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Event-Triggered Predictive Networked Control Systems with Network Imperfections and External Disturbance

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ABSTRACT

This paper presents a novel event-triggered predictive control (ETPC) approach for the stabilization of discrete-time output- feedback networked control systems (NCSs). The studied NCS is considered to be subject to both random external input and output disturbances, and network imperfections including random communication delay, random packet dropout, packet disorder, limitation of network bandwidth, and network resources. In the proposed algorithm, an observer-based event detector is designed for reducing the number of sent packets through the communication network using the estimated system states by the Luenberger observer. In this way, the system's energy resources are saved and network-induced effects are skipped. A switched predictive controller with multiple gains are used to compensate for network-induced effects. Controller gains are designed compatible with different possible values of delays and packet dropouts. A novel augmented representation of the state-space equations of the system is derived to design observer gain and controller gains. The asymptotic stability of the system is guaranteed by designing the observer and controller based on the Lyapunov function through solving linear matrix inequalities (LMIs). Putting all the aforementioned points together has made the whole framework presented in this paper a comprehensive one. The effectiveness of the proposed approach is demonstrated by comparative simulation results.

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I. INTRODUCTION

Networked control systems (NCSs) are systems that utilize the communication network for data exchange between different parts of the system. The insertion of the communication network in traditional control systems has led to more flexible systems with easier maintenance [1]. Robot networks [2], intelligent transportation systems [3], laparoscopy [4], and cyber-physical systems [5] are some of the applications of NCSs. On the other hand; since there are always imperfections in real networks; the use of the communication network has introduced new challenges to conventional control systems. Some of these challenges are network bandwidth limitation, delay, packet dropout, congestion, and packet disorder. Dealing with these issues has received noticeable attention in the last decade. Readers are referred to surveys [6]-[8] and the references therein. Delay and packet dropout are the most important challenges among all the network-induced effects. Therefore, researchers have paid considerable attention

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to different compensation methods for these two challenges.

An effective method for confronting with delay and the packet dropout effect; after their occurrence; is using the predictive control method which can be either centralized or decentralized. Paper [9] is an example of the decentralized predictive control method in which a robust decentralized model predictive control scheme for systems subject to state and input constraints is introduced. Papers [10] and [11] are examples of the centralized predictive control method. In [10], a switched predictive control method for NCSs exposed to both delay and packet dropout is investigated. In [11], an algorithm based on Kalman filter for systems exposed to time delay is introduced.

Another method is reducing the number of sent packets by confining them to those which are critically necessary for maintaining the system's performance at the desired level. This approach is called the event-triggered control (ETC) method. In conventional time-triggered control method system state(s)/output(s) are sampled periodically and all of them are sent through the network. However, in the ETC method, the sampled data is sent only if a predetermined inequality is violated. Readers are referred to the survey [12] and the references therein.

By combining predictive control and ETC in networked control systems, an effective approach called the event-triggered predictive control (ETPC) method was introduced. Controlling spacecraft rendezvous hovering phases [13], freeway traffic [14], and embedded artificial pancreas system [15] are some of the wide applications of the ETPC method.

In [16], a cost function is proposed for calculating the required control signal for the stabilization of the system using an ETPC method, but neither delay nor packet dropout is considered. In [17], an ETPC method is investigated for output feedback NCSs exposed to delay and packet dropout, but no disturbance is considered. Reference [18] addresses the ETPC problem for NCSs subject to communication delay, in which either the value of the communication delay is less or more than the sampling time are discussed separately. In [19], the ETPC method is studied using a fuzzy predictive controller for NCSs with packet dropout. Reference [20] discusses the ETPC method for NCSs subject to communication delay while using two event-detector blocks, one in the sensor side and the other on the controller side.

In [21], an ETPC strategy is proposed for solving the existence of an unsynchronized delay in both sensor-to-controller and controller-to-actuator channels. Paper [22] uses a Luenberger observer for estimating the system states and utilizes an event-triggered mechanism for saving network resources. Moreover, an augmented model and a piecewise linear model are introduced to derive the stability condition in the presence of network delay.

In [23], a state-feedback NCS under delay, packet loss, and limited network resources is studied. An ETPC scheme is proposed in which, similar to the current paper, a switched controller is deployed; however, unlike the present paper, no disturbance is considered. A gain scheduled extended state observer is employed in the ETPC scheme proposed in [24] which stabilizes the NCS in the presence of delay, packet dropout, packet disorder, and input disturbance. Unlike the present paper, [24] has not considered output disturbance and has not used a switched controller.

The system studied in this paper is a linear time-invariant system exposed to random input and output external disturbances. Network-induced delay, packet dropout, and packet disorder along with the limitation of network bandwidth and resources are taken into account. Since system states are required for calculating the control signal, an observer is utilized for estimating the system state based on the system output sampled by the sensor. The estimated system state is then passed to the "event detector" block which determined whether a pre-determined event has occurred. If the event has happened, the last estimated system state is sent to the predictive controller through the feedback network channel. The "event detector" block determines the necessity of each piece of data for transmitting to the controller and, thus, significantly saves network bandwidth and resources.

The data sent to the controller is exposed to network-induced delay, packet dropout, and packet disorder. Therefore, a predictive controller along with a buffer is utilized for compensating the network effects. The data sent through the feedback channel is first received by the "Buffer 1" block which decides whether the received data is newer than the data already in the buffer. The buffer block keeps the newest data and passes it to the "controller" block. For increasing the compatibility of the controller with different values of network delay and packet dropout, multiple gains are considered for the controller, so the resultant controller is a switching predictive controller.

The control signal sent to the actuator side is also subject to delay and packet dropout, so a data packet is created by the controller which contains different values of control signal compatible with different possible values of delay and packet dropout. This data packet is then received on the actuator side by the selector block. This block is designed such that it can deal with packet disorder in addition to delay and packet dropout. The data packet first entered the "Buffer 2" block which acts similarly to "Buffer 1". It keeps the newest data packet and passes it to the "control signal selector" block which chooses the appropriate control signal among different control signals in the data packet and passes it to the actuator to be applied to the plant. The event detector condition and controller and observer gains are designed based on the Lyapunov function, so that the asymptotic stability of the system in the presence of the aforementioned network imperfections is guaranteed.

Unlike many other papers in which the disturbance effect is either neglected or compensated through specific blocks in the system's architecture; which leads to more complexity and energy consumption in the NCS; in this paper the disturbance effect problem is resolved while designing the ETPC method. Furthermore, in order to take into account external disturbances and network imperfections, a novel augmented representation of the state-space equations of the system is derived. The augmented representation of the system can be used as a suitable base for analyzing systems with different control methods in other works.

The remainder of this paper is organized as follows: The investigated system and the structure for the implementation of the proposed ETPC method are described in Section 2. In section 3 the main results are explained in which two derived theorems for the asymptotic stability of the proposed ETPC method are included. Section 4 is dedicated to presenting the effectiveness of the proposed method by two comparative simulation results. Finally, the conclusions are included in Section 5.

Notation. Throughout this paper, $\Re^n$ and $\Re^{n\times m}$ are the n-dimensional and $n\times m$-dimensional Euclidean space, respectively. The superscript "-1" denotes the inverse of an invertible matrix, and the superscript "T" denotes the transpose of a matrix or a vector. "I" and "0" represent the identity matrix and the zero matrix with appropriate dimensions, respectively. The inequality $P<0$ indicates the negative-definiteness of the symmetric matrix P. The symbol "$*$" denotes a term induced by symmetry in a symmetric matrix. $\|v\|_2$ represents the second Euclidean norm of the vector v.

II. System Description

The studied networked control system is described as

$$x(k+1)=Ax(k)+Bu(k)+E_1w_1(k) \quad (1)$$

$$y(k)=Cx(k)+E_2w_2(k) \quad (2)$$

$$x(0)=x_0 \quad (3)$$

where $x\in\Re^n$, $u\in\Re^m$ and $y\in\Re^l$ denote the state vector, control input, and system output, respectively; $w_1\in\Re^p$ and $w_2\in\Re^q$ are input disturbance and output disturbance, respectively, and both of them belong to $L_2(0,+\infty)$; A,B,C,E_1 and E_2 are known constant matrices with appropriate dimensions; and the initial value of the system state is denoted by x_0.

The proposed structure of the event-triggered predictive NCS in this paper is depicted in Fig. 1. At each instant k, the observer estimates the system state; then, the event detector decides whether an event has happened or not. If an event has happened, $\hat{x}(k)$ is sent to the controller through the network; if not, $\hat{x}(k)$ is discarded. The predictive controller generates a data packet containing predictive control signals based on the last received data and sends the sequence to the actuator. On the actuator side, first, a selector selects the appropriate control signal among the received predictive control signals based on the delay imposed on the last received data packet. Then, the selected control signal is sent to the actuator in order to be applied to the plant.

The following assumptions are considered for the NCS in this paper:

Assumption 1. [17] The sensor, controller and actuator are time-driven with the same sampling period T and the packets sent through the network are with time stamps.

Assumption 2.[17] The number of network-induced packet losses in the feedback and feedforward channels are denoted by L_{fb} and L_{fw}, respectively, and both are random numbers. The upper bounds of L_{fb} and L_{fw} are L_1 and L_2, respectively.

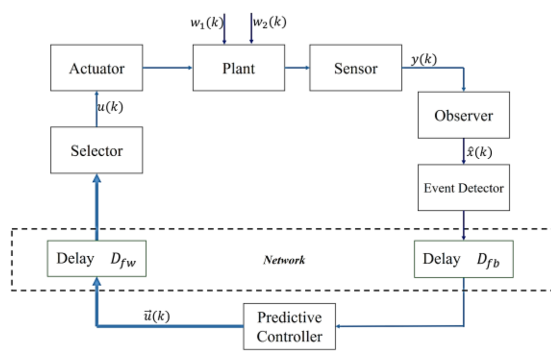

Fig. 1. The proposed structure of the event-triggered predictive NCS.

Assumption 3.[17] The random network-induced delay in the feedback and feedforward channels are denoted by D_{fb} and D_{fw}, respectively. The upper bounds of D_{fb} and

D_{fw} are D_1 and D_2, respectively.

Assumption 4. Without loss of generality, it is considered that

$$\alpha_1\|w_1(k)\|_2^2 \le \beta_1\|x(k)\|_2^2 \tag{4}$$

$$\alpha_2\|w_2(k)\|_2^2 \le \beta_2\|x(k)\|_2^2 \tag{5}$$

in which α_i and β_i, $i = 1,2$, are four constant values.

Assumption 5. Without loss of generality, it is assumed that the sizes of w_1, w_2, and y are the same, which means that $l = p = q$. This can happen by adding enough '0's to those vectors with a smaller size.

A. *Observer-based Event Detector*

The proposed observer for the NCS is the Luenberger observer which is described as

$$\hat{x}(k+1) = A\hat{x}(k) + Bu(k) + L(y(k) - C\hat{x}(k)). \tag{6}$$

$\hat{x}$ and u are the observed state and the input of the observer at instant k, respectively. Matrix L is to be designed such that the asymptotic stability of the system is guaranteed.

In order to reduce unnecessary data transmission in the feedback network, an event detector is considered. Using an ETC scheme saves network bandwidth and energy resources. At each instant, a triggering condition is checked. If the condition is violated, the last sampled data is sent through the network; otherwise, it is discarded. In this paper, the triggering condition is as

$$k_{i+1} = \begin{cases} \min\{k| \left(\hat{x}(k) - \hat{x}(t_i)\right)^T \Phi_1 \left(\hat{x}(k) - \hat{x}(t_i)\right)\} > \hat{x}^T(k)\Phi_2\hat{x}(k), & k < k_i + R + 1 \\ k_i + R + 1, & k \ge k_i + R + 1 \end{cases} \tag{7}$$

where Φ_1 and Φ_2 are known positive definite symmetric matrices; t_i is the last instant a data packet was sent through the network. The condition states that, after a data packet is sent at k_i, for R instants, the inequality is checked. If no violation occurs during these R instants, the newest sampled data at $k_i + R + 1$ is sent, whether a violation occurs or not.

Thereby, at each sampling instant k, the sensor samples the system output ($y(k)$) and passes it to the observer. The observer estimates the system states ($\hat{x}(k)$) using Equ. (4). The estimated state is then sent to the "event detector" block. The "event detector" block decides based on Equ. (7) whether $\hat{x}(k)$ must be sent to the controller or not.

B. *Predictive Controller*

Fig. 2 demonstrates the internal architecture of the predictive controller in the NCS. A buffer is used to store the latest packet received through the feedback channel. In order to deal with the packet disorder, at each instant, only that packet with the newest timestamp is kept and the older packets are discarded.

Fig. 2. The internal structure of the predictive controller

For the system without time delay, the control signal is generated based on the equation

$$u(k_i) = K_0\hat{x}(k_i) \tag{8}$$

where $K_0 \in \Re^{m\times n}$ is the control gain matrix which will be designed later.

Each sent data may be affected by network delay and packet loss. A suitable approach for generating the proper control signal by the predictive controller is using a controller with different constant gains, as

$$u_{k_i-f+i|k_i-f} = K_i\hat{x}(k_i - f) \tag{9}$$

where $i = 1,2,\dots,f, f \in \{1,\dots,D_{fb} + L_{fb}\}$. $u_{k_i-f+i|k_i-f}$ is the predictive control signal for instant $k_i - f + i$ based on the available data from instant $k_i - f$. K_i is the corresponding controller gain in order to predict the control signal i step(s) ahead.

Generated control signals are supposed to be sent to the actuator and are exposed to delay and packet loss in the feedforward channel. If the generated control signal based on a sent packet by event detector at instant k_i is not lost during the transmission, then it will be used at instant $k_i + D_{fb} + L_{fb} + D_{fw} + L_{fw}$ on the actuator side. Thus, by setting $N = D_{fb} + L_{fb} + D_{fw} + L_{fw}$, $N + 1$ different controller gains must be considered.

The packet generated by the predictive controller is as

$$\vec{u}(k) = [u_{k|k_i}^T \ u_{k+1|k_i}^T \ u_{k+2|k_i}^T \ \dots \ u_{k+l|k_i}^T]^T. \tag{10}$$

k_i denotes the instant in which the newest data ($\hat{x}(k_i)$) available on the controller side was sent by the event detector. l is as $l = D_{fw} + L_{fw}$ and $k \ge k_i$.

Consequently, the state space equations of the system can be rewritten as

$$x(k+1) = Ax(k) + BK_i\hat{x}(k-i) + E_1w_1(k) \tag{11}$$

and the observer equation is as

$$\begin{aligned}\hat{x}(k+1) &= A\hat{x}(k) + BK_i\hat{x}(k-i) \\ &\quad + L\big(Cx(k) + E_2w_2(k) - C\hat{x}(k)\big) \\ &= (A - LC)\hat{x}(k) + BK_i\hat{x}(k-i) \\ &\quad + LCx(k) + LE_2w_2(k)\end{aligned} \tag{12}$$

Therefore, the resultant augmented state-space equations of the NCS are

$$\bar{x}(k+1) = \bar{A}_j\bar{x}(k+1) + \bar{E}_1\bar{w}_1(k) \quad , j = 1, \dots, N, \tag{13}$$

$$y(k) = \bar{C}\bar{x}(k+1) + \bar{E}_2 w_2(k) \tag{14}$$

in which

$$\bar{x}(k) = [x^T(k), x^T(k-1), \dots, x^T(k-N), \hat{x}^T(k), \hat{x}^T(k-1), \dots, \hat{x}^T(k-N)]^T$$

$$\bar{E}_1 = \begin{bmatrix} E_1 & 0_{(N+1)n\times q} \\ 0_{(2N+1)n\times q} & LE_2 \\ & 0_{Nn\times q} \end{bmatrix}, \qquad \bar{E}_2 = [E_2 \quad 0_{l\times q}],$$

$$\bar{C} = [C \quad 0_{l\times(2N+1)n}],$$

$$\bar{w}_1(k) = \begin{bmatrix} w_1(k) \\ w_2(k) \end{bmatrix}, \qquad \bar{A}_j = \begin{bmatrix} A_1 & A_{2j} \\ A_3 & A_{4j} \end{bmatrix}$$

where

$$A_1 = \begin{bmatrix} A & 0_{n\times Nn} \\ I_{Nn} & 0_{Nn\times n} \end{bmatrix},$$

$$A_{2j} = \begin{bmatrix} 0_n & BK_j & 0_{n\times(N-j)} \\ & 0_{(N+1)n\times(N+1)n} & \end{bmatrix}, \quad A_3 = \begin{bmatrix} LC & 0_{n\times Nn} \\ 0_{Nn\times(N+1)n} & \end{bmatrix},$$

$$A_{4j} = \begin{bmatrix} A - LC & 0_{n\times(j-1)n} & BK_j & 0_{n\times(N-j)} \\ & I_{Nn} & 0_{Nn\times n} & \end{bmatrix}.$$

C. Selector

Fig. 3 presents the internal structure of the selector block. Buffer 2 is the block solving packet disorder problem. This buffer compares the timestamp of the newly received packet through the feedforward channel with the one already existing in the buffer. If the received packet has newer timestamp, it is stored in the buffer and used by the actuator; otherwise, it is ignored and the existing one in the buffer is used by the actuator until a newer packet becomes available.

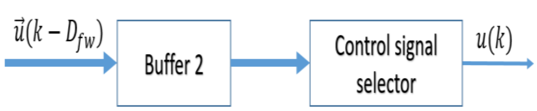

Fig. 3. The internal structure of the selector block

Then, the control signal selector selects the appropriate control signal among different elements of the packet received from the controller.

III. MAIN RESULTS

Lemma 1.[10] (Schur complement): For a symmetric matrix $L = \begin{bmatrix} L_{11} & L_{12} \\ L_{12}^T & L_{22} \end{bmatrix}$, the following statements are equivalent:

(1) $L < 0$

(2) $L_{11} < 0, L_{22} - L_{12}^T L_{11}^{-1} L_{12} < 0$

(3) $L_{22} < 0, L_{11} - L_{12} L_{22}^{-1} L_{12}^T < 0$

Theorem 1. The system described by Equs. (13) and (14) is asymptotically stable if the following LMI holds:

$$\Omega(A_j, P) = \begin{bmatrix} \bar{A}_j^T P \bar{A}_j - P + \beta_1 I & \bar{A}_j^T P \bar{E}_1 \\ * & \bar{E}_1^T P \bar{E}_1 - \alpha_1 I \end{bmatrix} < 0,$$

$$j = 1,2, \dots, N. \tag{15}$$

Proof. The following Lyapunov functions are considered for the system described by Equs. (11) and (12)

$$V_j(x(k)) = \bar{x}^T(k) P \bar{x}(k). \quad j = 1,2, \dots, N$$

Based on Assumption 4, $\alpha_1\|w_1(k)\|_2^2 \le \beta_1\|x(k)\|_2^2$; then,

$$\Delta V_j - \alpha_1\|w_1(k)\|_2^2 + \beta_1\|x(k)\|_2^2$$

$$= V_j\big(x(k+1)\big) - V_j\big(x(k)\big) - \alpha_1\|w_1(k)\|_2^2 + \beta_1\|x(k)\|_2^2$$

$$= \bar{x}^T(k+1)P\bar{x}(k+1) - \bar{x}^T(k)P\bar{x}(k) - \alpha_1 w_1^T(k)w_1(k) + \beta_1 x^T(k)x(k)$$

$$= (\bar{A}_j\bar{x}(k) + \bar{E}_1 w_1(k))^T P \left(\bar{A}_j\bar{x}(k) + \bar{E}_1 w_1(k)\right) - \bar{x}^T(k)P\bar{x}(k) - \alpha_1 w_1^T(k)w_1(k) + \beta_1 x^T(k)x(k)$$

$$= [\bar{x}^T(k) \quad w_1^T(k)] \begin{bmatrix} \bar{A}_j^T P \bar{A}_j - P + \beta_1 I & \bar{A}_j^T P \bar{E}_1 \\ * & \bar{E}_1^T P \bar{E}_1 - \alpha_1 I \end{bmatrix} \begin{bmatrix} \bar{x}(k) \\ w_1(k) \end{bmatrix}$$

so if $\Omega(A_j, P) < 0$, then $\Delta V_j - \alpha_1\|w_1(k)\|_2^2 + \beta_1\|x(k)\|_2^2 < 0$, and it is concluded that $\Delta V_j < 0$. Thus, based on the Lyapunov function theorem, the asymptotic stability of such system is guaranteed.

After determining the sufficient condition for the asymptotic stability of the system, the controller gains must be designed. For this purpose, matrices $\bar{A}_j$ and $\bar{E}_1$ are rewritten in new forms.

By defining matrices

$$\tilde{B} = \begin{bmatrix} B \\ 0_{Nn\times m} \\ B \\ 0_{Nn\times m} \end{bmatrix}, \qquad \tilde{I} = \begin{bmatrix} 0_{(N+1)n\times n} \\ I_n \\ 0_{Nn\times n} \end{bmatrix},$$

$$\tilde{C} = [C \quad 0_{l\times Nn} \quad -C \quad 0_{l\times Nn}],$$

$$\bar{I}_j = [0_{n\times(N+j+1)n}\ I_n\ 0_{n\times(N-j)n}],$$

$$\tilde{A} = \begin{bmatrix} A_1 & 0_{(N+1)n} \\ 0_{(N+1)n} & A_1 \end{bmatrix}$$

$\bar{A}_j$ can be written as

$$\bar{A}_j = \tilde{A} + \tilde{B}K_j\bar{I}_j + \tilde{I}L\tilde{C}, \tag{16}$$

and by defining

$$\tilde{E}_1 = \begin{bmatrix} E_1 & 0_{2(N+1)n\times q} \\ 0_{(2N+1)n\times q} & \end{bmatrix},$$

$$\hat{I} = \begin{bmatrix} 0_{(N+1)n\times n} \\ I_n \\ 0_{Nn\times n} \end{bmatrix}, \qquad \tilde{E}_2 = [0_{l\times q} \quad I_q]$$

$\bar{E}_1$ can be written as

$$\bar{E}_1 = \tilde{E}_1 + \hat{I}L\tilde{E}_2. \tag{17}$$

Theorem 2. Suppose that there exist positive definite matrix P and matrices L and $K_j, j \in \bar{N}, \bar{N} = \{0,1,\dots,N\}$ such that matrix inequalities

$$\Gamma(A_j,P) = \begin{bmatrix} -P+\alpha_1 I & * & * \\ 0 & -\beta_1 I & * \\ \tilde{A}+\tilde{B}K_j\bar{I}_j+\tilde{I}L\tilde{C} & \tilde{E}_1+\hat{I}L\tilde{E}_2 & -P \end{bmatrix} < 0, \quad j \in \bar{N} \tag{18}$$

hold. Then, the system described by Equs. (13) and (14) with the controllers described by Equ. (9) is asymptotically stable.

Proof. Following the result obtained from Theorem 1, $\Omega(A_j,P)$ can be written as

$$\begin{bmatrix} \bar{A}_j^T P\bar{A}_j - P + \beta_1 I & \bar{A}_j^T P\bar{E}_1 \\ * & \bar{E}_1^T P\bar{E}_1 - \alpha_1 I \end{bmatrix} =$$

$$\begin{bmatrix} -P+\beta_1 I & 0 \\ * & -\alpha_1 I \end{bmatrix} + \begin{bmatrix} \bar{A}_j^T P \\ \bar{E}_1^T P \end{bmatrix} P^{-1} [P\bar{A}_j \quad P\bar{E}_1].$$

Based on Lemma 1 and Equs. (13) and (14),

$$\begin{bmatrix} -P+\beta_1 I & 0 \\ * & -\alpha_1 I \end{bmatrix} + \begin{bmatrix} \bar{A}_j^T P \\ \bar{E}_1^T P \end{bmatrix} P^{-1} [P\bar{A}_j \quad P\bar{E}_1] =$$

$$\begin{bmatrix} -P+\alpha_1 I & * & * \\ 0 & -\beta_1 I & * \\ \bar{A}_j & \bar{E}_1 & -P \end{bmatrix} =$$

$$\begin{bmatrix} -P+\alpha_1 I & * & * \\ 0 & -\beta_1 I & * \\ \tilde{A}+\tilde{B}K_j\bar{I}_j+\tilde{I}L\tilde{C} & \tilde{E}_1+\hat{I}L\tilde{E}_2 & -P \end{bmatrix} \tag{19}$$

Since in Theorem 1 the sufficient condition for the asymptotic stability of the system is $\Omega(A_j,P) < 0$; based on Equ. (1٩) and Lemma 1; it is equivalent to $\Gamma(A_j,P) < 0$.

IV. SIMULATION

In this section, the effectiveness of the proposed algorithm in this paper is demonstrated via two examples. Both examples are chosen from the literature and both systems are affected by delay, packet disorder, packet dropout, and input and output disturbances.

Example 1. In this example the plant studied in [10] is considered, and the stability of the system under network imperfections and disturbances is investigated. The ETPC scheme proposed here and the algorithm proposed in [10] are both applied to the system and the results are compared with each other from the stability point of view.

The state space equations of the system are

$$x(k+1) = Ax(k) + Bu(k) + E_1 w_1(k)$$

$$y(k) = Cx(k) + E_2 w_2(k)$$

in which

$$A = \begin{bmatrix} -0.85 & 0.271 & 0.488 \\ 0.482 & 0.1 & 0.24 \\ 0.002 & 0.3681 & 0.707 \end{bmatrix}, B = \begin{bmatrix} 0.5 & 0.1 \\ 0.3 & -0.4 \\ 0.2 & 0.5 \end{bmatrix},$$

$$C = \begin{bmatrix} 0.1 & 0.2 & 1 \\ 0.4 & 0.3 & 0.1 \end{bmatrix}, \quad E_1 = I_{3\times3}, E_2 = 0.1I_{2\times2}.$$

The constants in Assumption 2 are selected as $\alpha_1 = 1$, $\beta_1 = 0.01$, $\alpha_2 = 1$ and $\beta_2 = 0.01$. The sampling period is set as $T = 0.01$. The upper bounds of random transmission delays and consecutive packet loss in feedback and feedforward channels are set as $D_1 = 2T, D_2 = T, L_1 = 1$ and $L_2 = 1$. The initial states of the plant and observer are $x(0) = [0.98, 0.8, -1.5]^T$ and $\hat{x}(0) = [0.8, 0.9, -1.35]$, respectively, and the upper bound of non-triggering is set as $R = 3T$.

First, the stability of the system under the proposed algorithm in [10] is investigated. Figs. 4 and 5 present the instability of the system states and system output, respectively, in the presence of delay and packet loss without compensation. In Figs. 6 and 7, the system states and system outputs using the proposed ETPC method in this paper are illustrated, respectively. Time diagrams in these two Figs. 6 and 7 show the effectiveness of the proposed method in this paper in compensation of both delay and packet loss and also demonstrate the rapid convergence of the system states towards stability.

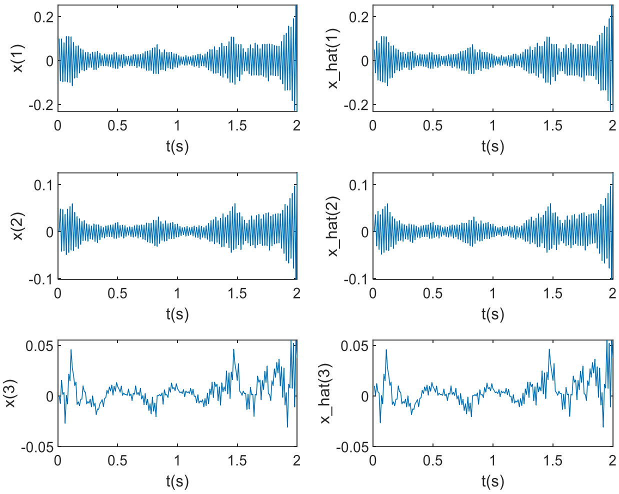

Fig. 4. System states under the algorithm proposed in [10] for Example 1.

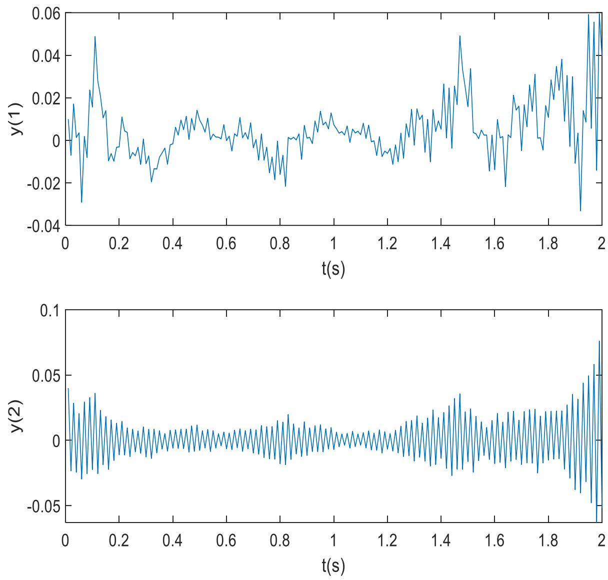

Fig. 5. System outputs under the algorithm proposed in [10] for Example 1.

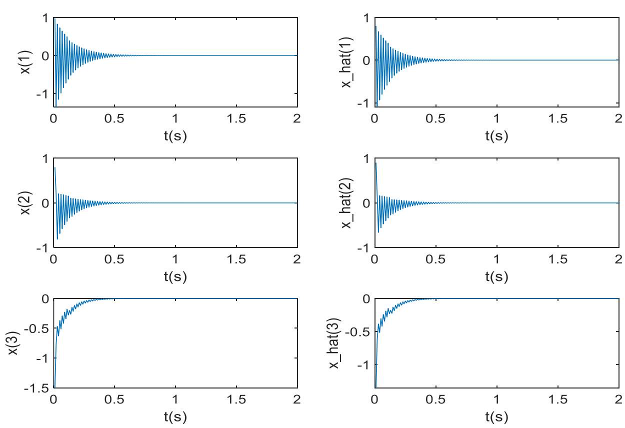

Fig. 6. System states and estimation of system states by the observer under the algorithm proposed in this paper for Example 1.

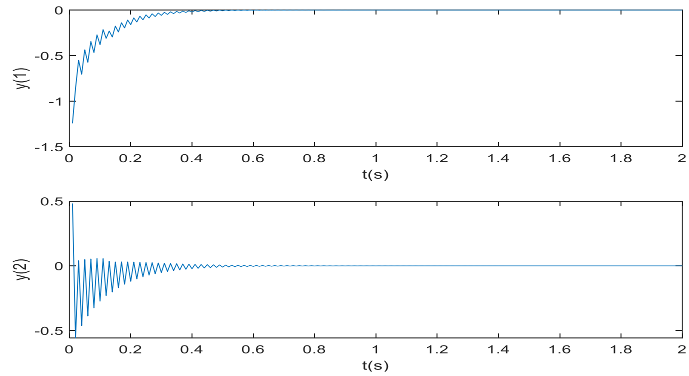

Fig. 7. System outputs under the algorithm proposed in this paper for Example 1.

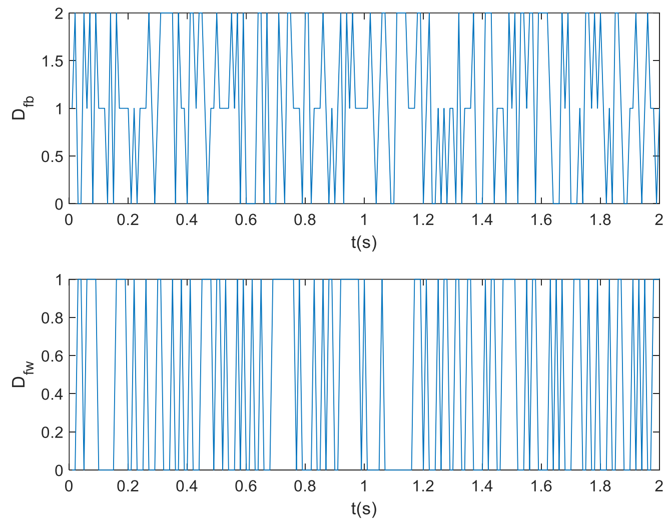

Fig. 8. Random delay in the feedback and feedforward channel of the communication network for Example 1.

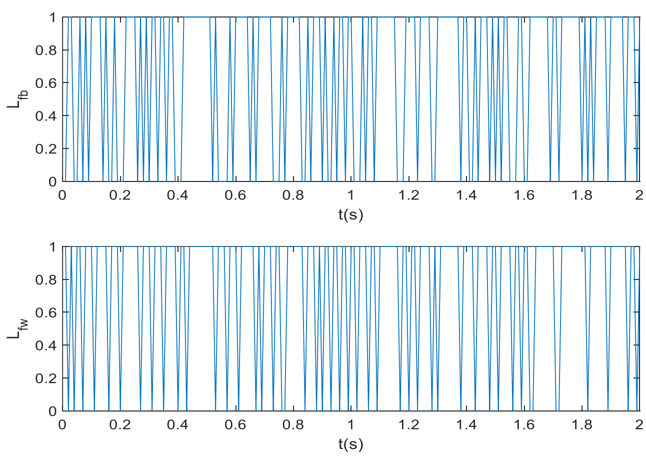

Fig. 9. Random packet loss in the feedback and feedforward channel of the communication network for Example 1.

Comparing the real system states and estimated system states in Fig. 6 represents the precision of the observer's estimations, which confirms the choice of the observer and the precision of the observer gain calculation via the proposed LMIs. The number of triggering instants shows that the event detector triggers 49 times among 200 sampling instants, which means more than 75% reduction in the number of sent packets by using the proposed control scheme in this paper.

Figs. 7 and 8 display the randomness of the occurrence of delay and packet loss, respectively, in both feedback and feedforward channels. They show that the simulated system has been considered in one of the worst cases in which almost every packet is exposed to both delay and packet loss in both feedback and feedforward channels.

Example 2. In this example the effectiveness of the algorithm is checked on the system studied in [23]. The studied system is similar to the one investigated in [10] but the method is different. The state space equations of the system are

$$x(k+1) = Ax(k) + Bu(k) + E_1 w_1(k)$$

$$y(k) = Cx(k) + E_2 w_2(k)$$

in which matrices are set as

$$A = \begin{bmatrix} -0.85 & 0.271 & -0.488 \\ 0.482 & 0.1 & 0.24 \\ 0.002 & 0.3681 & 0.707 \end{bmatrix}, \quad B = \begin{bmatrix} 0.5 & 0.1 \\ 0.3 & -0.4 \\ 0.2 & 0.5 \end{bmatrix},$$

$$C = \begin{bmatrix} 0.1 & 0.2 & 1 \\ 0.4 & 0.3 & 0.1 \end{bmatrix}$$

$$E_1 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \\ 0 & 1 \end{bmatrix}, \quad E_2 = I_{2\times 2}.$$

The constants considered in Assumption 2 are selected similar to Example 1, as $\alpha_1 = 1$, $\beta_1 = 0.01$, $\alpha_2 = 1$ and $\beta_2 = 0.01$. The sampling period is set as $T = 0.01$. The upper bounds of random transmission delays and consecutive packet loss in feedback and feedforward channels are set as $D_1 = 2T, D_2 = T, L_1 = 1$ and $L_2 = 1$. The initial states of the plant and observer are $x(0) = [-0.4, 0.1, 0.2]^T$ and $\hat{x}(0) = [0.38, 0.08, 0.16]$, respectively, and the upper bound of non-triggering is set as $R = 3T$.

Figs. 10 and 11 investigate the stability of the system in the presence of network imperfections and disturbances, while the ETPC algorithm in [23] is applied to the system. Both Figs. 10 and 11 show that the system cannot tolerate the network imperfections, and system states and system output diverge.

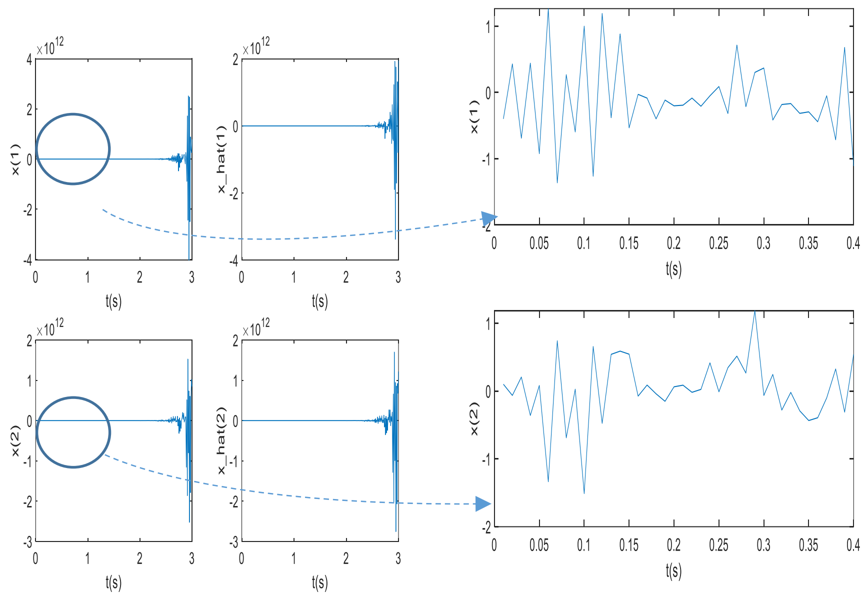

Fig. 10. System states under the algorithm proposed in [23] for Example 2.

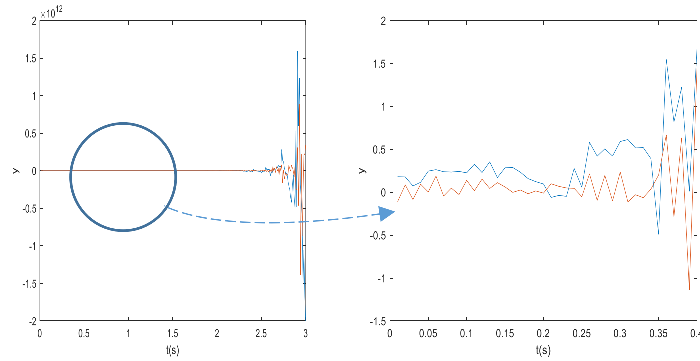

Fig. 11. System outputs under the algorithm proposed in [23] for Example 2.

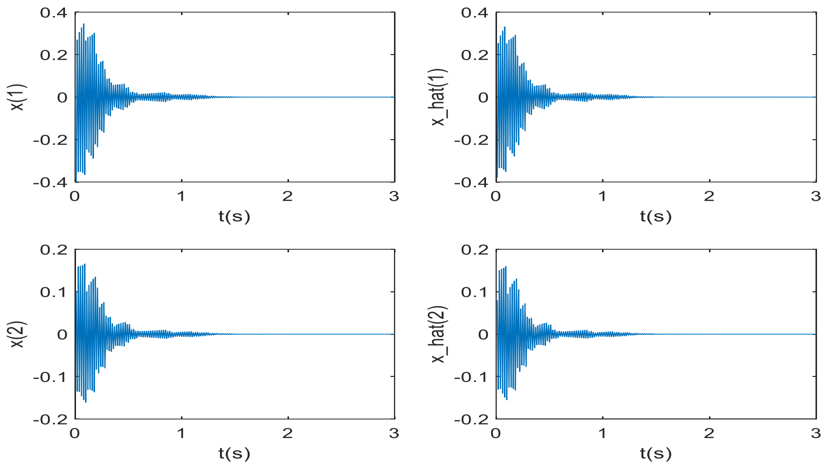

Fig. 12. System states and estimation of system states by the observer under the algorithm proposed in this paper for Example 2.

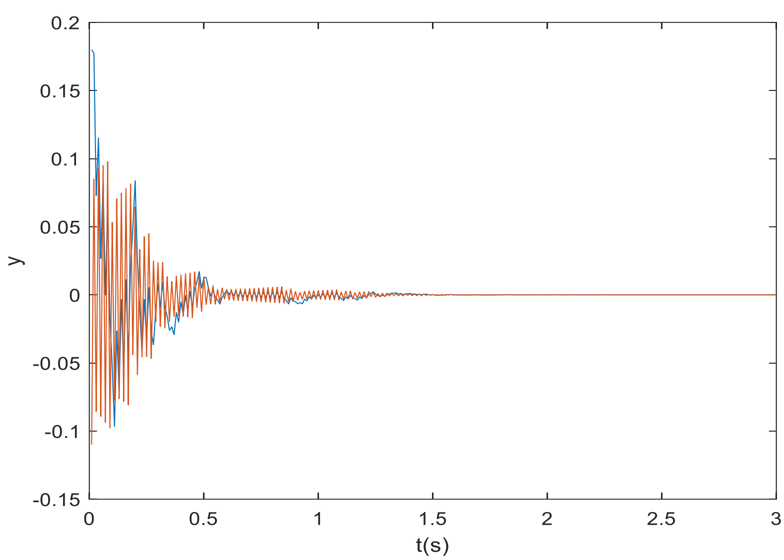

Fig. 13. System outputs under the algorithm proposed in this paper for Example 1.

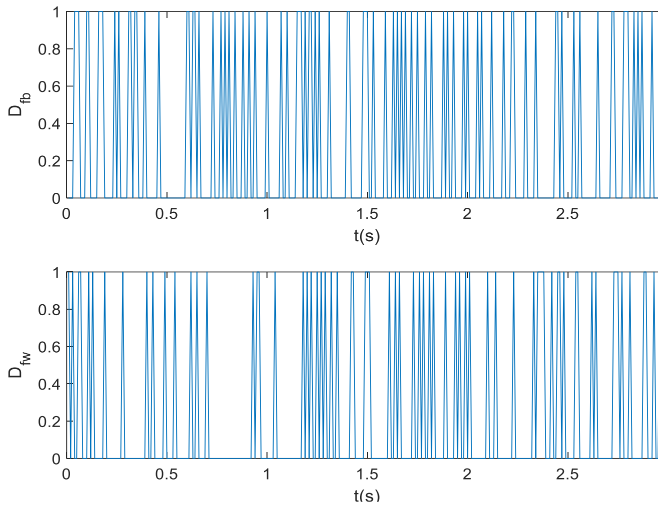

Fig. 14. Random delay in the feedback and feedforward channel of the communication network for Example 2.

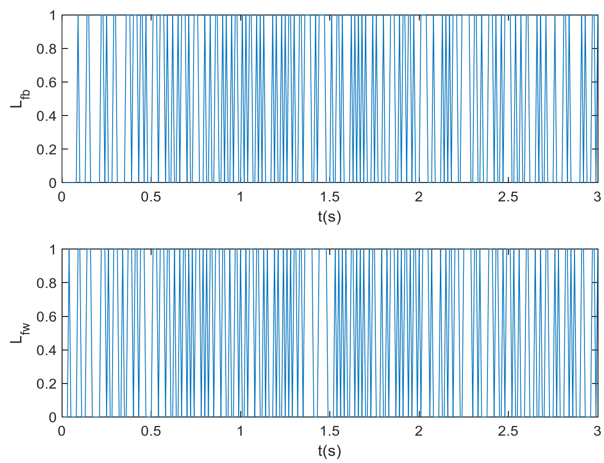

Fig. 15. Random packet loss in the feedback and feedforward channel of the communication network for Example 2.

Figs. 12 and 13 depict the effectiveness of the proposed algorithm in this paper for stabilizing the system exposed to the network imperfections and disturbances. Figs. 12 and 13 show the rapid convergence of system states and system output, respectively, clarifying that network imperfections are highly compensated by the proposed algorithm in this paper. Based on Fig. 12, since the trajectories of the estimation of system states follow the trajectories of the system states, the appropriate choice of the observer and the precision of the observer gain calculated are confirmed.

The number of triggering instants shows that the event detector triggers 246 times among 500 sampling instants. More than 50% reduction in the number of sent packets using the control scheme proposed in this paper, indicates the great effectiveness of the control scheme in saving network bandwidth and resources.

Figs. 14 and 15 display the randomness of the occurrence of delay and packet loss, respectively, in both feedback and feedforward channels. They show that; similar to example 1; the simulated system has been considered in one of the worst cases in which almost every packet is exposed to both delay and packet loss in both feedback and feedforward channels.

V. Conclusion

In this paper, the problem of designing an asymptotically stable ETPC for an output-feedback networked control system was investigated. The considered NCS structure was assumed to be exposed to external input and output disturbances and network imperfections, including delay, packet dropout, packet disorder, and limitation of network bandwidth and resources. An observer-based event-detector was exerted to confine the sent data packets to those which were critically necessary for the stabilization of the system. Thus, network resources and bandwidth were saved, and the effect of network transmission on the entire process was noticeably limited.

Using a switched predictive controller with multiple gains led to a more flexible controller than conventional controllers with one fixed gain. By deriving a new augmented representation of state-space equations of the system, observer gain and controller gains were calculated through solving LMIs. Thus, the asymptotic stability of the system was guaranteed based on the Lyapunov function theorem. Two selectors were also employed on the controller side and the actuator side of the network to deal with packet disorder. To demonstrate the effectiveness of the proposed ETPC method, two examples were presented. Both simulated systems were considered in one of their worst cases in which almost every packet was exposed to random delay and random packet loss in the communication network. Simulation results depicted the rapid convergence of the system states and outputs in both examples under the algorithm proposed in this paper, while system states and system outputs diverged under the algorithms proposed in papers [10] and [22]. The number of packets sent through the network showed more than 75% reduction in the first example and more than 50% reduction in the second example, in comparison with the conventional time-triggered controllers. This reduction has led to saving network bandwidth and network resources noticeably.

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