

Simulations for Time Delay Compensation in Networked Control Systems

Sumit Vardhan, *Student Member, IEEE*, and Rajiv Kumar, *Member, IEEE*

Abstract—Time delay plays a critical role in the performance of real-time Networked Control Systems (NCS). It can destabilise the NCS as it deteriorates the performance and stability of networked control systems. Communication networks inevitably introduce delays in NCS. Therefore, it is necessary to compensate the time delay. The time taken by the system depends upon the characteristics of the network such as topology and routing algorithms used in the network. However, this paper adopts the prediction based delay compensation technique by the use of Smith Predictor. The stability analysis has been done for different plant transfer functions. Transport layer protocol User Datagram Protocol (UDP) has been used for communication. Simulations have been done with help of MATLAB/Simulink. It has been illustrated that delay compensation depends upon the order and time constant of the system.

Index Terms—Delay compensation, Networked Control Systems, PID Controller, Smith predictor.

I. INTRODUCTION

NETWORKED Control Systems (NCS) are real-time distributed systems where components such as sensors, controllers, and actuators are connected through communication network [1]. The network as a medium of interconnection may be wired or wireless. A typical networked control system has been shown in Fig.1. In an NCS, information is exchanged through the network among various control system components.

Sumit Vardhan is pursuing the Bachelor of Technology degree in Electronics and Communication Engineering from Jaypee University of Information Technology, Waznaghat, Solan, H.P., INDIA 173234 (e-mail: sumitvardhan2008@gmail.com).

Rajiv Kumar is faculty with the Department of Electronics and Communication Engineering, Jaypee University of Information Technology, Waznaghat, Solan, H.P., INDIA 173234 (e-mail: rajiv.kumar@juit.ac.in).

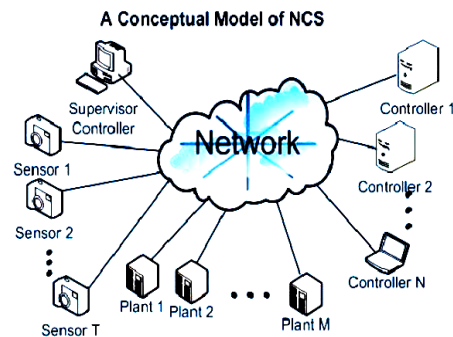


Fig. 1. A Generalised Model of NCS [2].

The applications of networked control systems can be divided into two broad categories: i) time-delay sensitive applications, and ii) time-delay insensitive applications. Time delay causes instability in time sensitive applications. Time delay plays a critical role here. If the time delay exceeds the tolerable time limit, the performance of the system deteriorates. This can also result in damage to the system. Tele-operation via networks is an example of time-delay sensitive application where it can be used for undersea operations, fire-fighting operations, surgery operations, and automated highway driving operations. On the other side, time delay insensitive applications include the systems where the deadlines are not critical. Examples of these applications are http, e-mail, DNS and ftp [2].

The networked control systems operate over the networks. So, there are many challenging issues which arise in the design process of NCS. Network reliability is one of the most important factor. The presence of network in networked control systems can introduce severe problems like delays, jitter, packet losses, etc. The time taken for the measurements by the system and to transmit a control signal to the actuator and other components in NCS depends upon the characteristics of the network such as topology and routing algorithms used in the network [2].

Networked control systems are distributed real-time systems. An NCS can be a multi-sensor and multi-actuator system. So, the bandwidth allocation in NCS should be given consideration. The scheduling methods and bandwidth allocation strategies should be such that they result in an optimal and efficient utilisation of the available bandwidth.

Since its inception, time delay has been a challenging problem in NCS. All types of delays severely degrade the performance of the system [1,2]. Generally, time delay is the sum of computation time, measurement time, process time and the time taken by the controller or command signal sent over the network. The design of NCS becomes complex since the network introduces time delay uncertainty in the NCS components (actuators, sensors, controllers). The performance of the system becomes worse when there arises condition of data loss [7]. Time delay in NCS destabilise the system and it does not give the required response [3]. So it is a necessity to design a controller for the compensation of time delays and for the improvement of the performance and stability of NCS.

There are various strategies for delay compensation and for making the system stable. These include Smith Predictor control, PID control, LQR control, fuzzy control, adaptive control, intelligent control, robust control and various control algorithms [2]. We have to modify these control strategies as per the requirements to compensate for delays and unpredictability.

II. NCS TIME-DELAY

In a networked environment, many challenges are to be taken care of during the design of NCS. The compensation of time delays is one of the challenges in NCS which is necessary for the optimal performance of the system. Time delay in NCS severely degrades the performance of the system and the system becomes unstable. So an estimator can be used for the compensation of time delay in NCS. The NCS estimator can predict the state of the plant and thus the control system components can take the necessary action without delay. The different types of time delay compensation schemes in NCS can be: Smith Predictor, PID controller, LQR controller, fuzzy controller, adaptive controller, intelligent controller, robust control, sliding mode controller etc.

A networked control system with plant, sensor, actuator, controller and network is shown in Fig.2. The centralized controller communicates with the actuator and sensor over the network [6].

The signal takes some time to transmit between the controller and actuator and between sensor and controller. The transmission time taken by the signal depends upon the topology, routing scheme and the scheduling policy used in the system [5].

There are three kinds of delays in Networked Control Systems:

1. Data transfer delay between the sensor and the controller, τ_k^{sc} .
2. Computational delay in the controller, τ_k^c .
3. Data transfer delay between controller and actuator, τ_k^{ca} .

where k indicates possible time dependence of delays [5,7].

The communication delay is the sum of τ_k^{sc} and τ_k^{ca} . The control delay, τ_k , in an NCS is the time between the instant a measurement signal is sampled and when it is used in the actuator for taking required action [6]. The control delay is the sum of the communication delays and computational delay,

$$\tau_k = \tau_k^{sc} + \tau_k^c + \tau_k^{ca} \quad (1)$$

The variations in delay also causes problem in the design of the Networked Control Systems. The variations in time delay makes the system time-invariant and thus its designing becomes complex. One of the ways to get rid of the time variations is the introduction of clocked buffers at the input of the controller node and the actuator node. This scheme makes the communication delay between the nodes deterministic. But it results in the use of old information which may result in degradation of the performance of the system.

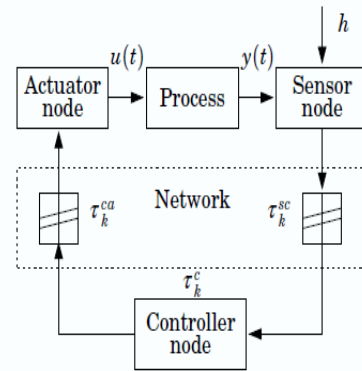


Fig. 2. The NCS Model [5].

III. METHODOLOGY ADOPTED FOR DELAY COMPENSATION

Generally, the classical tuning formula for typical PID controllers provides unsatisfactory results in the control systems where the time delay exceeds the critical value. The stability of the networked control systems should always be the first concern and the controllers should be designed considering the stability and delay-characteristics of the NCS. Network-induced delay is one of the major problems in NCS. The network-induced delays occur when the data is exchanged among the sensors, controllers and actuators across the communication network. This delay can degrade the performance of the NCS if the control system is designed without considering it and it can destabilise the system.

Packet loss is another problem in NCS. Packet loss occurs due to noise, interference, node failures and packet collisions in the network. In Internet Protocol (IP) networks, Transport layer protocols: Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) are used for the transmission of data from one process to another. Depending upon the protocol used, the packets are either retransmitted or not if they are lost or received with error at the receiving end. TCP is connection-oriented reliable transport layer protocol. It uses an acknowledgment mechanism to check the error-free arrival of data. In TCP, messages are retransmitted in case of loss of data or erroneous arrival of packets. The packets arrive in the correct packet order at the receiver side. On the other hand, UDP is connection-less and unreliable transport layer protocol. There are no retransmissions in UDP and the packets may arrive in out-of-sequence manner at the receiver end. The retransmissions and acknowledgments can lead to congestion as the network gets loaded. Therefore, UDP is much faster than TCP, but it is also unreliable.

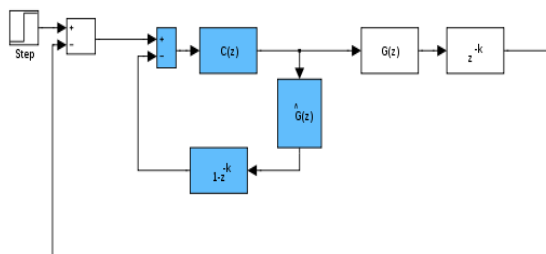


Fig. 3. Smith Predictor.

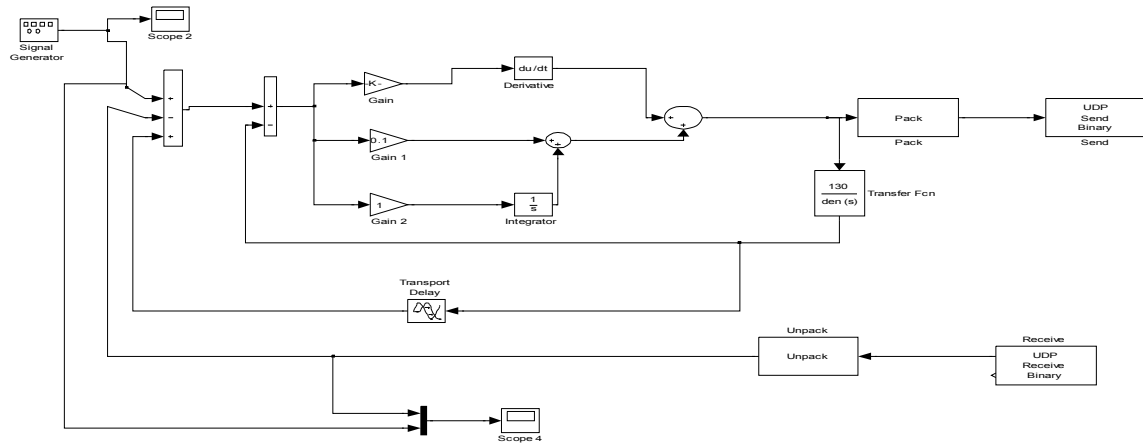
Various strategies have been developed to compensate time delay and cope with this problem [8]. Smith Predictor developed by O.J Smith in

1950 is used as a predictive controller in networked control systems to compensate time delay [9]. The Smith Predictor consists of PID controller with process mathematical model in the feedback loop.

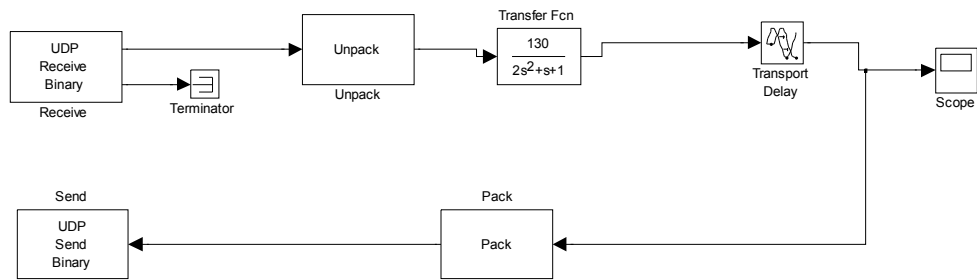
Smith Predictor acts as an estimator for the system. It is a feedback control technique having a minor loop[9]. It provides a virtual system to PID controller without time delay. This technique of delay compensation can be applied to the networked control systems that have long loop delays. Fig.3 shows the block diagram of Smith Predictor which is being used for delay compensation in the networked control systems. The block diagram consists of the plant which lies in the negative feedback loop with both feed forward and feedback delays. $G(z)$ represents stable, delay free part of the plant which is strictly proper rational function. $G(z)$ with delay is in the feedback loop. $C(z)$ represents controller part[9]. The reference input shown in Fig.3 is step function. There are two feedback loops. The output loop is used to feed the output back to the input. With this loop alone, the system will not give the optimal performance because it is feeding back the delayed and outdated information which leads to degraded performance of the system. So, the inner loop which contains the predictor and the plant model controls the system by feeding back the predicted output of the plant taking time delay into account.

IV. SIMULATIONS

The simulations of Networked Control System have been performed using MATLAB/Simulink. The simulink models with network are shown in Fig.4. The simulink blocks are simulated in host PC and remote PC. The sending simulink model with Smith Predictor is kept in host PC and receiving simulink block with the plant is kept in remote PC. This configuration forms an environment of closed loop networked control system. The Transport layer protocol User Datagram Protocol (UDP) is used for sending data over the network. UDP has been preferred over TCP since UDP provides increased speed of communication and TCP introduces more delays and can lead to undesirable performance of the NCS. UDP Send and UDP Receive blocks have been used in the simulink models. The step response of the system without network and with network are shown in the graphs shown in Fig. 6.



Host PC



Remote PC

Fig. 4. Simulink Blocks used for Delay Compensation in NCS

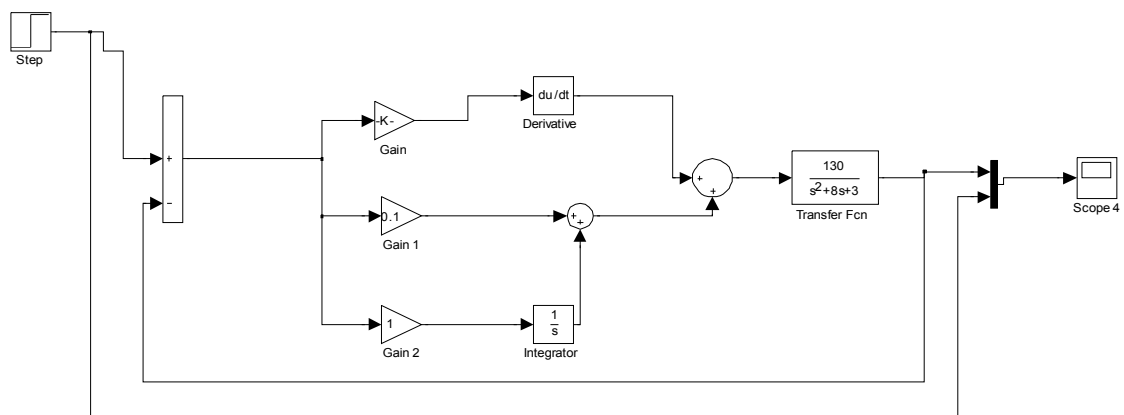
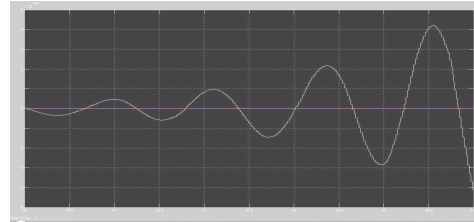
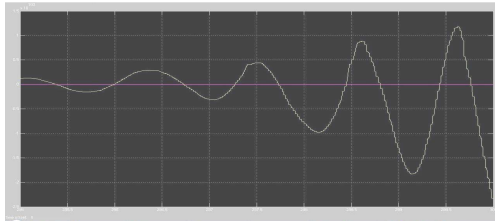
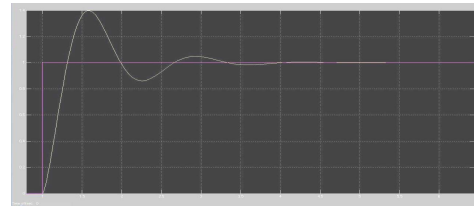
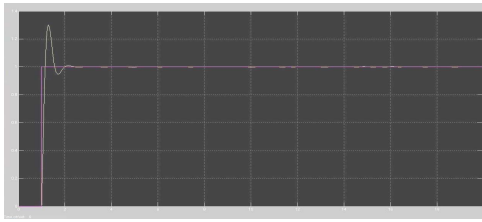
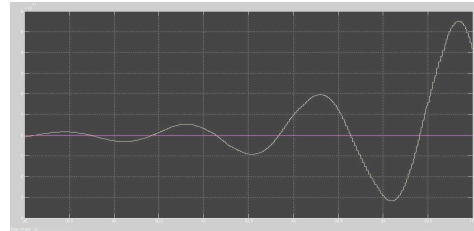
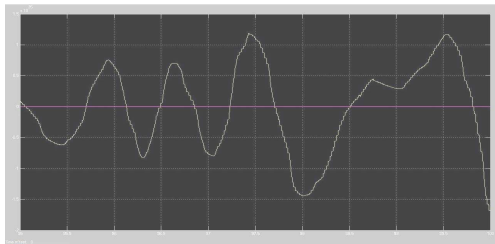
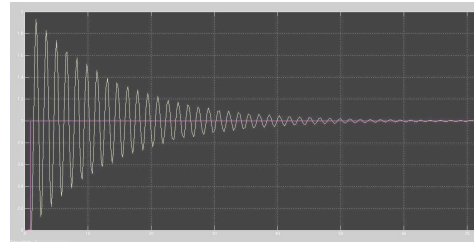
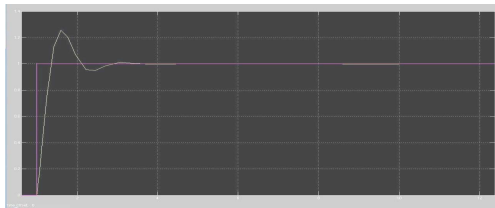


Fig. 5. Simulink Block used to control the plant using PID controller



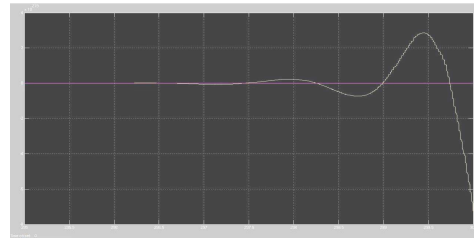
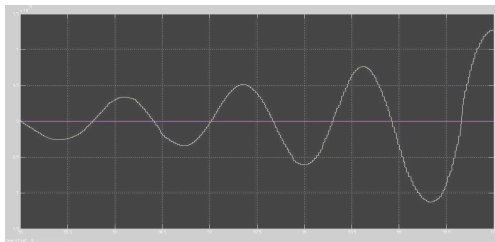
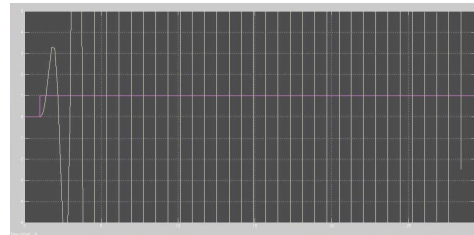
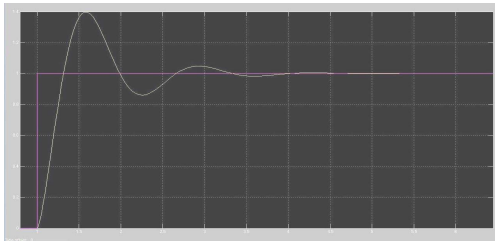
Case (i): When plant transfer function is:
 $130/(s + 0.5)$

Case (iv): When plant transfer function is:
 $130/(0.1s^2 + 5s + 6)$



Case (ii): When plant transfer function is:
 $130/(5s + 10)$

Case (v): When plant transfer function is:
 $130/(s^2 + 8s + 3)$



Case (iii): When plant transfer function is:
 $130/(10s + 10)$

Case (vi): When plant transfer function is:
 $130/(2s^2 + s + 0.5)$

Fig. 6. Responses considering different plant transfer functions : (i) In each case, upper graph shows responses with PID controller only (without network), and (ii) In each case, response in lower graph is with Smith Predictor (with network).

V. RESULT AND DISCUSSION

Results of the simulink models of Fig. 4 and Fig. 5 have been shown in Fig. 6. Following six different transfer functions have been used for simulations:

Case (i): When plant transfer function is

$$130/(s + 0.5)$$

Case (ii): When plant transfer function is:

$$130/(5s + 10)$$

Case (iii): When plant transfer function is:

$$130/(10s + 10)$$

Case (iv): When plant transfer function is:

$$130/(0.1s^2 + 5s + 6)$$

Case (v): When plant transfer function is:

$$130/(s^2 + 8s + 3)$$

Case (vi): When plant transfer function is:

$$130/(2s^2 + s + 0.5)$$

The simulations of the networked control system have been performed using Simulink block diagram shown in Fig.4. Step responses of the considered NCS have been shown in lower graph of each case in Fig. 6. This set of Simulation blocks gives the step response considering network between the Host PC and Remote PC. In Fig. 6, upper graph in each case shows the step response obtained from Simulink block of Fig. 5. UDP has been used since it is much faster than the TCP and it provides increased communication speed as compared to the TCP transport layer protocol. Use of TCP instead of UDP would lead to more delay values and degraded system performance. The performance of the control system has been investigated using control algorithms like PID controller and Smith Predictor in the networked environment. Simulation shows that delay compensation is possible with the help of Smith predictor. Response of both first-order and second-order systems has been shown with the help of simulations. The performance of NCS depends upon the order of the system. Time-delay varies for the systems with different orders. The design of the control algorithm and the controller should take into account the characteristics of NCS and the order of the system. Better results are possible by proper tuning of the components of the predictor.

ACKNOWLEDGMENT

Authors are sincerely thankful to **Dr. Y. Medury, COO, Jaypee Education System** for his continuous support and motivation in the current project.

REFERENCES

- [1] A. Bemporad, W.P.M.H. Heemels, M. Johansson, Networked Control Systems, Springer, 2010.
- [2] Rachna A. Gupta, Mo-Yuen Chow, "Networked Control System: Overview and Research Trends," IEEE Transactions on Industrial Electronics, Vol. 57, Issue 7, pp 2527 – 2535, 2010.
- [3] K. Ogata, Modern Control Engineering, Prantice Hall of India, New Delhi, 2010.
- [4] Li LI and Fei-Yue WANG, "Control and Communication Synthesis in Networked Control Systems".
- [5] John Nilsson, Real-Time Control Systems With Delays, PhD. Thesis, 1998.
- [6] Simon Coman, V.Comnac, Cr. Boldisor, R.Demeter, "Networked Control Systems for DC Electrical Drives," Scientific Bulletin of the Petru Maior University of Tirgu Mures, vol. 5, pp 61-64 2009.
- [7] Sachi Mittal, Anwar S Siddiqui, "Networked Control System : Survey and Direction , Journal of Engineering Research and Studies, vol.I, Issue II, pp 35-50, 2010.
- [8] Veronesi Massimiliano , "Performance Improvement of Smith Predictor Through Automatic Computation of Dead Time," Yokogawa Technial Report, pp 26-30, 2003.
- [9] Higashimita Tamaku, Kawasaki, "Smith Predictor Control and Internal Model Control - A Tutorial"

Sumit Vardhan is student member of IEEE. He is pursuing the Bachelor of Technology degree in Electronics and Communication Engineering from Jaypee University of Information Technology, Waknaghat, Solan, H.P., INDIA . His research interests include control, communication and computing systems.

e-mail: sumitvardhan2008@gmail.com

Rajiv Kumar received the B.Tech. degree in 1994 from College of Technology, G.B. Pant University of Agriculture & Technology, Pantnagar and the M.Tech. degree from Regional Engineering College, Kurukshetra (Kurukshetra University) with specialization in Control System. He started his career as a teaching associate from National Institute of Technology (NIT), Kurukshetra. He is currently with the Department of Electronics and Communication Engineering at Jaypee University of Information Technology, Waknaghat, Solan. He obtained his Ph.D. in network reliability in the year 2010 from NIT under the supervision of Prof. Krishna Gopal. Rajiv Kumar is member of IEEE and Life Member of ISTE, IETE, Forum of Interdisciplinary Mathematics and System Society of India. His research interests include cyber- physical systems and network reliability.

web: www.juit.ac.in

e-mail: rjv.ece@gmail.com, rajiv.kumar@juit.ac.in