Jurnal
Teknologi

Full Paper

A Reference-Model Controller to Mitigate the Effect of Time Delay Change in a Networked Control Systems

Article history
Received
27 April 2015
Received in revised form
15 June 2015
Accepted
25 November 2015

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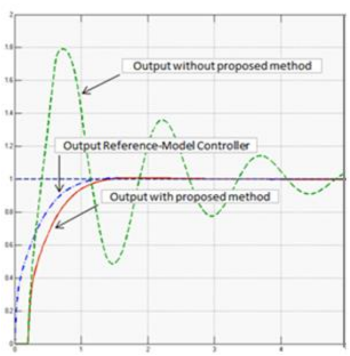
Graphical abstract



Abstract

Various methodologies have been proposed to improve system performance caused by time delay in the network systems. The purpose of this paper is to present an algorithm for mitigating the effect of time delay varying in a Networked Control Systems (NCSs) using a Reference Model Controller. The proposed method is to supervise and measure the transfer function of plant over the network, the result is used to update the reference-model plant. In this experiment, the reference-model used PID controller. The real plant will be driven by the output of PID Controller over the network. With this method, the output of reference-model plant will not be influenced by the delay time varying on the network. The time delay used in this experiment is 0,8s with time delay varying from 0,4s to 1,6s. This time delay is measured directly from the network used by The MatLab software system which is integrated in the reference-model systems. Fact on the filed shows that for the transfer function of reference-model is updated depends on the quality of plants. The good quality plant does no need to update frequently. So this condition can reduce the load of communication and accelerate the control algorithm.

Keywords: Networked Control Systems, Reference-Model Controller, PID Controller

1.0 INTRODUCTION

Network Control Systems (NCSs) are one of the research areas in The Laboratory of Control System at State Polytechnic of Bandung which is focused in tele-controlling for rural area application. The technological progress in controller, networking, and internet brings much interest in NCSs researches and how to exploit the technology [1-2]. This technology induces problems of time delay varying. The problem of time delay (e.g., transport delay, dead time, long distance network communication, execution time of software) is a phenomenon that occurs in physical systems such as sensors, actuators, and network communication. To avoid negative effects on the system performance, control engineers need to account for the time delays when designing a control system [3-4]. The solution for the very big amount of data operated by the system (refer Figure 1) was developed and explained in a study on row index data access matrix method [5].

Generally, the configuration of experimental systems used in this paper (Figure 1) was based on studies by Rida, Feryonika, and Cucun [6] as well as Loden and Hung [7]. The command signal is issued by a controller through the network to a Motor DC in a plant. The input signal and the output signal of the real plant are sent through the network to a controller to update the plant accordingly.

Several methods about time delay issues in networked control systems will be reviewed in Section 2.0. The proposed method, i.e. the reference-model controller is described in Section 3.0; including the block diagram systems used in this experiment. Detail of the experiment results of this algorithm are presented in Section 4.0.

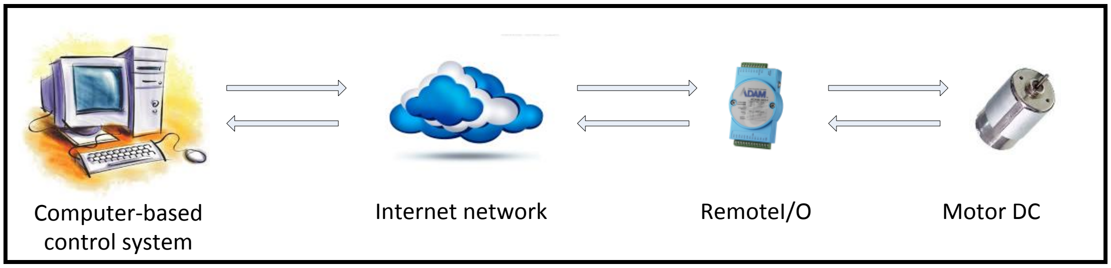


Figure 1 General configuration of experiment systems.

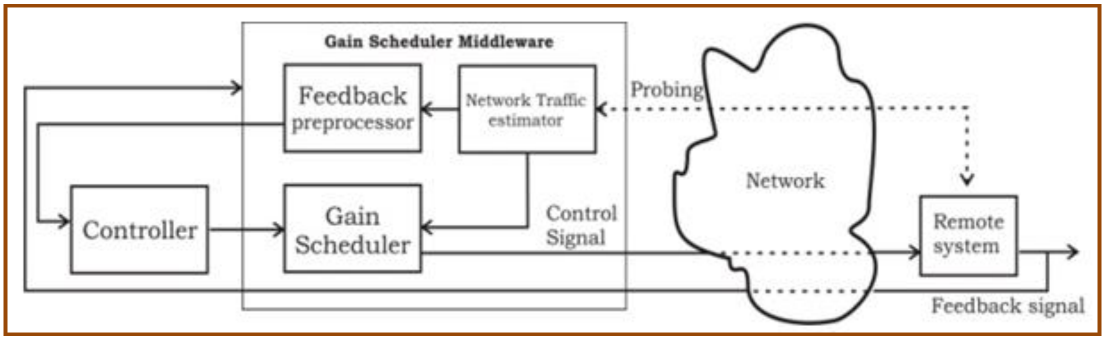


Figure 2 Gain scheduler middleware design [8].

2.0 PREVIOUS RESEARCH

Modern communication technology had created convenience in controlling large distributed systems within wide areas. An array of distributed sensors, actuators, and controllers can be interconnected through common network medium that can bring advantages in low installation cost, ease of maintenance and installation, as well as flexibility and speed to reconfigure [9]. However, there are also several issues in control system such as networked delay, sampling, transmitting methods and data dropout [10]. In this paper, the researcher's discussion is focused on control strategies applied to enhance system response due to change of time delay. Several control strategies will be discussed in the following subsections.

2.1 Robust Control

Robustness in the control scheme is considered due to difficulties to get the ideal mathematical model of the controlled system. To deal with the robust system, bode plot of the system must be known since it provides information about phase and frequency response. The advantages of control design based on bode plot are that it provides exact results for time delay systems and finds the relative stability [11]. A stability system based on bode plot is defined as a negative feedback closed loop system that is unstable if the frequency response of the open loop has an amplitude ratio greater than 1 at the crossover frequency.

To solve the frequency crossover in the open loop transfer function at the phase -180^0, Equation (1) was used.

$$\arg\left(G_{\mathrm{openLoop}}(j\omega)\right) = -180 \qquad (1)$$

where G is denoted as the transfer function of the system (multiplication of controller and plant transfer function). Amplitude Ratio (AR) is then calculated by using Equation (2).

$$AR = \left|G_{\mathrm{openLoop}}(j\omega)\right| \qquad (2)$$

If AR >1, the closed loop system is unstable.

Bode plot analysis, by find phase and gain margin, is then used to assess the stability of the feedback systems. Gain margin (GM) is defined as the change in open loop gain required to make the system unstable, Based on Equation (3), GM can withstand the changes in the system parameters before becoming unstable in closed-loop systems [13].

$$GM > 1 \qquad (3)$$

where $GM = \frac{1}{AR_{co}}$, AR_{co} is amplitude of open loop transfer function of the system at crossover frequency (ω_{co} where $\emptyset = -180^0$). Based on bode stability criterion, the stability can be reached when$\emptyset = -180^0$, AR=1. Another part of bode plot analysis is phase margin (PM) which is defined as the amount of phase angle that can be decreased before the system become unstable. The stability can be derived based on Equation (4).

$$\mathrm{PM} > 0 \tag{4}$$

where $\mathrm{PM} = \emptyset_{pm} + 180^0$

$\emptyset_{pm}$ is the phase angle when amplitude of G(s) = 1 which occurs at a frequency ω_{pm} .

By using the aforementioned method, the robust control system can be designed to overcome time delay problem.

2.2 Smith Predictor

This method, proposed in the 1950's is usually used in factory processes, i.e. within the control systems in the large plants but with fixed delays in signal propagation [7]. This method is effective for systems with fixed delays. However, poor disturbance rejection is considered as a weakness of the method.

2.3 Middleware (Gain Scheduling)

This method was proposed by Tipsuwan and Chow [8] who modeled the delays as shifted exponential probability densities. The mean delay time is calculated from experimental results and then used as nominal value to design their gain scheduling middleware approach. This method has been applied to enable a PI-Controller, Equation (5) is applied in the DC motor with networked condition.

$$G_c(s) = \frac{K_p\left(s+\left(\frac{K_i}{K_p}\right)\right)}{s} = \frac{K_p(s+Z_c)}{s} \tag{5}$$

where Z_c is constant.

The middleware measures the delay in the system and uses the information to adjust an additional outer loop gain parameter β. When time delay is small, the loop gain is increased. If delay times increase, the gain is lowered to maintain system stability and performance. The value of β for given time delay is known *a priori.* A lookup table is generated offline using an optimal design based on cost functions. Structure of control strategy is depicted in Figure 2.

2.4 Adaptive Retuning PID

The adaptive retuning PID method is a basic idea of the algorithms presented in this paper. This method was proposed by Loden and Hung [7] as extended work by Tipsuwan and Chow [8]. PID controller was used due to the inherently robustness against time delay and advantage over PI controller whereby phase lead (phase advance) is possible. The algorithms consist of three main steps: (1) Measuring present time delay of system; (2) Calculating corresponding phase margin lost due to the delay; and (3) Updating PID parameters to recover lost phase margin and return the closed-loop system nominal conditions.

Equation (6) is the form of PID controller where zero locations are dependent on two parameters, i.e. T_i and T_d.

$$G_c(s) = K_p(1 + \frac{1}{T_i s} + T_d s) \tag{6}$$

Based on Equation (7) and Equation (8), the relationship between T_i, T_d, magnitude and phase can be described in Figure 3 and Figure 4. Based on Figure 3, it can be clearly seen that by modifying T_i and T_d, the controller phase can be modified. At the same time, modification of T_i and T_d does not vary the controller gain (refer Figure 4).

$$|G_c(T_i, T_d)| = \sqrt{1 + \left(\frac{1-\omega^2 T_i T_d}{\omega T_i}\right)^2} \tag{7}$$

$$\angle\emptyset_c(T_i, T_d) = \arctan\left(\frac{1-\omega^2 T_i T_d}{\omega T_i}\right) \tag{8}$$

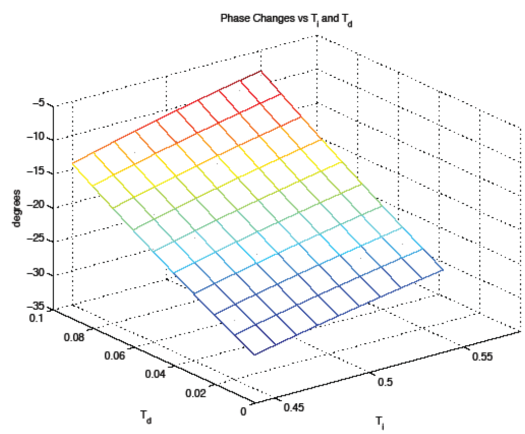


Figure 3 Phase change due to Ti and Td variation.

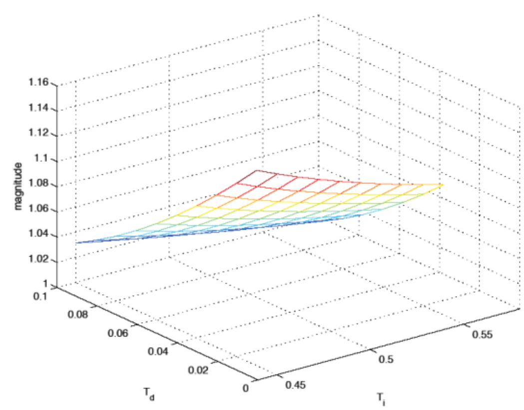


Figure 4 Gain change due to Ti and Td variation.

The control algorithm is aimed to recover phase margin that was lost from the changing delay (problem always appears in NCSs). The recovering strategy is by adjusting parameters T_i and T_d so that the new controller phase compensates for the change in phase delay. Detail of the algorithm is described as follows:

a. Find delay change in network system, δt. In network technology, it can be found by typing 'ping' command.
b. Calculate the phase delay change as stated in Equation (9)

$$\delta \emptyset_m = \omega \; x \; \delta t \; x \frac{180^0}{\pi} \tag{9}$$

c. Based on Taylor series expansion, Equation (8) can be set as Equation (10)

$$\emptyset_c(\mathrm{T_i}, \mathrm{T_d}) = \emptyset_c(\mathrm{T_{i0}}, \mathrm{T_{d0}}) + \nabla\emptyset_c \begin{bmatrix} \delta T_i \\ \delta T_d \end{bmatrix} \tag{10}$$

Where $\nabla\emptyset_c$ is the gradient of the compensator phase with respect to the compensator parameters. Substracting the nominal phase $\emptyset_c(\mathrm{T_{i0}}, \mathrm{T_{d0}})$ from both sides yields the change in controller phase due to adjusting controller gains to develop Equation (11).

$$\delta \emptyset_m = \nabla\emptyset_c \begin{bmatrix} \delta T_i \\ \delta T_d \end{bmatrix} \tag{11}$$

By finding $\delta \emptyset_m$ and $\nabla\emptyset_c$, the incremental change in controller parameters $(\delta T_i, \delta T_d)$ can be derived.

d. Based on the values of δT_i and δT_d, the PID controller parameters are finally updated.

3.0 METHOD PROPOSED

The model time-delay of network communication used the Pade approximation method. The high-order Pade approximations produce very sensitive configuration to perturbations [12]. The present work used the time-delay model of Tipsuwan and Chow [8] who modeled the delays as shifted exponential probability densities. The mean delay time is calculated from the experimental results. Tipsuwan and Chow used the mean delay time as a nominal value to design their gain scheduling middleware approach and subsequently adjusted the loop gain via gain scheduling by adjusting additional PI controller to overcome the delay time effect [8].

Previous studies by the researcher have applied the method proposed by Loden and Hung using the real plant DC motor. The round trip time delay between several internet nodes has been studied based on the method proposed by Tipsuwan and Chow [5] [6].

The method developed in this paper is based on the algorithm was developed by NLoden and Hun [7] and by Tipsuwan and Chow [4] to mitigate the degradation of system performance caused by time delay. In this work, several configurations to improve algorithm are made. The method proposed is called the reference-model controller. The reference-model controller is a model that will produce the desired output for a given input [13]. The PID Controller used like the system used by Loden and Hun [7]. The plant used a DC Motor, similar to a plant used by Loden and Hun as well as Tipsuwan and Chow [7] [8]. The method applied to this DC motor was than examined to the DC motor as show in Figure 9. The proposed algorithm contains two steps. First, measure present time delay of the system and determine PID parameters. Second, identify the transfer function of the real plant and update the reference-model.

3.1 Experiment Block Diagram

This experiment used the block diagram shown in Figures 5-7. The block diagram consist of three parts, the closed-loop system standard (Figure 5), the closed-loop system over network without proposed method (Figure 6) and closed-loop system over network with proposed method (Figure 7). These block diagrams are used to compare signal response and effect time delay with proposed method and without proposed method.

3.2 Measuring Transfer Function of Real Plant and Updating the Transfer Function of Reference-Model

This step have goal to assure that real plant transfer function Motor DC-22 and reference-model transfer function Motor DC-21 have always the same transfer function. The procedure is measuring, collecting the data input and output of the real plant Motor DC-22, and then transferring the data measurement to observer in the reference-model controller. The observer will calculate the transfer function and then update Motor DC-21 as a reference-model plant.

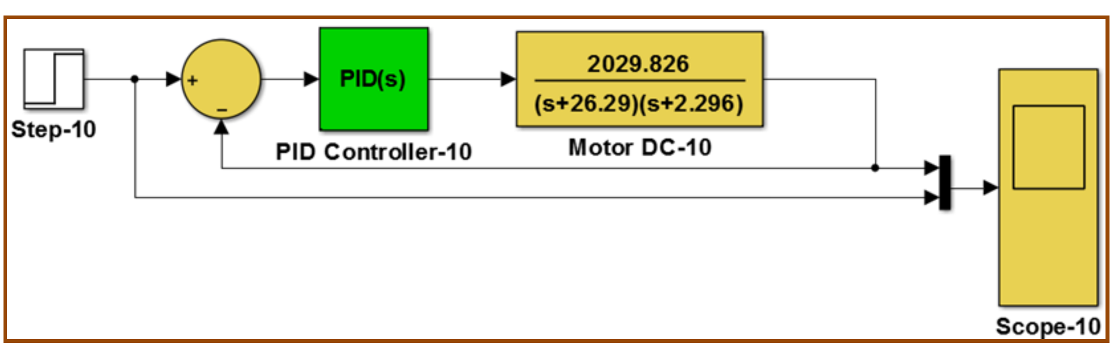


Figure 5 Closed-loop System Standard.

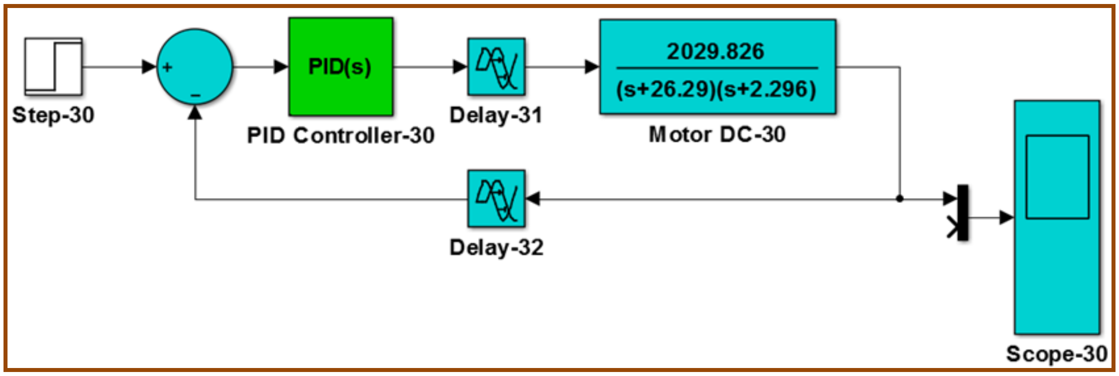


Figure 6 Closed-loop System pass through the network *without* using the proposed method.

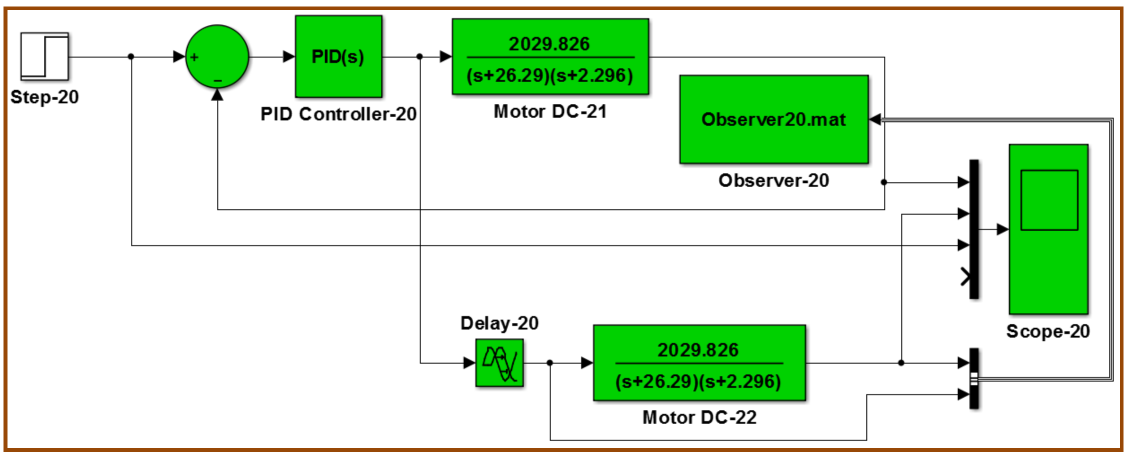


Figure 7 Closed-loop System Closed-loop System pass through the network *with* using the proposed method.

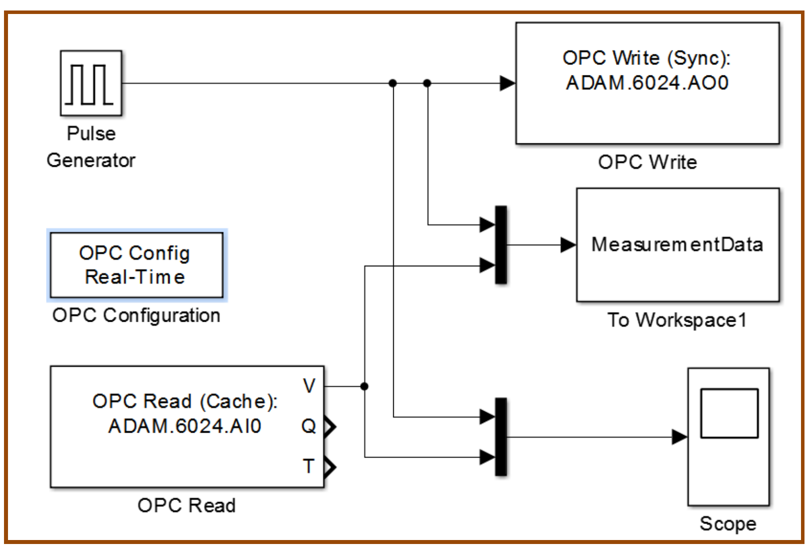


Figure 8 Block diagram for calculating time delay system.

In the next step, the controller updates the transfer function of the reference-model. This task is done by the software of controller. The updating schedule process is done depend on quality of the plant characteristics. It is mean, the update process is not always executed in every loop of calculation. It could be daily, weekly, or monthly. So this condition can reduce the load of communication network and accelerate the control process.

3.3 Measuring System Time Delay

The present time delay of the system is measured using the RTT (Round Trip Time) to determine the nominal delay. The nominal delay used to determine P, I and D of PID Controller-20 as shown in Figure 7.

Block diagram for calculating time delay is shown in Figure 8. The Adam 6024 remote I/O was used to send the signal command and to receive the response from Motor DC-22 over the network via OPC and MatLab software. The results from data measured, shown in Table 1 and Figure 11, give nominal delay time 0.8s with minimum time delay 0.4s and maximum delay time 1.6s.

4.0 RESULTS AND DISCUSSION

4.1 Plant Model

The block diagram shown in Figures 5-7 used MatLab as analysis software and human machine interface software. The hardware experiment system is realized by the system shown in Figure 9 and the software experiment system is realized by the system shown in Figure 10. The Adam 6024 remote I/O data acquisition was used to acquire, to transmit and to receive data used.

The second-order transfer function system and the dynamic of a DC motor are used as expressed in Equation (12). This plant model is the same model used by Loden and Hung [7] and Tipsuwan and Chow [8].

$$G_p(s) = \frac{2029.826}{(s+26.29)(s+2.296)} \tag{12}$$

As described by Loden and Hung [7] as well as Tipsuwan and Chow [8], the open loop step response of plant is shown in Figure 12. The settling time to reach 95% of steady state value is 1.35 seconds (Figure 12). The locations of the poles are at -26.29 and -2.296 as seen from the denominator of Equation (12). Diagram pole-zero of Equation (12) is shown in Figure 13. The pole location clearly indicates open loop stability of the plant.

As described in block diagram system in Fig. 7, the command signal from PID Controller-20 will be delayed by the network Delay-20. And the responses of Motor DC-22 also will be delayed. The data of plant response or the data of plant transfer function will be sent to the observer. This data is used by the observer to calculate and update the plant of reference-model transfer function. And then the feed-back signal is generated by the plant of reference-model to summing point to produce the error signal for PID Controller-20. The output of PID Controller-20 is used to drive the real plant over the network.

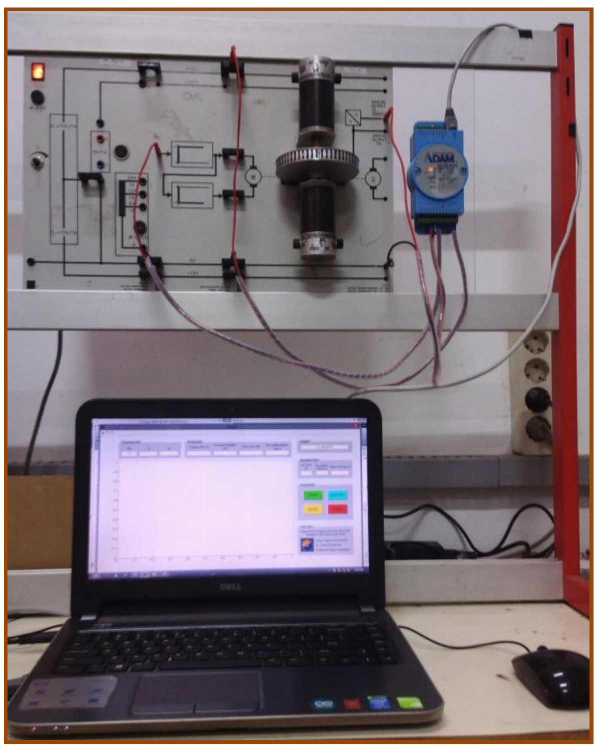


Figure 9 Plant of hardware experiment systems.

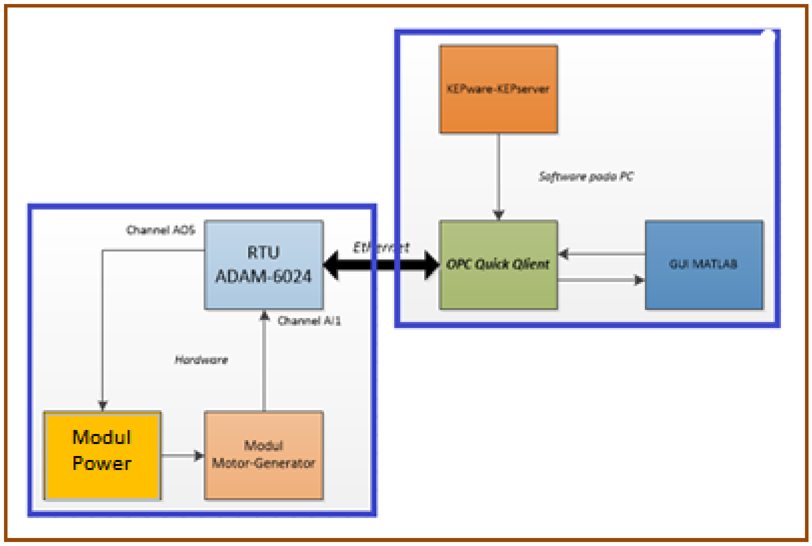


Figure 10 Block diagram of software experiment systems.

4.2 Measuring System Time Delay

By sending the data over the network and capture the return data from the plant, so the difference time between sending time and receiving time can be calculated. This time delay known the RTT (Round Trip Time). By experiment, all of time delay data was noted as shown in Figure 11 and Table 1. The nominal delay is determined by choosing the value of the time delay which appears most often. By the experiments, the nominal time delay is 0.8s, the maximum time delay is 1.6s and the minimum time delay is 0.4s. The nominal delay used to determine P, I and D of PID Controller-20 in Figure 7.

4.3 Adjustment of PID Controller

To apply proposed method with time delay nominal, PID controller must be adjusting to response desired. The nominal time delay is used 0.8s (Table 1 and Fig. 11). This nominal time delay is used to adjust the parameters of PID Controller-20 in the reference-model. The transfer functions of PID Controller represented by G_C. The expressions of PID Controler-20 are given by:

$$\boldsymbol{G_c}(s) = \boldsymbol{P} + \boldsymbol{I}\frac{1}{s} + \boldsymbol{D}\frac{N}{1+N\frac{1}{s}} \qquad (13)$$

where:

P : gain parameter P
I : gain parameter I
D : gain parameter D
N : filter coefficient N

By the result of nominal time delay 0.8s and by process of adjustment and tuning PID Controller-20 parameter, so the parameters of PID Controller are:

P = 0.0530004889250036
I = 0.117631667929381
D = 0.00551915855498791
N = 402.758084101541

Table 1 Measurement Data of Time Delay

Time Delay (s)	Sum of Data
0,4	15
0,6	108
0,8	111
1	13
1,2	3
1,6	1

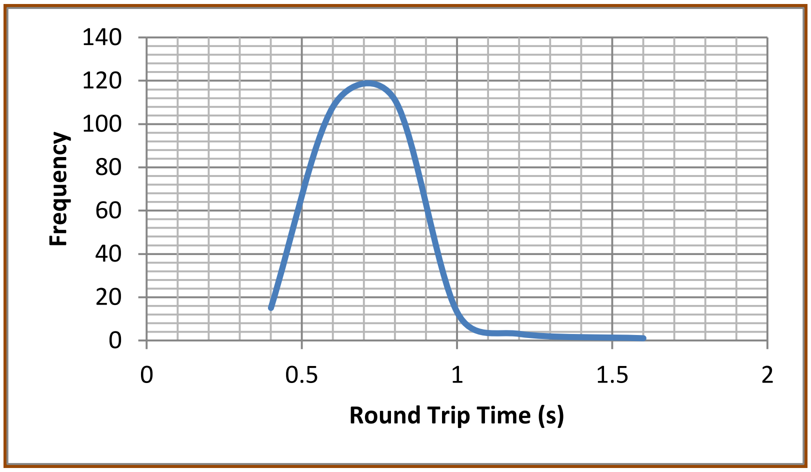


Figure 11 Experiment Results of Round Trip Time Delay.

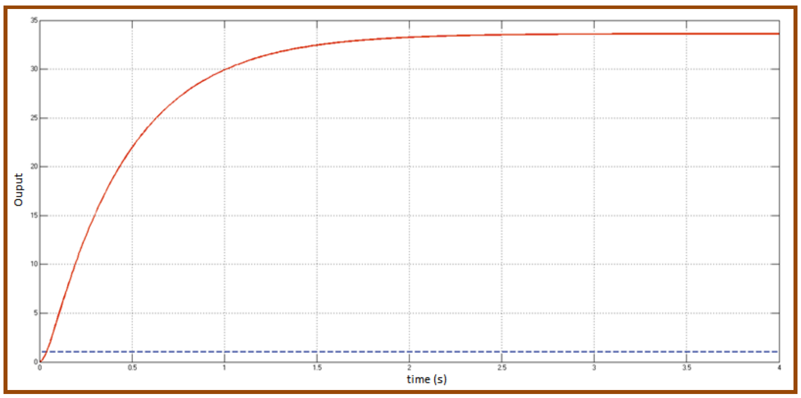


Figure 12 The open-loop step response of Motor DC-22.

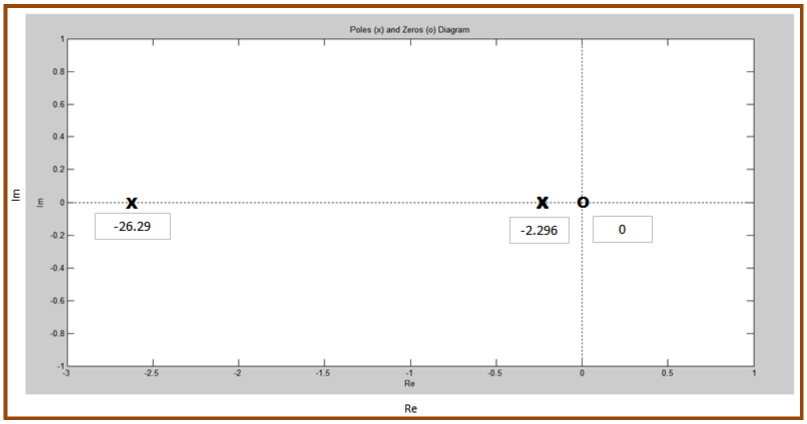


Figure 13 Diagram of Pole (x) and Zero (o) Motor DC-22.

4.4 Plant Identification

The identification process is to find the transfer function of plant to be updated to the reference-model. This process executed by the controller. This paper used the system identification tool available in MatLab and the result of reference-model transfer function is:

$$G_{crm} = \frac{2029.8}{(s+26.29)(s+2.296)} \tag{14}$$

.

The Equation (14) is equal to Equation (12). So, the transfer of the real plant is equal to the transfer function of reference-model plant.

4.5 Comparison of Results

Plots of the difference systems from step response are shown in Figure 15. The reference-model response is dash dot line plot (blue), the output without reference-model is dash line plot (green), and the output with reference-model is solid line plot (red).

For the system without reference-model (Fig. 5), the minimum time delays 0.4s RTT give the output of signal relatively wavy (Fig. 14). Meanwhile, the system that uses the reference-model has the signal relatively the same as the output of the reference-model delayed. And the output relatively is not wavy.

If the time delay increases (Figure 15), the system without reference-model tends to be unstable. Meanwhile, the system that uses the reference-model, the output signal relatively the same as the output of the reference-model delayed. And the output is still not wavy.

In Figures 14 and 15, it has been shown that the reference-model controller works well to mitigate the effect of time delay change in a Networked Control Systems.

Furthermore, the difference between the algorithms described in section 2.4 Adaptive Retuning PID with the algorithm proposed in this paper can be described as follows:

- Algorithm described in section 2.4 is an adaptive retuning PID. It updated the PID parameters based on the value of the time delay by using a lookup table every looping of program.
- Algorithm proposed in this paper is a reference-model controller. It updated the parameters of reference plant. Updating process conducted depends on the quality of product and the updating process is in real time or online. So it is better in terms of algorithm completion speed.

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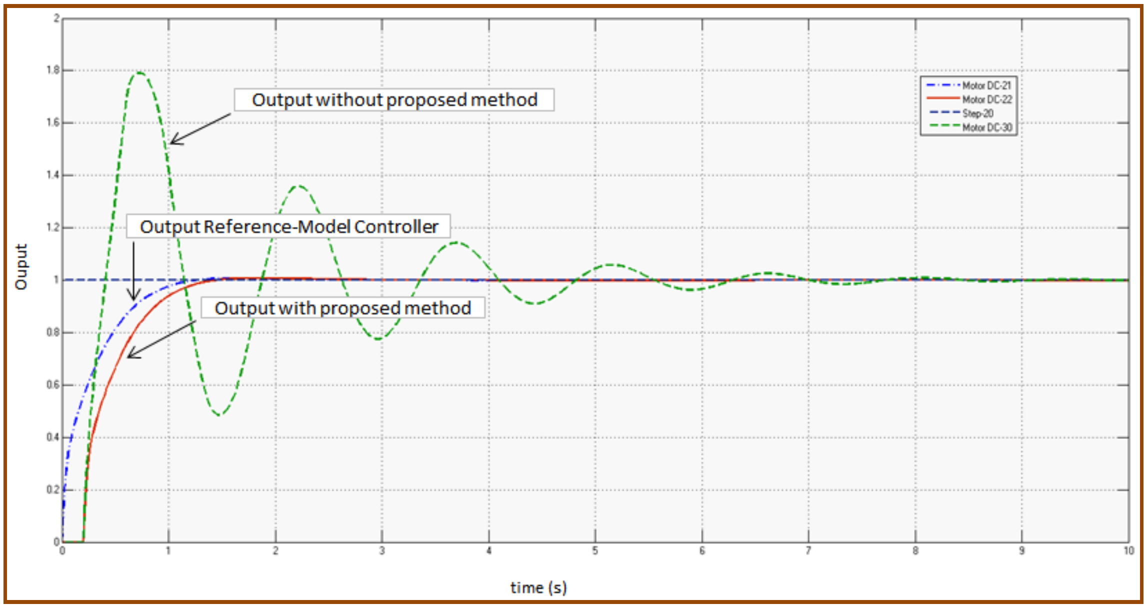

Figure 14 Output Comparison (between *with* and *without* proposed method at time delay 0.4s RTT).

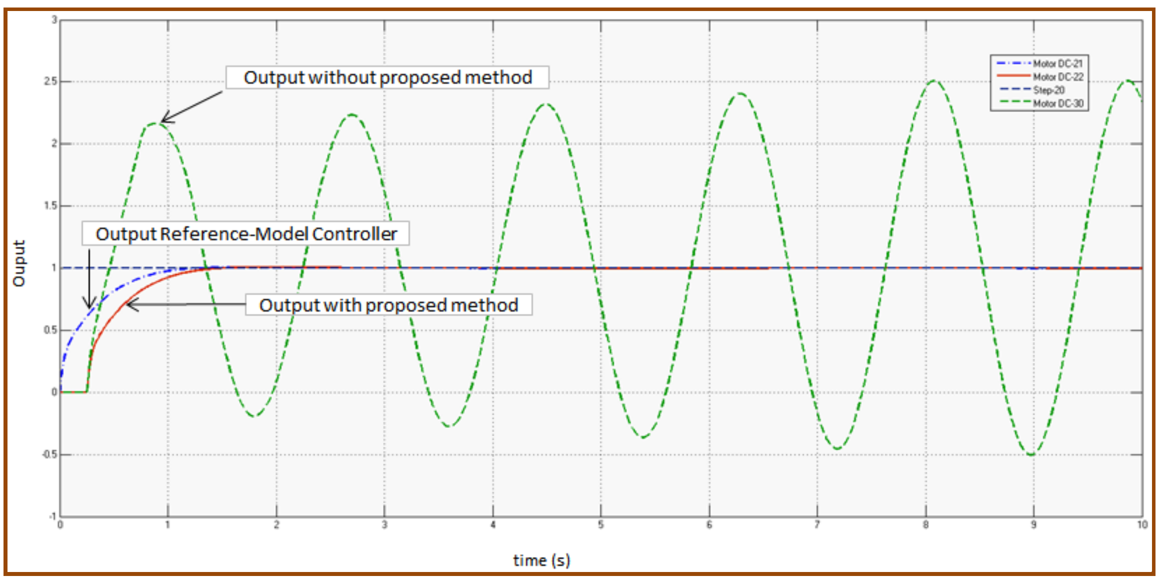

Figure 15 Output Comparison (between *with* and *without* proposed method at time delay 0.5s RTT).

5.0 CONCLUSIONS

NCSs research is growing, especially for application in remote areas. Various methodologies have been proposed to improve system performance caused by time delay in the network. This paper presents the use of reference-method models using the internet network. The transfer function of reference-model is updated depend on the quality of plants. The feedback signal generated by the reference-model is used to improve system performance. And it has been shown that the reference-model controller work well to mitigate the effect of time delay change in a Networked Control Systems.

In completing this paper, future research will combine the method proposed by Loden and Hung to adjust P, I and D of the PID Controller [7] and using reference-model method proposed in this paper in our NCSs configuration and plants for application in rural area.

Acknowledgment

Acknowledgment is addressed to Nathan B. Loden and John Y. Hung that have given some ideas on the implementation of the research conducted in the Laboratory of Distributed Control Systems and HMI/Scada. Acknowledgment is addressed also to the laboratory staffs and my students in Electrical

Engineering Department, Bandung State Polytechnic, Indonesia.

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