Time-stamped Generalized Predictive Control of Networked Control Systems with Random Delay

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***Abstract*—The key point of the networked control systems is that conventional generalized predictive control algorithm cannot deal with random delays, packet losses and vacant sampling. In this paper, the time-stamped generalized predictive control (TSGPC) with fuzzy rectification is proposed to deal with this problem. The TSGPC use time-stamped to calculate the real delay and the LMS adaptive recursive algorithm of weight coefficient are used to estimate the induced delay. In order to reduce the transmission times between the controller and the actuator, a threshold that is set in advance would be used to decide whether the control information are sent to the actuator or not. The control information is ensured optional or sub-optional by using this method. The fuzzy rectification is used to control the increasing of the prediction error. The simulation results show that the TSGPC with fuzzy rectification can trace the desired output precisely.**

***Index Terms*—networked control systems, time-stamped, TSGPC, fuzzy rectification**

I. Introduction

Networked control systems (NCS) are distributed feedback control systems closed via a shared band limited digital communication network, which connects sensor nodes, actuator nodes and controller nodes together to exchange information and control signals [1-3]. Such NCS have received increasing attentions in recent years due to their low cost, simple installation and maintenance, and high reliability. The study of NCS is an emerging interdisciplinary research area, combining among others control theory, communication theory and computer science. Significant research work has been done within the last decade on NCS, making available systematic stability analysis and design tools from a different point of view [4].Despite lots of advantages the network brings to the control system, potential issues such as network induced time delays and packet dropouts arise that may degrade system performance and even cause system instability [5-7].

Three main issues raised in NCS are network-induced delay, data transmission dropout, and bandwidth and packet size constraints. As is known, network induced delay can significantly degrade the performance and even lead to instability of NCS, so the maximum allowable size of network-induced delay are an important indexes in the sense of guaranteeing system stability. Many researchers have studied stability analysis and controller design for NCS with linear controlled plant (namely, linear NCS) in the presence of network-induced delay [8-10]. The stability problem of NCS with short time delays is studied and the constant stabilizing state feedback gain is obtained [11]. Time based time delay analysis of the NCS is provided to explain how it affects network systems and an adaptive Smith predictor control scheme is designed [12]. Time delay is considered in an independent layer to design a stabilizing controller based on model predictive control approach [13]. The maximum allowable delay bounds are obtained for the stability of NCS and are used as the basic parameters for a scheduling method for NCS [14]. So far, the stability synthesis for the NCS with time delays has not been fully investigated.

Fuzzy control is a useful approach to solve the control problems of nonlinear systems. Takagi-Sugeno (T-S) fuzzy system [15] is a popular and convenient tool to approximate nonlinear systems because of its simple structure with local dynamics. Descriptor system, which are also referred to as singular systems, implicit systems , generalized state-space systems, differential algebraic systems, have been extensively studied for many years. A fuzzy model [16] in the descriptor form is introduced, and stability and stabilization problems for the system are addressed. Recently, more and more attention has been paid to the study of fuzzy descriptor systems [17-19]. Therefore, it is meaningful to employ fuzzy descriptor model in NCS systems design. However, to the best of our knowledge, the fuzzy descriptor NCS with time-delay has not yet been fully investigated.

Generalized predictive control algorithm that based on model predictive control is another more successful application of control algorithms [20]. Since a larger sampling period is used, GPC particularly suit to the constraint conditions of communications. However, the traditional generalize predictive control algorithm can not effectively deal with the random delays and packet losses in the networked control systems [2, 21], so in this paper, the generalized predictive control algorithm based on the time-stamped function with fuzzy rectification is proposed. Using this algorithm, TSGPC is extended to handle random delays, packet losses and vacant sampling in networked control systems.

The paper is organized as follows. After the Introduction, Section II formulates the problem. Section III describes the new algorithm for NCS with random

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delay. The main results are presented in section III. Number examples are included to demonstrate the power of this method in Section IV. And finally in the section V some conclusion remarks are given.

II. Problem Statements

Figure 1 gives the networked control systems structure with a time-stamped of generalized predictive control function. where τ^{sc} is the delay from the sensor to the controller and τ^{ca} is the delay from the controller to the actuator, the computational delay of the processor is usually small when compared to network-induced delays since processor coded with the control algorithm works at a higher speed; hence, for the sake of simplicity, it is usually ignored in the analysis of NCS. Sensors, actuators and controllers keep time synchronization, single packet is transmitted. It is assumed that the sensor node, the actuator node, and the controller have an identical sampling period h. T represents time-driven, E represents event-driven.

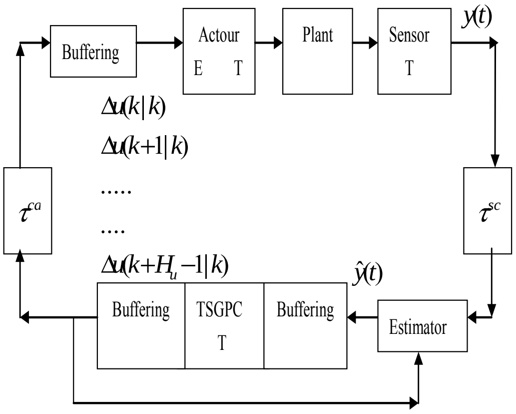

Figure 1. The structure of Networked Control Systems.

The sensor node samples the outputs, combines them into one data packet (Note: sensor-to-controller data packets contain the τ^{ca} information, which is determined by the actuator, and then τ^{ca} which is passed on to the sensor node is to be sent back to the controller node), and then transmits the data packet to the controller node. Each data packet is time stamped so that the delay information can be extracted at the controller node so as to indicate how old the received measurement is. At the controller, the received sensory data are stored in a shared memory. The model predictive controller and the identifier use these stored data history. At each sampling interval, τ^{sc} is determined first, the number of measurements that need to be estimated by the minimum effort estimator to fill in the missing sensory data up to the current k-th sampling instant, is determined using τ^{sc} and the age of the latest sensor data. Then the output of the estimated system is updated into the shared memory. Besides using in the subsequent computations of control actions, the predicted output can be used in the next sample instant if there is an event of vacant sampling or data losses. Figure 2 gives the timing diagram of the networked control systems. Where $\tau^{sc}=2h, \tau^{ca}=2h$

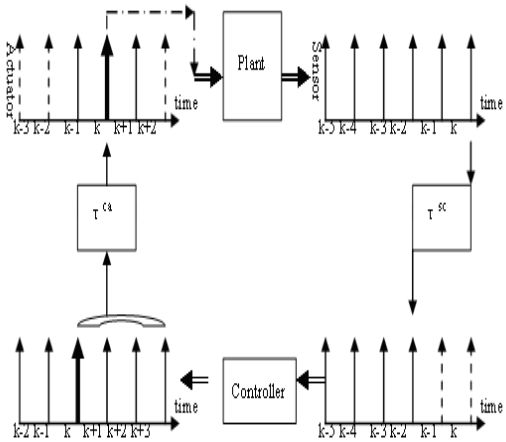

Figure 2. The timing diagram of Networked Control Systems.

III. Description Of The Algorithm

The predictive networked control strategy developed in this paper assumes the packet losses will happen if the delay exceeds a pre-set time interval. It should be noted that with sensory data estimation and actuator buffering, the developed networked control strategy treats the event of out-of-order data and the event of vacant sampling the same as packet losses. This is because at a particular time instant, older data that arrive at the controller is used to replace the data histories for use in prediction and estimation. On the other hand, older data that arrive at the actuator will be discarded if newer data are available. This is true as long as the sequential occurrences of out-of-order data, vacant sampling, or packet losses, are within the worst-case delay.

Generalized predictive control use a polynomial type estimator and employs a multivariable input-output model of the CARIMA [20, 22, 23] form to describe the object that interfered by the random events:

$$A(z^{-1})y(k)=B(z^{-1})u(k-1)+\frac{1}{\Delta}c(z^{-1})e(k). \tag{1}$$

Where y,u,e is the control input vector, and the output vector, and zero-mean white noise, z^{-1} is the postpone operator, $\Delta=1-z^{-1}$ is the different operator, $A(z^{-1})$ and $C(z^{-1})$ are $p\times p$ Matrix polynomial matrices, $B(z^{-1})$ is a $p\times m$ polynomial matrix.

A. Delay Estimator Design

AR model and the LMS [24-26] algorithm are used to track the random time delays in the networked control systems. Γ_k can be defined as: $\Gamma_k=\sum_{i=1}^{n}\delta_i\tau_{k-i}$, where δ_i is a weighting coefficients for i>0, ε_i can be defined as $\varepsilon_k=\tau_k-\Gamma_k$, where ε_i is a fitting residual. In order to make the variance ε_i is very small, δ_i need to be dynamically adjusted. At the k-th sampling instant, the weighting coefficients vector form is expressed as $\delta_k = [\delta_{1k}, \delta_{2k}, ..., \delta_{nk}]^T$, n of delayed data up to the k-th instant is expressed as:

$$T_k = [\tau_{k-1}, \tau_{k-2}, ..., \tau_{k-n}]^T. \tag{2}$$

The AR model about time delayed on network is obtained as:

$$\Gamma_k = \sum_{i=1}^{n} \delta_{ik} \tau_{k-i} = T_k^T \delta_k. \tag{3}$$

In which $\varepsilon_k = \tau_k - \delta_k^T T_k$

$$E[\varepsilon_k^2] = E[\tau_k^2] - 2R_{\tau T}^T \delta_k + \delta_k^T R_{TT} \delta_k. \tag{4}$$

In which $R_{\tau T} = E[\tau_k T_k] = E[\tau_{k-1}\tau_k, \tau_{k-2}\tau_k, ..., \tau_{k-n}\tau_k]^T$

$$R_{TT} = E[T_k \ T_k^T] = E\begin{bmatrix} \tau_{k-1}\tau_{k-1} & \tau_{k-1}\tau_{k-2} & \dots & \tau_{k-1}\tau_{k-n} \\ \tau_{k-2}\tau_{k-1} & \tau_{k-2}\tau_{k-2} & \dots & \tau_{k-2}\tau_{k-n} \\ \dots\dots\dots & & & \\ \tau_{k-n}\tau_{k-1} & \tau_{k-n}\tau_{k-2} & \dots & \tau_{k-n}\tau_{k-n} \end{bmatrix}$$

Using (4), the mean square error of delay is a quadratic function of weights coefficients and a parabolic shape surface function with a unique minimum value, hence, gradient method can be used to seek the minimum value. According to the steepest descent method, δ_{k+1} can be defined as $\delta_{k+1} = \delta_k - \mu\nabla(k)$, μ is a very small number named convergence factor, $0 \prec \mu \prec 1/\lambda_{\max}$, in which: $\lambda_{\max}$ is the maximum eigenvalue of R_{TT}. It is very difficult to calculate the $\nabla(k)$ accurately, so the actual calculation is replaced with its estimate of $\hat{\nabla}(k)$:

$$\hat{\nabla}(k) = \hat{\nabla}E[\varepsilon_k^2] = \nabla[\varepsilon_k^2] = 2\varepsilon_k \nabla[\varepsilon_k] = -2\varepsilon_k T_k,$$

the LMS adaptive recursive algorithm of weight coefficient is obtained as:

$$\delta_{k+1} = \delta_k - \mu\hat{\nabla}(k) = \delta_k + 2\mu\varepsilon_k T_k. \tag{5}$$

Once the networked delay has been estimated, the value is rounded. The estimate value can be used to control the NCS, at the same time, the new measurement of time delay is used to replace the data histories which has been stored in the controller memory.

B. TSGPC Design

In order to predict the required j-step-ahead future control signal that will drive the system to track a desired trajectory, an extension to the multivariable Generalized Predictive Control [27] is used for this purpose. Here an optimal set of current and future changes in control signal: $\Delta u(k+j)$ for $j = 0,1,2,......,H_u$ is sought to continuously minimize the quadratic cost function:

$$\begin{aligned} &V_k(H_1, H_2, H_u) = \\ &\sum_{j=H_1}^{H_2} \left\| y^*(k+j \mid k) - y_r(k+j) \right\|_Q^2 + \\ &\sum_{j=1}^{H_u} \left\| \Delta u(k+j-1) \right\|_R^2. \end{aligned} \tag{6}$$

Where $y^*(k+j \mid k)$ is the j-steps ahead-predicted system outputs based on the history up to the time instant k, and $y_r(k+j)$ are the reference future trajectories. $H_1, H_2 H_u$ are, respectively, the minimum and maximum prediction horizons, and the control horizon, where $1 \le H_1 \le H_2 \quad H_u \le H_2$. The weighting sequence matrices Q and R are diagonal and positive definite.

The Diophantine equation:

$$I_m = E_j^k(z^{-1})\Delta A(z^{-1}) + z^{-j} F_j^k(z^{-1})$$

Combining the Diophantine equation and (1) yield,

$$\begin{aligned} &y^*(k+j \mid k) = F_j^k(z^{-1})y(k) + \\ &E_j^k(z^{-1})B(z^{-1})\Delta u(k+j-1). \end{aligned} \tag{7}$$

Where

$$\deg(E_j^k(z^{-1})) = j-1$$
$$\deg(F_j^k(z^{-1})) = \deg(A(z^{-1})).$$

This term can be separated into two parts by introducing the new equation:

$$T(z^{-1}) = \Delta A(z^{-1})E_j^k(z^{-1}) + z^{-j}F_j^k(z^{-1}). \tag{8}$$

In which:

$$E_j^k(z^{-1}) = 1 + \sum_{i=1}^{j-1} e_{j,i} z^{-i} \qquad F_j^k(z^{-1}) = \sum_{i=0}^{n_a} f_{j,i} z^{-i}$$

T(z^{-1}) is defined as filter polynomial, and generally the first order,

Here

$$\bar{G}_j^k(z^{-1}) = G_j^k(z^{-1}) + z^{-(j-d+1)}E_j^k(z^{-1}). \tag{9}$$

In which:

$$\bar{G}_j^k(z^{-1}) = B(z^{-1})E_j^k(z^{-1})$$

$$\deg \bar{G}_j^k = n_b + j - 1 \quad \deg G_j^k = j - d$$

$$\deg E_j^k = n_b - 2 \quad d = \tau^{sc} + \tau^{ca}$$

Combining (8), (9) and (1) yield,

$$\begin{aligned} &y^*(k+j \mid k) = G_j^k(z^{-1})\Delta u_f(k+j-d) \\ &+E_j^k(z^{-1})\Delta u_f(k-1) + F_j^k(z^{-1})y_f(k) \\ &= G_j^k(z^{-1})\Delta u_f(k+j-d) + \bar{F}_j^k. \end{aligned} \tag{10}$$

In which

$$y_f(k) = y(k)/T(q^{-1}) \qquad u_f(k) = u(k)/T(q^{-1})$$

$\bar{F}_j^k = E_j^k(z^{-1})\Delta u_f(k-1) + F_j^k(z^{-1})y_f(k)$ is the free response term. This term can be easily computed recursively by utilizing (1) as:

$$\overline{F}_{j+1}^{k} = z(I-\Delta A(z^{-1}))\overline{F}_j^{k} + B(z^{-1})\Delta u(k+j). \tag{11}$$

With $\overline{F}_0^{\,k} = y(k)$ and $\Delta u(k+j) = 0$ for $j \geq 0$.

Considering the three prediction horizons H1, H2 and Hu, where j=H2-H1, the matrix form of the j-step-ahead prediction is obtained as:

$$Y_{H_{12}}^{*} = G_{H_{12u}} \Delta U_{H_u} + \overline{F}_{H_{12}} \tag{12}$$

$$Y_{H_{12}}^{*} = \left[y^{*}(k+H_1)^T \quad y^{*}(k+H_1+1)^T \quad ..... \quad y^{*}(k+H_2) \right]$$

$$\Delta U_{H_u} = [\Delta u(k)^T, \Delta u(k+1)^T, ..., \Delta u(k+H_u-1)^T]$$

$$\overline{F}_{H_{12}} = [F_{H_1}^{k\ T}, F_{H_1+1}^{k\ \ T}, ..., F_{H_2}^{k\ T}]$$

$$G_{H_{12u}} = \begin{bmatrix} G_{H_1-1} & G_{H_1-2} & ..... & G_{H_1-H_u} \\ G_{H_1} & G_{H_1-1} & ..... & G_{H_1-H_u+1} \\ ... & ... & .... & .... \\ G_{H_2-1} & G_{H_2-2} & ... & G_{H_2-H_u} \end{bmatrix} \in \Re^{p(H_2-H_1+1)\times mH_u}$$

With $G_q = 0_{p\times m}$ for $q \prec 0$. Using the matrix notation of (2), the TSGPC quadratic cost function can be written as:

$$\begin{aligned} &V_k = \\ &(G_{H_{12u}}\Delta U_{H_u} + \overline{F}_{H_{12}} - y_r)^T \overline{Q}(G_{H_{12u}}\Delta U_{H_u} \\ &+\overline{F}_{H_{12}} - y_r) + \Delta U_{H_u}^T \overline{R} \Delta U_{H_u} \\ &\overline{Q} = diag(Q_1, Q_2, ..., Q_{H_2-H_1+1}) \\ &\overline{R} = diag(R_1, R_2, ..., R_{H_u}). \end{aligned} \tag{13}$$

By performing either quadratic programming or analytical differentiation to minimize V_k with respect to the optional sequence of control action are obtained as:

$$\Delta U_{H_u} = \left[G_{H_{12u}}^T \overline{Q} G_{H_{12u}} + \overline{R} \right]^{-1} G_{H_{12u}}^T \overline{Q}(y_r - \overline{F}_{H_{12}}). \tag{14}$$

C. Fuzzy Rectification

The prediction error of the TSGPC is also increased with the increasing length of the prediction step, so, the fuzzy rectified [28, 29] method is used to improve the control precision. Figure 3 shows the block diagram of TSGPC with fuzzy rectification.

Define the estimation error as $\varepsilon(k) = \hat{y}(k) - y_r(k)$ and the gradient of $\varepsilon(k)$ as $\Delta\varepsilon(k)$, both of them are the inputs of the fuzzy rectification, l_ε is the normalized parameter of the $\varepsilon(k)$, $l_{\Delta\varepsilon}$ is the normalized parameter of the $\Delta\varepsilon(k)$, the rectified equation:

$$\Delta U_c = l_1 \Delta U_{H_u} + l_2 \Delta U_f. \tag{15}$$

The parameter l_1 and l_2 can be adjusted to improve the control precision. Fuzzy membership function adopt uneven distributed triangle. Based on the following analysis, we develop 49 fuzzy rules.

If $\varepsilon(k)$ and $\Delta\varepsilon(k)$ are both positive numbers, it indicates that the prediction error trend will increase, and then we can deduce that the input control is too small, so the output control (ΔU_f) will be increased.

If $\varepsilon(k)$ is positive number, and $\Delta\varepsilon(k)$ is zero, it indicates that the prediction error trend will remain unchanged, and then the input control can be properly reduced, the output control (ΔU_f) is middle center.

If $\varepsilon(k)$ is positive numbers, and $\Delta\varepsilon(k)$ is negative number, it indicates that the prediction error trend will reduce, and then the input control can be reduced to the minimum, the output control (ΔU_f) is small.

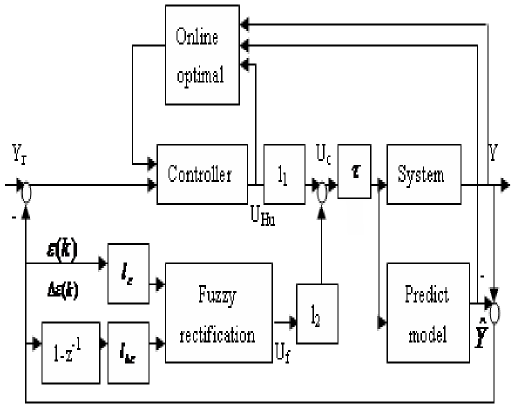

Figure 3. The block diagram of TSGPC with fuzzy rectification

Ⅳ. SIMULATION

In order to demonstrate the validity of the proposed methods, a numerical example is involved to illustrate the effectiveness of the proposed criteria. TrueTimel.5 is the simulation software.

A. Time Delay Prediction

TrueTime Network Module is adopted for randomly generating a ground of N = 500 delay data samples. The values thereof fluctuate at 0-6 sampling periods. The sampling period is 0.01s. The LMS adaptive recursive algorithm of weight coefficient is adopted for forecasting delay. The comparison between sample delay and delay after forecast is shown in figure 4 and 5. (Vertical axis is the size of the delay, unit: millisecond). It is observed that the LMS adaptive recursive algorithm of weight coefficient prediction method can effectively predicate delay variation trend.

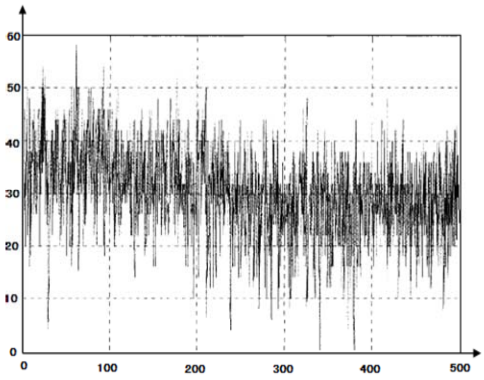

Figure 4. Network delay distribution map

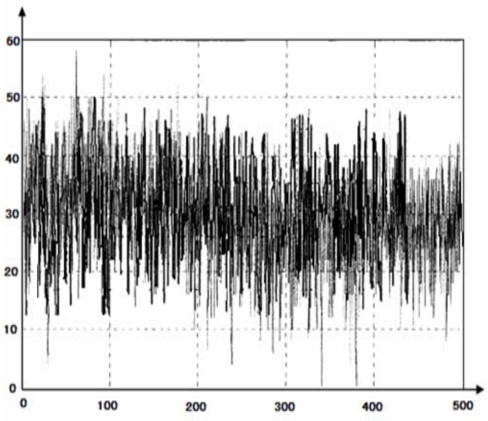

Figure 5. Network delay forecast map of LMS

B. *TSGPC Algorithm Simulation*

The networked control system consists of the sensor nodes, the actuator nodes, the controller nodes and an interference node. Fig.6 is a good example of a platform design.

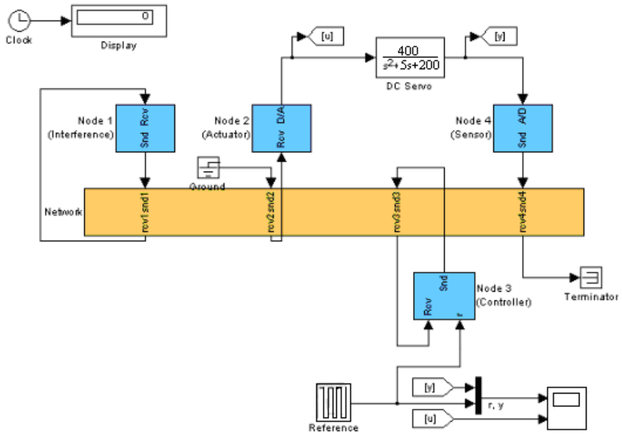

Figure 6. The simulation platform of NCS

The transfer function of controlled plant is defined as $G(s) = 400/(s^2 + 5s + 200)$, the discrete model is $A(z^{-1})y(k) = B(z^{-1})u(k-1)$, in which

$$A(z^{-1}) = 1 - 1.355z^{-1} + 0.7788z^{-2}$$
$$B(z^{-1}) = 0.4422 + 0.4063z^{-1}$$

The reference signal is square signal. The square signal simulation results are shown in figure 7 and figure 8.

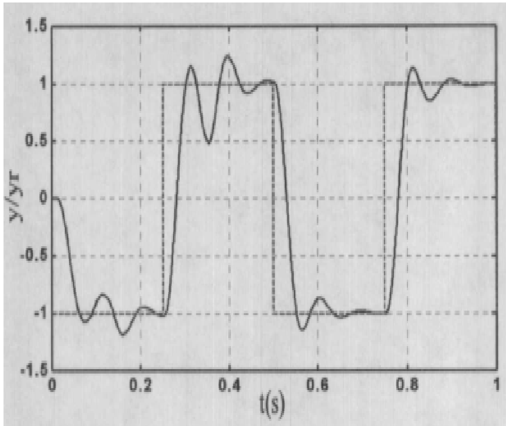

Figure 7. The output trajectory of time delay

We conclude that using the present method, the capacity of tracking the reference signal has been remarkably improved.

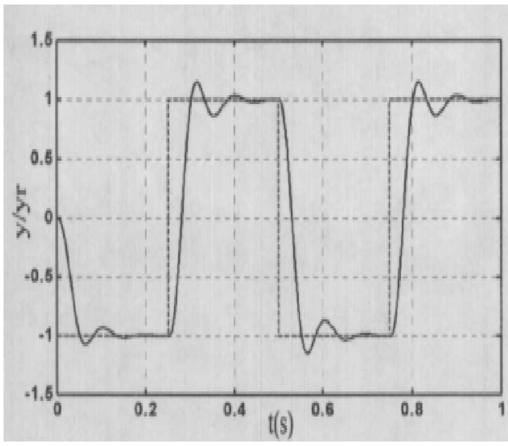

Figure 8. The output trajectory with fuzzy rectified

V. CONCLUSION

According to the characteristics of packet losses, vacant sampling and random delay, the time-stamped Generalized Predictive Control (TSGPC) with fuzzy rectified control is proposed from the perspective of generalized predictive control. The algorithm is derived theoretically; simulation results show that the algorithm has a strong identification capabilities and tracking predict abilities. In short, TSGPC with fuzzy rectified control significantly improves the performance of networked control systems.

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