Variable sleep period control of energy-efficient network interfaces for QoP-aware networked control systems

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Abstract: In networked control systems, the quality of performance (QoP), such as in terms of consistent tracking errors, must be maintained at a constant level. A QoP-aware sleep mechanism in network interfaces can reduce the amount of traffic or the communication rate while maintaining the QoP. However, in a QoP-aware sleep mechanism with a fixed sleep period, the sleep period cannot be entered effectively when the length of the steady-state period is changed; e.g., when the command frequency is changed. This study proposes a variable sleep period control method to reduce the communication rate while adapting to the tracking error. The simulations confirm that, when compared to methods with a fixed sleep period, the proposed method reduces the communication rate regardless of the command frequency.

Keywords: energy-efficient network, sleep control, networked control system, motion control, quality of performance, cyber-physical system

Classification: Network

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1 Introduction

Networked control systems (NCSs) have primarily been utilized in industrial applications [1]. In a networked motion control system, a controller can remotely control distributed actuators via communication networks. In recent years, the demand for energy savings in the network interfaces of NCSs has increased [2, 3]. To achieve energy-efficient NCSs, sleep mechanisms such as the low-power idle mode for Energy-Efficient Ethernet [4] and the cyclic sleep mode for point-to-multipoint optical networks [5] have been investigated.

Send-on-delta (SoD) sampling, which is an event-triggered sampling technique, is effective in reducing the amount of traffic in NCSs, which results in lower power consumption in transceivers [6]. In the SoD-based sleep mechanism, data transmission occurs only when the time-series variation of the data exceeds a certain threshold. In [7], the SoD-based sleep mechanism was applied to a networked motion control system. Moreover, a modified communication disturbance observer (MCDOB) was implemented to compensate for the performance degradation due to the network-induced time delays and sleep-induced data losses. However, the SoD-based sleep mechanism cannot guarantee the control performance, such as in terms of consistent tracking errors. Thus, a quality-of-performance (QoP)-aware sleep mechanism was proposed to maintain a certain level of control performance [8]. The QoP-aware sleep mechanism with a fixed sleep period determines whether or not the transmitters enter the sleep period by using a fixed threshold for tracking errors. In the case of a fixed sleep period, the transmitters cannot enter the sleep period effectively when the length of the steady-state period is changed; e.g., when the command frequency is changed.

Therefore, in this study, a variable sleep period control method is proposed for a QoP-aware energy-efficient NCS to reduce the communication rate while adapting to the tracking error. In the proposed method, the sleep period is determined according to the tracking error between the command and response values in a networked motion control system when the transmitter enters the sleep period. The conducted simulations confirm that the variable sleep period reduces the communication rate when compared to the fixed sleep period, regardless of the command frequency.
2 QoP-aware NCS with energy-efficient network interfaces

The configuration of a QoP-aware networked motion control system with sleep-enabled network interfaces is depicted in Fig. 1. The controller and motor modules are connected via a communication network to control the rotational angle of a direct-current (DC) motor remotely. The transmission delays for the forward and feedback paths are defined as $T_1$ and $T_2$, respectively. The sleep-enabled transmitters in the controller and motor modules are operated based on the cyclic sleep mode [5]. Once a transmitter enters the sleep period, it does not transmit any data until the predetermined sleep period ends. When no data are received at a corresponding receiver, the latest value transmitted before the sleep period is entered is used. In Fig. 1, $\theta^{cmd}$, $u$, and $\theta^{cmd}$ denote the angular command, voltage reference, and angular response, respectively. The subscripts $s$ and $a$ indicate the latest value transmitted before the sleep period is entered and the delayed value employed on the receiver side, respectively.

![Fig. 1. NCS with QoP-aware sleep mechanism.](image)

The controller module comprises a proportional-derivative (PD) controller, MCDOB, forward sleep trigger (FWST), and transceiver. The PD controller calculates the voltage reference $u$ on the basis of the tracking error $e$. The MCDOB compensates for transmission delays and sleep-induced data losses so as to stabilize the system [7]. The FWST controls the transmitter state $S_c$, which indicates the status (active or sleep), and the sleep period $T_{s1}$ on the basis of the tracking error $e = \theta^{cmd} - \theta^{res}$. The motor module comprises a DC motor, disturbance observer (DOB), feedback sleep trigger (FBST), and transceiver. The transfer function of the DC motor is expressed as $K/(\tau s^2 + 1)$, where $K$, $\tau$, and $s$ denote the steady-state gain, time constant, and Laplace operator, respectively. The DOB is implemented to compensate for system disturbances such as the load torque. The transfer function of the DC motor is nominalized as $K_n/(\tau_n s^2)$ by the DOB, where the subscript $n$ indicates a nominal value. The FBST controls the transmitter state $S_m$, which indicates the status (active or sleep), and the sleep period $T_{s2}$ on the basis of the tracking error $e' = \theta^{cmd} - \theta^{res}$. 
3 Variable sleep period control

This section describes the QoP-aware sleep mechanisms employing the conventional fixed sleep period and proposed variable sleep period. Figure 2 depicts the relationship between the sleep period and tracking error in each mechanism. The sleep period and error correspond to $T_{s1}$ and $e$ in the FWST, and $T_{s2}$ and $e'$ in the FBST, respectively.

![Fig. 2. Sleep period control on the basis of tracking error.](image)

As illustrated in Fig. 2(a), in the conventional mechanism, a transmitter enters the fixed sleep period $T_s$ if the tracking error is less than the threshold $h_e$. During the sleep period, the transmitter does not transmit any data to the corresponding receiver. The transmitter becomes active after the lapse of $T_s$. Thereafter, the FWST or FBST determines whether or not the transmitter should enter the sleep period again on the basis of the tracking errors $e$ and $e'$, respectively. A drawback in the case of the fixed sleep period is that the state of the control responses is not considered. If the sleep period is set to a larger value, the threshold should be a smaller value to maintain the tracking error at a constant level. This means that the transmitter can enter a long sleep period only when the tracking error is small; e.g., in the steady state. Therefore, if a high-frequency command is input, the sleep period is rarely entered. For the sleep period to be entered even when the tracking error is large; e.g., in the transient state, the threshold can be set to a larger value. In this case, the sleep period should be set to a smaller value to suppress the increase in the tracking error. However, the transmitter can only enter a short sleep period, even if a low-frequency command is input.

The variable sleep period control method is therefore proposed to trigger the transmitter to enter the sleep period while adapting to the tracking error, even if the command frequency is changed. As indicated in Fig. 2(b), the proposed method has two error thresholds, $h_{e,l}$ and $h_{e,u}$. The sleep period is set to 0 if the tracking error is greater than or equal to the threshold $h_{e,u}$, and it is set to the maximum sleep period $T_{s,u}$ if the tracking error is less than or equal to the threshold $h_{e,l}$. If the tracking error is between the two thresholds, the sleep period varies linearly between the maximum threshold $T_{s,u}$ and minimum sleep period $T_{s,l}$. In the FWST and FBST, the sleep periods $T_{s1}$ and $T_{s2}$ are determined as in (1) and (2), respectively.
Through the proposed method, the transmitter can be triggered to enter a short sleep period when the tracking error is large and a long sleep period when the tracking error is small.

4 Simulation

To confirm the effectiveness of the proposed variable sleep period control method, simulations were performed herein. The controller module, transmission delays, and motor modules were programmed in a LabVIEW environment. The PD gains $K_p$ and $K_d$ were set to 225 and 30, respectively, designed such that the unit step response could be critical damping. The nominal steady-state gain of the motor $K_n$ and nominal time constant of the motor $\tau_n$ were set to 1.53 and 0.0254, respectively. The cut-off frequencies of the DOB and MCDOB were both set to 300 rad/s. The transmission delays for the forward and feedback paths, namely $T_1$ and $T_2$, respectively, were both set to 20 ms. In the variable sleep control method, the minimum sleep period $T_{s,1}$, maximum sleep period $T_{s,u}$, lower error threshold $h_{e,l}$, and upper error threshold $h_{e,u}$ were set to 10 ms, 80 ms, 0.02 rad, and 0.1 rad, respectively. Two setup types were considered for the fixed sleep period for comparison: $(T_{s,1}, T_{s,u}, h_e) = (T_{s,1}, T_{s,1}, h_{e,u})$ and $(T_{s,1}, T_{s,u}, h_e) = (T_{s,u}, T_{s,u}, h_{e,l})$. In the simulations, a square wave was input as an angular command for 20 s, the amplitude of which was set to 1 rad. The frequency of the square wave was changed from 0.01 to 1 Hz. The two types of fixed sleep periods and variable sleep periods were compared in terms of the integral square error (ISE) and communication rate. The communication rate is defined as the time occupancy of the period during which a transmitter is active.

Figure 3 presents the results of the ISE, communication rate on the forward path, communication rate on the feedback path. In Fig. 3(a), the variable sleep period and fixed sleep period with $T_{s,u}$ generated larger ISEs than those of the fixed sleep period with $T_{s,1}$. This is because a longer sleep period was used in the former cases when the response approached the steady state. In Figs. 3(b) and 3(c), the fixed sleep period with $T_{s,u}$ exhibited lower communication rates than those in the case of $T_{s,1}$ in the low-frequency range, whereas the fixed sleep period with $T_{s,1}$ exhibited lower communication rates than those in the case of $T_{s,u}$ in the high-frequency range. This is because, in the case of the fixed sleep period with $T_{s,1}$, a long sleep period could not be entered even in the steady state for a low-frequency command, and in the case of the fixed period with $T_{s,u}$, a short sleep period could not be entered in the transient state for a high-frequency command. The variable period exhibited lower communication rates than those for both types of fixed sleep periods regardless of the command frequency, because the sleep period could be adjusted in that case while adapting to the tracking error.
5 Conclusions

This letter proposed a variable sleep period control method for a QoP-aware NCS with energy-efficient network interfaces. The proposed method changed the sleep period by adapting to the tracking error so as to reduce the communication rates on the forward and feedback paths. The simulation results demonstrated that the proposed method could reduce the communication rate when compared to the two types of fixed sleep periods regardless of the command frequency, at the expense of the ISE.

Acknowledgment

This work was supported in part by JSPS KAKENHI, Grant Number 18K11275.