An Adaptive Delay Compensation Technique for Wireless Sensor and Actuator Network

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Abstract

This paper proposes an adaptive wireless-network-induced delay compensation technique for Wireless Sensor and Actuator Network (WSAN). It is well known that network delays and packet losses over wireless network incur a great challenge over performance as well as stability of WSAN-based control systems. This paper presents a time-varying delay compensator exploiting Adaptive Smith Predictor with constant delay buffer. Experimental results with rotary-type inverted pendulum as actuator to be controlled remotely show that the proposed technique increases performance of the WSAN-based control system.

Keywords: *Adaptive Smith Predictor, wireless-network-induced delay, WSAN*

1. Introduction

Cyber-physical control systems are becoming increasingly vulnerable to time-varying delay due to current trends in employing sensors and actuators via wireless communication protocol like IEEE 802.15.4 [1, 2, 10]. However, the time-varying delay characteristic of wireless communication is hard to capture and compensate for it accurately in real-time. Figure 1 shows an empirical evaluation of IEEE 802.15.4 network end-to-end delay examined by previous studies [11]. It describes more transmitters and larger MSDU size, say the payload size of MAC layer, increases the likelihood of packet collision, resulting in a considerable increase of both packet loss rate and end-to-end delay.

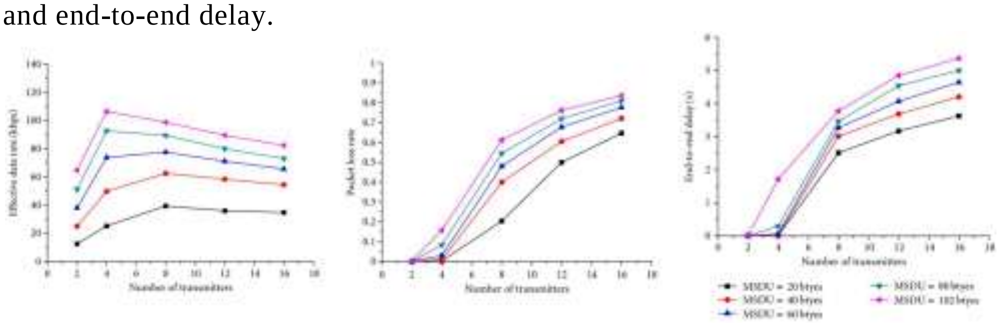


Figure 1. Evaluating IEEE 802.15.4 Network QoS Metrics [11]

Delay compensation is becoming increasingly important due to the above time-varying delay characteristic over wireless network as shown in Figure 1. In particular, when it is employed in WSAN-based control systems, the situation is getting worse because traditional

PID controller may poorly deal with network-induced delay as it increases, resulting in severe performance degradation and even further instability of the WSAN-based control system [3, 5, 6. 7]. Figure 2 describes that employing only the PID controller can poorly deal with wireless-network-induced time-varying delay, resulting in severe performance degradation of controlling the rotary-type inverted pendulum.

Figure 2. Inverted Pendulum's Control Performance Evaluation

Motivated by the above empirical observation, this paper proposes a time-varying delay compensation technique exploiting Adaptive Smith Predictor with constant delay buffer. The rest of this paper is organized as follows: Section 2 describes the basic idea of the proposed scheme to exploit virtually constant property with delay buffer. Section 3 presents how to implement the proposed adaptive delay compensator. Section 4 presents the methodology to evaluate the proposed scheme. Finally, section 5 concludes this paper.

2. Exploiting Virtually Constant Property with Buffer

The proposed compensation technique for reducing the impact of network-induced delay exploits OWD (One-Way Delay) measurement to obtain the sensor-controller delay τ_{sc} and a constant delay buffer to make time-varying controller-actuator delay τ_{ca} into constant delay so that the total delay may be estimated by their sum $\tau = \tau_{sc} + \tau_{ca}$, as shown in Figure 3. Before computing the control command at each sampling time, the OWD technique can easily measure τ_{sc} by employing the time-stamped data packets under the assumption of synchronized system architecture. However, τ_{ca} cannot be obtained in time with any delay measurement technique because it occurs after the control command has already been computed at the current sampling time with a delay compensation technique. To overcome this issue, the proposed scheme uses a constant delay buffer similar to be employed in [2, 9], located just before the actuator to make τ_{ca} into constant value.

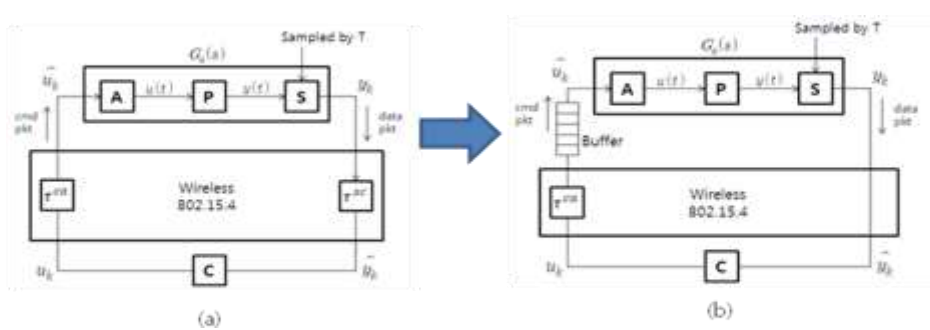


Figure 3. WSAN-based Control System: (a) Original Scheme, (b) OWD Scheme

The proposed delay compensation technique employs Smith Predictor, which is a sort of predictive controller for systems with pure time delay and can be described as Figure 4(a) [10]. $G_m(s)$ is defined by the prediction model of the $G(s)$ and $e_m^{-\tau s}$ is defined by the prediction value of $e^{-\tau s}$. The closed loop transfer function of the system is given by equation (1).

$$\frac{Y(s)}{R(s)} = \frac{C(s)e^{-\tau s}G(s)}{1+C(s)e^{-\tau s}G(s)-C(s)e_m^{-\tau s}G_m(s)+C(s)G_m(s)} \tag{1}$$

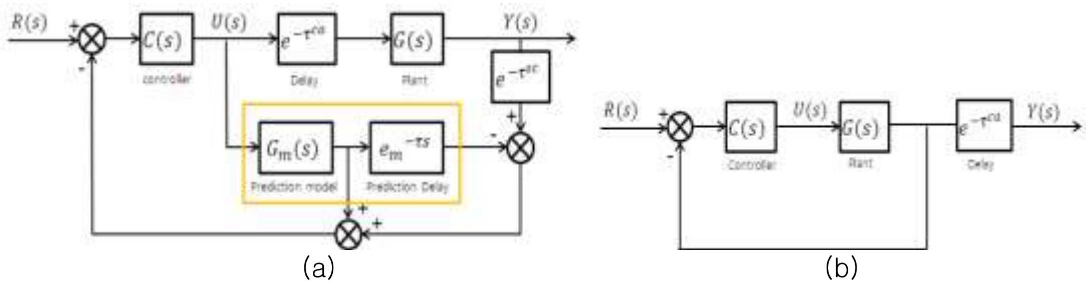


Figure 4. Block Diagram of (a) Smith Predictor, (b) Equivalent to Equation (2)

If $G_m(s) = G(s)$ and $e_m^{-\tau s} = e^{-\tau s}$, then the above equation (1) can be transformed as the following simple equation (2), letting the Smith Predictor estimate actual delay value accurately and compensate well for the delay. Figure 4(b) describes the equivalent block diagram to Figure 4(a), if the aforementioned assumptions are satisfied.

$$\frac{Y(s)}{R(s)} = \frac{C(s)e^{-\tau s}G(s)}{1+C(s)G(s)} \tag{2}$$

Unfortunately, the above conditions to make equation (2) are quite strict to be satisfied in practical situation for the following reasons: First of all, there is always an error between plant and prediction model. Secondly, it is not easy to measure sensor-controller delay τ_{sc} without any synchronization scheme between network nodes. Finally, τ_{ca} cannot be obtained in real-time. However, with the proposed OWD measurement technique, the last two reasons can be easily eliminated, causing to fully reconstruct the overall system's delay value.

3. Delay Compensation with Adaptive Smith Predictor

It is well known that the naïve Smith Predictor is quite sensitive to time-varying delay characteristic resulting in prohibitively poor performance to be employed for WSAN-based control system. That's why the proposed compensation technique uses a constant delay buffer to achieve virtually constant delay over wireless network, which makes smith predictor to operate more efficiently. Although the naïve Smith Predictor with fixed/constant network delay manages well to compensate for the delayed sensor data from the plant output and compute an effective control command to the actuator considering the estimated delay, it is not good enough to deal with time-varying delay typical to WSAN-based control system.

The proposed scheme exploits a constant delay buffer to keep time-varying controller-to-actuator delay constant and measure sensor-to-controller delay dynamically in real-time, and makes Adaptive Smith Predictor (ASP) to compensate for the dynamically changing delay.

Figure 5 shows a systematic diagram of the proposed delay compensation technique even with time-varying delay for WSAN-based control system.

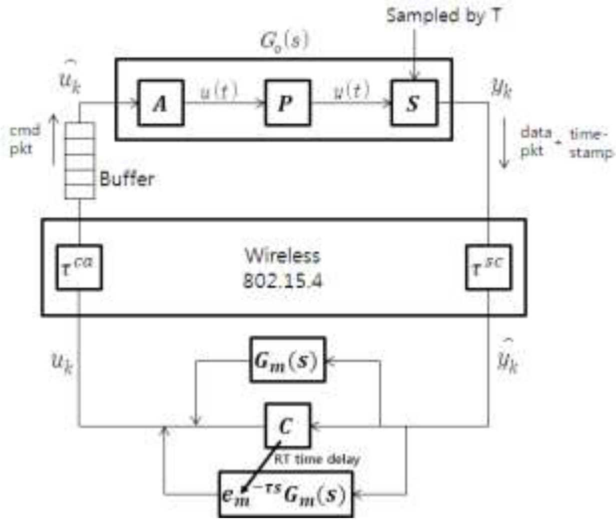
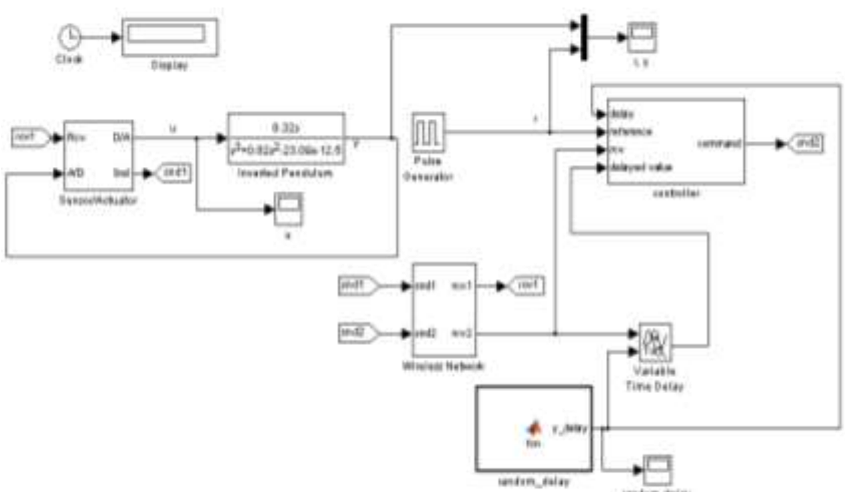


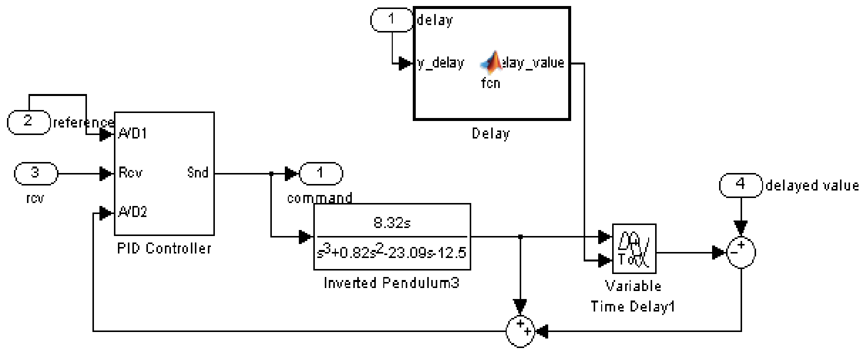
Figure 5. Block Diagram of Time-varying Delay Compensator with ASP

4. Experimental Results

As an example of actuator employed in WSAN, a rotary-type inverted pendulum has been considered and modeled. Truetime [4] and Matlab/Simulink co-simulation have been used to evaluate performance of the proposed ASP scheme. As an initial configuration, the sampling period was set to 10 ms and 500 data was collected during 5 seconds. Every sensor, actuator and controller nodes consisting of WSAN were considered to communicate each other with IEEE 802.15.4 wireless communication protocol. Suppose that there is no packet loss between controller and actuator to focus on evaluating the proposed delay compensation technique. Figure 6 describes a simulation configuration to be used in the evaluation procedure.



(a) Simulation block of overall WSAN-based control system



(b) Simulation block of internal controller

Figure 6. Simulation Block Diagram

The following simulation results assume that time-varying delay for the single hop in wireless environment randomly varies from 4 ms to 8 ms, which means end-to-end delay varies from 40 ms to 80 ms if WSAN is composed of 10 hops between controller-to-actuator and sensor-to-controller. Figure 7 compares the control performance of rotary-type inverted pendulum over wireless network: red dashed line denotes PID controller without any compensation, black dashed line denotes Smith Predictor compensation without constant delay buffer, and green solid one denotes the proposed Smith Predictor compensation exploiting fairly constant delay property with buffer [10]. Figure 7 shows that the proposed scheme increases the performance compared with other techniques.

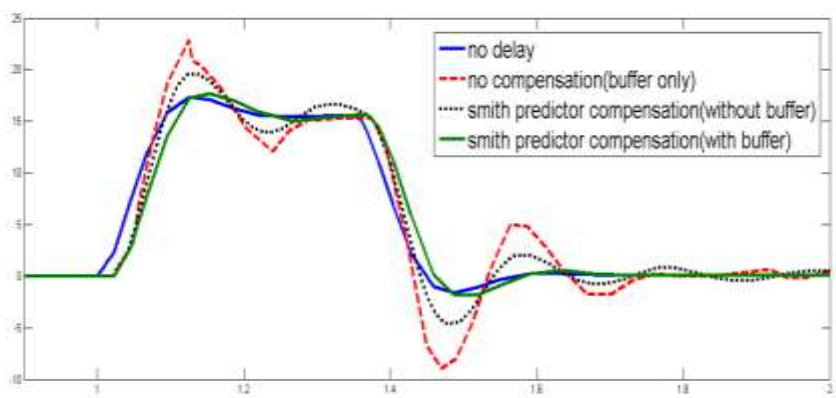
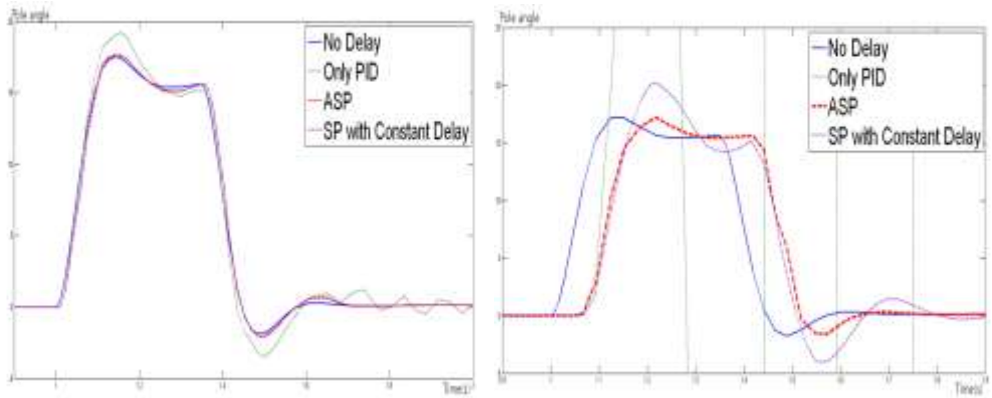


Figure 7. Performance Comparison of Control Schemes without/with Constant Delay Buffer

Figure 8 compares the control performance between single-hop and multi-hop WSAN-based control system with no delay(blue), PID controller only(green), SP with constant delay buffer(purple), and the proposed ASP(red) cases. Note that employing only PID controller in the WSAN-based control system gets unstable as delay increases in multi-hop case. However, Figure 8 shows that both SP with constant delay buffer and ASP are managing well even in multi-hop case. When comparing the Mean Squared Error (MSE), the proposed ASP is superior to SP with constant delay buffer by improving 25% of overall control performance.



(a) (b)

Figure 8. Performance Comparison: (a) Single-hop Case, (b) Multi-hop Case, say 10 hops

5. Conclusion

This paper proposed a time-varying delay compensation technique exploiting Adaptive Smith Predictor with constant delay buffer. Experimental results with rotary-type inverted pendulum as actuator to be controlled remotely show that the proposed technique increases performance of the WSAN-based control system.

Acknowledgements

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