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Compensation of Time-Varying Delay in Networked Control System over Wi-Fi Network

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Abstract: In this study, we design a state predictor-based output feedback controller that compensates for unavoidable time-varying network delays in networked control systems (NCSs) over Wi-Fi networks. We model time-varying network delays as time-varying input delays of NCSs over Wi-Fi networks. The designed controller consists of a linear quadratic regulator (LQR), a full-order observer, and a time-varying step-ahead state predictor. The state predictor plays a key role in compensating for the time-varying input delay by providing the LQR with an estimation of future states ahead by the current network delay time. The time-varying network delays are acquired in real time by measuring the time differences between sent and received control data packets. We verify the stability and compensation performance of the designed controller by performing extensive experiments for an NCS in which a rotary inverted pendulum is controlled over Wi-Fi networks.
Keywords: networked control system (NCS), Wi-Fi network, time-varying delay, state predictor, rotary inverted pendulum.

1 Introduction

Networked control systems (NCSs) are spatially distributed systems in which sensors, actuators, and controllers exchange I/O information through a shared band-limited digital communication network. NCSs have been applied to a broad range of areas such as wireless sensor networks (WSNs), remote surgery, haptics collaboration over the Internet, automated highway systems, and unmanned aerial vehicles (UAVs) [4, 10, 25]. In particular, wireless networked control systems (WNCSs) have been increasingly applied in different fields because of the need for mobile operations, flexible installations, and rapid deployment in many applications.

As an alternative solution to wired NCSs, WNCSs are considered as primary solutions of networked control applications because of their simple configuration and mobility. However, the reliability and real-time performance of WNCSs are lower than for wired NCSs because with wireless networks, the sizes of network delays abruptly changes over time owing to the dynamic state variation of wireless networks. It is commonly known that even a small time delay in control system feedback loops can make the whole system oscillating or unstable [4, 15, 25], and it is obvious that fluctuating time-varying delays severely degrade the stability and performance in WNCSs.

In order to deal with the network delays, various control schemes for WNCSs are proposed in [1–3, 5–9, 11–14, 16–23, 26, 27]. These include: fuzzy-based control [6, 22], predictor-based control [13, 27], PID-based control [7, 14, 19, 20], H_∞ filter-based control [1, 5, 17, 21, 23], fault-tolerant-based control [3, 9], linear quadratic regulator (LQR)-based control [8], linear matrix inequality (LMI)-based control [18], Kalman filter-based control [12, 16, 26], and observer-based control [11].

When constructing these control schemes, it is necessary to model the network delays. In [1,3,8,16,22], the network delays are modeled as constant-valued delays or bounded time-varying delays that do not suitably describe the rapidly fluctuating time-varying delays in WNCSs. In [2,5–7,9,11–14,17–21,23,26,27], the network delays are modeled as time-varying delays, but the stability and performance of proposed control schemes are demonstrated only by performing network or numerical simulations using OPNET++, TRUETIME network simulators, or Matlab/Simulink. Considering dynamically changing states of wireless networks, the stability and performance of controllers designed for WNCSs must be verified by performing experiments over real wireless networks.

Moreover, all of the controllers in [1–3, 5–9, 11–14, 16–23, 26, 27] were designed under the assumption that the network delays are known in advance in the form of constant-valued or time-varying delays for all operation times. However, this is not the case in real operations of WNCSs, but time-varying network delays must be measured in real time, and should be used for the control action to compensate for the time-varying delays. Hence, a real-time measurement method for time-varying network delays must be designed and be a part of WNCSs.

In order to cope with the problems in the existing results of WNCSs, we design a state predictor-based output feedback controller to compensate for the time-varying network delays of NCSs over Wi-Fi networks. We model Wi-Fi network delays as time-varying input delays, and we design a control scheme consisting of an LQR, a full-order observer, and a time-varying step-ahead predictor. Moreover, we design a real-time measurement method for time-varying network delays, and we use the measured delays to construct the state predictor in real time. To apply the designed control scheme, we construct a WNCS hardware platform where the rotary inverted pendulum is controlled over Wi-Fi networks, and we conduct extensive experiments to verify the stability and performance of the designed predictor-based controller.

This paper is organized as follows. In Section 2, we formulate the control problem. In Section 3, we propose the design of a state predictor-based output feedback controller. In Section 4, we propose a delay-measurement method in a WNCS hardware platform. In Section 5, we conduct experiments and discuss the results. In Section 6, we conclude the paper.

2 Problem formulation

We consider a WNCS over a Wi-Fi network, where the plant belongs to the class of single-input multi-output systems, and the controller output is transferred via a Wi-Fi network, as depicted in Fig. 1. In order to precisely describe the dynamic changes in the network state of WNCS, we model the network delays as time-varying delays, $d(k)$, and we assume that the measured values of the plant output are directly available for the construction of the controller. With respect to the models of the plant and controller, we choose discrete-time models because modern controllers are usually implemented using digital computers [2], and continuous-time controllers inevitably involve a degrading discretization process during implementation. The discrete-time linear plant including the network delays is described by the following model.

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k-d(k)) \\ y(k) &= Cx(k), \end{aligned} \tag{1}$$

where $x(k) \in \mathbb{R}^n$ is the system state, $u(k) \in \mathbb{R}$ is the control input, $d(k)$ is the time-varying input delay, $y(k) \in \mathbb{R}^q$ is the plant output, and it is assumed that the pair (A, B) are controllable and (A, C) are observable.

The goal of this paper is summarized as follows. First, we design a state predictor-based output feedback controller for a discrete-time linear system (1) in order to compensate for the

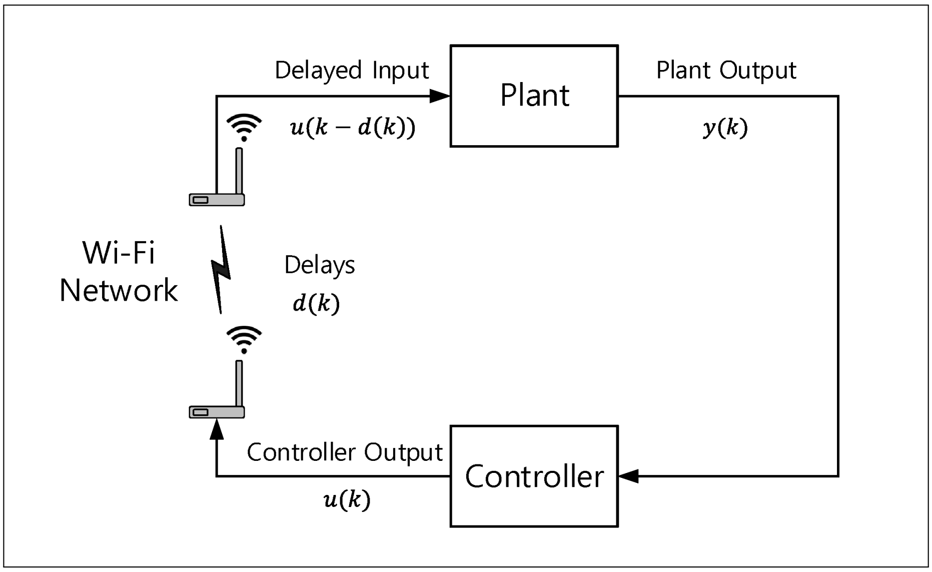


Figure 1: Structure of WNCS over Wi-Fi network.

time-varying input delay and regulate the system output to a desired reference. Second, we develop a real-time method to measure the time-varying network delays in Wi-Fi networks. The measured network delays are used for the implementation of the designed controller in real time. Finally, we construct the hardware platform of a WNCS with a rotary inverted pendulum as the plant for experiments of the designed controller.

3 Design of predictor-based feedback controller

We design the predictor-based feedback controller by performing the following three steps. In the first step, we design a full-state feedback controller for the plant with no input delay by applying discrete-time LQR theory. In the second step, we design a full-order observer that estimates the plant states. In the last step, we design a state predictor for the compensation of the time-varying input delay.

First, we design a static state feedback controller $u(k) = -Kx(k)$ for the plant (1) with no input delay (i.e., with $d(k) = 0$) such that the designed controller can stabilize the plant (1); that is, the matrix $(A - BK)$ becomes Schur stable. The existence of the stabilizing state feedback gain, K, is guaranteed by the assumption that the pair (A, B) is controllable [24]. By applying the discrete-time LQR theory, we can easily obtain the optimal state feedback controller

$$u(k) = -Kx(k), \tag{2}$$

which stabilizes the plant system (1) with no input delay and minimizes the following quadratic cost function:

$$J(u) = \sum_{k=1}^{\infty} \left(x(k)^T Q x(k) + R u^2(k) \right), \tag{3}$$

where the state-cost matrix, Q, and the performance index constant, R, are design parameters [24].

The implementation of the state feedback controller (2) requires knowledge of all state variables, and it is necessary to estimate the system state, $x(k)$, from the measurement of the system output $y(k)$. For this purpose, we design the full-order observer as follows.

$$\begin{aligned} \hat{x}(k+1) &= A\hat{x}(k) + Bu(k-d(k)) + L\left(y(k) - \hat{y}(k)\right) \\ \hat{y}(k) &= C\hat{x}(k), \end{aligned} \tag{4}$$

where $\hat{x} \in \mathbb{R}^n$ is the estimated state, $\hat{y} \in \mathbb{R}^q$ is the estimated output, and $L \in \mathbb{R}^{n\times q}$ is the observer gain, which is designed such that the matrix $(A - LC)$ becomes Schur stable; that is, the designed observer becomes exponentially stable [24]. Then, for the designed observer (4), it holds that $\hat{x}(k)$ exponentially converges to $x(k)$, and it is proven that the estimated state, $\hat{x}(k)$, can be used to construct the state feedback controller (2) instead of the unavailable actual state, $x(k)$.

Finally, we seek the final controller that is constructed with the estimated state as

$$u(k-d(k)) = -K\hat{x}(k), \tag{5}$$

which can be alternatively written as

$$u(k) = -K\hat{x}(k+d(m)), \tag{6}$$

where m satisfies $m - d(m) = k$, and it is non-implementable because it requires future values of state. However, the $d(m)$-step-ahead predictor is designed in [2] as

$$\hat{x}(k+d(m)) = A^{d(m)}\hat{x}(k) + \sum_{j=k-d(m)}^{k-1} A^{k-j-1}Bu(j), \tag{7}$$

which yields the implementable predictor-based feedback controller

$$u(k) = -K\left[A^{d(m)}\hat{x}(k) + \sum_{j=k-d(m)}^{k-1} A^{k-j-1}Bu(j)\right]. \tag{8}$$

The closed-loop system with the designed controller (8) is globally exponentially stable in the sense of the norm $\left(|\hat{x}(k)|^2 + \sum_{j=0}^{D-1} |u(k+j-d(m+j))|^2\right)^{1/2}$, where D is an upper bound of the time-varying input delay [2].

Remark 1. In order to implement the designed controller (8), we must find m satisfying $m - d(m) = k$ at each time k, which requires some knowledge of future input delay, $d(m)$. Practically, it is difficult to know the future time-varying input delay in advance. We overcome this problem by measuring the time-varying delay at the plant input, and adopting the measured delay as an estimate of $d(m)$.

The overall structure of the WNCS with the designed controller is depicted in Fig. 2. As shown in Fig. 2, the delayed input value is applied to the plant input, and the measured delays in real time are used as the time-varying input delay, $d(m)$, for the state predictor. Once the time-varying input delay, $d(m)$, is estimated, the state predictor can compensate for the time-varying delay and stabilize the entire closed-loop system.

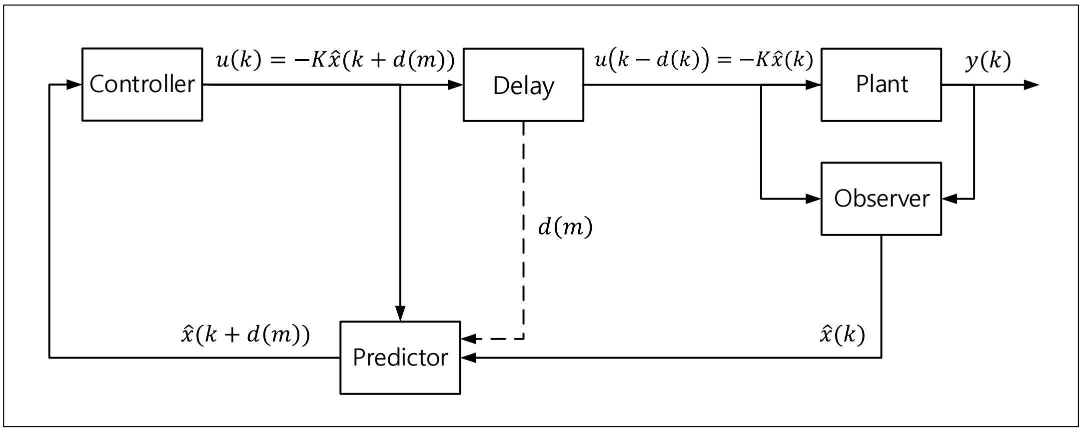


Figure 2: WNCS with the predictor-based feedback controller.

4 Delay measurement method in WNCS hardware platform

As emphasized in Remark 1, in order to implement the designed controller (8), we need to measure the time-varying delay in real time that occurs in WNCS. In this section, we design a delay-measurement method for WNCS over Wi-Fi networks by extending the method proposed in [25] to measure WSN (Wireless Sensor Network) delays in real time.

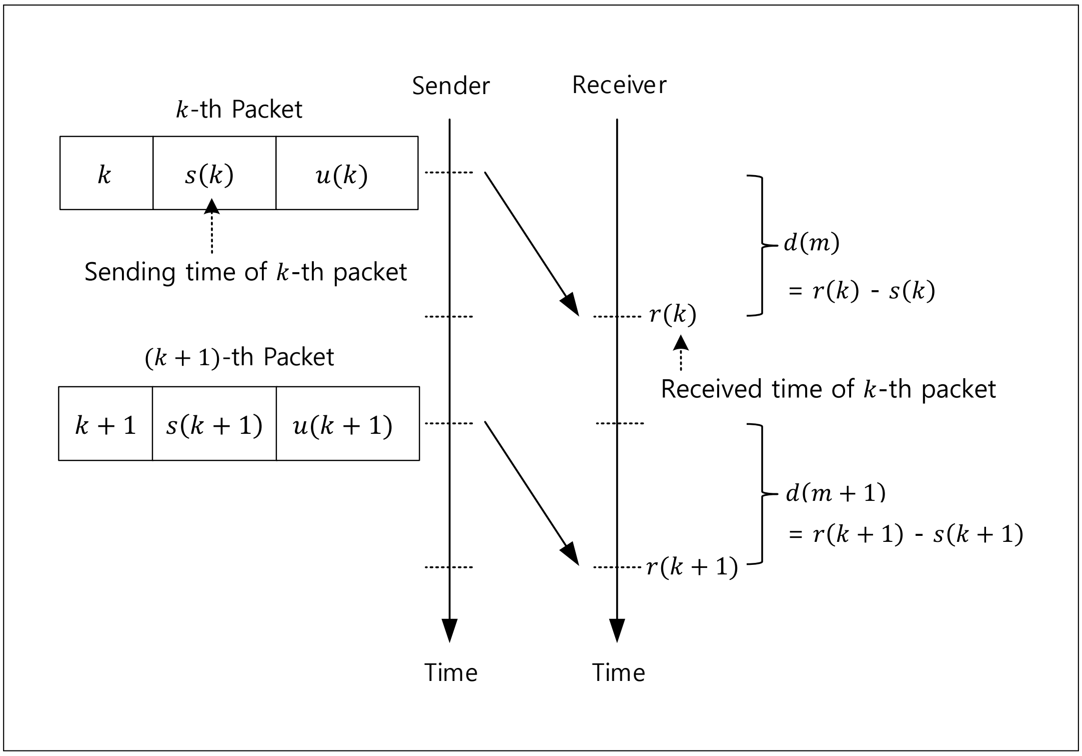


Figure 3: Measurement method for time-varying network delay.

The basic idea of the delay-measurement method is to measure the transmission delay of signal packets from the controller output to the plant input. When controller output packets are sent, the time of sending is appended to the packets; when they are received at the plant input, the transmission delay is calculated by subtracting the time of sending from the present time.

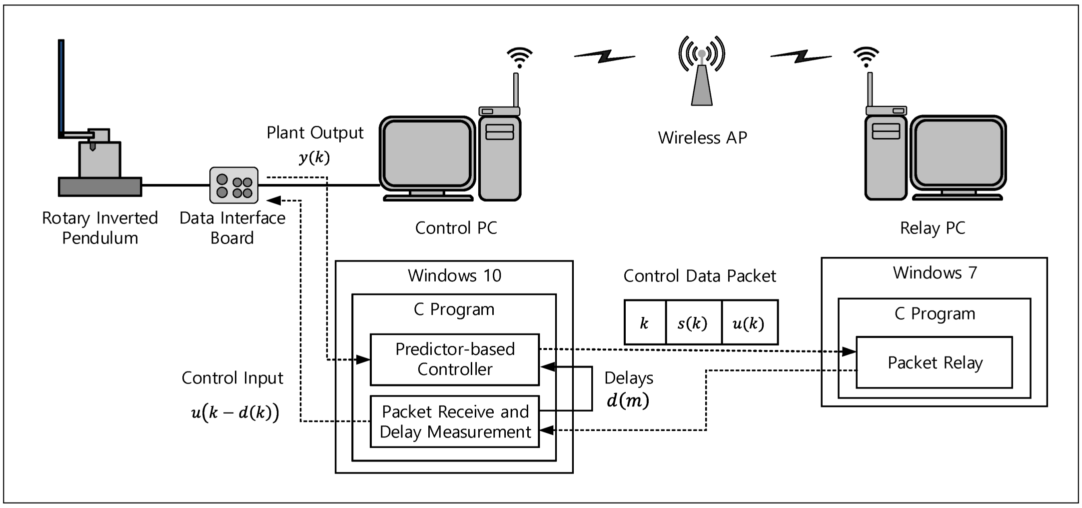


Figure 4: Structure of WNCS hardware platform.

Then, the calculated transmission delay is used to generate the next time-step controller output as the estimated delay of $d(m)$ in (8). This basic operation principle is depicted in Fig. 3 in the level of transmission packets.

In order to implement and verify the designed controller and the delay-measurement method, we construct the WNCS hardware platform, as depicted in Fig. 4, where the rotary inverted pendulum is chosen as the physical plant to be controlled. The rotary inverted pendulum is well known to be nonlinear and unstable, and it is commonly accepted as a test plant to demonstrate the stability and performance of designed controllers [4].

As shown in Fig. 4, the pendulum is connected through a data interface board to an Intel i7-6700 3.4 GHz desktop PC (control PC), which acquires the pendulum position data, computes the control input, and transmits the control input to another Intel i5-3570 3.4 GHz desktop PC (relay PC) over a Wi-Fi network. The relay PC retransmits received packets from the control PC to the control PC over the Wi-Fi network, which results in the time-varying delay in the WNCS.

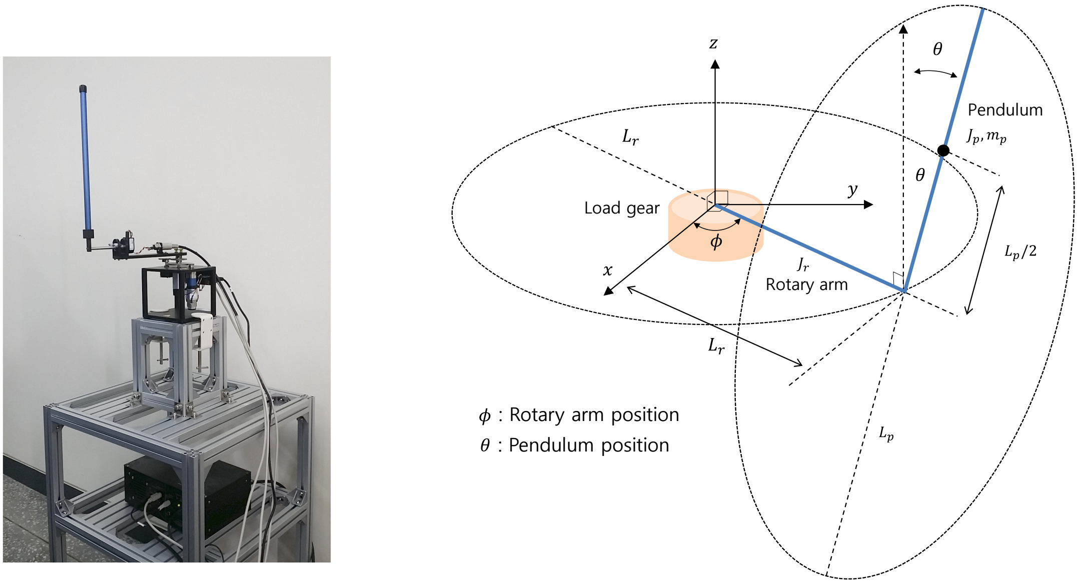
The delay-measurement method is implemented on the control PC such that the sending time is added to each sending packet, and the received time of each packet from the relay PC is recorded. Then, by subtracting the sending time from the received time, the current network delay is obtained and used as an estimate of $d(m)$ in (8).

5 Experiment

5.1 Implementation of designed controller

As mentioned in Chapter 4, we choose the rotary inverted pendulum as the physical plant; Fig. 5 shows the photograph and schematic diagram of the pendulum's movement, and the actual parameters of the pendulum are listed in Table 1.

In order to apply the designed controller (8) to the pendulum over the Wi-Fi network, we first linearize the continuous-time nonlinear model of the pendulum. Then, we convert the continuous-time linear model into the discrete-time linear model because the controller is designed based on a discrete-time linear system. We compute the linearized equations using the Taylor series expansion, and the discretized equations using the zero-order hold discretization method. Based on the parameters in Table 1 and the sampling period of $2ms$, we obtain the following discrete-



(a) Photograph of rotary inverted pendulum (b) Schematic diagram and coordinate system

Figure 5: Rotary inverted pendulum.

Table 1: Parameters of rotary inverted pendulum.

Parameters	Description	Value
L_r	The Length of the Rotary Arm	$21.6cm$
J_r	The Moment of Inertia of the Rotary Arm	$9.98 \times 10^{-4}kg.m^2$
m_r	The Mass of the Rotary Arm	$0.257kg$
L_p	The Length of the Pendulum	$33.7cm$
J_p	The Moment of Inertia of the Pendulum	$0.0012kg.m^2$
m_p	The Mass of the Pendulum	$0.127kg$
η_g	The Efficiency of the Gearbox	$0.90(\pm 10\%)$
K_g	The Total Gear Ratio of the High-Gear	70
η_m	The Efficiency of the Motor	$0.69(\pm 5\%)$
k_t	The Current-torque Constant of the Motor	$7.68 \times 10^{-3}N - m/A$
k_m	The Back-EMF Constant of the Motor	$7.68 \times 10^{-3}V/(rad/s)$
R_m	The Armature Resistance of the Motor	$2.6\Omega(\pm 12\%)$
B_p	The Viscous Damping Coefficient of the Pendulum	$0.0024Nm(s/rad)$
B_r	The Viscous Friction Torque of the Pendulum	$0.0024Nm(s/rad)$

time linear model for the rotary inverted pendulum system.

$$\begin{aligned} x(k+1) &= \begin{bmatrix} 1 & 0.0002 & 0.0019 & 0 \\ 0 & 1.0002 & -0.0001 & 0.0020 \\ 0 & 0.1554 & 0.9125 & -0.0016 \\ 0 & 0.2368 & -0.0842 & 0.9975 \end{bmatrix} x(k) + \begin{bmatrix} 0.0002 \\ 0.0002 \\ 0.1594 \\ 0.1533 \end{bmatrix} u(k) \\ y(k) &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} x(k). \end{aligned} \tag{9}$$

where the state vector $x(k)$ and output vector $y(k)$ consist of the rotary arm position ϕ, the pendulum position θ, and their velocities as

$$\begin{aligned} x(k) &= \begin{bmatrix} \phi(k) & \theta(k) & \dot{\phi}(k) & \dot{\theta}(k) \end{bmatrix}^T \\ y(k) &= \begin{bmatrix} \phi(k) & \theta(k) \end{bmatrix}^T, \end{aligned} \tag{10}$$

and the input, $u(k)$, is the motor input voltage.

Now, we are ready to construct the designed controller (8). We obtain the state feedback gain by applying the LQR method to the plant model (9) using the following parameters in the cost function (2):

$$Q = \begin{bmatrix} 30 & 0 & 0 & 0 \\ 0 & 30 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \text{ and } R = 1, \tag{11}$$

which yields the state feedback gain as

$$K = \begin{bmatrix} 5.3456 & -24.8038 & 2.9490 & -3.3639 \end{bmatrix}, \tag{12}$$

which assigns the eigenvalues of $(A-BK)$ to $\{0.9114, 0.9699, 0.9902+0.0039j, 0.9902-0.0039j\}$ and makes $(A-BK)$ Schur stable.

With respect to the observer, the eigenvalues of $(A-LC)$ must be selected much faster than the eigenvalues of $(A-BK)$. Considering the eigenvalues of $(A-BK)$ from the state feedback, we select the desired eigenvalues of $(A-LC)$ as $\{-0.2000, -0.2100, -0.2200, -0.2300\}$, which yields the following observer gain:

$$L = \begin{bmatrix} 2.3441 & -0.0100 \\ -0.0955 & 2.4262 \\ 666.0953 & -6.2360 \\ -77.0342 & 735.4454 \end{bmatrix}. \tag{13}$$

Using (9), (11), and (13), we can implement the predictor-based feedback controller as

$$u(k) = -K \left[A^{d(m)} \hat{x}(k) + \sum_{j=k-d(m)}^{k-1} A^{k-j-1} B u(j) \right]. \tag{14}$$

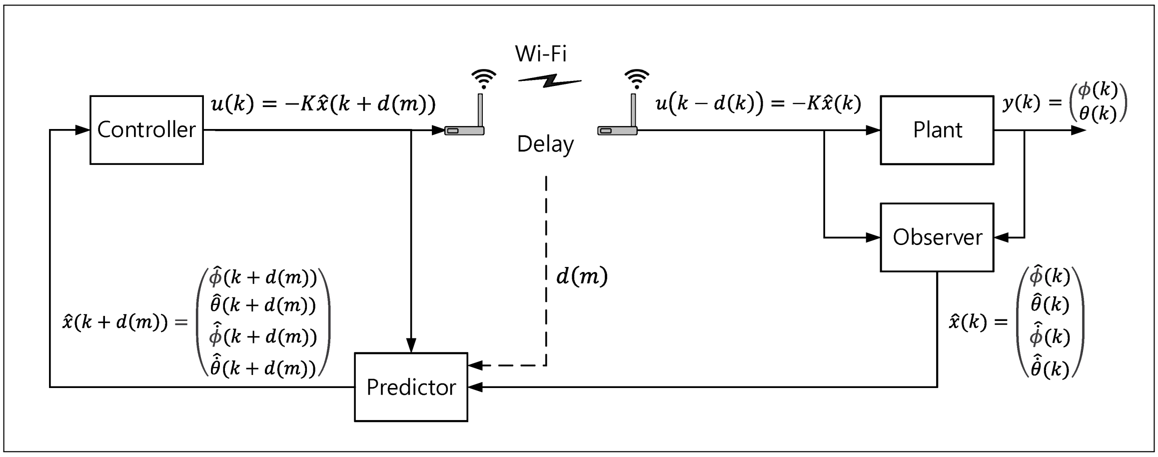


Figure 6: WNCSs in the second and the third case.

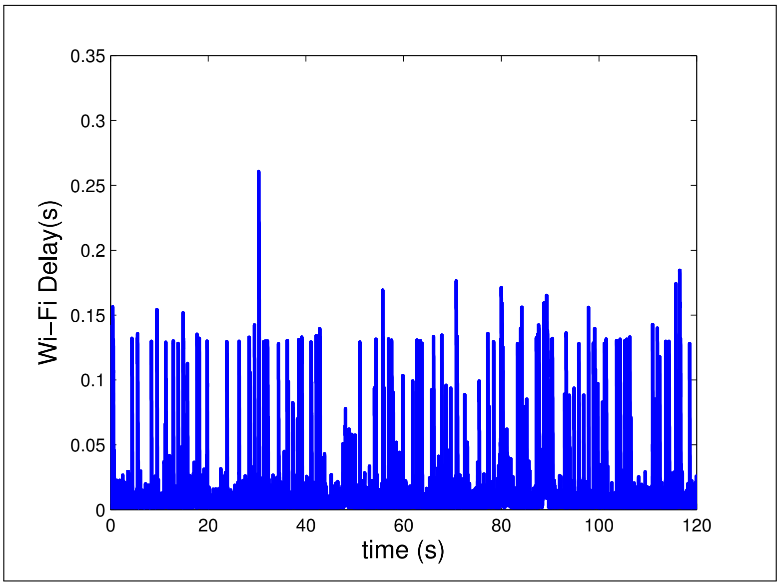
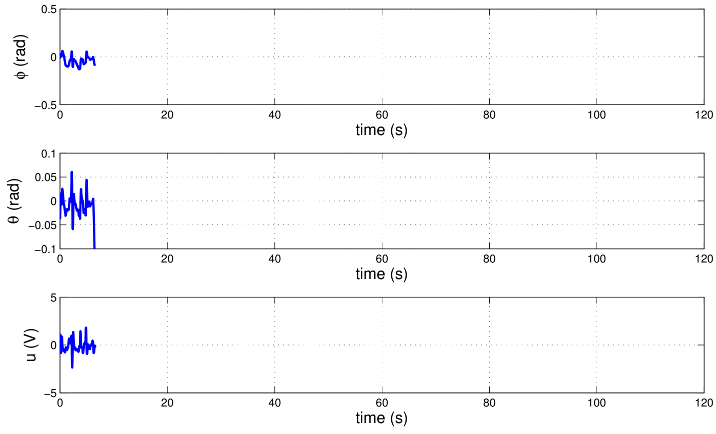
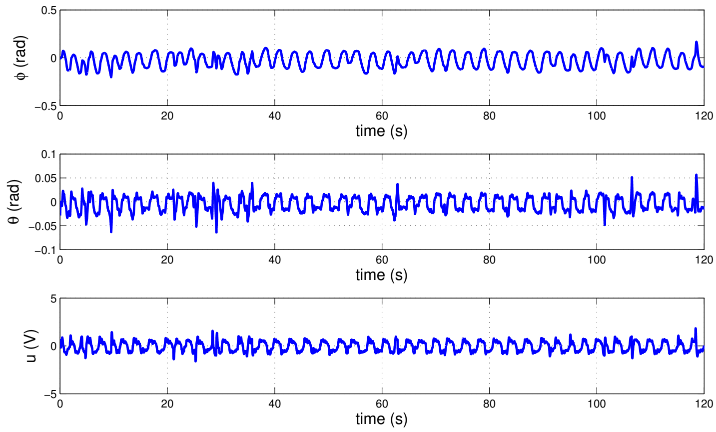


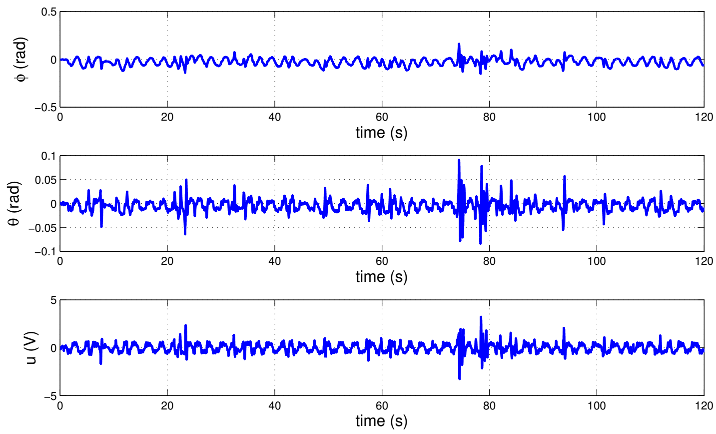
Figure 7: Time-varying delay in Wi-Fi network.



(a) Without the state predictor



(b) With the state predictor using the constant delay



(c) With the state predictor using the time-varying delay

Figure 8: Response of rotary inverted pendulum (ϕ is the rotary arm position, θ is the pendulum position, and u is the input voltage)

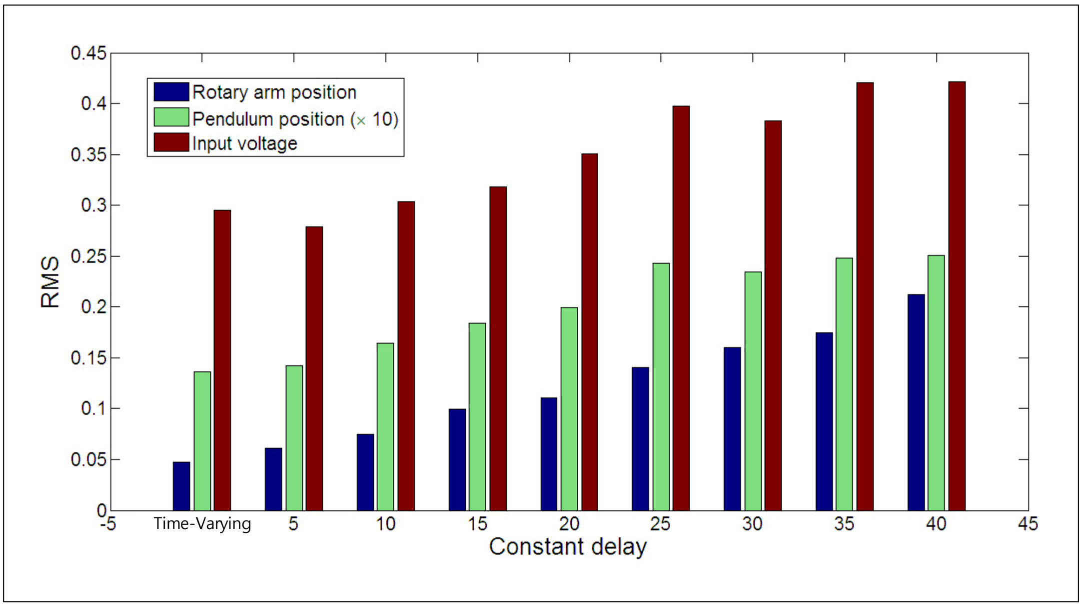


Figure 9: RMS values of state and input variables.

5.2 Discussion of experiment results

In our experiments, we consider three cases. The first case is the WNCS only with the state feedback (12) and the observer (13) without the state predictor (14). The experimental result of the first case is shown in Fig. 8(a), which demonstrates that the pendulum cannot be controlled because it falls down at around $6s$. This is because the time-varying delay is not compensated and destroys the stability.

In order to verify the stability and performance of the designed controller for WNCSs over Wi-Fi networks, we conduct several extensive experiments on the hardware platform constructed in Chapter 4. A detailed configuration of the experimental set-up is depicted in the block diagram of Fig. 6.

Before presenting the experiment results for the controller performance, we discuss the true extent of time-varying delays that occurred in the WNCS by measuring the real delays in Wi-Fi networks for a $120s$ period with a $2ms$ sampling rate. The measurement delays are shown in Fig. 7 and it is obvious that the delays in Wi-Fi networks fluctuate extensively and are relatively large, and they must be compensated to realize stable operation of the WNCS. The maximum, average, and minimum delays in Fig. 7 are $260.5ms$, $14.1ms$, and $1.3ms$, respectively.

The second case is the WNCS with the state feedback (12), the observer (13), and the state predictor (14), but the time-varying delay is approximated to a constant delay such that $d(m)$ is selected as a constant in (14). That is, the state predictor (14) with a constant $d(m)$ is applied to the WNCS with time-varying delays, and Fig. 8(b) shows the experimental result when $d(m) = 10$, which demonstrates that the pendulum is adequately controlled, and is kept in the upright position with small oscillations of the state variables, with only a constant-delay compensation. However, we observe that when we conduct the same experiments with various constant-delay values, only the delay within the range of $5 \leq d(m) \leq 41$ can stabilize and control the pendulum kept in the upright position.

The third case is the WNCS with the state feedback (12), the observer (13), and the state predictor (14) using the measured time-varying delay, $d(m)$. Fig. 8(c) shows the experimental result for the third case, which demonstrates that the pendulum is adequately controlled, and is kept in the upright position with small oscillations of the state variables, as expected.

From Fig. 8(b) and 8(c), we observe that the amplitudes in Fig. 8(b) are larger than those in Fig. 8(c) for both state and input variables, which demonstrates that the time-varying delay compensation exhibits better performance than the constant-delay compensation. In order to highlight the better performance quantitatively, in Fig. 9, we display the root mean square (RMS) values of state and input variables for both the time-varying delay compensation and several constant-delay compensations that are computed for the experiment interval ranging from $0s$ to $120s$. Considering the performance in terms of both the state and input variables, Fig. 9 demonstrates that the time-varying delay compensation achieves the best performance.

6 Conclusion

We designed a state predictor-based output feedback controller for NCSs over Wi-Fi networks, and we constructed the WNCS hardware platform for many different experiments. In order to design a feedback controller to compensate for time-varying network delays, we proposed a three-step design process. We designed a state feedback controller based on the LQR theory, the observer estimates the full-state of the system, and the predictor predicts the future state for the plant input. We acquired the time-varying network delays in real time by measuring the time difference between sending and received control data packets. We used the measured delays for the designed controller in real time, which allows the controller to precisely compensate time-varying delays. A distinct feature compared to other studies involving WNSCs is that we verified the stability and performance of WNCSs even by considering the time-varying delays in Wi-Fi networks and conducting real experiments on the WNCS hardware platform.

The designed controller can be applied to a specific class of WNCSs over Wi-Fi networks, where only the controller output is connected to the plant input via Wi-Fi networks. This limitation provides the motivation for carrying out a challenging future study, in which we aim to extend the results obtained in this paper to realize the control of more general WNCSs over Wi-Fi networks, where the plant input and output are connected to the controller output and input, respectively, through Wi-Fi networks. In this case, the network delays between the plant output and the controller input can be modeled as the time-varying output delays of the plant, which would require a new observer design scheme that estimates system states from the time-varying delayed output.

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