An Approach to Reduce Network Delay and Packets Disorder with Network Control System

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Abstract – *This short examinations the predictive controller outline of pre-arranged systems with communication delays and information misfortune. A net-worked predictive control conspire is utilized to make up for communication delays and information misfortune effectively as opposed to latently. Based on analysis of the closed-loop networked predictive control systems, a design strategy of the predictive controller is proposed. The planned predective controller can accomplish the coveted control execution and further more ensure the systems strength. A numerical case shows the remuneration for correspondence deferral and information misfortune in organized systems utilizing the proposed predective controller plan system.*

***Key Words*: Communication delay, data loss, networked control systems (NCSs), predictive control , Network stability, packet loss, packet delay.**

1. INTRODUCTION

A feedback control system where in the control loop is barren through a real-time network is known as a networked control system (NCS), which includes fieldbus con-trol systems constructed on the origin of bus technology (e.g., DeviceNet, ControlNet, and LonWorks) and Internet-based control systems using general computer networks. The NCS is a totally conveyed continuous input control system that is a combination of sensors, controllers, actuators, and correspondence systems .The insertion of the communication network in the feedback control loop makes the analysis and the design of an NCS complex. In particular, the accompanying issues should be addressed [1], [2].

1) The network-induced delay (sensor-to-controller delay and controller-to-actuator delay) that happens while trading information among gadgets associated with the common system, which will be either steady or time differing, can corrupt the execution of control frameworks composed immediately and can even destabilize the systems.

2)The network can be seen as a web of inconsistent trans-mission ways. A few packets endure transmission delay as well as, surprisingly more dreadful, can be lost during transmission. Hence, how such packet dropouts influence the execution of a NCS is an issue that must be considered.

3) The plant outputs might be transmitted utilizing numerous system packets (so-called multiple packet transmission) because of the data transfer capacity and packet size imperatives of the network. Just a section or none of the packets might appear on the controller side by the time of control calculation because of the intercession of the network medium with other nodes on the network.

As there are an ever increasing number of uses of NCSs in industry, for example, activity, correspondence, flying, and space flight, more consideration around there has been paid to the plan, examination, and technology of the NCS [3]–[5]. For the most part, there are three types of NCS strategies: type 1—planning techniques that assurance network QoS; type 2—control strategies that certification systemk nature of execution (QoP); and sort 3—integrating schedul-ing and control strategies that consider both QoS and QoP. For type 1, the accompanying planning techniques have been created: a booking convention organized transporter sense numerous entrance with impact shirking in view of the IEEE 802.11 remote standard [6], a sampling time scheduling method of network bandwidth allocation and sampling period decision for multi-loop NCSs in virtue of the notion “window,” specifically, the administration window of every transmission information in network [7], a QoS remote control technique through a Process-Field-Bus token-passing protocol [8], and a remote QoS-based sampling strategy [9]. For type 2, there are numerous control techniques created for NCSs, for instance, the queuing method [10], the event-based technique [11], and the output feedback nonlinear NCS method[12].

For compose 3, the accompanying issues have been studied: the sampling period optimization issue under schedulability limitations [13], the optimal scheduling issue under both rate monotonic schedulability requirements and NCS security imperatives [2], and the NCS examination and simulation issue solved by two MATLAB-based toolboxes: Jitterbug and True-Time

What's more, the outline issue of the closed-loop NC within the sight of communication delays and data packet dropou has been tended to in [2] and [14]– [18]. NCSs under limited un-certain access delay and packet dropout effects impacts are defined as discrete-time switched systems with arbitrary switching, and afterward the plan issue of NCSs has been decreased to the comparing issue of switched systems [19], [20], which empowers us to apply the current speculations of switched systems to NCSs [21]. To diminish the traffic load, a tested information NCS plot has been introduced, and a few conditions for worldwide exponential stability of the closed-loop systems by means of state/output feedback without/with communication delays have been set up in [22]. A few issues identified with network data transfer capacity requirements and system movement clog in NCSs have been contemplated in [23] and [24]. Web based control has additionally been considered for practical applications, for instance, Internet-based control frameworks as a control device [25], [26] and Internet robots [27].

The recent research of NCSs mainly focuses on networked systems with some very strict assumptions on communication delay (e.g., constant delay or delay in either a feedback or for-ward channel). Most design methods of closed-loop NCSs have recently been obtained from direct applications of those design methods for time-delay systems [28], [29]. They are normally passive to reduce the effect of the communication delay and data loss in a conservative way. In fact, there is a challenging issue on NCSs: how to actively compensate for communication delays and overcome data dropouts and design the controller in a less conservative way. This brief utilizes a networked pre-dictive control scheme to compensate for communication delay in both the feedback and forward communication channels and also to avoid data dropout. It proposes a design strategy of the predictive controller for networked systems.

II. NETWORKED PREDICTIVE CONTROL SCHEME

Based on the location of networks in a system, there are many different structures for NCSs. For example, networks in an NCS can be located between the sensor and the controller, between the actuator and the controller, and/or between the reference and the controller. In this brief, the structure of a networked predictive control system for study is shown in Fig. 1

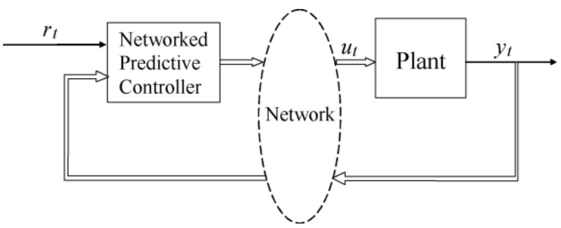

Fig. 1.Networked predictive control system.

For the sake of simplicity, the following assumptions are made: 1) The communication delay in the feedback channel (i.e., from the sensor to the controller) is bounded by n_b 2).The communication delay in the forward channel (i.e., from the controller to the actuator) is bounded by n_f. 3) The number of consecutive data package drops in both the feedback and forward channels is bounded by n_d . 4) The data transmitted through a network are with a time stamp.

In a practical NCS, there exists data loss. For instance, if the data packet does not arrive at a destination in a certain transmission time (i.e., the upper bound of the communication delay), it means that this data packet is lost based on commonly used network protocols. From the physical point of view, it is natural to assume that only a finite number of consecutive data dropouts can be tolerated in order to avoid the NCS becoming open loop. The time stamp of the data transmitted through a network is very important for NCSs. This is because a control sequence of a control system is based on time. In addition, the synchronization is also an issue in NCSs. There exist various ways to synchronize the time clocks in digital components (or computers). The problem of synchronization errors and their effects on feedback loops that are closed over communication networks has been studied by researchers, e.g., [30]. As this brief mainly discusses the stability of NCSs, it is assumed that the components in the system have been synchronized.

Consider the following linear discrete-time plant:

$$X_{t+1}=Ax_t + Bu_t$$
$$Y_t = Cx_t \qquad (1)$$

where x_t ⍰ ^{n} , y_t ⍰ ^{l}, and u_t ⍰ ^{m} are the state, output, and input vectors of the system, respectively, and A ⍰ $^{n\times n}$, B ⍰ $^{n\times m}$, and C ⍰ $^{l\times n}$ are the system matrices.

From assumptions 1–3, let $\tau = n_f + n_d$ and $k = n_b + n_d$. It is assumed that the states of the plant are not measurable. To obtain the state vector of the plant for the controller design on the controller side, an observer is designed as

$$\hat{x}_{t-k+1|t-k} = A\hat{x}_{t-k|t-k-1} + Bu_{t-k} + L_{(y_{t-k}-\hat{y}_{t-k})}$$

$$\hat{y}_{t-k} = C\hat{x}_{t-k|t-k-1} \qquad (2)$$

where $\hat{x}_{t-i|t-j}$ ⍰ ^{n} $(i < j)$ denotes the state prediction fortime $t - i$ on the basis of the information up to time $t - j$, $\hat{y}_t$ ⍰ ^{l} is the output vector of the observer at time t, and the gain matrix L ⍰ $^{n\times l}$, which can be designed using standard observer design approaches.

Although the observer provides a one-step ahead prediction of the states using the output at time $t - k$, the state predictions from time $t - k + 2$ to $t + \tau$ are still not known. Based on the information available on the controller side, the other state predictions up to time $t + \tau$ can be constructed by

$$\hat{x}_{t-k+i|t-k} = A\hat{x}_{t-k+i-1|t-k} + Bu_{t-k+i-1} \quad (3)$$

for $i = 2, 3, \ldots, k + \tau$. From assumptions 1–3, it is clear that both τ and k are fixed. Then, all control inputs from $t - k$ to $t + \tau - 1$ are available on the controller side, although some of them are not applied to the plant at time t. Thus, the state predictions given by (3) can be calculated based on the available output y_{t-k} of the system.

When the states of the plant are estimated, there are many control methods available for the system. To illustrate the networked predictive control strategy, which was proposed in [31], the observer-based state-feedback control method is employed. Therefore, the control prediction to be generated on the controller side is

$$u_{t+\tau|t-k} = k\hat{x}_{t+\tau|t-k} \quad (4)$$

where K ⍰ $^{m\times n}$ is the controller gain matrix. On the actuator side the control input will be taken as

$$u_t = u_{t-k-\tau} = k\hat{x}_{t|t-k-\tau} \quad (5)$$

It is clear that the delay can be compensated by the above control strategy. In [20], it has already been shown that the control performance of the closed-loop networked predictive control system is similar to the one without a network (i.e., the closed-loop local control system).

There are several ways to deal with the data loss in net-work communication protocols. For example, the lost data will be required to resend in the Transmission Control Protocol (TCP)/IP. However, in real-time NCSs, this TCP/IP mechanism will cause more communication delay and is not acceptable for some control systems. For the real-time data transmission in NCSs, the User Datagram Protocol/IP is widely used because of the short communication delay. Recently, there have been three main methods to deal with the control input data loss for real-time NCSs. Method 1 is that if the control input data drop, the control input is set to zero [32]. Method 2 is that if the control input data drop, the control input keeps the previous one until new data arrive [33]. Method 3 is that if the control input data drop, the control input uses the control prediction [20], [31]. These methods have advantages and disadvantages. Method 1 is simple, but the control input causes unsmooth switching, which may not be allowed in some systems, and it is very difficult to provide the desired control performance. Method 2 has a smooth switching control input, but it is hard to achieve the desired control performance. Method 3 provides the desired control performance, but it costs a little communication efficiency. In this brief, to deal with the data dropout, the following mechanism is used. In case the output data in the feedback channel drop, the following data at time t are sent from the sensor side to the controller side:

$$[\, y_t \quad y_{t-1} \quad \cdots y_{t-nd} \,] \quad (6)$$

Similarly, to prevent the control data loss in the forward chan-nel, the following control predictions at time t are sent from the controller side to the actuator side:

$$[\, u_{t+\tau|t-k} \quad u_{t+\tau-1|t-k-1} \quad \cdots \quad u_{t+nf|t-k-nd} \,] \quad (7)$$

It can be seen from (6) and (7) that some data transmitted through network are not used for the NCS. This will cost a little transmission efficiency, which is a disadvantage of the proposed strategy but is not a big issue because of fast communication networks. On the positive side, the main issues in NCSs, which are communication delays and data loss, can be solved by the above networked predictive control strategy.

III. DESIGN OF THE NETWORKED PREDICTIVE CONTROLLER

Since the communication delays and data loss are involved, the description of closed-loop NCSs plays a key role in the design of the predictive controller. An effective compact de-scription of closed-loop networked predictive control systems introduced in Section II is derived below. A strategy of designing the predictive controller for networked systems is given here. It is clear from (2) that if the time is shifted for k steps forward, the observer can be rewritten as

$$\hat{x}_{t+1|t} = A\hat{x}_{t|t-1} + Bu_t + L_{(yt-\hat{y}t)}$$

$$\hat{y}_t = C_{\hat{x}t|t-1} \quad (8)$$

Subtracting (8) from (1) result in the following state error equation :

$$e_{t+1} = (A-LC)_{eu} \quad (9)$$

where $e_t = x_t - x\hat{}_{t|t-1}$. From the state prediction equation (3), it can be obtained that

$$\hat{x}_{t+\tau|t-k} = A^{k+\tau-1}\hat{x}_{t-k+1|t-k} + \sum_{i=2}^{k+t} A^{k+\tau-i}Bu_{t+i-k-1} \quad (10)$$

Similarly

$$\hat{x}_{t+\tau|t-k+1} = A^{k+\tau-2}\hat{x}_{t-k+2|t-k+1} + \sum_{i=3}^{k+\tau} A^{k+\tau-i}Bu_{t+i-k-1}$$

$$= A^{k+\tau-2}(A\hat{x}_{t-k+2|t-k+1} + Bu_{t+i-k+1}$$

$$+ L_{(yt-k+1-\hat{y}t-k+1)})$$

$$+\sum_{i=3}^{k+\tau} A^{k+\tau-i}Bu_{t+i-k-1}$$

$$= A^{k+\tau-1}\hat{x}_{t-k+1|t-k} + \sum_{i=2}^{k+\tau} A^{k+\tau-i}Bu_{t+i-k-1}$$

$$+A^{k+\tau-2}LCe_{t-k+1} \quad (11)$$

which uses (2). Subtracting (11) from (10) yields the following:

$$\hat{x}_{t+\tau|t-k} = \hat{x}_{t+\tau|t-k+1} - A^{k+\tau-2}LC\, e_{t-k+1} \quad (12)$$

Using the above recursively result in

$$\hat{x}_{t+\tau|t-k} = \hat{x}_{t+\tau|t+\tau-1} - \sum_{i=0}^{k+\tau-2} A^i LC_{et+\tau-i-1} \quad (13)$$

Let $t + \tau$ be replaced by t in the above equation, which gives

$$\hat{x}_{t|t-k-\tau} = \hat{x}_{t|t-1} - \sum_{i=0}^{k+\tau-2} A^i LC_{et+t-i-1} \quad (14)$$

From the networked predictive control strategy, the control input of the plant in (5) is

$$u_t = K\hat{x}_{t|t-k-\tau} = K\left(\hat{x}_{t|t-1} - \sum_{i=0}^{k+\tau-2} A^i LC_{et-i-1}\right) \quad (15)$$

Substituting u_t in (1) by (15) lead to

$$x_{t+1} = Ax_{t|} + BK\left(\hat{x}_{t|t-1} - \sum_{i=0}^{k+\tau-2} A^i LC_{et-i-1}\right)$$

$$= Ax_{t|} + BK\left(x_{t-et} - \sum_{i=0}^{k+\tau-2} A^i LC_{et-i-1}\right)$$

$$= \left(Ax_{t|} + BK\right)\left(x_{t-et} - \sum_{i=0}^{k+\tau-2} A^i LC_{et-i-1}\right) \quad (16)$$

Therefore, it is clear from (9) and (16) that the closed-loop system can be described by

The above is equivalent to the following compact form:

$$\begin{Bmatrix} x_{t+1} = (A+BK)x_t - BKe_t - \sum_{i=0}^{k+\tau-2} BKA^i LC_{et-i-1} \\ e_{t-j+1} = (A-LC)e_{t-j}, \end{Bmatrix}$$

For j= 0,1 ………,k+ τ -1

(17)

To above is equation to the following compact form :

$$\begin{bmatrix} x_{t+1} \\ E_{t+1} \end{bmatrix} = \begin{pmatrix} \Gamma & \Theta(k-t) \\ 0 & \wedge \end{pmatrix} \begin{bmatrix} x_t \\ E_t \end{bmatrix} \quad (18)$$

Where E$_t$ =[e_t^T e_{t-1}^T …….. $e_{t-\tau-nb+1}^T$]^T $\in \Re^{n(\tau+nb)\times 1}$

, $\Gamma = A + BK \in \Re^{n\times n}$, $\wedge = diag\{A-LC \quad A-LC \quad A-LC\}$

$\in \Re^{n(\tau+nb)\times n(nb+\tau)}$,

$$\theta(k,\tau) = [-BK \quad -BKLC \quad -BKALC \quad -BKA^{K+\tau-2}LC \quad 0 \quad ....]$$

$\in \Re^{n*n(nb+\tau)}$ and $e^t = x_t - \hat{x}_{t|t-1}$

Therefore, with the networked predictive controller given by (5), the closed-loop Networked Predictive Control system can be described by (18). It is a known fact that an up-triangular system is stable if and only if its sub matrices in the diagonal line of the closed-loop system matrix are stable (see [34, Proposition 2.9]). Therefore, it is clear from (18) that the closed-loop networked predictive control system is stable if and only if the eigenvalues of matrices Γ and Λ are within the unit circle. This implies that the eigenvalues of matrices $(A + BK)$ and $(A - LC)$ must be within the unit circle. Clearly, the stability of the closed-loop networked predictive control systems is not related to communication delays. This is a significant step for the design of networked predictive control systems.

From the above, it indicates that the separation principle for the observer-based state feedback control is still held in the networked predictive control system. Therefore, the predictive controller of networked systems can be designed using the following two-stage design scheme.

1) Design the gain matrix L. This can follow the normal design procedure of observers.
2) Design the gain matrix K. This can be achieved using the same design procedure of local control systems (i.e., there is no network in the closed-loop system).

Since the networked predictive control method can provide the similar control performance as the one given by the local control system [31], the above design scheme largely simplifies the design procedure of the predictive controllers for networked systems.

IV. SIMULATED EXAMPLE

To illustrate the networked predictive control scheme, a servo control system was considered [21]. For the sampling period of 0.04 s, the discrete-time model of the servo system is described by

$$A = \begin{bmatrix} 1.120 & 0.213 & -0.335 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 0.0541 & 0.1150 & 0.0001 \end{bmatrix}$$

The initial conditions of the system states and the observer states were set to be [5, 5, −5] and [0, 0, 0], respectively. Following the design strategy of the networked predictive con-troller described in Section III, let the desired poles of the closed-loop state feedback control system without a network be [−0.4, 0.7 + 0.6*i*, 0.7 − 0.6*i*] and the desired poles of the observer be [0.1, 0.3, 0.5]. Using the pole assignment method, the observer gain matrix L and the control gain matrix K were designed to be

$$L = \begin{bmatrix} 4.9113 \\ -0.4055 \\ 9.2845 \end{bmatrix}, K = \begin{bmatrix} -0.0541 & 0.5030 & 0.0050 \end{bmatrix}$$

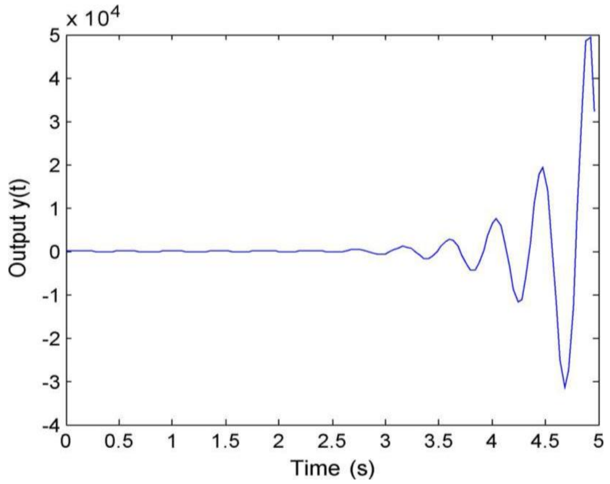

Fig. 2. Networked control without compensating for the communication delay.

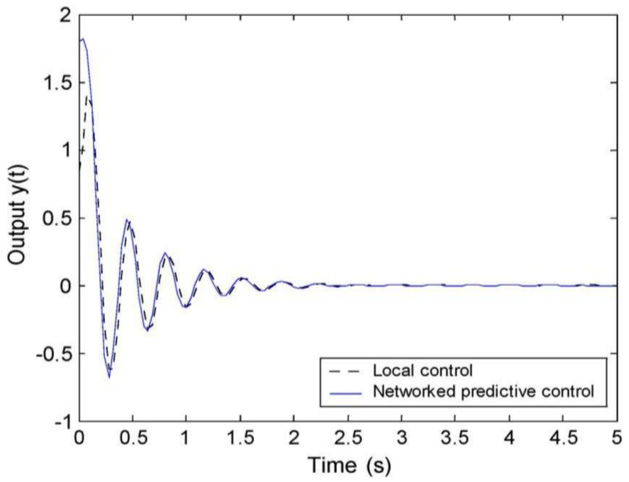

Fig. 3 Networked predictive control.

Two cases are considered below.

Case 1) Networked control without delay compensation. In this case, the delay in the communication chan-nels is not compensated, that is, the networked predictive control strategy is not employed, but a normal feedback control is used. It is also assumed that there exists a one-step communication delay in the forward channel and no delay in the feedback channel. Therefore, the controller is given by $u_t = K\hat{x}_{t-1/t-2}$. The simulation results in Fig. 2 show that the system is unstable.

Case 2) Networked predictive control. The networked pre-dictive control strategy is used to compensate for the communication delay. The parameters of the networks in the forward and feedback channels are $n_f = 3$ (the maximum delay in the forward channel), $n_b = 2$ (the maximum delay in the feed-back channel), and $n_d = 1$ (the maximum number of consecutive data loss in each communication channel).

The simulation results given in Fig. 3, where, for the sake of comparison, the output curve of the networked predictive con-trol system is shifted for seven sampling steps backward (seven is the maximum communication delay in the system, which is the worst one), demonstrate that the closed-loop system is stable, and the performance of the closed-loop networked predictive control system is the same as that of the local closed-loop control system (i.e., there is no network in the closed-loop system), except the first several steps. When the communication delay increases, the performance and the stability of the closed-loop networked predictive control do not modify.

V. DISCUSSION AND CONCLUSION

This brief has addressed a design problem of NCSs with communication delay and data loss. The networked predictive control scheme has been introduced to compensate for com-munication delay and data loss. A strategy of designing the predictive controller for networked systems has been proposed so that the closed-loop networked predictive control system can achieve the desired control performance and also guarantee the system stability.

Being compared with other existing networked control meth-ods, for example, given in [15], [21], and [22], the proposed predictive control scheme for NCSs in this brief has two important advantages. One is that the control performance of closed-loop NCSs is the same as that of the closed-loop control system without a network, except in the initial period of the system response. The other is that the necessary and sufficient stability conditions of the closed-loop NCS are not related to communication delays and data loss. The above advantages have been confirmed by the simulation results given in this brief.

In this brief, only ideal plants (i.e., linear models) to be controlled have been considered for the design of networked predictive control systems. Most practical control systems are nonlinear with internal uncertainties (e.g., modeling errors) and external uncertainties (e.g., random disturbances), which was discussed in [35]. The proposed control scheme in this brief is currently being studied for the above practical systems. Although there still exist various challenging issues, it is con-jectured that similar results may be achievable.

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