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Predictive Control Strategy for a Wireless Networked System

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Abstract: As the technology matures, wireless networks are being widely used in industry and homes providing mobile users with significant benefits. In this paper, a networked recursive predictive control method is proposed for the general packet radio service (GPRS) wireless network. Such an implementation has a long random network delay and high data dropout rates. Practical experiments have been carried out to demonstrate the effectiveness of the proposed predictive control scheme.

1. INTRODUCTION

Wireless networked control systems (WNCSs) have become one of the fast growing sectors in control theory and industrial applications (Goodman *et al.*, 1992; Cheng and Holtzman, 1997), particularly in the automotive and aeronautical industries where many sensors and actuators are placed at different locations with limited installation space. In wireless networked control systems, sensor information and control signals are exchanged between the different system components (Zhang *et al.*, 2005; Koskie and Gajic, 2006) through a wireless network. There are many attractive advantages of introducing wireless networks to control system. For example, wireless network control not only can reduce the cost and time for the installation and maintenance, but also can greatly minimize the installation space of the whole control system. Beside these, easy reconfiguration is another attractive characteristic of wireless network control (Zhu *et al.*, 005; Montestruque and Antsaklis, 2003; Chen *et al.*, 2004).

GPRS is a bearer service for the Global System Mobile (GSM) communication which simplifies the wireless access to data networks with 56 Kbit/sec data transmission rate (Stuckmann *et al.*, 2002). Its widespread availability and low price per Kilobyte are two key benefits of the GPRS network that make it an attractive technology to replace the existing equipment or to deploy new wireless solutions. GPRS optimizes the network and radio resource so that it uses the radio resource only when there is a package needed to be sent or received. As a true package technology, it only occupies the network when a payload is being transmitted. GPRS can also provide immediate connectivity, high throughput and completely transparent IP support by using the point-to-point protocol (PPP).

In this paper, a networked predictive control strategy is proposed and a real-time implementation for the GPRS wireless network is presented.

2. CHARACTERISTICS OF THE WIRELESS NETWORK

Before designing the networked predictive controller for the networked control systems, some basic characteristics of the GPRS network were established. When real-time networked control applications exchange packages between the different network devices by using TCP/IP and UDP/IP, the network delay and data dropout are affected by the traffic load between different network nodes. In order to evaluate the effect of traffic load, several experiments were implemented to establish:

1) the relationship between the system sampling rate and network delay.

2) the relationship between the packet size and network delay.

Three experiments were designed and carried out at different system sampling periods T_p of 0.04, 0.1 and 0.2 second. The experiment results are given in Figure 1. In order to clearly display the relationship between the network delay and system sampling period, the network delay was set to zero when data dropout occurred. As shown in Figure 1, the data dropout rate and the network delay are greatly affected by the sampling period. For example when the system sampling period is 0.04 and 0.2 second, the maximum network delay is up to 8.96 seconds and 2.2 seconds, respectively.

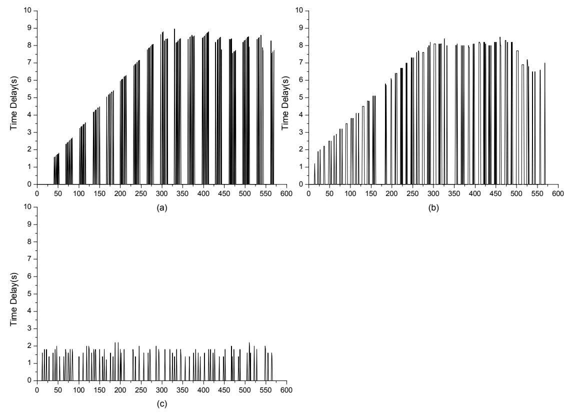

Figure 1. The relationship between the sampling period T_p and network delay. (a) T_p = 0.02s (b) T_p =0.04 s (c) T_p =0.2s

In order to test the intrinsic relationship between transmission packet sizes and the network delay in the GPRS wireless network, another five experiments were designed and undertaken. The sampling period of the GPRS network system was set to be 0.2 second and the transmission packet sizes P_s were set to be 16 bytes, 32 bytes, 64 bytes, 96 bytes and 160 bytes, respectively. The network delay increases slightly with the increase of data package sizes as shown in Figure 2.

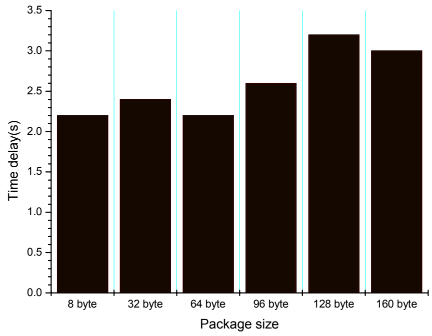

Figure 2. The relationship between the network delay and packet sizes.

3. DESIGN OF NETWORKED CONTROL SYSTEM

When the system information and control signals are transmitted through wireless networks with limited bandwidth, the network delay and data dropout due to the path loss, half-duplex operation of transceivers and channel error, is unavoidable (Willig *et al.*, 2005). The key challenge in designing networked control systems is how to compensate for the network delay and data dropout.

A recursive predictive control scheme is proposed to deal with networked control systems with the random network delay in the forward and feedback channels.

Since the networked control system is a switched control system in the case of the random network delay, the theory of switched control systems was used to determine the stability of the closed-loop system.

This section introduces the design and stability analysis of the recursive predictive control scheme. It was assumed that the round trip network delay is upper bounded, that is, $0 \le \lambda_k + \tau_k \le \bar{N}$, where λ_k is the network delay from the sensor to the controller (the feedback network delay), τ_k is the network delay from the controller to the actuator (the forward network delay) and $\bar{N}$ is the upper bound of the round trip network delay. It has also been assumed that the model is the same as the plant without disturbances and model uncertainties. The structure of the proposed system is showed in Figure 3. It mainly consists of 3 parts: a buffer, control prediction generator and network delay compensator. The buffer is used to store the historical data of the controller output $u(k)$ and plant output $y(k)$. All this data is put into one package and sent to the controller side. For example, considering a linear system in the discrete domain, $\bar{m}$ is the highest order of the plant and controller numerators, $\bar{n}$ is the highest order of the plant and controller denominators. Then the packages $\left[u(k),\cdots,u(k-\bar{m})\right]^T$ and $\left[y(k),\cdots,y(k-\bar{n})\right]^T$ will be sent to the controller side at time k.

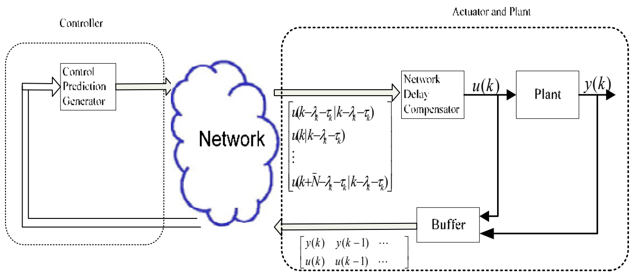

Figure 3. The networked predictive control system using the recursive predictive method.

The control prediction generator is used to receive system information, identify the plant model and generate the control prediction sequence at time k.

$$\left[u(k\,|\,k) \quad u(k+1\,|\,k) \quad \cdots \quad u(k+\bar{N}\,|\,k)\right]^T,$$

which is put into one package and then sent to the actuator side. The network delay compensator chooses a controller output according equation 1 at time k

$$u(k) = u(k\,|\,k-\lambda_k-\tau_k) \qquad (1)$$

The proposed method can also compensate for data dropout which is another factor that highly degrades the performance of the networked control system. For example, if there is a data dropout at time $k+1$, the $u(k+1\,|\,k-\lambda_k-\tau_k)$ is used as $u(k+1)$. The structure of the control prediction generator is shown in Figure 4.

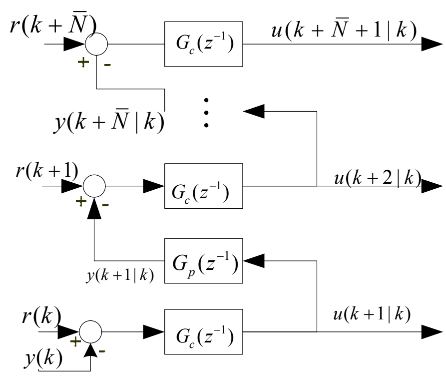

Figure 4. The structure of the control prediction generator.

Consider a single-input single-output system

$$y(k) = z^{-1}G_p(z^{-1})u(k) \tag{2}$$

where $G_p(z^{-1})$ is the plant model defined by

$$G_p(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{b_0 + b_1 z^{-1} + \cdots + b_m z^{-m}}{1 + a_1 z^{-1} + \cdots + a_n z^{-n}} \tag{3}$$

and $A(z^{-1}) \in \Re^{1\times n}$ and $B(z^{-1}) \in \Re^{1\times m}$ are polynomials.

Without considering the network delay and data dropout, a virtual local controller $G_c(z^{-1})$ is designed as

$$G_c(z^{-1}) = \frac{D(z^{-1})}{C(z^{-1})} = \frac{d_0 + d_1 z^{-1} + \cdots + d_p z^{-p}}{1 + c_1 z^{-1} + \cdots + c_q z^{-q}} \tag{4}$$

where $C(z^{-1}) \in \Re^{1\times q}$ and $D(z^{-1}) \in \Re^{1\times p}$ are polynomials.

The first step ahead controller output prediction can be obtained as

$$u(k\,|\,k) = G_c(z^{-1})(r(k) - y(k)) \tag{5}$$

Combining equation 4 and 5 gives

$$u(k\,|\,k) = D(z^{-1})r(k) - \sum_{i=1}^{p} c_i u(k-i) - \sum_{j=0}^{q} d_j y(k-i) \tag{6}$$

When the round trip delay is constant (Elteto and Molnar, 1999), the controller only sends $u(k+\tau_{RT}\,|\,k)$ to the actuator side as the control value $u(k+\tau_{RT})$, where τ_{RT} is the constant round trip network delay. Since $[u(k) \quad u(k+1) \quad \cdots \quad u(k+\tau_{RT}-1)]$ are known by the controller at time k, the one-step ahead plant output prediction can be determined by

$$y(k+1\,|\,k) = z^{-1}G_p(z^{-1})u(k+1) \tag{7}$$

Combining equation 3 and 7 yields

$$y(k+1\,|\,k) = \sum_{i=0}^{m} b_i u(k-i+1) - \sum_{j=1}^{n} a_j y(k-j+1) + B(z^{-1})D(z^{-1})r(k) \tag{8}$$

Following the above procedures, the plant output prediction of $y(k+\tau_{RT}-1\,|\,k)$ and control prediction $u(k+\tau_{RT}\,|\,k)$ can be obtained as follows:

$$y(k+\tau_{RT}-1\,|\,k) = -\sum_{i=1}^{n} a_{i-1} y(k+\tau_{RT}-i) + \sum_{i=0}^{m} b_{i-1} u(k+\tau_{RT}-i) + B(z^{-1})D(z^{-1})r(k+\tau_{RT}-2) \tag{9}$$

$$u(k+\tau_{RT}\,|\,k) = -\sum_{i=0}^{p} c_i u(k+\tau_{RT}-i) + \sum_{i=1}^{q} d_i y(k+i+\tau_{RT}) + D(z^{-1})r(k+\tau_{RT}-1) \tag{10}$$

It is assumed that the reference is zero without loss of generality in the analysis of system stability. Combining equations 1 and 10 gives

$$u(k+\tau_{RT}) = -\sum_{i=0}^{p} c_i u(k+\tau_{RT}-i) + \sum_{i=1}^{q} d_i y(k+i+\tau_{RT}) \tag{11}$$

Then

$$\frac{u(k)}{y(k)} = \frac{D(z^{-1})}{C(z^{-1})} \tag{12}$$

Since $u(k)/y(k)$ is the transfer function including the control prediction generator, feedback delay and forward delay, the stability of the control system is network delay independent if the round trip network delay is constant.

In the case of the random network delay, the one-step ahead plant output prediction can be obtained by

$$y(k+1\,|\,k) = G_p(z^{-1})u(k+1\,|\,k) \tag{13}$$

Then equation 13 can be rewritten in the following form

$$y(k+1\,|\,k) = \sum_{i=1}^{m} b_i u(k-i+1) + b_0 u(k+1\,|\,k) - \sum_{j=1}^{n} a_j y(k-j+1) \tag{14}$$

Then the plant output prediction $y(k+\bar{N}-1\,|\,k)$ and controller output prediction $u(k+\bar{N}\,|\,k)$ in the case of random round trip delay can be obtained as follows:

$$y(k+\bar{N}-1|k)=-\sum_{i=1}^{\min(\bar{N}-2,n)} a_i y(k+\bar{N}-1-i|k)$$
$$-\sum_{i=\tau-1}^{n} a_i y(k+\bar{N}-i-1)+\sum_{i=0}^{\min(m,\bar{N}-2)} b_i u(k+\bar{N}-i-1|k)$$
$$+\sum_{i=\bar{N}-1}^{m} b_i u(k+\bar{N}-i-1) \tag{15}$$

So that

$$\tilde{Y}_k = A_1\tilde{Y}_k + B_1 Y_{pk} + C_1\tilde{U}_k + D_1 U_{pk} \tag{16}$$

where

$$\tilde{Y}_k = \begin{bmatrix} y(k+1|k) & y(k+2|k) & \cdots & y(k+\bar{N}-1|k) \end{bmatrix}^T$$

$$Y_{pk} = \begin{bmatrix} y(k) & y(k-1) & \cdots & y(k-n+1) \end{bmatrix}^T$$

$$\tilde{U}_k = \begin{bmatrix} u(k+1|k) & u(k+2|k) & \cdots & u(k+\bar{N}|k) \end{bmatrix}^T$$

$$U_{pk} = \begin{bmatrix} u(k) & u(k-1) & \cdots & u(k-m) \end{bmatrix}^T$$

$$A_1 = -\begin{bmatrix} 0 & 0 & 0 & \cdots & 0 & 0 \\ a_1 & 0 & \cdots & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ & & a_{\bar{N}-2} & \cdots & a_1 & 0 \end{bmatrix}$$

$$B_1 = -\begin{bmatrix} a_1 & a_2 & \cdots & \cdots & a_n \\ a_2 & a_3 & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{\bar{N}-1} & \cdots & \cdots & \cdots & 0 \end{bmatrix}$$

$$C_1 = \begin{bmatrix} 0 & 0 & \cdots & \cdots & 0 & 0 \\ b_0 & 0 & \cdots & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{\bar{N}-2} & \cdots & \cdots & \cdots & b_0 & 0 \end{bmatrix}$$

$$D_1 = \begin{bmatrix} b_0 & b_1 & \cdots & \cdots & b_m \\ b_1 & \cdots & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ b_{\bar{N}-1} & \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

and

$$\tilde{U}_k = A_2\tilde{U}_k + B_2 U_{ck} + C_2\tilde{Y}_k + D_2 Y_{ck} \tag{17}$$

where

$$Y_{ck} = \begin{bmatrix} y(k) & y(k-1) & \cdots & y(k-q+1) \end{bmatrix}^T$$

$$U_{ck} = \begin{bmatrix} u(k) & u(k-1) & \cdots & u(k-p) \end{bmatrix}^T$$

$$A_2 = -\begin{bmatrix} 0 & 0 & 0 & \cdots & 0 & 0 \\ d_0 & 0 & \cdots & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & 0 \\ a_{\bar{N}-2} & \cdots & \cdots & \cdots & d_0 & 0 \end{bmatrix}$$

$$B_2 = -\begin{bmatrix} d_1 & d_2 & \cdots & \cdots & d_p \\ d_2 & d_3 & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{\bar{N}-1} & \cdots & \cdots & \cdots & 0 \end{bmatrix}$$

$$C_2 = -\begin{bmatrix} 0 & 0 & \cdots & \cdots & 0 \\ c_1 & 0 & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{\bar{N}-2} & \cdots & \cdots & \cdots & c_1 \end{bmatrix}$$

$$D_2 = -\begin{bmatrix} c_1 & c_2 & \cdots & \cdots & c_q \\ c_1 & \cdots & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{\bar{N}-1} & \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

In order to analyse the stability of the networked control system using the proposed recursive predictive method with random network delay, equation 16 is rewritten in the following form:

$$\tilde{Y}_k = A_1\tilde{Y}_k + B_3 Y_k + C_1\tilde{U}_k + D_3 U_k \tag{18}$$

where

$$Y_k = \left[y(k+\lambda_k+\tau_k), \cdots, y(k+\lambda_k+\tau_k-\bar{n}) \right]^T$$
$$U_k = \left[u(k+\lambda_k+\tau_k), \cdots, u(k+\lambda_k+\tau_k-\bar{m}) \right]^T$$
$$B_3 = \begin{bmatrix} 0_{(\bar{N}-1)\times(\lambda_k+\tau_k)} & B_1 & 0_{(\bar{N}-1)\times(\bar{n}-n-\lambda_k-\tau_k+1)} \end{bmatrix}$$
$$D_3 = \begin{bmatrix} 0_{(\bar{N}-1)\times(\lambda_k+\tau_k)} & D_1 & 0_{(\bar{N}-1)\times(\bar{m}-\lambda_k-\tau_k-m)} \end{bmatrix}$$

Equation 18 can be rewritten as

$$\tilde{Y}_k = (I-A_1)^{-1}(B_3 Y_k + C_1\tilde{U}_k + D_3 U_k) \tag{19}$$

where the inverse of matrix $I-A_1$ exists because it is an upper triangular matrix with non-zero elements on its diagonal line.

Following the same procedure described above, equation 17 can be rewritten in the following matrix form

$$\tilde{U}_k = A_2\tilde{U}_k + B_4U_k + C_2\tilde{Y}_k + D_4Y_k \qquad (20)$$

where

$$B_4 = \begin{bmatrix} 0_{(\bar{N}-1)\times(\lambda_k+\tau_k)} & B_2 & 0_{(\bar{N}-1)\times(\bar{n}-q-\lambda_k-\tau_k)} \end{bmatrix}$$
$$D_4 = \begin{bmatrix} 0_{(\bar{N}-1)\times(\lambda_k+\tau_k)} & D_2 & 0_{(\bar{N}-1)\times(\bar{m}-\lambda_k-\tau_k-p-1)} \end{bmatrix}$$

Substituting $\tilde{Y}_k$ in equation 20 by equation 19 results in

$$\tilde{U}_k = \hat{E}_kY_k + \hat{F}_kU_k \qquad (21)$$

where

$$\hat{E}_k = (I - C_2 - A_2(I-A_1)^{-1}C_1)^{-1}(B_4 + A_2(I-A_1)^{-1}B_3)$$
$$\hat{F}_k = (I - C_2 - A_2(I-A_1)^{-1}C_1)^{-1}(D_4 + A_2(I-A_1)^{-1}D_3)$$

Since $(I - C_2 - A_2(I-A_1)^{-1}C_1)^{-1}$ is an upper triangular matrix with non-zero elements on its diagonal line, its inverse exists.

The system transfer function can be reformulated in the following state space form:

$$Y_{k+1} = AY_k + BU_k \qquad (22)$$

Where

$$A = \begin{bmatrix} -a_1 & -a_2 & \cdots & -a_{n-1} & -a_n & 0_{(\bar{n}))(\bar{n}-n)} \\ & & I_{(\bar{n}-1)\times(\bar{n}-1)} & & & \end{bmatrix}$$
$$B = \begin{bmatrix} b_0 & b_1 & \cdots & b_m & 0_{\bar{m}\times(\bar{m}-m)} \\ & 0_{(\bar{m}-1)\times(\bar{m}-1)} & & & \end{bmatrix}$$

According to equation 1

$$u(k+\lambda_k+\tau_k) = u(k+\lambda_k+\tau_k \mid k)$$
$$= \begin{bmatrix} O_{1\times(\bar{N}-\lambda_k-\tau_k)} & 1 & O_{1\times(\lambda_k+\tau_k-1)} \end{bmatrix}(\hat{E}_kY_k + \hat{F}_kU_k) \qquad (23)$$

Let

$$\begin{bmatrix} \delta_0(\lambda_k,\tau_k) & \cdots & \delta_{\bar{n}}(\lambda_k,\tau_k) \end{bmatrix} = \begin{bmatrix} O_{1\times(\bar{N}-\lambda_k-\tau_k-1)} & 1 & O_{1\times(\lambda_k+\tau_k-1)} \end{bmatrix}\hat{E}_k$$
$$\begin{bmatrix} \theta_0(\lambda_k,\tau_k) & \cdots & \theta_{\bar{m}}(\lambda_k,\tau_k) \end{bmatrix} = \begin{bmatrix} O_{1\times(\bar{N}-\lambda_k-\tau_k-1)} & 1 & O_{1\times(\lambda_k+\tau_k-1)} \end{bmatrix}\hat{F}_k$$

Combining Equations 22 and 23 leads to the following closed-loop system:

$$\begin{bmatrix} Y_{k+1} \\ U_{k+1} \end{bmatrix} = \Lambda(\lambda_k,\tau_k)\begin{bmatrix} Y_k \\ U_k \end{bmatrix} \qquad (24)$$

where

$$\Lambda(\lambda_k,\tau_k) = \begin{bmatrix} -a_1 & \cdots & -a_n & 0 & \cdots & 0 & b_0 & \cdots & b_m & 0 & \cdots & 0 \\ & & I_{\bar{n}\times\bar{n}} & & & & & & O_{\bar{n}\times(\bar{m}+2)} & & & \\ \delta_0(\lambda_k,\tau_k) & \cdots & \delta_{\bar{n}}(\lambda_k,\tau_k) & & & & \theta_0(\lambda_k,\tau_k) & \cdots & \theta_{\bar{m}}(\lambda_k,\tau_k) & & & \\ & & O_{\bar{m}\times(\bar{n}+2)} & & & & & & I_{\bar{m}\times\bar{m}} & & & \end{bmatrix} \in \Re^{(\bar{n}+\bar{m}+2)\times(\bar{n}+\bar{m}+2)}$$

Since the network delays λ_k and τ_k are random, equation 24 is actually a switched system. Thus, a simple criterion (Sun, 2005)of checking the stability of the networked control system using the proposed method is given below.

If there exists a positive definite matrix P such that

$$\Lambda(\lambda_k,\tau_k)^T P\Lambda(\lambda_k,\tau_k) - P < 0 \,\forall\lambda_k \text{ and } \forall\tau_k$$

the closed-loop networked predictive control system is stable.

4. EXPERIMENTS

A servo control system was set up in the University of Glamorgan to illustrate the performance of the networked recursive predictive control method in the case of the GPRS wireless system.

When the system sampling period was 0.2 second, and this was well within the Nyquist frequency, the model of plant was identified as

$$G_p(z^{-1}) = \frac{-0.02178z^{-1} + 0.440994z^{-2} - 0.323738z^{-3} + 0.095965z^{-4}}{1 + 1.830z^{-1} + 1.10763z^{-2} - 0.31954z^{-3} + 0.047466z^{-4}} \qquad (25)$$

The basic configuration of the networked servo control system through the GPRS network is shown in Figure 5.

The network prediction generation was implemented on a server computer (Pentium 4 3.2G 1.5GB RAM), while the network delay compensator was implemented on an AT91RM9200 actuator board running embedded Linux. The actuator board has two functions. The first task was to compress the plant angle signal data into a package and send it to the server computer through a GPRS modem.

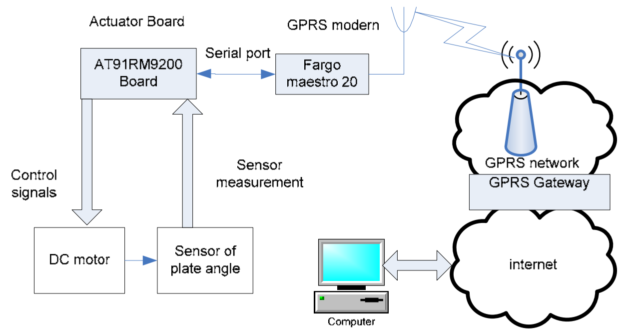

Figure 5. The Implementation diagram of the GPRS wireless networked servo control system.

The package is used on the controller side to identify the model of the plant and calculate the control prediction sequence. The second task is to choose an appropriate control prediction according to equation 1 and then drive the DC motor.

A virtual local PID controller, which was designed without consideration of the network delay and data dropout, is employed in this paper. The parameters of the proportional (K_p) and integral (K_I) are 0.4 and 0.1, respectively.

The practical experimental results of the system are shown in Figure 6. The solid line is the result of the proposed method; the dash line is the response of the network control system using the traditional method and the dot line is the step response of the local control system without the network delay.

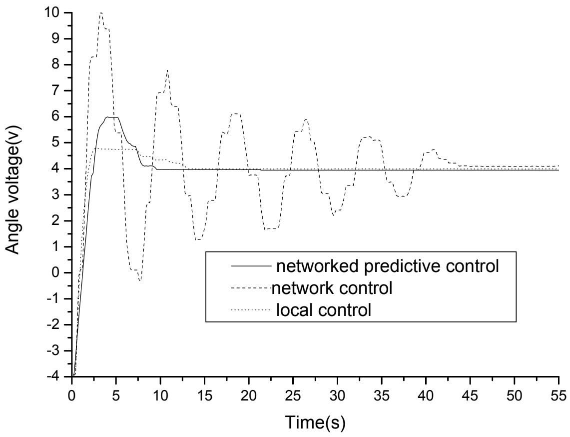

Figure 6. The experimental result of local control system, network control without considering network delay and networked predictive control using the recursive method.

It is shown that the proposed recursive predictive control method can provide acceptable responses compared with the networked control system using the traditional control method that is designed without considering the network delay. This confirms that the proposed method can actively compensate for the network delay of the GPRS wireless network.

5. CONCLUSIONS

In this paper, a recursive networked predictive control scheme was proposed for the GPRS wireless networked control systems. The design of the proposed method was studied in detail. The stability of the closed-loop networked predictive control system also has been addressed. The practical experiments were carried out to evaluate the performance of the proposed method. The experiment results of the networked predictive control strategy were compared with conventional control methods. It was shown that the networked predictive control can actively compensate for both constant and random network delays.

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