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MODIFIED DIGITAL CONTROLLER REDESIGNING BY PLANT INPUT MAPPING (PIM) APPROACH FOR DELAYED DYNAMIC CONTROL SYSTEMS

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Abstract: *A networked control system (NCS) is a closed loop control system over a data network, in which Processes according to past values are affected by delay. While delays; more than expected, will make the system unstable; Using Predictors algorithm like Smith predictor is one way to predict delay in networked control system but not the best. In this paper a new structured controller has been developed with plant input mapping (PIM) approach in order to reach better results in comparison with the systems equipped by modified Smith predictor. Although redesigning digital controller by PIM performed better in higher delays but showed some weaknesses in small delay in compare with local approach in terms of overshoot and settling time.*

1 INTRODUCTION

A networked control system (NCS) is a closed loop control system over a data network. Networks reduce wiring, connections complexity and the cost of devices and they ease the use. Delay and pocket loss in data transmission are two important values in real-time controlling. Predicting this delay and knowing past state of system in are one of the ways to emission controlling orders. The Smith predictor algorithm is a famous method for systems affected by delay. Using this method, which invented by Dr. Smith in 1954, and many developed schemes which provided can be useful in NCSs. Although in next year's many papers published in direction of improving its weakness in omitting the disturbances; so authors concentrated on improved models. In 1994 an improved structure which leads to significant improvements in its regulatory capacities for reference inputs and disturbances; has been provided [1]. Later many studies were done on auto-tuning controller models. So in 1994 Palmore and Blau presented an auto tuning Smith predictor algorithm for some stable systems [2]. In a similar work [3] a modified Smith predictor with an auto-tune and self-tune by relay feedback introduced. However, they both use the describing function approximation to a relay in their analysis, which can perform results in errors in estimation of the plant model parameters. Also their results are limited to stable processes only [1]. An auto tuning Smith predictor algorithm was presented for low order systems in order to increase the Smith Predictor's performance, which can cover both stable and unstable systems [4]. Using linear least squares is the other advantageous of this method. This new pattern was presented in frequency domain, by optimization method, while the approximate answer is calculating by Linear Least Squares [4]. Result of reviewing more than three hundred valid essays and finally providing three tables that assorted done by structure type, model, and systems stability which affected by delay; caused a fine reference for researches [5]. Analyzing controlling systems under network usually have been done on network or controller. A lot of essays can be find which has supported the both cases in a same time. Also in that year Research Center for Automatic Control of Henry University of France with the cooperation of Laboratory of Process Control and Automation of Helsinki University of Finland presented a general analyze on controlling systems under network [6]. At first the method was based on the maximum bound of delay for transferring data packet over the net. Then Delay range was calculated and predicted for improving performance of controlling systems.

In direction to different combination of smith predictor; a simple method was presented to design an improved predictor controller which contained two controllers [7]. These controllers were reference input tracking and included a proportional-derivative (PD) controller as disturbance rejection controller. The first one is responsible for reducing the maximum overshoot and settling time and was designed without considering delay. In 2008, a modified smith predictor for controlling second order systems affected by delay was presented [8]. This method showed its usefulness for both systems with or without zero. To performing this method three controllers are needed in a same time. Further in a work a new scheme presented which contained Integrates controller and Smith Predictor to build a controller [9]. In spite of changes in delay in network, these controllers show also less sensitivity to high frequency measurement noise and disturbances than PI or PID controllers. . In [10], a single neuron PID controller combined with adaptive Smith predictor was proposed to achieve better compensation effect. The traditional Smith predictor is sensitive to parameter uncertainties, leading to compensation failure when the time delay is stochastic. Single neuron PID controller is adopted to improve the adaptability and the robustness of system with the ability of self-learning and the simple structure. New adaptive Smith predictor can ensure the model error converge to zero. Besides, it does not include the delay model, thus the network time delay does not need to be measured or estimated.

In [11], a robust disturbance reduction scheme using an Artificial Neural Network (ANN) for linear systems with small time delays was presented. It was assumed that the nominal linear systems are stable, minimum phase and relative degree one systems. The proposed structure is an integration of a modified Smith predictor and an ANN-based disturbance reduction scheme. Unlike other disturbance rejection methods, the proposed approach does not require information about unknown load disturbance frequencies

As realized; two ways were considered to confront delay in systems simultaneously; predictor method and robust control. Predictor method usually is using by network when the exact time of delay has been calculated and the second method; when there is not an exact estimation of delay of a network and only the maximum bound is known. Effect of delay in Plant Input Mapping (PIM) method has been studied in a system which was controlled by a first order controller. It was simulated by software and at last the results have been compared with Tustin method as a general discretization method, then the systems stability analyzed by considering variable delay and sampling period.

Digital control systems performance, especially PIM method that is a new technique in designing digital controllers which the procedure is starts by designing in continues domain; has been tested, while full study over system’s behavior during inter-sampling periods have been done. The PIM method, has some possible drawbacks observed in the closed-loop step response: first a steady-state error, and second a pure time delay. The first problem might occur when the plant is unstable, and the second one occurs, when the analog controller is not bi-proper. By modifying the original PIM method these two drawbacks can be resolve [12].

2 MODIFIED SMITH PREDICTOR ALGORITHM

Considering plant in discrete-time domain, $P_d(z)$ affected by delay z^{-k} in sending and receiving data. If $P_d(z)$ (Plant without delay affecting) is controlled by $C_d(z)$ with unite feedback, the system transfer function from input to output will be:

$$N_d(z) = \frac{C_d(z)P_d(z)}{1+C_d(z)P_d(z)} \tag{1}$$

Now if we have the controller $\overline{C_d}(z)$ for the delayed plant $P_d(z)z^{-k}$, the equivalent system will be:

$$\overline{N_d}(z) = N_d(z)z^{-k} \tag{2}$$

$$\frac{\overline{C}_d(z)P_d(z)z^{-k}}{1+\overline{C}_d(z)P_d(z)z^{-k}} = z^{-k}\frac{C_d(z)P_d(z)}{1+C_d(z)P_d(z)} \tag{3}$$

So:

$$\overline{C}_d(z) = \frac{C_d(z)}{1+C_d(z)P_d(1-z^{-k})} \tag{4}$$

Hence the obtained controller is as figure bellow:

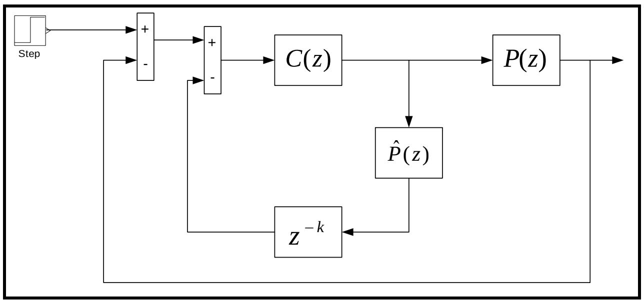

Figure 1: Predictor controller by Smith method

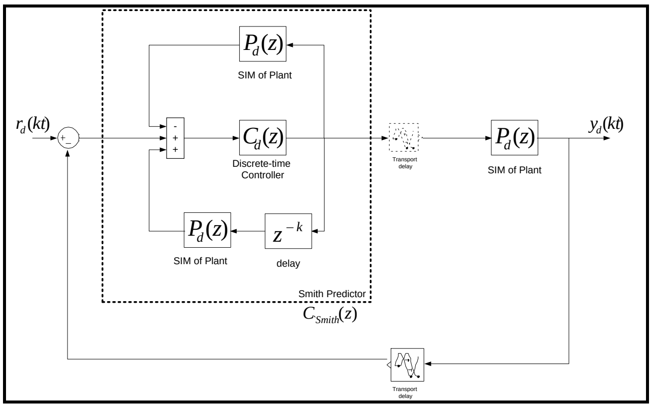

Figure 2: Smith predictor controller based on maximum bound delay in network with delay [9]

As it seems in Fig (1), there are two feedback loops, while the outer loop is feeding the system input with output data; for seconds while there is not exists new data, the system is going to be under control. In Fig (2), the modified Smith predictor has been presented by considering the maximum network delay and existence the predictor in networked control system [9].

Implementer of this model claims that; it is useful for systems with stable delays. If delay in network is more than predicted in Smith algorithm, it will cause instability. Unfortunately it has been specified that, method doesn't work well in systems that are open-loopy unstable. The controller transfer function which equipped by Smith predictor is:

$$C_{Smith}(z) = \frac{C_d(z)}{1 + C_d(z)P_d(z)(1 - z^{-k})} \qquad (5)$$

As it was noticed, in denominator of controller, the term of $P_d(z)$ has been appeared. This causes pole-zero cancellation between controller and plant; therefore system will become unstable. In fact pole-zero cancellation, hiding the natural frequency, while internally appearing. It should be considered that Pole-zero cancellation in systems is acceptable only if $\mathrm{Re}\,\lambda \geq 0$. Additionally, if plant has unstable poles; by increasing the delay, Smith predictor wouldn't be helpful anymore for stabilizing the system.

As an example; the introduced below system is belongs to a DC motor which is open loopy unstable system.

$$\frac{d}{dt}\begin{bmatrix}\theta \\ \omega \\ i\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 \\ 0 & 0 & 97.46 \\ 0 & -28.471 & -34.67\end{bmatrix}\begin{bmatrix}\theta \\ \omega \\ i\end{bmatrix} + \begin{bmatrix}0 \\ 0 \\ 3.593\end{bmatrix}[v] \tag{6}$$

Fig. 3 and Fig. 4 are showing results of comparing systems including Smith predictor in conditions without and with considering delay in network. As far as the Plant has an unstable pole, by increasing the delay ten times more; the controller performance will decrease and cause instability in system. So an improved structure has been presented, which works better in facing with high delays in network, in addition to removing the mentioned problems.

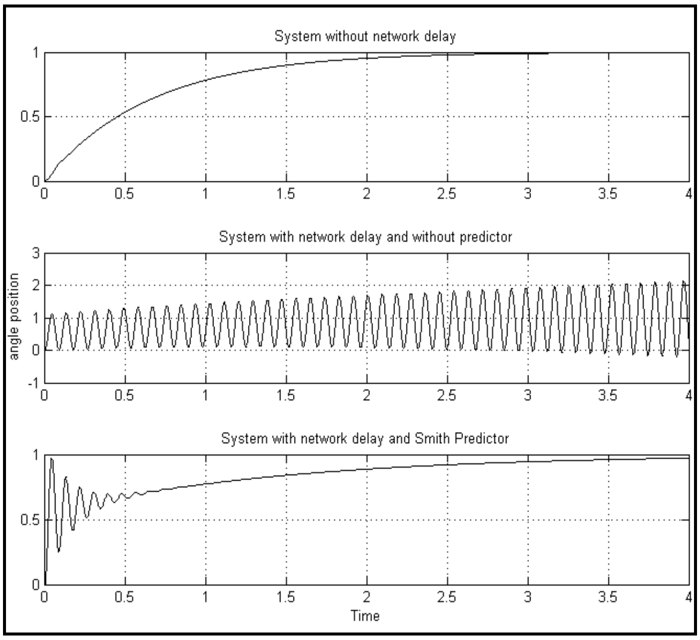

Figure 3: System with sampling time=0.05 and network's delay=0.005

3 REDESIGNING BY PIM METHOD

As it was noticed, redesigning digital controller by PIM method is one of indirect-method of designing with global approach. As mentioned the problems in Smith predictor structure, redesigning by PIM; with the aim of increasing stability was used. The re-designing steps simplicity in continues-domain is shown in figure 5. It is remarkable that, on base of this work; here $C_c(s)$ is the controller that is equipped by modified Smith Predictor and calculated like previous section.

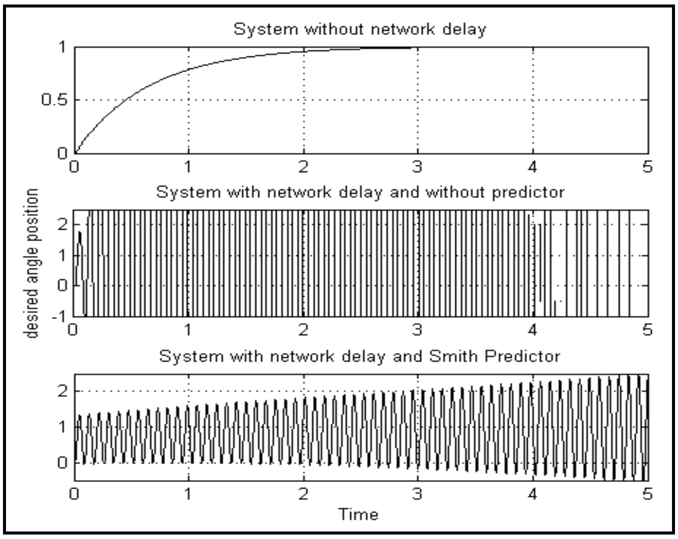

Figure 4: System with sampling time=0.05 and network's delay=0.05

After reaching to Plant Input Transfer Function (PITF), it's the time to manage closing the networked control system's loop. The system now is prepared for PIM method. Closed-loop system will have three different controllers which the calculation is clearly formulated in [12].

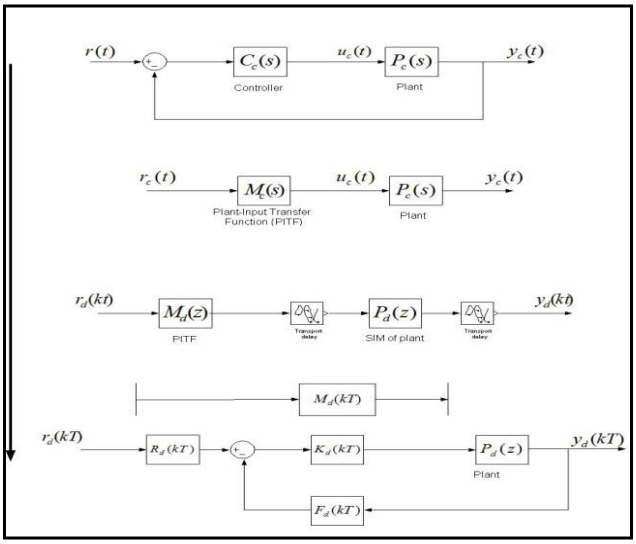

Figure 5: Digital Redesign by PIM method for delayed systems networked

These methods applied for comparison in two different systems:
System (1):

$$P_c(s) = \frac{10}{(s^2 + s)} \tag{7}$$

$$K_c(s) = \frac{0.416s + 2}{(0.139s + 1)} \tag{8}$$

Where $P_c(s)$ indicate the plant transfer function and $K_c(s)$ is the controller transfer function.

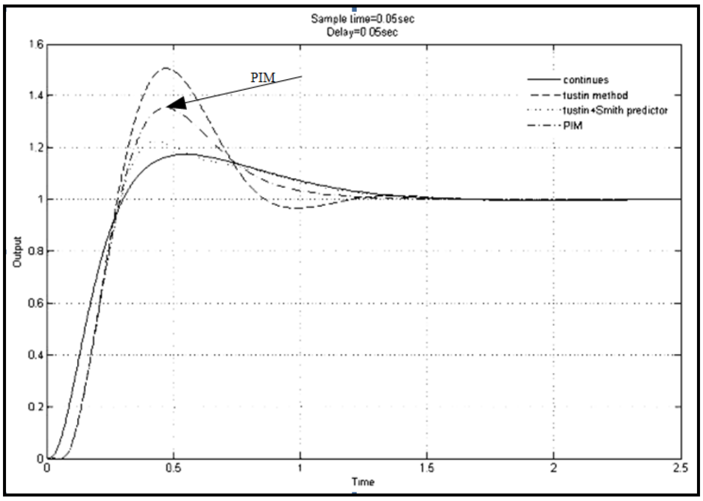

Figure 6: Comparing method based on PIM with Tustin method equiped with Smith predictor,with sampling time=0.05 and delay time=0.10 in network (system 1)

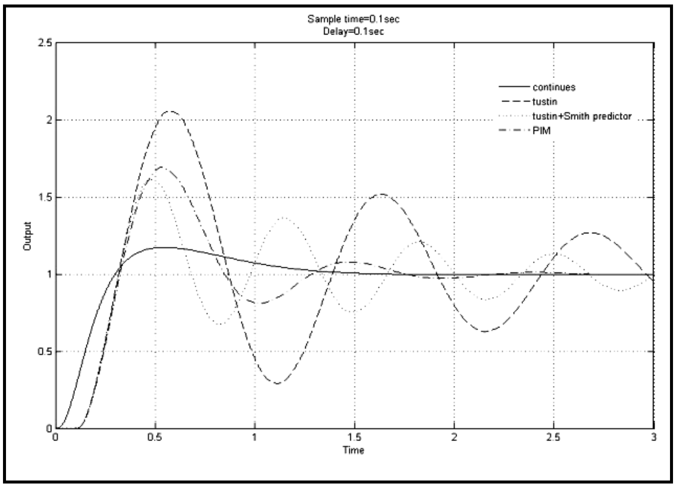

Figure 7: Comparing method based on PIM with Tustin and Tustin method equiped with Smith predictor,with sampling time=0.10 and delay time=0.10 in network (system 1)

Here in order to discretizing; Tustin method was applied for local method in simulations in which the controller included predictor. Also for PIM method as global approach, as it's described in its manual, it is using Zero order hold (ZOH) method. Following; another system considered [13];

System (2);

$$P_c(s) = \frac{6000}{(s^2 + 32.44s + 20)(s + 30)} \tag{9}$$

$$K_c(s) = \frac{(s^2 + 10.42s + 20)}{s(s + 10)} \tag{10}$$

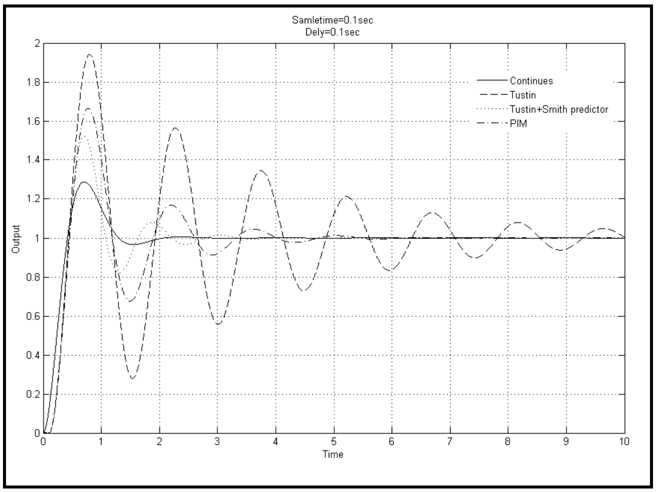

Figure 8: Comparing method based on PIM with Tustin and Tustin method having Smith predictor,with sampling time=0.10 and delay time=0.10 in network(system 2)

Where $P_c(s)$ is the plant transfer function and $K_c(s)$ is the controller transfer function.

Let’s try the systems by decreasing the sampling rate and increasing the network delay to see the systems response in figure (9):

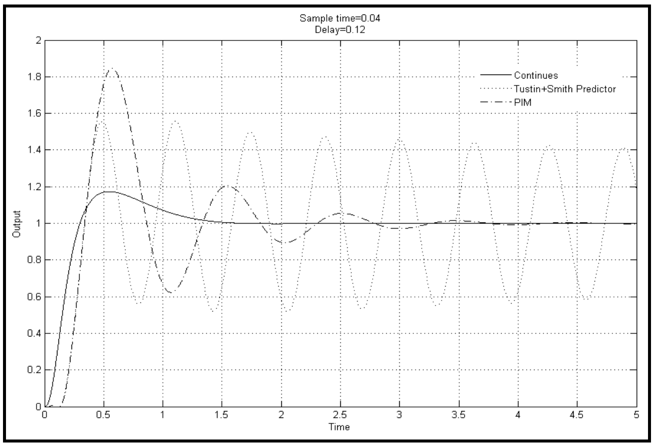

Figure 9: Comparing method based on PIM with Tustin and Tustin method having Smith predictor, with sampling time=0.04 and delay time=0.12 in network(system 2)

The system's response, shows that; in small delays and high sampling rate, the local approach is performing better by considering the overshoot and settling time; but by increasing the network delay; PIM is approaching to steady conditions faster, while in local method, system oscillating and critically approaching to unsteady conditions.

4 CONCLUSION

According to the results which validated; in small delays and high sampling rate; the local approach which is equipped by Smith Predictor is performing better by considering the overshoot and settling time. But by increasing the network delay or decreasing the sampling rate, redesign method for digital controller by Plant input mapping (PIM) is approaching to steady conditions faster, while in local method, system oscillating and critically approaching to unsteady conditions.

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