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Experimental verification of a delay compensation algorithm for integrated communication and control systems

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Advances in the technology of complex control systems demand high-speed and reliable communications between the individual components and subsystems for decision making and control. This can be accomplished by integrated communication and control systems which use asynchronous time-division-multiplexed networks. Unfortunately, these networks introduce randomly varying distributed delays as a result of time-division multiplexing. A predictor–controller algorithm has been developed with the objective of mitigating the detrimental effects of the network-induced delays that are distributed between the sensor(s), controller and actuator(s) within a control loop. This paper presents the implementation and verification of the above delay compensation algorithm. Performance of the delay compensator has been experimentally verified on an IEEE 802.4 network testbed for velocity control of a d.c. servomotor.

1. Introduction

Complex dynamical systems, such as advanced aircraft and spacecraft, autonomous manufacturing processes, and nuclear power plants, require reduction of direct human intervention in control and decision-making processes and its replacement by hierarchical levels of automatic control (Åström *et al.* 1986) as much as practicable. On the other hand, a distributed intelligent control system requires extensive interactions between its subsystems and components. Such interactions, if the devices are not collocated, can be efficiently carried out via an asynchronous time-division-multiplexed data communication network. This concept of integrated communication and control systems (ICCSs) has already been adopted in aeronautics and astronautics (Ray 1987), computer-integrated manufacturing (CIM) (Ray 1988 b, Ray and Phoha 1989) and is being actively pursued for integrated control of chemical processes (Ray 1988 a), nuclear power plants (Edwards and Ray 1990) and future generation automobiles (Kiencke 1988).

This paper presents the experimental verification of a delay compensation scheme for ICCSs with identical sensor and controller sampling rates. The proposed delay compensator is intended to alleviate the detrimental effects of network-induced delays by using a multistep predictor–controller. The key idea in the compensator design is to monitor the data when it is generated and to keep track of the delay associated with it. With this knowledge, a control algorithm has been formulated to maintain the delay constant as seen by the controller. Therefore the closed-loop control system can be treated as finite

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dimensional, linear, time invariant and deterministic provided that the plant, observer and controller are deterministic. Therefore, in contrast with a stochastic control system as reported in our earlier publications (Liou and Ray 1991 a, b, Ray *et al.* 1993), the proposed delay-compensated system can be conveniently analysed and synthesized using the standard time-domain and frequency-domain tools.

The major assumption in the above multistep delay compensation algorithm is that the (network-induced) randomly varying delays are bounded. This assumption is justified in view of the facts that firstly networks are designed such that the offered traffic bears a safe margin relative to its critical value (Ray (1987, 1988 a) and secondly any unbounded delay would render the feedback loop open. Therefore, having specified a confidence level, an upper bound can be assigned to each of the distributed randomly varying delays. The number of the delayed steps is then determined from these bounds. An observer feeding upon the delayed measurements can be used to estimate non-delayed inputs into the controller. Although the compensated system may use the original control law that was designed for the system without being subjected to induced delays, it is logical to tune the controller gain matrices to enhance robustness of the delay-compensated system (Shen and Ray 1993).

2. The observer-based delay compensator

The sensor, controller and actuator are assumed to have identical sampling rates. Furthermore, we assume the sensor, actuator and controller to be synchronized, that is the time skew between their sampling instants is maintained at zero. Although the problem of synchronizing a distributed network is quite complex and yet to be solved, we have adopted a rather simple approach of using a high-priority signal at prescribed intervals to reset the respective sensor or actuator and controller clocks and to maintain a loose synchronization between the sensor, controller and actuator. Under these conditions, the plant dynamics of the delayed system at the sample time k are modelled as

$$x_{k+1} = Ax_k + Bu_{k-\Delta_1} \quad \text{(plant dynamics with delayed control)} \tag{1}$$

$$y_k = Cx_k \quad \text{(sensor measurement)} \tag{2}$$

$$z_k = y_k - \Delta_2 \quad \text{(delayed output)} \tag{3}$$

$$u_k = x(z_k) \quad \text{(control function)} \tag{4}$$

where $x \in R^n$, $u \in R^s$ and $y \in R^m$, and the matrices A, B and C are of compatible dimensions; the finite non-negative integers Δ_1 and Δ_2 represent the number of delayed samples in control inputs and measurements respectively. The control law u_k is a linear function of the history $Z_k = \{z_k, z_{k-1}, \ldots\}$ of the delayed sensor data. The objective is to obtain a control function that mitigates the detrimental effects of the induced delays on the control system performance.

Several investigators have addressed the problems of delay compensation in closed loop control systems. An intuitive approach (Isermann 1981) is to augment the system model to include delayed variables as additional states. Unfortunately, this approach renders some of the states uncontrollable even if the original system is completely controllable (Marianni and Nicoletti 1973, Drouin *et al.* 1985). For the case of delayed control inputs, Pyndick (1972) proposed a predictor for the optimal state trajectory based on past control inputs. Zahr and Slivinsky (1974) considered the problem of controlling a computer-controlled system with measurement and computational delays. In their approach the state transition matrix is used in conjunction with the delayed state measurements to obtain an estimate of the present state of the system. It was pointed out that the delays in multivariable systems may result in

(i) an increase in the magnitudes of the transients, and poor response during the intersampling time;
(ii) loss of decoupling between individual single-input single-output control loops although decoupling may be restored for a stable process at the steady state and
(iii) a possible decrease in stability margin.

Their algorithm was verified by simulation but the use of an asymptotic observer was not discussed.

The approach of Zahr and Slivinsky (1974) for compensation of constant delays that affect the input or output variables of a system consists in predicting the current system output. However, if the state transition matrix is used to predict the output, the plant state variables must be obtained first. Moreover, the output measurements might be corrupted with noise. An observer can be used for estimation of the delayed states and then the state transition matrix can be used to predict the current state. This multistep observer imposes additional dynamics, and hence a phase lag in the control system, which is not always desirable; nevertheless, such a sensitive system is likely to be unstable when it is subjected to delays.

The observer parameters can be selected to attenuate high-frequency noise in the measurements. If the measurement noise is considerable, the proposed algorithm could be extended to include a stochastic filter (Anderson and Moore 1979) instead of a deterministic observer. Also, a reduced order observer or a functional observer (Kailath 1980, Chen 1984) can be used to reduce the observation lag.

The basic equations used in the multistep delay compensation scheme, proposed earlier by Luck and Ray (1991), whose implementation and verification are presented in this paper are delineated below:

plant model:

$$x_{k+1} = Ax_k + Bu_k; \quad y_k = Cx_k \tag{5}$$

observer model:

$$z_{k+1/1} = Az_{k/1} + Bu_k + L_k(y_k - Cz_{k/1}) \tag{6}$$

p-step predictor:

$$z_{k+1/p} = Az_{k/p-1} + Bu_k \quad \text{for } p \geqslant 2 \tag{7}$$

predictive control:

$$u_k = \Gamma_k z_{k/p} \tag{8}$$

where

$$\begin{aligned} z_{k/r} &:= \hat{x}_{k|k-r} \\ &= \text{prediction of } x_k \text{ based on the measurement history } \{y_{k-r}, y_{k-r-1}, \ldots\} \end{aligned} \tag{9}$$

A block diagram for the above predictor–controller algorithm is shown in Fig. 1, and its functionalities are explained as follows. First, using a specified confidence interval, an upper bound can be assigned to each of the distributed randomly varying delays Δ_1 and Δ_2. These bounds are denoted r and q units of sampling period respectively. The observer is designed such that, at sample instant k, it feeds upon a sensor measurement generated at sample instant $k - r$. If more fresh sensor data are available, it has to be kept in a first-in first-out buffer for later processing. This guarantees a constant sensor delay as seen by the observer. Using the delayed data the observer (6) estimates $z_{k-r+1/1}$. Next, the state variable model of the plant is used in (7) recursively on $z_{k-r+1/1}$, to obtain a prediction of the plant state at the sampling instant $k + q$, that is $z_{k+q/r+q}$. The control output obtained using this prediction is $u_k = \Gamma_{k+q} z_{k+q/r+q}$. A first-in first-out buffer of size q is used at the actuator terminal.

Although the implementation of (5)–(9) in the delay compensation algorithm is apparently a straightforward task, it must be shown that the resulting closed-loop control system is stable or that the controller and observer dynamics can be selected separately as it is for the well known standard observer–state feedback control loop. The main hindrance in verifying separation of controller and observer dynamics is the inclusion of the predictive equation (7). Luck and Ray (1991) have shown that the resulting closed-loop equations can be expressed as

$$\begin{bmatrix} x_{k+1} \\ e_{k-p+1} \end{bmatrix} = \begin{bmatrix} A + B\Gamma_k & -B\Gamma_k \theta_k \\ 0 & (A - L_{k-p}C) \end{bmatrix} \begin{bmatrix} x_k \\ e_{k-p} \end{bmatrix} \tag{10}$$

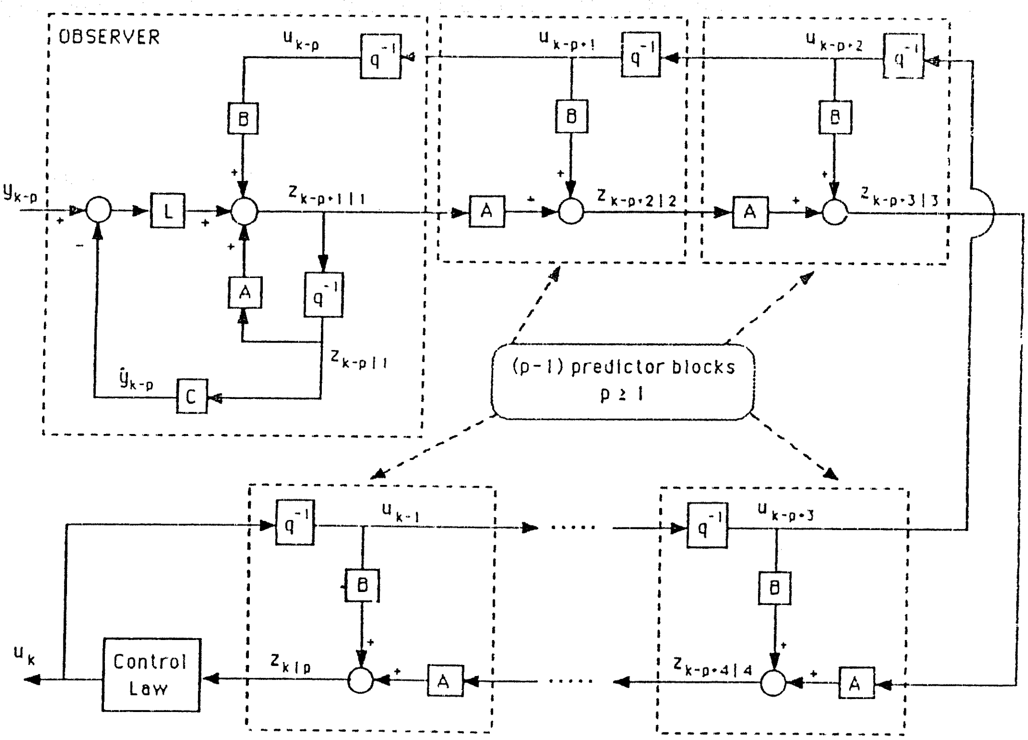

Figure 1. Schematic diagram of a p-step delay compensation algorithm.

where

$$e_k := x_k - z_{k/1} \tag{11}$$

and

$$\theta_k = \begin{cases} \prod_{j=1}^{p.}(A - L_{k-p+j-1}C) + \sum_{i=1}^{p-1}\left(A^{i-1}L_{k-i}C\prod_{j=1}^{p-i}(A - L_{k-p+j-1}C)\right) & \text{if } p \geqslant 2 \\ \mathrm{I} & \text{if } 0 \leqslant p < 2 \end{cases} \tag{12}$$

If $L_k = L$ and $\Gamma_k = \Gamma$, that is if the observer and controller gain matrices are constant, then (10) determines the stability of the compensated system due to separation of the controller and observer, and that the delays do not affect the closed-loop dynamics in the absence of modelling uncertainties. However, if modelling uncertainties are present, it can be readily shown by following the approach of Thau and Kestenbaum (1974) that the order of the closed-loop control system increases significantly. For instance, modelling errors in matrices A, B and C induce a fourfold increase over the order of the augmented system matrix in (10) if a two-step delay is assumed (Luck and Ray 1991). However, by neglecting the modelling errors in the matrix B, the order of the augmented system is doubled by modelling errors in matrices A and C.

Loss of sensor and control data is not accounted for in the delay compensation algorithm. However, if the network recurrently loses data, the plant may be rendered unobservable or unreachable. Under these circumstances, the notion of observability (reachability) can be extended as shown by Luck *et al.* (1991). If the plant satisfies the condition of this extended observability (reachability) under recurrent loss of sensor (control) signals, then the delay compensator may still function in a possibly degraded mode. Performance analysis of the delay compensator under recurrent loss of data is addressed in this paper; it is also a subject of future research.

3. Performance verification of the delay compensation algorithm

Performance of the constant-delay compensation algorithm, described in the previous section, has been verified by experimentation with closed-loop velocity control of a d.c. servomotor. The motor assembly is connected to a microcomputer through an analogue-to-digital (A/D)–digital-to-analogue (D/A) interfacing board. The efficacy of the delay compensation algorithm is examined by comparing the performance of a proportional–integral (PI) controller without delay compensation against that of the same controller with delay compensation.

The experiment has been conducted in two phases:

(i) checking the performance of the proposed delay compensation algorithm when the sensor data is simply delayed by a multiple of sampling periods;

(ii) examining the performance of the compensation algorithm in the presence of data rejection and vacant sampling (i.e. no new sensor data arrival at the controller during a sampling interval).

3.1. *The plant model*

The plant under control is a constant-excitation d.c. servomotor assembly that is modeled as a first-order linear time-invariant system. Such a model is consistent with the standard approach for velocity control of a constant-excitation d.c. motor. The time constant of the motor was experimentally identified to be 1·7 s. The steady-state characteristics of the motor–tachogenerator combination were determined from experimental data as

$$\omega = \begin{cases} KV - b & \text{for } V < \dfrac{b}{K} \\ 0 & \text{for } -\dfrac{b}{K} \leqslant V \leqslant \dfrac{b}{K} \\ KV + b & \text{for } V < -\dfrac{b}{K} \end{cases} \tag{13}$$

where ω is the velocity in radians per second, V is the control input in volts, $K = 3{\cdot}33 \text{ rad s}^{-1}\text{V}^{-1}$; and $b = 11{\cdot}3 \text{ rad s}^{-1}$.

A linear model of the plant dynamics is obtained by neglecting the bias term, that is by setting b equal to zero in (12). A weak integral action was used to compensate for the possible steady-state error due to Coulomb friction and other modelling errors.

3.2. *Verification of the delay compensation algorithm*

In this phase of the experiment the d.c. motor assembly is interfaced to a microcomputer. A constant delay in the sensor data is generated by storing the incoming data from the A/D converter into a first-in first-out buffer. Upon initialization, the contents of the buffer is set equal to the first measurement, that is the system is assumed to be at steady state. Newly arrived data from the A/D converter are pushed into the buffer, and data for the controller are popped out of the buffer. The resulting delay in the sensor data is equal to the capacity of the buffer.

Figures 2–6 compare the responses of the observer-based control system with those of the control system without the observer under different settings of the induced delay. The controller and observer poles are set at $z = 0{\cdot}5 \text{ s}^{-1}$ and $z = 0{\cdot}15 \text{ s}^{-1}$ respectively, the gain of the PI controller is $1{\cdot}5 \text{ V rad}^{-1}\text{ s}$, and the sampling period is set at 0·3 s. The maximum input to the motor is restricted to 10 V to avoid any potential damage; this corresponds to motor angular velocity of about 22 rad s^{-1} at steady state.

As expected, the performance of the system with the observer is comparable with that without the observer for the zero-delay case as seen in Fig. 2. The observer-based controller produces a small steady-state error because the integrator acts upon the estimate of the state and not on the true system output. It is the bias term in the plant response that prevents the observer from perfectly tracking the system output. A brief description of the arrangement for bias compensation is presented below.

Uncertainty in the model parameters of continuous-time systems with zero eigenvalues will invariably yield a steady-state estimation error (Thau and Kestenbaum 1974). A constant bias can be interpreted as a mode with a zero

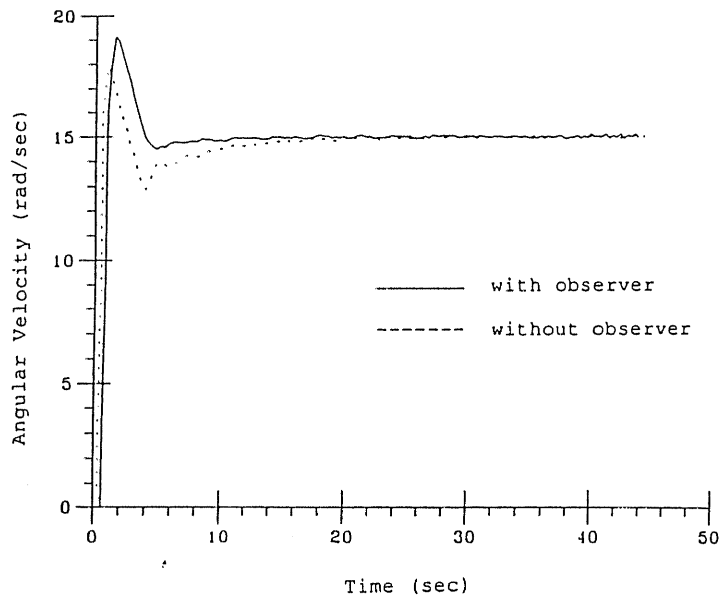

Figure 2. Dynamic response of the motor (emulated delay, 0; reference velocity, 15 rad s^{-1}).

eigenvalue. It is possible to estimate the bias by including it as an additional state variable in the system model (Isermann 1981). The tracking properties of the observer can also be improved by providing it with well structured information about the plant nonlinearities. For instance, the input to the observer can be modified as follows:

$$u_{\mathrm{obsv}} = \begin{cases} u_{\mathrm{cntrl}} - \dfrac{b}{K} & \text{if } u_{\mathrm{cntrl}} > \dfrac{b}{K} \\ 0 & \text{if } |u_{\mathrm{cntrl}}| \leqslant \dfrac{b}{K} \\ u_{\mathrm{cntrl}} + \dfrac{b}{K} & \text{if } u_{\mathrm{cntrl}} < -\dfrac{b}{K} \end{cases}$$

where u_{obsv} is the modified input to the observer and u_{cntrl} is the actual input to the d.c. motor. This modification mimics the nonlinearities in the motor by adding information about the bias to the observer without increasing the order of the observer. Selected results of experimentation, to be presented next, indicate that the steady-state tracking errors are almost eliminated in the modified observer.

Figures 2–4 show comparisons of the dynamic responses of the delay compensated system using the modified observer input and the traditional PI controller for different delays. The controller and observer poles were set at $z = 0{\cdot}1$ and $z = 0{\cdot}0$ respectively, the gain was 0·09 V rad^{-1} s, and the sampling period was set at 0·3 s. The above-mentioned parameter settings were found to yield reasonably good system responses for different delays. The responses of the delay-compensated system are less oscillatory than those of the uncompensated system for delays of one and two sampling periods.

The motor halts at speeds below 12 rad s^{-1} because of the deadband nonlinearity. This causes a jerky response of the system when the control

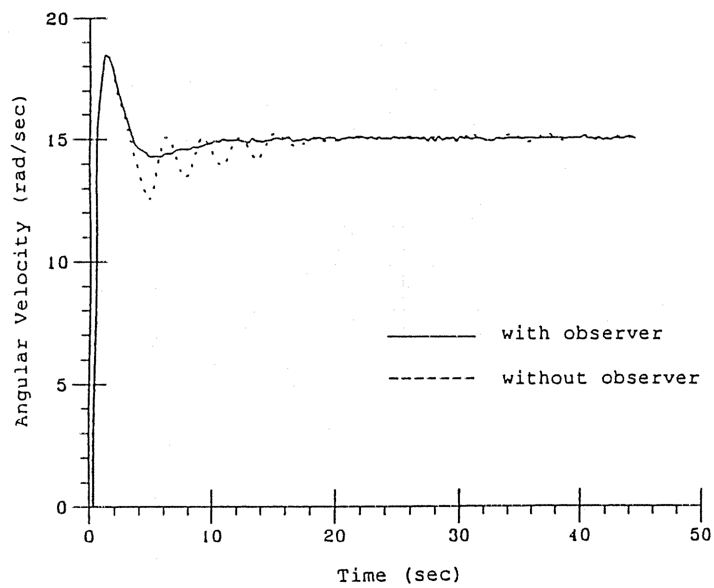

Figure 3. Dynamic response of the motor (emulated delay, T; reference velocity, 15 rad s^{-1}).

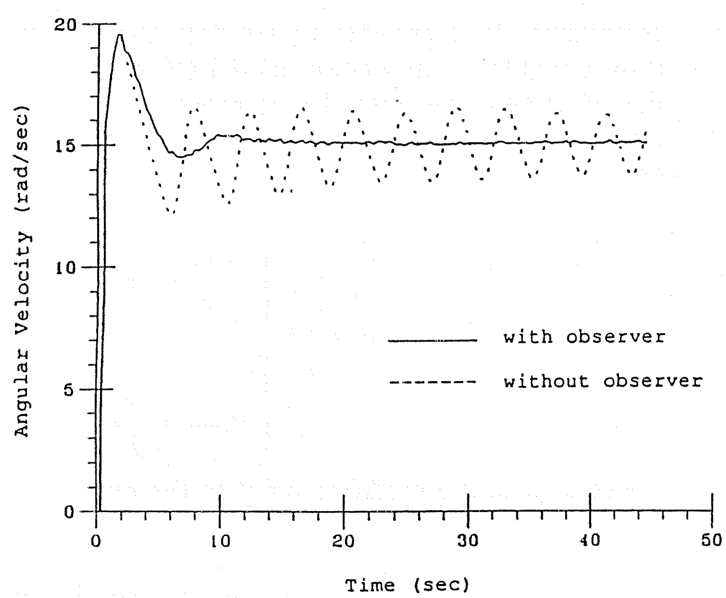

Figure 4. Dynamic response of the motor (emulated delay, $2T$; reference velocity, 15 rad s^{-1}).

reference is set close to 12 rad s^{-1} as seen in Fig. 5. In general, it was observed that the responses of both compensated and uncompensated systems improve regardless of the size of the delay as the magnitude of the reference input is increased. This is expected because, as the reference speed is increased, the effect of Coulomb friction is diminished. Since the plant under test is nonlinear, the dynamic characteristics of the control system are a function of the reference input. As a result of the nonlinearities, limit cycles appear in the uncompensated system response as seen in Fig. 5. The predictive properties of the observer-

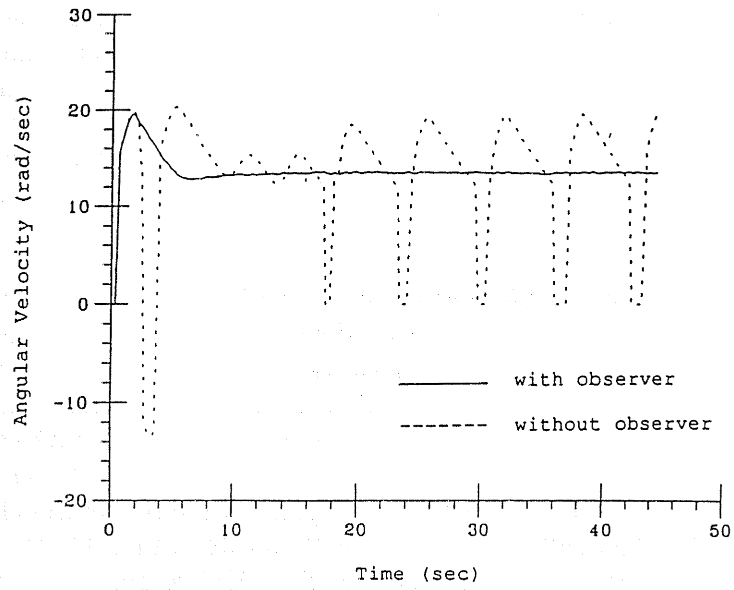

Figure 5. Dynamic response of the motor (emulated delay, $2T$; reference velocity, $13\cdot5\ \mathrm{rad\,s^{-1}}$).

based control algorithm largely alleviates this limit cycle problem for delays of one or two sampling periods.

Figure 6 shows that, with a larger delay of three sampling periods, the compensated system response does exhibit a limit cycle which is of lower magnitude (three times smaller) and higher frequency (three times faster) than that of the uncompensated system. However, it is important to realize that a delay of three sampling periods, in this case, is approximately half the time

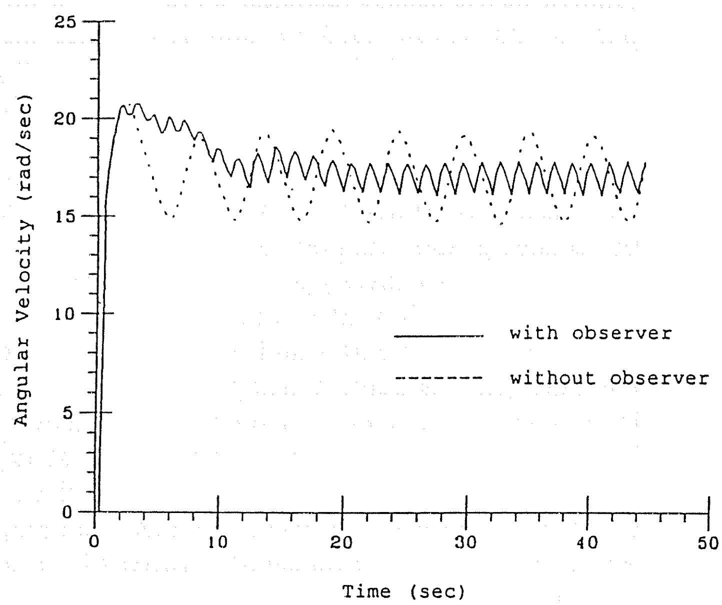

Figure 6. Dynamic response of the motor (emulated delay, $3T$; reference velocity, $17\ \mathrm{rad\,s^{-1}}$).

constant of the d.c. motor, and that the controller cannot compensate for disturbances affecting the continuous plant during the sampling interval nor during the delay period. Considerable deterioration of the closed-loop response should be expected with an increase in the delay. This reveals a weakness of the constant-delay compensation algorithm since fresh information about the effect of disturbances may be forced to wait in the buffer for later processing.

3.3. *Verification of the delay compensation algorithm on a network testbed*

In the second experimental setup, the d.c. motor assembly is controlled using a communication network. The experiments were conducted with a 10 $\mathrm{Mbits\,s^{-1}}$ network testbed which uses the IEEE 802.4 linear token passing bus and IEEE 802.2 logical link control protocols in an ISO compatible network architecture including the transport protocol (MAP/TOP Users' Group 1987).

The testbed is equipped with three terminal interface units, and five host computers that can communicate with each other via the network medium or directly, using a pair of RS 232C communication ports. For the test setup, the plant under consideration consists of a tachogenerator and a servomotor which serve as the sensor and the plant respectively and are connected to a microcomputer in the network. Another microcomputer serves as the controller.

A traffic load generator emulates the scenario of a large number of stations and varying traffic on the network by use of only two terminal interface units. The locations of all odd-numbered stations are emulated on the microcomputer host 1 and those of even-numbered stations on the microcomputer host 2; the two microcomputers communicate with each other via the network. The host 1 also provides the A/D and D/A conversion functions for the tachogenerator and the servomotor and is designated as station 1 in the logical ring. The controller is located at host 2 and could be designated with any even station number, that is the controller station can be hosted in different positions in the logical ring relative to the sensor–actuator station. Since the host 2 functions as an integral part of the traffic load generator, another microcomputer host 3 is directly connected to host 2. This host 3 provides a multiprocessing environment for host 2. The control algorithm is resident in host 3. The complete arrangement is shown schematically in Fig. 7.

Identical sensor and controller sampling periods of 0·3 s are considered, and the sensor–controller time skew Δ_s is set to zero. The network traffic is varied by changing the number of stations in the network. The purpose of the experiment is to investigate the performance and robustness of the proposed delay compensation algorithm to vacant sampling and data rejection. The controller receiver buffer and the sensor transmitter buffer are of size one. Since the time skew is zero, a delay of at least one sampling period is ensured. By increasing the number of stations in the network, the sensor-to-controller data latency is increased. However, if the data latency exceeds one sampling period, vacant sampling (i.e. no sensor data arrival during a sampling interval) at the controller station could occur. In this situation, some of the sensor data may also be rejected at the transmitter buffer of the sensor terminal.

The controller pole and observer poles were placed at $z = 0{\cdot}5$ and $z = 0{\cdot}15$ respectively. The gain was set at $0{\cdot}15\ \mathrm{V\,rad^{-1}\,s}$. For all cases, the dynamic response of the compensated system was superior to that of the uncompensated

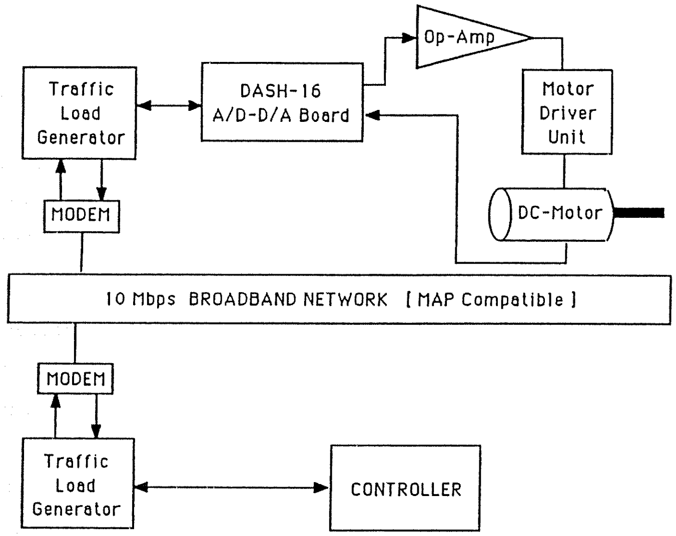

Figure 7. Experimental setup at the network testbed facility.

system. The compensated system response yielded a steady-state error which can be reduced as discussed before by augmenting the order of the observer to include an estimation of the bias or by incorporating *a-priori*-obtained bias information through the observer input. Typical results are shown in Fig. 8. Both compensated and uncompensated systems were less sensitive to data rejection and vacant sampling, when the controller pole was set closer to unity. On the other hand, bringing the controller pole close to unity results in a sluggish system response. Optimal design of the compensated control system has not been addressed in this paper; it is a subject of further research.

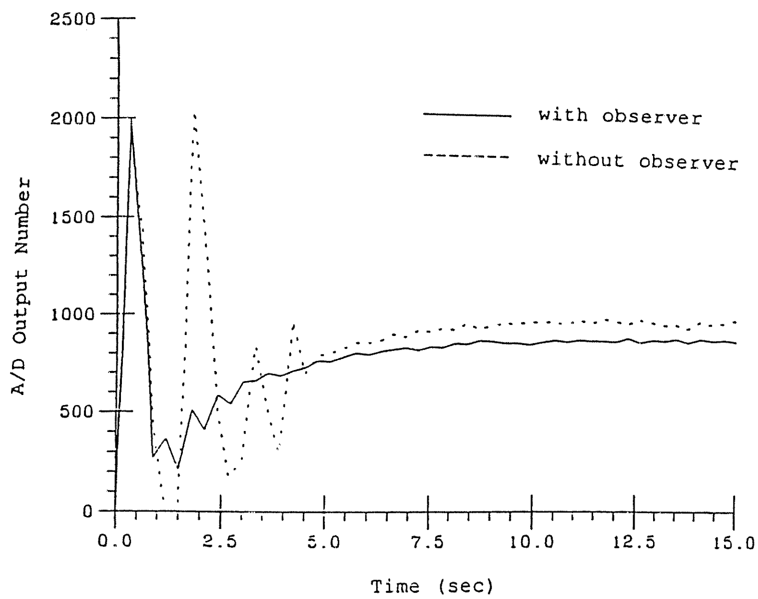

Figure 8. Dynamic response of the motor number of stations in the network, 30; network induced delay, T; reference velocity, 18 rad s^{-1}.

3.4. *Simulation of a flight control system*

The dynamic performance of the delay compensator has also been examined by combined discrete-event and continuous-time simulation of the flight control system of an advanced aircraft that uses the SAE linear token passing bus for data communications. The simulation was conducted in the combined discrete-event and continuous-time setting with real-time event scheduling.

Simulation results were generated under the following conditions.

(1) There are 31 terminals that share the network medium.
(2) Traffic is periodic with a sampling period of 50 ms for all terminals.
(3) Terminal 1 operates as both sensor and actuator terminals with its transmitter queue serving the sensor and its receiver queue serving the actuator.
(4) Terminal 2 operates as the controller terminals with its transmitter queue handling actuator commands and its receiver queue handling sensor data.
(5) Terminals 1 and 2 have fixed message lengths with information part $L = 64$ bits.
(6) Every terminal, except the controller, *simultaneously* receives a message at the beginning of the sample.
(7) The terminals 3–31 have identical message lengths which are varied to regulate the traffic in the network.
(8) The controller and actuator are collocated, that is the controller output, from terminal 2, is directly connected to the actuator input, that is terminal 1.
(9) The following two alternative protocols can be selected in the simulation program: IEEE 802.4 token bus (10 Mbits s^{-1} data transmission rate); SAE linear token passing bus using optical fibre medium (100 Mbits s^{-1} transmission rate).

The state variable model of the plant, excluding the sensor data conversion factor of $180/\pi$, is described below. The motion dynamics are given by

$$\begin{bmatrix} \dfrac{d\delta_e}{dt} \\ \dfrac{dW}{dt} \\ \dfrac{dQ}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{\tau_e} & 0 & 0 \\ Z_{de} & Z_w & Z_q + U_0 \\ S_1 & S_2 & S_3 \end{bmatrix} \begin{bmatrix} \delta_e \\ W \\ Q \end{bmatrix} + \begin{bmatrix} \dfrac{1}{\tau_e} \\ 0 \\ 0 \end{bmatrix} u$$

The output equation is

$$\begin{bmatrix} \alpha \\ A_n \\ Q \end{bmatrix} = \begin{bmatrix} 0 & \dfrac{1}{U_0} & 0 \\ -S_4 & -S_5 & -S_6 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \delta_e \\ W \\ Q \end{bmatrix}$$

where δ_a is the elevator command, that is input to the actuator, δ_e is the elevator deflection, that is actuator output, W is the normal longitudinal velocity, Q is the pitch rate, α is the angle of attack and A_n is the normal acceleration.

$$S_1 = M_{de} + M_{wd} Z_{de}, \quad S_4 = \frac{Z_{de} + rS_1}{g}, \quad S_2 = M_w + M_{wd} Z_w$$

$$S_5 = \frac{Z_w + rS_2}{g}, \quad S_3 = M_q + M_{wd}(Z_q + Z_w), \quad S_6 = \frac{Z_q + rS_3}{g}$$

where $g\,(= 32{\cdot}2\ \mathrm{ft\,s^{-2}})$ is the gravitational acceleration, $r\,(= 12{\cdot}268\ \mathrm{ft})$ is the distance from the centre of gravity of the airframe to the accelerometer. $\tau_e\,(= \frac{1}{20}\ \mathrm{s})$ is the actuator time constant and $U_0\,(= 1005{\cdot}3\ \mathrm{ft\,s^{-1}})$ is the reference flight speed.

The dimensional stability derivatives for longitudinal motion used in the simulation are

$$Z_w = -3{\cdot}1332\ \mathrm{s^{-1}}, \quad Z_{de} = -202{\cdot}28\ \mathrm{ft\,s^{-2}}, \quad Z_q = -16{\cdot}837\ \mathrm{ft\,s^{-1}},$$

$$M_w = -0{\cdot}01429\ \mathrm{s^{-1}\,ft^{-1}}, \quad M_q = -2{\cdot}6864\ \mathrm{s^{-1}}, \quad M_{wd} = -0{\cdot}001\,15\ \mathrm{ft^{-1}},$$

$$M_{de} = -40{\cdot}465\ \mathrm{s^{-2}}$$

For digital computer simulations a discrete-time version of the controller was implemented. The sensor and controller sampling times were chosen to be 50 ms to compare the observer–controller performance against the unmodified controller design. The measured variables are the angle α of attack, the normal acceleration A_n and the pitch rate Q. All three poles of the discrete observer are placed at $0{\cdot}3\ \mathrm{s^{-1}}$.

In general, the responses of the state variables indicate that the dynamic performance of the flight control system is improved significantly with the use of the compensated control scheme. Figure 9 shows the transient response of the

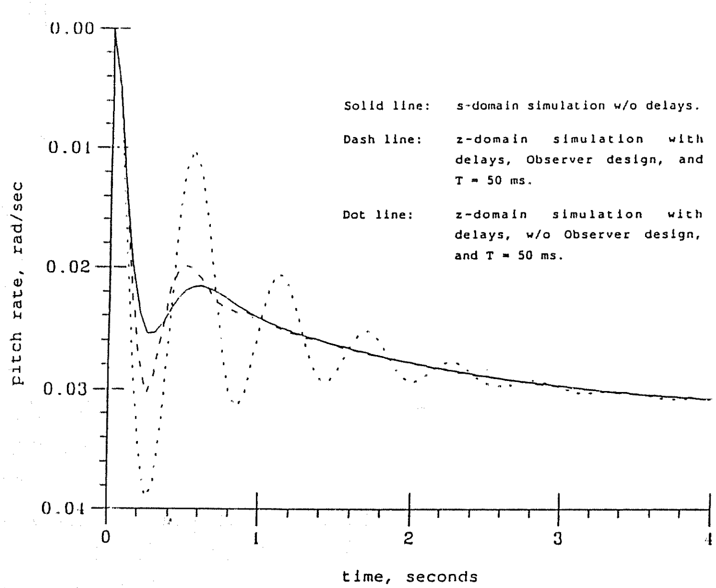

Figure 9. Dynamic response of pitch rate.

pitch rate to a unit step change in the reference signal. As expected, the response of the compensated system, that is with the observer, is less oscillatory than that of the uncompensated system, that is without observer. The benefits of this less oscillatory response are better dynamic response, smaller control effort and actuator wear.

4. Implementation of the multistep delay compensator

When the controller-to-actuator data are subjected to network-induced varying delays, a procedure described in this section can be used to enhance the observer tracking capabilities. Here we assume that the actuator sampling rate is very fast relative to the plant dynamics and a zero-order hold filter is implemented at the actuator input. Note that this can be accomplished without affecting the network traffic. Since the actuator sampling rate does not affect the network traffic, it is possible to set its sampling rate much faster than the sensor–controller sampling rate. A fast actuator sampling rate would justify the requirement that the actuator responds quickly to the incoming controller data.

By installing a clock at the controller station, the instant of transmission of the controller data can be recorded. The instant of arrival of the controller data at the actuator can be calculated since the message transmission delay is known. Let $u_1, u_2, \ldots, u_n$ be the controller outputs arriving at the actuator at the instants $t_1, t_2, \ldots, t_n$, with $kT \leqslant t_1 < t_2 < \cdots < t_n < (k+1)T$. The state variable ω can then be expressed as

$$\omega_{k+1} = a^* \omega_k + b_1 u_1 + \cdots + b_n u_n$$

where

$$a^* = \exp\left(-\frac{T}{\tau}\right)$$

and

$$b_i = \int_{t_{i-1}}^{t_i} \exp\left(\frac{-(t_i - x)}{\tau}\right) K \frac{\mathrm{d}x}{\tau} = K\left[1 - \exp\left(\frac{-(t_i - t_{i-1})}{\tau}\right)\right]$$

The observer is given by

$$\hat{\omega}_{k+1} = a^* \hat{\omega}_k + b_1 u_1 + \cdots + b_n u_n + L(y_k - c^* \hat{\omega}_k)$$

The separation property still applies to the above-described observer because the terms including the control input do not affect the estimation error if the plant and the observer models match identically. The above-described procedure readily applies to higher order finite-dimensional linear time-invariant systems.

5. Summary, comments and conclusions

A control law for compensation of the detrimental effects of distributed network-induced delays in ICCSs has been proposed. Implementation of the delay compensation algorithm, followed by experimental test and simulation results have been presented. Experimentaion with a constant-excitation d.c. servomotor in an IEEE 802.4 network testbed assembly has demonstrated that the proposed predictor–controller can compensate for induced delays in presence of plant modelling uncertainties, nonlinearities and disturbances, and measurement noise. Simulation of the flight control system of an advanced aircraft within a network environment also shows that the delay compensator is capable of improving the system dynamic performance. However, further analytical and experimental research, especially in the area of performance and stability robustness, is needed.

The above delay compensation strategy is suitable for decision making and control in interactive dynamical processes, such as those in advanced aircraft, spacecraft, manufacturing automation, nuclear power, chemical process and automotive applications, where a communication network interconnects the individual subsystems and components. The network should be designed such that the induced delays, albeit being randomly varying, are bounded relative to a specified confidence interval. The proposed delay compensation algorithm is based on deterministic state estimation and linear state feedback control. The deterministic observer can be replaced by a stochastic observer without any structural modifications of the delay compensation algorithm. However, if a feedforward–feedback control law is chosen instead of the state feedback control law, then the observer needs to be modified in the same way a conventional non-delayed control system should be. The separation property of the classical Luenberger observer has been shown to hold true for the proposed delay compensator.

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