ANALYSIS AND APPLICATIONS OF THE MOTION MESSAGE ESTIMATOR FOR NETWORK CONTROL SYSTEMS

Chen-Chou Hsieh and Pau-Lo Hsu

ABSTRACT

The time-delay effect in network systems is unavoidable because of its limited transmission bandwidth. In real-time network control systems (NCS), all messages are required to be transmitted or received to meet specifications of the deadline. Therefore, the data dropout may thus occur in NCS due to its time delay in a stochastic nature. In this paper, a motion message estimator is proposed to construct a real-time motion NCS to significantly reduce the data-dropout effect. Both simulation and experimental results indicate that a 3rd-order message estimator based on the Taylor expansion can be properly implemented in NCS for industrial motion control systems. Furthermore, since the uncertainties of the NCS estimator are greatly suppressed by applying the message, experimental results indicate that its integration with the feedforward control leads to significantly improved accuracy for the NCS implemented on an industrial computerized numerical control (CNC) machine tool.

Key Words: Motion message estimator, data-dropout, NCS, feedforward control.

I. INTRODUCTION

In modern industries, techniques of network communication have been rapidly developed and there is a trend to integrate network protocol into traditional control systems as the networked control system (NCS) [1, 2]. Although NCS possesses some advantages such as low cost, extensibility, flexibility, and easy maintenance, the unavoidable time-delay effect induced in the network seriously degrades its control performance and also reduces system reliability and stability [3]. Recently, different approaches were proposed for NCS to mainly compensate for the time-delay effect like the queuing methodology [4], the sampling time scheduling [5], the gain scheduling proportional integral (PI) control [6], scheduling and control co-design [7], and robust control [8, 9].

A general network system is basically an event-triggered system and the time delay is the main concern. However, the real-time motion NCS, which includes the fixed sampling time and an interpolator to conduct provided motion contouring commands, is a typical event/time-triggered system [10]. When the network communication becomes heavy, some network nodes may not properly receive/transmit messages on time and the data dropout may thus occur. In general, the dropout rate of the network is closely related to both the network transmission rate and the specified sampling period. The data dropout not only increases system uncertainty of the NCS, but also it degrades motion accuracy in tracking and contouring [11]. A Markov chain with two states treated as the vacant sampling can be applied to model the data dropout in a stochastic nature [12]. Moreover, to handle the data dropout, there are two approaches: (i) using the past control signals to estimate the lost data [13] and (ii) including the estimator which is based on the power spectral density of NCS output signals [14, 15].
This paper proposes a message estimator for the motion NCS to compensate for its dropout effect. Both simulation and experimental results have shown that a message estimator with a 3rd-order Taylor expansion is effective for estimating missing motion signals. Moreover, the motion control performance on the NCS is satisfactory by including the estimator in the controller. Since the proposed structure leads to a more reliable motion NCS with less uncertainty, it has been successfully integrated with the feedforward control design to achieve high-precision motion accuracy \cite{16, 17}. The proposed network control structure has been successfully realized on a DYNA MTYE 1007 CNC machine tool to prove the feasibility of the present motion NCS.

II. NCS DATA DROPOUT

Motion systems with synchronized control on multiple axes are designed mainly to meet specifications of precision accuracy in tracking or contouring. When motion control systems are realized on the NCS, the data bus containing either the command messages or the feedback measurements are transmitted through the network protocol, as shown in Fig. 1. The induced time delay in the NCS is unavoidable and the transmitted message may miss the hard real-time deadline, the sampling time $T$, and it always leads to erroneous motions in precise systems. Thus, the caused data dropout is crucial to motion performance in the real-time NCS. For the controller area network (CAN) bus, Table 1 shows all experimental measurements of the dropout rate with different transmission rates and sampling periods. Experimental results indicate that the dropout rate significantly decreases as the sampling period increases. Note that the control performance of the system also decreases as the sampling period increases in NCS \cite{3}. Therefore, to select a proper sampling time for the NCS, it is a trade-off between the network transmission and the control performance.

The data dropout occurs randomly on the network transmission either in command or feedback measurement signals. Actually, the dropout commands are properly estimated since most commands are relatively smooth compared with the measurements \cite{10, 11}. Therefore, this paper focuses on compensating the effect of the measurement data dropout. To model the data dropout in transmitting the feedback message data, Fig. 2 shows that $d$ is a binary process with probability distribution of $P(d[k] = 1) = \varepsilon$, $P(d[k] = 0) = 1 - \varepsilon$, and the data dropout occurs when $d[n] = 1$ \cite{11, 12}.

The transmitted feedback signal $\bar{y}[n]$ is modeled as

$$\begin{cases} 
\bar{y}[k] = y[k] & \text{if } d[k] = 0 \\
\hat{y}[k] = 0 & \text{if } d[k] = 1
\end{cases} \iff \text{dropout.} \quad (1)$$

Experimental results with an 1 ms sampling period and a 500 K bit/s transmission rate are shown in Fig. 3. Results indicate that the data dropout which occurred in the feedback data directly affects the system performance. In the present experiments, the missing feedback messages are all treated as 0 values and it makes the designed controller to loss efficacy. To compensate for the dropout data, the designed message estimator $F(z)$ is shown in Fig. 4 and the NCS can be expressed as

$$\begin{cases} 
\bar{y}[k] = y[k] & \text{if } d[k] = 0 \\
\hat{y}[k] = \hat{y}[k] & \text{if } d[k] = 1
\end{cases} \iff \text{compensated dropout.} \quad (2)$$

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Transmission rate & $T = 2 \text{ ms}$ & $T = 1 \text{ ms}$ \\
\hline
1 Mbit/s & 0.48\% & 0.49\% \\
500 bit/s & 0.51\% & 19.97\% \\
250 bit/s & 20.21\% & 42.14\% \\
\hline
\end{tabular}
\caption{The data dropout rate of CAN bus transmission rate.}
\end{table}
The power spectral density of the system output response are as [15]

\[
S_{yy}(z) = \left| \frac{P(z)}{1 - D(z)P(z)} \right|^2 S_{ww}(z) + \left| \frac{D(z)P(z)}{1 - D(z)P(z)} \right|^2 \frac{1}{1 - \varepsilon} \Delta
\]

(3)

\[
S_{\hat{y}\hat{y}}(z) = \left| \frac{P(z)(D(z) - 1)}{1 - D(z)P(z)} \right|^2 S_{ww}(z) + \left| \frac{D(z)(1 - P(z))}{1 - D(z)P(z)} \right|^2 \frac{1}{1 - \varepsilon} \Delta
\]

(4)

\(| \cdot |\) means magnitude and \(D(z) = 1 - \varepsilon/1 - \varepsilon \cdot F(z)\). For \(\varepsilon = 0, \Delta = 0\); for \(\varepsilon > 0, \Delta\) is the unique positive solution to the following equation

\[
\Delta = \frac{1}{2\pi} \left[ \int_{-\pi}^{\pi} \left| \frac{P(e^{jw})D(e^{jw}) - 1}{1 - D(e^{jw})P(e^{jw})} \right|^2 S_{ww}(e^{jw}) \, dw \right]
\]

\[
+ \frac{1}{2\pi} \left[ \int_{-\pi}^{\pi} \left| \frac{D(e^{jw})(1 - P(e^{jw}))}{1 - D(e^{jw})P(e^{jw})} \right|^2 \, dw \cdot \frac{1}{1 - \varepsilon} \cdot \Delta \right.
\]

(5)

where \(w\) is the frequency. Moreover, the networked control system shown in Fig. 4 can be transformed to an linear time-invariant (LTI) system as shown in Fig. 5. The optimal dropout compensator \(F(z)\) can be thus designed by minimizing the power spectral density of the output response \(y[k]\) under the noise contamination \(n[k]\) [14, 15].

### III. MOTION MESSAGE ESTIMATORS

Based on the structure shown in Fig. 4, the output of a message estimator will estimate the missing message when the dropout happens as in (2). The missing messages can be thus recovered to some extent to improve performance of the motion NCS. For the messages in a relatively low frequency, the improvement of control performance with a simple 1-delay message estimator is acceptable [13]. However, as the frequency of the transmitted/received signals increases, the motion NCS owns faster dynamics and the improvement of the 1-delay message estimator is limited.

#### 3.1 The order of the estimator

In the present paper, a Taylor message estimator is proposed for the motion NCS, because most dynamics of motion commands or motion measurements can be represented by a Taylor expansion with a suitable order, except the motion commands containing significant variation, as shown in Fig. 6 with different dynamic natures. Fig. 7 shows that the transmission error decreases when the order of the Taylor estimator increases for smooth commands. However, it also shows that the transmission error increases when the order of the Taylor estimator increases for commands with significant variation. Therefore, the selection of orders of the Taylor estimator is very important in motion NCS. Hence, this paper used the integrated absolute errors (IAE) of transmission errors as a performance index to determine the orders of the Taylor estimator. Results shown in Fig. 8 indicate that the 3rd-order Taylor message estimator is more suitable in real applications by concerning different motion commands.
3.2 3rd-order Taylor message estimator

If the current $k$th position data $P(k)$ is lost, the 3rd-order Taylor expansion is processed to estimate the velocity, $\hat{v}_{k-1}$, from the past data

$$\hat{v}_{k-1} = \Delta P_{k-1} + \frac{1}{2} \cdot (\Delta P_{k-1} - \Delta P_{k-2})$$
$$+ \frac{1}{8} \cdot (\Delta P_{k-1} - 2\Delta P_{k-2} + \Delta P_{k-3}) \quad (6)$$

where

$$\Delta P_{k-1} = P(k - 1) - P(k - 2),$$
$$\Delta P_{k-2} = P(k - 2) - P(k - 3),$$
$$\Delta P_{k-3} = P(k - 3) - P(k - 4)$$

The estimated value of the current position command can be expressed as

$$\hat{P}(k) = P(k - 1) + \hat{v}_{k-1}. \quad (7)$$
By combining (6) and (7), the estimated current result from the past four sequential messages is obtained as

\[ \hat{P}(k) = \frac{21}{8} \cdot P(k-1) - \frac{19}{8} \cdot P(k-2) + \frac{7}{8} \cdot P(k-3) - \frac{1}{8} \cdot P(k-4). \]  

(8)

Alternatively, the 3rd-order Taylor message estimator \( F(z) \) can be simply expressed in the z-transform as

\[ F(z) = \frac{21}{8} z^{-1} - \frac{19}{8} z^{-2} + \frac{7}{8} z^{-3} - \frac{1}{8} z^{-4}. \]

(9)

IV. SIMULATION RESULTS

4.1 Noise command signals

In the simulation analysis, the NCS structure shown in Fig. 4 was built on MATLAB. The dynamic model of the DYNA CNC machine tool obtained from the system identification procedure was adopted as

\[ P(z) = \frac{0.30554z^{-2} - 0.023766z^{-3} + 0.11104z^{-4} + 0.028834z^{-5} - 0.012243z^{-6} + 0.020811z^{-7} - 0.089113z^{-8}}{1 - 0.70669z^{-1} + 0.1934z^{-2} - 0.1511z^{-3} - 0.02566z^{-4} + 0.02801z^{-5}} \]

Moreover, three different message estimators were implemented for verifying the noise reduction and control performance as: (i) the 1-delay estimator, \( F(z) = z^{-1} \), (ii) the optimal estimator \([14, 15]\), and (iii) the proposed 3rd-Taylor estimator. The dropout rate is chosen as \( \varepsilon \in [0, 0.6] \). For the cases where the input command \( r[k] \) is the white noise with zero mean, Fig. 9 indicates that, based on the index of the auto-correlation value \( R_{yy} \), the optimal dropout compensator results in the best noise reduction to suppress the noise contamination effect up to a 20% data dropout rate. On the other hand, the 3rd-order Taylor message estimator performs the worst for noise reduction. Note that the Taylor message estimator mainly estimates the missing message from the past data but the noise signals are unpredictable. Therefore, the obtained results also imply that the Taylor message estimator is not suitable for the highly noise-contaminated NCS.

4.2 Circular motion command

In real applications, motion commands in general are simple signals like G01, G02 and G03 in CNC codes as linear, clockwise and counter-clockwise circular motions, respectively. Basically, a 3rd-order Taylor expansion is suitable to represent the most basic CNC motion commands. Here, a sinusoidal wave on a single axis with the magnitude 50 mm under the feedrate 3000 mm/min as input \( r[k] \) is adopted to verify the circular motion performance of NCS. Results of three different message estimators under different dropout rates are shown in Fig. 10. Simulation results indicate that applying the optimal dropout compensator leads to the worst control accuracy and its dropout rate is limited to 20% only. Theoretically, the optimal dropout compensator is designed to minimize the power spectral density of the output signals due to the noise input and it is not suitable for the cases with contouring commands. On the other hand, the proposed 3rd-order Taylor message estimator results in the best control performance when the dropout rate is as high as to 50%.
4.3 NURBS motion commands

The circle and butterfly contours are selected as the test control commands produced by applying the non-uniform rational B-Spline (NURBS) curve interpolator \[18, 19\]. The NURBS interpolator can create free-form curves easily by manipulating the values of control points, weight and knot vectors. The mathematical formulation of NURBS curve can be described as

\[
C(p) = \sum_{i=0}^{n} \frac{\sum_{k=0}^{n} R_{i,k}(p)Z_{i,k}(p)\psi_{i}}{\sum_{i=0}^{n} Z_{i,k}(p)\psi_{i}} V_{i} = \sum_{i=0}^{n} R_{i,k}(p)V_{i} \tag{10}
\]

and

\[
R_{i,k}(p) = \frac{Z_{i,k}(p)\psi_{i}}{\sum_{i=0}^{n} Z_{i,k}(p)\psi_{i}} \tag{11}
\]

where \(V_{i}\) is the control points; \(\psi_{i}\) is the corresponding weights of \(V_{i}\); \(n + 1\) is the number of control points; \(k\) is the order of the NURBS curve; \(Z_{i,k}(p)\) is the \(k\)th order B-spline basis function; \(R_{i,k}(p)\) is the rational basis function. With the circular commands and the butterfly commands \[20\], Figs 11 and 12 show that the proposed motion estimator can significantly improve control performance as data dropout occurs.

V. EXPERIMENTAL RESULTS

5.1 CAN bus

The proposed approach was also verified on a CNC machine tool driven by the AC servo motor. The message estimator together with the controller were implemented on the TI TMS320F2812 DSP microcontroller and its internal CAN protocol was used to transmit/receive messages of the position commands and feedback measurements. The transmitted messages missing the deadline of the fixed sampling time were counted as the data dropout in a time base. Without applying the message estimator, a sinusoidal command was provided with a CAN transmission rate at 250 K bit/s. Its missing message transmission error at every sampling period 1 ms was recorded as shown in Fig. 13. Experimental results shown in Fig. 14 indicate that the proposed 3rd-order Taylor message estimator effectively reduces the network transmission errors around \(\frac{1}{100}\).

5.2 CNC applications

Furthermore, the proposed 3rd-order Taylor message estimator and the controller were applied to the DYNA MTYE 1007 CNC machine in a NCS structure, as shown in Fig. 15. The sinusoidal command message
with the position amplitude 50 mm under the feedrate 3000 mm/min are shown on Fig. 16. Experimental results indicate that without the message estimator, the significant tracking error of NCS on CNC leads to a relatively unstable system, as shown in Fig. 17. By applying the proposed Taylor message estimator, the motion NCS not only becomes more stable but also greatly reduces the tracking error.

5.3 Feedforward control on NCS

The feedforward control has been successfully applied to motion systems by canceling poles and zeros of the plant model to improve tracking accuracy [16, 17]. Apparently, the model-based feedforward design is not suitable for general NCS because the dynamic model of a general NCS is usually uncertain due to both the time-delay effect and the data dropout. Since the proposed message estimator may recover the missing message in the NCS to render a more reliable NCS model, the feedforward control structure as shown in the Fig. 18 integrated with the Taylor message estimator becomes feasible.

The basic feedforward structure of the zero phase error tracking control (ZPETC) shown in the Fig. 19 cancels all removable poles and zeros in the position control loop [16]. For those unstable zeros, their conjugate zeros are added to compensate for their phase error through the entire frequency range. If the transfer
function of the original position loop is

$$T(z^{-1}) = \frac{z^{-d} \cdot B(z^{-1})}{A(z^{-1})} = \frac{z^{-d} \cdot B_u(z^{-1})B_u(z^{-1})}{A(z^{-1})}$$

(14)

the transfer function of the ZPETC can be expressed as [17]

$$Z_p(z^{-1}) = \frac{z^{-d} \cdot A(z^{-1}) \cdot B_u(z)}{B_u(z^{-1}) \cdot B_u(1)^2}.$$  

(15)

Then, the total transfer function $P(z^{-1})$ becomes

$$P(z^{-1}) = Z_p(z^{-1}) \cdot T(z^{-1}) = \frac{B_u(z)B_u(z^{-1})}{B_u(1)^2} = \frac{|B_u(z^{-1})|^2}{B_u(1)^2}.$$  

(22)

Thus, ZPETC leads to zero phase error in all frequency range. Besides, the DC gain is unity at zero frequency, as in (22).

Based on the measured results of the CAN bus shown in Table 1, simulation results shown in Figs 20–22 indicate that both the 1-delay message estimator and the optimal dropout compensator present unsatisfactory performance as the dropout rate increases. The tracking accuracy of the controller combining the Taylor estimator and the ZPETC leads to significant improvement in motion accuracy as shown in Fig. 22. Experimental
VI. CONCLUSIONS

The dropout rate of the CAN bus increases rapidly even when the transmission rate slightly decreases, as shown in the Table 1. Therefore, the dropout effect of the NCS causes the serious motion error in precise motion systems. Basic motion control commands (CNC G-code RS-273-A, RS-274-B) can be properly described in both the position and the velocity. From both analytical and experimental results, the proposed 3rd-order message estimator can be suitably applied to the motion NCS to satisfactorily compensate for the missing commands or measurements.

In this paper, the novel control structure containing a 3rd-order Taylor message estimator is successfully applied to the motion NCS to improve the control performance significantly. Both simulation and experimental results are summarized as in the following:

1. Fig. 8 indicates that the 3rd-order Taylor message estimator is more suitable in real applications by considering different motion commands (both smooth and abruptly-changed). Moreover, simulation results indicate that the proposed 3rd-order Taylor estimator is effective in both the high and the low noise-contaminated signals.

2. In real applications of the present message estimator, the dropout data must be smooth and predictable, like position commands or velocity commands. Because the velocity, the acceleration, and the jerk are the first, second, and third derivatives of the position, the present 3rd-order Taylor message estimator is applicable to motion NCS to cover all information of the missing messages of the commands or measurements.

3. In practice, all motion commands and paths of CNC or robots are predictable and the proposed message estimator in NCS is suitable. Experimental results of the CNC machine tool indicate that by applying the proposed 3rd-order Taylor message estimator, the maximum tracking error is reduced from 12 mm to 2.4 mm.

4. The present 3rd-order Taylor message estimator not only reduces the tracking error, but also degrades the NCS model uncertainty to achieve reliable motion. By integrating the feedforward control together with the message estimator, the present NCS model uncertainty is reduced and results shown in Fig. 23 indicate that the tracking error further decreases from 2.4 mm to 0.08 mm.

5. The communication delay is basically stochastic in nature. If it is less than one sampling period $T$, its delay effect on the degradation of NCS performance is negligible. However, as the delay becomes more serious, say several times the sampling interval $T$ like in the Ethernet, the data dropout will also become more serious and special design should be considered, such as applying the Smith predictor.

By applying the proposed message estimator, advanced control design can be further employed for the motion NCS design to render satisfactory precision and responses. However, the proposed approach is feasible only as the data dropout rate is small and the missing message can be estimated in a deterministic approach. As the dropout rate increases to 50%, other statistical approaches to determine the stochastic model of the missing messages and to take proper actions may thus be required [21].

REFERENCES


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Chen-Chou Hsieh received the B.S. degree from Da-Yeh University, Taiwan in 2000, and the M.S. degree from the National Chiao-Tung University, Taiwan in 2002, where he is currently working toward the Ph.D. degree. His research interests include CNC motion control, networked control systems, and auto-tuning.

Pau-Lo Hsu (M’91) received the B.S. degree from National Cheng Kung University, Taiwan, the M.S. degree from the University of Delaware, and the Ph.D. degree from the University of Wisconsin-Madison, in 1978, 1984, and 1987, respectively, all in mechanical engineering. Following two years of military service in King-Men, he was with San-Yang (Honda) Industry during 1980–1981 and Sandvik (Taiwan) during 1981–1982. In 1988, he joined the Department of Electrical and Control Engineering, National Chiao Tung University, Hsinchu, Taiwan, as an associate professor. He became a professor in 1995. From 1998 to 2000, he served as the chairman of the department. He was the elected President of the Chinese Automatic Control Society in 2001–2002. His research interests include mechatronics, CNC motion control, servo systems, and network control systems.