OPTIMAL CONTROL FOR DISTRIBUTED CONTROL SYSTEMS

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ABSTRACT:

In modern cities, factories and high technology operations are run using distributed control. Distributed control involves the use of computer networks. Computer networks consist of computers on both ends, sensors, actuators, and communication links. However, control over computer networks faces many problems such as the delay and loss of control message and the delay or loss of sensor data. This paper proposes a new method such that the control system can handle the network delays and at the same time find an optimal controller. The method uses the modified zero-order hold to account for the delays and uses the linear matrix inequality optimization method to find the controller. This method also takes advantage of the polynomial representation of systems and constraints and places norm constraints on the problem.

KEYWORDS: Optimal Control, Distributed Networks, Delayed Systems, Deadbeat.

1. INTRODUCTION

Advances in control and computer technologies make control systems more complex. A simple embedded control system often contains a multitasking real-time kernel and supports networking. Due to the market demands, the cost of the system needs to be kept at a minimum. For optimal use of computing resources, the control algorithm and the control software designs need to be considered at the same time.

Many computer-controlled systems are distributed systems consisting of computer nodes and communication network connecting the various systems. It is common to have the sensor, actuator, and the controller to reside on different nodes. The controllers are often implemented as one or several tasks on a microprocessor with real-time operating system. The CPU time and the communication bandwidth can be considered as shared resources.

Constant sampling intervals and constant or negligible control delays from sampling to actuation are typical assumption in digital control theory. However, in practice this can rarely be the story. Within a node, tasks interfere with each other through preemption and blocking when waiting for common resources. The execution times of these tasks themselves may be data dependent or may vary due to hardware features such as caches. On the distributed level and based on the communication protocols, the communication network introduces delays that can be deterministic. The increased use of commercial off-the-shelf hardware and software components introduce temporal nondeterministic delays.

The use of networks to transmit data in a manufacturing system introduces advantages both in the physical setup and in software implementation. For example, networked control system, NCS, increases system reliability and testability, enhances resource utilization and reduces weight, space, power and wiring requirements.

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However, timing problems can arise when implementing real-time control systems. For instance, the network can cause time-varying delays in the communication within the system.

In this paper, we attempt to overcome these problems, or, at least, reduce their effects on system performance. In other words, we seek to efficiently use the finite bus capacity while maintaining good closed-loop control system performance, including stability, rise time, overshoot and other design criteria.

To achieve our goal, one main approach for accommodating all of these issues in NCS design is taken. The approach is based on treating the network protocol and traffic as given conditions and design control strategies that explicitly take the delay issue into account. In doing so, a computer-aided design software, MATLAB, program is used for numeric computation and data visualization, and in the design of different types of controllers to compensate for the induced-delay.

This paper is organized as follows: Section 2 presents a brief description of NCSs and their advantages and disadvantages, and reviews some previous work on NCSs. Section 3 involves the factors affecting NCSs performance, such as communication delays, and sampling time. Section 3 also deals with the main subject of research, the stabilizing of NCSs with network-induced delays. Section 4 is devoted to designing various types of controllers to compensate for the delay effects in NCSs. The design approaches that are followed to design these controllers are: phase-lead and phase-lag, pole-placement, state feedback, and deadbeat design approach. Following that, we report experimental results over a physical network. Finally, we present our conclusions and offer proposals for future trends.

2. NETWORKED CONTROL SYSTEMS

2.1 What is a Networked Control System?

The concept of NCS is used to describe a feedback control system in which the feedback control loop is closed via a real-time network. The defining feature of this kind of systems is that information (reference input, plant output, control input, .etc.) is exchanged using a shared communication medium among control system components (actuator, controller, sensor,…etc.) , as illustrated in Figure 2.1.

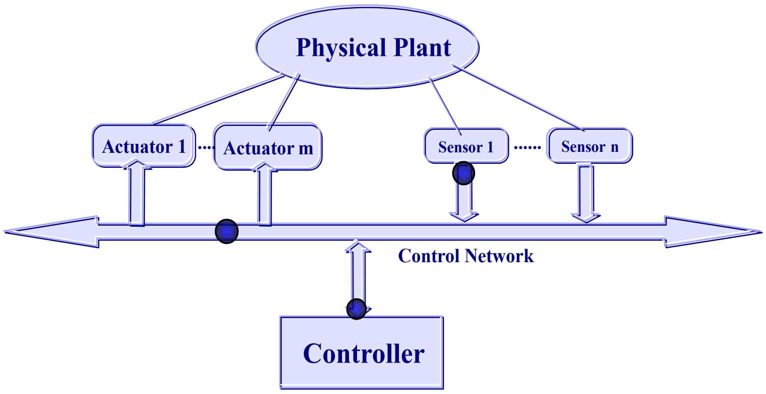

Figure 2.1, A typical NCS setup and information flows

This structure introduces new problems such as (possibly random) delays in the control loop, lost measurement and control signals, temporal constrains (deadlines) of different tasks and then scheduling the CPU and network to meet all constraints during runtime. The delay introduced by the computer system may cause significant performance degradation. A control system can be built by connecting a number of continuous- and discrete-time systems. Each subsystem may have optional noise and cost specifications. For the simplest case, the discrete-time systems are assumed to be updated in order during the control period. For each discrete system a random delay can be specified that must elapse before the next system is updated.

The data network, generally speaking, use large data packets and relatively infrequent bursty transmission over a wide area, with high data rates to support the transmission of large files. Data networks generally do not have hard real times (i.e. time critical) constraints. Control networks, in contrast must shuttle countless small but frequent packets among a relatively large set of nodes to meet the time-critical requirements [1].

Another concept of interest is Distributed Control System (DCS). A DCS is one of the types of computer system that has been designed to control industrial processes. DCSs get their name from their architectural design. Processing is distributed between lots of processors instead of one " super computer" performing all computer control functions. Normally the processors are built into separate modules that are optimized for a particular function. Often, the separate modules are physically distributed around a plant.

2.2 Components of DCS

A distributed control system consists of

1. Several local controllers, each able to handle several control loops simultaneously;
2. Interconnecting digital data links, together with organizing protocols;
3. At least one coordinating controller;
4. A central information display unit;
5. Machines (system plants), sensors, and actuators.

The configuration of the data links and the protocols for data transfer determine the character of the network [2]. Most networks for computer control have a central information display unit [3]. Machines are those parts of the system that achieve the physical implementation of the process, which can be considered from the control point of view as plants. Usually a system, called the control actuator, is required to drive the plant. The sensor (or sensors) measure(s) the response of the plant, which is then compared to the desired response [4].

On the other hand, the insertion of the communication network in the feedback control loop makes the analysis and design of an NCS complex [5]. The performance factors of communication systems that impact the requirements of control systems are transmission time, response time, message delay, message collisions, message throughput, packet size, network utilization, deadline meeting, etc. For control systems, candidate control networks generally must meet two important criteria: bound time delay and guaranteed transmission. That is, a message should be transmitted successfully within a predetermined time. Lost or excessive delayed messages from a sensor to an actuator may deteriorate system performance or result in instability [1].

Thus, in analyzing NCSs, the following issues need to be addressed. The first issue is the network-induced delay (sensor-to-controller delay and controller-to-actuator delay) that occurs while exchanging data among devices connected to the shared medium. This delay, either constant or time-varying, can degrade the performance of control systems designed without considering the delay and can even destabilize the system. Next, the network can be viewed as a web of unreliable transmission paths. Some packets not only suffer transmission delay, even worse, they can be lost during transmission. Thus, such packet drops out affect the performance of an NCS, and is an issue that must be taken into account. Moreover, plant outputs may be transmitted using multiple network packets (so-called multiple-packet transmission), due to the bandwidth and packet size constraints of the network. Because of the arbitration of the network medium with other nodes on the network, chances are that all / part / none of the packets could arrive by the time of control calculation [5]. Elaydi discussed such structures and protocols of these networks [6].

2.4 Review of Previous Work

Halevi and Ray considered a continuous-time plant and discrete-time controller and analyzed the integrated communication and control system (ICCS) using a discrete-time approach [7,8]. They studied a clock-driven controller with mis-synchronization between plant and controller. The system was represented by an augmented state vector that consists of past values of the plant input and output, in addition to the current state vectors of the plant and controller. This resulted in a finite-dimensional, time-varying discrete-time model. They also took message rejection and vacant sampling into account [8].

Nilson also analyzed NCSs in the discrete-time domain [9]. He further modeled the network delays as constant, independently random, and random but governed by an underlying Markov chain. From there, he solved the LQG optimal control problem for the various delay models. He also pointed out the importance of time-stamping messages, which allowed the history of the system to be known [9].

In Walsh et al., the authors considered a continuous plant and a continuous controller. The control network, shared by other nodes, is only inserted between the sensor nodes and the controller. They introduced the notion of maximum allowable transfer interval (MATI), which supposes that successive sensor messages are separated by at most α seconds. Their goal was to find that value of α for which the desired performance (e.g., stability) of an NCS is guaranteed to be preserved [10].

Elaydi also analyzed NCS with communication delays modeled as uniform random delays. From there, he gave a solution to the controlling problem ranging from choosing the type of communication medium to redesigning the controller taking into account the mean average of the delays [6].

3. STABILITY OF NETWORKED CONTROL SYSTEMS

3.1 Background: -

Traditionally, control algorithms have been designed without taking into consideration the implementation details. However, when networks are to carry feedback signals for a control system, the limited bandwidth induces unavoidable communication delays. To successfully analyze the behavior of a networked control system, the type and location of these delays must be characterized and their effect on the performance of the control system must be understood [11].

- **Communication Delay**

These delays are called network-induced delays, that result from the effect of closing the feedback control loops in NCSs over a communication network. The data from the sensors to the controller and from the controller to the actuator are multiplexed via a single communication medium a long with traffic from other control loops and management functions. The two types of communication delays, from sensors to controller, τ_{sc}, or from controller to actuators, τ_{ca}, are introduced in the form of access delay to the network medium [6].

- **Computational Delay**

These delays result from the time required by the controller to handle the calculation and implementation of the control algorithm on the data available on its inputs. This delay is often very small compared to communication delay, and thus can be ignored.

3.2 Stability of NCSs with Network-Induced Delay

The NCS model considering Network-Induced Delay consists of a continuous plant and a discrete controller as shown in Figure 3.1. The actuators and sensors are connected to a communication network. These units receive and send control information to the centralized controller, respectively. The centralized controller is connected to the network, and communicates with sensors and actuators by sending messages over the network. Sending a message over a network typically takes some time.

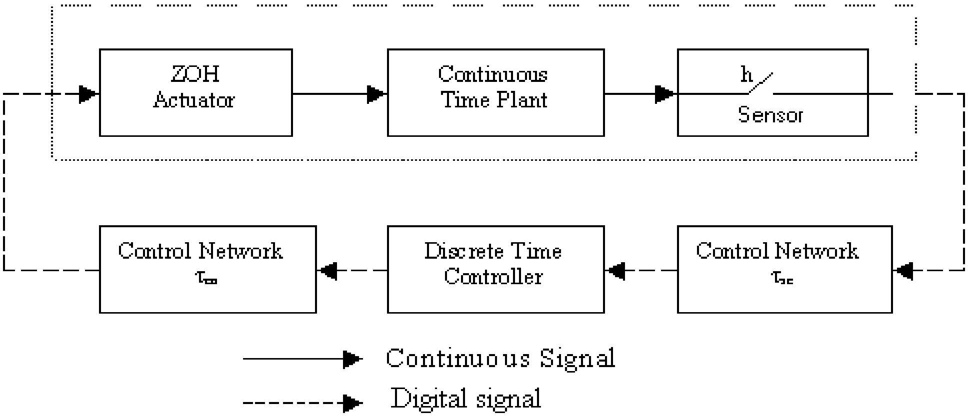

Figure 3.1, The NCS model with Network-Induced Delay

There are two sources of delay from the network: sensors-to-controller, τ_{sc}, and controller-to-actuator, τ_{ca}. Any controller computational delay can be absorbed into either τ_{sc} or τ_{ca} without loss of generality. For fixed control law (time invariant controllers), the sensor-to-controller delay and controller-to-actuator delay can be lumped together as $\tau = \tau_{sc} + \tau_{ca}$, where τ is called a control delay [5]. A control delay for a control system is the time from when a measurement signal is sampled to when it is used in the actuator [10].

The simplest model of the network delay is to model the delay as being constant for all transmission in the communication network. This can be a good model even if the network has varying delays, for instance, if the time scale in the process is much larger than the delay introduced by the communication. In this case the mean value or may be the worst-case delay can be used in the analysis [10].

3.3 Sampling of Systems with Network Delays: -

The theory of continuous-time systems with time delays is complicated because the systems are infinite-dimensional. It is, however, easy to sample systems with time delays because the control signal is constant between sampling instants, which makes the sampled-data system finite-dimensional [12].

Based on the sampling theorem, therefore, the sample rate must be at least twice the required closed loop bandwidth of the system. In practice, however this theoretical lower bound would be too slow for an acceptable time response. The desired sampling for a reasonably smooth time response is

$$6 \leq \frac{\omega_S}{\omega_{BW}} \leq 40 \qquad \text{......................................}(3.1)$$

Where ω_S is the sampling frequency and ω_{BW} is the highest frequency in the system.

A command input can occur at any time throughout a sample period; therefore, there can be a delay of up to a full sample period before the digital controller is aware of a change in the command input. In the following, we will look at the relation between the delay and sampling period and its effect on the system performance [6].

3.4 NCS Design Approaches: -

The main approach taken to optimize performance of NCSs in the presence of control time delays, is to treat the network protocol and traffic as given conditions and design control strategies that explicitly take the delay issue into account. In the next section, control strategies will be formulated to handle the NW induces delay.

4. APPROACHES AND SIMULATION RESULTS

4.1 Problem Formulation

In this section, we will limit the discussion to the design of controllers that compensate for the induced delays in a NCS. The system is assumed to be single-input, single-output, one actuator, one sensor, and one controller. Thus, most of the existing work has focused on the same module we will deal with.

The control system of a linear, finite-dimensional, time-invariant model of the continuous-time plant and discrete–time controller, respectively is simulated.

The DCS model, with no delays, is illustrated in Figure 4.1. The system consists of a DC motor plant, a zero-order hold, and a controller with a gain of 113.

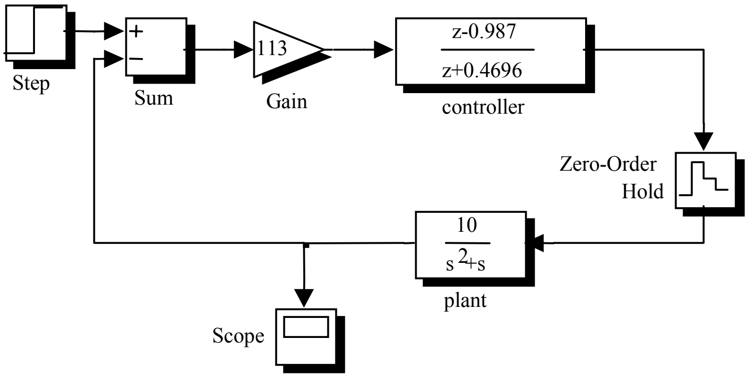

Figure 4.1 DCS model with no delays

The results of simulation of such a system illustrated in Figure 4.2, showed that the behavior of the system meets the following specifications: Overshoot ≤ 15%, rise time ≤ 2sec., settling time ≤ 5sec., and steady state error = 0.1.

In order to investigate the system behavior in the presence of communication time delays, two types of delays are inserted into the system, sensor-to-controller delay, and controller-to-actuator delay.

These delays are implemented using z-transform for both delays and set to equal to a maximum delay of one sampling period, and are considered to be uniform, randomly distributed, and transport delays. The effect of these delays is clearly shown in Figure 4.3. With varying the amount of delay for each of the transport delays, we notice that for rather small delays, the behavior of the system is still satisfactory.

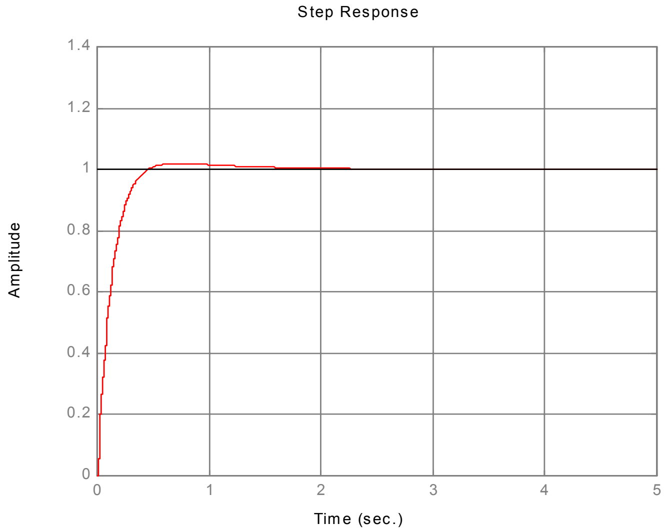

Figure 4.2 Simulation of the system in Figure 4.1

In the following sections, basically we will conduct the problem of designing various types of digital controllers in attempting to compensate for the effect of communication delays. The design of the controller in these sections will be performed in the z-domain.

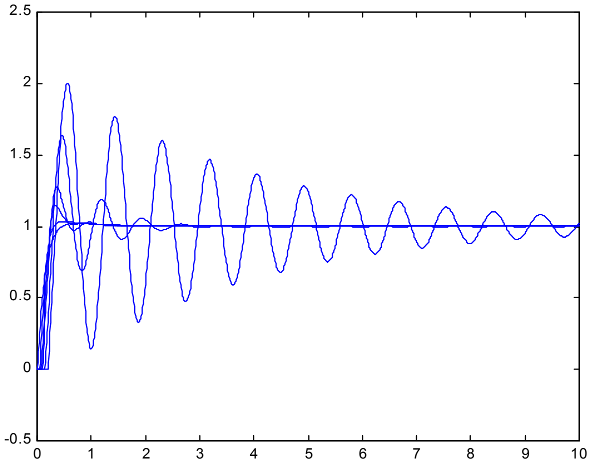

Figure 4.3, Different runs for the system with delays

4.2 Phase-lead and phase-lag Technique

For our specific system, the insertion of a communication delay will result in a phase-lag, which will force the system into the instability region. To compensate for this phase-lag, a phase-lead controller is required, if the delay is assumed to be 0.5 T, where T is the sampling period, the required digital phase-lead controller is found to be

$$D(z) = 15\,\frac{(z-0.987)}{(z+0.469)} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.2.1)$$

This controller can tolerate a delay up to 2.4 sampling periods.

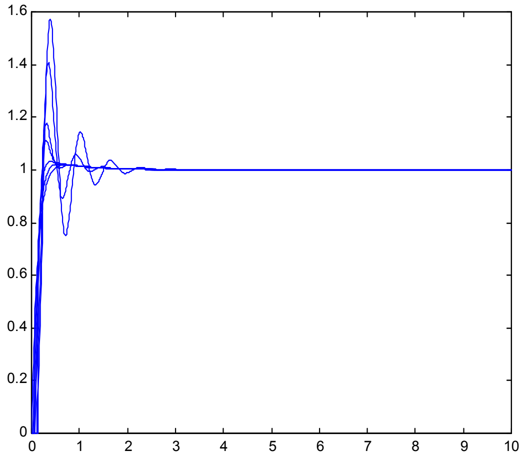

Figure 4.4, System behavior for different delays

4.3 Pole Placement Technique

The design results in the assignment of the poles of the closed-loop transfer function to any desired locations given that we have all the states of the system available for feedback. The simulation of the resultant system is illustrated in Figure 4.5. The system starts with an initial delay that is due to the controller-actuator delay, but with time advance the system will rise within 2 seconds, after that it will track the input in an accurate manner.

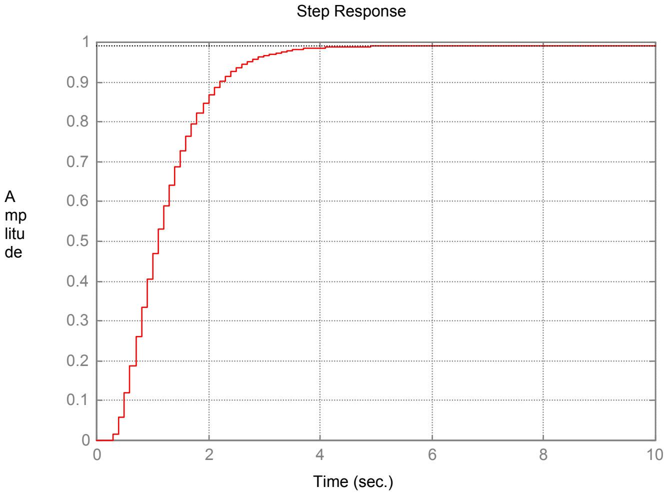

Figure 4.5, Compensation of delay
2T < t_d < 3T using Pole Placement technique.

4.4 State Estimation Approach

Thus far, we have dealt with the problem with induced delay and how to decrease its destabilizing effect on the system performance. However, if the delay is large enough so that the controller is not aware of the output states, a loss problem is introduced. Estimating the lost states to make them available for the control calculations will solve such problem. One point that should be taken into account is that the state estimating design approach is effective with the sensor-to-actuator delay. Controller-to-actuator delay is different, however, in that the controller does not know how long it will take the control signal to reach the actuator; therefore, no exact correction can be made at the time of control calculation.

The states of the system to be observed are x(k), the states of the observer are q(k) and we desire that q(k) are approximately equal to x(k).

For the predictive observer, the state equation is

$q(k+1) = (A-GC)\, q(k) + G\, y(k) + B\, u(k)$ …….……………………… (4.4.1)

Where A, B, C are the state space matrices of the original system, G is to be specified from Ackermann's equation,

A prediction observer can be considered as a digital controller with the transfer function,

$D(z) = k(zI - A + BK + GC)^{-1}\, G$ ……………………………………… (4.4.3)

Where K is the gain matrix that has been determined by Pole Placement technique.

Simulation results of the system using a predictive observer is shown below in Figure 4.5.

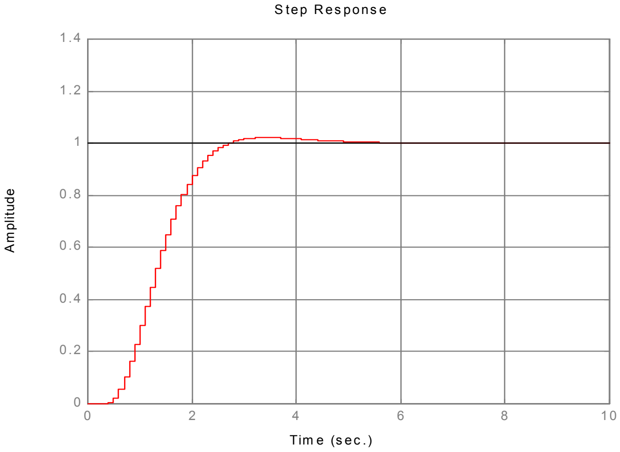

Figure 4.6, Toleration of a delay $2T < t_d < 3T$ by a Predictive Observer

4.5 Deadbeat control Approach

A system is said to be a deadbeat system if all it's poles lie at the origin. This is the FIR property. Therefore a ripple free control problem has several goals; the closed loop system is internally stable, the error of the system must go to zero after a finite number of steps, and the control signal settles to its final form after a finite number of steps.

Employing of this method in the problem of delay compensation for our specific system resulted with a controller, based on a delay of 0.5T, given by

$$C(z) = 1.0e+004 \frac{1.0023z^3 - 2.6008z^2 - 2.1968z - 0.5983}{z^3 - 1.2513z^2 - 0.4975z + 0.7487} \quad \text{...(4.5.1)}$$

4.6 Comparison of The Controllers Obtained

In this subsection, we provide a comparative analysis of the controllers that have been designed to overcome the problem of induced – delay in NCSs. Table 4.1 show a comparison among the behavior of these controllers.

Table 4.6.1 System parameters for various types of controllers with different values of delay

Techniques	Delay	Overshoot %	Rise Time (Sec)	Settling Time (Sec)	Steady-state error %	Initial Delay (Sec)
Phase-Lead	0.5T	2.5	0.4	2	0.01	0.0
	2.5T	18	0.4	3.5	0.1	0.3
Pole-Placement	0.5T	2	0.3	1.5	0.01	0.2
	2.5T	0	1.8	4	0.01	0.4
Predictive State Estimator	0.5T	5	0.8	4	0.01	0.3
	2.5T	2	1.25	5	0.1	0.5
Deadbeat	0.5T	30	0.1	0.5	0.1	0.0
	2.5T	Unstable System				

5. CONSLUSION AND FUTURE TRENDS

Although more and more control systems are being implemented in a distributed fashion with networked communication, the unavoidable time delays in such systems impact the achievable performance. In this paper, we gave solutions to the subject of stability of network control system in the presence of induced-time delays. The approach is to deal with the network protocol as a given condition, and try to overcome the problem of delay by designing various types of controller that compensate for the delay effect. We have presented four types of design approaches to achieve this goal: phase-lead, pole-placement, state feedback, and deadbeat. Several numerical examples involving various amounts of delays were presented to demonstrate the efficiency of the proposed approaches using MATLAB. The design of these controllers resulted in an excellent behavior of the control system though the existence of a delay of up to three sampling periods.

Our future efforts will focus on the use of a combination of deadbeat and state estimator controller design for networked control system. This will include conducting experimental studies of control network for control applications. We then plan to use this analysis as the basis for future research about the random delays in NCSs, with probability distributions governed by an under laying Marcove chain.

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