Introduction to Networking for Integrated Control Systems

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ABSTRACT: An integrated control system has disparate and spatially distributed subsystems interconnected via a common communication channel. Digital data from sensor to controller and from controller to actuator are multiplexed along with traffic from other control loops and management functions. The asynchronous time-division multiplexing introduces time-varying and possibly stochastic delays in the control loops, degrading system dynamic performance. The paper presents an introduction to approaches for integrated control system design, which requires interactions between the disciplines of communication systems and control systems.

Introduction

Integrated control systems arise in complex dynamical processes such as autonomous manufacturing plants, electric power plants, advanced aircraft and spacecraft, and electronically controlled transport vehicles. These systems require high-speed, reliable communications between subsystem components that perform diverse but interrelated functions ranging from real-time active control to information display and routine maintenance support [1]-[5]. These activities are coordinated by spatially dispersed computers, intelligent terminals, sensors, and actuators. A network serves to systematically interconnect the subsystem components as well as to achieve a better utilization of the resources [1]-[3].

The technology of networking in distributed information processing and control systems can be classified into two broad categories [6], [7]: (1) point-to-point dedicated connections and (2) asynchronous time-division multiplexing. The major advantages of multiplexed networks over point-to-point connections include the following: reduced wiring and power requirements, flexibility of operations, evolutionary design process, and ease of maintenance, diagnostics, and monitoring. The integrated control system network in Fig. 1 illustrates how a control loop can be closed using the common communication medium. Data from sensor to controller and from controller to actuator are multiplexed via a single communication medium along with the traffic from other control loops and management functions. Unfortunately, the system dynamic performance can be adversely affected by delays induced by the multiplexed network; these delays are in addition to the sampling time delay inherent in digital control systems.

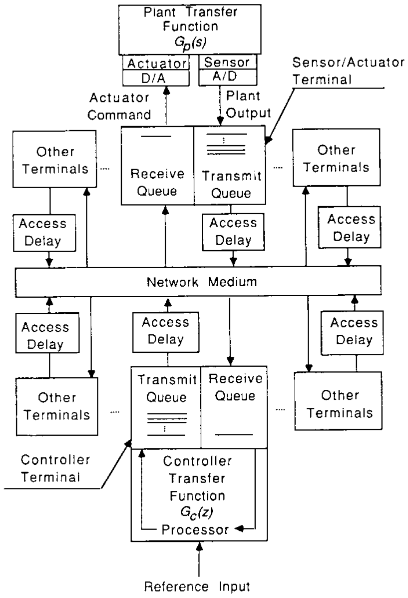

Fig. 1. Schematic diagram for an integrated control system network.

While the detrimental effects of network-induced delays on the dynamic performance of feedback control systems are evident in very fast processes (e.g., flight control systems in tactical aircraft [8]), these delays often are considered to be insignificant in relatively slow processes, such as those encountered in manufacturing and processing plants. However, as the number of network users increase, the augmented traffic causes a larger data latency, and its impact on the control system performance cannot be ignored [9]. The detrimental effects of data latency on system dynamic performance are aggravated further by missynchronization between control-loop components and loss of data from saturation of buffers. Figure 2 illustrates how network-induced time-varying delays, designated θ_{sc} (sensor to controller) and θ_{ca} (controller to actuator), enter the control system.

Analysis and design of integrated control systems require interactions between the disciplines of communication systems and control systems. It may be appropriate to compare the notions of delay since it is used in both disciplines. In communication systems, delay is primarily caused by queuing and serial transmission of bits associated with those messages that arrive successfully at the destination terminal [7], [8]; messages that are corrupted by noise or deleted due to queue saturation at the buffer are not included in this definition. In control systems, delay is related to the question: How old are the data that are currently used? When no messages are rejected, the two notions of delay are similar; otherwise they are different.

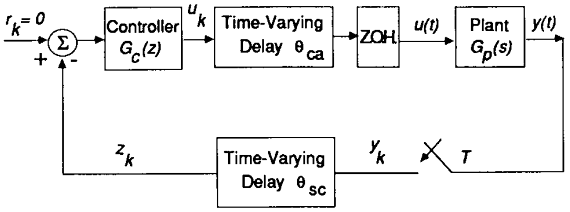

Fig. 2. Control system with delay.

In the continuous-time setting, the control law for a given plant model is represented as a transfer function or a state-space realization. In the discrete-time setting, an additional parameter of importance is the sampling time [10]. In an integrated control system, the sampling time T is essentially the sensor message interarrival time and can be considered as a common parameter of the control system and the communication network. From the point of view of control, smaller values of the sampling time T (with

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the exception of sensitivity to the roundoff errors in the controller computer) are desirable because the discrete-time control law more closely approximates its continuous-time design. On the other hand, a smaller sampling time, i.e., a higher sampling frequency, implies larger network traffic, which, for a given transmission speed, increases the data latency in the communication network.

The networking requirements for an integrated control system may vary with specific applications. For example, in an autonomous manufacturing environment, the prime objective of the network is integration of computer-controlled complexes of robots, automated machine tools, material handling devices, and guided vehicles on the shop floor with communication complexes for engineering design, and plant and office management. The major objective for networking in an advanced aircraft is to design an integrated control system that serves various management, avionics, and fly-by-wire control functions to ensure safe and reliable missions. Similarly, in electric power and chemical processing plants, distributed control systems can regulate the essential and time-dependent process variables—e.g., reactor thermal power, bulk temperature, and feed rates—and also provide necessary support for plant monitoring, fuel scheduling, and preventive maintenance.

Although ample research papers in modeling and simulation of communication networks have been published [11]-[13], the significance of network-induced delays in stability of feedback control systems has been addressed only in a few cases [4], [8], [9], [14]-[16]. The objectives of this paper are to provide an introduction to the evolving field of networking for integrated control systems and to summarize some of the pertinent research in this area.

Analysis of Delayed Control Systems

Several approaches for analyzing the dynamic performance and stability of delayed control systems have been suggested [17]-[25]. Most of the literature on delayed systems deals with the case of constant delays, but some results concerning time-varying delays have been presented, e.g., Yorke [17], Hirai and Satoh [18], Ikeda and Ashida [19], and Belle Isle [20], [21]. For a network with randomly distributed traffic, the delay in the control loop could be a stochastic process. The use of stochastic Lyapunov functions for stability analysis of systems with randomly varying delays has been suggested by Belle Isle [20], [21].

Network-induced delays in the feedback loop for an integrated control system are sensor-controller delay and controller-actuator delay, as shown in Fig. 2. Since both these delays are time varying, they may not be lumped together, in general. However, the digital control algorithm is time invariant; therefore, the two delays could be lumped together under certain restricted conditions [14], [15].

Lumping the two delays (Fig. 2) does not necessarily solve the problem of control system design because the lumped delay could still be a time-varying quantity. This makes the system analysis and design difficult, because the feedback control system specifications usually are given in terms of phase margin and gain margin in the frequency domain or in terms of smallest delay rate, overshoot, rise time, settling time, etc., in the time domain. The specifications of the frequency-domain data are stated in view of linear time-invariant systems. Approaches for solving time-varying delay problems are discussed below.

Given a linear finite-dimensional time-invariant system with a lumped time-varying delay placed between the controller and actuator, the closed-loop digital control system is approximately represented in continuous time as shown below, where $\mathbf{x}$ is the state vector, $\mathbf{A}$ and $\mathbf{B}$ are constant matrices, and $L(t)$ is a scalar nonnegative function of time $t \geq 0$.

$$d\mathbf{x}(t)/dt = \mathbf{A}\mathbf{x}(t) - \mathbf{B}\mathbf{x}(t - L(t)) \quad (1)$$

A first-order system illustrates how the complexity of dynamic performance analysis increases with time-varying delays. A sufficient condition for uniformly asymptotic stability of a first-order system, with scalar x, A and B in Eq. (1), has been shown by Yorke [17] to be that the maximum of L is less than $(1.5)/B$ when A is identically zero, i.e., the plant is a pure integrator. It is interesting to note that, if the system is assumed to have a constant delay q equal to the maximum of $L(t)$ for all time t, then the above condition can be relaxed to q being less than $\pi/(2B) \approx 1.57/B$. This suggests that replacing $L(t)$ by its maximum may not be appropriate. Similar results have been derived by Hirai and Satoh [18] using a different approach.

An overview of methods for analyzing delayed control systems follows.

Stochastic Lyapunov Function

The underlying principle is the same as the well-known Lyapunov method [22], except that the definitions of norms are modified to accommodate the time-varying delay argument and the differential operators are defined in a stochastic setting. Bell Isle [20], [21] used this method to derive a sufficient condition for stability.

D-Partition Method

This procedure gives the region(s) in the parameter space within which the system is stable. Given a scalar system such as Eq. (1), the method defines region(s) in the plane of scalars A and B within which the system is stable for a given constant delay q. Rekasius [23] adopted this concept to identify stable regions for systems with the constant delay q or as a function of q. The analytical basis for this approach was modified by Thowsen [24]. Except for traditional graphical approaches such as Nyquist's [26] and Mikhailov's [27], the algebraic approach presented by Rekasius is one of the few methods that gives necessary and sufficient conditions for stability of control systems with constant delays. This method has a potential for application to integrated control system design if an equivalent constant-delay system could be identified to replace the time-varying delays.

Method of Steps

In this approach adopted by Hirai and Satoh [18], the time-varying delay is assumed to be a constant time lag over an interval. Consequently, the term with the time-varying delay argument in the equation remains a constant within each time period. Thus, the output at the time instant $(n + 1)T$ can be expressed recursively in terms of the output at the time instant nT as a function of the sampling time T and system parameters. The necessary and sufficient condition for the stability of a scalar autonomous system is that the output decreases strictly monotonically.

A common drawback in some of the design methodologies for time-delayed systems, for example, with Bell Isle [20], [21] and Mori et al. [25], is that the stability criterion does not involve the exact magnitude of the delay and its functional characteristics and constraints in the case of time-varying delays. Such results are very conservative since stability is guaranteed for a wide range of the delay. As a result, many of these criteria have limited practical significance.

A discrete-time approach for analyzing delayed systems following the concept of the method of steps has been proposed by Ray and Halevi [14]-[16]. A brief description of this approach is presented here. If the plant and controller are time invariant and the control inputs are piecewise constant, the system can be represented by an augmented state vector, which consists of past values of the plant input and output in addition to the current state vectors of the plant and controller. Thus, the problem of time-varying delays is treated by a *finite-dimensional* time-varying discrete-time system, where the delays are not restricted to be integer multiples of a given time period. From the perspectives of analysis and design for integrated control systems, the proposed method of Ray and Halevi [14]-[16] has the following advantages.

- The two time-varying delays in Fig. 2 can be treated separately; unlike the other methods, these delays are not required to be lumped.
- The delays can be a discrete function of time or a discretely sampled sequence of a continuous function.

Summary and Discussion

The asynchronous time-division multiplexed networking in integrated control systems introduces time-varying and possibly stochastic delays that are distributed between system components. These delays result from data latency and missynchronization between network terminals as well as from a loss of messages due to queue saturation at buffers or data corruption. The network-induced delays can degrade the system dynamic performance and are a source of potential instability in complex dynamical processes such as autonomous manufacturing plants and advanced aircraft and spacecraft.

Both simulation and analytical techniques are required for performance evaluation of integrated control systems. Although combined discrete-event and continuous-time simulation provides valuable insight into complex problems [8], [9], analytical techniques are computationally more efficient and yield more conclusive results if the underlying assumptions are acceptable. The analysis should complement simulation, and they both can be used to verify accuracy and efficacy of the integrated control system.

Research in analysis of systems with varying delays has been rather limited. A discrete-time approach, which represents the delayed system by a finite-dimensional time-varying or stochastic model, is apparently a viable option for analysis and design of integrated control systems. Two options for design are as follows: (1) identical sampling rates of the sensor and controller, which are periodically synchronized to maintain the desired time skew between their sampling instants; and (2) faster sampling rates for the sensor in order to reduce the frequency of occurrence of vacant sampling [14]-[16]. Another area of research is compensation of network-induced delays by stochastic or deterministic observers [28].

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Society Secretary and Administrator

A key person on the Executive Committee of the IEEE Control Systems Society is Ray DeCarlo of Purdue University, who is the Secretary/Administrator of the Society. The Secretary/Administrator is appointed annually and serves during the calendar year. Ray has done an outstanding job the past two years (with the help of his outstanding secretary, Cathy Tanner), and he will continue to serve in 1989. Following is an edited version of some of his duties.

The Bylaws of the IEEE Control Systems Society state that "Secretarial duties shall include the responsibility of sending out notices according to plans delineated by the Board of Governors or laid down in the Society Bylaws; preparing the agenda for and recording the minutes of all meetings of the Board of Governors and general meetings of the Society and making such reports of these activities as may be required by the Board of Governors, the IEEE Technical Activities Board or the IEEE Bylaws."

Board of Governors

The Society Board of Governors consists of: (a) eight Executive Committee members; (b) six members appointed by the President-Elect and who serve their one-year terms concurrently with the appointing president; and (c) eighteen members elected by Society members. The elected members serve three-year terms—six new members are elected each year. Nominations for Board memberships are made either by petition or by the Nominations Committee.

The Secretary/Administrator notifies the membership before February 15 that Board nominations may be done by petition, generally by announcements in the October, December, and February issues of the *Magazine*. Petition candidates have until March 15 to submit their petitions to either the Secretary/Administrator or the Nominating Committee. A petition must be signed by at least twenty-five Society members (in good standing). Signatures and memberships should be verified through IEEE.

The semiannual meetings of the Society Board of Governors are held during the American Control Conference (ACC) in June and the Conference on Decision and Control (CDC) in December of each year. Approximately six weeks before the scheduled Board meeting, the Secretary/Administrator should begin compiling a preliminary agenda for the meeting. Agenda items generally fall into two main categories: action items and information/discussion items. The action items vary, of course, from one meeting to the next (with the exception of Budget Reports, which appear on every agenda, and the Election of Officers, which appears on the agenda each June).

The Secretary/Administrator is responsible for recording the minutes at the Board of Governors meeting. The minutes should be fairly detailed; actual wording of motions and amendments should be included, together with who made and seconded motions, and the vote count.

Executive Committee

The Society Executive Committee holds Tuesday and Thursday breakfast meetings at both the ACC and CDC. The Tuesday breakfast meeting is held before the afternoon Board meeting and the agenda includes items to be brought up at the Board meeting as well as other Society business. There is no formal agenda for the Thursday breakfast meeting. Items for discussion include items from the Tuesday meeting or new matters brought up at the Board meeting.

Between the semiannual Board meetings, much of the ongoing business of the Society is carried out by the Executive Committee, which makes use of a service called Compmail. Compmail is an electronic mail and information system established by the IEEE Computer Society. Members of the Society Executive Committee, the Conference Board Chair, and other designated Society members use the Compmail service for communication.

Technical Committees and Working Groups

Each Society Technical Committee has associated with it several Working Groups that focus on specialized topics. Society members are asked to join the Working Groups of their choice by completing the Working Group form and mailing it to the corresponding Technical Committee chairperson. Around May, the Working Group form is sent to each Society member along with the ballots for election to the Society Board of Governors.

Awards Book

In December 1987, the Board of Governors voted to establish a formal Honors and Awards Book to be kept by the Secretary/Administrator. The Vice President for Member Activities is responsible for having the chairpersons of each Awards Committee notify the Secretary/Administrator of award recipients in November of each year for inclusion in the Society Awards Book. Names of award recipients will be entered in the book by a calligrapher.