Paper:

Suppression of Disturbances in Networked Control Systems Based on Adaptive Model Predictive Control and Equivalent-Input-Disturbance Approach

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This paper presents an adaptive control strategy to compensate for packet losses, time delay, and exogenous disturbances in a networked control system (NCS). An adaptive model predictive controller (AMPC) combined with an equivalent-input-disturbance (EID) estimator to improve the control performance in the structure of an NCS. We use the AMPC to design an adaptive rate, which guarantees the control performance and the tracking performance of the controlled plant with time delay. The EID estimator compensates for the exogenous disturbances and pocket losses. A comparison with the conventional EID approach through the experiments demonstrates the validity of the AMPC-EID control method.

Keywords: Networked control system (NCS); equivalent input disturbance (EID); adaptive model predictive control (AMPC); disturbance rejection.

1. Introduction

The emergence and development of the Internet, as well as the emergence of the network control system (NCS), has attracted the attention of many researchers [1]. An NCS is a control system in which components of the control loop exchange information through the network. Its characteristic is that the command and feedback of the control system are transmitted in the form of packets in the network [2]. The NCS has many challenges including a new control strategy, reliability of communication and fault-tolerant control technology, and so on.

The research of control field mainly includes predictive controller, delay compensation technology [3], stability analysis [4], packet losses suppression [5], and exogenous disturbances suppression [6]. Although the conventional approaches have made breakthrough progress in dealing with 1-2 of these problems respectively, when these problems appear in an NCS at the same time, an effective method in dealing with these problems is particularly important.

An accurate object parameter model is the basis of modern control theory. The industrial process is often time-varying, nonlinear, with strong coupling and uncertainty, so it is difficult to obtain the accurate object parameter model, which will greatly reduce the control effect. Model predictive control (MPC) is an algorithm for the above problems [7]. Predictive control consists of a predictive model, feedback correction, rolling optimization, and reference trajectory. This method has the advantages of easy modeling, strong robustness, and good dynamic control performance. Adaptive model predictive control can effectively track the state of the system and does not need to know the specific information of the controlled object, so it has been widely used in the field of automatic control [8].

In the active disturbance suppression methods, the equivalent-input-disturbance (EID) method combines the advantages of disturbance observer (DO) and extended state observer (ESO) [9]. Add gain matrix, stable zero, an internal model of disturbance, and improved compensator to improve the performance of the EID in recent research. Some successful application of the EID method has been verified, such as delay system [11, 12], nonlinear system [13], and uncertainty system [14]. Since the model of the state observer is invariant, the disturbance suppression performance will be reduced in the face of a large parameter jump. Therefore, the combination of AMPC and EID is meaningful.

Aiming at the problem of poor control performance caused by time-varying uncertainty and external disturbance of the controlled object, a method based on AMPC and EID (called AMPC-EID hereafter) is proposed in this paper. The main function of AMPC is to design an adaptive rate, which can deal with the influence of the change of the parameters of the controlled object on the control performance. EID effectively compensates for exogenous disturbance, packet loss, and time delay.

This paper is organized as follows: Section 2 describes the configuration of AMPC-EID control system. Section 3 discusses the stability of the control system and designs the parameters. Section 4 verifies the AMPC-EID method through numerical simulations. And Section 5 presents some concluding remarks.

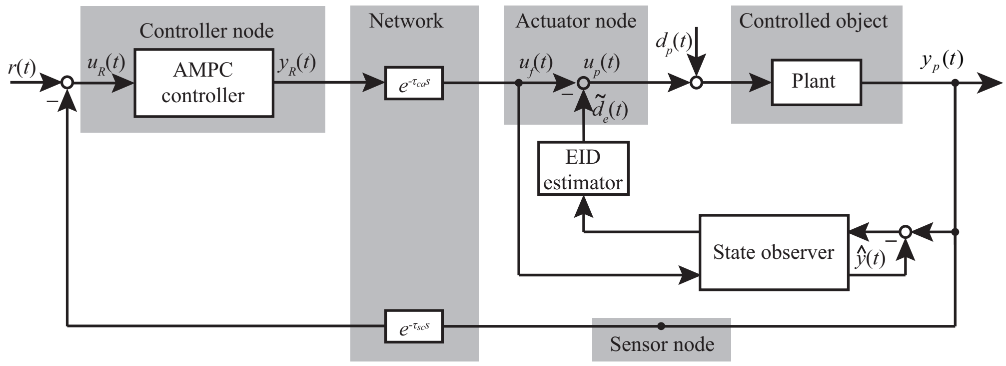

Fig. 1. Structure of an AMPC-EID-based NCS

2. Configuration of AMPC-EID Control System

In an AMPC-EID based NCS (Fig. 1), the controller, the controller node, the network, the plant, and the sensor node make up the whole control system. Time delays usually exist in two parts in the network: τ_{sc} and τ_{ca}, are the main issues that affect the stability of the system.

The plant is

$$\begin{cases} \dot{x}_p(t) = A_p x_p(t) + B_p \xi(t) u_p(t) + B_{dp} d_p(t) \\ y_p(t) = C_p x_p(t) \end{cases} \quad (1)$$

where $\xi(t)$ is an indicator of received packets; $x_p(t)$, $u_p(t)$, and $y_p(t)$ are the state, input, and output of the plant, respectively; A_p, B_p, B_{dp}, and C_p are constant matrices; and $d_p(t)$ is a bounded exogenous disturbance;

Let $d_\xi(u_p(t))$ represents packet losses, and

$$\begin{cases} \xi(t) u_p(t) = u_p(t) + d_\xi(u_p(t)) \\ d_\xi(u_p(t)) = [1 - \xi(t)] u_p(t). \end{cases} \quad (2)$$

Assume that

$$|d_\xi(u_p(t))| \leq d_{\xi M}, \ \forall t > 0 \quad (3)$$

holds for a positive constant $d_{\xi M}$.

$d_\xi(u_p(t))$ and $d_p(t)$ are considered as exogenous disturbances of the system according to the definition of an EID. There is a signal, $d_e(t)$ has the same effect on the output as $d_\xi(u_p(t))$ and $d_p(t)$ do. The plant (1) is rewritten as

$$\begin{cases} \dot{x}_p(t) = A_p x_p(t) + B_p[u_p(t) + d_e(t)] \\ y_p(t) = C_p x_p(t). \end{cases} \quad (4)$$

To observe the state of the plant (1), an observer is

$$\begin{cases} \dot{\hat{x}}_p(t) = A_p \hat{x}_p(t) + L[y_p(t) - C_p \hat{x}_p(t)] + B_p u_f(t) \\ \hat{y}_p(t) = C_p \hat{x}_p(t) \end{cases} \quad (5)$$

where L is the observer gain; $\hat{x}_p(t)$ is the state of the observer; and $u_f(t)$, $\hat{y}_p(t)$ are the input and output of the observer.

The state-feedback control law $u_f(t)$ is

$$u_f(t) = y_R(t - \tau_{ca}). \quad (6)$$

As discussed in [9], the estimation of the EID in present paper, $\hat{d}_e(t)$ in Fig. 1 is

$$\hat{d}_e(t) = B^+ L C_p[x_p(t) - \hat{x}_p(t)] + u_f(t) - u_p(t) \quad . \quad (7)$$

where $B^+ = (B_p^{\mathrm{T}} B_p)^{-1} B_p^{\mathrm{T}}$.

The lowpass filter is

$$\begin{cases} \dot{x}_F(t) = A_F x_F(t) + B_F \hat{d}_e(t) \\ \tilde{d}_e(t) = C_F x_F(t) \end{cases} \quad (8)$$

where and A_F, B_F and C_F are real matrices, $x_F(t)$ is the state of filter, $\tilde{d}_e(t)$ is the filtered EID. The transfer function of the filter $F(s)$ satisfies $|F(j\omega)| \approx 1, \ \forall \omega \in [0, \omega_r]$, ω_r is the highest angular frequency selected for disturbance estimation. And the cut-off frequency of the lowpass filter is usually chosen to be $5-10$ times as ω_r.

The control input of EID-based closed-loop control system is

$$u_p(t) = u_f(t) - \tilde{d}_e(t). \quad (9)$$

To develop an adaptive parameter estimation algorithm, we discretize the model of plant (4) and obtain the state equation of AMPC controller

$$\begin{cases} x_p(k+1) = A_c x_p(k) + B_c u_p(k) + B_v v(k) + B_d d_p(k) \\ y_p(k) = C_c x_p(k) + D_v v(k) + D_d d_p(k). \end{cases} \quad (10)$$

where matrixes A_c, B_c, B_d, B_v, C_c, D_v, and D_d are time-varying parameter matrixes; v is the input measurement interference; The variable k is the current control time.

3. Stability analysis and the parameters design of AMPC-EID Control System

In the system design, It is feasible to design controller parameters from the stability condition. This section discusses the stability condition and controller design of the AMPC-EID control system.

3.1. Stability Analysis

The exogenous signals do not affect the stability condition of the control system. Thus set them to be zero. Define $\Delta x_p(t) = x_p(t) - \hat{x}_p(t)$. Fig. 2 is redrawn from the

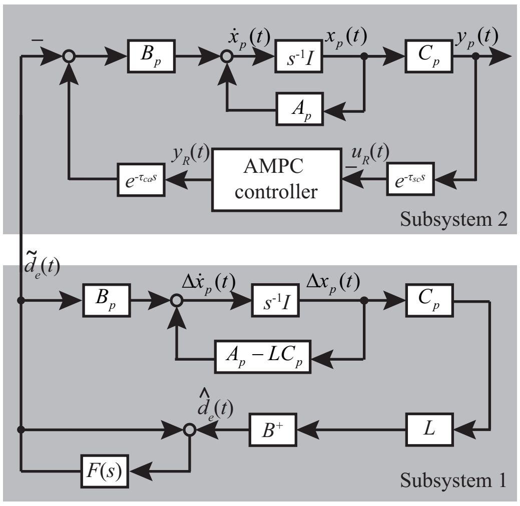

Fig. 2. Configuration of AMPC-EID control system.

relationship between objects in the AMPC-EID control system.

According to Separation Theorem [16], the control signal is transmitted from subsystem 1 to subsystem 2 [Fig. 2]. When subsystem 1 and subsystem 2 are stable, the whole system is stable.

3.2. Disturbance Rejection

In Subsystem 1, a dual system of the plant (1) is

$$\begin{cases} \dot{x}_d(t) = A_p^{\mathrm{T}} x_d(t) + C_p^{\mathrm{T}} u_d(t) \\ y_d(t) = B_p^{\mathrm{T}} x_d(t). \end{cases} \quad \ldots\ldots \quad (11)$$

A state feedback parameterized by a scalar $\rho > 0$ is considered as

$$u_d(t) = L_\rho^{\mathrm{T}} x_d(t). \quad \ldots\ldots \quad (12)$$

Applying perfect regulation [15], an L_ρ^{T} can be obtained that ensures

$$\lim_{\rho \to \infty} [sI - (A_p - L_\rho C_p)]^{-1} B_p = 0. \quad \ldots\ldots \quad (13)$$

Set the transfer function from $\tilde{d}_e(t)$ to $\hat{d}_e(t)$ as

$$G_e(s) = B^+(sI - A_p)[sI - (A_p - LC_p)]^{-1} B_p. \quad . \quad (14)$$

We can get that $[sI - (A_p - LC_p)]^{-1} B_p$ is part of $G_e(s)$. A suitble ρ makes $\|G_e F\|_\infty < 1$. Therefore, the given low-pass filter and L, which satisfy the stability condition and anti-disturbance ability of subsystem 1, can be obtained.

3.3. AMPC Controller Design

In Subsystem 2, to design an AMPC controller, it is necessary to develop a suitable adaptive parameter estimation method, which can explicitly consider future model improvement. Set the control period to be the same as the simulation step and the system input and output to be constant. Use the continuous linear method, the Simpons rule, and the expm function to update the internal model matrix. Therefore, combining definitions in (10), the matrix A_d and B_d are described as

$$\begin{cases} A_d = \mathrm{expm}(A_c \times T_s),\ B_d = (h/3) \times A_i \times B_c, \\ A_i = \mathrm{eye}(n_x) + A_d + 4\mathrm{expm}(A_c h) \\ \qquad + 2\mathrm{expm}(2A_c h) + 4\mathrm{expm}(3A_c h). \end{cases} \quad (15)$$

where A_i is the state matrix corresponding to each segment of the unit step size; h is the length of each segment in unit step, $h = T_s/4$; n_x is the dimension of state quantity.

According to the updated model information of each control cycle, we use the deviation between the reference system information and the current system information to design an incremental model. This model is described as

$$\begin{cases} x_p(k+1) = \bar{x}_p + A_d(x_p(k) - \bar{x}_p) + B_d(u_p(k) - \bar{u}_p) \\ y_p(k) = \bar{y}_p + C_c(x_p(k) - \bar{x}_p) + D_v(u_p(k) - \bar{u}_p). \end{cases} \quad (16)$$

where $\bar{x}_p$ is the system state; $\bar{y}_p$ is the output of system state; $\bar{u}_p$ is the system input.

In the process of controlling the plant, the expected stable following is realized by the deviation between the output and the reference input. Considering the stability of the controlled plant, we set the limit constraints on the control input of the controlled plant as

$$u_{min}(t+k) \leq u(t+k) \leq u_{max}(t+k) \quad \ldots\ldots \quad (17)$$

where $[-3; -1.13] \leq u(t+k) \leq [1.13; 3]$.

Relaxation variables $J(k)$ are introduced into the objective function to increase the feasible solution

$$J(k) = \sum_{i=1}^{N_p} ||y(k+i|t) - \bar{y}(k+i|t)||_Q^2 + p\varepsilon^2. \quad . \quad . \quad (18)$$

where N_p is the prediction time domain; p is the weight coefficient; ε is relaxation factor; Q is a weight matrix.

In the process of assigning the weight of the output variables of the objective function, we use the Optimization Toolbox to solve the corresponding control sequence, and take the first element of the control sequence as the control incremental input system, enter the next control cycle, and repeat the process continuously, to realize the AMPC control.

4. Case Study

In plant (1)

$$A_p = \begin{bmatrix} -2 & 0 \\ 4 & -5 \end{bmatrix}, B_p = \begin{bmatrix} 4 \\ 0 \end{bmatrix}, B_{dp} = \begin{bmatrix} 1 \\ 1.2 \end{bmatrix},$$
$$C_p = \begin{bmatrix} 5 & 1.2 \end{bmatrix}.$$

In the system, the time delays τ_{ca} and τ_{sc} were random delays, and the maximums of them were 0.1 s and 0.2 s, respectively. And the reference input

$$r(t) = 1200\ \mathrm{N} \quad \ldots\ldots \quad (19)$$

From time 10 s to 20 s, let the exogenous disturbance $d_p(t)$ be

$$d_p(t) = 15(\sin 4\pi t + \cos 2\pi t + \sin \pi t + \sin 0.5\pi t). (20)$$

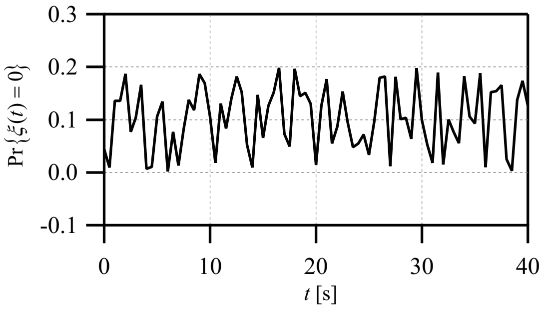

Fig. 3. Packet losses in AMPC-EID-based NCS.

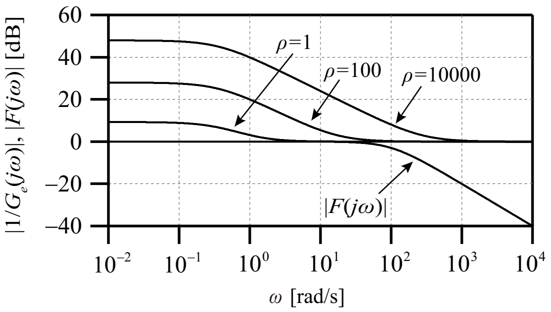

Fig. 4. Tuning results of ρ for prescribed $F(s)$.

Considering the possible characteristics of the exogenous disturbance. Chose ω_r to be 30 rad/s, the parameters of filter are selected as

$$A_F = -300,\ B_F = 300,\ C_F = 1. \quad \dots \dots \quad (21)$$

A performance index for the system (11) was

$$J_d = \int_0^{\infty} \{\rho x_d^{\mathrm{T}}(t) Q_d x_d(t) + R_d u_d^2(t)\} dt \quad \dots \quad (22)$$

where

$$Q_d = \mathrm{diag}\{1,\ 10^{-4},\ 10^{-4}\},\ R_d = 1. \quad \dots \quad (23)$$

Tun the parameter ρ to guarantee $\|G_e F\|_\infty < 1$, draw a Bode figure [Fig. 4], then found $\rho = 10^4$, and the parameter of the state observer was

$$L = [86.04\ \ 0.43]^{\mathrm{T}}. \quad \dots \dots \quad (24)$$

In the NCS, the probability distribution of packet losses in the NCS was a random number in the range [0, 0.2] (Fig. 3). That means the probability of control input $u_p(t)$ receives the signal from the network is random.

In the AMPC controller, setting the value of control time domain $N_c = 2$ and the value of prediction time domain $N_p = 10$. Simulation results in Fig. 5 show that the EID estimator estimates the external disturbance effectively from the the comparison of $d_p(t)$ and $\tilde{d}_e(t)$. And the control method effectively compensated for the exogenous disturbances and results in the output $y_p(t)$ with the low tracking error. During the disturbance adding time, the maximum tracking error is just 6.61 N.

When compared with the conventional EID method, the

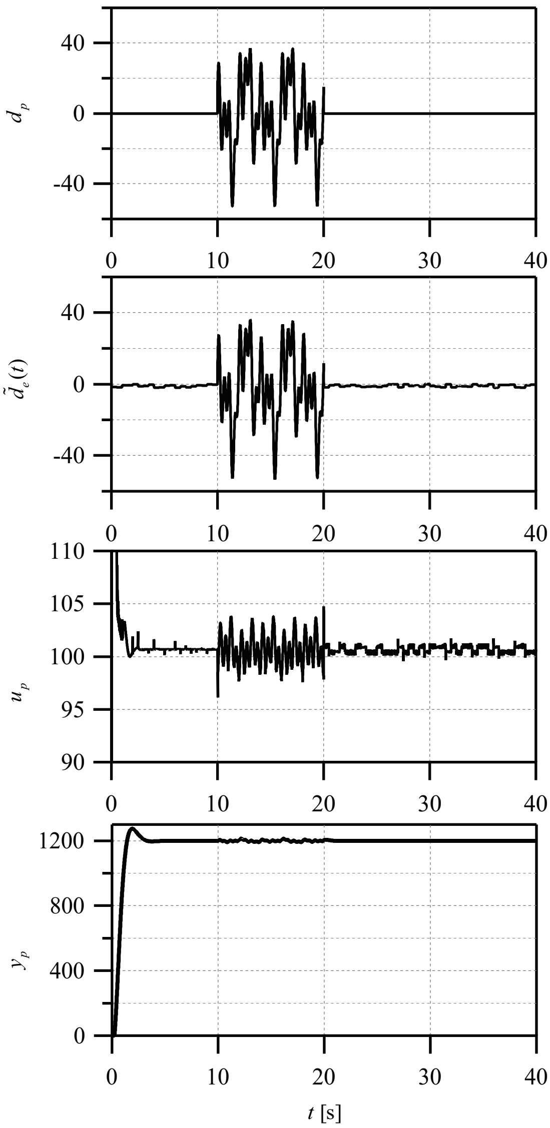

Fig. 5. Simulation results of AMPC-EID control system

$y_p(t)$ of these two methods are shown in Fig. 6. The maximum tracking error is 31.20 N during 10 - 20 s of the EID control method, which is about 4.72 times of the AMPC-EID control method.

5. Conclusion

This study described an AMPC-EID approach to improving the disturbance-rejection performance in an NCS. The packet losses and exogenous disturbances were taken to be exogenous disturbances on the control channel. We used the EID estimator to estimate the disturbance. We divided the whole system into two subsystems to derive the stability condition. We designed the observer gain by applying the concept of perfect regulation. Moreover, we designed the AMPC controller by embedding a tracking-performance index. Simulation results of the numerical examples show that our method compensates for time de-

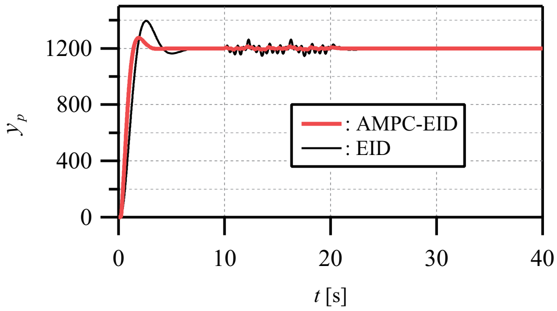

Fig. 6. Output response of AMPC-EID and EID

lays, packet losses, and disturbances; and it is better than the conventional EID method. This method has some improvements as follows:

(1) An AMPC-EID method is newly introduced to improve the disturbance-rejection performance.

(2) The time delays, packet losses, and exogenous disturbances simultaneously exist in the NCS have been compensated.

(3) This structure of the AMPC controller has two degrees of freedom that ensure satisfactory disturbance-suppression.

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