The 31st International Technical Conference on Circuits/Systems,
Computers and Communications (ITC-CSCC 2016)

Burst Data Transmission and Time-Delay Compensation for Energy-Efficient Networked Motion Control

Takahiro Funakoshi[1] and Ryogo Kubo[2]
Department of Electronics and Electrical Engineering, Keio University
3–14–1, Hiyoshi, Kohoku-ku, Yokohama-shi, Kanagawa 223–8522, Japan
E-mail : [1]funakoshi.takahiro@kbl.elec.keio.ac.jp, [2]kubo@elec.keio.ac.jp

Abstract: This paper proposes an energy-efficient networked control system (NCS) using burst data transmission and time-delay compensation techniques. The proposed techniques enable energy-efficient operation of the NCS by making its network interfaces enter a low-power sleep mode when no data are exchanged between the controller and plant. Simulations using a networked motion control system show that the proposed techniques can effectively generate idle periods of the network interfaces for energy-efficient operation and achieve stable position control of an electric motor.

Keywords—**Networked Control System, Motion Control, Energy Efficiency, Time Delay, Burst Transmission**

1. Introduction

A networked control system (NCS) is distributed control system over networks [1]. In networked motion control, controllers, actuators, and sensors are connected over a network to frequently exchange control and response signals, as shown in Fig. 1. The advantages of networked motion control systems are, for example, enabling remote and integrated control, the ease of implementation, and scalability. Networked motion control is used in various fields, such as sensor network and unmanned automated systems [2]. However, according to the growth of information and communication technology (ICT), the power consumption in the networks has increased [3]. The NCSs are no exception in that they use high-speed networks and consume large amount of electric power.

There are many researches about energy-efficient networking and NCSs. Singh *et al.* [4] proposed forward error correction (FEC) techniques based on fuzzy inference system to improve reliability of low-power wireless NCSs for energy efficiency. Ozger *et al.* [5] proposed the method to convey the measurement packets by the energy limited sensor nodes to the Kalman filter to estimate wireless NCSs efficiently. The frequent exchange of data packets causes the increase in power consumption of communication interfaces. Event-based data-sampling and sleep-based power-saving strategy has been studied to widen the data transmission interval [6]. We applied the strategy to an NCS with broadcast-based optical network interfaces in [7]. In addition, it is known that burst data transmission improves the energy efficiency of Ethernet links, which is called Energy-Efficient Ethernet (EEE) [8]. The burst data transmission widens the data transmission interval, and the network interfaces can enter a low-power sleep mode during the idle periods [9].

The conventional studies generated data loss in the sleep mode or had no delay compensation techniques, and it causes the performance degradation of the NCS. A communication disturbance observer (CDOB) has been studied as a time-delay compensator [10]. The CDOB estimates time-delay effects as a network disturbance (ND) to compensate them without time-delay models even if there are time-varying delays. Furthermore, the CDOB can compensate data loss as the ND [11]. The CDOB can be more robust to time-varying delay by implementing with jitter buffer which suppresses the fluctuation of time delays [12].

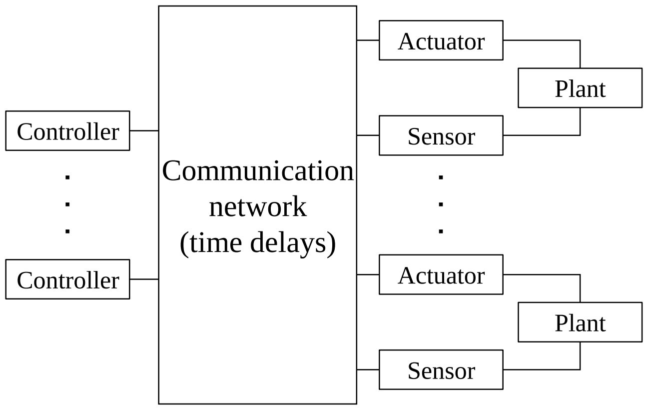


Figure 1. Networked motion control system.

This paper proposes an energy-efficient NCS using burst data transmission and time-delay compensation techniques. The proposed techniques make it possible to reduce the power consumption of the network interfaces without an excessive performance degradation of the NCS. The effectiveness of the proposed techniques are confirmed by the simulations using a networked motion control system.

This paper is organized as follows. The following section proposes an energy-efficient NCS using burst data transmission and time-delay compensation techniques. Simulation results are shown in Section 3. Finally, our conclusion is described in Section 4.

2. Energy-Efficient NCS

This section describes the energy-efficient networked motion control system with the proposed burst data transmission and time-delay compensation techniques.

2.1 Burst data transmission

The burst data transmission technique is applied to the networked motion control system, which is comprised of the controller, network, and electric motor, as shown in Fig. 2. The proposed technique includes buffering, burst transmission, and regeneration processes for the feedback path, i.e.,

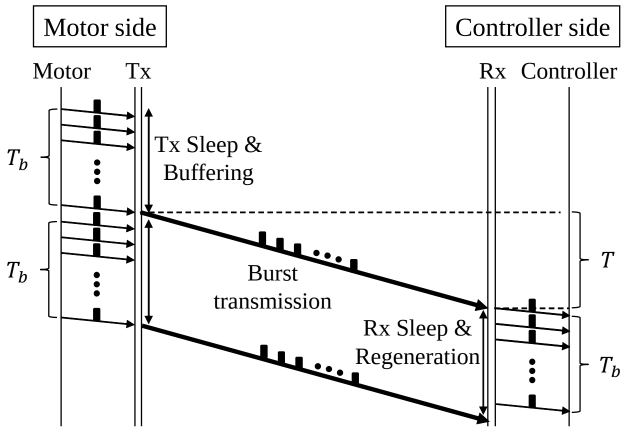


Figure 2. Buffering, burst transmission, and regeneration.

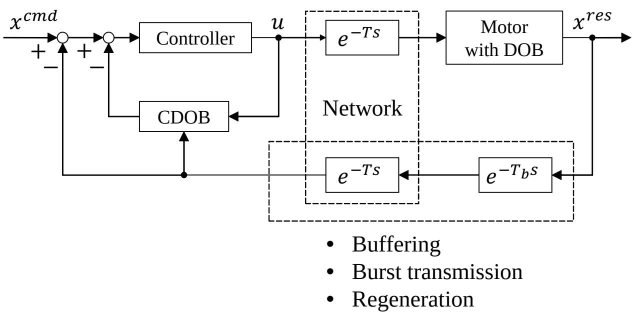


Figure 3. Proposed control system.

the path from the motor to the controller. On receiving the response signals generated by the motor or sensor, the transmitter on the motor side buffers the data and makes the network interfaces enter the sleep mode during the idle period T_b. After the idle period T_b, the transmitter sends all the buffered data to the controller over the network with the time delay T. The receiver on the controller side receives the data and regenerates them at intervals according to the control period. Therefore, these processes can be simply considered as a time delay of $T_b + T$.

2.2 Control system

The block diagram of the proposed system is shown in Fig. 3, where x^{cmd}, u, x^{res}, and s denote the position command, control input, position response, and Laplace operator, respectively. The disturbance observer (DOB) is implemented on the motor side to achieve robust motion control against disturbances [13]. It is assumed that the one-way time delay T is a constant value for simplicity in this research. The buffering, burst transmission, and regeneration processes are represented as a time delay of T_b. The proposed system has the network interfaces in the feedback path with the sleep mode. The time delays T and T_b may degrade the stability and performance of the system. In this research, the communication disturbance observer (CDOB) is implemented as a time-delay compensator [10].

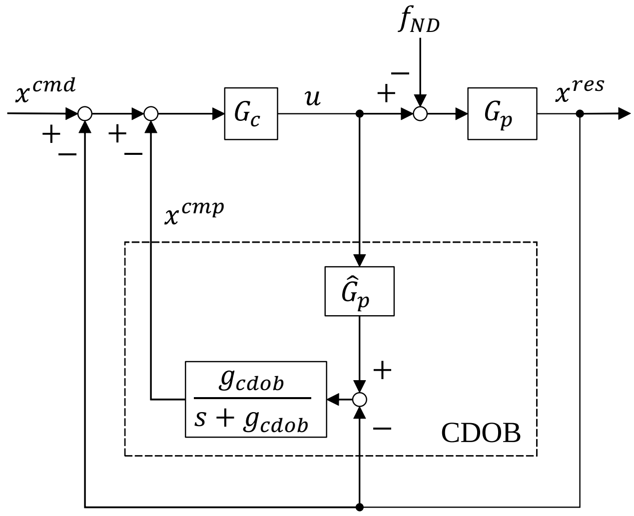


Figure 4. Networked motion control system with CDOB.

2.3 CDOB

The CDOB estimates and compensates the time delays as a network disturbance (ND) by using a nominal model of the motor. It needs no time-delay models, and can be applied to the system with time-varying delays.

The block diagram of the networked motion control system with the CDOB is shown in Fig. 4, where G_c and G_p are the transfer functions of the controller and motor, respectively. The CDOB estimates the effect of time delays of the system as the ND, f_{ND}, that is expressed as (1)

$$f_{ND} = (1 - e^{-(2T+T_b)s})u, \tag{1}$$

where $2T + T_b$ is the sum of the round-trip time delay and the idle period. When the transfer function of the nominal model of the motor, $\hat{G}_p$, is equal to G_p, the output of the CDOB x_{cmp} is calculated as (2)

$$x_{cmp} = \frac{g_{cdob}}{s + g_{cdob}} G_p f_{ND}, \tag{2}$$

where g_{cdob} denotes the cut-off frequency of the CDOB. If the cut-off frequency of the low pass filter (LPF) g_{cdob} is large enough, the transfer function of the total control system is expressed as (3)

$$\frac{x^{res}}{x^{cmd}} = \frac{G_c G_p e^{-Ts}}{1 + G_c G_p}. \tag{3}$$

The denominator of the transfer function does not include time delays. Therefore, the effect of the ND is completely compensated by x_{cmp}.

3. Simulation

This section shows simulation results to confirm the validity of the proposed techniques.

Table 1. Simulation parameters.

Transfer function of the controller	$6.64 + 0.664s$
Transfer function of the motor	$\frac{1.53}{s(0.0254s+1)}$
Time delay of the network T	10 ms
Burst transmission interval T_b	50, 100 ms
Cut-off frequency of the DOB	10 rad/s
Cut-off frequency of the CDOB	100 rad/s
Control period	1 ms

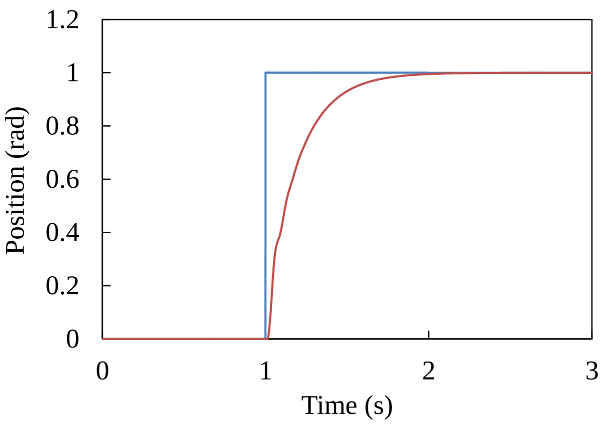


Figure 5. Simulation results of conventional position control.

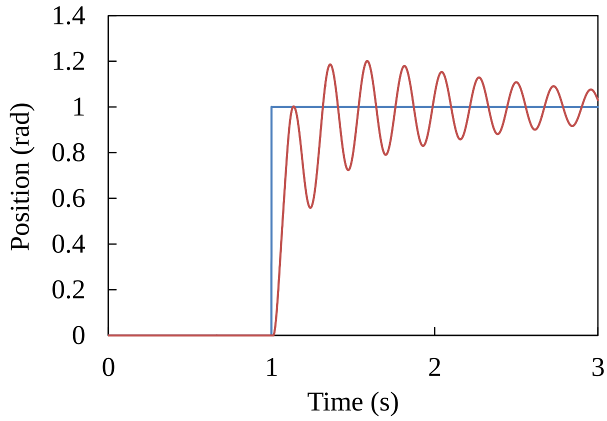
3.1 Setup

The simulations were performed to show the effectiveness of the proposed techniques. In the simulations, we performed remote position control of a direct-current (DC) motor, and assessed the step response. The parameters used in the simulations are shown in Table 1. The controller is designed so as to obtain critical damping response.

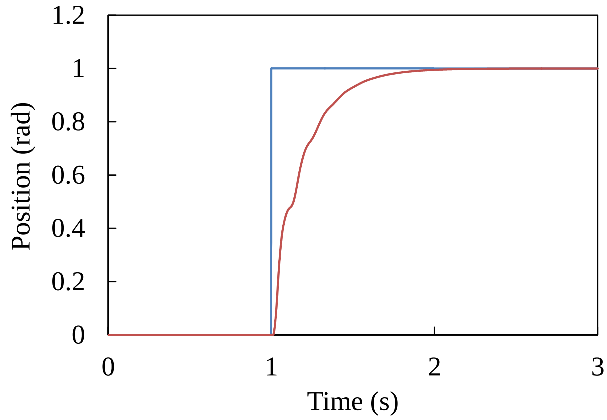
3.2 Results

The simulation results are shown in Figs. 5–7. Figure 5 shows the results using the conventional remote position control with the CDOB. Figures 6(a) and 6(b) show the results using the burst data transmission without the CDOB and with the CDOB, respectively, when the burst transmission interval were set to 50 ms. Figures 6(a) and 6(b) show the results using the burst data transmission without the CDOB and with the CDOB, respectively, when the burst transmission interval were set to 100 ms. In each figure, the position command, i.e., the step input, and position response are shown. Table 2 shows the energy efficiency that can be assessed by an active rate of the network interfaces.

In Fig. 5, the response was converged to the step command due to the CDOB-based time-delay compensation. However, the frequent exchange of data caused the degradation of energy efficiency. In Fig. 6(a), the burst data transmission, which could reduce the power consumption of network interfaces, generated the oscillatory response because of the time delays. In Fig. 6(b), the proposed techniques provided better performance in both energy efficiency and control stability



(a) Burst data transmission without CDOB



(b) Burst data transmission with CDOB

Figure 6. Simulation results ($T_b = 50$ ms).

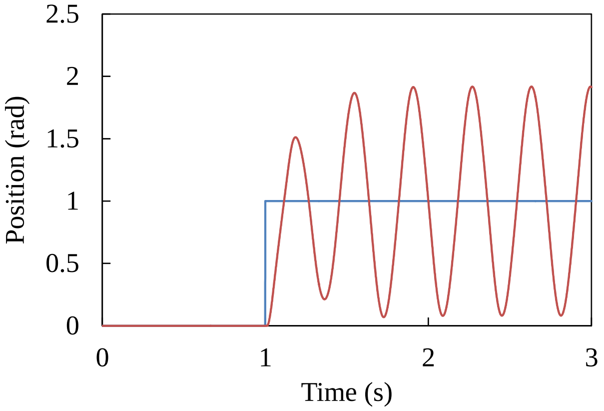
Table 2. Summary of the simulation results.

	Active rate	Steady-state error
Fig. 5	100 %	2.7×10^{-5} rad
Fig. 6(a)	2 %	7.6×10^{-2} rad
Fig. 6(b)	2 %	2.9×10^{-5} rad
Fig. 7(a)	1 %	9.2×10^{-1} rad
Fig. 7(b)	1 %	3.3×10^{-5} rad

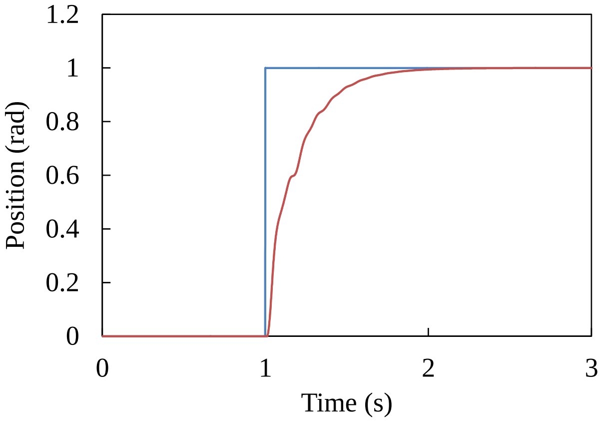
than the cases of Fig. 6(a). In Fig. 7(a), long burst transmission interval could reduce the power consumption compared with Fig. 6(a). However, it generated greater oscillatory response because of the increase of time delays. In Fig. 7(b), the proposed techniques could compensate long burst transmission interval and provided better performance than the case of Fig. 7(a).

4. Conclusion

This paper proposed the networked motion control system with the burst data transmission and time-delay compensation techniques. The burst data transmission reduced active rate of the network interfaces. The processes of buffering, burst transmission, and regeneration could be considered as a



(a) Burst data transmission without CDOB



(b) Burst data transmission with CDOB

Figure 7. Simulation results ($T_b = 100$ ms).

time delay and be compensated with the CDOB. The simulation results showed that the proposed techniques effectively generated idle periods of the network interfaces and achieved stable position control of the motor.

Acknowledgment

This research was supported in part by JSPS KAKENHI Grant Number 16K16049, Kenjiro Takayanagi Foundation, and SECOM Science and Technology Foundation.

References

[1] J.P. Hespanha, P. Naghshtabrizi, and Y. Xu, “A Survey of Recent Results in Networked Control Systems,” *Proceedings of the IEEE*, vol. 95, no. 1, pp. 138–162, Jan. 2007.

[2] R.A. Gupta and M.Y. Chow, “Networked control system: Overview and research trends,” *IEEE Transactions on Industrial Electronics*, vol. 57, no. 7, pp. 2527–2535, July 2010.

[3] G. Fettweis and E. Zimmermann, “ICT energy consumption — Trends and challenges,” *Proceedings of the 11th International Symposium on Wireless Personal Multimedia Communications (WPMC 2008)*, Sep. 2008.

[4] J. Singh and D. Pesch, “Stability of wireless networked control system using energy-efficient fuzzy based adaptive error control,” *Proceedings of the 4th Joint IFIP Wireless and Mobile Networking Conference (WMNC 2011)*, pp. 1–8, Oct. 2015.

[5] M. Ozger and O. Akan, “Maximization of energy-efficiency under convergence constraint in wireless networked control systems,” *Proceedings of the 2015 IEEE International Conference on Communications (ICC 2015)*, pp. 5973–5978, June 2015.

[6] M. Miśkowicz, “Event-based sampling strategies in networked control systems,” *Proceedings of the 10th IEEE International Workshop on Factory Communication Systems (WFCS 2014)*, pp. 1–10, May 2014.

[7] T. Funakoshi and R. Kubo, “Cyclic sleep control of network interfaces in feedback path for energy-efficient networked control systems,” *Proceedings of the 2nd IEEJ International Workshop on Sensing, Actuation, Motion Control, and Optimization (SAMCON 2016)*, V-6, pp. 1–2, Mar. 2016.

[8] P. Reviriego, J.A. Hernadez, D. Larrabeiti, and J.A. Maestro, “Burst transmission for Energy-Efficient Ethernet ,” *IEEE Internet Computing*, vol. 14, no. 4, pp. 50–57, July 2010.

[9] S.R. Yang, S.Y. Yan, and H.N. Hung, “Modeling UMTS power saving with bursty packet data traffic,” *IEEE Transactions on Mobile Computing*, vol. 6, no. 12, pp. 1398–1409, Dec. 2007.

[10] K. Natori, R. Oboe, and K. Ohnishi, “Stability analysis and practical design procedure of time delayed control systems with communication disturbance observer,” *IEEE Transactions on Industrial Informatics*, vol. 4, no. 3, pp. 185–197, Aug. 2008.

[11] R. Kubo and K. Natori, “Dependable networked motion control using communication disturbance observer,” *Proceedings of the 27th International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC 2012)*, D-T1-05, pp. 1–4, July 2012.

[12] R. Imai and R. Kubo, “Introducing jitter buffers in networked control systems with communication disturbance observer under time-varying communication delays,” *Proceedings of the 41st Annual Conference of the IEEE Industrial Electronics Society (IECON 2015)*, pp. 2956–2961, Nov. 2015.

[13] K. Ohnishi, M. Shibata, and T. Murakami, “Motion control for advanced mechatronics,” *IEEE/ASME Transactions on Mechatronics*, vol. 1, no. 1, pp. 56–67, Mar. 1996.