Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

The Motion Message Estimator in Networked Control Systems

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Abstract: The networked control system (NCS) in industrial applications, such as computerized numerical control (CNC) machine tools and robots, possess advantages of simple wiring, expansion flexibility, and easy maintenance. However, the introduced network delay is unavoidable. Moreover, in real-time synchronized multi-axis NCS, all motion messages transmitted through the network are required to be received in time to meet specifications of the deadline. However, the data dropout may occur in NCS due to its time delay in a stochastic nature, and it also may results in degradation of motion accuracy. In this paper, a motion message estimator is proposed to construct the real-time networked industrial applications to reduce the data-dropout effect. Analytical results indicate that a 3rd-order message estimator based on the Taylor expansion successfully suppresses the uncertainties in NCS due to the dropout effect. Furthermore, this paper also proposes the networked cross-coupled control (CCC) structure to improve the contouring accuracy of the multi-axis NCS. Results indicate that the variation of the contouring error in the multi-axis NCS is suppressed greatly by applying the proposed networked CCC. Finally, experimental results indicate the proposed motion message estimator leads to improved accuracy on an industrial CNC machine tool with the NCS implementation.

1. INTRODUCTION

In modern industries, because 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) (Zhang et al., 2001; Walsh et al., 1999). 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 (Lian et al., 2002). Recently, different approaches were proposed for NCS to mainly compensate for the time-delay effect like the gain scheduling PI control (Tipsuwan et al., 2004), scheduling and control co-design (Lu et al., 2004), and so on.

A general network system is basically an event-triggered system and the time delay is mainly concerned. 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 (Hsieh et al., 2005). 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 (Hsieh et al., 2006). A Markov chain with two states treated as the vacant sampling can be applied to model the data dropout in a stochastic nature (Nilsson, 1998). Moreover, to handle the data dropout, there are two approaches: (1) using the past control signals to estimate the lost data (Ling et al., 2002) and (2) including the estimator which based on the power spectral density of NCS output signals (Ling et al., 2003; 2004).

In this paper, a motion message estimator is proposed to significantly reduce the data-dropout effect in NCS. Simulation results indicate that a 3rd-order message estimator based on the Taylor expansion can suppress the uncertainties of the NCS. Furthermore, this paper also proposes the networked CCC structure to improve the contouring error of the multi-axis NCS. Simulation results indicate that the variation of contouring accuracy of the multi-axis NCS is suppressed greatly by applying the proposed networked CCC. Moreover, the proposed motion NCS has been successfully realized on a DYNA MTYE 1007 CNC machine tool to improve it motion accuracy.

2. NCS DATADROPOUT

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.

978-1-1234-7890-2/08/$20.00 © 2008 IFAC 10.3182/20080706-5-KR-1001.3643

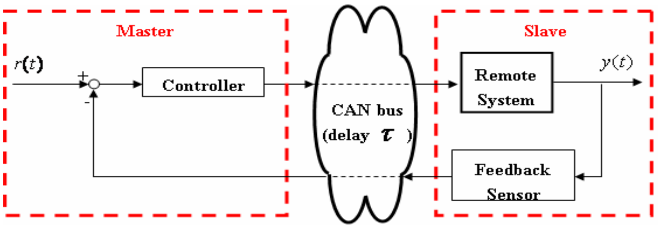


Fig. 1. Networked control systems

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. Therefore, this paper focuses on compensating the effect of the measurement data dropout. To model the data dropout in transmitting the feedback message data, 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 $d[n]=1$. The transmitted feedback signal $\bar{y}[n]$ is modeled as

$$\begin{cases} \bar{y}[k]=y[k], & \text{if } d[k]=0 \\ \bar{y}[k]=0, & \text{if } d[k]=1 \quad \Leftarrow \text{ dropout} \end{cases} \tag{1}$$

Experimental results with an 1 ms sampling period and a 500K bit/s transmission rate are shown in Fig. 2. Results indicate that the data dropout 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. 3 and the NCS can be expressed as in the following:

$$\begin{cases} \bar{y}[k]=y[k], & \text{if } d[k]=0 \\ \bar{y}[k]=\hat{y}[k], & \text{if } d[k]=1 \quad \Leftarrow \text{ compensated dropout} \end{cases} \tag{2}$$

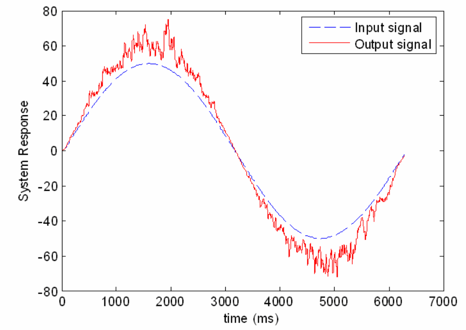


Fig. 2. Experimental results with data dropout rate = 19.97%

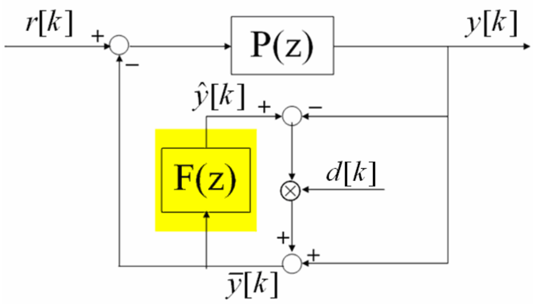


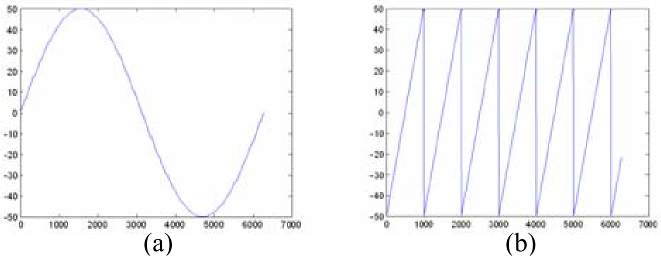
Fig. 3. NCS with the dropout compensator (Ling et al., 2004)

3. MOTION MESSAGE ESTIMATORS

Based on the structure shown in Fig. 3, the output of a message estimator will estimate the missing message when the dropout happens as in Eq. (2). The missing messages can be thus recovered to some extents 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 (Ling et al., 2002). 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 thus limited.

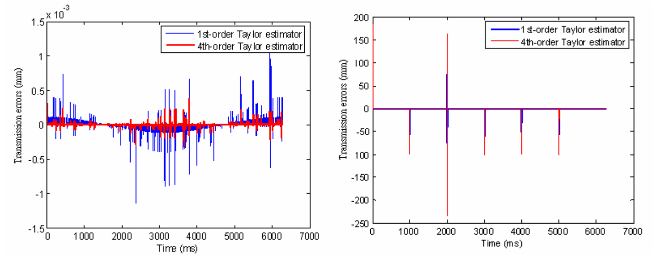
3.1 The order of the estimator

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. 4 with different dynamic natures. Fig. 5 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. So 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. 6 indicate that the 3rd-order Taylor message estimator is more suitable in real applications by concerning different motion commands.



(a) (b)

Fig. 4. Motion commands with (a) smooth variation, (b) Significant variation



(a) smooth variation (b) significant variation

Fig. 5. Simulation results with the Taylor message estimator

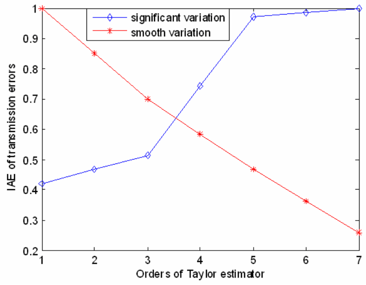


Fig. 6. Analysis of compensation effects with different order

3.2 3^{rd}-order Taylor message estimator

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

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

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

$$\hat{P}(k) = P(k-1) + \hat{v}_{k-1} \tag{4}$$

By combining Eq. (3) and Eq. (4), the estimated current result from the past four sequential messages is obtained as

$$\hat{P}(k) = \frac{21}{8}\cdot P(k-1) - \frac{19}{8}\cdot P(k-2) + \frac{7}{8}\cdot P(k-3) - \frac{1}{8}\cdot P(k-4) \tag{5}$$

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

$$F(z) = \frac{21}{8}z^{-1} - \frac{19}{8}z^{-2} + \frac{7}{8}z^{-3} - \frac{1}{8}z^{-4} \tag{6}$$

4. SIMULATION RESULTS

4.1 Noise command signals

In the simulation analysis, the NCS structure shown in Fig. 3 was built on Matlab. The dynamic model of the DYNA CNC machine tool obtained from the system identification procedure was adopted as

$$P(z) = \frac{\begin{pmatrix} 0.30554z^{-2} - 0.023766z^{-3} + 0.11104z^{-4} + 0.028834z^{-5} \\ - 0.012243z^{-6} + 0.020811z^{-7} - 0.089113z^{-8} \end{pmatrix}}{1 - 0.70669z^{-1} + 0.1934z^{-2} - 0.15112z^{-3} - 0.02566z^{-4} + 0.028011z^{-5}}$$

Moreover, three different message estimators were implemented for verifying the noise reduction and control performance as: (1) the 1-delay estimator, $F(z) = z^{-1}$, (2) the optimal estimator ((Ling et al., 2003; 2004)), and (3) the proposed 3^{rd}-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. 7 indicate 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 3^{rd}–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.

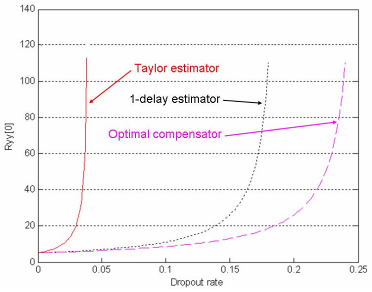


Fig. 7. Output PSD with white noise input

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 third-order Taylor expansion is suitable to represent most the basic CNC motion commands. Here, a sinusoidal wave in 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. 8. Simulation results indicate that by applying the optimal dropout compensator, it 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 3^{rd}-order Taylor message estimator results in the best control performance when the dropout rate is as high as to 50%.*

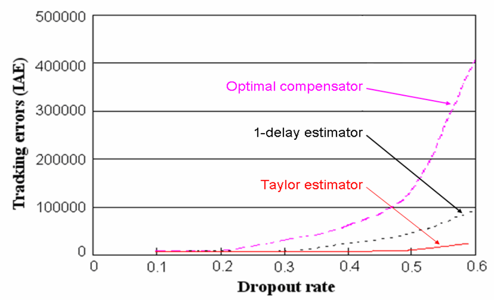


Fig. 8. Tracking accuracy of different message estimators

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 (Gopi et al., 1997). 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 follows:

$$C(p)=\frac{\sum_{i=0}^{n} Z_{i,k}(p)\psi_i V_i}{\sum_{i=0}^{n} Z_{i,k}(p) W_i}=\sum_{i=0}^{n} R_{i,k}(p) V_i \qquad (7)$$

and

$$R_{i,k}(p)=\frac{Z_{i,k}(p)\psi_i}{\sum_{i=0}^{n} Z_{i,k}(p)\psi_i} \qquad (8)$$

where V_i is the control points; ψ_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 kth order B-spline basis function; $R_{i,k}(p)$ is the rational basis function. With the circular commands and the butterfly commands (Yeh et al., 1999), Fig. 9 show that the proposed motion estimator can significantly improve control performance as data dropout occurs.

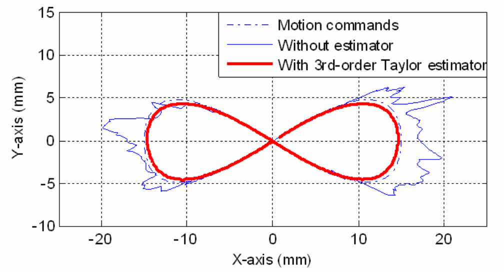


Fig. 9. NURBS simulation results as $\varepsilon = 19.97\%$

4.3 The Networked CCC Structure

In multi-axis motion control systems, the cross-coupled control (CCC) is particularly applied to improve motion contouring accuracy in practice, as shown in the Fig. 10 (Yeh et al., 2002; 2003). By applying CCC, the contouring accuracy of systems will greatly improve, when the CCC gain increases, as shown in the Fig. 11. However, the phase margin and the gain margin will degrade with increasing the CCC gain value as shown in the Fig. 12. Moreover, it will be worst in NCS. Fig. 13 shows the maximum of contouring errors will be significantly increased in higher CCC gain when the data dropout happens. Therefore, the CCC needs to modify to suitably apply in the NCS.

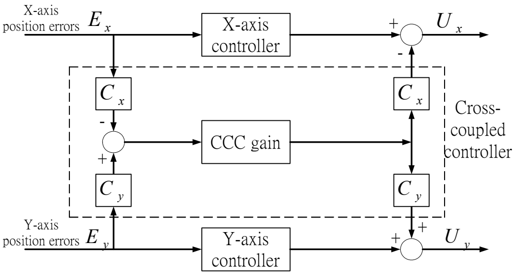


Fig. 10 The Cross-coupled control structure.

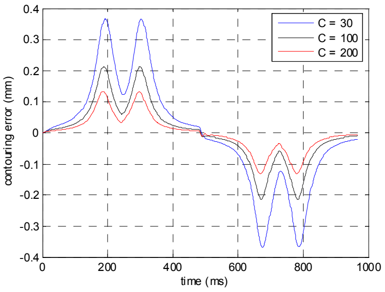
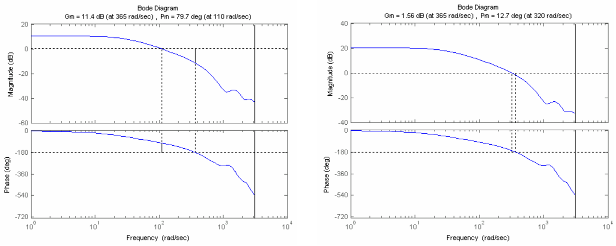


Fig. 11 The contouring error with different CCC gain.



(a) *(b)*

Fig. 12. The gain and phase margin in different CCC gain value (a) CCC gain = 100(GM = 11.4 dB, PM = 79.7 deg), (b) CCC gain = 200(GM = 1.56 dB, PM = 12.7 deg)

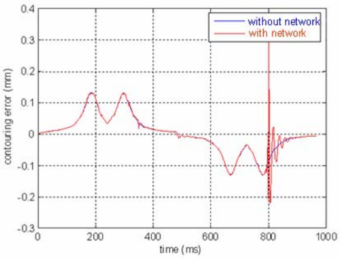


Fig. 13 contouring errors with network and w/o network (CCC gain = 200)

This paper proposes the robust CCC structure to improve the stability and the accuracy of NCS. The curvature of the trajectory is adopted as an index to choose the CCC gain value. The curvature of the trajectory is estimated as shown in the following:

$$K = \frac{|y''|}{(1+y'^2)^{3/2}}$$

The curvature is applied to decide the suitable CCC gain. The simulation result is shown in the Fig. 14. The robust CCC and the fixed CCC with higher gain has almost the same contouring accuracy. Furthermore, the data dropout rate will be added in simulation to test the stability of NCS. The simulation results, as shown in the Fig. 15, shows that the robust CCC owns the best contouring accuracy in NCS. However, the proposed robust CCC would be suitable to apply in the NCS to improve the stability and the contouring accuracy of the NCS.

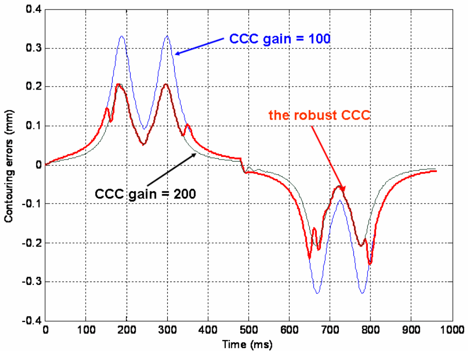


Fig. 14 Contouring errors comparison with CCC gain =100, CCC gain = 200 and the robust CCC

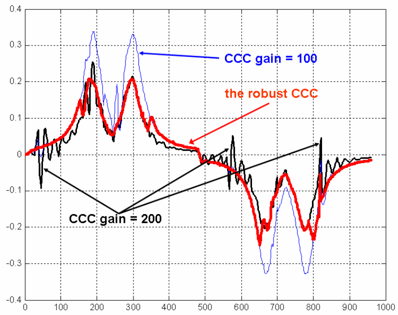


Fig. 15 Contouring errors comparison with CCC gain =100, CCC gain = 200 and the robust CCC with data dropout rate = 19.97%

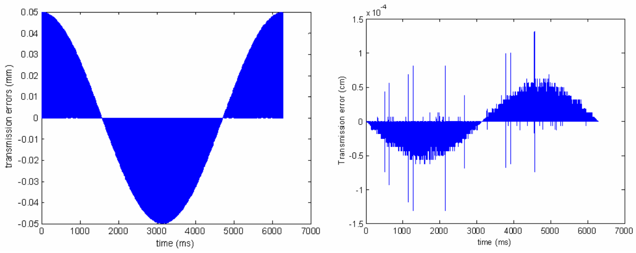
5. EXPERIMENTAL RESULTS

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. For the controller area network (CAN) bus, Table 1 shows all measured dropout rates with three different transmission rates and two sampling periods. Experimental results indicate that the dropout rate significantly decreases as the sampling period increases. Note that in real applications, the control performance of the system also degrades as the sampling period increases in general. To select a proper sampling time for the NCS in real applications, it is a trade-off by concerning both the network transmission and the control performance. The proposed message estimator will be applied to improve NCS performance even with a short sampling period by dealing with the data-dropout effect. In a real plant without applying the message estimator, a sinusoidal command was provided with a CAN transmission rate at 250K bit/s and the missing message transmission error at every sampling period 1 ms was recorded as shown in Fig. 16 (a). Experimental results as shown in Fig. 16 (b) indicate that the proposed 3rd-order Taylor message estimator effectively reduces the network transmission error around $\frac{1}{100}$.

Table 1. The data dropout rate of CAN bus transmission rate

Transmission rate	Dropout rate $T = 2\ ms$	Dropout rate $T = 1\ ms$
1M *bit/s*	0.48%	0.49%
500 *bit/s*	0.51%	19.97%
250 *bit/s*	20.21%	42.14%



(a) (b)

Fig. 16 Transmission error (a) without message estimator, (b) with Taylor message estimator

5.2 CNC applications

Furthermore, the proposed 3^{rd}*–order Taylor message estimator and the controller were applied to the DYNA MTYE 1007 CNC machine in a NCS structure, as shown in Fig. 17. The sinusoidal message with the position amplitude 50 mm under the feedrate 3000 mm/min are adopted as a input command. 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. 18. By applying the proposed Taylor message estimator, the motion NCS not only becomes more stable but also greatly reduces the tracking error.*

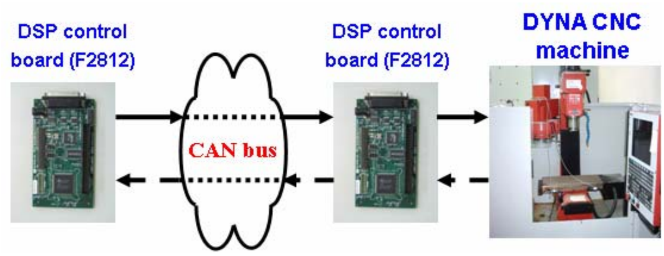


Fig. 17 Experimental setup

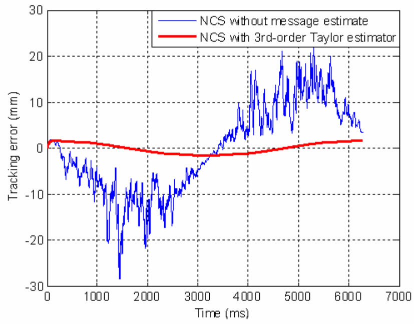


Fig. 18 Experimental results with/without the message estimator.

6. 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 NCS structure containing a 3rd-order Taylor message estimator is successfully applied to the motion NCS to improve the control performance significantly. Fig. 18 indicates that the 3rd-order Taylor message estimator improve tracking accuracy in an industrial CNC machine tool. In the future, the proposed CCC and the 3rd-order Taylor message estimator will be applied to CNC machine tools to realize the high-speed-high-precision multi-axis NCS.

ACKNOWLEDGEMENTS

This work was supported by National Science Council of the Republic of China under the Contract NSC 95-2221-E-009 - 100 -MY2

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