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Adaptive Time Delay Compensation Process in Networked Control System

Yong-Gil Kim*, Kyung-Il Moon**,+

* *Department of Computer Security, Chosun College of Science & Technology, Korea*
e- mail : ygkim@cst.ac.kr

**,+ *Department of Computer Engineering, Honam University, Korea*
Corresponding author : kimoon@honam.ac.kr

Abstract

Networked Control System (NCS) has evolved in the past decade through the advances in communication technology. The problems involved in NCS are broadly classified into two categories namely network issues due to network and control performance due to system network. The network problems are related to bandwidth allocation, scheduling and network security, and the control problems deal with stability analysis and delay compensation. Various delays with variable length occur due to sharing a common network medium. Though most delays are very less and mostly neglected, the network induced delay is significant. It occurs when sensors, actuators, and controllers exchange data packet across the communication network. Networked induced delay arises from sensor to controller and controller to actuator. This paper presents an adaptive delay compensation process for efficient control. Though Smith predictor has been commonly used as dead time compensators, it is not adaptive to match with the stochastic behavior of network characteristics. Time delay adaptive compensation gives an effective control to solve dead time, and creates a virtual environment using the plant model and computed delay which is used to compensate the effect of delay. This approach is simulated using TrueTime simulator that is a Matlab Simulink based simulator facilitates co-simulation of controller task execution in real-time kernels, network transmissions and continuous plant dynamics for NCS. The simulation result is analyzed, and it is confirmed that this control provides good performance.

Keywords: *Networked Control System, Delay, Adaptive compensation, True Time.*

1. Introduction

Networked Control System (NCS) has been wide application in industrial automation. It includes the use of computer network and control theory, and research areas are mainly effects of network on the system and controller design for delay compensation and stabilization. Co-design is also interest topic for many researchers [5]. NCS is corresponding to a closed control system with a real-time network in feedback [6].

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+ Corresponding Author: kimoon@honam.ac.kr
Tel: +82-62-940-5400, Fax: +82-62-940-5078
Department of Computer Security, Chosun College of Science & Technology, Korea

Bus architecture is useful in extending physical set-up of wires connected between central control computer with each sensor and actuator. Mostly Ethernet device network or control network are used in NCS. Recent interest is to use wireless network in NCS [2]. Wireless sensor networks (WSN) have been extensively researched for over a decade, because they provide appealing possibilities for distributed, flexible and ubiquitous sensing applications, where each node in the network performs sensing, data processing and communication functions. The highly distributed nature of WSN provides fault tolerant and adaptive to dynamically changing environments [15]. Based on the communication channels used in the NCS architecture, it is divided into two classes. The NCS with single communication channel is treated as a class A, and the system with two level channels is known as class B. There are divided according to use of controller in the system like direct structure and hierarchical structure. In both class, there is a network and due to insertion of this communication network, delays in control loop from controller to actuator and sensor to controller are introduced along with controller processing delay and natural delay. Apart from delay like packet drop outs, jitters are also present [17]. A delay is the source of performance degradation and destabilization of a stable system by decreasing the phase margin of the system by the amount of delay. System stability is one of important issue in the system analysis and control design. Many results have appeared in the literature to analyze the closed-loop stability in the presence several NCS issues. In general, these approaches can be classified into indirect type and direct type. Indirect control type assumes that there is no delay associated in the system, followed by a suitable dead time compensator for delay compensation. Direct control is quite simpler as it takes the delay in account at the time of controller design. The PID controller is mostly used in indirect approach along with a suitable dead time compensator like smith predictor. The objective of a PID controller design only depends upon fine tuning of its parameter gains. Many advanced tuning methods like analytical tuning, prediction approach tuning, auto-tuning and tuning based on system gain and phase margin specifications has been developed [7]. Phase margin and gain margin based PID controller tuning makes the system robust by bounding the system margins in between a predefined value. Manually tuning procedure is very tedious and time consuming, and the resultant system performance mainly depends on the experience and the process knowledge the engineers. To avoid this, the relay feedback auto-tuning method enables the controller to be tuned automatically on demand from an operator or an external signal. To evaluate the stability of a PID controlled system with uncertainties, such as varying time-delays, robust control techniques can be used. For example, the robustness of different PID tuning methods for a case process with parameter uncertainties has been investigated in [3]. A PID controller itself is not sufficient for NCS, and a delay compensator must be incorporated. A survey on dead time compensators is detailed in [8]. Smith predictor is the most commonly used dead time compensators used in industrial applications, the benefit lies in that the structural simplicity and easy implementation. NCS analysis using switched system is described in [16]. A switch system divides the whole systems as several subsystems according to delays in a transmission interval. Then, designing a suitable controller for each subsystem stabilizes the systems as a whole. The NCS may consider as a sampled data system as a continuous plant dynamics interacting with the discrete nature of the network. Designing of digital controllers for a sampled data system is done by using lifting technique [9]. A networked predictive control has two main units: the control prediction generator, to generate a set of future control predictions and the network delay compensator, used to compensate the effect of unknown random network delay [10]. An optimal cost control of NCS uses an upper bound on a given performance index, and the system performance degradation is guaranteed to be less than this bound. Conditions of asymptotic stability for networked control system with long time delay are presented. There are methods like sliding mode control and Kalman filter based estimator are also some topics of interest in NCS [11]. In model based NCS, an explicit model of the plant is used to produce an estimate of the plant state behavior between transmission times. This control architecture has as its main objective the reduction of the data packets transmitted over the network. In this way, the amount of bandwidth necessary for feedback control to maintain certain stability and performance criteria is minimized The control and communication co-design is a new and interesting research [13]. In the co-design approach, network issues such as time delay, packet dropout, and bandwidth limitation will be considered simultaneously with control system issues such as stability and control performance. Generally, the network scheduling in NCSs is to assign a transmission schedule to each transmission entity based on a scheduling algorithm. The NS-2 network simulator is a network simulation package developed at the Information Sciences Institute at the University of Southern California. NS-2 provides many powerful objects to simulate different types of networks and network architectures, as well as different types of nodes and traffic patterns. However, some problems that influence performance of an NCS are appeared (such as network-induced delays, sampling period, data packet dropout, network scheduling and stability). All the major issues raised in NCSs is the unreliable transmission paths because of limited bandwidth and large amount of data packet transmitted over one line, which may result in transmission delays and data packet dropout.

This paper presents a development framework for design of a real-time networked servo control system for investigation of issues due to use of communication channel. Indirect control is considered first without delay followed by design a suitable delay compensation method. A robust tuning method based on gain margin and phase margin specification is discussed. However, it is not well implemented in real-time networked control of servo system. The Smith predictor is the most commonly used dead time compensators used in industrial applications, and the benefit is in that the structural simplicity and easy implementation. However, it is not adaptive to match with the stochastic behavior of network characteristics. Thus, we suggest an adaptive delay compensation process for efficient control. Time delay adaptive compensation gives an effective control to solve dead time, and creates a virtual environment using the plant model and computed delay which is used to compensate the effect of delay. This design approach is simulated using TrueTime simulator which is a Matlab Simulink based simulator facilitates co-simulation of controller task execution in real-time kernels, network transmissions and continuous plant dynamics for NCS. The simulator software consists of a Simulink block library. The various network blocks allow nodes to communicate over simulated wired or wireless networks. The result has been analyzed, and it is confirmed that this control provides good performances.

2. Related Study

In general, networked control system (NCS) is implemented using a network through which the feed-back path is closed such that the sensors and actuators can communicate with the controller. In the NCS, a network is used to connect the system components and controller. Broadly the networks used in the networked control system are classified as dedicated and non-dedicated networks. A dedicated network is known as control network and non-dedicated network as data network. A dedicated network is concerned about the constant and frequent packets transmission among a relatively large set of nodes. Non-dedicated networks use large data packets and relatively infrequent transmission rates, with high data rates to support the transmission of large data files. Some of the current control networks used for design NCS are Ethernet, Device Net and Control Net. Ethernet is of non-dedicated type while other two are dedicated networks. Ethernet is type of local area networking solution widely used in the home, office. Ethernet uses the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) mechanism for resolving contention on the communication medium. Ethernet is a nondeterministic protocol and does not support any message prioritization.

At high network loads, message collisions are a major problem because they greatly affect data throughput and time delay which may be unbounded control net are typical examples of token-passing bus or deterministic networks control networks. As in general token-passing buses, the node with the token can only send data and provides excellent throughput and efficiency at high network loads. Device Net/CAN is a serial communication protocol developed mainly for applications in the automotive industry but also capable of offering good performance in other critical industrial applications. The CAN protocol uses CSMA/Arbitration on Message Priority (CSMA/AMP) medium access method. Thus the protocol is message oriented, and each message has a specific priority that is used to arbitrate access to the bus in case of simultaneous transmission. CAN is a deterministic protocol optimized for short messages and very slow data rate.

According to network used in the NCS there are two types of configuration of NCS namely level one and level two communication configuration. Further the level one communication configuration is again classified as direct structure and hierarchical structure. The NCS in the direct structure is the mostly used which comprises of a controller and a system consists of sensors and actuators are connected by a common sharing network to perform remote closed-loop control. The control signal and the sensor measurement are encapsulated into data packets for transmission across the network. A controller and a remote system are in closed loop using a network. Here it shown a single sensor and actuator where, there are many sensors and actuators may present in a practical implementation with multiple controllers. The hierarchical structure has controller and a remote closed loop system. The only difference between a direct and hierarchical structure is the controller. Two controllers are used namely main and remote controller. The main controller computes and sends the reference signal in a packet via a network to the remote system. The remote system then processes the reference signal to perform local closed-loop control and returns to the sensor measurement to the main controller for networked closed-loop control.

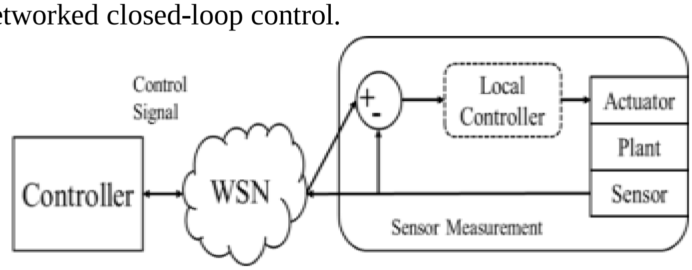

Figure 1. WSN Control System Configuration

Similar to the direct structure, the main controller can be implemented to handle multiple networked control loops for several remote systems. This structure is widely used in several applications including mobile robots and remote operation. The use of either the direct structure or the hierarchical structure is based on application requirements and designer's preferences. Control and analysis methodologies for the direct structure could also be applied for the hierarchical structure by treating the remote closed loop system as a pure plant. A NCS structure is shown in Fig.1, a main controller and a remote system are connected by a network. Main controller calculates the reference signal for the remote controller. The role of remote controller is to look after the uncertainty of the system only. A two-level communication model as its name suggests, it has two levels are connected by communication channels as shown in Fig.2. Such a NCS uses microcontrollers as intermediate communicator to communicate with the both the channels. A system with sensors and actuators is in the closed loop with the plant through a communication network. A kind of field bus dedicated to real-time control network used for communicating plant to microcontroller. It is known as level one communication. In level two, the microcontrollers with a high-level computer system through another communication network. This network is typically non-dedicated networks like local area network, wide area network (WAN), or possibly the Internet. As shown in Fig.2, microcontrollers communicate with system components using a dedicated network in level-1 and with a high level controller using a non-dedicated network in level-2 communication.

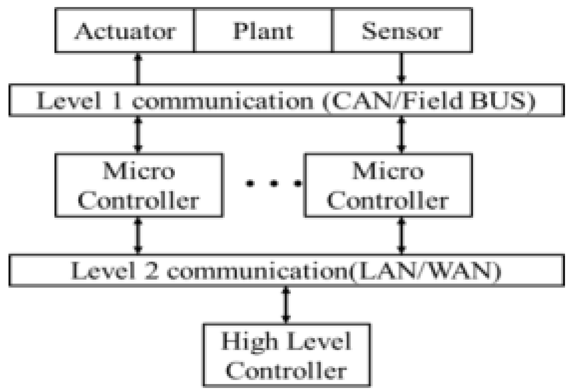

Figure 2. Level-2 Configuration of NCS

Use of networks for connecting the control system components like sensors, controllers, and actuators in any process can effectively reduce the complexity of systems, with nominal economical investments, eliminate unnecessary wiring. It is easy to add more sensors, actuators and controllers with very little cost and without heavy structural changes to the whole system. Potential applications of NCS are including space explorations, terrestrial exploration, factory automation, remote diagnostics and troubleshooting, hazardous environments, experimental facilities, domestic robots, automobiles, aircraft, manufacturing plant monitoring, nursing homes or hospitals, remote robotics and remote operation [12].

The issues involved in NCS are broadly classified into two categories namely network issues due to use of network and control performance due to presence of network in the system. Network issues deals with bandwidth allocation, scheduling and network security where the control problem deals with stability analysis and delay compensation. As the network used is having limited bandwidth, optimizing the performance of an NCS can be achieved by proper balancing of network sampling and bandwidth allocation with the resulting network performance degradation. The maximum bound of the network sampling is called maximum delay bound. Within it stability of the system is guaranteed in spite of the performance degradation. A network scheduling method is required to reduce a basic sampling time within the maximum allowable delay bound, while guaranteeing real-time transmission of sporadic and periodic data, and to minimize network utilization for non-real time message. Network security is another problem in a NCS which is more concern on type of network used and network administrator. There should be provisions and policies adopted by the network administrator to prevent and monitor unauthorized access of the computer network and network-accessible resources.

Control issues involve various delays present in NCS and packet dropouts in a network. In an NCS, various delays with variable length occur due to sharing a common network medium [17]. They are called network-induced delays, controller processing delay and natural delay of plant. The natural delay is the delay associated with the system itself known as transportation lag of the system. Controller processing delay is the amount of time required by the controller to calculate the control input. Generally these delays are very less and mostly neglected. The delay of concern here is the network-induced delays, it occurs when sensors, actuators, and controllers exchange data packet across the communication network. Networked induced delay arises from sensor to controller (backward channel delay) and controller to actuator (forward channel delay). Packet dropouts in NCS occur due to node failures, improper network scheduling or data packet collisions. Due to this Although In most network protocols a non-transmitted packet only retransmit for a limited time and after this time has expired, the packets are dropped. Furthermore, for real-time feedback control data such as sensor measurements and calculated control signals, it may be advantageous to discard the old non-transmitted message and transmit a new packet if it becomes available. In this way, the controller always receives fresh data for control calculation.

DC motors are most widely used actuators in servo position, speed regulation control systems. Basically DC motors are torque transducers, converting electrical energy to rotational mechanical energy. For analysis of control system we require a mathematical model of a system. Equivalent circuit of a DC motor is shown in Fig.3. In figure 3, R_a is armature resistance (ohm), L_a armature inductance (H), $i_a(t)$ armature current (Ampere), $V_a(t)$ applied armature voltage (volts), $e_b(t)$ back emf (volts), $T_m(t)$ torque developed by motor (Nm), B_m Viscous friction of motor shaft (Nm/rad/s), and φ magnetic flux.

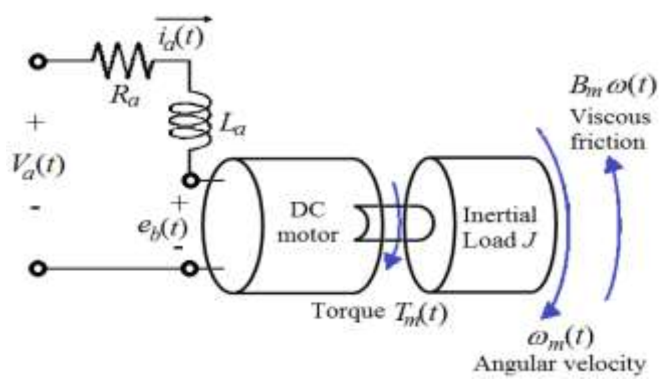

Figure 3. A Schematic of DC motor

The control input of the motor is applied as the input voltage $v_a(t)$ of the armature terminals. In servo applications, the DC motor is usually used in linear range. So we assume that the torque developed by motor $T_m(t)$ proportional to the flux φ and armature current $i_a(t)$

$$T_m(t) = k_m(t)\varphi i_a(t) \tag{1}$$

As the flux is constant, the equation 1 can be written as

$$T_m(t) = k_i\, i_a(t) \tag{2}$$

The motor back emf is proportional to speed of the motor is described as

$$e_b(t) = k_b\, \dot{\theta}_m(t) \tag{3}$$

Here k_i is motor torque constant, k_b the back emf constant, and θ_m angular displacement of the motor shaft (rad). The differential equation for the DC motor circuit (no-load) is

$$L_a \dot{i}_a(t) + R_a i_a(t) + e_b(t) = V_a(t) \tag{4}$$

The torque equation is

$$j_m\ddot{\theta}_m(t) + B_m\dot{\theta}_m(t) - k_i i_a(t) = 0 \tag{5}$$

Using Laplace transformation with zero initial conditions, we get the transfer function (input voltage $V_a(s)$ and output position $\theta_m(s)$) of the DC motor as a third order equation

$$G(s) = \frac{\theta_m(s)}{V_a(s)} = \frac{K_i}{(j_m s^2 + B_m s)(L_a s + R_a) + K_i K_b s} \tag{6}$$

Assuming that armature circuit inductance L_a is very small (usually negligible). So the above equation becomes a second order transfer function as

$$G(s) = \frac{K_i}{R_a j_m s^2 + R_a B_m s + K_i K_b s} \tag{7}$$

The servo motor is equipped with A/D, D/A converters, PWM converters and others. So, identification of each individual component is a bulky procedure. Hence we can identify the system as a whole including all the components. Providing input voltage to the servo motor and obtain the corresponding position as output, and by using these input and output data model of the servo system is identified.

3. Adaptive Compensating Control Design

A robust tuning method is usually based on gain margin and phase margin specification. However, this control is not well choice for NCS. So, a delay compensation process can be used for efficient control. Time delay adaptive compensation gives an effective control to solve dead time, and creates a virtual environment using the plant model and computed delay which is used to compensate the effect of delay.

3.1 Robust Controller Design

The delay problem causes a decreased phase margin that includes a lower damping ratio and a more oscillatory response for the closed-loop system performance in NCS. Therefore, robust controller design method is required by using gain and phase margin. The objective of this design is to keep the phase and gain margin of a delayed system fixed at a certain value. Thus, the system becomes a stable state in presence of delay. This tuning method is known as frequency domain/parameter plane tuning method. Consider a servo system which contains a time delay element, its transfer function is shown as follows.

$$G_p(s) = \frac{K}{s^3 + a_1 s^2 + a_2 s + a_3} e^{-\tau s} \tag{8}$$

where τ is the delay time of the system. Using a second-order approximation, the time domain and frequency domain specifications are approximately converted into interval gain margins and phase margins.

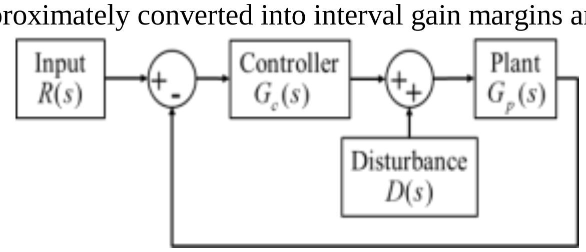

Figure 4. Typical Controller Block diagram

Fig.4 shows the block diagram of the considered system where the transfer functions of the process and the controller are denoted as $G_p(s)$ and $G_c(s)$, respectively. $D(s)$ is the external disturbance. An error actuated PID controller has the following transfer function:

$$G_c(s) = K_p + K_i / s + K_d s \tag{9}$$

The forward open-loop transfer function of the control system is:

$$G_o(s) = G_c(s)G_p(s) = N(s)/D(s) \tag{10}$$

By letting $s = j\omega$,

$$\begin{aligned} G_o(j\omega) &= |G_o(j\omega)|e^{j\phi} \\ \phi = \angle G_o(j\omega) &= \tan^{-1}\left(\mathrm{Im}(G_o(j\omega)/\mathrm{Re}(G_o(j\omega))\right) \end{aligned} \tag{11}$$

A gain-phase margin tester function is defined as the following

$$F(j\omega) = D(j\omega) + Ae^{j\omega}N(j\omega),\ A = 1/G_o(j\omega) \tag{12}$$

It can be seen that $F(\cdot) = 0$ for all ω. The open loop transfer function can be rewritten using the controller structure (9) as $G_c(s)G_p(s)$. Putting $s = j\omega$, the numerator of $G_c(s)G_p(s)$ is

$$\begin{aligned} N(j\omega) &= K(X_N + jY_N) \\ X_N &= (k_i - k_d\omega^2)\cos(\omega T) + k_p\omega\sin(\omega T) \\ Y_N &= k_p\omega\cos(\omega T) - (k_i - k_d\omega^2)\sin(\omega T) \end{aligned} \tag{13}$$

The denominator of $G_c(s)G_p(s)$ is

$$\begin{aligned} D(j\omega) &= X_D - jY_D \\ X_D &= \omega^4 - a_2\omega^2, Y_D = a_1\omega^3 - a_3\omega \end{aligned} \tag{14}$$

Define

$$\begin{aligned} B_1 &= KA\omega\sin(\theta + \omega T), C_1 = KA\cos(\theta + \omega T) \\ D_1 &= X_D - k_d\omega^2 C_1 \end{aligned} \tag{15}$$

And

$$\begin{aligned} B_2 &= KA\omega\cos(\theta + \omega T), C_2 = KA\sin(\theta + \omega T) \\ D_2 &= -Y_D + k_d\omega^2 C_2 \end{aligned} \tag{16}$$

Then, we can find

$$k_p = \det\begin{pmatrix} C_1 & D_1 \\ C_2 & D_2 \end{pmatrix} / \det\begin{pmatrix} B_1 & C_1 \\ B_2 & C_2 \end{pmatrix} \tag{17}$$

$$k_i = -\det\begin{pmatrix} B_1 & D_1 \\ B_2 & D_2 \end{pmatrix} / \det\begin{pmatrix} B_1 & C_1 \\ B_2 & C_2 \end{pmatrix} \tag{18}$$

3.2 Adaptive Time Delay Control

Assume that a process model is given by $G(s) = G_0(s)e^{-\tau s}$, where $G_0(s)$ is the delay free part of the system, and $C(s)$ is the controller for this, then the close loop transfer function $H(s)$ is the following:

$$H(s) = C(s)G_0(s)/(1 + C(s)G_0(s)) \tag{19}$$

Also, consider the delayed plant $G(s)$ and a controller $C_d(s)$, then the close loop transfer function $H_d(s)$ is the following:

$$H_d(s) = C_d(s)G(s)/(1 + C_d(s)G(s)) \tag{20}$$

As the equation (19) has no delay, so the response of close loop transfer function is attained under proper design of controller. The objective of adaptive predictor is to eliminate the delay effects in (20) by designing a suitable controller C_d. It can be stated as

$$H_d(s) = H(s)e^{-\tau s} \tag{21}$$

It is not possible to use the actual plant and delay in the actual closed loop, so it is replaced with an adaptive model $G^*(s)$ of actual plant and estimated closed loop delay as τ^*. Then we can find the value of C_d as the following.

$$C_d(s) = C(s)/(1 + C(s) - C(s)G_0^*(s)e^{-\tau s}) \tag{22}$$

A block diagram of this predictor is shown as Fig.5.

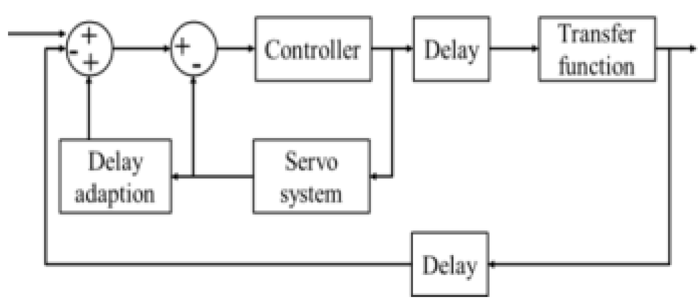

Figure 5. Block Diagram of Adaptive Predictor

4. Simulation

In NCS, co-design is important to utilization of system resources, to achieve the optimized system performance and for better understanding of the system. True Time is a Matlab/Simulink based simulator for networked and embedded control systems that has been developed at Lund University since 1999 which facilitates co-simulation of networked system. It is used as a communication channel between controller and plant. For Delay estimation, we used two computers that are connected with a LAN. The process starts with sending a sinusoidal signal from computer 1 to 2 then receiving the same from computer 2 to 1. Difference of time between the amplitude of signal sent from computer 1 to 2 and received by computer 1 from 2 will give the amount of delay. We used UDP communication blocks of XPC target in Simulink library for this experiment. Fig.6 shows the configuration of computer 1 and 2. Fig.7 shows the reference signal and delayed signal. The delay is estimated as 0.053sec. For the transfer function of servo system, third order model response has best fit percentage of 93.61. So we choose a third order model. After performing the identification procedure, we used a system transfer function with K = 53.27, a_1 = 9.48, a_2 = 36.19, and a_3 = 0.82.

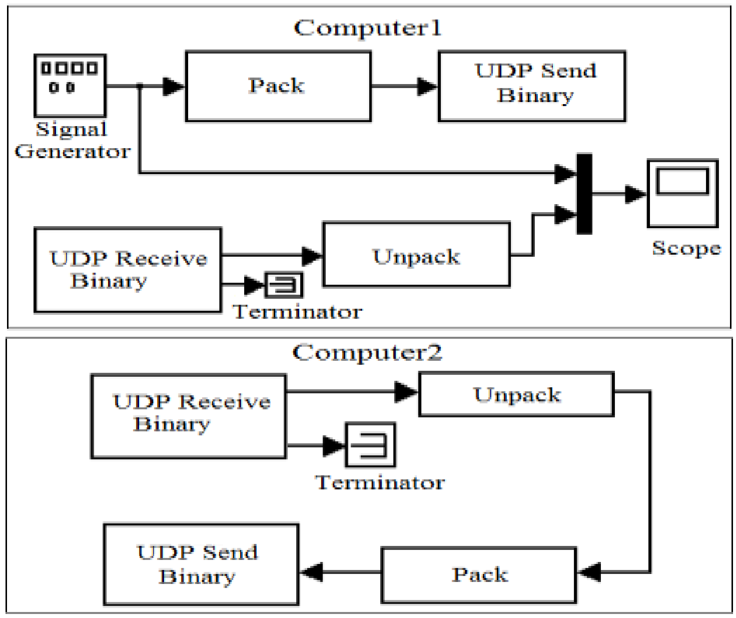

Figure 6. Delay Compensation (UDP Communication)

The servo setup is composed of a mechanical and digital part. Digital part is the intermediate between computer algorithm and mechanical part. The ADC converts the real physical measurements to digital data so that a Matlab code based controller can utilize to generate a control signal to DAC and this analog signal drives the servo system again to generate a physical measurement. A networked architecture using True Time is shown in Fig.8 and Fig.9 with robust controller and adaptive predictor respectively and the corresponding response is shown in Fig.10. We have found that the adaptive predictor gives better results than the PID Controllers. A simple experimental delay measurement is presented and used in adaptive predictor. It can be concluded that adaptive predictor gives the best result in presence of delay.

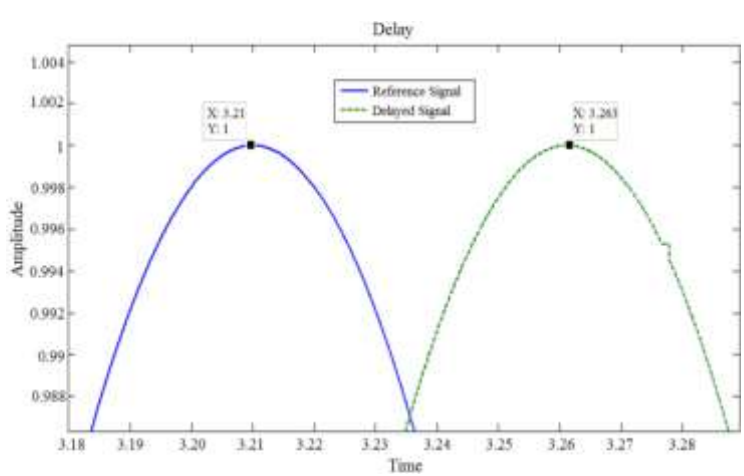

Figure 7. Delay between two computers

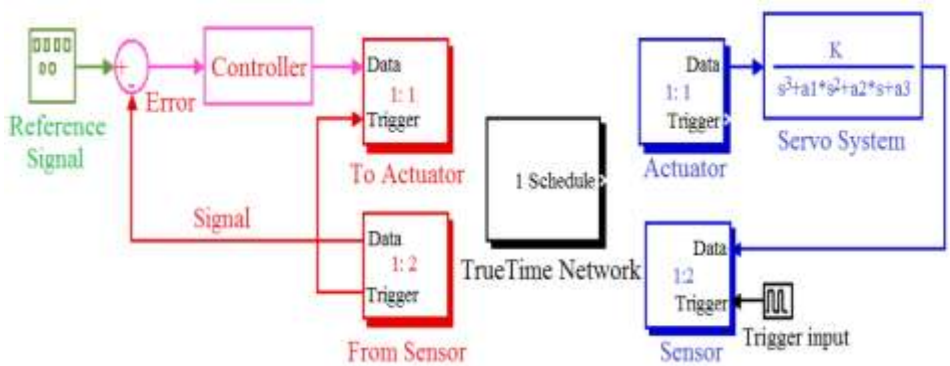

Figure 8. Networked controller in True Time

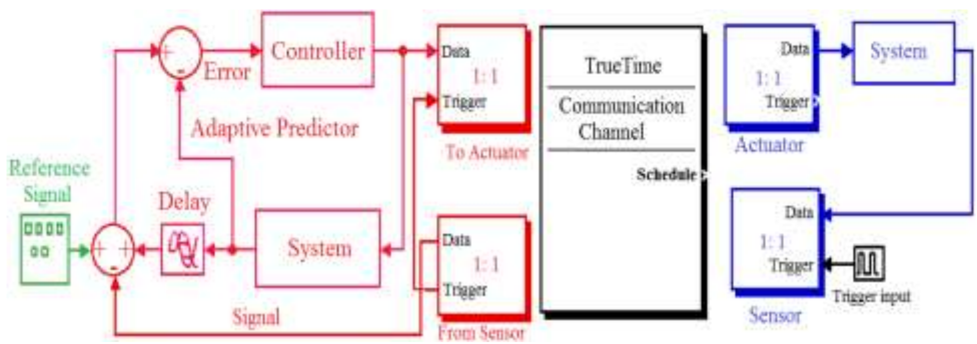

Figure 9. Networked Adaptive Predictor structure in True Time

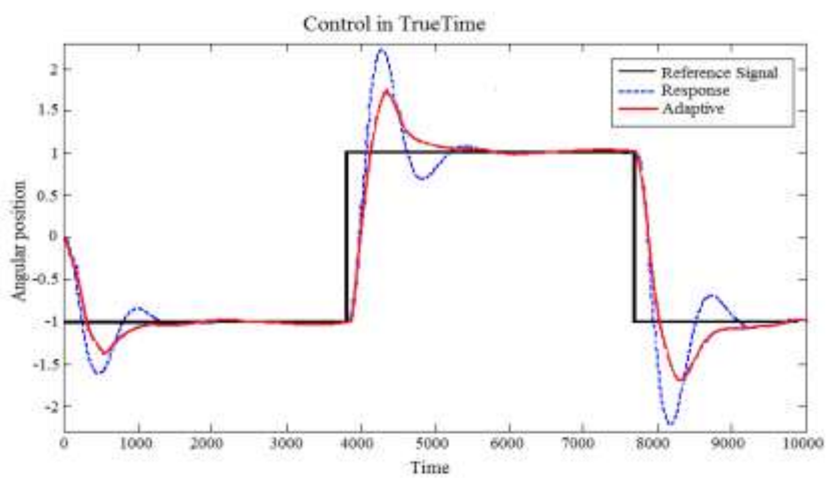

Figure 10. Adaptive response in True Time Simulator

5. Conclusion

Networked control system uses communication network in implementing feedback control ways. The controller for a NCS can be categorized into indirect and direct design. A direct design considers the delay as well as packet loss characteristics with system dynamics. So, it gives more information about each instant of the system. However, it needs an asymptotic stabilization of system, and this stabilization must consider some packet losses and delay. An indirect design considers first without delay followed by design a suitable delay compensation technique. A PID controller with a Smith predictor can be used in real time networked control of servo system. The Smith predictor is the most commonly used dead time compensators used in industrial applications, the benefit is in that the structural simplicity and easy implementation. However, it is not adaptive to match with the stochastic behavior of network characteristics. This paper proposed an adaptive controller design with respect to development of a real-time networked servo system, and implemented adaptive control by using True Time simulator. The results have been analyzed and it is confirmed that this controller provide good performance. But, the networked servo control system here is confined to a LAN. This may be extended to internet based servo control system.

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