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Design of Smith-like Predictive Controller with Communication Delay Adaptation

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***Abstract*—**This paper addresses the design of predictive networked controller with adaptation of a communication delay. The networked control system contains random delays from sensor to controller and from controller to actuator. The proposed predictive controller includes an adaptation loop which decreases the influence of communication delay on the control performance. Also, the predictive controller contains a filter which improves the robustness of the control system. The performance of the proposed adaptive predictive controller is demonstrated by simulation results in comparison with PI controller and predictive controller with constant delay.

***Keywords*—**Predictive control, adaptation, communication delay, communication network.

I. Introduction

WIDE class of industrial processes has a similar behavior that can be described by the mathematical model with time delay. These are thermal and chemical processes, pneumatic systems with long transmission, transportation systems, etc. The time delay may causes unstability and/or degradation of performance of controlled process when exceeds a critical value. The traditional PID controller is used for controlling of processes when time delay has a small value. In the case of large value of time delay, PID controllers exhibit poor control performance [1].

Many modern industrial systems are hierarchical organized and distributed over the communication network with decentralized control [2]. A feedback system wherein the control loop is closed through a real-time communication network is known as a networked control system (NCS). The main feature of NCS is the exchange, through communication networks, of system information and control signals between various physical components. So this type of system has the advantage of greater flexibility over traditional control systems, including greater flexibility in diagnosis and maintenance procedures.

The control over networks is the next frontier. Control Area Network (CAN) has the potential of supporting interactions between sensors, actuators, and even micro-controllers embedded in a plant, all without physical connections. With appropriate software, embedded devices may be able to automatically connect to each other, form control loops, and even self-assemble into fully functional applications on-the-fly. Currently, a typical mid-range automobile has about 45 micro-controllers connected by CAN [3]. There are also several challenges though. For example, one has to contend with unreliable communication and delays. Also, the overall system features the integration of several complex technologies such as networking, sensing, actuation, computing, and control. In addition, there are the difficulties of dealing with a distributed system. Finally, one must design such systems to be reliable [4].

The overall NCS performance is always affected by network delays since the network is tied with the control system. Delays are widely known to degrade the performance of a control system. Existing constant time-delay control methodologies may not be directly suitable for controlling a system over the network since network delays are usually time-varying, especially in the Internet. Therefore, to handle network delays in a closed-loop control system over a network, an advanced methodology is required [5].

A number of time delay compensation and prediction schemes have been developed and/or improved with modifications as shown in [6] and [7]. The performance of Smith Predictor Control was studied experimentally in [8]. It shows that the system performs well if the process model is accurate, but that performance degrades rapidly with inaccuracy in the process parameters and time delay.

Several control design methods for systems with varying time delays have appeared in recent literature including an estimation and self-tuning method proposed in [9], a variable structure controller [6], and a model reference adaptive approach [10]. Also, many control methodologies, such as probabilistic predictor-based delay compensation methodology [11], optimal stochastic control methodology (LQG) [12], non-linear and perturbation theory [13], sampling time scheduling methodology [14] and fuzzy logic modulation methodology [15], have developed for networked control system. For systems with large time delays, most design approaches use a prediction mechanism as part of the controller to simulate the process for given system parameters and time delay.

In this paper we proposed a predictive controller with adaptation of variable time delay between sensor and

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controller with aim to decrease an influence of communication delays on the closed-loop control performance over the CAN network.

II. Networked Predictive Control System

The proposed predictive control system with adaptation of communication delay is shown in Fig. 1. This system includes PI controller, DC motor as a plant, discrete model of process, communication network, adaptation loop of communication delay, filter and appropriate sensor and actuator. Controller, sensor and actuator represent communication network nodes. The brief description of proposed control system is given in this section.

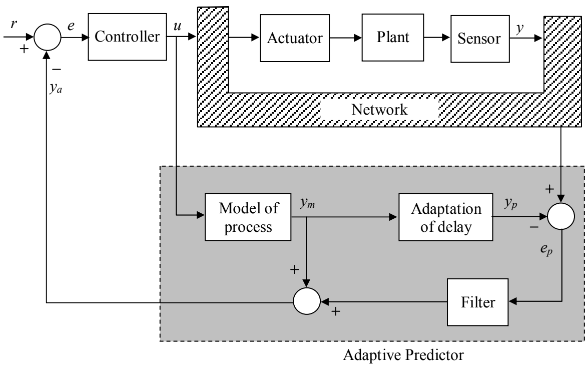

Fig. 1 Predictive Networked Control System with Adaptation of Communication Delay

A. Description of Communication Network

In this paper we used CAN communication network under TrueTime Matlab Toolbox[1]. This toolbox simulates medium access and packet transmission in the CAN network and supports CSMA/AMP protocol. It stands for Carrier Sense Multiple Access with Arbitration on Message Priority. If the network is busy, the sender will wait until it occurs to be free. If a collision occurs (again, if two transmissions are being started within 1 microsecond), the message with the highest priority (the lowest priority number) will continue to be transmitted. If two messages with the same priority seek transmission simultaneously, an arbitrary choice is made as to which is transmitted first. (In real CAN applications, all sending nodes have a unique identifier, which serves as the message priority).

Controller, sensor and actuator are connected through network. Data transfers between the controller and the actuator will induce network delays in addition to the controller processing delay. Network delays in an NCS can be categorized from the direction of data transfers as the sensor-to-controller delay τ^{sc} and the controller-to-actuator delay τ^{ca}. The delays are computed as:

$$\begin{aligned} \tau^{sc} &= t^{cs} - t^{se}, \\ \tau^{ca} &= t^{rs} - t^{ce}, \end{aligned} \qquad (1)$$

where t^{se} is the time instant that the actuator encapsulates the measurement to a frame or a packet to be sent, t^{cs} is the time instant that the controller starts processing the measurement in the delivered frame or packet, t^{ce} is the time instant that the main controller encapsulates the control signal to a packet to be sent, and t^{rs} is the time instant that the system starts processing the control signal. Fig. 2 shows the corresponding timing diagram of network delay propagations.

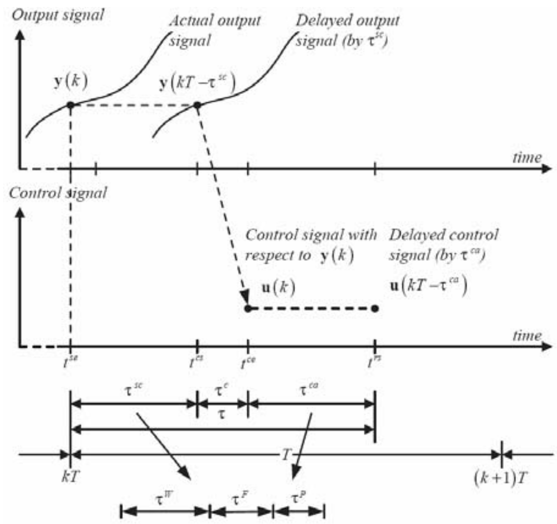

Fig. 2 Timing diagram of network delay propagations

In fact, both network delays can be longer or shorter than the sampling time T: The controller processing delay τ^c and both network delays can be lumped together as the control delay τ for ease of analysis. This approach has been used in some networked control methodologies. Although the controller processing delay τ^c always exists, this delay is usually small compared to the network delays, and could be neglected. In addition, the sampling periods of the main controller and of the actuator may be different in some cases. The delays τ^{sc} and τ^{ca} are composed of at least the following parts [16]:

- Waiting time delay τ^W. The waiting time delay is the delay, of which a source (the controller) has to wait for queuing and network availability before actually sending a frame or a packet out.
- Frame time delay τ^F. The frame time delay is the delay during the moment that the source is placing a frame or a packet on the network.
- Propagation delay τ^P. The propagation delay is the delay for a frame or a packet traveling through a physical media. The propagation delay depends on the speed of signal transmission and the distance between the source and destination.

These three delay parts are fundamental delays that occur

[1] TrueTime Toolbox is product of the Department of Automatic Control, Lund Institute of Technology, Sweden.

on a local area network. When the control or sensory data travel across networks, there can be additional delays such as the queuing delay at a switch or a router, and the propagation delay between network hops. The delays τ^{sc} and τ^{ca} also depend on other factors such as maximal bandwidths from protocol specifications, and frame or packet sizes.

It is assumed that communication delays from the sensor to controller and from controller to actuator are variables (random), have the same values and they are uniform distributed. The Simulink model for generation of these delays is depicted in Fig. 3.

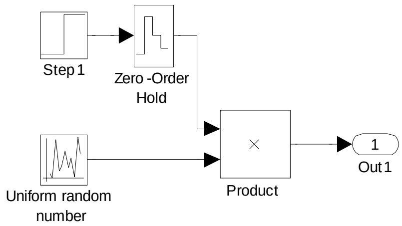

Fig. 3 System for generating a uniform distributed random signal

Communication delays which are larger then a sample time (discretization delay) are considered in the paper. The sample time is chosen to be 0.03 s. The communication time delay generated with simulation scheme in Fig. 3, changed from 0 to 3*T (T is sample time), is shown in Fig. 4.

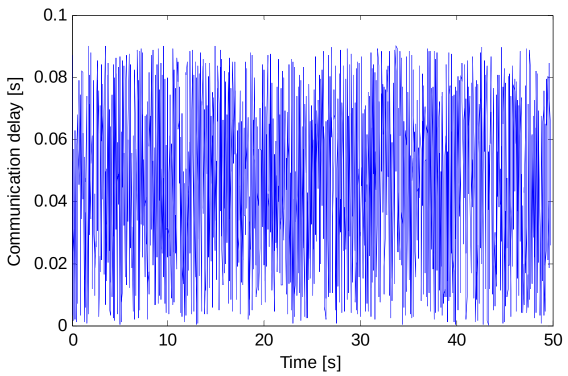

Fig. 4 Time distribution of communication delay under interval $[0,3T_d]$

B. Process Model and PI Controller

The PI controller is designed using technical optimum technique. We used discrete model of PI controller described by following equation:

$$G_r(z) = \frac{K_r T z}{T_i z - T_i}, \quad (2)$$

where K_r is proportional gain and T_i is integral time constant.

The process is represented by DC motor in the Laplace form:

$$G(s) = \frac{1}{0.1s^2 + 0.7s + 1}. \quad (3)$$

The process model, which predicts the future behavior of process, is given in discrete form as follows:

$$G_m(z) = \frac{0.012593z^{-1} + 0.011742z^{-2}}{3 - 5.4072z^{-1} + 2.43175z^{-2}}. \quad (4)$$

In the following section, the design of predictive controller will be described.

III. Design of Networked Predictive Controller

The proposed networked predictive controller contains the ordinary controller, the process model, the adaptation of delay loop and an appropriate filter. Process model and ordinary controller have described in the previous section.

The adaptation algorithm is derived with assumption that average communication delays from the sensor to the controller and from the controller to the actuator are equal. Both delays are variables and uniform distributed.

In adaptation loop, the communication delay in the predictive controller is calculated based on N previous delays in the network from the sensor to the controller:

$$d = 2\frac{\sum_{i=1}^{N} \tau^{sc_i}}{N}, \quad (5)$$

where τ^{sc_i} is communication delay from the sensor to the controller in i-th step. Therefore, the average value of N previous delays is calculated in this way.

For improving of robustness of the control system a first-order filter is included in the feedback loop. The transfer function of the filter is given by:

$$G_f(z) = \frac{1}{1 - T_f z^{-1}}, \quad (6)$$

where T_f is a time constant of the filter.
It is recommended to set T_f as follows:

$$T_f = \frac{T_c}{\alpha}, \quad (7)$$

where T_c is a whole communication delay. The parameter α influences on the robustness of the control system. Smaller values of α provides better system robustness, while greater value of it ensures faster compensation of disturbance influence.

IV. Simulation Results

Validations of proposed adaptive predictive controller in comparison with direct and predictive controllers are investigated on DC motor using Matlab/Simulink program. In this section the influence of communication delays, sensor to controller and controller and actuator, on control system performance will be considered. In these simulations, we assume that these delays are variables and take the same values. The control performance of the closed-loop system for three different communication delays is considered. Their average values are equal to 3**T*, 6**T* and 9**T*, respectively. Two different input signals are applied to the system: step and sequence of pulses. The parameters of adaptive predictive controller are: K_r=1.25, T_i=0.5 s, T=0.03 s and T_f=0.2 s.

Simulation results achieved by the step reference input are shown in Figs. 5-8. In Fig. 5 the time responses of the direct control system outputs (no prediction included) with and without communication delays are presented. The average delay is equal to 3**T*. The time responses of the system with predictive control, together with previous two are depicted in Fig. 6. Simulation results with larger values of average network communication delays: 6**T* and 9**T* are illustrated on Figs. 7 and 8, respectively. The networked DC motor control system with communication delay adaptation has superior performance than without delay adaptation as indicated by the lower overshoot.

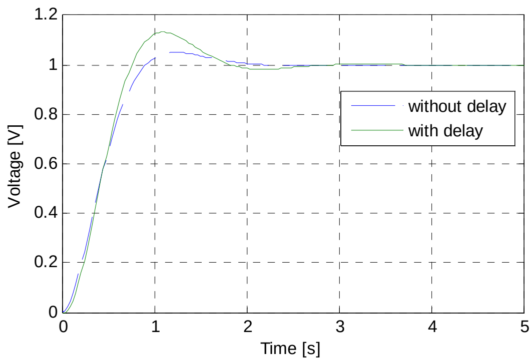

Fig. 5 Step time responses of motor voltage with transportation delay (average value is 3**T*) and without delay under PI control

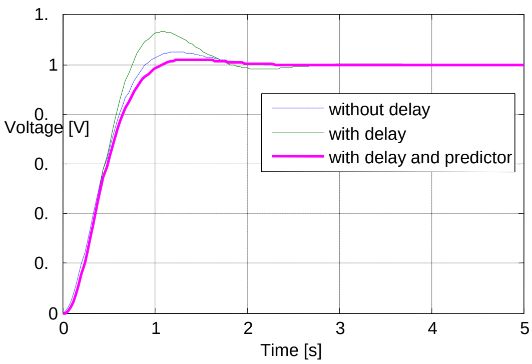

Fig. 6 Step time responses of motor voltage with PI control (with and without time delay) and predictive control with time delay. Average value of time delay is set to 3**T*

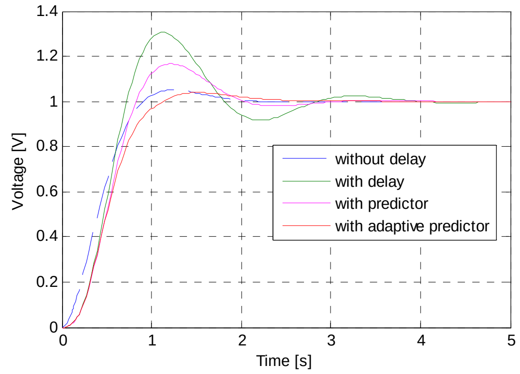

Fig. 7 Step time responses of motor voltage with PI control, predictive control and predictive control with adaptation time delay. Average value of time delay is 6**T*

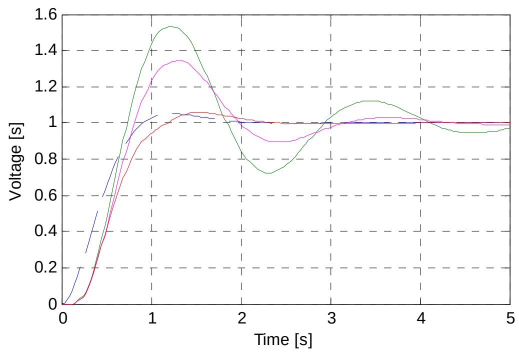

Fig. 8 Step time responses of motor voltage with PI control, predictive control and predictive control with adaptation time delay. Average value of time delay is 9**T*

The simulation results of direct, predictive and adaptive predictive controls, with the pulse sequence as an input signal, are shown in Figs. 9-11. From these figures it can be concluded that control performance by direct and predictive controls with growth of delay are violated. In these cases, the adaptive predictive controller demonstrates a good robustness behavior. Consequently, the networked predictive control scheme with adaptation loop can actively compensate for the certain value of a communication (network) delay.

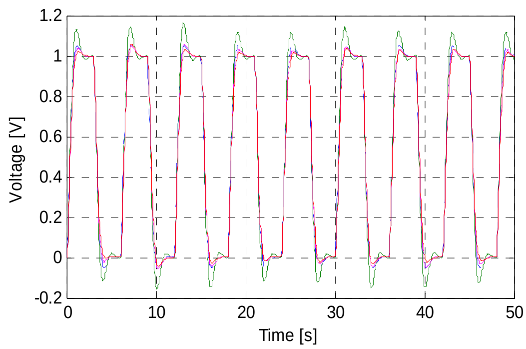

Fig. 9 Time responses of motor voltage on the pulse sequence: PI control without delay (---) and with delay (—), predictive control (—) and predictive control with adaptation delay (—). Average value of time delay is 3**T*

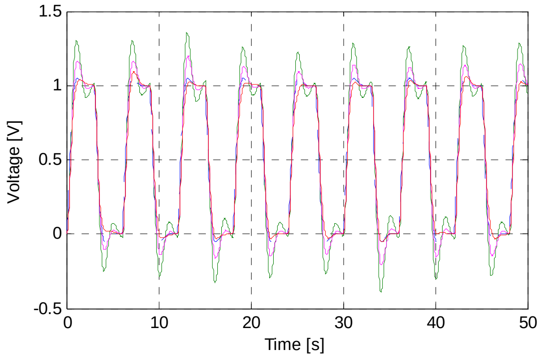

Fig. 10 Time responses of motor voltage on the pulse sequence: PI control without delay (---) and with delay (—), predictive control (—) and predictive control with adaptation delay (—). Average value of time delay is 6**T*

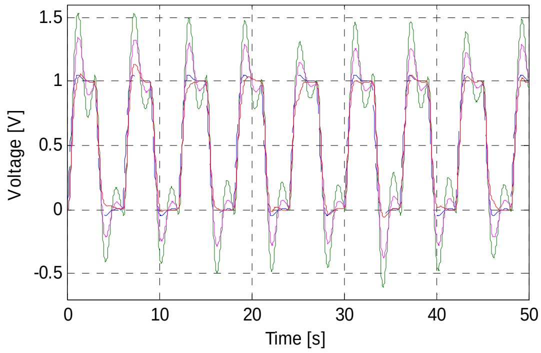

Fig. 11 Time responses of motor voltage on the pulse sequence: PI control without delay (---) and with delay (—), predictive control (—) and predictive control with adaptation delay (—). Average value of time delay is 9**T*

V. Conclusion

In this paper, the adaptive predictive controller is designed to overcome the shortcomings of the influence of communication delays among the nodes, such as controller, sensor and actuator, in the network. The main component of the proposed adaptive predictive controller is an adaptation delay loop. This loop provides the satisfactory control performance when the communication delay is greater then sample time (even nine times). The simulation results obtained show good performance of the proposed predictive controller with an adaptation time delay loop.

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