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Stability Analysis Of Predictive Control In Networked Control System Using Switching Control

R. Farasat, M. Nasiri*

Department of Mechanical Engineering, Golpayegan College of Engineering, Isfahan University of Technology, Isfahan, Iran

ABSTRACT: Predictive control is one of the effective methods to reduce the effect of time delay and data dropout in networked control systems. In the proposed predictive control method, the control data is predicted as long as it covers the time delay and data dropout in the network, and the estimation of state variables is performed using the Kalman filter. By sending a package containing the predicted control data to the actuator and selecting the appropriate control data, the desired control performance of the system can be achieved. In this paper, the networked control system is considered as a switching system with an arbitrary switching signal. A criterion for evaluating the stability of the closed-loop system with time delay and data dropout is presented based on the theory of switching systems. Time delay and data dropout are selected as switching parameters and a subset of switching dynamic systems is created in the discrete state space. By providing the Lyapunov function for all subsets and solving matrix inequalities, the stability of the system can be investigated. The simulation results show the effect of data dropout on the stability of the system by considering the time delay in the forward and feedback channels.

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1. INTRODUCTION

With the pervasiveness of communication networks, the use of networked control systems is also becoming more widespread [1]. A networked control system is a closed-loop system in which the control loop is closed through a real-time network. In particular, the use of the Internet as a communication network can lead to monitoring and control over a very wide range of systems, which has made the study of networked control systems much more attractive and more important [2, 3]. Controlling systems through a communication network can lead us to large-scale simplicity and improvement in the control system set, but practically, the essence of communication networks will cause problems in this direction, some of these problems are time delay, data loss, sampling, data transfer methods, and the possibility of disruption in the network, making it more difficult to use conventional control methods [4]. In this paper, time delay and data dropout are selected as switching parameters and a subset of switching dynamic systems is created in the discrete state space. The stability of the closed-loop system with time delay and data dropout is analyzed based on the theory of switching systems.

2. CONTROLLER DESIGN

Consider the discrete-time state-space model of the Multiple-Input Multiple-Output (MIMO) system as Eq. (1).

*Corresponding author's email: m.nasiri@iut.ac.ir

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k + w \\ y_k &= Cx_k + v \end{aligned} \tag{1}$$

Considering the assumptions of controllability, observability, and bounded network delay in forward and feedback channels and using Kalman filter as state observer and Linear Quadratic Regulator (LQR) controller, compensation for time delay and data dropout in the feedback channel will be done. The maximum delay in forward and feedback channels respectively represented as M_1 and N_1 which are positive integers, also the maximum number of data dropout in forward and feedback channels respectively represented as M_d and N_d which are positive integers. The network data dropout will be modeled by γ in the observer equations as shown in Eq. (2), which $\gamma = 1$ means the signal received by the controller and $\gamma = 0$ means data dropout.

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + \gamma_k K_k (y_k - C\hat{x}_{k|k-1}) \tag{2}$$

According to j that indicates occurred delay in the feedback channel, the predictor predicts the state variable as shown in Eq. (3).

$$\begin{aligned} \hat{x}_{k|k-j} &= A^j (I - \gamma_{k-j} K_{k-j} C)\hat{x}_{k-j|k-j-1} \\ &+ \sum_{n=1}^{j} A^{j-n} Bu_{k-j+n-1} + \gamma_{k-j} A^j K_{k-j} y_{k-j} \end{aligned} \tag{3}$$

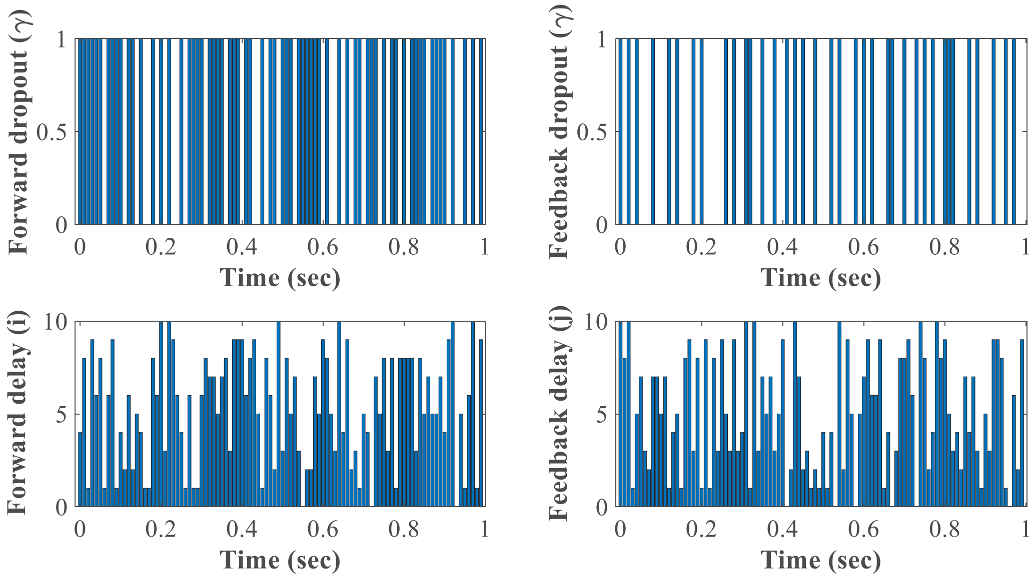

Fig. 1. Time-delay and data dropout in feedback and forward channels

Similar to the process performed to compensate for the feedback channel delay, can be express for the forward channel as well, that the result shown in Eq. (4).

$$\hat{x}_{k+M_1|k-j} = (A+BL)^{M_1+M_d}\,\hat{x}_{k|k-j} \tag{4}$$

The controller will send a set of predictions to the actuator side through the communication network as shown in Eq. (5).

$$\left[u^T_{k|k-j}, u^T_{k+1|k-j}, \ldots, u^T_{k+i|k-j}, \ldots, u^T_{k+M_1|k-j}, \ldots, u^T_{k+M_1+M_d|k-j}\right]^T \tag{5}$$

On the actuator side, the compensator will choose the proper control input to achieve desired performance.

3. STABILITY ANALYSIS

Delays in feedback and forward channels are bounded as shown in Eq. (6). Therefore, there are $4(N_1+1)(M_1+1)$ possible sets of delays and data dropout for stability analysis

$$\begin{aligned} i &= \{0,1,2,\ldots,M_1\} \\ j &= \{0,1,2,\ldots,N_1\} \end{aligned} \tag{6}$$

The vector of state variables for stability analysis is selected as shown in Eq. (7).

$$\begin{aligned} X(k) = \big[& x^T_k, x^T_{k-1}, \ldots, x^T_{k-N_1}, \ldots, x^T_{k-N_1-M_1}, \\ & u^T_{k-1}, u^T_{k-2}, \ldots, u^T_{k-N_1}, \ldots, u^T_{k-N_1-M_1}, \\ & \hat{x}^T_{k|k-1}, \ldots, \hat{x}^T_{k-N_1+1|k-N_1}, \ldots, \hat{x}^T_{k-N_1-M_1|k-N_1-M_1-1} \big] \end{aligned} \tag{7}$$

Eventually, the equations of the system with the observer and the controller can be expressed as Eq. (8).

$$X(k+1) = \Lambda X(k) \tag{8}$$

where $\Lambda \in R^{[2n(M_1+N_1+1)+m(M_1+N_1)]^2}$. If all the eigenvalues of the matrix Λ are within a unit circle, it can be concluded that the control system is asymptotically stable, also by using linear matrix inequalities and the implication of the switching systems stability analysis can be achieved.

4. RESULTS AND DISCUSSION

The dynamic equations of the rotary inverted pendulum are used to simulate the proposed control method. Moreover, the Makarov model is used for modeling the random bounded delays and data dropout as shown in Fig. 1.

Two general cases are investigated. First, the presence of data dropout in the communication network and then, the network without data dropout. These two cases are compared to understanding the effectiveness of the proposed control method on compensating delay problems on the networked control system. Also, when the delay in one of the forward or backward channels is equal to zero, the effects of time delay in another channel on the control system should be examined separately. As a result of the proposed control method, the performance of the system for controlling the inverted pendulum angle when the time delay in the forward channel is equal to zero and the time delay in the feedback channel increases step by step is shown in Fig. 2.

The simulation results of the control system presented in this paper are compared with the results obtained in [2] and the better performance of the proposed method is illustrated as shown in Fig. 3.

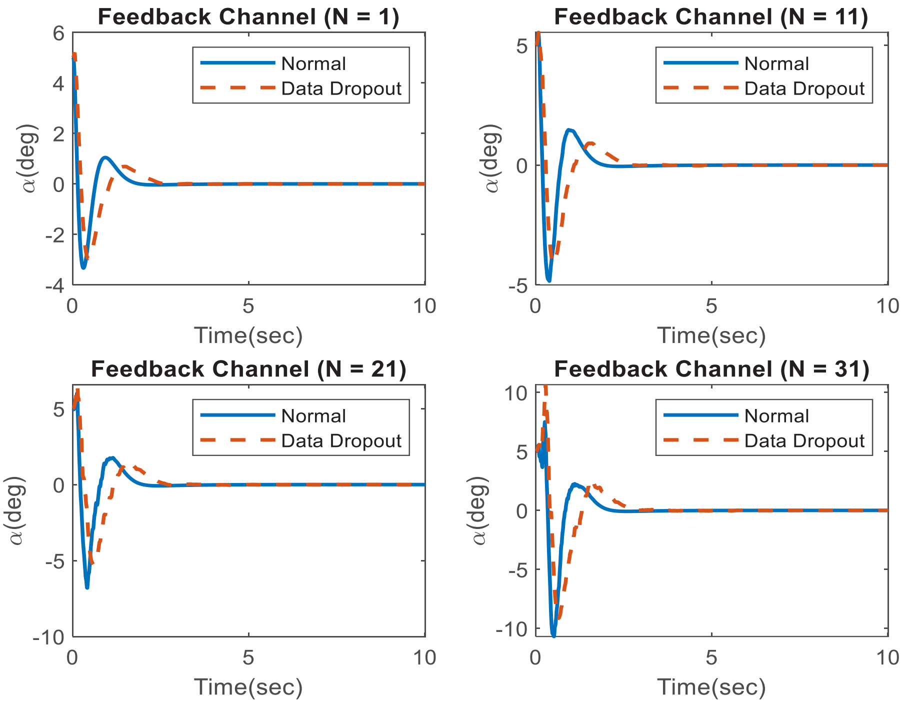

Fig. 2. Performance of the control system with or without data dropout

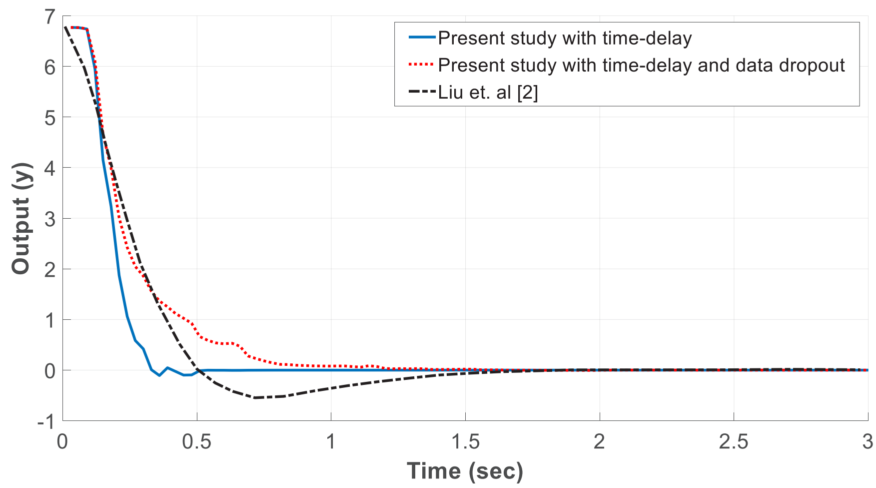

Fig. 3. Comparison and validation of the proposed method

5. CONCLUSIONS

The stability of the predictive method in network control systems has been investigated. The control strategy contains the LQR controller, Kalman observer, and state predictor. The dynamic equations of the system in the state-space are obtained by considering all the components of the system in the discrete-time state. The effect of time delay and data dropout on stability has been investigated using the approach of switching systems. Time delay and data dropout as switching signals create a set of dynamic modes for the system. The stability of the switching system is obtained by using matrix inequalities and the performance of the system in different cases of data dropout and time delay in the feedback and forward channels has been considered. The results obtained from a rotary inverted pendulum show a greater effect of data dropout on the instability of the system in the feedback channel compares to the forward channel.

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