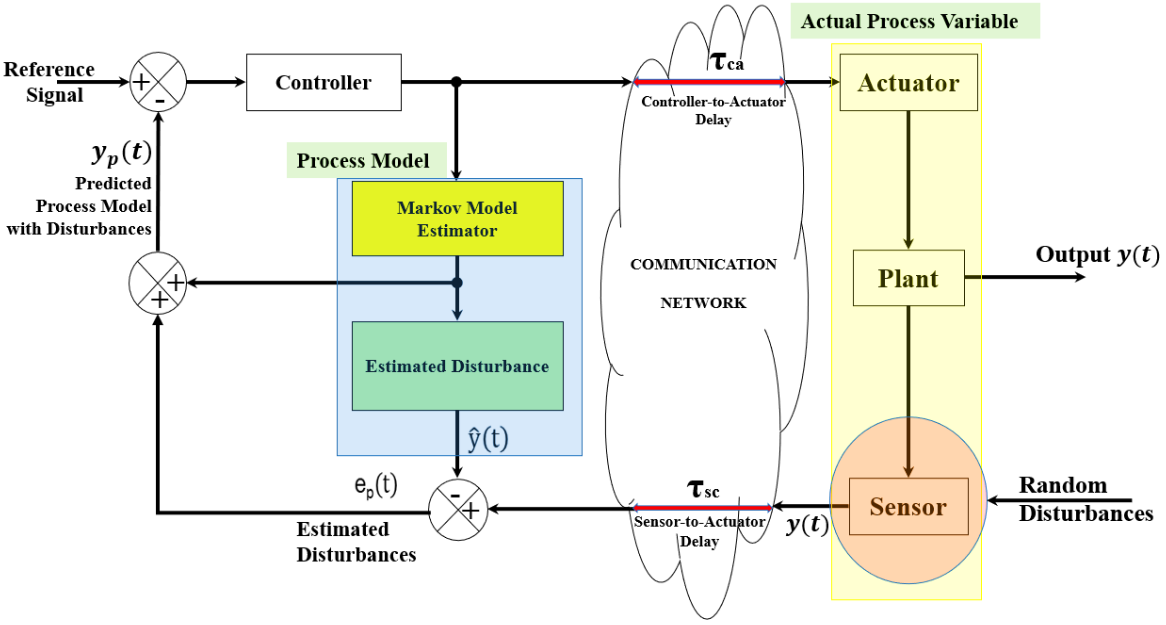


Figure 4.1: Markov Approach based Smith Predictor Controller

A state transition schematic, which contains distinctive states of the system and permits for the examination of upcoming actions by taking the pace of transition of states into account, can be employed. Fig. 4.2 illustrates how Markov models describe the sequential illustration of foreseeable events between the two states. It can be concluded from the figure, i.e., how NCS include transition process that can be signified either by the successful arrival or the rejection or dropout of a packet. Estimating the optimum delays is accomplished through using these transitions.

The possible sequence of transition to predict of the state achieved after number of transitions can be analyzed using this Markov-based delay estimation technique. It admeasures the likelihood of the system in a specific state, it estimates the count of system transitions between the two mentioned states and time for which a system spend duration in a particular state.

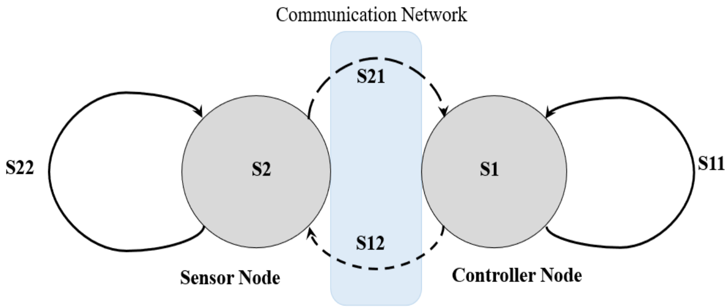


Figure 4.2: Markov model of induced delay in NCS

For each fruitful transition between the states i.e., transition from sensor node to controller node can be noted as packet received otherwise it can be regarded as packet dropout.

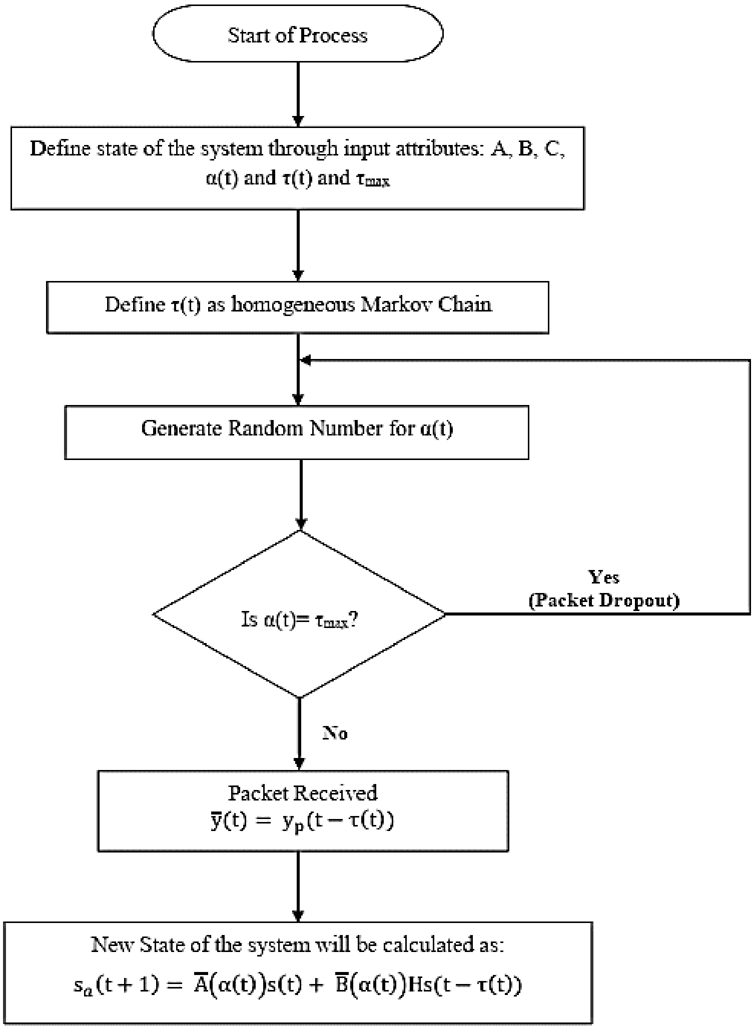

Start of Process
Define state of the system through input attributes: A, B, C, $\alpha(t)$ and $\tau(t)$ and τ_{max}
Define $\tau(t)$ as homogeneous Markov Chain
Generate Random Number for $\alpha(t)$
Is $\alpha(t)=\tau_{max}$?
Yes
(Packet Dropout)
No
Packet Received
$\bar{y}(t) = y_p(t-\tau(t))$
New State of the system will be calculated as:
$s_a(t+1) = \bar{A}(\alpha(t))s(t) + \bar{B}(\alpha(t))Hs(t-\tau(t))$

Figure 4.3: Flowchart to predict the process model of the plant in NCS

The Markovian Jump Linear Systems (MJLS) to conduct various procedures proves beneficial such that, various types of accidental complications such as component failures, subsystem upgradation / maintenance or extension helps in implementing the tasks smoothly.

The transition matrix related to Fig. 4.2 can be represented as:

$$\Theta = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \tag{4.1}$$

The transition probability matrix enables to predict the dynamics of state-space model of the plant containing network-induced delay and involved under NCS operation. Fig. 4.3 elaborated the flowchart to predict the state-space model of the actual plant for PPM.

This strategy calculates the unpredictable feedback time lag and relates it to the anticipated perturbation or disturbance e_p (t), that modifies the perturbation parameters for the projected system, using the Markov method. Thus, for the prediction of delay and packet-drop modifications the state equation is implemented in the modified Smith Predictor Controller is being suggested. Table 4.1 depicts the technique that is developed for estimating latency and packet dropouts in a network.

Table 4.1: Feedback Delay estimation algorithm using Markov approach

Algorithm for feedback delay estimation in NCS	
Step 1:	Define the state model of the system as, $s_a(t+1) = As_p(t) + Bu(t)$
Step 2:	Define the output of the plant as, $y_p(t) = Cs_p(t)$
Step 3:	Suppose τ(t) to be the delay introduced between sensor – controller network modelled as Markov Chain
Step 4:	Consider α (t) defines the state of the link between sensor – controller. Such that, If, $\alpha(t) = 0$, means packet is received successfully and $\bar{y}(t) = y_p\big(t - \tau(t)\big)$ Whereas if, $\alpha(t) = 1$, the packet is lost $\bar{y}(t) = y_p(t-1)$

Step 5: The behavior of sensor-controller delay is modelled as:

$$\bar{y}(t) = \big(1 - \alpha(t)\big)y\big(t - \alpha(t)\big) + \alpha(t)\bar{y}(t - 1)$$

Such that,

$$\alpha(t) = \begin{cases} 0, \text{ for X as a closed event and packet is timely received} \\ 1, \text{ for X as an open event and packet is dropped out} \end{cases}$$

Step 6: The delay will affect the next state of the system. Hence, the controller will be given as:

$$u(t) = K\big(\alpha(t), \tau(t)\big)y(t)$$

Here, $K\big(\alpha(t), \tau(t)\big)$ is output feedback controller gain.

Step 7: To Check the controllability of the system

$$s(t) = [s_p(t)^T \quad \bar{y}(t - 1)^T]^T$$

Step 8: Modify the system state defined in Step 1 using Step 7 we get,

$$s_a(t + 1) = A[s_p(t)^T \quad \bar{y}(t - 1)^T]^T + BK(\alpha(t), \tau(t))\bar{y}(t)$$

$$s_a(t + 1) = \bar{A}\big(\alpha(t)\big)s(t) + \bar{B}\big(\alpha(t)\big)Hs\big(t - \tau(t)\big)$$

Hence, the It is accomplished in the Smith Predictor Controller as a Markov technique that predicts the unpredictable feedback delay and corresponds it to an anticipated perturbation ep (t), which affects the disturbance variables for the expected operation that modifies the state-space equation.

4.4 Random Delay Modeling using Markov Approach

Markovian jump linear systems (MJLSs) are considered to be a select category of hybrid systems that operate in a predictable manner under certain conditions. The modelling of network-induced delays may be accomplished through the use of Markov models, which can be used to predict the behaviour of delays in the networked control system. This results in a probability distribution of data transmission via the network, which leads to the mode-independent control technique being used in the network. The State-Space model for the observed plant can be given as:

$$s_a(t + 1) = As_p(t) + Bu(t) \tag{4.2a}$$

$$y_p(t) = Cs_p(t) \tag{4.2b}$$

A, B, C and D are known real constants with suitable proportions, $\mathrm{s_p(t)} \in \mathrm{R^n}$, $\mathrm{s_a(t+1)}$, $\mathrm{y_p(t)}$ and $\mathrm{u(t)}$ signifies current state, anticipated state of the system, plant output and control plant input respectively.

Suppose $\tau(\mathrm{t})$ indicate the time delay of the feedback loop that is being modelled by the Markov Approach. Such that, Markov Chain can be modeled for $\tau(\mathrm{t})$ can have the values.

$$\overline{\mathrm{X}}_2 = \{0,1,2 \dots, \mathrm{x}_2\} \tag{4.3}$$

X denotes network switches between s-c, $\alpha(\mathrm{t})$ denotes the state s and $\alpha(\mathrm{t}) = [0,1]$

When X is in $\alpha\ (\mathrm{t}) = 0$, depicts the successful reception of data packet and

$$\overline{\mathrm{y}}(\mathrm{t}) = \mathrm{y_p}\big(\mathrm{t} - \tau(\mathrm{t})\big) \tag{4.4}$$

Whereas if X is in the state $\alpha(\mathrm{t}) = 1$ the packet is lost

$$\overline{\mathrm{y}}(\mathrm{t}) = \mathrm{y_p}(\mathrm{t} - 1) \tag{4.5}$$

A mathematical formulation of sensor-to-controller delay may be found here as:

$$\overline{\mathrm{y}}(\mathrm{t}) = \big(1 - \alpha(\mathrm{t})\big)\mathrm{y}\big(\mathrm{t} - \alpha(\mathrm{t})\big) + \alpha(\mathrm{t})\overline{\mathrm{y}}(\mathrm{t} - 1) \tag{4.6}$$

where,

$$\alpha(\mathrm{t}) = \begin{cases} 0, \text{if packet received shows X is closed} \\ 1, \text{if packet is lost thus the packet is lost} \end{cases}$$

Now, input to mode dependent output feedback controller presented as:

$$\mathrm{u(t)} = \mathrm{K}\big(\alpha(\mathrm{t}), \tau(\mathrm{t})\big)\mathrm{y(t)} \tag{4.7}$$

Here, $\mathrm{K}\big(\alpha(\mathrm{t}), \tau(\mathrm{t})\big)$ is output feedback controller gain.

Suppose, $\mathrm{s(t)} = [\mathrm{s_p(t)^T} \quad \overline{\mathrm{y}}(\mathrm{t}-1)^{\mathrm{T}}]^{\mathrm{T}}$ is augmented state vector. For control vector (4.7) the closed loop system of (4.2a) becomes,

$$\mathrm{s_a(t+1)} = \mathrm{A}[\mathrm{s_p(t)^T} \quad \overline{\mathrm{y}}(\mathrm{t}-1)^{\mathrm{T}}]^{\mathrm{T}} + \mathrm{BK}(\alpha(\mathrm{t}), \tau(\mathrm{t}))\overline{\mathrm{y}}(\mathrm{t}) \tag{4.8}$$

$$\mathrm{s_a(t+1)} = \overline{\mathrm{A}}\big(\alpha(\mathrm{t})\big)\mathrm{s(t)} + \overline{\mathrm{B}}\big(\alpha(\mathrm{t})\big)\mathrm{Hs}\big(\mathrm{t} - \tau(\mathrm{t})\big) \tag{4.9}$$

$$\mathrm{s(t)} = \phi(\mathrm{t})$$

$$\mathrm{t} = -\tau_{\mathrm{max}}, -\tau_{\mathrm{max}} + 1, \dots 0,$$

Here,

$$\overline{A}(\alpha(t)) = \begin{bmatrix} A\alpha(t & BK(\alpha(t), \tau(t) \\ 0 & \alpha(t)I \end{bmatrix} \tag{4.10}$$

$$\overline{B}(\alpha(t)) = \begin{bmatrix} (1\text{-}\alpha(t))BK(\alpha(t),\tau(t))C \\ (1\text{-}\alpha(t))C \end{bmatrix} \tag{4.11}$$

$H = [I \quad 0]$, $\tau_{max} = \max\{\alpha(t)\}$ and $\phi(t)$ with initial condition of $x(t)$
In the system (4.9), $\{\alpha(t), t \in Z\}$ and $\{\tau(t), t \in Z\}$ are two separate discrete time homogeneous Markov chains that take values from a constrained set of possibilities $\overline{X} = \{0,1\}$ and $\overline{X_2} = \{0,1,2, \ldots., x_2\}$ for transition probabilities:

$P_r\{\alpha(t+1) = j|\alpha(t) = i\} = \Pi_{ij}$ from i to j

$$\Pi_i = P_r(\Pi_0 = i)$$

$P_r\{\tau(t+1) = n|\tau(t) = m\} = \lambda_{mn}$ from m to n

where, $\Pi_{ij} \geq 0$ and $\lambda_{mn} \geq 0$ for all $i, j \in Z_1, Z_2$

$$\sum_{j=0}^{1} \Pi_{ij} = 1 \text{ and } \sum_{n=0}^{s_2} \lambda_{mn} = 1$$

For $\alpha(t) = i$, $i \in \overline{X_1}$ and $\alpha(t)$ in mode i=0 and i=1 the $\alpha(t)$ in (4.9) take value $\alpha(t) = 0$ and $\alpha(t) = 1$ respectively. $\overline{A}(\alpha(t))$ and$\overline{B}(\alpha(t))$ are known constant matrices of appropriate dimensions.

To emphasize this point, consider that the closed - loop system in equation (4.9) is a Markov jump linear system with two Markov chains. These two Markov chains characterize the performance of the network under conditions of s-c time delays and packet dropouts, respectively. This permits to examine and synthesis NCS by employing a Markov jump linear system, and it also aids in the forecasting of the updated state space model of the plant. This strategy calculates the uncertain feedback delay and compares it to the anticipated perturbation $e_p(t)$, which modifies the perturbation variables for the anticipated process, using the Markov Approach.

4.5 Simulation Results and Discussion

The proposed modified Smith Predictor Controller is a Markov Approach based Model Predictive assisted approach to modify the State-Space equation of the predicted model.

The transition probability matrix between the two subsystems is given as,

$$\Theta = \begin{bmatrix} 0.7 & 0.3 \\ 0.9 & 0.1 \end{bmatrix}$$

The modified Smith Predictor Controller designed to control dynamics of DC motor over network using UDP protocol to send control signal is shown in Fig. 4.5. The input step function is set at T_{step} = 1sec, with Initial value equal to zero. While simulating a dynamic system, it is necessary to check for perturbations in the system state variables for each time step, using the technique of zero-crossing detection. Because discontinuities generally signify substantial changes in a stochastic process, it is crucial to accurately mimic discontinuity points. Instead, the findings might lead to erroneous interpretations of the system's behavior.

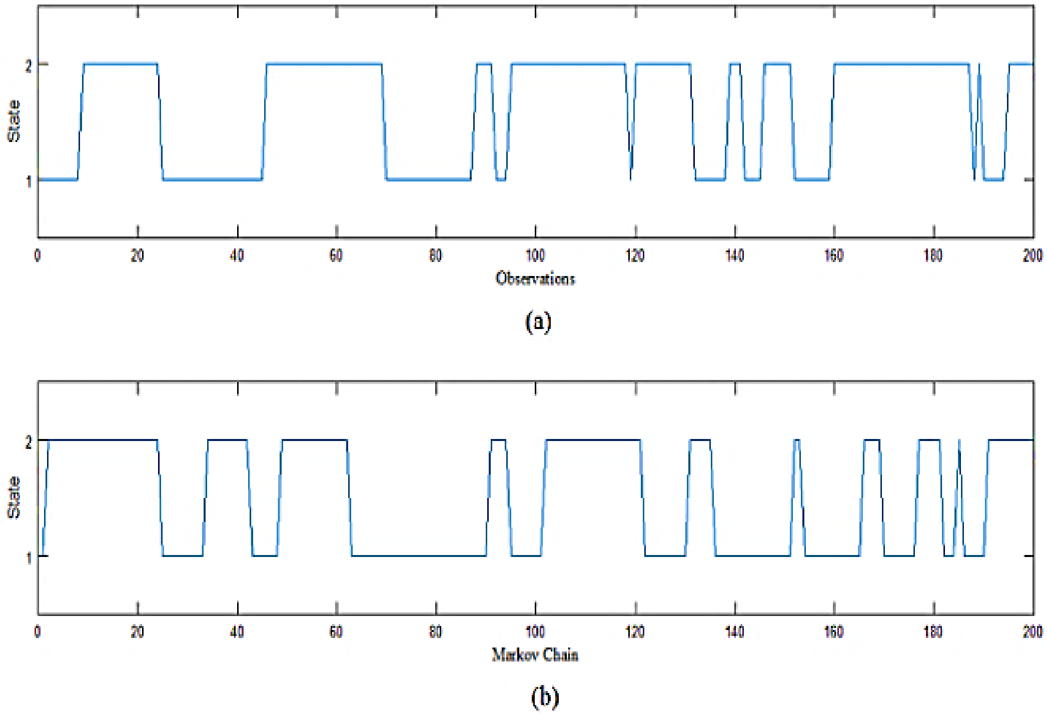


Figure 4.4: (a) Markov Approach based observation
(b) Sequence of Markov Chain between the states

As a result, the system now has zero-error crossing detection enabled. To realize the NCS approach in Simulink local host protocol is used to transmit and receive the control signal. The deadtime is introduced into the system operation using The Markov Approach is implemented by including function block in Simulink for which variables are defined in MATLAB. The transient and steady state response are recorded in the Table 4.2. The different results obtained after simulation are compared to analyse the performance improvement. The proposed modified Smith Predictor Controller shows trivial improvement in comparison to the different controllers simulated under similar conditions. In the table minimum and maximum percentage improvement of the proposed modified controller is presented signifying the performance appropriateness in controlling the operational stability. Therefore, the objective of this comparison is not to show considerable improvements in performance but to show that the proposed controller can have better performance when compared to other control techniques. The modified Smith Predictor Controller gives a good response for disturbance rejection and for set point change, since it combines the best features of Markov Approach in Smith Predictor Controller configuration. The proposed modified SPC is implemented on DC motor of third order that cover a number of applications in real time system. It is evident from the Table 4.2 that an improvement of 25.3 % in Rise Time when compared to Smith Predictor Controller observed by [33], it shows that the actuation of the controller to the plant is quick in terms of transient phenomena.

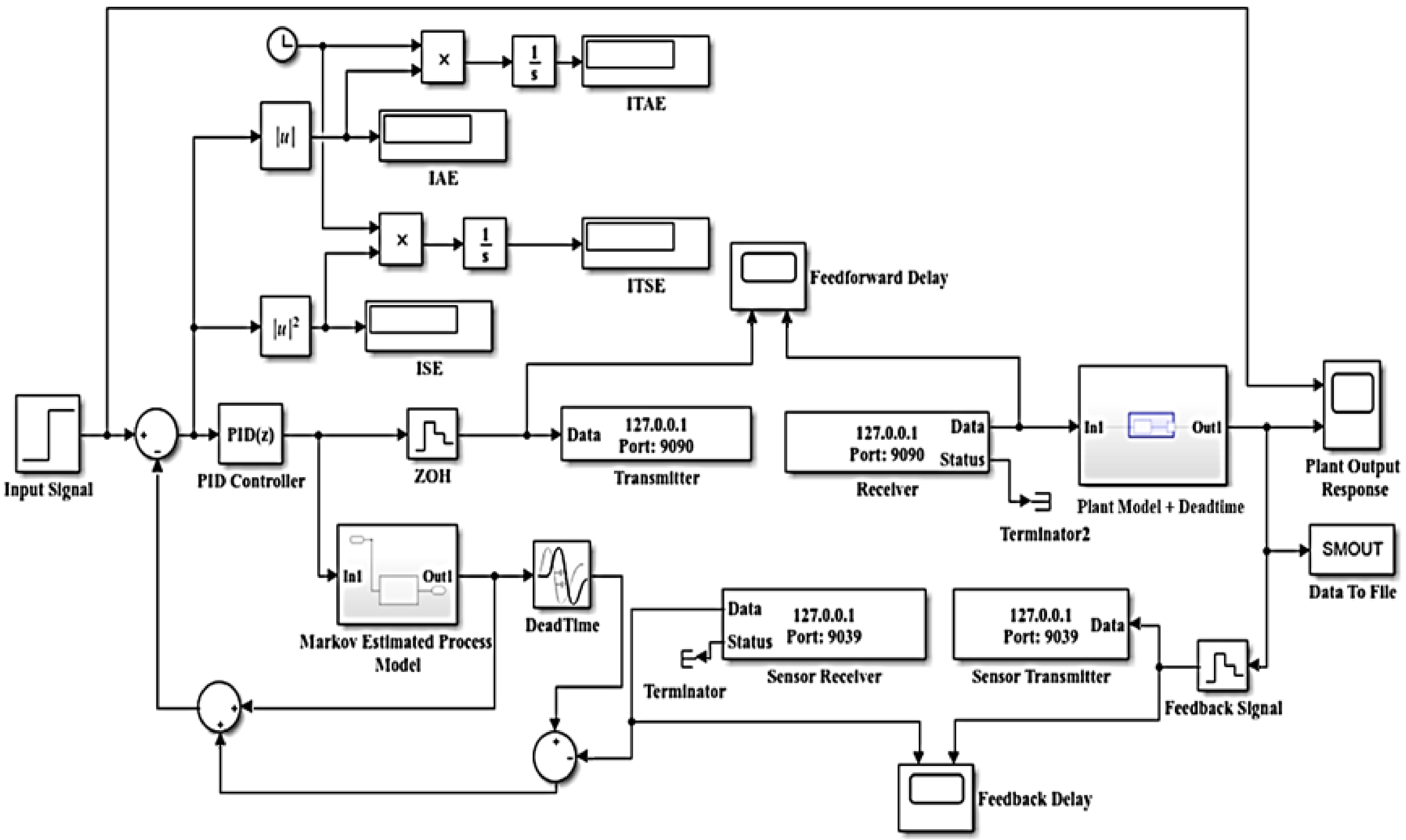


Figure 4.5: Simulink Block Diagram of Markov Approach based NCS

Table 4.2: Comparison of Controller Parameters

Reference	Control Approaches	Results				
		Rise Time (in Seconds)	**Slew Rate (/ksec)**	**Overshoot (in %)**	**Settling Time (in Sec)**	**Signal to Error Ratio (SER)**
[30]	Adaptive Smith Predictor	0.054	72.152	0.534	0.425	4.372
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[32]	Modified Smith Predictor	0.00271	----------	0.514	0.457	5.118
[31]	Markovian Jump Linear System	0.0047	----------	1.24	----------	6.041
[18]	Event Based Controller	0.0754	----------	0.98	----------	5.991
Proposed NCS Controller	**Markov Approach based Smith Predictor Controller**	**0.0012**	**106.337**	**0.505**	**0.316**	**7.269**
Minimum Percentage Improvement		**25.3 %**	**19.3 %**	**9.5 %**	**7.0 %**	**16.8 %**
Maximum Percentage Improvement		**98.40%**	**68.46%**	**59.27%**	**87.41%**	**89.24%**

A significant improvement of 7.0 % in Settling Time is observed on comparing with [32], indicating that the controllers bring the system to steady-state 0.024 seconds (24.0 milliseconds) faster when compared to the other controllers shown in this table [32].

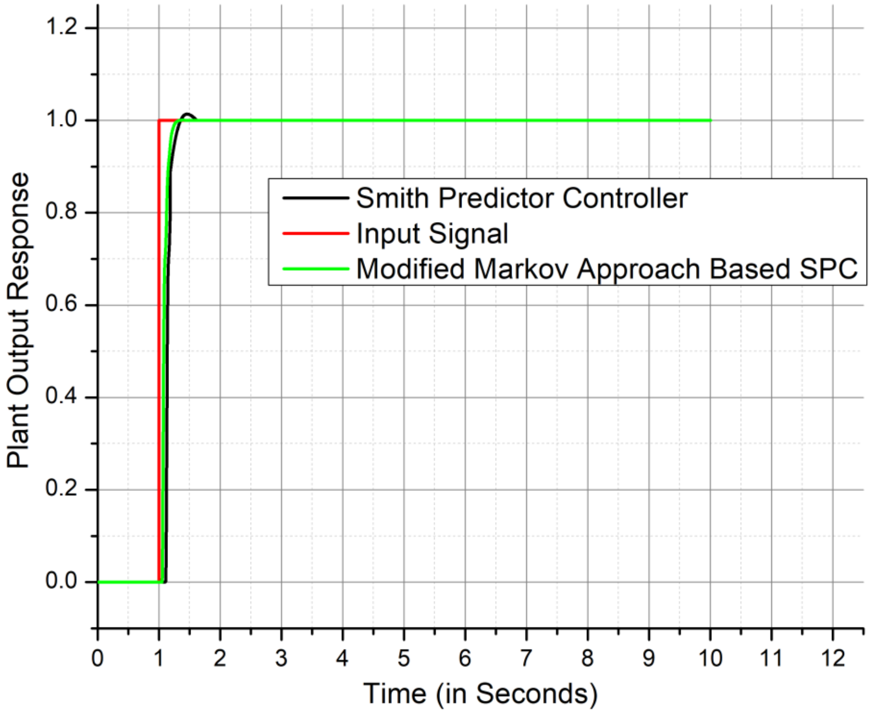


Figure 4.6: Comparison of Output Response of different controllers

Table 4.2 shows a considerable increase of 16.8 % in the signal to error ratio (SER) for SPC when compared to the SER mentioned for other controllers in the table [30], shows that the system is efficiently robust toward the noise involved in the NCS operation using modified Markov Approach based Smith Predictor controller. A minimum of positive variation in the plant overshoot causes the time delay to decrease a while hence the proposed Markov Approach based modified Smith Predictor Controller shows early settling of transient response and shows an improvement of 9.5% in the Overshoot as compared to [31]. The plant response as shown in Fig. 4.6 indicates that modified Markov Approach based Smith Predictor Controller (MSPC) shows the smoother steady state behavior and faster transient response as compared to Smith Predictor Controller. Since a number of controller parameters are involved to design the robust and optimal controllers so instead of deriving each of the parameters related to the controller designer derive the performance metrics (See, Appendix B) of the controllers and analyse the efficacy of the controllers in terms of disturbance rejection, operational stability, performance and robustness.

Table 4.3: Comparison of Integral Absolute Error (IAE)

Deadtime (in Seconds)	PID	SPC	MSPC	Difference (SPC-MSPC)	% Improvement w.r.t. SPC
60	24.2	7.124	3.516	3.608	50.65
50	0.1041	0.03141	0.0141	0.01731	55.11
40	0.1512	0.05221	0.02326	0.02895	55.45
30	0.00185	0.000697	3.23E-04	0.00037432	53.70
20	0.000795	0.000321	9.23E-05	0.00022875	71.26
10	1.87E-04	8.79E-05	2.41E-05	0.00006375	72.57
5	1.76E-05	1.24E-05	3.14E-06	0.00000926	74.67
2	8.61E-08	6.00E-08	1.22E-08	4.777E-08	79.64
0.2	2.89E-08	2.22E-08	4.90E-09	1.7302E-08	77.94

The integral performance criteria have been used to determine tuning parameters for the proposed modified controller. To confirm the robustness and operational stability of controller the integral performance metrics are considered as cost function (J). Considering the minimization of the cost function proves the reliability and robustness of the controller. There are several integral performance criteria which may be used to minimize the error signals such as IAE, ISE, ITAE and ISE. The ISTE criterion has been chosen to modify the tuning parameters for the proposed modified Smith Predictor Controller is simulated for deadtime from 0.2 sec to 60 sec. As explained in the Chapter 1, NCS is categorized into two applications Time-Sensitive and Time-Insensitive. The time sensitive applications require emergent response of actuator action. Even a delay of few seconds could ameliorate the purpose of application. So, for the modified Smith Predictor Controller lower limit of performance is limit to 0.2 seconds. On the other hand, a time-insensitive applications did not require an emergent response of actuator action but still need a recognition to timely response to the control signal directed by controller, so an upper limit of performance is limit to 60 seconds. This range of operation between 0.2 – 60 seconds by the proposed modified controller for an NCS cover almost all the application areas, either time-sensitive or time-insensitive.

Table 4.4: Comparison of Integral Squared Error (ISE)

Deadtime (in Seconds)	MSPC	PID	SPC	Difference (SPC-MSPC)	% Improvement w.r.t. SPC
60	2.01E-15	1.99E-13	9.41E-15	7.40E-15	78.64
50	2.48E-18	9.87E-14	9.57E-18	7.09E-18	74.09
40	2.51E-19	5.67E-15	9.25E-19	6.74E-19	72.88
30	2.36E-18	4.85E-17	8.21E-18	5.85E-18	71.28
20	7.05E-20	6.32E-19	2.57E-19	1.87E-19	72.57
10	9.99E-23	1.97E-21	3.68E-22	2.68E-22	72.85
5	2.69E-23	1.30E-22	8.63E-23	5.94E-23	68.83
2	3.23E-30	1.42E-30	9.94E-30	6.71E-30	67.52
0.2	1.56E-31	8.99E-30	4.93E-31	3.37E-31	68.30

A comparison of the performance parameters such as “Integral Absolute Error” (IAE), “Integral Squared Error” (ISE), “Integral Time Absolute Error” (ITAE) and “Integral Time Squared Error” (ITSE) between “PID controller” (PID), “Smith Predictor Controller” (SPC) and Markov Approach based proposed modified Smith Predictor (MSPC)controller are shown in Table 4.3 to Table 4.6 respectively. The Table 4.3 is showing a comparison detail of IAE values obtained for the modified Smith Predictor controller, PID controller and Smith Predictor Controller designed in Chapter 3. Each of the controller is simulated for designed NCS in Simulink. During the operation a deadtime of 0.2 sec to 60 sec is introduced in the NCS to check the operation reliability and performance limit of the controller. A percentage improvement of proposed modified controller in comparison to the Smith Predictor controller is mentioned at each value of deadtime introduced in the NCS operation. At large deadtime of 60 sec the PID controller have greater IAE value than SPC and MSPC which shows the sluggishness in the operation of PID controller by about 70.56% than SPC. As the deadtime is decreased this behavior of PID improves to 23.18%. Looking at the IAE comparison between MSPC and SPC at various deadtime periods. Though SPC has good response as compared to PID but it is further improved by MSPC by 50.65% at large deadtime of 60 sec. However, the improvement gradually increased as the deadtime in NCS is decreased. For time-sensitive with deadtime of 0.2 sec in NCS an improvement of 77.94% can be observed from the table. It can be evaluated from the

Table 4.3 that MSPC have an average improvement of 64.7% over SPC which shows that ability to suppress small errors by proposed controller is 64.7% better than SPC. Hence for small errors the proposed MSPC will achieve stability faster than SPC.

Table 4.5: Comparison of Integral Time Absolute Error (ITAE)

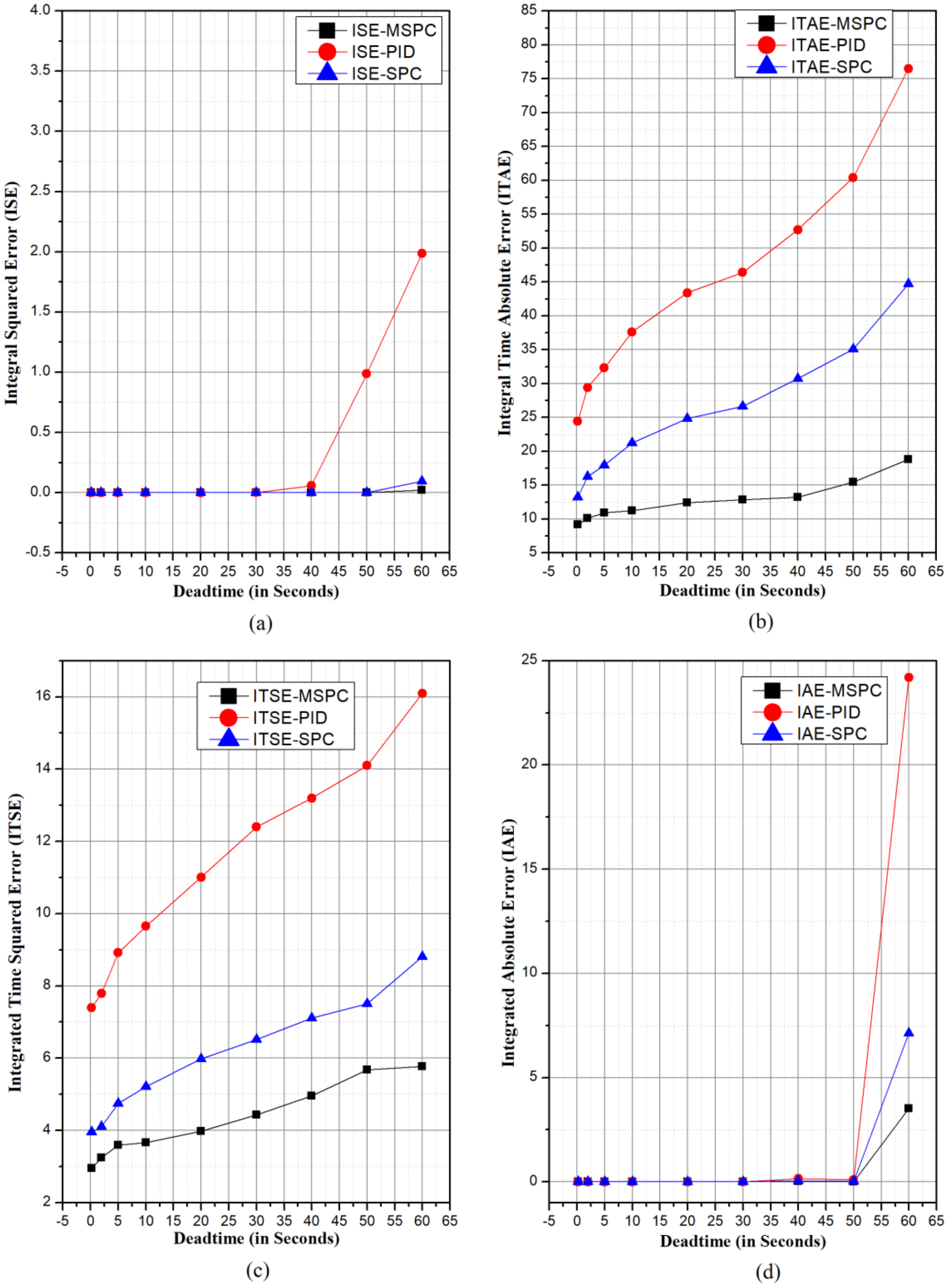
Deadtime (in Seconds)	**MSPC**	**PID**	**SPC**	**Difference (SPC-MSPC)**	**% Improvement w.r.t. SPC**
60	18.79	76.5	44.71	25.92	57.97
50	15.44	60.4	35.09	19.65	56.00
40	13.24	52.7	30.75	17.51	56.94
30	12.85	46.4	26.65	13.8	51.78
20	12.41	43.4	24.8	12.39	49.96
10	11.24	37.6	21.24	10	47.08
5	10.89	32.3	17.92	7.03	39.23
2	10.11	29.4	16.25	6.14	37.78
0.2	9.2	24.4	13.19	3.99	30.25

In attempting to create performance measures for optimum control, such as linear tracking control, the ISE of the controller is validated. A comparison of ISE parameter obtained for different controllers such as PID, SPC and MSCP is mentioned in Table 4.4. These performance metrics are measured at different deadtimes introduced in the NCS operation. It can be observed from the table that MSPC is showing 78.64% of percentage improvement than SPC at a deadtime of 60 sec. It concludes that the proposed modified controller reduces the impact of large deadtime since the ISE performance metric is assessed for compensating the effect of large deadtimes involved in the NCS as squared errors add more to the signal's value. Even at small deadtime the performance of proposed modified controller is proving 68.30% improvement. Overall, for ISE performance metric it can be analysed form the Table 4.4 that MSPC is showing an average improvement of 71.88% as compared to SPC, which shows that MSPC reduce the impact of large deadtime quicker as compared to SPC. Hence, an early rejection of disturbance from the system that will lead the NCS to reduce the induced delay and improves operational stability of the system by using proposed modified controller.

Table 4.6: Comparison of Integral Time Squared Error (ITSE)

Deadtime (in Seconds)	MSPC	PID	SPC	Difference (SPC-MSPC)	% Improvement w.r.t. SPC
60	5.769	16.1	8.81	3.041	34.52
50	5.68	14.1	7.51	1.83	24.37
40	4.96	13.2	7.11	2.15	30.24
30	4.43	12.4	6.52	2.09	32.06
20	3.98	11.01	5.98	2	33.44
10	3.668	9.65	5.21	1.542	29.60
5	3.59	8.92	4.75	1.16	24.42
2	3.249	7.79	4.11	0.861	20.95
0.2	2.95	7.4	3.95	1	25.32

In order to improve operational stability by reducing delay induced in the network, the ITAE performance criterion is analysed. The Table 4.5 shows a variation in percentage improvement of ITAE parameter for different controllers from 30.25% to 57.97% for deadtime of 0.2 sec to 60 sec respectively. For large deadtime the proposed modified controller improves the delay compensation by 57.97%. From the table it can be analysed that there is 47.44% of average improvement by MSPC over SPC. Hence, shows that MSPC can 47.44% faster to stabilize the transient response of the system as compared to SPC. The modeling of APV by using Markov Approach based modified Smith Predictor controller improves the stability and operational performance of the NCS. The ITSE predicts the modeling error and improve the robustness of the controller. An improvement of 25.32% to 34.52% for deadtime ranging from 0.2 sec to 60 sec shows that MSPC can predict the APV faster as compared to SPC. For a large deadtime of 60 sec the APV model prediction is 34.52% quicker as compared to the SPC whereas, for time-sensitive application the prediction probability of MSPC is 25.32% improved in comparison to the APV model prediction rate of SPC. On an average of the prediction probability of MSPC is 28.32% rapid as compared to SPC. A diagrammatical comparative analysis of IAE, ISE, ITAE and ITSE of the all the controllers mentioned in the Table 4.3 – Table 4.6 is diagrammatically represented in Fig. 4.7.



(a)

(b)

(c)

(d)

Figure 4.7: Comparison of performance metrics (a) Integrated Squared Error (ISE), (b) Integral Time Absolute Error (ITAE), Integral Time Squared Error (ITSE) and (d) Integral Absolute Error (IAE) of PID, SPC and MSPC controllers at different deadtimes

The curve shows comparative curves of different performance criterion at deadtime ranging from 0.2 sec to 60 sec. And it can be observed from the comparative analysis that MSPC improving the performance and robustness of NCS to compensate induced delays. By addressing the uncertainty in the parameter estimation, the suggested improved Markov Approach based Smith Predictor controller demonstrates significant improvement. Finally, in order to gain superior monitoring and robust stability in the application, a number of simulations were undertaken.

4.6 Conclusion

To construct the updated State-Space Equation of the plant, which serves as a predicted process model of the Smith Predictor Controller, the Markov Approach is used in this chapter, and it is implemented in Simulink 2020. This modified SPC is simulated to regulate the dynamics of a DC Motor in an NCS. It is evident from the obtained results that the proposed modified SPC has significant improvements in terms of settling time, maximum overshoot, signal-to-error ratio, rise time, and slew rate, with improvements of 7.0 %, 9.5 %, 16.8 %, 25.3 %, and 19.3 % respectively, over the control approaches considered by other authors for their studies. These modifications demonstrate that the suggested modified SPC controller has a reliable and robust controller performance. Further, in this chapter a comparison of the proposed modified SPC to other controllers has been done that clearly indicate the improvements in performance measures. It is apparent that the proposed controller's resilience attributes, such as transient response, reliability in model prediction, and superior performance for large deadtime operations, are significantly more trustworthy than other controllers mentioned in the chapter.

CHAPTER 5

MARKOV APPROACH AND KALMAN FILTER BASED SMITH PREDICTOR CONTROLLER

5.1 Introduction

The Smith Predictor Controller is a model-based controller that performs proficiently relying on how precisely the process model and deadtime are anticipated in line with the real process model. Smith Predictor's performance degrades substantially or becomes inconsistent as a result of modelling inaccuracies, particularly deadtime, which can vary depending on the operating phenomenon.

Researchers over the time modify the Smith Predictor Controller to develop the process model but hardly focus on estimation of deadtime [146]–[148]. [149] discusses about the manual estimation of deadtime for process improvement of the Smith Predictor Controller. But due to uncertainty in the process variable behavior the manual estimation of the deadtime does not always give satisfactory results. Hence, an estimation technique that depends upon the weighted input from the output of the actual process is introduced in the system to make accurate deadtime estimation for reliable, robust and predictive process [150].

Kalman filtering is a technique that offers approximations of certain random parameters precise measurements taken over a period of time. Kalman filters have shown to be quite beneficial in a variety of applications. It has a straightforward design and necessitates a modest amount of computational performance.

5.2 Kalman Estimation Approach

The Bayesian solution to the issue of sequentially approximating the states of a dynamical system for both linear and Gaussian state development and measurement processes is the Kalman Estimation [151]. Consider the state space model of the form as:

$$\mathrm{x_n = F_n x_{n-1} + v_n} \tag{5.1a}$$

$$y_n = H_n x_n + w_n \tag{5.1b}$$

where F_n and H_n represents the matrices with appropriate dimensions, v_n and w_n is Gaussian random state noise vector with zero mean and covariance matrix Q_n, and Rn respectively. The Gaussian and linear state space model for a dynamical system can be represented by eq.(5.1) The conditional probability density functions (pdfs), $p(x_n|x_{n-1})$ and $p(y_n|x_n)$ for the state and measurement vectors, respectively, are then given by the Gaussian pdfs

$$p(x_n|x_{n-1}) \equiv \mathcal{N}(x_n; F_n x_{n-1}, Q_n) \tag{5.2a}$$

$$p(y_n|x_n) \equiv \mathcal{N}(y_n; H_n x_n, R_n) \tag{5.2b}$$

where the notation $\mathcal{N}(*; m, P)$ represent Gaussian pdf with mean m and covariance P. Suppose that the initial state distribution p.x0/ is also Gaussian. Considering the sequential Bayesian estimation procedure, under the stated conditions, the posterior pdf $p(x_n|Y_n)$ at time step n can be shown to be Gaussian:

$$p(x_n|Y_n) \equiv \mathcal{N}\left(x_n; m_{n|n}, P_{n|n}\right) \tag{5.3}$$

Here, $m_{n|n}$ and $P_{n|n}$ denote Gaussian posterior mean and covariance at time step n. The Kalman Filter equations are given by

$$m_{n|n-1} = F_n m_{n-1|n-1} \tag{5.4a}$$

$$P_{n|n-1} = F_n P_{n-1|n-1} F_n^T + Q_n \tag{5.4b}$$

$$S_n = H_n P_{n|n-1} H_n^T + R_n \tag{5.4c}$$

$$K_n = P_{n|n-1} H_n^T S_n^{-1} \tag{5.4d}$$

$$m_{n|n} = m_{n|n-1} + K_n\left(y_n - H_n m_{n|n-1}\right) \tag{5.4e}$$

$$P_{n|n} = P_{n|n-1} - K_n H_n P_{n|n-1}) \tag{5.4f}$$

For n = 1,2…. Here, eq. (5.4a) – (5.4f) represent the prediction steps and eq. (5.4c) – (5.4f) comprise the update step.

Table 5.1: Kalman Estimation Process

Algorithm: Kalman Estimation Process
Input: Linear Gaussian state space model and a set of measurements $\{y_1, y_2, y_3 \ldots, y_n\}$. Output: Estimates of the state $x_1, x_2, \ldots, x_n$ at time steps n = 1, 2…., N.
Input at n = 0, to mean and covariance of the Gaussian state distribution $\mathcal{N}\left(x_0; m_{0\|0}P_{0\|0}\right)$.
For time steps n = 1, 2, … N,
1. Carry out the prediction step $m_{n\|n-1} = F_n m_{n-1\|n-1}$ $P_{n\|n-1} = F_n P_{n-1\|n-1} F_n^T + Q_n$
2. Compute the estimate $\hat{x} = m_{n\|n}$ of the state x_n using the update step $S_n = H_n P_{n\|n-1} H_n^T + R_n$ $K_n = P_{n\|n-1} H_n^T S_n^{-1}$ $m_{n\|n} = m_{n\|n-1} + K_n\left(y_n - H_n m_{n\|n-1}\right)$ $P_{n\|n} = P_{n\|n-1} - K_n H_n P_{n\|n-1})$

5.3 WORKING OF KALMAN ESTIMATION PROCESS

The working of Kalman Filter can be understood through Fig. 5.1. The three main blocks represented 1,2 and 3 presents iterative calculations. To calculate the Kalman gain, error in the estimate or the original error and error in the data are utilized as user input. Through this the current estimate can be calculated by considering the measured value and previous estimate as first input and after each step previous estimate will be used iteratively. The measured value and previous estimate will initiate the system to compute the current estimate. On comparing with the previous calculated value and current estimate will update the current value and iteratively calculate the Kalman gain to get closer to the actual value. Using Fig. 5.1 this can be easily understood.

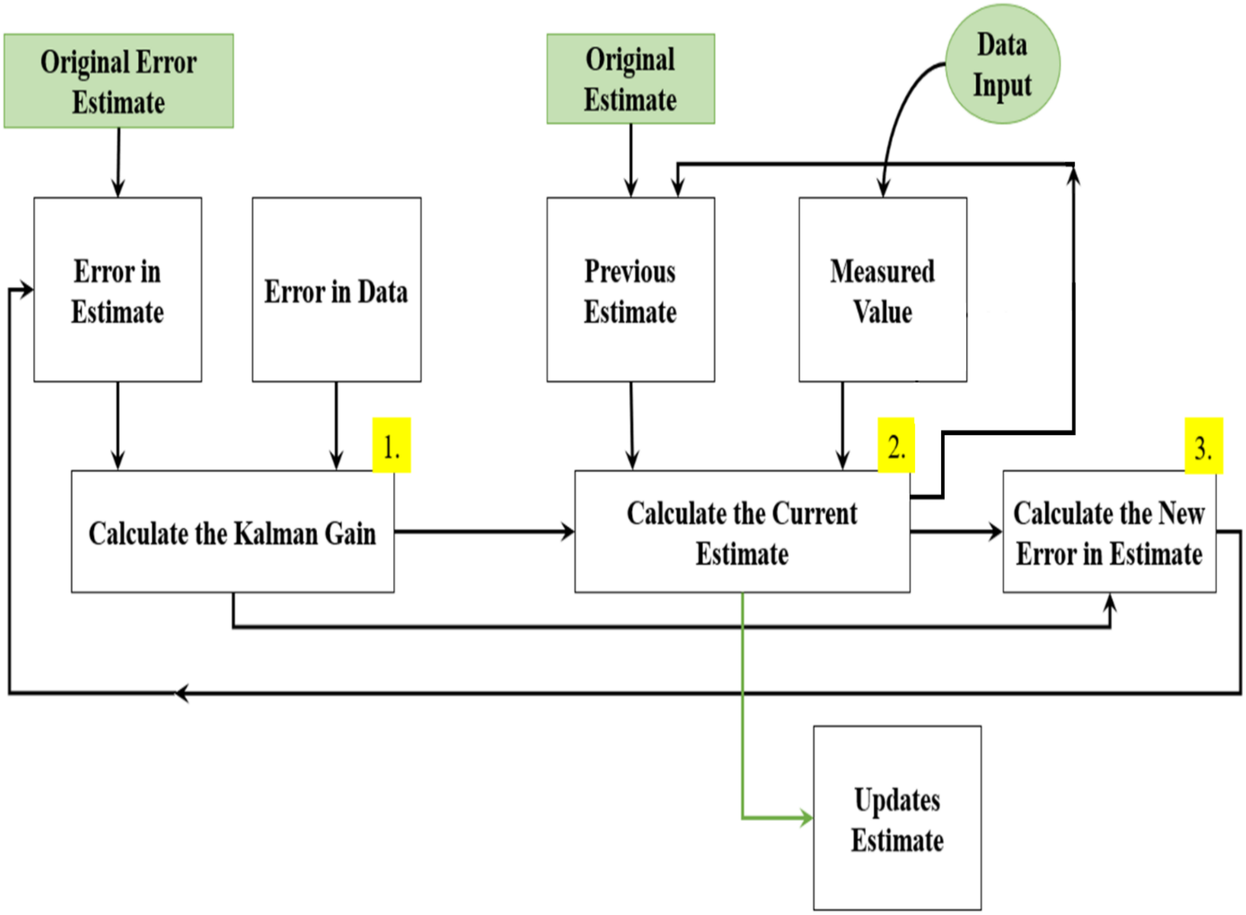


Figure 5.1: Stepwise Estimation of Deadtime using Kalman Estimator

Based upon the design algorithm and process mentioned the block diagram of proposed modified Kalman-Markov Approach based Smith Predictor controller can be illustrated from Fig. 5.2. Here, it can be observed that the Markov Approach is used to predict the Actual Process Model (APM) of the Actual Process Variable (APV) and Kaman Filter based Estimator is used to estimate the deadtime involved in the APV. The resultant feedback signal or estimated disturbance is the difference of response obtained by APV and PPM.

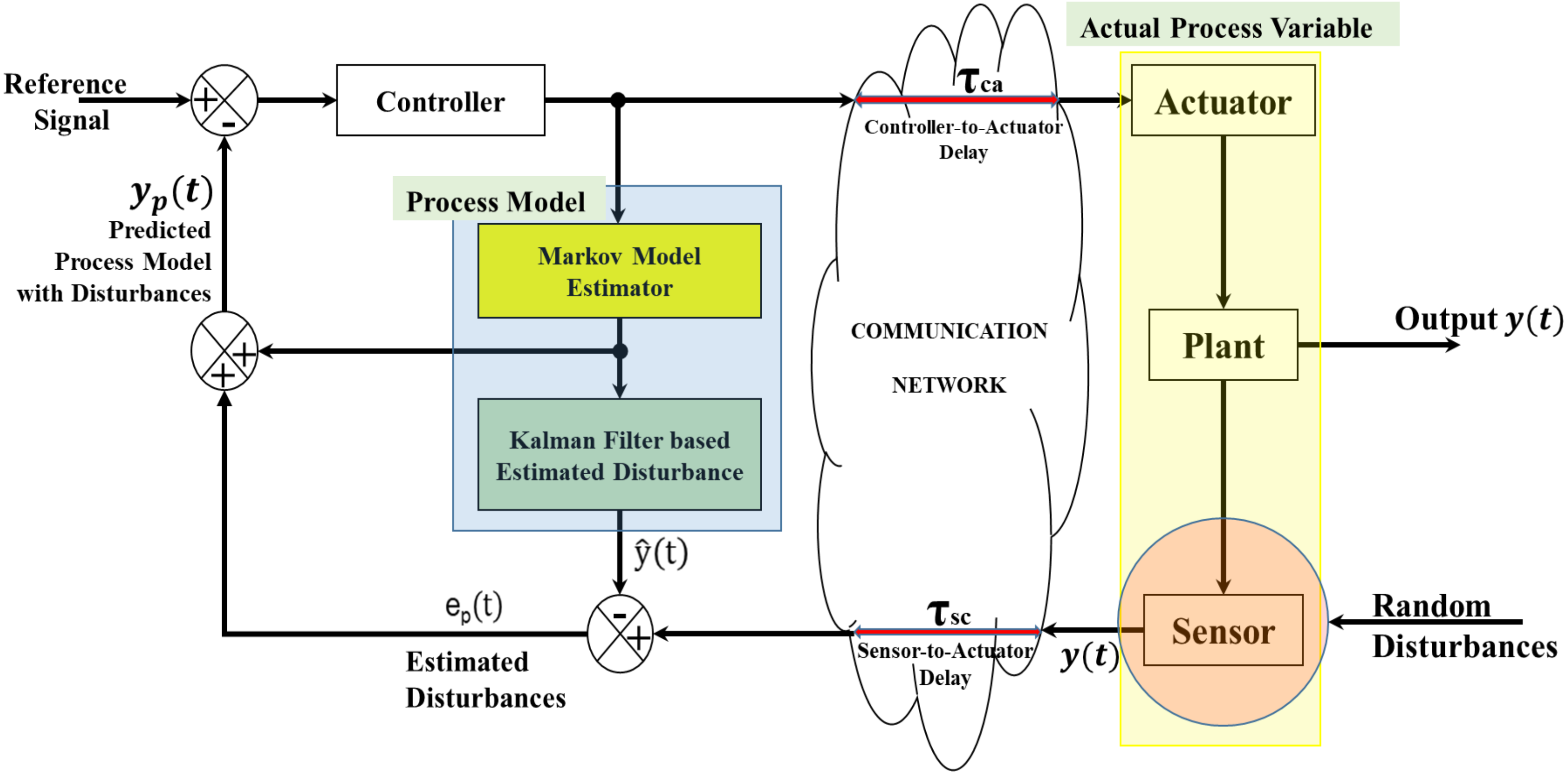


Figure 5.2: Schematic Block of Smith Predictor Controller modified using Markov Approach and Kalman Estimation Technique

5.4 Simulation Results and Discussion

5.4.1 Simulation Setup

The Networked Control System is designed in Simulink. Here, transmitter and receiver are realized to be connected through any type of network i.e., LAN, MAN, WAN, Wireless or Internet. The network local protocols are used to make a link between them in the Simulink. The controller used to regulate the control signal in the SPC is a PID controller. The Markov Estimated Model block and Kalman Estimated Deadtime block can be observed as Model Predictor block and deadtime estimator. The dynamics of the plant model which is a derived model of DC motor is controlled through proposed modified SPC on NCS platform.

5.4.2 Performance Analysis and Discussion

The transient and steady state response are recorded in the Table 5.2. The different results obtained after simulation are compared to analyse the performance improvement. The proposed modified Smith Predictor Controller shows trivial improvement in comparison to the different controllers simulated under similar conditions. Therefore, the objective of this comparison is not to show considerable improvements in performance but to show that the proposed modified controller can have improved performance in comparison to other control techniques introduced in the literature. In the table minimum and maximum improvements of the proposed modified controller is presented showing that the characteristics of the proposed controller indicating a range of perfection in terms of controller characteristics. The proposed modified Smith Predictor Controller (KMSPC) gives a good response for disturbance rejection and for set point change, since it combines the best features of Markov Approach and Kalman Estimation Technique in Smith Predictor Controller configuration. The gain obtained for the Kalman Filter Estimator are [5.5992; 15.6258; 20.8246; 50.6893]. It is evident from the Table 5.2 that an improvement of 31.25 % in Rise Time when compared to Smith Predictor Controller observed by [33], it shows that the actuation of the controller to the plant is quick in terms of transient phenomena. A significant improvement of 26.1 % in Settling Time is observed on comparing with [32], indicating that the controllers bring the system to steady-state 0.089 seconds (89.0 milliseconds) faster when compared to the other controllers shown in this table [32].

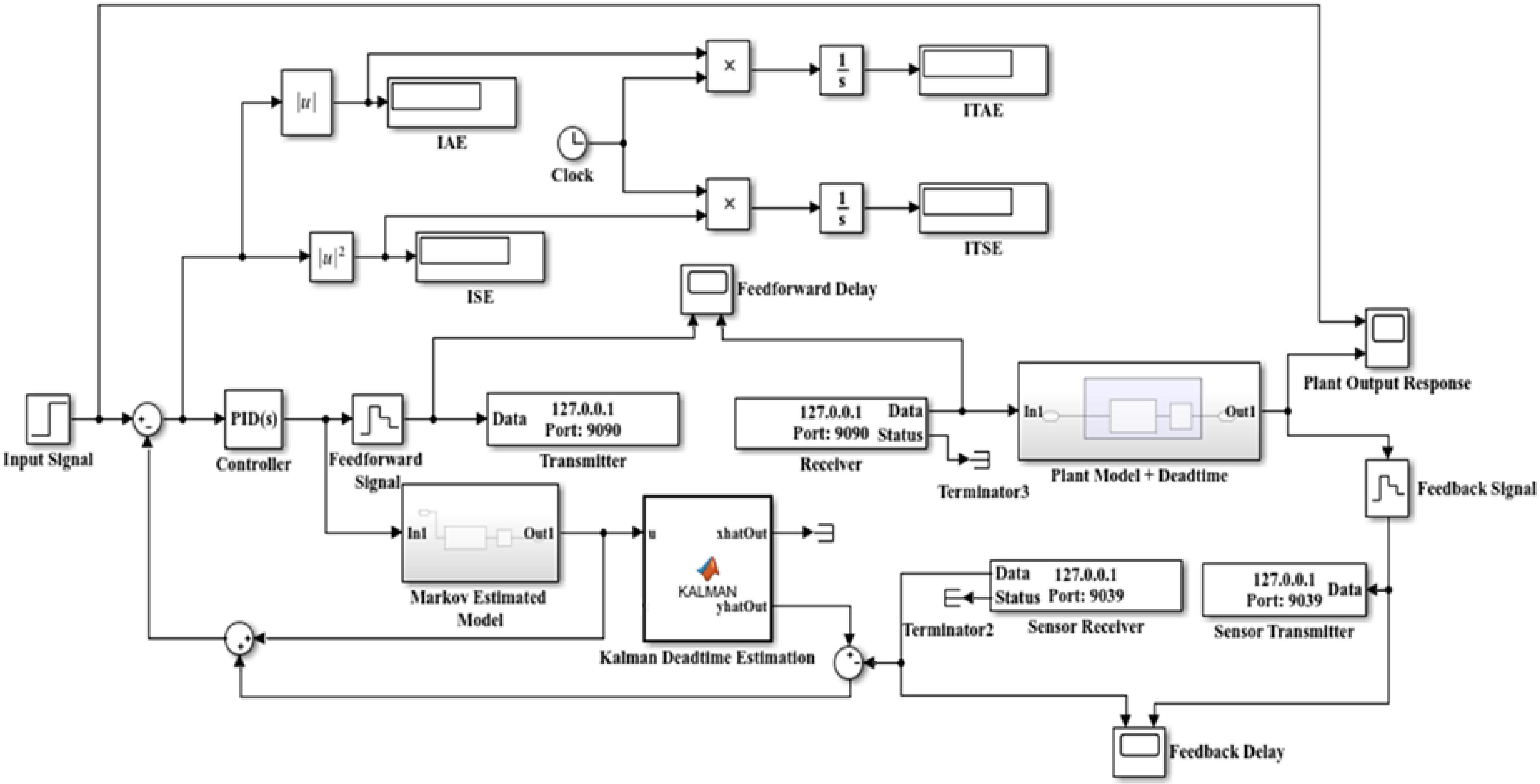


Figure 5.3: The Simulink Block Diagram of Kalman Estimation and Markov Approach based Modified Smith Predictor Controller

Table 5.2: Comparison of Transient Response of Predictive Approaches based SPC with Transient Response in Literature

Reference	**Control Approaches**	**Results**				
		Rise Time (Seconds)	**Slew Rate (/ksec)**	**Overshoot (in %)**	**Settling Time (Seconds)**	**Signal to Error Ratio (SER)**
[30]	Adaptive Smith Predictor	0.054	72.152	0.534	0.425	4.372
[34]	Smith Predictor	0.0187	63.12	0.457	2.51	4.148
[33]	Improved Predictive Control Method	0.0016	89.142	0.544	0.340	--------
[32]	Modified Smith Predictor	0.00271	----------	0.514	0.457	5.118
[31]	Markovian Jump Linear System	0.0047	----------	1.24	----------	6.041
[18]	Event Based Controller	0.0754	----------	0.98	----------	5.991
Proposed Modified NCS Controller – I	**Markov Approach based Smith Predictor Controller (MSPC)**	**0.0012**	**106.337**	**0.505**	**0.316**	**7.269**
Minimum Percentage Improvement		**25.3 %**	**19.3 %**	**9.5 %**	**7.0 %**	**16.8 %**
Maximum Percentage Improvement		**98.40%**	**68.46%**	**59.27%**	**87.41%**	**75.24%**
Proposed Modified NCS Controller – II	**Markov Approach + Kalman Estimation based SPC (KMSPC)**	**0.0011**	**117.91**	**0.505**	**0.251**	**8.120**
Minimum Percentage Improvement		**31.25 %**	**32.3 %**	**9.5 %**	**26.1 %**	**25.6 %**
Maximum Percentage Improvement		**98.54%**	**86.80%**	**9.5%**	**90.0%**	**95.7%**

Table 5.2 shows a considerable increase of 25.6 % in the signal to error ratio (SER) for SPC when compared to the SER mentioned for other controllers in the table [30], shows that the system is efficiently robust toward the noise involved in the NCS operation using modified Markov Approach and Kalman Estimation based Smith Predictor controller (KMSPC). The slew rate measures the maximum rate of change of plant response. A higher value of slew rate defines the maximum compensation of induced delay and least probability of packet dropout. The KMSPC has 32.3% improvement over [32] shows that it more reliable in term of its robust operation in NCS. A minimum of positive variation in the plant overshoot causes the time delay to decrease a while hence the KMSPC shows early settling of transient response and shows an improvement of 9.5% in the Overshoot as compared to [31]. The plant response presented in Fig. 4.6 shows that modified Markov Approach based Smith Predictor Controller (MSPC) shows the smoother steady state behavior and faster transient response as compared to Smith Predictor Controller. Since a number of controller parameters are involved to design the robust and optimal controllers so instead of deriving each of the parameters related to the controller designer derive the performance metrics (See, Appendix B) of the controllers and analyse the efficacy of the controllers in terms of disturbance rejection, operational stability, performance and robustness.

On comparing the results of MSPC and KMSPC it is found the there is also a significant improvement. The Settling Time, Rise Time, SER and Slew Rate for KMSPC are showing an improvement of 9.1%, 5.95%, 19.1% and 8.8% respectively. The overshoot for the both the proposed modified controllers MSPC and KMSPC is same i.e., 9.5% of improvement over [29].

The integral performance criteria have been used to determine tuning parameters for the proposed modified controller. To confirm the robustness and operational stability of controller the integral performance metrics are considered as cost function (J). Considering the minimization of the cost function proves the reliability and robustness of the controller. There are several integral performance criteria which may be used to minimize the error signals such as IAE, ISE, ITAE and ISE. The ISTE criterion has been chosen to modify the tuning parameters for the proposed modified Smith Predictor Controller is simulated for deadtime from 0.2 sec to 60 sec.

As explained in the Chapter 1, NCS is categorized into two applications Time-Sensitive and Time-Insensitive. The time sensitive applications require emergent response of actuator action. Even a delay of few seconds could ameliorate the purpose of application. So, for the modified Smith Predictor Controller lower limit of performance is limit to 0.2 seconds. On the other hand, a time-insensitive applications did not require an emergent response of actuator action but still need a recognition to timely response to the control signal directed by controller, so an upper limit of performance is limit to 60 seconds. This range of operation between 0.2 – 60 seconds by the proposed modified controller for an NCS cover almost all the application areas, either time-sensitive or time-insensitive.

A comparison of the performance parameters such as “Integral Absolute Error” (IAE), “Integral Squared Error” (ISE), “Integral Time Absolute Error” (ITAE) and “Integral Time Squared Error” (ITSE) between “PID controller” (PID), “Smith Predictor Controller” (SPC) and Markov Approach based proposed modified Smith Predictor controller (MSPC) and proposed Markov Approach and Kalman Estimation Technique based modified Smith Predictor controller (MKSPC) are shown in Table 5.3 to Table 5.6 respectively. In the Chapter 4, a comparative analysis of performance metrics between MSPC and SPC was presented.

Table 5.3: Comparison of Integral Absolute Error (IAE)

Deadtime (Seconds)	**PID**	**SPC**	**MSPC**	**KMSPC**	**Difference (MSPC – KMSPC)**	**% Improvement w.r.t. MSPC**
60	24.2	7.124	3.516	1.07	2.446	69.57
50	0.1041	0.03141	0.0141	0.00487	0.00923	65.46
40	0.1512	0.05221	0.02326	0.00784	0.01542	66.29
30	0.00185	0.000697	3.23E-04	0.000107	0.00021568	66.84
20	0.000795	0.000321	9.23E-05	2.55E-05	0.00006675	72.36
10	1.87E-04	8.79E-05	2.41E-05	5.19E-06	1.89134E-05	78.48
5	1.76E-05	1.24E-05	3.14E-06	6.24E-07	2.5162E-06	80.13
2	8.61E-08	6.00E-08	1.22E-08	1.89E-09	1.0325E-08	84.56
0.2	2.89E-08	2.22E-08	4.90E-09	7.39E-10	4.1592E-09	84.92

In this section a comparative analysis between the two modified controllers i.e., MSPC and KMSPC is presented. The Table 5.3 is showing a comparison detail of IAE values obtained for the PID, SPC, MSPC and MKSPC. Each of the controller is simulated for designed NCS in Simulink. During the operation a deadtime of 0.2 sec to 60 sec is introduced in the NCS to check the operation reliability and performance limit of the controller.

The percentage improvement of KMSPC in comparison to MSPC is mentioned at each value of deadtime introduced in the NCS operation. At large deadtime of 60 sec the KMSPC shows an improvement of 69.57% comparing to the IAE of result of MSPC. It shows that estimation of deadtime using Kalman Estimation Technique reduces the effect of large errors. Whereas, at small deadtime of 0.2sec the improvement reaches to 84.92% as compared to MSPC. It shows that there is a gradual improvement in IAE with decrease in deadtime involved in the NCS. Hence it proves that KMSPC can achieve faster stability at small deadtime and can be observed as a significant controller for time-sensitive applications such as unmanned aerial vehicles (UAV), teleoperation or telesurgery and disaster management robots. The KMSPC has an average improvement of 74.29% over MSPC at different deadtimes.

Table 5.4: Comparison of Integral Squared Error (ISE)

Deadtime (Seconds)	MSPC	PID	SPC	KMSPC	Difference (MSPC – KMSPC)	% Improvement w.r.t. MSPC
60	2.01E-15	1.99E-13	9.41E-15	3.55E-16	1.65E-15	82.32
50	2.48E-18	9.87E-14	9.57E-18	4.93E-19	1.99E-18	80.11
40	2.51E-19	5.67E-15	9.25E-19	4.84E-20	2.03E-19	80.73
30	2.36E-18	4.85E-17	8.21E-18	5.42E-19	1.82E-18	77.00
20	7.05E-20	6.32E-19	2.57E-19	1.49E-20	5.56E-20	78.85
10	9.99E-23	1.97E-21	3.68E-22	2.28E-23	7.71E-23	77.22
5	2.69E-23	1.30E-22	8.63E-23	5.37E-24	2.15E-23	80.04
2	3.23E-30	1.42E-30	9.94E-30	6.56E-31	2.57E-30	79.68
0.2	1.56E-31	8.99E-30	4.93E-31	3.07E-32	1.26E-31	80.37

In attempting to create performance measures for optimum control, such as linear tracking control, the ISE of the controller is validated. To reduce the impact of large deadtime, the ISE performance metric is assessed since squared errors add more to the signal's value. It can be analyzed form the Table 5.4 that KMSPC is showing an average improvement of 79.59% as compared to SPC, which shows that KMSPC reduce the impact of large deadtime quicker as compared to MSPC. Hence, an early rejection of disturbance from the system that will lead the NCS to reduce the induced delay and improves operational stability of the system by using proposed modified controller.

Table 5.5: Comparison of Integral Time Absolute Error (ITAE)

Deadtime (Seconds)	**MSPC**	**PID**	**SPC**	**KMSPC**	**Difference (MSPC – KMSPC)**	**% Improvement w.r.t. MSPC**
60	18.79	76.5	44.71	12.96	5.83	31.03
50	15.44	60.4	35.09	9.825	5.615	36.37
40	13.24	52.7	30.75	8.755	4.485	33.87
30	12.85	46.4	26.65	6.9	5.95	46.30
20	12.41	43.4	24.8	6.195	6.215	50.08
10	11.24	37.6	21.24	5.12	6.12	54.45
5	10.89	32.3	17.92	3.515	7.375	67.72
2	10.11	29.4	16.25	3.07	7.04	69.63
0.2	9.2	24.4	13.19	1.995	7.205	78.32

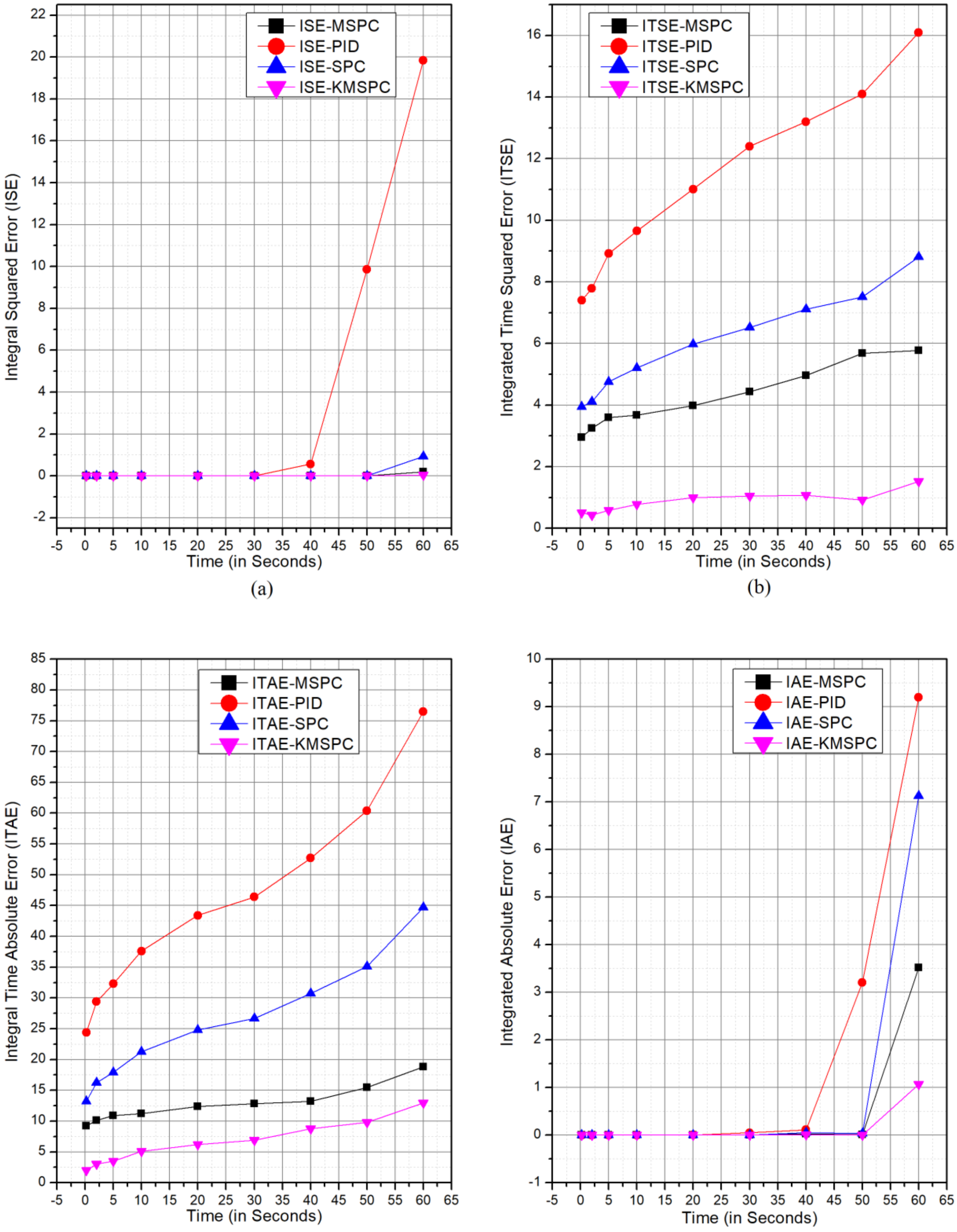
In order to improve operational stability by reducing delay induced in the network. The ITAE performance criterion is analysed, the Table 4.5 shows a variation in percentage improvement from 31.03% to 78.32% for deadtime of 0.2 sec to 60 sec respectively. It can be evaluated form the table that there is 51.97% of average improvement by KMSPC over MSPC. It shows that KMSPC can 51.97% faster stabilize the transient response of the system as compared to SPC.

The modeling of APV by using Markov Approach and Kalman Estimation Technique based modified Smith Predictor controller (KMSPC) improves the stability and operational performance of the NCS. The ITSE predicts the modeling perturbations and improve the sturdiness of the controller. An improvement of 73.64% to 83.05% for deadtime ranging from 0.2 sec to 60 sec shows that KMSPC can predict the APV faster as compared to MSPC.

Table 5.6: Comparison of Integral Time Squared Error (ITSE)

Deadtime (Seconds)	MSPC	PID	SPC	KMSPC	Difference (MSPC – KMSPC)	% Improvement w.r.t. MSPC
60	5.769	16.1	8.81	1.5205	4.2485	73.64
50	5.68	14.1	7.51	0.915	4.765	83.89
40	4.96	13.2	7.11	1.075	3.885	78.33
30	4.43	12.4	6.52	1.045	3.385	76.41
20	3.98	11.01	5.98	1	2.98	74.87
10	3.668	9.65	5.21	0.771	2.897	78.98
5	3.59	8.92	4.75	0.58	3.01	83.84
2	3.249	7.79	4.11	0.4305	2.8185	86.75
0.2	2.95	7.4	3.95	0.5	2.45	83.05

For a large deadtime of 60 sec the APV model prediction is 73.64% quicker as compared to the MSPC whereas, for time-sensitive application the prediction probability of MSPC. On an average of the prediction probability of KMSPC is 79.97% rapid as compared to MSPC. A diagrammatical comparative analysis of IAE, ISE, ITAE and ITSE of the all the controllers mentioned in the Table 5.3 – Table 5.6 is diagrammatically represented in Fig. 5. The curve shows comparative curves of different performance criterion at deadtime ranging from 0.2 sec to 60 sec. And it can be observed from the comparative analysis that MSPC improving the performance and robustness of NCS to compensate induced delays.



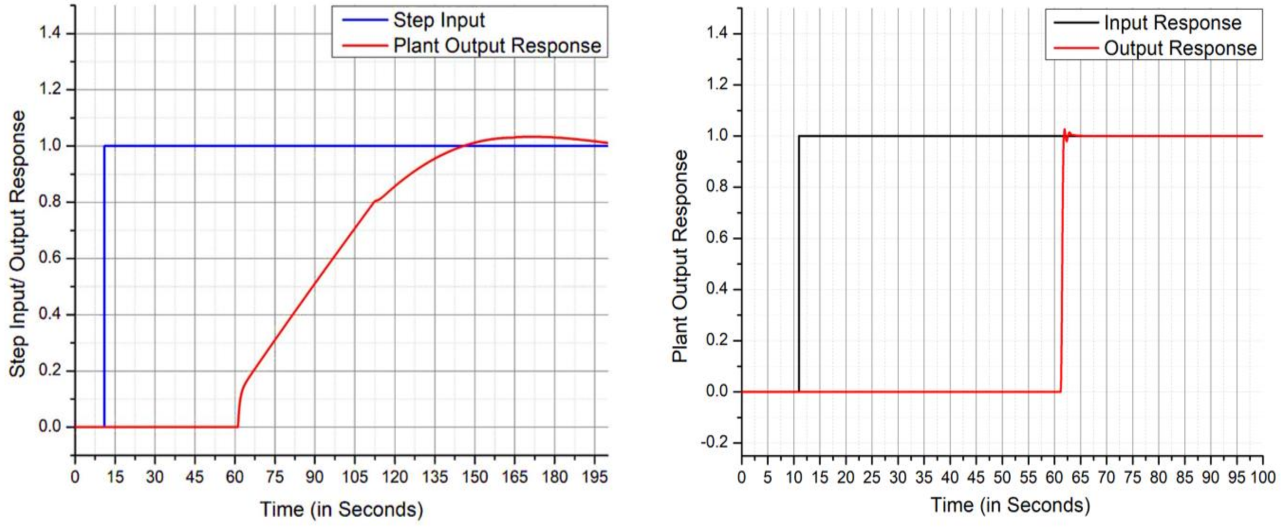
(a)

(b)

(c)

(d)

Figure 5.4 Comparison of performance metrics (a) Integrated Squared Error (ISE), (b) Integral Time Absolute Error (ITAE), Integral Time Squared Error (ITSE) and (d) Integral Absolute Error (IAE) of PID, SPC and MSPC controllers at different deadtimes



Unstable Plant Output Response by PID Controller at Large Deadtime, t = 60 sec Ref. Chapter 1, Fig. 1.8

The Plant Output Response of Markov Approach and Kalman Estimation based Modified Smith Predictor Controller (KMSPC) at a Delay of t = 60 sec

Figure 5.5: Comparative Analysis of Plant Response using PID controller and KMSPC at Large Deadtime, t = 60 Sec

For an NCS, initially to control PID controller was used as a review study for understanding of the concepts and fundamental knowledge. As explained in Chapter 1 through Fig.1.8 that a PID controller when face large deadtime for NCS where network can be of any type it shows sluggish behavior. This restricts the usage of PID controller for large deadtime application and even in time time-sensitive applications because the condition for occurrence of deadtime is unpredictable. It was studies in Chapter 1 that for large deadtime the PID controller shows the plant response as mentioned in Fig. 5.5(a). After introducing the proposed Smith Predictor controller, it is observed through controller parameters obtained in Chapter 4 and 5 for proposed MSPC and KMSPC controllers that the plant response is improved significantly. The plant output response for KMSPC at large deadtime can be observed through Fig.5.5(b). It is visible here that beneficial change in settling time, slew rate and other controller parameters improves not only the plant response but also compensate the induced delay and reduce the probability of packet dropout. Therefore, KMSPC improves the stability and operational performance of the system.

5.5 Conclusion

The proposed modified SPC is designed in this chapter, by introducing Markov Approach and Kalman Estimation Technique in the Predicted Process Model of the SPC. The model is estimated through Markov Approach and deadtime is estimated through Kalman Technique. These proposed modifications boost the controller performance in terms of transient and steady-state response. The inclusion of these techniques in the proposed modified controller improves its settling time by 26.1%, rise-time by 31.25%, overshoot and SER by 9.5% and 25.6% respectively as compared to controllers proposed by authors cited in the reference. The improvements prove the robust control performance of the proposed controller. The modified controller in this chapter shows a significant improvement in IAE, ISE, ITAE and ITSE as compared to the proposed controllers proposed in previous chapter 4. Kalman Estimation and Markov Approach based proposed modified SPC (KMSPC) shows an average improvement of 74.29% in IAE, 79.59% in ISE, 51.97% of improvement in ITAE and 79.97% of improvement in ITSE over the MSPC for the deadtime ranges from 0.2 sec to 60 sec. The obtained improved performance metrics for the proposed modified controller (KMSPC) prove the precision in model prediction, delay compensation, and stability towards large deadtime. A comparative representation of all the controllers is shown in Fig. 5.4. that shows the deadtime compensation for large deadtime.

CHAPTER 6

NETWORKED CONTROL BASED APPLICATIONS

The networked control system is the most fundamental and significant research area in the 21st century. Almost every field of science and technology is finding its application in regard to NCS. As discussed in Chapter 1, that NCS have time sensitive or time insensitive applications. So, in this thesis author published work related to NCS for two-time sensitive application and one for the time insensitive application. The applicability of the proposed algorithms is implemented in one of the applications related to Healthcare Sector.

6.1 DESIGN AND WORKING OF THIRD EYE SYSTEM (TES)

Transformation of technology in the social, economic, and defense sectors can be achieved through the integration of image recognition with a networked control system.[15], [152]–[154]. Networked control systems and image recognition algorithm form the third eye system as seen in Fig. 6.1.

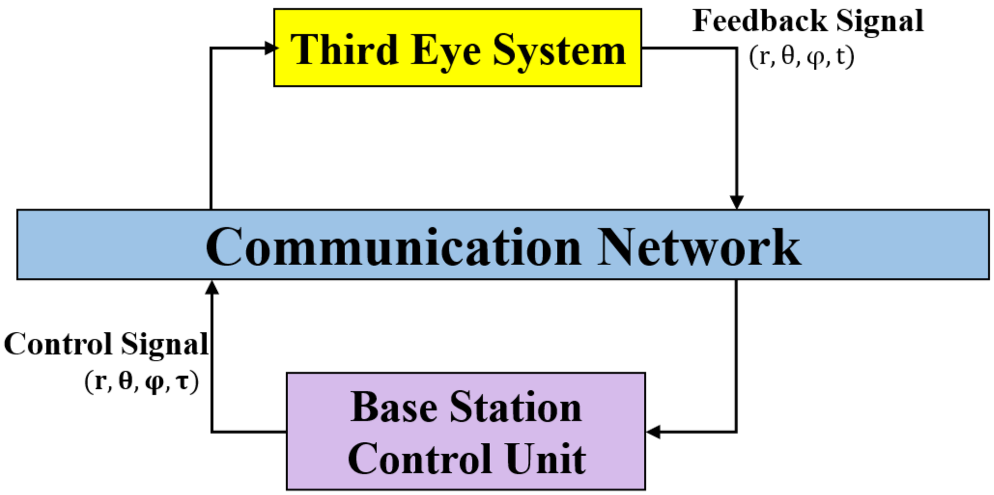

Third Eye System
Feedback Signal
(r, θ, φ, t)
Communication Network
Control Signal
$(\mathbf{r}, \boldsymbol{\theta}, \boldsymbol{\varphi}, \boldsymbol{\tau})$
Base Station
Control Unit

Figure 6.1: Block diagram of third eye system

A time-invariant system state-model can be shown as:

$$\dot{x}_i = f_i(x, \theta, \phi, t) \tag{6.1}$$

where $\dot{x}_i = \frac{dx}{dt}$ and each of function $f_i(x, \theta, \phi, t)$ for i = 1, 2, …, n is a function defining non-linearity in terms of parameters defined earlier.

This system is composed of two modules, the first of which is known as the battlefield control module (Mbf), and the latter of which is known as the base-station control module (Mbs). The Mbf is put alongside the soldier on the battlefield, while the Mbs is deployed at the base station. Fig. 6.2 depicts the modules of the Mbf in more detail. It is made up of two parts: the gun controller unit and the camera-sensor controller unit. The camera-sensor unit (CSU) put on the soldier's shoulder, gathers real-time photos of the battlefield that are not visible to the soldier's visual field of vision. These photos, together with a time stamp, are communicated to the base station for feature extraction over the secure communication network. The controlling user at the base station is in charge of keeping an eye on and regulating the two console units.

The CSU provides feedback to the Mbs in order to create a control action for the GCU, which serves as an actuator for the weapon. The Mbs is responsible for performing an important step known as the categorization process. Attributes of image sequences that are suspicious are identified by the interpolation of real-time visuals obtained from high-resolution camera sensors into proactive methodologies of detecting the apprehensive qualities in the visuals.

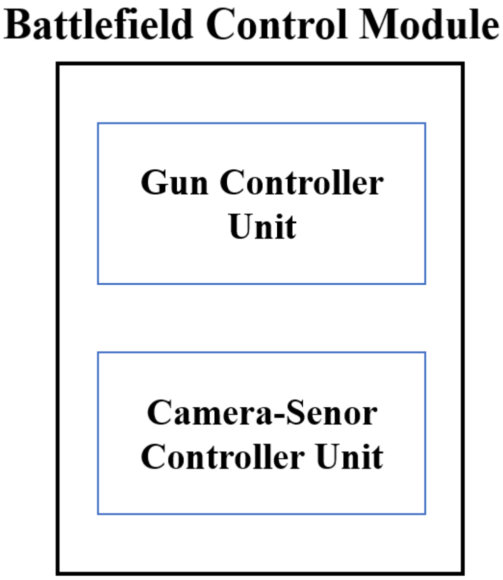


Figure 6.2: Components of battlefield control module

Object categorization in a visual can be achieved through various approaches to extract the characteristics of the visual received from the battle ground [155], [156]. For the purpose of extracting the necessary information, a number of algorithms may be developed. Further to activate the gun controller unit a control signal is transmitted over the network, when it detects a potentially unsafe entity in the visuals. This allows it to respond against any dangerous scenarios. According to Fig. 6.3, the control signal delivered from the base station to the GCU comprises the enemy's polar coordinates as well as a time stamp, and it is sent to the GCU through the radio link so a reliable and secure network is the necessity of the system [157]. Spherical coordinate system is a subset of curvilinear coordinates, which are highly useful for describing the location on a sphere or spheroid since they are very straightforward to use.

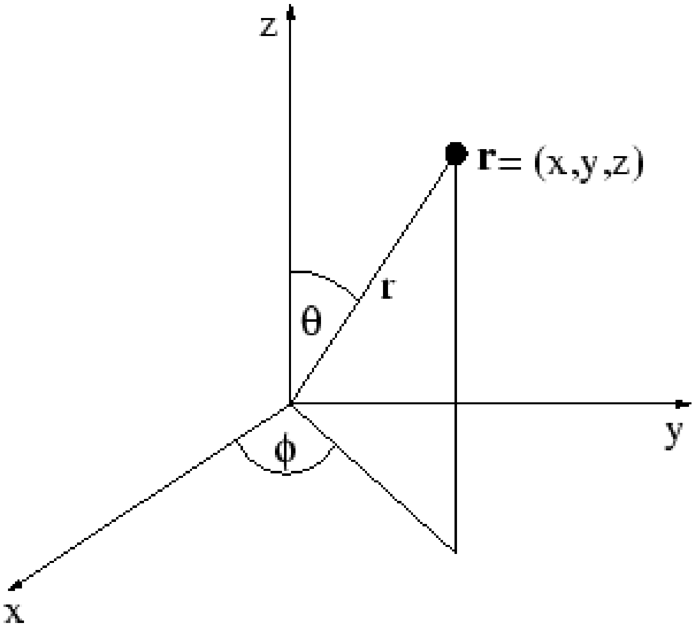


Figure 6.3: Parameters of transmitted control signal

Here,

‘r’ is an estimation of the proximity between the subject and the combatant, $r > 0$,

‘θ’ referred to as the polar angle, $0 \leq \theta \leq \pi$ and

‘φ’ is azimuthal angle or the zenith angle or colatitude with $\varphi = 90^0 - \delta$, where δ is latitude, $0 \leq \varphi \leq \pi$.

The gun controller actuator will ascertain its orientation and strike the suspect based on the polar coordinates obtained from the control signal.

6.1.1 Flowchart and Algorithm

Flowcharts are visual representations of a procedure, whereas algorithms are logical step-by-step representations. With their assistance, the third eye system may be simply comprehended. The base station device receives images with noise from the broadcast. Image enhancement techniques are used to eliminate the blemishes caused by this disturbance. As illustrated in Fig. 6.4, the collected pictures undergo several image processing algorithms to recognize the characteristics of the visual. These approaches preserve the visuals' integrity and improve their qualities. Using these processing methods, the images obtained may be utilized to analyse the battlefield conditions precisely and generate a control signal in accordance with that analysis.

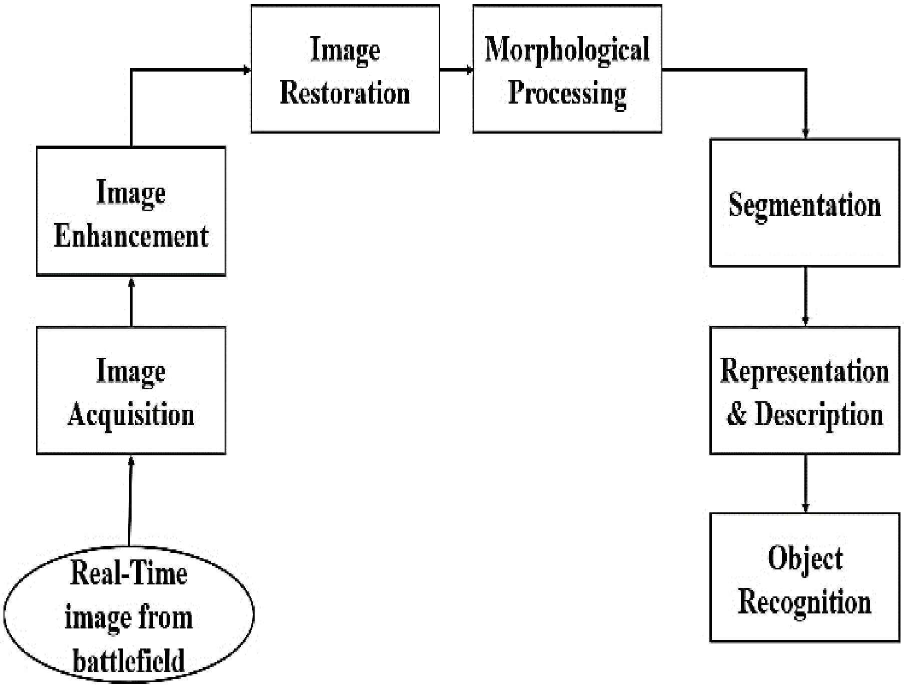


Figure 6.4: Different image processing techniques

TES is a third visual support for troops on the battlefield or espionage operations since the camera mounted on their outfit is scans the places the combatant's senses are not seeing. This third eye delivers real-time images to the Mbf over the network, where the team sitting evaluates and directs the control action to the mounted gun actuator with the camera. Fig.6.5 shows a flowchart of the complete procedure, making it easy to follow along and understand. As long as no suspicious behaviour is detected in the visuals, a null control is transmitted to the gun actuator in order to maintain communications.

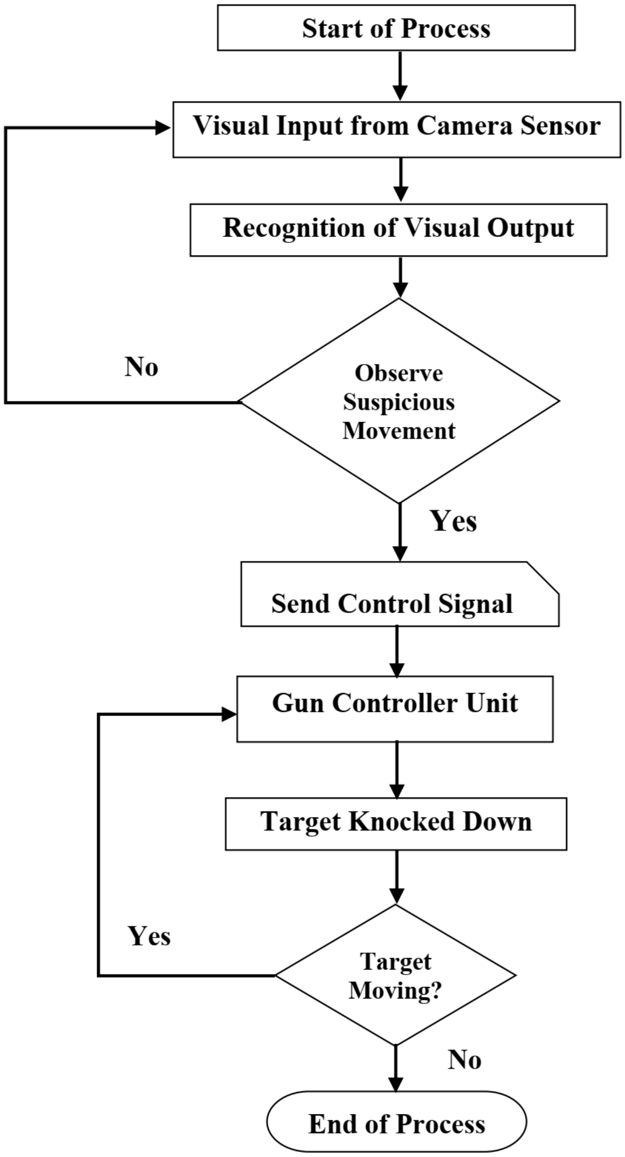


Figure 6.5: Data flow diagram of Third Eye System

An illustration of the proposed Third Eye System's intricate operation may be found in Figure 6.6.

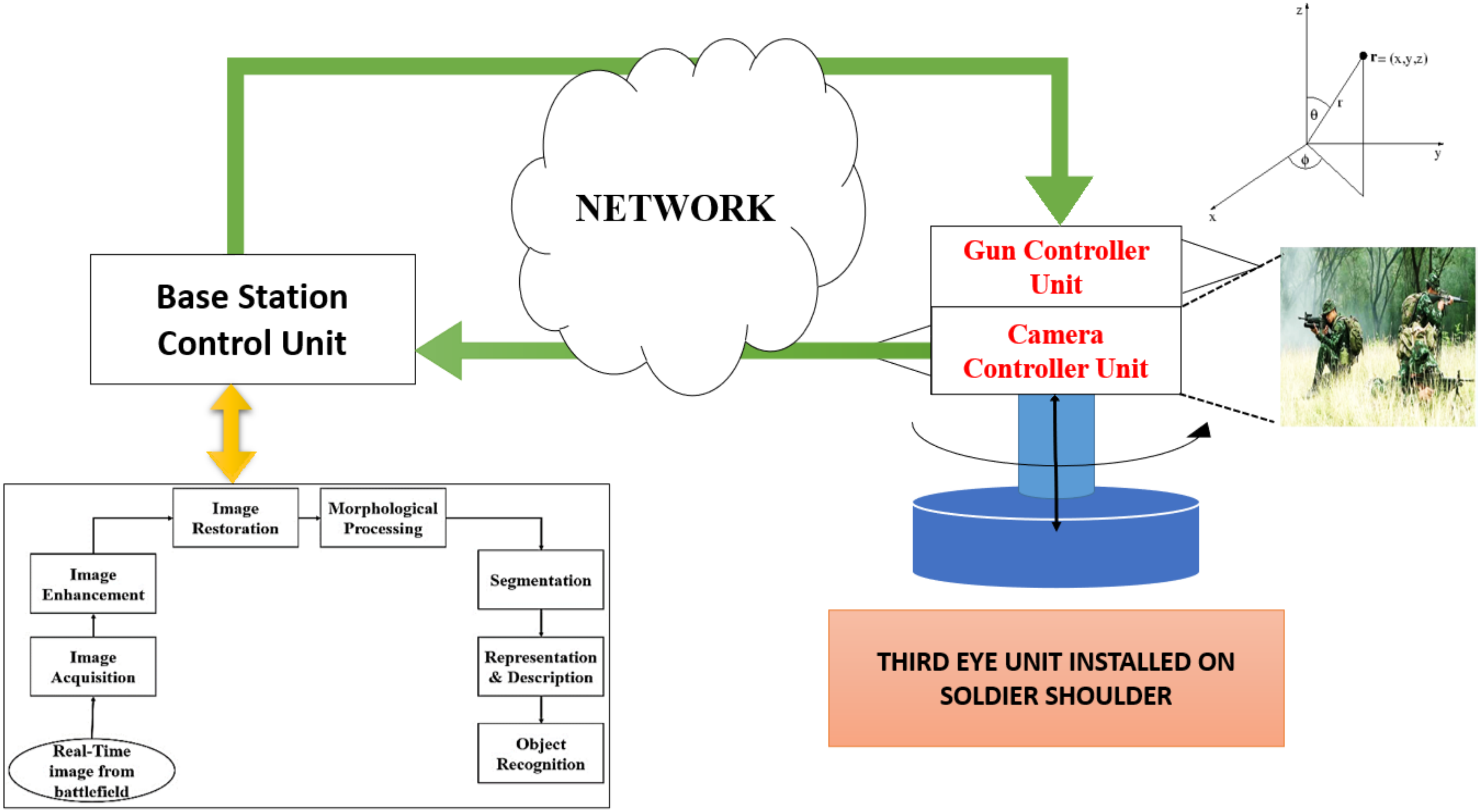


Figure 6.6: Working of Third Eye System

Table 6.1: Algorithm of Third Eye System

```
Algorithm: Third Eye Detection

Input: $x^{(i)}$, $\mu_i$, k, d
Output: Control signal to Third eye system for any suspicious movement

BEGIN{
        STEP0: Variable declaration
               $x^{(i)} \leftarrow$ Case for state i
               $\mu_i \leftarrow$ Centroid intensity
               $k \leftarrow$ Number of Clusters
               $d \leftarrow$ Distance metric
        STEP1: Input Image from Third Eye System
               Compute Intensity Distribution
               Initialize centroid with k random intensities
               Initialize $\{u_i\}i^k = 1$
       STEP2:  FOR: Each Cluster $C_j$
       STEP3:  Repeat:
       STEP4:  Cluster the points based on their intensities from the Centroid intensities
               $c^{(i)} = \arg\min_j \left\| x^{(i)} - \mu_i \right\|^2$
       STEP5:  Compute the centroid for each of the cluster
               $\mu_i = \frac{\sum_{i=1}^{m} 1\{c_{(i)=j}\} x^{(i)}}{\sum_{i=1}^{m} 1\{c_{(i)=j}\}}$
               where i iterates over the all intensities, j iterates over all the centroids.
       STEP6:  UNTIL: cluster labels of the image does not change anymore
               ENDFOR
       STEP7:  COMPARE: For any element shift of cluster labels
       STEP8:  SEND: Control Signal
    } END
```

In order to acquire meaningful results from a picture, comparable characteristics and qualities are kept in the image during the segmentation process. This method scours a visual for all of its details [14].

Both hard clustering and soft clustering, also known as K-means and C-means clustering respectively, can be used to group data. The K-means clustering methodology has a higher level of reliability than other methods since we are trying to extract meaningful information from real-time visuals received via a network.

A collection of data is allocated to one of k possible categories using k-means clustering. In the segmentation, each cluster is identified by its data member and its cluster center. All distances to other cluster members are taken into account when determining a centroid, and it is this location where all distances to other cluster members are equal. Each pixel's Euclidean distance may be determined as follows:

$$d = \|p(x, y) - c_k\| \tag{6.2}$$

Where, p (x, y) is the position of pixel at (x, y)th of the input image, c_k is center for kth cluster. Euclidean distance is used to allocate all pixels to the closest centers. As a result, the new center position is determined as follows:

$$c_k = \frac{1}{k}\sum_{y \in c_k}\sum_{x \in c_k} p(x, y) \tag{6.3}$$

followed by a series of iterations in order to achieve the desired level of tolerance. The K-means method is an iterative one. The K-means cluster is designed to maximize intra-cluster similarity while minimizing inter-cluster equality.

6.1.2 Results and Discussion

Understanding many features of the third eye system and working to optimize them is critical for the system to be implemented efficiently. A per discussion in the following section, third-eye systems rely exclusively on imaging techniques to perform their functions. While the network must be available for whole time, a comprehensive command over an actuator is essential. Examples of how we employed K-means clustering on visuals retrieved from the battlefield control module may be seen in Fig.6.4. K-means clustering is used because it is quicker than hierarchical clustering and other approaches when dealing with a high variety of variables, making it ideal for extracting information from visuals.

Actuator characteristics must be carefully controlled if accuracy is to be maintained. A servo motor is used to attach the gun's installation so that it may be precisely directed.

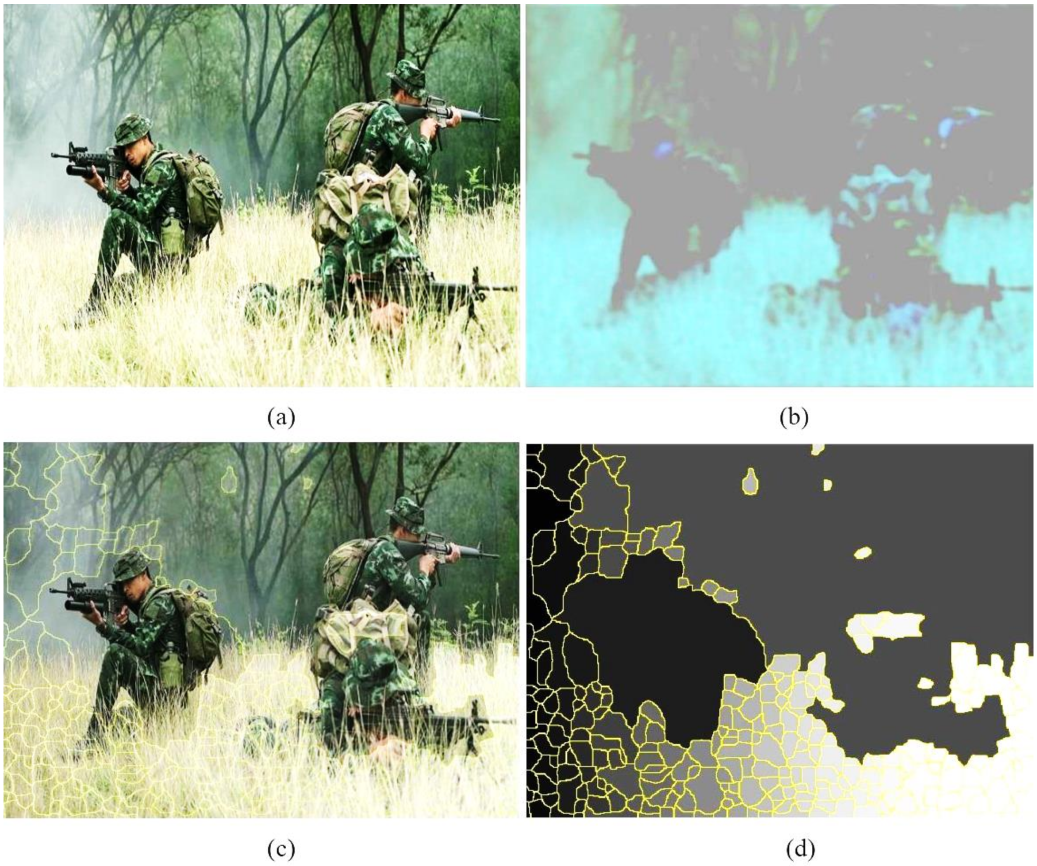


Figure 6.7: (a) Original image, (b) processed image, (c) colored partitioned image and (d) grayscale partitioned image

6.1.3 Observations

Equipment managed by humans is being phased out in favour of networked control systems, according to early trends. For any military force in the future, the integration of networked control systems with cognitive technologies such as artificial intelligence and robotics, as well as image recognition, would be the crucial determinant of both self-protective and attacking capabilities. It is proposed in this application that a third eye system be developed as a creative technique that will provide our warriors with a unique option to technology and heroism, enabling them to be both powerful and fearless. Using edge computing and different artificial intelligence and machine learning techniques, additional dimensions in the third eye system may be reached in the future.

6.2 NCS based Polyhouse Production

6.2.1 Methodology and Proposed Architecture

The contemplation of precision farming is not only quality production of crops but also to reduce the labor involved in tilthing of land, learn new techniques of sowing of seeds, manuring, and irrigation of the field in polyhouse. Networked control systems lead to lower utilization of resources and higher yields [158]–[160]. Due to artificial manure, the fertile fields suffered greatly, but due to NCS involvement in polyhouse farming, the use of artificial manure has been reduced and the quality of crops such as vegetables, fruits and flowers etc. has improved. In today's time when every single drop of water is extremely valuable, the maintenance of networked control system in Polyhouse has given the opportunity to spread the power of new irrigation techniques with minimal use of water [161].

As we have already explained that under a polyhouse, different types of crops are produced under controlled natural conditions. Various devices are used to control these natural conditions (air, water, light, humidity) [8], [162]–[164]. Traditionally, humans felt themselves living there and controlled it as needed. In such a case, everything depends on the education and knowledge of that person.

But a networked control system installed in the polyhouse farming brings different knowledgeable partner in the scenario as described in Fig. 6.8. The entire stream of information inside the polyhouse starts with different type of sensors installed in the polyhouse [165], [166].

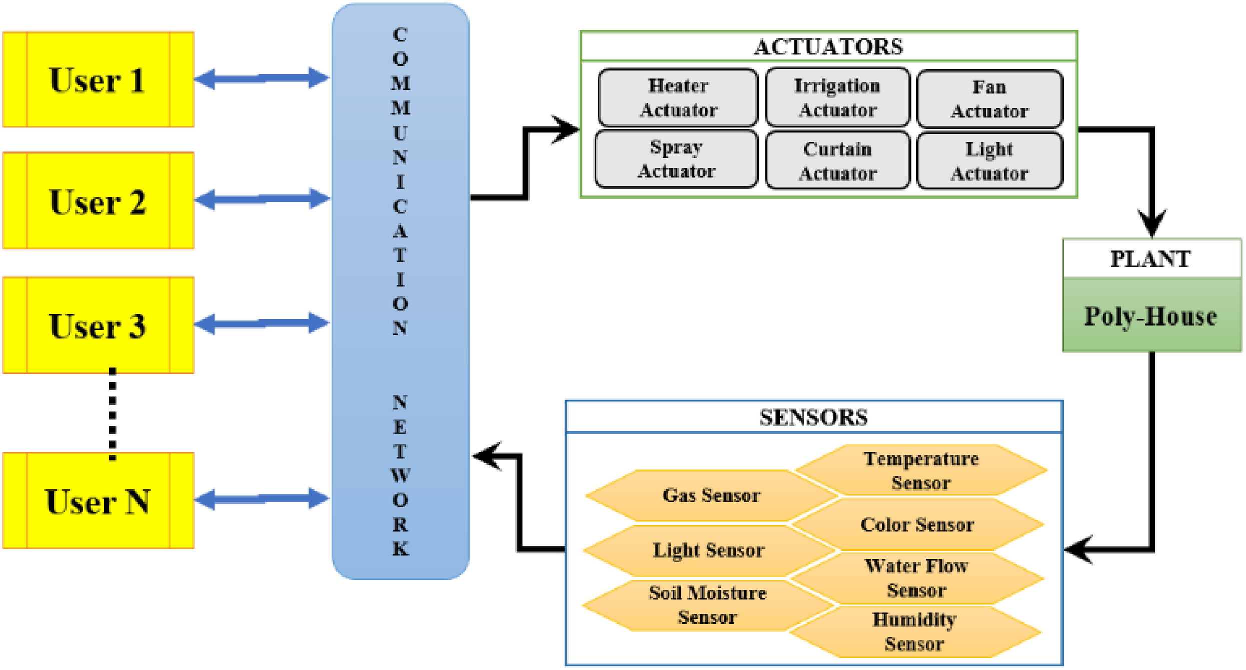


Figure 6.8: Block Diagram of Networked Control Polyhouse Farming

These sensors collect the real time information of different parameters inside the polyhouse and send these information chunks through a communication network to different users distributed over the network for further analysis and action. The physical conditions of a polyhouse can be controlled by distributed users over the network by sending a control signal to actuators installed in the polyhouse.

The three-level networked control and monitoring architecture for polyhouse precision farming can be understood with the help of Fig. 6.9. This architecture not only provide the autonomous control of the polyhouse but also keeps record of the progress of planation phases of the crops. In a polyhouse, sensors are kept at level one because these observe the physical conditions inside the polyhouse in terms of real time domain signals. Sensor node collects different type of real time data at different rates from all the sensors distributed inside the polyhouse [167]–[169]. In the second level, the collected information is transmitted through public cloud gateway to various users distributed over the network. This level has further two sub-levels, actuator-control level and data acquisition level. The former sub-level i.e., actuator-control level owes the responsibility of analysis of data and produces the control signal as needed by the actuator inside the polyhouse whereas, the later sub-level is responsible for data acquisition for further processing and future reference.

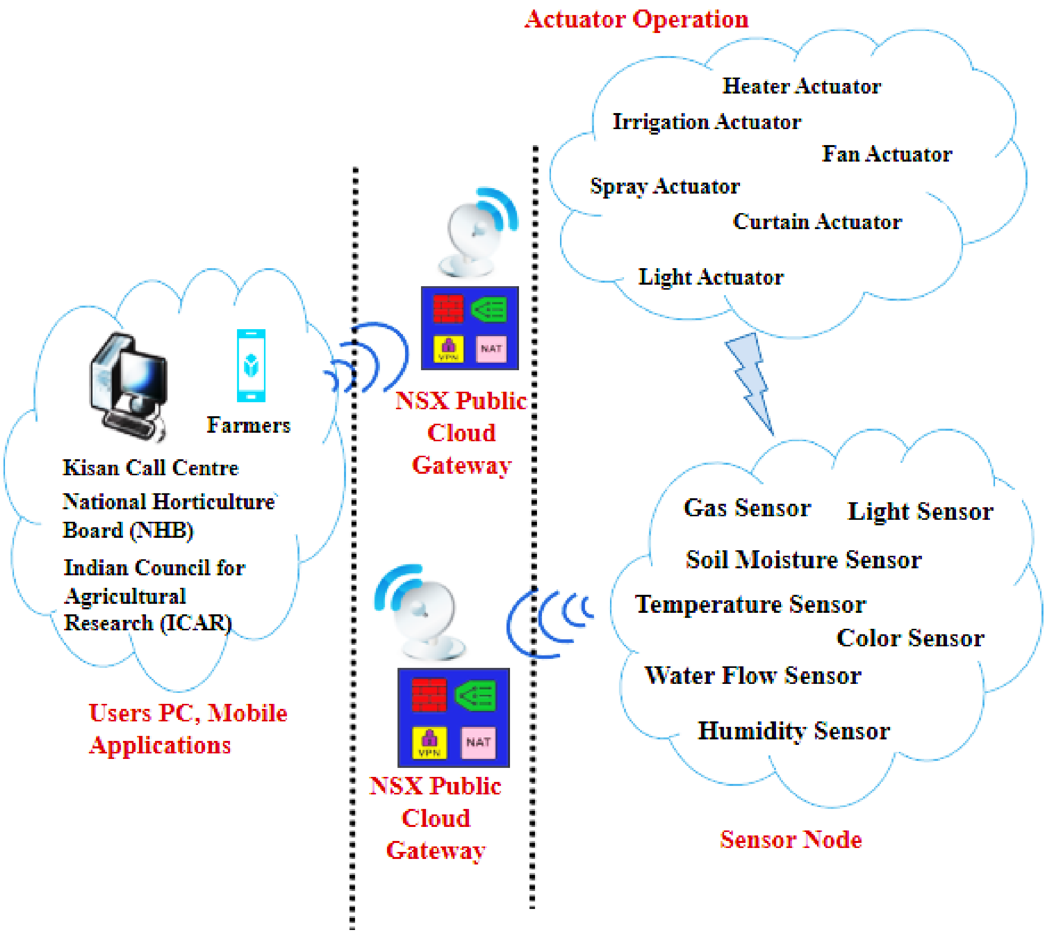


Figure 6.9: Networked Control System Architecture for Polyhouse Precision Farming

The data acquisition can be implemented at the owner level as well as at the level of various Government agencies, research and development organizations and agricultural institutes/ universities. The data acquisition at these agencies/organizations/ institutes or universities will assist the farmer of the polyhouse to know the specifics related to the yield of crops growing in the Polyhouse, the facts related to controlling the environment, and the various types of diseases in the crops and their prevention. This will further help the research and development agencies and research students of the various institutes/ universities to prepare hybrid crop immune to disease and high yielding. The third level is to regulate the actuators inside the polyhouse as per the control signal. All actuators are controlled by a microcontroller inside the polyhouse, these can be Raspberry Pi, Beaglebone, or Odroid XU4 [162], [170]. The actuator operation changes the environmental conditions of the polyhouse, which are further recoded by the sensors.

6.2.2 Simulation Results

The camera-sensor installed in the polyhouse captured different images of the crop leaves, and then those images were processed using different types of image processing techniques to identify the affected areas in the leaf. These affected areas have been analysed to detect various diseases in the crops. To understand, we took the leaf image of pea crop from a polyhouse near Shimla, this image was processed through image segmentation technique to locate the affected area on the leaf. In the similar manner number of images have been captured from the scattered area of the polyhouse to inspect the disease affected area and accordingly the quantity of spray through networked control system is decided by the command user.   This technique will the help the research and development agencies to understand various crop related disease in the polyhouse farming.

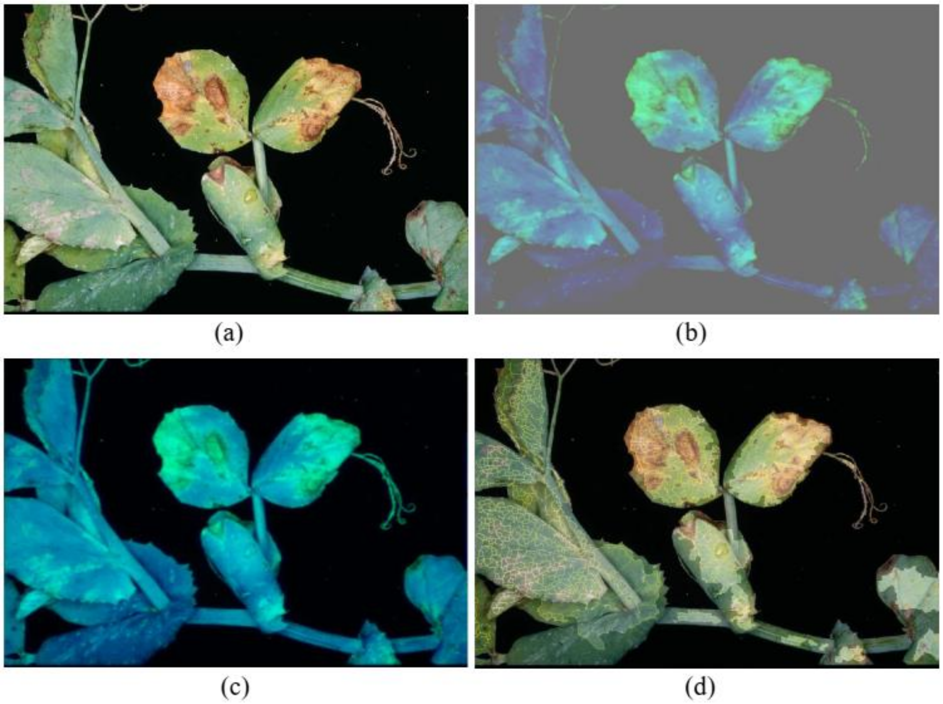


Figure 6.10: Image Segmentation of leaves to detect various Crop diseases

In Fig. 6.10, is the original image captured by camera-sensor, followed by (b), (c) and (d) output images obtained after image segmentation that can differentiate between healthy portions of the leaf to the affected area of the leaf. The computational procedure carried of these techniques, benefits to deliver the optimum results at very early stage of growing disease in the plants.

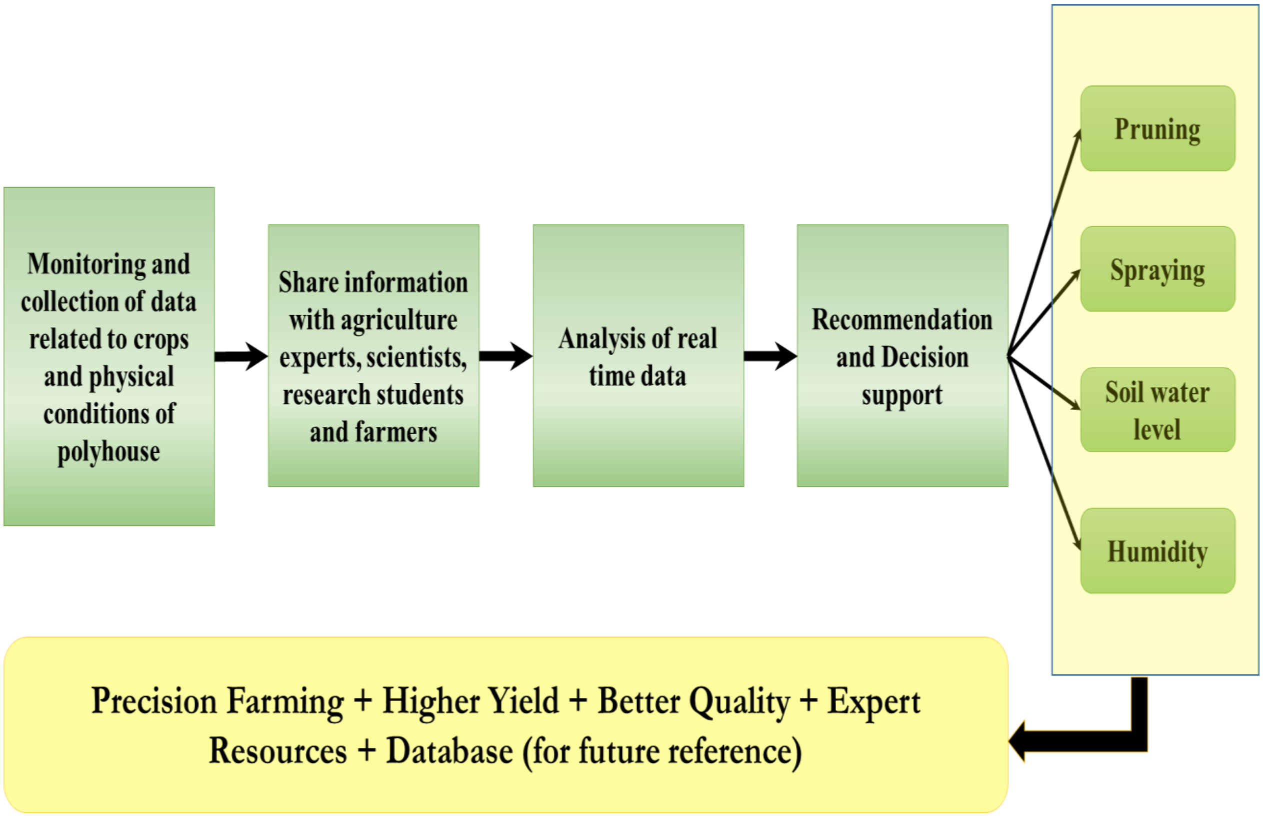

Monitoring and collection of data related to crops and physical conditions of polyhouse
Share information with agriculture experts, scientists, research students and farmers
Analysis of real time data
Recommendation and Decision support
Pruning
Spraying
Soil water level
Humidity
Precision Farming + Higher Yield + Better Quality + Expert Resources + Database (for future reference)

Figure 6.11: Functions of Proposed NCS based Polyhouse System

As mentioned in Fig. 6.11the inclusion of NCS in polyhouse can give precision in farming that would lead to higher yield and better-quality crops. The expert resources can intervene the working of NCS based polyhouse farming for research and development purpose. The various agriculturists can take benefit out of the database obtained through progressive farming to develop hybrid crops.

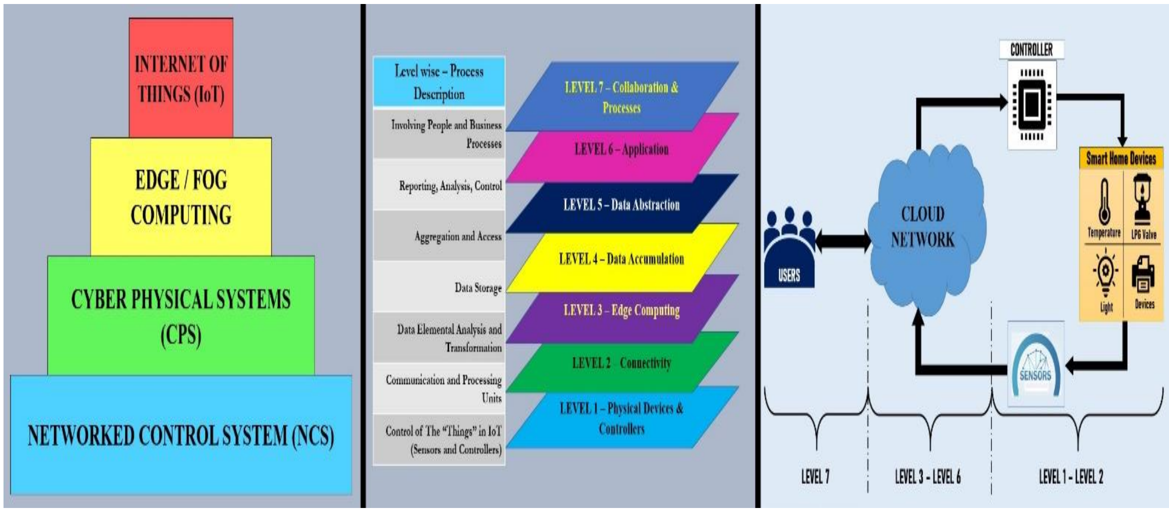
6.2.3 Observations

Under the controlled conditions of environment as per the required by crops sown in the polyhouse, their yield can be achieved 2 to 4 times as compared to the crops cultivated in the open fields. Different crops and flowers are grown in the polyhouse during offseason and their duration of cultivation is less as compared to open field cultivation. The integration of networked control system in polyhouse empowers farmers for remotely monitoring and handling capabilities of different devices in the polyhouse. With the introduction of NCS, the farmers get to know about the complete status of crops. In addition, the image processing techniques incorporated into the network control system make them aware of the crop-cycle of plants grown in the polyhouse. NCS helps scientists and researchers to develop new improved varieties of agriculture by data stored in the databases. NCS helps us to grow quality and advanced crops with less time taken to grow crops in polyhouses because diseases associated with crops, nutritional deficiencies, adapted environment are all easily known with the help of NCS.

6.3 Smart Home Health Mobile Application (SHHMA)

6.3.1 Concept and Motivation

Internet of Things (IoT) is an amalgamation of different configurable resources that allow geographically spread users through networks to access diverse, convenient, and on-demand services [20]. This technological progress leads to several applications, such as smart cities [172], smart grid [173], smart homes, industries, ease through smart transportation, smart healthcare services, surveillance are few that shows the expansion of IoT [174]–[176]. This progression has enabled the increased connectivity of several different devices with interoperable communication protocols and software. It enables connecting everything or anything for anyone at any time at any place. Hence, the foremost system characteristics that IoT needs to support are diversification, scalability, wireless technologies to share data ubiquitously around the globe, energy-efficient solutions, proficiency in tracking and localization, self-organization competencies, and semantic reciprocality and data management [157], [177] This rises a sophisticated relationship of IoT with a feedback control system. Since traditional feedback control system is modernized through the involvement of network as a networked control system (NCS). Fig. 6.12 (a), describes the inter-relationship among IoT and NCS to approach various services through the network. It is evident in Fig. 6.12(b) that level 1 and level 2 as per IoT Reference Model published by IoT World Forum (IoTWF), represents the connectivity, control, and monitoring of physical devices to generate data accessed by end-user at level 7. These two subsequent levels responsible are for data delay and dropout which may destabilize the system. And Fig. 6.12(c) represents the illustration of a networked control system where possible delays can be observed [178]–[180].


INTERNET OF THINGS (IoT)
EDGE / FOG COMPUTING
CYBER PHYSICAL SYSTEMS (CPS)
NETWORKED CONTROL SYSTEM (NCS)
Level wise – Process Description
Involving People and Business Processes
Reporting, Analysis, Control
Aggregation and Access
Data Storage
Data Elemental Analysis and Transformation
Communication and Processing Units
Control of The "Things" in IoT (Sensors and Controllers)
LEVEL 7 – Collaboration & Processes
LEVEL 6 – Application
LEVEL 5 – Data Abstraction
LEVEL 4 – Data Accumulation
LEVEL 3 – Edge Computing
LEVEL 2 – Connectivity
LEVEL 1 – Physical Devices & Controllers
CONTROLLER
Smart Home Devices
Temperature
LPG Valve
Light
Devices
USERS
CLOUD NETWORK
SENSORS
LEVEL 7
LEVEL 3 - LEVEL 6
LEVEL 1 - LEVEL 2

(a) (b) (c)

Figure 6.12: (a) representing the basic framework of IoT and other Technologies, (b) representing the IoT Reference Model as per IoTWF and (c) representing the incorporation of NCS in IoT at Level 1 - Level 2

The provision of aided services allows for a more pleasant and suitable routine. The main function of any intelligent smart home-health computerization system is to help patients track and manage networked enabled services and devices [181]. In this context, the author is encouraged to design a system that not only regulate and command the home though also motivates patients to live in a better way. Smart home health automation was applied in several sectors as an evolving industry of IoT [182]. These techniques led to supervision and care of recently discharged patients, disabled and elderly people by monitoring their movement in-out of the house, manage and control appliances remotely for their wellbeing and providing healthcare services at their doorstep. Though, the design of the system that can control your home appliances and monitor your health is yet to be fully explored [183]. In light of this, consider the following scenario: David is a Covid patient who has just been released from the hospital after recovering from the infection but still requires his physiological vitals to be regularly checked by his doctor, and he is advised to live in quarantine. For David to live in isolation pleasantly, he needs to be able to control each appliance installed in the home remotely while lying in the bed and have connectivity through social networks. We developed the notion of constructing an intelligent home-health automation system to help people in the predicament of David. The system presented detects and archives physiological properties in a module, passes the information on to a physician, and also controls the residential equipments. The country has enacted social distances, reduced physical communication, and remained at home to restrict the spread of the infection. For patients who have had positive tests, but do not have indications, self-isolation or self-quarantine is also advisable for a few days. It is suggested to remain in solitude for patients with Covid positive reports [184]–[186]. The patients living in isolation can be monitored remotely through the proposed Smart home-health application on regular basis and their physiological reports can be wirelessly administered by concerned doctor for further diagnosis and medication. To this, the author expands the scope of the application and provide patients with a convenience that patients in their own home can fill and submit automated Covid-19 assessment form with COVID-19-related illnesses to the doctor. After careful examination of the filled in data doctor will discuss the findings related to Covid-19 infection [187]–[190].

Sometimes the patient may have to adjust his/her position in the house, regulate his/her thermostat at home or adjust any other environmental components which may change the recorded physiological metric. About external factors that influence physiological parameters, this article draws upon the relational neural network (RNN) as a widespread context (RNN). The concept of RNN is extensively described in this work to draw the reference concerning the parameters affected by the change in physical parameters [191]–[193].

6.3.2 Scope of the Proposed System

Remote health monitoring, consultations, and prescriptions have all become possible thanks to the networked assisted Internet of Things.

Sensors, actuators, microcontrollers, and boards are elements of networked control system that have made it possible for doctors to access patients’ information to monitor their health despite having to come to the hospital. On the patient side, technology has considerably aided in reducing stress because patients no longer have to wait in lines in hospitals and thus can transmit reports to their doctors via IoT-enabled health monitoring equipment.

Additionally, patients' physiological parameters can be recorded and transferred to a database for review by a clinician for medical diagnosis and therapeutic guidance. Because the proposed system is designed for pleasant daily activities in the home, disabled and elderly persons are also taken into account. The home is remotely managed in our suggested system via a designed mobile platform put on a smartphone, and the user may also contact the doctor via another module within the same app. The approach other than Covid-19 disease is also centred on medical issues such as persistent chronic diseases.

6.3.3 System Architecture

The challenging times of the Covid-19 epidemic have given us the versatility to explore innovation in technology to its full potential. Smart Healthcare application is popped out as a new application field in such critical situations, which have huge possibilities to bring ease in the lifestyle of the people.

The proposed Smart healthcare system is elaborated in Figure 1 that depicts the working design of the application. Three modules are presented in the figure as the doctor's side (DS), the controller's side i.e., home device network management (HDNM), and the patient's side (PS). The doctor’s side consists of the Hospital’s list, database, and monitoring module of the doctor. To perform control action and connectivity among sensors and other devices Raspberry Pi 3 Model B+ is used as a microcomputer that will control the actuation mechanism of all the appliances as shown in Fig.6.13. The physiological parameters also depend upon the physical conditions around us in which we breathe and the physical movement of the body. So, it is of utmost importance that we must take care while measuring the physiological parameters. Likewise, the blood pressure rises for a person in continuous motion as compared to a person at rest. Similarly, the blood sugar level or body temperature also varies with the time of eating a meal and surrounding temperature. To conclude accurate physiological measurement of a person a relation among these parameters is established using basic relation neural network.

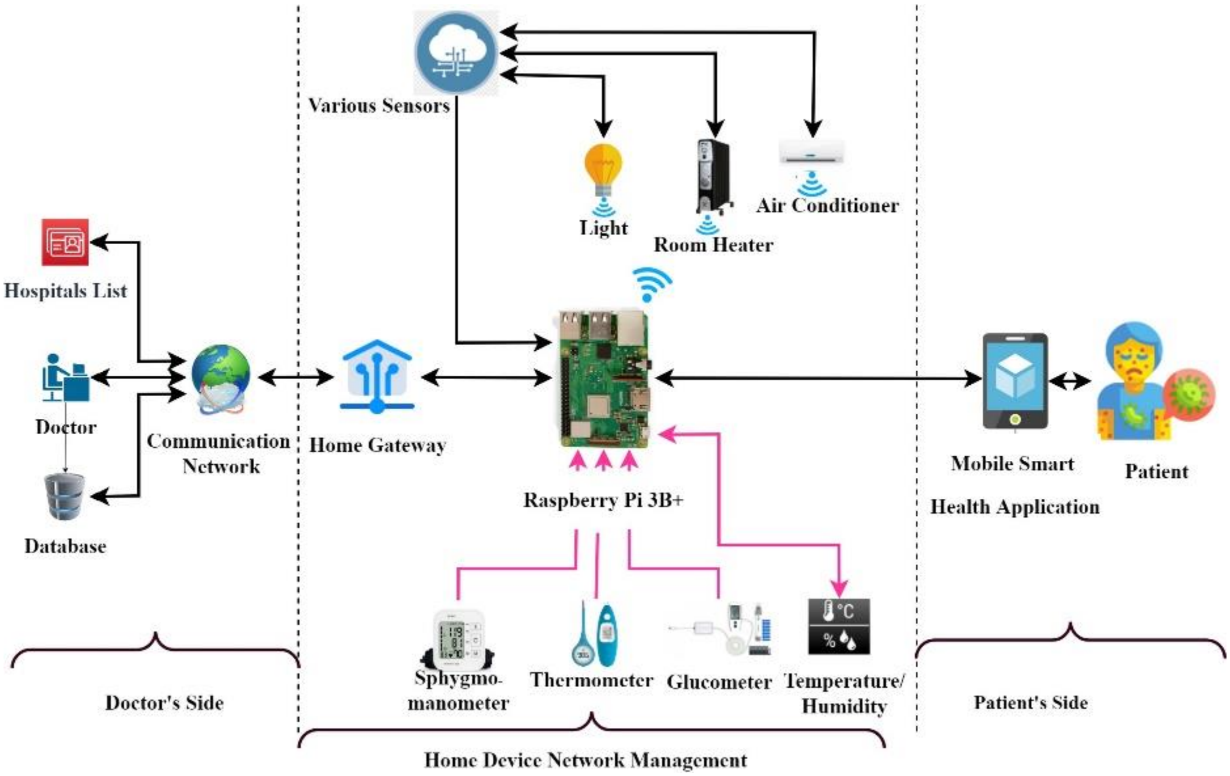


Figure 6.13: Proposed system architecture elaborating connectivity and control components

The hardware components to build the system include the following:

Sensors: In the proposed framework of information from the patient's body that is wirelessly sent to the microprocessor via the home router portal, the variety of sensors installed with the patient are often used to record information stored in a database and transmitted to the doctor via the world wide web. The equipment and sensors help to relieve human stress [194].

Raspberry Pi Board: The system's functionality is overseen by the microcomputer. IoT devices and utilities are linked to the Raspberry pi for data gathering and communication inside the network, as well as to the smartphone device for home services and control. Household appliances parameters are transmitted and so regulated using the digital pins found on circuits. Home appliances rely heavily on boards for their operations.

6.3.4 Relational Neural Network

Relational reasoning, according to the author, is the method of interpreting how elements are interconnected and applying that knowledge to achieve a higher-level purpose [136], [156], [195]. Our primary design approach is to create an architectural backbone that allows a model to learn to rationalize data and compute correlations between segregated data, the architecture is shown in Fig.6.14, building bricks are put together and make use of the architecture of a neural network model that dictates how the individual neurons are linked to one another, and hence how all of the input characteristics interact [196].

The domain structure, or collection of relational rules that govern how distinct interactions, entities, and features interact in the domain, dictates the design of a relational neural network.

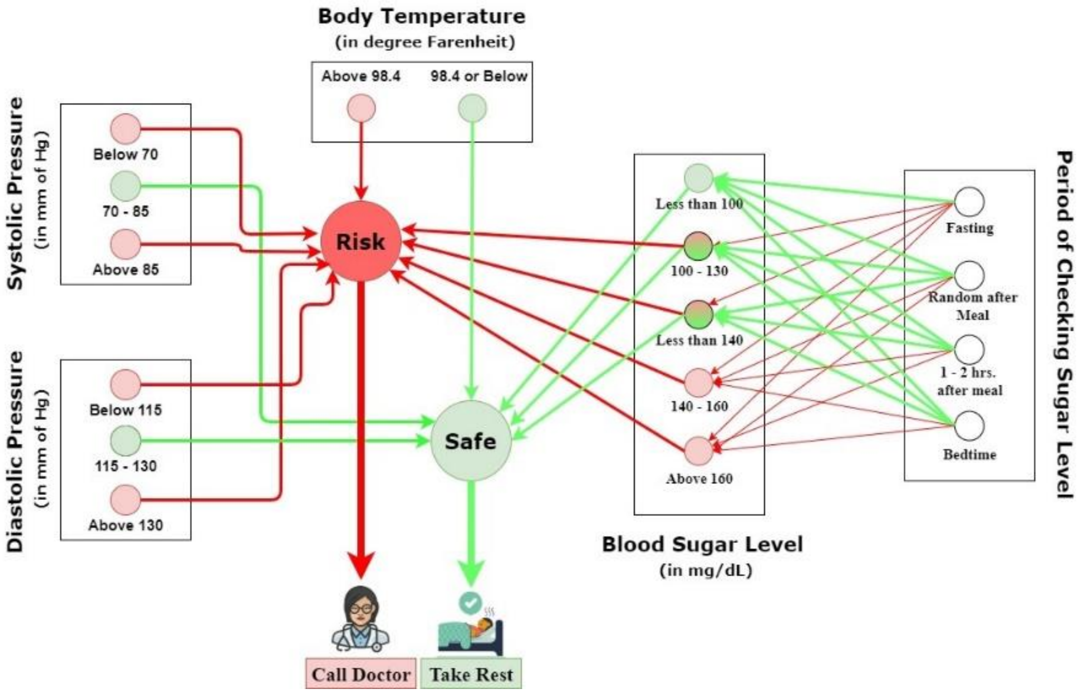


Figure 6.14: Representation of Basic Relational Neural Network for the proposed system

6.3.5 Design and Working

A room in the house has been chosen as the work's regulated area. The temperature, cooling system, and other basic home equipment such as the light switch and television are among the features that the program will control. The user enters the desired temperature into the built mobile application for home temperature management, which is then saved in the Raspberry Pi’s memory unit. The DHT11 humidity and temperature sensors are used to record the temperature. If the system temperature is below the intended value set as input by the user, the user is notified and the system switches on the heater to warm up the environment. If the detected temperature is more than the referenced value, the air conditioner immediately switches on to maintain the required input. To control other home devices, the user selects the appropriate device on the mobile app, and a signal is transmitted to the microcomputer Raspberry Pi that conducts the required operation on the device.

Table 6.2: Algorithm representing the working of Control Elements and their response

Steps:	Algorithm 1:
Step 1	Initiate
Step 2	Initialize HD
Step 3	Evaluate the initial state of HD
	If HD = n (where n = total number of configured devices
Step 4	Start NC
	Else, go to step 3
	If NC = 1; $\forall$ HD $\in$ NC, here 1 defines the connectivity
Step 6	Start CHD
	Else, repeat step 4
	While NC && CHD = 1; continue till the reference value is attained
Step 7	Switch on SBD and DBD
Step 8	Record values of SBD and DBD
	If SBD $\in$ {70 – 85} && DBD $\in$ {115 – 130}
Step 9	Activate Message: Take Rest
	Else, Initiate Call to Doctor
	End If
Step 10	Switch on BSL
Step 11	Record BSL
	If BSL $\in$ {70 – 140}
Step 12	Activate Message: Take Rest
	Else, Initiate Call to Doctor
Step 13	Switch on BT
Step 14	Record value BT

```
        If BT < 98.4
Step 15 Record after 4 hours
Step 16 Else, Initiate Call to Doctor
Step 17 Send all values to Database
        End
```

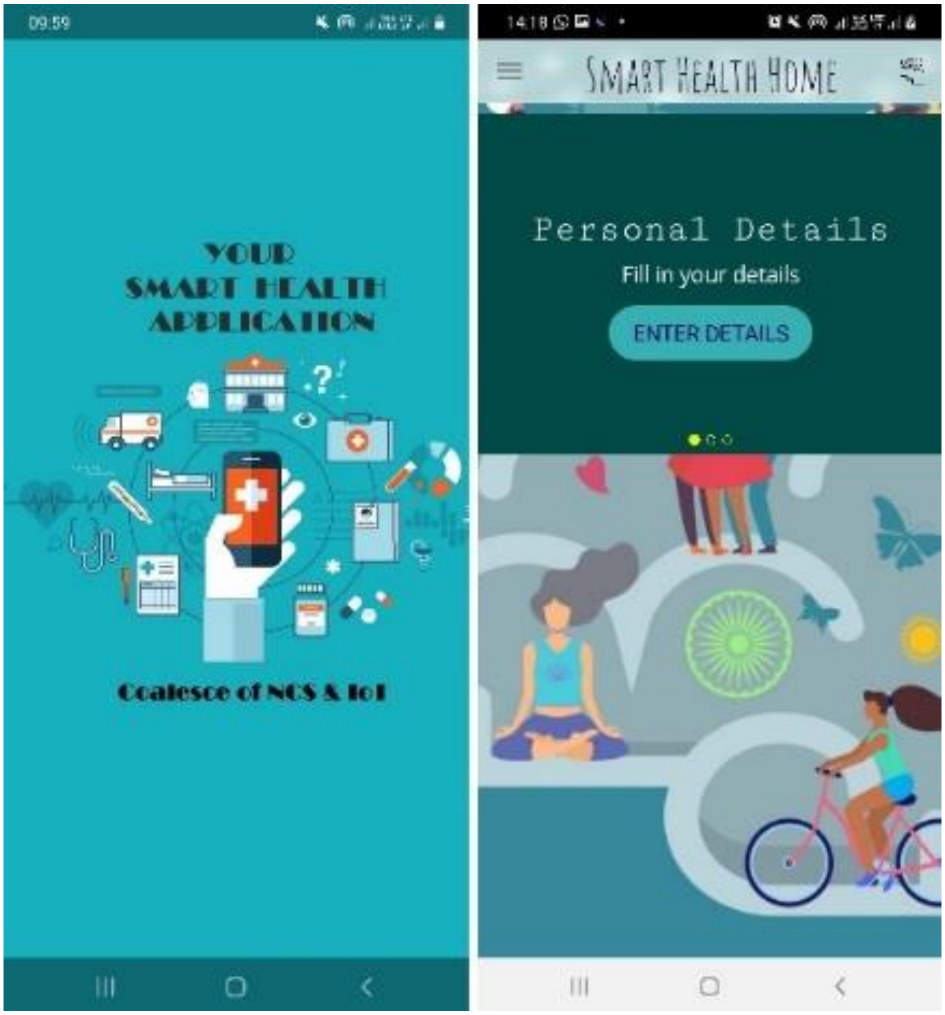
The Smart Health Monitor's architecture consists of physiological parameters that must be checked by the patient and then entered into the Smart Health Android application for monitoring and control. Logging onto the application requires credentials; users must submit a username and password to gain access to the system. Physiological factors that can be assessed include body temperature, blood glucose level, and systolic and diastolic blood pressure. This specially built application will deliver these parameters to the doctor. Physiological parameters can also be gathered wirelessly using a body sensor. For system development and physician feedback, the measured parameters will be kept in a database. The Raspberry-pi microprocessor will send an alarm message or email to the doctor through the internet if the recorded physiological parameters do not fall within Algorithm 1's prescribed range. And the doctor will communicate with the patient by phone, chat, message, or video call over the internet using the built-in program. To arrive at a final choice, algorithm 1 employs a basic relational neural network algorithm to achieve needful actions for precise evaluations. The following terminologies are used to define the algorithm 1:

HD describes the home device, NC describe network connection, CHD describe control home device, SBD describe systolic blood pressure follow a normal range between 70 – 85, DSD describe diastolic blood pressure follow normal range as between 115 – 130, BSL describe blood sugar level with a range between 70 – 140 checking at different periods such as Fasting, Random after the meal, 1 – 2 hours after meal or during Bedtime.

BT describes the body temperature with range safe value, SV < 98.4 and AV > 98.4 as Alert value.

6.3.6 Results and Discussion

The proposed smart health-home application is an android mobile phone and web-based application. The start-up window of the application is shown in Fig. 6.15(a). The main screen of the application informs to enter personal details of the patient, as illustrated in Fig. 6.15(b), these details are stored in the database as a future reference of the patient’s information for the convenience of the doctor.



(a) (b)

Figure 6.15: (a) showing the starting screen, (b) main window of the application

The framework design, as previously described, does have patient and doctor sides. Following the successful login, the customer (patient) can utilize the software to execute the following fundamental operations shown in Fig. 6.16 as:

- Control housing gadgets
- Contact Medical Practitioner for medication and prescriptions

- Report virus indications to the doctor while in quarantine
- Converse with the doctor on live video
- Send routine physiological readings for a routine check-up
- Order ambulance for any emergency
- Schedule a medical appointment
- View medical data
- Contact with friends while in quarantine through various social platforms
- Book for any blood or other Test in the prescribed laboratories
- Order Prescribed meals from different cuisines

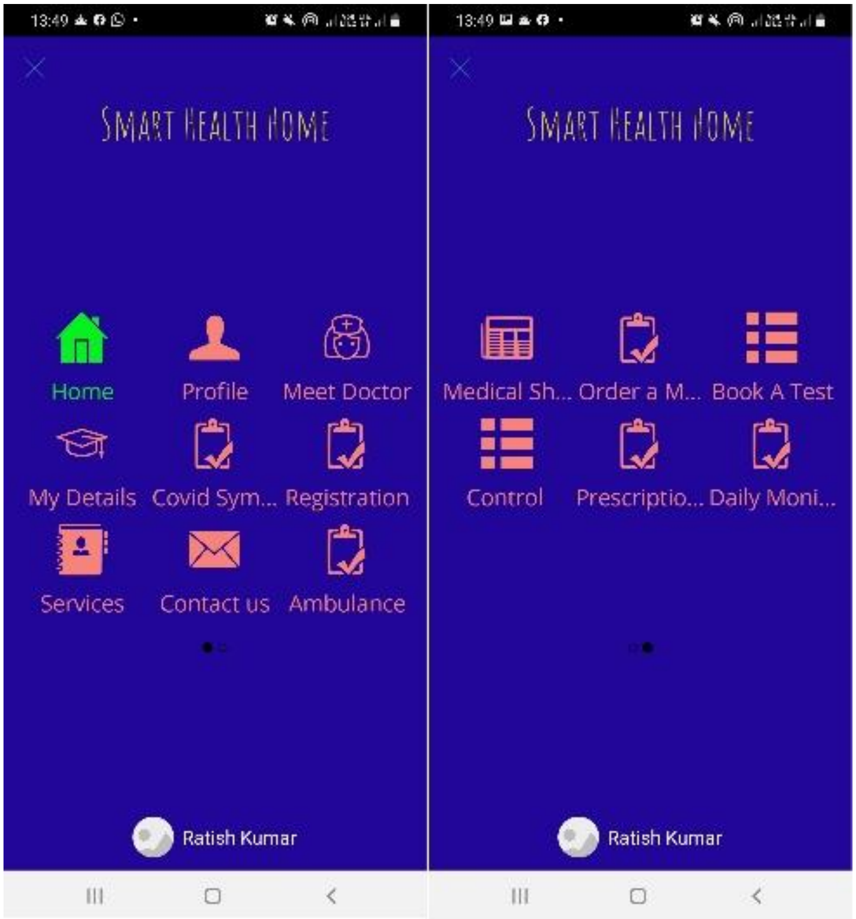
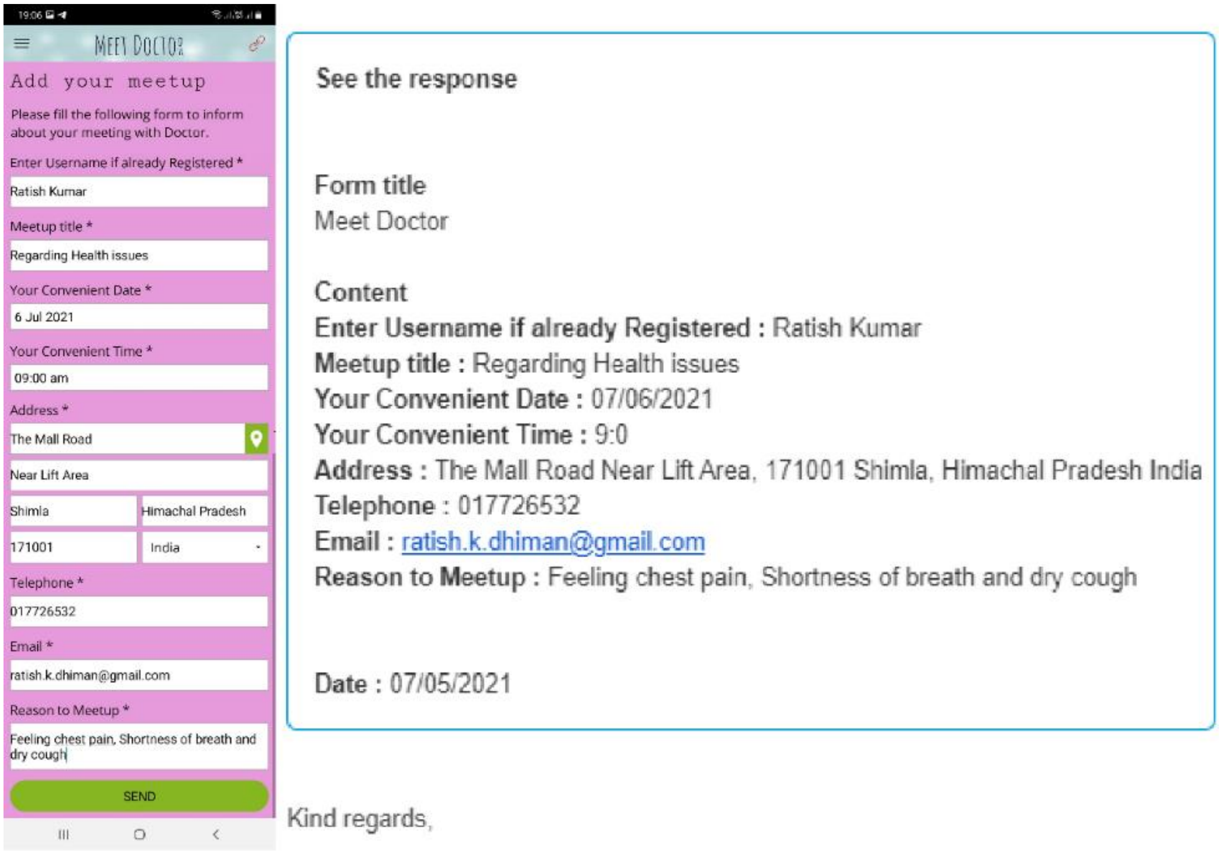


Figure 6.16: Representing the various items in the menu of the application

The patient can sign in and complete out the necessary information to consult with the doctor, as well as can schedule a meeting with a doctor as per convenience. As an example, in Fig. 617, (a) the form for a meeting request is filled out, and (b) shows the doctor's side where the doctor receives the meeting request. Every individual is being gripped by the infectious virus Covid-19, thus there is constantly a fear of becoming infected. The online applications ask for your input and display the findings, but they never are satisfied as they are automated.



Add your meetup

Please fill the following form to inform about your meeting with Doctor.

Enter Username if already Registered *
Ratish Kumar

Meetup title *
Regarding Health issues

Your Convenient Date *
6 Jul 2021

Your Convenient Time *
09:00 am

Address *
The Mall Road
Near Lift Area
Shimla
Himachal Pradesh
171001
India

Telephone *
017726532

Email *
ratish.k.dhiman@gmail.com

Reason to Meetup *
Feeling chest pain, Shortness of breath and dry cough

See the response

Form title
Meet Doctor

Content
Enter Username if already Registered : Ratish Kumar
Meetup title : Regarding Health issues
Your Convenient Date : 07/06/2021
Your Convenient Time : 9:0
Address : The Mall Road Near Lift Area, 171001 Shimla, Himachal Pradesh India
Telephone : 017726532
Email : ratish.k.dhiman@gmail.com
Reason to Meetup : Feeling chest pain, Shortness of breath and dry cough

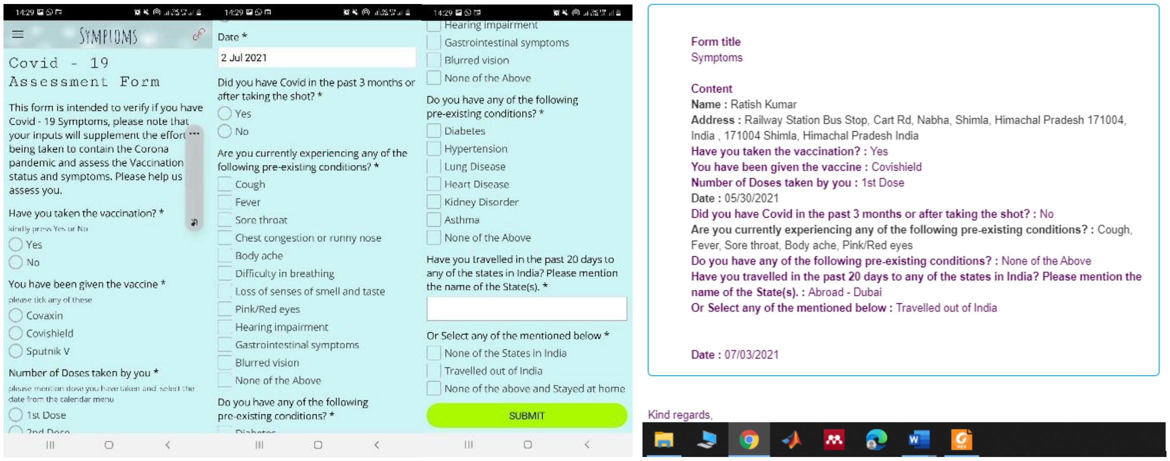
Date : 07/05/2021

Kind regards,

(a) (b)

Figure 6.17: (a) Representing the form filled by a patient in mobile application, (b) Response received by the doctor for further concern.

The virus is new to the world and requires a physician's interpretation for every individual for its recognition. So, in this application, the author introduces a Covid-19 assessment form, as shown in Fig. 6.18(a), which will be filled out and delivered to the doctor, who will then notify the patient about the next steps after a thorough examination. Fig. 6.18(b) depicts the form received from the doctor (b).



Covid - 19 Assessment Form

This form is intended to verify if you have Covid - 19 Symptoms, please note that your inputs will supplement the effort being taken to contain the Corona pandemic and assess the Vaccination status and symptoms. Please help us assess you.

Have you taken the vaccination? *
kindly press Yes or No
○ Yes
○ No

You have been given the vaccine *
please tick any of these
○ Covaxin
○ Covishield
○ Sputnik V

Number of Doses taken by you *
please mention dose you have taken and select the date from the calendar menu
○ 1st Dose
○ 2nd Dose

Date *
2 Jul 2021

Did you have Covid in the past 3 months or after taking the shot? *
○ Yes
○ No

Are you currently experiencing any of the following pre-existing conditions? *
□ Cough
□ Fever
□ Sore throat
□ Chest congestion or runny nose
□ Body ache
□ Difficulty in breathing
□ Loss of senses of smell and taste
□ Pink/Red eyes
□ Hearing impairment
□ Gastrointestinal symptoms
□ Blurred vision
□ None of the Above

Do you have any of the following pre-existing conditions? *
□ Diabetes
□ Hypertension
□ Lung Disease
□ Heart Disease
□ Kidney Disorder
□ Asthma
□ None of the Above

Have you travelled in the past 20 days to any of the states in India? Please mention the name of the State(s). *

Or Select any of the mentioned below *
□ None of the States in India
□ Travelled out of India
□ None of the above and Stayed at home

Form title
Symptoms

Content
Name : Ratish Kumar
Address : Railway Station Bus Stop, Cart Rd, Nabha, Shimla, Himachal Pradesh 171004, India , 171004 Shimla, Himachal Pradesh India
Have you taken the vaccination? : Yes
You have been given the vaccine : Covishield
Number of Doses taken by you : 1st Dose
Date : 05/30/2021
Did you have Covid in the past 3 months or after taking the shot? : No
Are you currently experiencing any of the following pre-existing conditions? : Cough, Fever, Sore throat, Body ache, Pink/Red eyes
Do you have any of the following pre-existing conditions? : None of the Above
Have you travelled in the past 20 days to any of the states in India? Please mention the name of the State(s). : Abroad - Dubai
Or Select any of the mentioned below : Travelled out of India

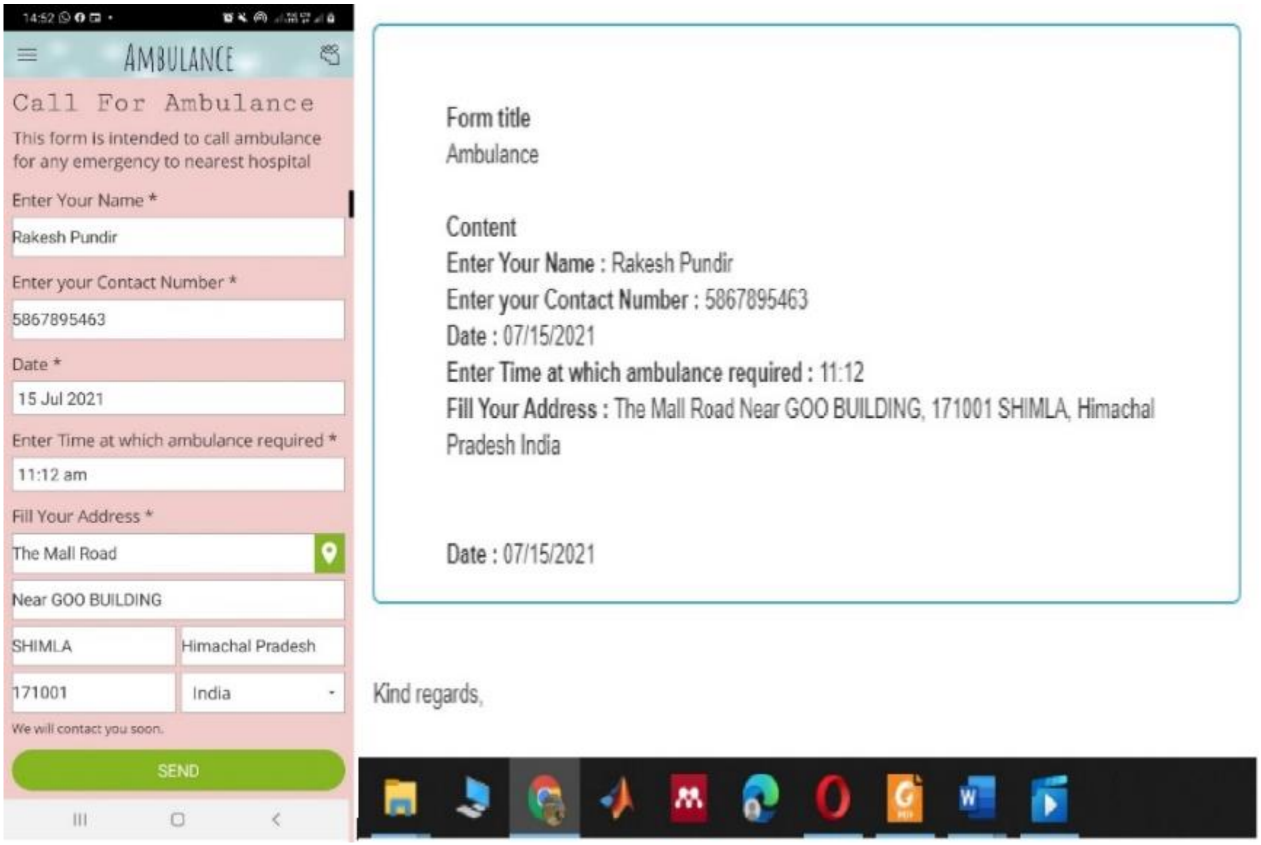
Date : 07/03/2021

Kind regards,

(a) (b)

Figure 6.18: (a) representing Covid-19 assessment form, (b) Response at doctor's end for decision

This application allows patients to request an ambulance at their leisure; all they have to do is fill out a form displayed in Fig. 6.19(a) and submit it immediately. The doctor and employees with information will receive a computerized request for further action; the doctor's side is represented in Fig. 6.19(b). In quarantine it is very difficult for the patients to be monitored by some medical practitioner, this application monitors the physiological parameters of the patient and records these parameters for any supervision. The blood pressure, blood sugar level, body temperature, etc., can be manually entered by the patient or caregiver or are wireless monitored through body sensor networks. These recorded parameters are evaluated for their satisfactory values and in case of any medical issue system automatically informs the doctor of an emergency.



Call For Ambulance

This form is intended to call ambulance for any emergency to nearest hospital

Enter Your Name *
Rakesh Pundir

Enter your Contact Number *
5867895463

Date *
15 Jul 2021

Enter Time at which ambulance required *
11:12 am

Fill Your Address *
The Mall Road
Near GOO BUILDING
SHIMLA
Himachal Pradesh
171001
India

We will contact you soon.

Form title
Ambulance

Content
Enter Your Name : Rakesh Pundir
Enter your Contact Number : 5867895463
Date : 07/15/2021
Enter Time at which ambulance required : 11:12
Fill Your Address : The Mall Road Near GOO BUILDING, 171001 SHIMLA, Himachal Pradesh India

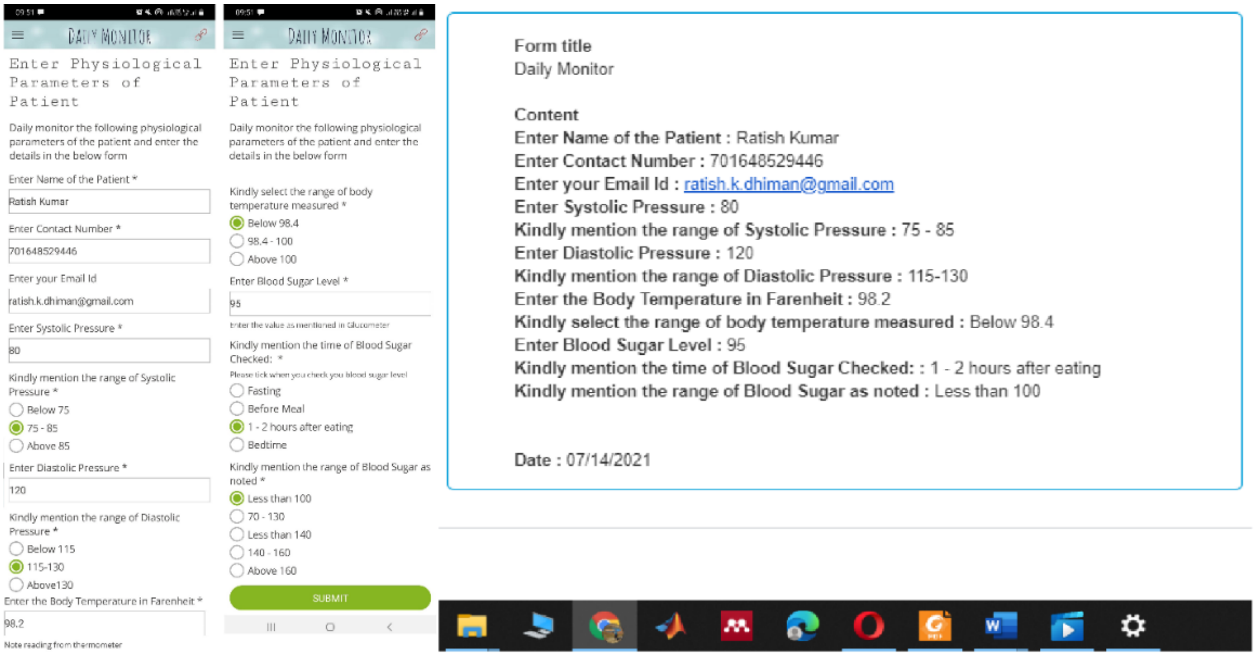
Date : 07/15/2021

Kind regards,

(a) (b)

Figure 6.19: (a) shows the filled request form for an ambulance by the patient, (b) the request form received at the doctor's side

Fig. 6.20(a) shows the daily monitoring form filled manually and Fig. 6.20(b) represents the filled form received on the doctor’s side, it contains all the necessary details regarding the physical vitals of the patient. Most of the time people forgot about the schedule of the medicines to be consumed, how and when they must be taken. The proposed application provides a medicine prescription facility.



DAILY MONITOR

Enter Physiological Parameters of Patient

Daily monitor the following physiological parameters of the patient and enter the details in the below form

Enter Name of the Patient *

Ratish Kumar

Enter Contact Number *

701648529446

Enter your Email Id

ratish.k.dhiman@gmail.com

Enter Systolic Pressure *

80

Kindly mention the range of Systolic Pressure *

○ Below 75
● 75 - 85
○ Above 85

Enter Diastolic Pressure *

120

Kindly mention the range of Diastolic Pressure *

○ Below 115
● 115-130
○ Above130

Enter the Body Temperature in Farenheit *

98.2

Note reading from thermometer

DAILY MONITOR

Enter Physiological Parameters of Patient

Daily monitor the following physiological parameters of the patient and enter the details in the below form

Kindly select the range of body temperature measured *

● Below 98.4
○ 98.4 - 100
○ Above 100

Enter Blood Sugar Level *

95

Enter the value as mentioned in Glucometer

Kindly mention the time of Blood Sugar Checked: *

Please tick when you check you blood sugar level

○ Fasting
○ Before Meal
● 1 - 2 hours after eating
○ Bedtime

Kindly mention the range of Blood Sugar as noted *

● Less than 100
○ 70 - 130
○ Less than 140
○ 140 - 160
○ Above 160

SUBMIT

Form title
Daily Monitor

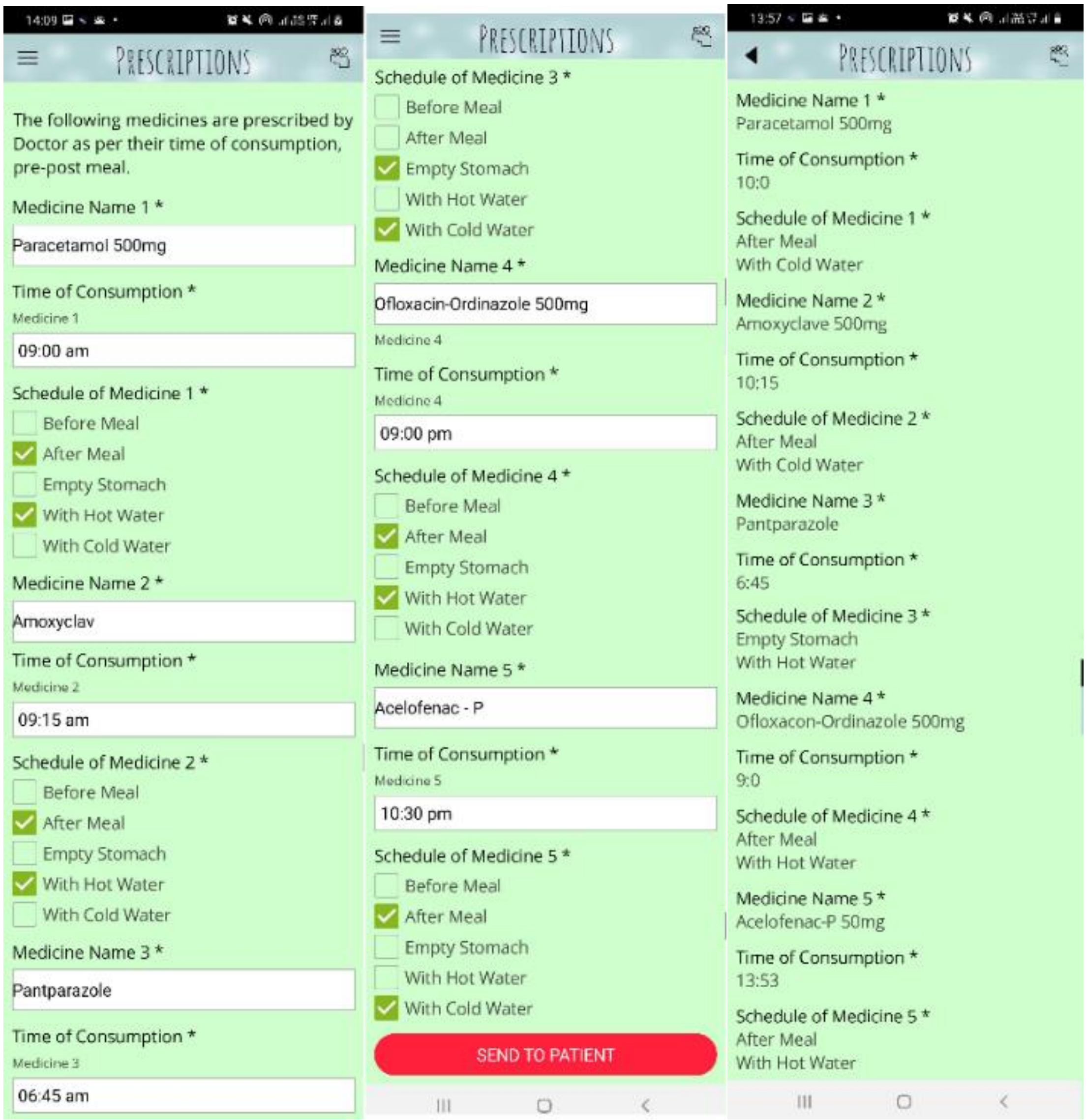
Content
Enter Name of the Patient : Ratish Kumar
Enter Contact Number : 701648529446
Enter your Email Id : ratish.k.dhiman@gmail.com
Enter Systolic Pressure : 80
Kindly mention the range of Systolic Pressure : 75 - 85
Enter Diastolic Pressure : 120
Kindly mention the range of Diastolic Pressure : 115-130
Enter the Body Temperature in Farenheit : 98.2
Kindly select the range of body temperature measured : Below 98.4
Enter Blood Sugar Level : 95
Kindly mention the time of Blood Sugar Checked: : 1 - 2 hours after eating
Kindly mention the range of Blood Sugar as noted : Less than 100

Date : 07/14/2021

(a) (b)

Figure 6.20: Representing physiological vital to be monitored and recorded by a patient, (b) representing the parameters received by the doctor to decide further prescriptions

The doctor filled the time and schedule of the medicine and sends it to the patient for their convenience. As an example, Fig. 6.21(a) is representing the filled medicine prescribed by the doctor and their time, Fig. 6.21(b) shows the patient's side the complete details in this regard. The intelligent home health app in this study is an electronic smartphone-web application. The overall purpose of this program is to enable social monitoring of patients having various illnesses, even though such diseases may be identified and treated wirelessly by doctors.



The following medicines are prescribed by Doctor as per their time of consumption, pre-post meal.

Medicine Name 1 *
Paracetamol 500mg

Time of Consumption *
Medicine 1
09:00 am

Schedule of Medicine 1 *
□ Before Meal
☑ After Meal
□ Empty Stomach
☑ With Hot Water
□ With Cold Water

Medicine Name 2 *
Amoxyclav

Time of Consumption *
Medicine 2
09:15 am

Schedule of Medicine 2 *
□ Before Meal
☑ After Meal
□ Empty Stomach
☑ With Hot Water
□ With Cold Water

Medicine Name 3 *
Pantparazole

Time of Consumption *
Medicine 3
06:45 am

Schedule of Medicine 3 *
□ Before Meal
□ After Meal
☑ Empty Stomach
□ With Hot Water
☑ With Cold Water

Medicine Name 4 *
Ofloxacin-Ordinazole 500mg
Medicine 4

Time of Consumption *
Medicine 4
09:00 pm

Schedule of Medicine 4 *
□ Before Meal
☑ After Meal
□ Empty Stomach
☑ With Hot Water
□ With Cold Water

Medicine Name 5 *
Acelofenac - P

Time of Consumption *
Medicine 5
10:30 pm

Schedule of Medicine 5 *
□ Before Meal
☑ After Meal
□ Empty Stomach
□ With Hot Water
☑ With Cold Water

Medicine Name 1 *
Paracetamol 500mg

Time of Consumption *
10:0

Schedule of Medicine 1 *
After Meal
With Cold Water

Medicine Name 2 *
Amoxyclave 500mg

Time of Consumption *
10:15

Schedule of Medicine 2 *
After Meal
With Cold Water

Medicine Name 3 *
Pantparazole

Time of Consumption *
6:45

Schedule of Medicine 3 *
Empty Stomach
With Hot Water

Medicine Name 4 *
Ofloxacon-Ordinazole 500mg

Time of Consumption *
9:0

Schedule of Medicine 4 *
After Meal
With Hot Water

Medicine Name 5 *
Acelofenac-P 50mg

Time of Consumption *
13:53

Schedule of Medicine 5 *
After Meal
With Hot Water

(a) (b)

Figure 6.21: (a) representing the medicine prescription form to be filled by the doctor, (b) showing the medical prescription received by the patient from the doctor.

The android smart application also includes software that allows for real-time monitoring of a treatment regimen, significantly reducing medical expenses and more importantly preventing the hospital from further exposure to intensely contagious diseases, especially when the majority of healthcare professionals are overwhelmed by COVID-19 pandemic patients.

6.3.7 Observations

In conclusion, the inclusion of the IoT in the home system has led to significant improvements in ease of life, web monitoring to home appliances, mobile universal healthcare, and enhanced health engagement, particularly for seniors and quarantined patients. Integrating remote monitoring with the healthcare system minimizes worry, lowers living costs, and allows for wireless connectivity with medical professionals. In this application author, suggest a smart home-medicare system for sickly, old, and disabled people. The proposed work was primarily aimed at making life easier for persons with medical conditions who must attend the hospitals frequently. The current method is suggested to lower the amount of physical medical appointments, hospital lines, and the expenditure of caring for the patients. The platform serves a dual purpose of health evaluation and controlling vital household appliances, allowing users to maintain a social life while also having their wellness regulated and monitored, which is especially important throughout a pandemic. By lowering the rate of virus transmission, the proposed strategy will have a significant influence on people's livelihoods. Patients who have been recognized with COVID-19 and are undergoing treatment will not have any need to wander around extensively, resulting in enhanced quality of care and a lower transmission rate. The developed mobile solution can be integrated as a doorway into current hospital online databases to benefit society. With the greater versatility of the developed approach, the exploration can be expanded to other areas. The association of IoT with NCS with this proposed application can be further extended to livestock monitoring and consultation with veterinary physicians for disease diagnosis, prescription, and treatment of diseases in domestic or pet animals.

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

As technology improves, networks of embedded devices become progressively frequent and pervasive, and at the same time, more complicated and demanding to assess the delay impact and unpredictability in the control operation.

The induced delays in the networked control system have disastrous implications and impair the system's operational performance. The implementation of predictive techniques in the Smith Predictor Controller to mitigate the delay in a Networked Control System is the primary focus of this thesis. The thesis uses predictive methodologies to circumvent the Smith Predictor Controller's constraint of asserting the process model and estimated deadtime. To anticipate the plant model equivalent to the actual process variable, a Markov Approach-based algorithm is proposed in the Smith Predictor Controller. The Markov Approach is useful since it examines the influence of delay on the real process variable and predicts the plant model for the Smith Predictor Controller adequately. The modified Smith Predictor Controller is developed and simulated employing the Simulink platform for regulating the dynamics of a DC Motor through a Networked Control System. The findings reveal that this strategy optimizes the system's transient and steady-state stability, as well as the controller's latency and performance characteristics.

The system deadtime inhibits plant responsiveness to achieve steady-state stability and also delays the system's rapid transient response. The proposed modified SPC displays great stability for prolonged deadtimes. However, the SPC deadtime estimate causes a bottleneck. This stumbling block is confronted by devising an algorithm that integrates Kalman Estimation Techniques, which is then implemented in the SPC with Markov Approach to accommodate for the delay impact and strengthen the applicability of the proposed modified SPC for longer deadtimes. The Kalman Estimation may be used to quickly predict the deadtime that is involved in the real process and, as a result, assists the controller in deciding whether to modify the control signal. The simulation results of the proposed modified SPC reveal that the proposed technique minimizes the complexity and computing work as compared to other control approaches mentioned in the literature. This assures that the intended performance is preserved as compared to other control approaches.

The proposed modified Smith Predictor Controller shows improved system operational stability, compensation of induced delays, reduce the effect of larger deadtime on NCS. These improvements justify the applicability of the proposed modified SPC for time-sensitive networked control applications such as teleoperation, disaster management operation, defense operation is few to name. In the thesis, time-sensitive and non-time-sensitive applications are discussed. The Evolution of Third Eye for Defense Covert Operations is proposed. This application is designed to help defense personal to execute covert operations. A mobile application named Smart Home Health mobile application (SHHMA) is designed to assist patients in-home/institutional isolation/quarantine and to patients living in remote areas, medical resources are scarce. NCS based remotely controlled and monitored polyhouse is proposed to regulate various parameters such as temperature, moisture, CO_2 gas, light, use of fertilizers, and water usage in the polyhouse.

In the future, the proposed architectural framework of the modified Smith Predictor Controller based on the Markov Approach and Kalman Estimation Technique (KMSPC) may be used for Mission and Life Critical Applications in Defense and Healthcare. The application of the proposed controller would improve the response time of the plant and compensate for the networked controlled induced delay. To cope-up with the non-linearity of the system, in the future, Extended Kalman Filter would be implemented to estimate the uncertainty in the deadtime.

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APPENDIX A

TRANSIENT RESPONSE SPECIFICATIONS

1. **Rise Time (T_r):** It is the time required for response to rise from 10% to 90% of the final value for overdamped systems and 0 to 100% of the final value for underdamped systems. The rise time is the reciprocal of the slope of the response at the instant, the response is equal to 50% of the final value. It is given by,

$$T_r = \frac{\pi - \theta}{\omega_d}$$

2. **Peak time (T_p):** It is the time required for the response to reach its peak value. It is also defined as the time at which response undergoes the first overshoot which is always peak overshoot.

$$T_p = \frac{\pi}{\omega_d} = \frac{\pi}{\omega_n\sqrt{1-\xi^2}}$$

3. **Peak Overshoot (M_p):** It is the largest error between reference input and output during the transient.

$$M_p = \left\{c(t)|_{t=T_p}\right\} - 1$$

$$\%M_p = e^{-\pi\xi/\sqrt{1-\xi^2}}$$

4. **Settling Time (T_s):** This is defined as the time required for the response to decrease and stay within specified percentage of its value that is within tolerance band.

$$T_s = \frac{1}{\xi\omega_n} = T$$

Here, ξ is the damping ratio, if its value is equal to zero then system will oscillate with maximum frequency. ω_n it is the natural frequency of oscillation of the system at $\xi = 0$. The damped frequency of oscillation is denoted as ω_d.

APPENDIX B

STANDARD PERFORMANCE METRICS

The optimized performance metrics are evaluated so that the design of all the factors to controller design become easy. To assess the performance of the feedback controller the following performance metrics are calculated as:

1. Integral Absolute Error (IAE): To consider the effect of large errors than the small errors involved in a controller IAE is measured using the relation given as:

$$\mathrm{IAE} = \int_0^\infty \left|y_{sp}(t) - y_s(t)\right| dt$$

This method essentially add-up all the errors from setpoint over time.

X_{sp} represents the set point value and X_s represents the sensor value.

2. Integral Time Absolute Error (ITAE): To obtain good controller parameters ITAE must be minimized.

$$\mathrm{ITAE} = \int_0^\infty t\left|y_{sp}(t) - y_s(t)\right| dt$$

3. Integral Squared Error (ISE): In a control system minimum value of ISE indicate that large errors in the system will be eliminated quickly.

$$\mathrm{ISE} = \int_0^\infty \left[y_{sp}(t) - y_s(t)\right]^2 dt$$

4. Integral Time Squared Error (ITSE): ITSE is better than IAE as errors area squared and thus contributed more to the value of the integral.

$$\mathrm{ITSE} = \int_0^\infty t\left[y_{sp}(t) - y_s(t)\right]^2 dt$$

Here, t indicates later errors. As time increases the square penalizes large errors.

APPENDIX C

MODELING OF DC MOTOR

A common actuator in control systems is the DC motor. It directly provides rotary motion and, coupled with wheels or drums and cables, can provide translational motion. The electric equivalent circuit of the armature and the free-body diagram of the rotor are shown in Fig. C.1

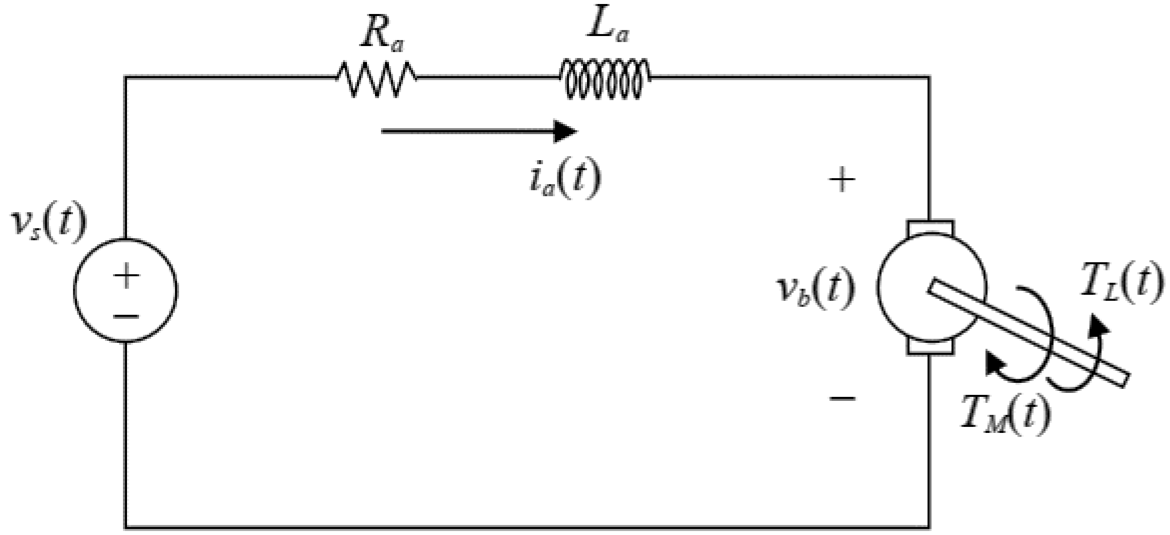

Fig. C.1 The electrical equivalent circuit of DC Motor

The system structure of DC Motor includes the armature resistance Ra and winding leakage inductance La. According to Kirchhoff's voltage law, the electrical equation of the DC motor is described as

$$\mathrm{R_a i_a + L_a \frac{di_a(t)}{dt} + v_b(t) = v_s(t)} \tag{C.1}$$

here $\mathrm{i_a(t)}$ is the armature current, $\mathrm{v_b(t)}$ is the back emf voltage and $\mathrm{v_s(t)}$ is the voltage source. The back emf voltage $\mathrm{v_b(t)}$ is proportional to the angular velocity $\omega(\mathrm{t})$ of the rotor in the motor, expressed as

$$\mathrm{v_b(t) = k_b}\omega(\mathrm{t}) \tag{C.2}$$

here $\mathrm{i_a(t)}$ is the back emf constant. In addition, the motor generates a torque $\mathrm{T_M}$ proportional to the armature current, given as

$$T_M = k_T i_a(t) \tag{C.3}$$

here k_T is the torque constant.

If the input voltage $v_s(t) = V_s$ is a constant, the resulted armature current $i_a(t) = I_a$ angular velocity $\omega(t) = \ \Omega$ torque, $T_M = T$ are also constant in the steady state. From eq. C.1 to C.3, we have

$$R_a I_a + k_b \Omega = V_s \tag{C.4}$$

$$T = k_T I_a \tag{C.5}$$

Under the conservation of power, we know that the input power $I_a V_s$ is equal to the external power $T\Omega$ and the power $R_a I_a^2$ consumed in the resistance, i.e.,

$$V_s I_a = T\Omega + R_a I_a^2 \tag{C.6}$$

Substituting v_s in eq. C.4 into C.6 yields

$$T = k_b I_a \tag{C.7}$$

From eq. C.5 and eq. C.7, we know that both k_T and k_b are the same. From eq. C.2, we can rewrite eq. C.1 and eq. C.3 as

$$R_a i_a(t) + L_a \frac{di_a(t)}{dt} + k\omega(t) = v_s(t) \tag{C.8}$$

$$T_M(t) = k i_a(t) \tag{C.9}$$

Where $k = k_T = k_b$. Besides, if the DC motor is used to drive an external torque $T_L(t)$ of payload, then its mechanical behavior is described as

$$J_M \frac{d\omega(t)}{dt}(t) + B_M \omega(t) = T_M(t) - T_L(t) \tag{C.10}$$

here J_M is the rotor moment of inertia and B_M is the frictional coefficient.

Based on eq. C.8, C.9 and C.10, the dynamic equation of the DC motor can be expressed as

$$R_a i_a(t) + L_a \frac{di_a(t)}{dt} + k\omega(t) = v_s(t) \tag{C.11}$$

$$B_M\omega(t) + J_M\frac{d\omega(t)}{dt} - +ki_a(t) = -T_L(t) \tag{C.12}$$

Note that the electrical time constant $\frac{L_a}{R_a}$ is often neglected since it is at least one order in magnitude smaller than the mechanical time constant $\frac{J_M}{B_M}$. In other words, by neglecting the term $\frac{di_a(t)}{dt}$, eq.C.11 becomes

$$i_a(t) = \frac{1}{R_a}v_s(t) - \frac{k}{R_a}\omega(t) \tag{C.13}$$

Substituting it into C.12, we have

$$\frac{d\omega(t)}{dt}(t) + \left(\frac{B_M}{J_M} + \frac{k^2}{J_M R_a}\right)\omega(t) = -\frac{1}{J_M}T_L(t) + \frac{k}{J_M R_a}v_s(t) \tag{C.14}$$

Clearly, the motor will encounter two external sources, the input voltage $v_s(t)$ to drive the motor and the torque $T_L(t)$ reacted from the payload.

Now, based on the above analysis, let's discuss the model of a DC motor in state-space and input-output description.

First, let's consider the case which require the DC motor to move in a constant speed. Then, the angular velocity is selected as the output, expressed as

$$y(t) = \omega(t) \tag{C.15}$$

From eq.C.11 and C.12 and choosing the state variables as $x_1(t) = i_a(t)$ and $x_2(t) = \omega(t)$ we have

$$R_a x_1(t) + L_a\dot{x}_1(t) + kx_2(t) = v_s(t) \tag{C.16}$$

$$J_M\dot{x}_2(t) + B_M x_2(t) - kx_1(t) = -T_L \tag{C.17}$$

Further rearranging eq. C.15 to eq. C.17 yields the state-equations

$$\dot{x}_1(t) = \frac{R_a}{L_a}x_1(t) - \frac{k}{L_a}x_2(t) + \frac{1}{L_a}v_s(t) \tag{C.18}$$

$$\dot{x}_2(t) = \frac{k}{J_M}x_1(t) - \frac{B_M}{J_M}x_2(t) + \frac{1}{J_M}T_L(t) \tag{C.19}$$

And the output equation

$$y(t) = x_2(t) \tag{C.20}$$

Hence, the state-space description is given as

$$\text{State equation: } \dot{x}(t) = Ax(t) + Bu(t) \tag{C.21}$$

$$\text{Output equation: } y(t) = Cx(t) \tag{C.22}$$

Where the state vector is $x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}$, the input vector is $u(t) = \begin{bmatrix} v_s(t) \\ T_L(t) \end{bmatrix}$, and the system matrices are $A = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{k}{L_a} \\ \frac{k}{J_M} & \frac{B_M}{J_M} \end{bmatrix}$, $B = \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & -\frac{1}{J_M} \end{bmatrix}$ and $C = \begin{bmatrix} 0 & 1 \end{bmatrix}$. Note that the state equation eq. C.21 can be rearranged as

$$\dot{x}(t) = Ax(t) + B_1u_1(t) + B_2u_2(t) \tag{C.23}$$

Where $u_1(t) = v_s(t)$, $u_2(t) = T_L(t)$, $B_1 = \begin{bmatrix} \frac{1}{L_a} \\ 0 \end{bmatrix}$ and $B_2 = \begin{bmatrix} 0 \\ -\frac{1}{J_M} \end{bmatrix}$. If the motor is operated without any payload T_L, i.e., $u_2(t) = T_L(t) = 0$, then the state equation eq. C.23 can be rewritten as

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{C.24}$$

Where the input $u(t) = v_s(t)$ and the input matrix is $B = \begin{bmatrix} \frac{1}{L_a} \\ 0 \end{bmatrix}$.

If the goal of control is to drive the DC motor to a desired angle, not a speed, then the output should be set as the angular position $y(t) = \theta(t) = \int_0^t \omega(\tau)d\tau$. To include the angular position, we often change the integral from $\theta(t) = \int_0^t \omega(\tau)d\tau$ into the differential form as below:

$$\dot{\theta}(t) = \omega(t) \tag{C.25}$$

And choose the new state variable $x_3(t) = \theta(t)$. As a result, the total system is changed into the state equation

$$\dot{x}_1(t) = -\frac{R_a}{L_a}x_1(t) - \frac{k}{L_a}x_2(t) + \frac{1}{L_a}v_s(t) \qquad (C.26)$$

$$\dot{x}_2(t) = \frac{k}{J_M}x_1(t) - \frac{B_M}{J_M}x_2(t) - \frac{1}{J_M}T_L(t) \qquad (C.27)$$

$$\dot{x}_3(t) = x_2(t) \qquad (C.28)$$

And the output equation

$$y(t) = x_3(t) \qquad (C.29)$$

In matrix form, we have

$$\text{State equation: } \dot{x}(t) = Ax(t) + Bu(t) \qquad (C.30)$$

$$\text{Output equation: } y(t) = Cx(t) \qquad (C.31)$$

$$x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix}, u(t) = \begin{bmatrix} v_s(t) \\ T_L(t) \end{bmatrix},$$

$$A = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{k}{L_a} & 0 \\ \frac{k}{J_M} & -\frac{B_M}{J_M} & 0 \\ 0 & 1 & 0 \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & -\frac{1}{J_M} \\ 0 & 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

LIST OF PUBLICATIONS

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1. Ratish Kumar, Rajiv Kumar, M. J. Nigam, “An Improved Lag-Time Compensation Technique in Distributed Networked Control System based on Smith Predictor,” Informatica (Slovenia), Volume -5, Issue -2021, pp. 5 – 11, https://doi.org/10.31449/inf.v45i5.3551. (Scopus & ESCI Indexed).

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