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Sliding Mode Resilient Control for TOD-based Servo System Under DoS Attack

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Abstract: This article studies the speed tracking control of multi-sensor servo systems with external disturbances and denial of service (DoS) attacks in networked control systems in recent years. A communication protocol-based sliding mode resilient control method is proposed in this paper, which can effectively maintain the servo system with multiple transmission channels to quickly recover to a stable state after being attacked by DoS attacks. Firstly, an observer based on the super-twisting algorithm is proposed to observe and estimate external disturbance. Secondly, for the selection of multiple sensors in networked transmission, a weight-based try-once-discard (TOD) protocol is used for analysis, and the most critical data is selected for transmission. Then, the DoS attack problem modeling in networked control is analyzed and a reaching law-based sliding mode control (SMC) algorithm is designed to perform closed-loop control of the system. Finally, the validity and feasibility of the proposed theory are proved by experiments and simulations.

Keywords: DoS attack, servo systems, SMC, speed tracking control, TOD protocol.

1. INTRODUCTION

Nowadays, with the rapid development of computer and automation control technology, networked control systems (NCSs) have caused extensive researches. NCS is a remote-control system in which the controllers, actuators, and sensors may be distributed in dispersive areas. The signals of the system are transmitted through the network [1]. The emergence of the NCSs simplifies and accelerate the improvement of control technology, while other problems caused by the uncertain of network commutation also show up like network attack and security, network congestion and delay, network load change and distributed collaboration problem, etc.

With regards to the problems of network attacks, many scholars have done a series of researches. In [2], the asynchronous filtering problem of nonhomogeneous Markov jump systems with deception attack is studied. In [3], Yan *et al*. focus on event-based security control for discrete-time stochastic systems with random events, especially DoS attacks and deception attacks. The attack model with compensation is established to describe the attack combination of NCS. When certain trigger conditions are met, an event trigger mechanism is used to reduce communication load by sending measurement signals. In [4], Li *et al*. summarize the problems of NCS under false data injection (FDI) attacks, which is a game process that the attacker decides the weakest part as an intrusion point. On the contrary, the NCS needs to allocate defense resources to maintain maximum data protection. The static output feedback control of fuzzy Markov switched singularly perturbed systems with deception attack and asynchronous quantized measurement output is studied in [5], in which both the pair quantizer and the static output feedback controller depend on the operating system, and their mode runs asynchronously through a hidden Markov model. The effectiveness of the proposed control strategy is proved through a DC motor model. In [6], to handle the problem of network-induced dropout system dynamics, a new optimal control method is proposed. A novel dropout Smith predictor is designed to predict the current state based on historical data measurements over the communication network, which can compensate the loss without requiring any knowledge of system dynamics.

To solve the network uncertain problems, different protocol models are abstracted from the communication network constraints to solve the problems under different conditions. Round-Robin (RR) protocol, the TOD protocol, and the Stochastic Communication (SC) protocol are three main communication protocols studied in the con-

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trol field. In communication transmission, only one node of data can enter the network for transmission. These protocols specify the rules for selecting nodes. SC protocol is usually modeled as Markov jump systems and has been widely researched. In [7], the problem of the static output-feedback control for a class of discrete-time linear semi-Markov jump systems is studied. In [8], Cheng *et al*. study the quantized nonstationary filtering problem for network-based Markov switching repeated scalar nonlinear systems. A more universal problem is researched. The measured output is characterized by packet loss, nonstationary quantized output, and simultaneous random-occurrence sensor nonlinearity. A filter based on a nonstationary Markov process is designed for these systems. The proposed theoretical results are proved through a practical example. In [9], the problem of moving horizon estimation for a class of discrete time-delay systems under RR protocol. The selection of nodes is sequential according to the nodes' order. In [10], the TOD protocol is adopted to prevent data from colliding for a linear system with multiply sensors. The protocol is updated and improved so that the sensor which has maximum error will priority transmit.

As for the problem of the control system, various advanced control algorithms have been proposed. For example, PID control [11], fuzzy control [12,13], h-infinity control [10,14,15], neural network control [16,17], event-triggered control [18,19], sliding mode control (SMC) [20–22], etc. Among these control methods, SMC has the advantages of a simple algorithm, strong robustness, and fast response, which can overcome the uncertainty of the system and be suitable for nonlinear systems. Some scholars have applied the SMC method to space robot control. SMC is a significant methodology for nonlinear control. Because of this, it has been diffusely researched recently. However, the shortcomings of SMC are also obvious. When the motion trajectory of the SMC moves close to the sliding surface, it usually moves back and forth within the sliding mode bandwidth, instead of directly moving to the equilibrium point, which is also the main problem in practical applications.

To damp out the jitters, there have been many kinds of research so far, including high-order SMC, adaptive SMC, etc. In [21], Liu *et al*. focus on solving the sliding mode control problem of continuous-time nonlinear networked control systems. Considering that the state information may not be fully obtained in practice, a state observer model is designed to estimate the state information. At the same time, a discrete-time event trigger mechanism is used to filter the sampled signals to reduce the bandwidth consumption and the transmission rate of resources. In [22], the sliding mode control problem for a class of discrete-time nonlinear network Markov jump systems with DoS attack is studied. By considering random denial-of-service attacks, a new sliding mode variable is designed, which considers the distribution information of probabilistic attacks. In [23], the finite-time sliding mode control problem for a class of Markov jump network physical systems is studied. It is assumed that control input signals transmitted over a communication network are vulnerable to network attacks. In this case, an adversary may probabilistically inject incorrect data into the control signals. At the same time, there may be random uncertainty and external disturbance of the peak limit. A suitable sliding mode controller is designed to drive the state trajectory to a specified sliding surface within a given finite time interval.

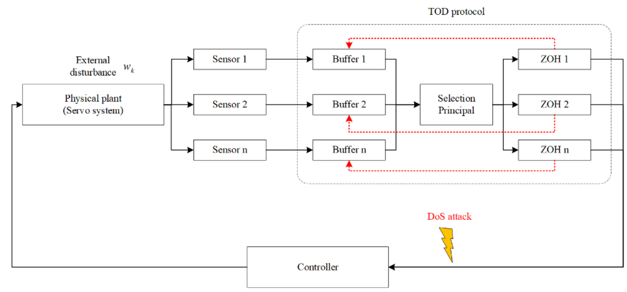

Fig. 1. Multi-sensor servo systems with external disturbances under DoS attack.

Inspired by the abovementioned papers, in this paper, a multi-sensor servo system with external disturbance and DoS attack is constructed. The main structure is shown in Fig. 1. The selection of multiple sensors is determined by the weight-based TOD protocol. Then, a super-twisting observer (STO) is presented to eliminate the errors of system states which are induced by switching sensors and external disturbance. Also, the DoS attack is considered and a reaching law-based SMC method is proposed to effectively control the servo system. Finally, the proposed control method is carried out through numerical simulations and practical experiments. The results illustrate the effectiveness.

The rest of this paper is composed as follows: In Section 2, the external disturbance of the servo system is modeled and reduced by the STO. In Section 3, the selection of probable sensors is decided according to the weight-based TOD protocol. DoS attacks are also analyzed. Based on this, the sliding mode controller is designed. Section 4 shows simulation and experiment results. Section 5 summarizes the conclusions of this article.

2. EXTERNAL DISTURBANCE AND OBSERVER

In this section, the servo system with external disturbance is formulated. An STO is designed to damp out the external disturbance.

2.1. System description and modelling

Consider the system dynamic as follows [24]:

$$x(k+1) = Gx(k) + Hu(k) + w(k), \tag{1}$$

where $x(k) = [x_1(k), x_2(k), \ldots, x_N(k)]^T$ and $u(k)$ are the system state and control input respectively. $w(k) = [w_1(k), w_2(k), \ldots, w_N(k)]^T$ is disturbance introduced by network or system parameter drift, N is set as 2 in this article.

Assumption 1: To simplify the further study, it is reasonable to assume that the external disturbance is bounded. And the system pair is controllable.

Remark 1: The external disturbances introduced in this paper are caused by network channel noise or system parameter drift. In the network transmission, the bandwidth of the channel is limited, so the disturbances here can be considered bounded. As for the disturbances caused by system parameter drift, since the signals input to the system are all bounded values, the electrical characteristics such as current and voltage that the equipment can carry are also limited. It can be considered that the disturbances of the system due to parameter drift are also bounded.

2.2. Observer design

To estimate the system states and reduce the effect of external disturbance, an observer-based on the super-twisting algorithm (STA) is designed. Define the errors of system states as follows:

$$e_1(k) = \hat{x}_1(k) - x_1(k), \tag{2}$$
$$e_2(k) = \hat{x}_2(k) - x_2(k), \tag{3}$$

where $\hat{x}(k) = \begin{bmatrix} \hat{x}_1(k) \\ \hat{x}_2(k) \end{bmatrix}$. Let $G = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$, $H = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$, (1) can be represented as

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} u(k) + \begin{bmatrix} w_1(k) \\ w_2(k) \end{bmatrix}, \tag{4}$$

which equals as follows:

$$x_1(k+1) = a_{11}x_1(k) + a_{12}x_2(k) + b_1u(k) + w_1(k), \tag{5}$$

$$x_2(k+1) = a_{21}x_1(k) + a_{22}x_2(k) + b_2u(k) + w_2(k). \tag{6}$$

Then the STO can be designed as

$$\hat{x}_1(k+1) = a_{11}\hat{x}_1(k) + a_{12}\hat{x}_2(k) + b_1u(k) + z_1, \tag{7}$$
$$\hat{x}_2(k+1) = a_{21}\hat{x}_1(k) + a_{22}\hat{x}_2(k) + b_2u(k) + z_2, \tag{8}$$
$$\hat{y}_i(k) = C_i\hat{x}(k), \tag{9}$$

where $z_1 = k_1|e_1(k)|^{\frac{1}{2}} sign(e_1(k)) + k_2e_1(k)$ and $z_2 = k_3sign(e_1(k)) + k_4e_1(k)$ are the correction terms, which are introduced to compensate for the disturbances. C_i is the constant matric with appropriate dimensions of the channel i. The differences between $C_1, C_2, \ldots, C_n$ are set to simulate the different quantifying errors and measuring noises between channels.

Furthermore, according to (2), (3), (7), (8), and (9), the error of system states can be written as

$$e_1(k+1) = a_{11}e_1(k) + a_{12}e_2(k) + z_1 - w_1(k), \tag{10}$$
$$e_2(k+1) = a_{21}e_1(k) + a_{22}e_2(k) + z_2 - w_2(k), \tag{11}$$

where k_1, k_2, k_3, and k_4 are gains that need to adjust. Eventually, both $e_1(k+1)$ and $e_2(k+1)$ will trend to zero, under which condition the estimation states can be seen as the actual ones. That is $\hat{x}(k) = x(k)$.

3. NETWORK ANALYZE AND CONTROLLER DESIGN

In this section, the network-introduced problems, like communication protocols and network attacks are considered and modeled. Also, a controller is designed to stabilize the system under uncertain network conditions.

3.1. Communication protocol

In networked control systems, control systems are often connected by way of a wireless network, while in a wireless network, transmission channels between different nodes are shared. Therefore, data collisions can occur during channel contention [25].

To avoid such problems, a communication protocol is required. TOD is an effective communication protocol to handle this kind of problem.

As is shown in Fig. 1, the measured output signal can be detailed represented as

$$y_k = \left[(y_k^1),\ (y_k^2),\ (y_k^3),\ \ldots,\ (y_k^n) \right]^T \in R^v, \tag{12}$$

where $y_k \triangleq y(k)$ and y_k^i represents the output signal of the i channel at the discrete-time k.

To prevent data collision in transmission, the TOD protocol is proposed. The protocol is applied to the feedback channel. After the sensor collects the data, it saves the data to the corresponding buffer.

Besides, the buffer also saves the signal returned from the ZOHs and the accumulated difference data of the current value and the previous one. The selection principle is used to select which sensor's data should be used for transmission in the current state.

Based on TOD protocol [10], the TOD protocol used in this paper can be briefly abstracted as follows:

At the beginning of the protocol operation, each sensor channel has the same priority and the same weighting factor. At this time, the selection strategy is based on the difference between the current measured value and the output value of the previous time stored in the buffer, and the channel with the largest difference has the highest priority.

If a channel with the same difference is generated, it is selected according to the accumulated value of the difference stored in the buffer, and the value having the highest value has the highest priority. At the same time, the weighting factor is dynamically adjusted according to the accumulated value.

Set the error of each data buffer $err_k^i = y_k^i - y_{k-1}^i$, so that the total buffer can be written as $E_k = \{err_k^1, err_k^2, err_k^3, ..., err_k^n\}$. The selected node at k is determined by the variable γ_k, where $\gamma_k \in [1, n]$.

Introduce a known positive definite matrix $W = \text{diag}\{w_1, w_2, w_3, ..., w_n\}$, where each component w_i represents the weight of the sensor i.

According to these, γ_k can be formulated as

$$\gamma_k = \arg\max_{1\le i\le n} \left(err_k^i\right)^T W\Theta_i err_k^i, \tag{13}$$

where $\Theta_i = \text{diag}\{\bar{\delta}(i-1), \bar{\delta}(i-2), \bar{\delta}(i-3), ..., \bar{\delta}(i-n)\}$, $\bar{\delta}()$ is a Kronecker delta which takes the value 0 or 1.

The data transmitted via the TOD protocol is defined as $\bar{y}_k \triangleq [y_k^1, y_k^2, y_k^3, ..., y_k^n]$, let $\bar{y}_k^i$ as a component of $\bar{y}_k$, which can be written as

$$\bar{y}_k = \begin{cases} y_k^i, i = \gamma_k, \\ \bar{y}_{k-1}^i, i \neq \gamma_k. \end{cases} \tag{14}$$

Hence, based on (13) and (14), the received signal via TOD protocol can be given as

$$\bar{y}_k = \Theta_{\gamma_k}\bar{y}_k + (I-\Theta_{\gamma_k})\bar{y}_{k-1}. \tag{15}$$

3.2. Model of DoS attack

In this model, the output signal of the physical layer is delivered to the cyber layer for transmission. The presence of an attacker is considered in the network transmission, and the attacker attempts to use the DoS attack to make the signal not be transmitted to the remote receiver. The system under the attack function can be abstracted as the following model:

$$y_k = Cx_k + \Psi\ell_k, \tag{16}$$

in which, $\Psi\ell_k$ is the attack term and $x_k \triangleq x(k)$. More detailed, Ψ is the attack function while ℓ_k represents the time that attack is launched. The attacker launches a DoS attack for the output signal y_k to offset the right signal in the period $[k_s^d, k_e^d]$, where k_s means the start time of the attack and k_e represents the end time. The progress can be formulated as

$$\begin{cases} \Psi = C, \\ \ell_k = -x_k, \ \ k \in [k_s^d, k_e^d], \\ \ell_k = 0, \ \ k \notin [k_s^d, k_e^d]. \end{cases} \tag{17}$$

Substitute (17) into (16), which can be further written as

$$\begin{cases} y_k^w = 0, \ \ k \in [k_s^d, k_e^d], \\ y_k^r = Gx_k, \ \ k \notin [k_s^d, k_e^d]. \end{cases} \tag{18}$$

Introduce η_k as the variable indicating whether the observation y_k is received or not by the feedback controller at k, which values 0 or 1. Let $\mathfrak{I}_k$ as the set of the data. So that the estimable observer can be formulated as

$$\hat{y}_k = \mathrm{E}(y_k \mid \mathfrak{I}_k) = \begin{cases} \bar{y}_k, \ \ \eta_k = 1, \\ \bar{y}_{k-1} = C\hat{x}_{k-1}, \ \ \eta_k = 0. \end{cases} \tag{19}$$

4. DESIGN OF SLIDING MODE CONTROLLER

The error of output defines as follows:

$$\varepsilon(k) = y_k^r - \hat{y}_k, \tag{20}$$

where $\hat{y}_k$ is the actual output value of the servo system under the DoS attack, while y_k^r is the reference input. The sliding mode function of discrete-time is designed as follows:

$$s(k) = \lambda_1\varepsilon(k) + \lambda_2\Delta\varepsilon(k), \tag{21}$$

where $\lambda_1 > 0$, $\lambda_2 > 0$ are the gain parameters. And $\Delta\varepsilon(k)$ is defined as $\Delta\varepsilon(k) \triangleq \varepsilon(k+1) - \varepsilon(k)$.

Thus, $s(k+1)$ can be formulated as follows:

$$\begin{aligned} s(k+1) =& \lambda_1\varepsilon(k+1) + \lambda_2\Delta\varepsilon(k+1) \\ =& (\lambda_1+\lambda_2)\varepsilon(k+1) - \lambda_2\varepsilon(k) \\ =& (\lambda_1+\lambda_2)(y_{k+1}^r - \hat{y}_{k+1}) - \lambda_2(y_k^r - \hat{y}_k), \end{aligned} \tag{22}$$

where $\hat{y}_k = \bar{y}_k\eta_k + \bar{y}_{k-1}(1-\eta_k)$. Introduce a sliding mode reaching law [26]

$$s(k+1) = (1-qT)s(k) - \sigma T\,\text{sgn}s(k) \triangleq \hat{s}(k+1). \tag{23}$$

where $\sigma > 0$, $(1-qT) > 0$, $q > 0$ and $T > 0$. T is the sampling period, q and σ are the adjustment coefficients for achieving a better approach.

So that

$$\hat{s}(k+1) = (\lambda_1+\lambda_2)(y_{k+1}^r - \hat{y}_{k+1}) - \lambda_2(y_k^r - \hat{y}_k). \tag{24}$$

Thus, the following formulation can be proven from inference

$$\hat{y}_{k+1} = y_{k+1}^r - (\lambda_1+\lambda_2)^{-1}\left[\hat{s}(k+1) - \lambda_2(y_k^r - \hat{y}_k)\right], \tag{25}$$

while

$$u_k = H^{-1}\left[C^{-1}\hat{y}_{k+1} - G\hat{x}_k\right]. \tag{26}$$

According to the formulation

$$\hat{y}_{k+1} = \bar{y}_{k+1}\eta_{k+1} + \bar{y}_k(1-\eta_{k+1}), \tag{27}$$

which is

$$\hat{y}_{k+1} = \begin{cases} \bar{y}_{k+1}, & \eta_{k+1} = 1, \\ \bar{y}_k, & \eta_{k+1} = 0. \end{cases} \tag{28}$$

When $\eta_{k+1} = 1$, then control law is formulated as follows:

$$\begin{aligned} u_k = & H^{-1}\{C^{-1}y^r_{k+1} - (\lambda_1+\lambda_2)^{-1}[(1-qT)s(k) \\ & - \sigma T \operatorname{sgn} s(k) - \lambda_2(y^r_k - \hat{y}_k)] - G\hat{x}_k\}. \end{aligned} \tag{29}$$

When $\eta_{k+1} = 0$, the output value $\hat{y}_{k+1} = \bar{y}_k$ and the control law equals the control input of last time.

Remark 2: The sliding mode function is designed like the form of the PID algorithm. The parameter $\lambda_1 > 0$ works as a proportional function. When the proportional function becomes larger, the magnification of the controller will get smaller and the curve of the controlled parameter will be more stable. On the contrary, the smaller the proportional function is, the greater the magnification of the controller and the more fluctuating the curve of the controlled parameter will be. Also, the parameter $\lambda_2 > 0$ works as a differential function. The differential action is mainly used to overcome the hysteresis of the controlled object and improve the response speed.

4.1. Proof of control stability

For the stability analysis, the following two theorems are presented.

Theorem 1: For the discrete-time system (1), when the reaching law is selected as (29), then the control strategy of the system is stable, and an arbitrary initial state will approach the switching surface.

Theorem 2: For the discrete-time system (1), when $y^r_k = r$ is a constant value, if appropriately select parameters $\lambda_1 > 0$, $\lambda_2 > 0$, then the closed-loop system can guarantee that $\lim_{k\to\infty}(r - \hat{y}_k) = 0$.

Proof: Define $error(k+1) = r - \hat{y}_{k+1}$, according to (27), it can be written as

$$error(k+1) = r - [\bar{y}_{k+1}\eta_{k+1} + \bar{y}_k(1-\eta_{k+1})]. \tag{30}$$

Case 1: $\eta_{k+1} = 1$.

$$\begin{aligned} error(k+1) &= r - \bar{y}_{k+1} \\ &= r + C\hat{x}_{k+1} \\ &= r + C(G\hat{x}_k + Hu_k). \end{aligned} \tag{31}$$

Substitute $\bar{y}_{k+1} = G\hat{x}_k + Hu_k$ into (29), the term $\bar{y}_{k+1}$ can be written as follows:

$$\begin{aligned} \bar{y}_{k+1} = & C\{G\hat{x}_k + \{C^{-1}y^r_{k+1} - (\lambda_1+\lambda_2)^{-1}[(1-qT)s(k) \\ & - \sigma T \operatorname{sgn} s(k) - \lambda_2(y^r_k - \hat{y}_k)] - G\hat{x}_k\}\} \\ = & y^r_{k+1} - (\lambda_1+\lambda_2)^{-1}[(1-qT)s(k) \\ & - \sigma T \operatorname{sgn} s(k) - \lambda_2(y^r_k - \hat{y}_k)]. \end{aligned} \tag{32}$$

Thus,

$$\begin{aligned} error(k+1) = & (\lambda_1+\lambda_2)^{-1}[(1-qT)s(k) \\ & - \sigma T \operatorname{sgn} s(k) - \lambda_2(y^r_k - \hat{y}_k)], \end{aligned} \tag{33}$$

where $y^r_k - \hat{y}_k$ equals to $r - \hat{y}_k$ according to Theorem 2.

Hence,

$$\begin{aligned} & error(k+1) \\ & = \frac{(1-qT)s(k) - \sigma T \operatorname{sgn} s(k) - \lambda_2 error(k)}{\lambda_1+\lambda_2}. \end{aligned} \tag{34}$$

Because of $\lambda_1 > 0$, $\lambda_2 > 0$ and $\lim_{k\to\infty} s(k) = 0$, so that $\lim_{k\to\infty} error(k) = 0$.

Case 2: $\eta_{k+1} = 0$

$$\begin{aligned} error(k+1) &= r + \bar{y}_{k+1} \\ &= r + C[G\hat{x}_{k-1} + Hu_{k-1}]. \end{aligned} \tag{35}$$

Similarly, substitute $\bar{y}_{k+1} = G\hat{x}_{k-1} + Hu_{k-1}$ into (29) and a similar result can be gotten. This finishes the proof. □

5. SIMULATION AND EXPERIMENT RESULTS

In this section, both numerical simulation and practical experiments are carried out to show the effectiveness of the proposed control methodology.

5.1. Numerical simulation

In this subsection, the numerical simulation is based on the servo system proposed in (1), the parameters are $G = \begin{bmatrix} 0.9647 & -0.0282 \\ 0.0196 & 0.9997 \end{bmatrix}$, $H = \begin{bmatrix} 0.0196 \\ 0.0002 \end{bmatrix}$, C_i are set as follows: $C_0 = [-0.2293 \;\; 1.4393]$, $C_1 = [-0.18 \;\; 1.5]$, $C_2 = [-025 \;\; 1.2]$, $C_3 = [-0.2 \;\; 1.2]$. External disturbance $w_1(k) = 3rand(k) + \sin(k)$, $w_2(k) = rand(k) + \cos(2k)$, $rand(k) \in [0, 1]$.

The prameters of the STO are set as $k_1 = -5$, $k_2 = -0.6$, $k_3 = 1$, $k_4 = 0.2$. The sliding mode controller parameters are $\sigma = 0.001$, $q = 30$, and $T = 0.02$, and the parameters introduced in the sliding surface are $\lambda_1 = 0.65$ and $\lambda_2 = 8.75$.

The initial conditions are as follows: $x(0) = [200, 300]^T$, $\hat{x}(0) = [0, 0]^T$, $u(0) = 0$, $y^r_0 > 0$. The simulation results are explained as follows:

Fig. 2 depicts the external disturbances added into the system, which are sinusoidal noises in general. There are 2 system states in total, external disturbance 1, 2 are injected to $x_1(k)$ and $x_2(k)$ respectively.

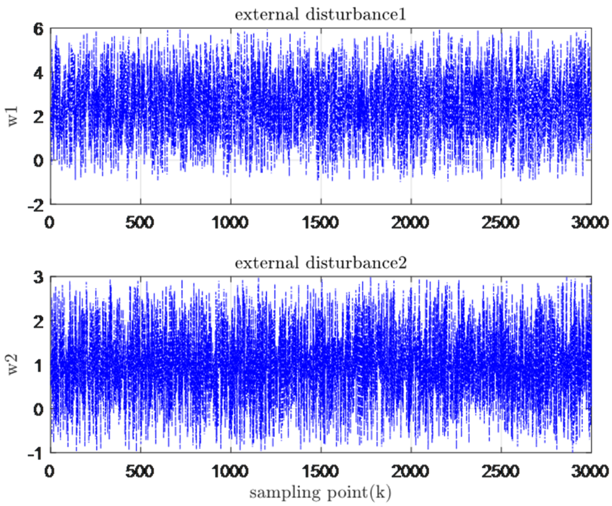

Fig. 2. External disturbances of the system.

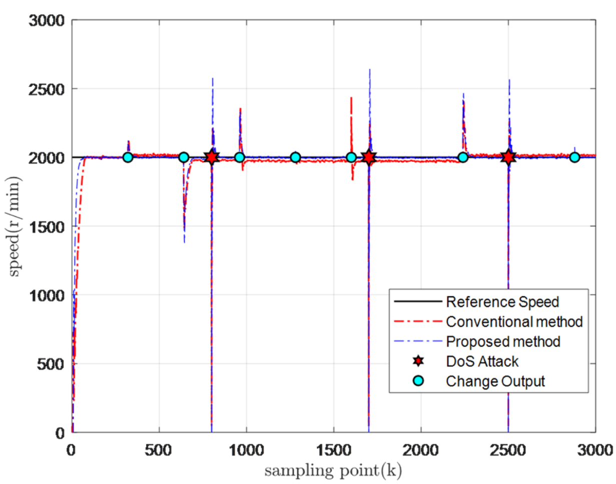

Fig. 3. Speed trajectories of simulation at a fixed speed.

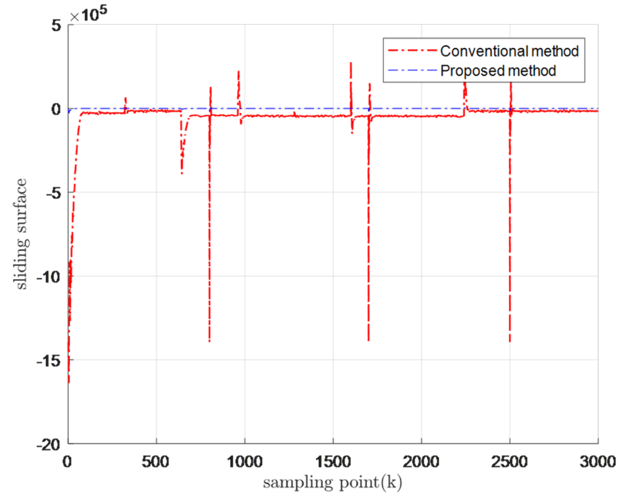

Fig. 4. The sliding surface of simulation at a fixed speed.

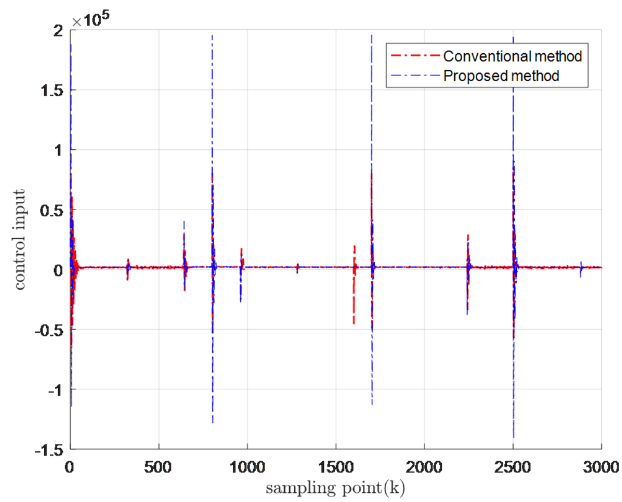

Fig. 5. Control input of simulation at a fixed speed.

Fig. 3 shows the tracking output at the speed of 2000 r/min with attacks. At about the 60th sampling point (about 1.2 s), the system starts to become stable under the control of the proposed method while the conventional one takes a slightly longer time. The system has multiple output channels while only one channel is selected to transmit data at a time. When the system gets the maximum error, which means the tracking speed deviating from the reference speed, the output channel will change. The dots in Fig. 3 represent the changing time. Also, when a DoS attack occurs, the data at that moment will lose. the system under the proposed control method can quickly become stable again. The static jitter of the conventional one is large, and when the channel is switched or the attack occurs, there may be a certain static error when re-tracking.

Fig. 4 shows the sliding surface of the simulation at a fixed speed. The sliding motion quickly converges to zero and it oscillates back and forth fractionally around 0 under the proposed method while the other one under conventional control has a certain approach error. Fig. 5 shows the control input of simulation at a fixed speed. When the system trends to be unstable, the controller will immediately prevent this motion.

Furthermore, to more profoundly show the effectiveness of the proposed control method, a further simulation at changed speed is carried out.

Fig. 6 shows the tracking output while speed varying from 1000 r/min to 2000 r/min with attacks. Similar to Fig. 3, At about the 60th sampling point (about 1.2 s), the system starts to become stable under the proposed method, which is a little faster than the conventional control method. When channel changes or DoS attack happens, the system will quickly converge to a stable state as well. It is worth noting that the conventional control method jitters violently at the speed of 1000 r/min. And at the speed of 1800 r/min, the method has a fixed static

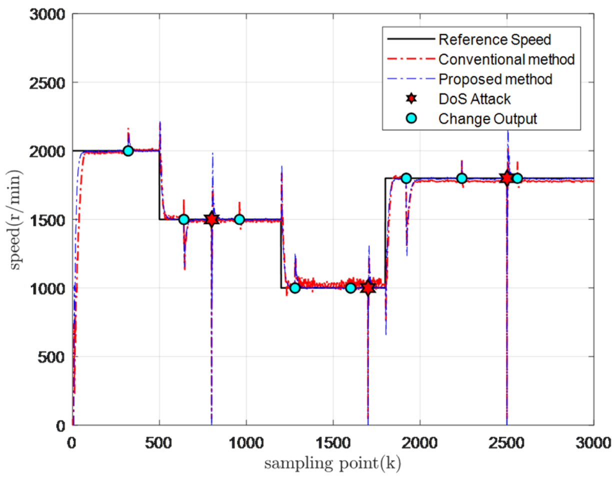

Fig. 6. Speed trajectories of simulation at a changed speed.

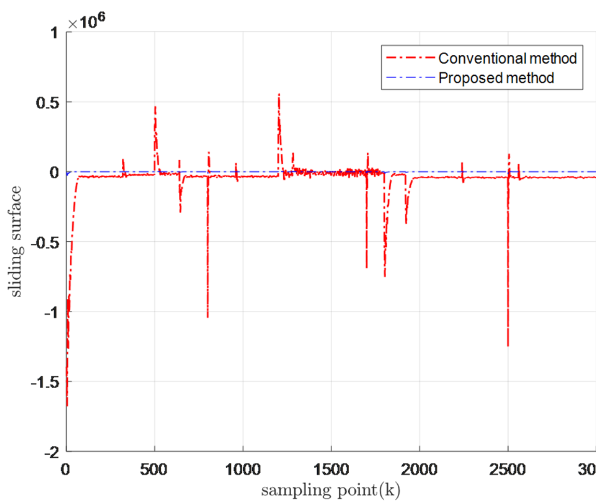

Fig. 7. The sliding surface of simulation at a changed speed.

tracking error.

Figs. 7 and 8 show the sliding surface and control input of the simulation at changed speed. When channel changes or attack launches, the controller will consume energy to prevent the system from being unstable. Notice that the conventional control method takes more resources due to the large jitters.

5.2. Practical experiment

To furtherly prove the method, a practical experiment based on the NetController Plant is carried out.

As is shown in Fig. 9, the plant is made up of a DC motor, a NetController, and a computer. Firstly, download the model from simulation software to the NetController through computer operation. Then the plant can start to work. The data information of the states, parameters, and

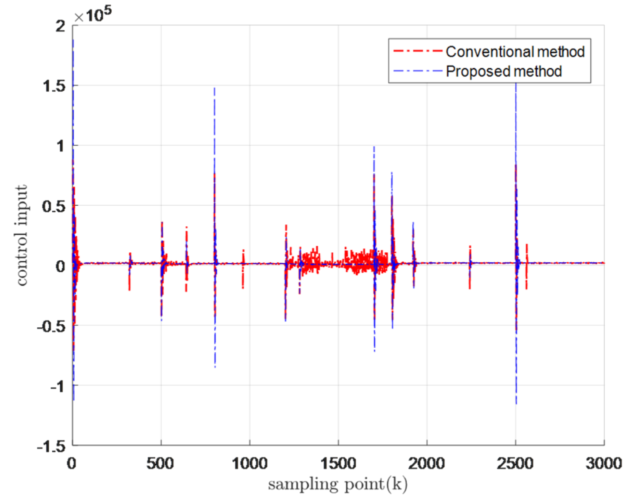

Fig. 8. Control input of simulation at a changed speed.

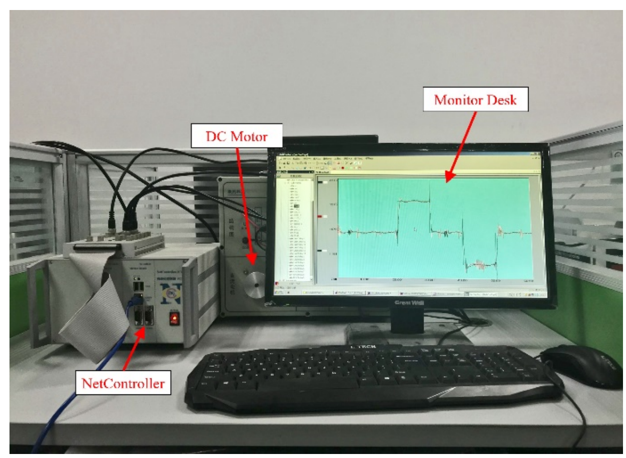

Fig. 9. DC motor system with networked controller.

waves can be obtained on the computer, which is sent back from NetController through the network. The DC motor system is selected as the servo system in this paper. The parameters are the same as the simulation parameters. The experiment results are explained in the following part.

Fig. 10 shows the tracking output at the speed of 1500 r/min with DoS attacks. Generally, the system under both control methods becomes stable slightly slower than in simulation. Even so, the proposed one still acts quicker than the conventional one. Also, it has smaller static jitters and tracking errors. Fig. 11 describes the trajectories of the sliding motion of the experiment at the fixed speed of 1500 r/min. The conventional control method has a larger sliding bandwidth, which is the reason for large jitters.

Fig. 12 shows the control input trajectories. When the channel changes or being attacked, the system will consume energy to become stable. The proposed method performs better generally.

Furthermore, to more profoundly show the effect of the

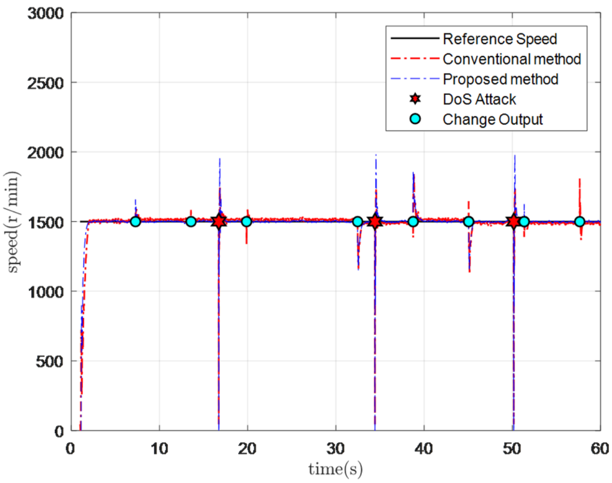

Fig. 10. Speed trajectories of the experiment at a fixed speed.

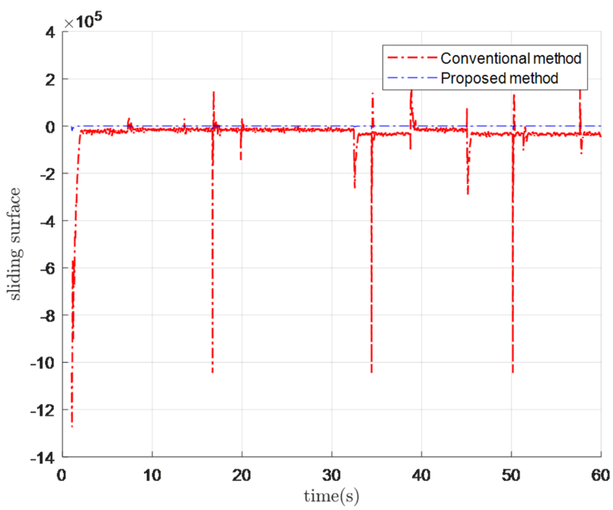

Fig. 11. The sliding surface of the experiment at a fixed speed.

control method, a further experiment at changed speed is carried out.

Fig. 13 shows the speed trajectories of the DC motor system with speed changing from 1000 r/min to 2000 r/min. Under the control of the proposed method, when the attack occurs or the channel changes, the system will temporarily deviate from a stable state and it will converge to reference speed promptly. However, the conventional method may occur tracking errors like the first channel change point. Similar to the simulation results, the conventional one also has huge jitters at the speed of 1000 r/min and gets fixed tracking errors at the speed of 1800 r/min.

Fig. 14 shows the sliding surface of the experiment at changed speed and Fig. 15 represents the corresponding control input. The system consumes energy and quickly becomes stable when the system trends to deviate from a stable state under the proposed method while the conventional one performs worse.

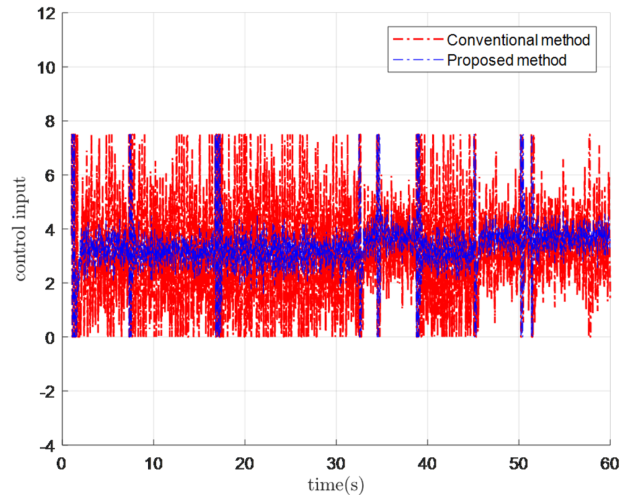

Fig. 12. Control input of experiment at a fixed speed.

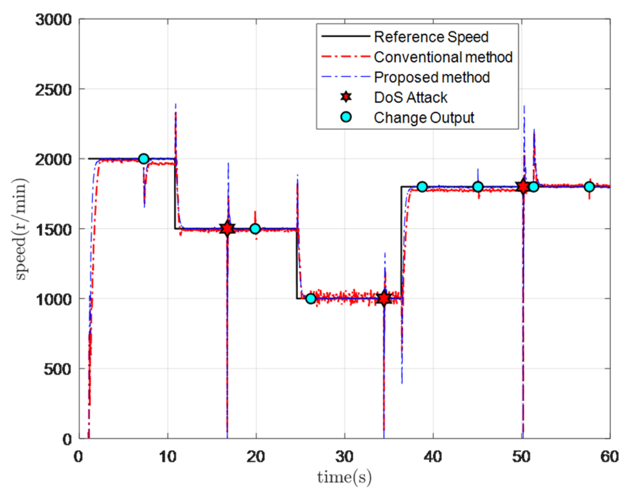

Fig. 13. Speed trajectories of the experiment at a changed speed.

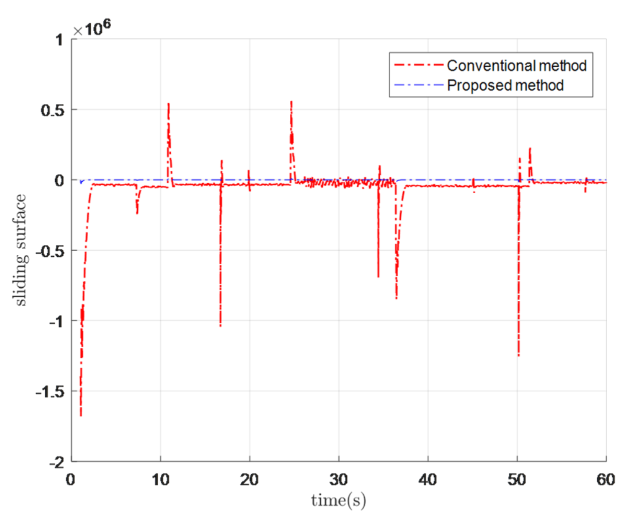

Fig. 14. The sliding surface of the experiment at a changed speed.

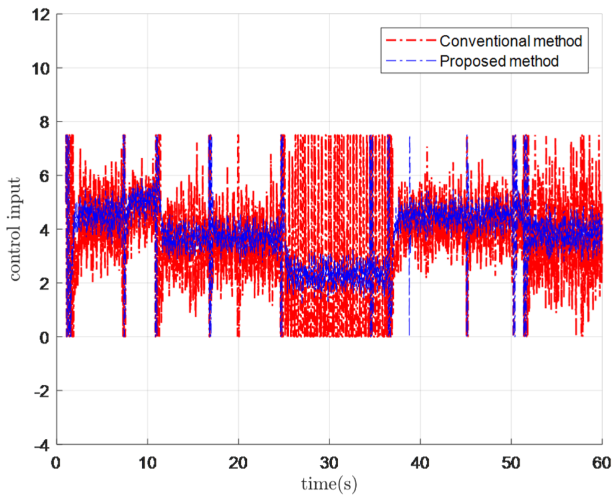

Fig. 15. Control input of experiment at changed speed.

6. CONCLUSION

In this paper, the speed tracking control of multi-sensor servo system with external disturbances and DoS attack is considered. To solve this problem, an STO is proposed to observe the system state and suppress the jitter. Aiming at the multi-channel transmission problem, a weight-based TOD protocol is proposed to select the transmission channel, and combined with the DoS attack problem in the network, a sliding mode control method based on the approach law is designed. Finally, the proposed control method is studied in numerical simulation and actual experiments. The results show that the method proposed in this paper is reliable. However, there are still some limitations in this paper. The proposed method is only deduced and verified in the second-order stationary linear system. However, in practice, the order of the research object may be high-order or nonlinear, and its system parameters may also change in real-time. Besides, the research in this paper focuses on how to quickly restore stability after the system is attacked, and subsequent research can also focus on attack detection and defense.

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