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Consensus Control for Looper Tension Control System Using Subspace Identification Method

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ABSTRACT The looper tension control system of hot strip mills is a typical multi-agent system, and the coupling effects among the agents are strong. However,it is difficult for us to establish the accurate coupling model for the looper tension control system. In this study, a distributed control strategy is proposed for the looper tension control system. With the subspace identification method, the local measurement of the looper control system and the information of its neighbors are used directly to develop the consensus control protocol without any knowledge of the looper tension system dynamics. The sufficient conditions for the consensus of multi-agent system with the proposed control protocol are proposed. In addition, a consensus control protocol with communication time delay is presented. Finally simulations are performed to verify the effectiveness of the control strategy.

INDEX TERMS Data driven, multi-agent, consensus control, looper tension control system.

I. INTRODUCTION

Over the past decade, cooperative control of multi-agent system has attracted an extensive attention, due to its broad applications in practice such as sensor networks [1], airspace crafts [2], formation control of mobile robots [3], and electric power systems [4]. Cooperative control of multi-agent system leads to a consensus problem [5], [6], within this framework, many modelling approaches have been exploited for the mathematical description of the dynamic of multi-agent system such as single integrator system, double integrator system and high-order system [7], [8].

In practice, agents share the information through a network, and consensus problem is considered for dynamic agents with fixed, switching topologies [9]–[11] or undirected interaction [12]. Communication delay and packet losses should be considered which have practicable significance. Many efforts have been devoted to the study of time delay system [13]–[16]. Both parameter time-varying communication delay and model uncertainties are considered for leader-tracking problem in [14]. The average consensus with time-varying delay is considered in [15], where the multi-agent systems are of dynamically changing topologies and multiple time-varying delays. The nonlinear time-delay systems over sensor networks subject to switching topology are proposed in [16].

Nevertheless, these existing model-based control schemes are usually too complex to applied to practice and obtained good results due to structure uncertainty and modeling error. Many solution methods and algorithms for unknown dynamics are considered to develop consensus control protocol [6], [17], [18], which can make effective use of the considerable system knowledge of the agents. In [18], a distributed model free adaptive control method is addressed for multi-agent systems with both fixed communication topology and switching topology. In [19], [20], reinforcement learning technique is introduced for the optimal control problem with completely unknown dynamics, and consensus control for networked agents is investigated in [21].

The hot strip mills composed of typically six or seven rolling stands is a typical multi-agent system. The looper installed at inter-stand positions reduces tension variations by changing its angle and rolling speed to ensure proper product quality and strip threading [22]. The looper system in hot rolling has the features of nonlinearity, strong coupling, uncertainty and multi-constrain. Many authors have

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proposed a variety of control schemes for these control problem [23]–[28] such as sliding mode variable structure control, model predictive control and multi-variable decoupling control. In [27], the dynamic mathematical model of hydraulic looper system is built at the vicinity of the working point, and model-based predictive controller is developed in [28], where the coupling effects of the neighbouring looper tension control system are considered. Furthermore,a multi-rate distributed control strategy is proposed for the looper tension control system in [29], where all the controllers of the agents are updated asynchronously in one cycle, and the measurement of neighbouring agents is employed to improve control performance.

In order to improve control performance, some authors adopt data driven control method to overcome the difficulties of modelling. In [30]–[32], the method of artificial intelligence is used to design controller for the looper tension control system. However, most of literatures adopt decentralized control strategy and focus on decoupling control between looper height control system and looper tension control system. But the main weakness of this control scheme remains. The interaction of neighbors is neglected, which degrades the control performance.

Motivated by the above observations, we consider data driven consensus control strategy using subspace identification method for looper tension control system. The main contribution of this paper is two-fold.

The first contribution is the distribute control strategy proposed for the looper tension control system. The measurement of neighbouring agents is used to develop consensus control protocol, and weight coefficients are used to emphasize the effects of the neighbouring agents. The second contribution is that the data driven control method is proposed for developing the consensus control protocol based on the subspace identification method. The sufficient conditions for reaching consensus with the proposed control protocol are proposed. In addition, the consensus control protocol with communication time-delay is proposed. Simulation results are carried out to demonstrate the validity and feasibility of the proposed method.

The remainder of this paper is organized as follows. In Section 2, the looper tension control system is formulated, and the problems to be studied are given. In section 3, the distributed control strategy based on the subspace identification method is proposed and the consensus control protocol is developed for the looper control system. The stability analysis with the proposed control protocol is presented in Section 4. The consensus control protocol with communication time-delay is developed in Section 5. Simulations are conducted to show the effectiveness of the proposed distributed control strategy in Section 6. Finally, conclusion remarks are summarized in Section 7.

II. PROBLEM STATEMENT

The looper control system as shown in Fig.1 is important for hot strip mills. One can see obviously that the looper tension of the ith rolling stand controlled by the rolling speed of the ith will be seriously impacted by the increment of the rolling speed of the $i+1$th stand. In addition, in the case of low tension, the looper angle increases to get proper tension, while in the case of high tension, the looper angle decreases to reduce strip tension. These interactions make it difficult to design a high precision controller for the looper tension control system.

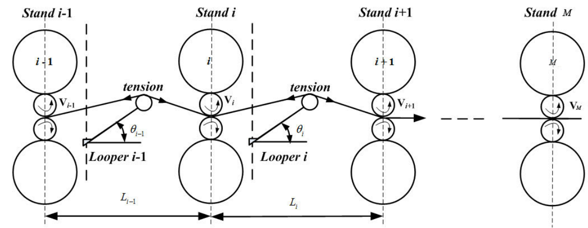

FIGURE 1. Configuration of looper tension system of hot strip mills.

A. LOOPER HEIGHT DYNAMICS

Apply Newton's law of motion to the ith looper control system, we can obtain the following equation [28]

$$\Delta\Omega_i = \Delta\Omega_{i\_T} + \Delta\Omega_{i\_W} + \Delta\Omega_{i\_D} = \Delta\Omega_{i\_T} + J_i\frac{d\Delta\omega_i}{dt} \quad (1)$$

where the subscript i denotes the ith looper system, J_i is the moment of inertia, ω_i is the looper angular speed, Ω_i is the looper motor torque, Ω_{i_W} is the weight torque, Ω_{i_T} is the strip tension torque, and Ω_{i_D} is the kinetic moments.

Using the following equation

$$\frac{d\Delta\omega_i}{dt} = \frac{\pi}{180}\frac{d^2\Delta\theta_i}{dt^2}, \quad (2)$$

we can get

$$\begin{aligned}\frac{d^2\Delta\theta_i}{dt^2} &= (\Delta\Omega_i - \Delta\Omega_{i\_T})\frac{1}{J_i}\frac{180}{\pi}\\ &= \frac{1}{J_i}\frac{180}{\pi}(\Delta\Omega_i - \frac{\partial\Omega_{i\_T}}{\partial\theta_i}\Delta\theta_i - \frac{\partial\Omega_{i\_T}}{\partial\tau_i}\Delta\tau_i). \quad (3)\end{aligned}$$

There is an interaction between the looper angle and strip tension.

B. LOOPER-TENSION DYNAMICS

The strip tension model of the ith stand can be described by the following equation [28]

$$\frac{d\Delta\tau_i}{dt} = \frac{E_i}{l_i}(\Delta V'_{i+1} - \Delta\bar{V}_i), \quad (4)$$

where $\Delta \overset{def}{=} 1 - z^{-1}$ with z^{-1} being the back shift operator, V_i is the rolling speed of the ith mill, $\bar{V} = V_i(1+f_i)$ is the delivery speed of the ith stand, f_i is the forward slip ratio, $V'_{i+1} = V_{i+1}(1-\gamma_{i+1})$ is the entry speed of the $(i+1)$th stand, γ_{i+1} is backward slip ratio, E is Young's modulus, l_i, and τ_i are length and tension of the strip between i and $(i+1)$th stand, respectively.

The increment equations of strip length of the ith stand can be written as

$$\Delta l_i = \int (\Delta V'_{i+1} - \Delta V_i)dt. \tag{5}$$

From Eqs. (4) and (5), we can obtain

$$\Delta \tau_i = \frac{E_i}{l_i}\Delta l_i = \frac{E_i}{l_i}\frac{dl_i}{d\theta_i}\Delta\theta_i, \tag{6}$$

where θ_i is the looper angle of ith stand. The looper tension model can be written as follows

$$\begin{aligned}\begin{bmatrix}\Delta\dot{\tau}_i(t,s)\\ \Delta\dot{V}_i(t,s)\end{bmatrix} &= \begin{bmatrix}\frac{E_i}{l_i}(-\frac{\partial\beta_{i+1}}{\partial\tau_i}V_{i+1}-\frac{\partial f_i}{\partial\tau_i}V_i) & -\frac{E_i}{l_i}(1+f_i)\\ 0 & -\frac{1}{T_{i\_V}}\end{bmatrix}\\ &\cdot\begin{bmatrix}\Delta\tau_i(t,s)\\ \Delta V_i\end{bmatrix}+\begin{bmatrix}0 & \frac{E_i}{l_i}(1-\beta_{i+1})\\ 0 & 0\end{bmatrix}\\ &\cdot\begin{bmatrix}\Delta\tau_{i+1}(t,s)\\ \Delta V_{i+1}\end{bmatrix}+\begin{bmatrix}0\\ \frac{1}{T_{i\_V}}\end{bmatrix}u_i\\ &+\begin{bmatrix}1\\ 0\end{bmatrix}\frac{1}{G_{i\_R}}\frac{E_i}{l_i}\frac{dl_i}{d\theta_i}\Delta\omega_i,\end{aligned} \tag{7}$$

where C_{i_m} is the looper motor gain coefficient, G_{i_R} is the reduction ratio, T_{i_v} and T_{i_l} are the time constants of ASR (automatic speed regulator) and LCR (looper current regulator), respectively. One can sees from Equ.(4),(6) and (7) that the looper tension of the ith stand can be controlled directly by the rolling speed v_i and v_{i+1}, and the looper tension control system can be impacted by the looper angel control system. In the paper, we design consensus control protocol for the multi-agent system, and try to control rolling speed cooperatively to maintain the strip tension at their desired values.

III. CONSENSUS CONTROL PROTOCOL

For the ith looper tension system, both τ_i and v_i can be measured directly. The output is the looper tension τ_i, and the control input is the rolling speed v_i. With the subspace identification technique [34], [35], the future output increase of looper tension $\tau_{i\_f} = [\Delta\tau_i(k), \ldots, \Delta\tau_i(k+N-1)]$ can be estimated using the future control input $\Delta v_{i\_f} = [\Delta v_i(k), \ldots, \Delta v_i(k+N-1)]$, the past control input $\Delta v_{i\_p} = [\Delta v_i(k-N), \ldots, \Delta v_i(k-1)]$ and the past output increment of looper tension $\tau_{i\_p} = [\Delta\tau_i(k-N), \ldots, \Delta\tau_i(k-1)]$, where $\Delta v_i(k) = v_i(k) - u_{i+1}(k)$. The subscript f and p denote the future and past respectively. We can identified the controller parameters directly with the measurement of local looper tension control system and information of its neighbors based on subspace identification technique and SVD (singular value decomposition). The controllers are designed without any knowledge of the agent dynamics, which can reduce the design effort and computational load.

Consider a multi-agent system of M linear agents. Their interaction topology is given by G. Assumed that the agent i is considered to have the following dynamics:

$$y_i(k+1) = f_i(y_i(k), u_i(k)), \tag{8}$$

where $y_i(k)$ is the output, $u_i(k)$ is the control input and $f_i(.)$ is an unknown function, respectively. At each sampling instant k, the communication network is reliable and the information can be transmitted instantaneously without time consumption. There exists a communication network among the M agent system, and the directed graph $G \triangleq \{v \quad \varepsilon \quad A\}$ is composed of a vertex set $v = [i, \quad i = 1, \ldots, M]$, an edge set $\varepsilon = v \times v$ denotes the edges of paired agents, and $A = [a_{ij}]$ denotes a weighted adjacency matrix with nonnegative adjacency elements $a_{ij} > 0$, where the pair $(i; j)$ represents that agent i is connected to j and can directly obtain information from j. If agent i can receive information from agent j then $a_{ij} > 1$, otherwise $a_{ij} = 0$. We assume there is no self-edge in the digraph G, i.e., $a_{ii} = 0$. For each agent i, its neighbors are denoted by the agents from which it can obtain information, and the index set for agent neighbors is denoted as $N_i \triangleq \{j|(i,j) \subset \varepsilon\}$. The graph G contains a spanning tree if and only if there exists a root node that can send information to all the other agents through directed paths.

For each agent i, when no noise is present, the actual future output Y_f lies in the combined row space, and the linear predictor equation can be written as follows.

$$\hat{Y}_f = L_w W_p + L_u U_f, \tag{9}$$

where $W_p = [U_p^T \quad Y_p^T]^T$ is the past input and output matrix, and U_f is future input sequence. L_w and L_u are subspace matrices corresponding to the states and inputs, respectively. The data block Hankel matrices for $u(k)$ represented as U_p and U_f.

$$U_{i\_p} = \begin{pmatrix} u_i(1) & u_i(2) & \ldots & u_i(j)\\ u_i(2) & u_i(3) & \ldots & u_i(j+1)\\ \vdots & \vdots & \ddots & \vdots\\ u_i(N-1) & u_i(N) & \ldots & u_i(N+j+1)\end{pmatrix},$$

$$U_{i\_f} = \begin{pmatrix} u_i(N) & u_i(N+1) & \ldots & u_i(N+j)\\ u_i(N+1) & u_i(N+2) & \ldots & u_i(N+j+1)\\ \vdots & \vdots & \ddots & \vdots\\ u_i(2N-1) & u_i(2N) & \ldots & u_i(2N+j+1)\end{pmatrix}$$

The output block Hankel matrices Y_p and Y_f can also be defined in the same way. N is the prediction horizon (or so-called H_p). By solving the following least-square problem, the output prediction $\hat{Y}_f$ can be extracted.

$$\min \| Y_f - (L_w \quad L_u)\begin{pmatrix}W_p\\ U_f\end{pmatrix}.\|_F^2 \tag{10}$$

The orthogonal projection of the row space of Y_f into the row space spanned by W_p and U_f, and (9) can be solved efficiently via QR decomposition.

$$\begin{pmatrix}W_p\\ U_f\\ Y_f\end{pmatrix} = RQ = \begin{pmatrix}R_{11} & 0 & 0\\ R_{21} & R_{22} & 0\\ R_{31} & R_{32} & R_{33}\end{pmatrix}\begin{pmatrix}Q_1^T\\ Q_2^T\\ Q_3^T\end{pmatrix} \tag{11}$$

By posing

$$L = \begin{pmatrix} L_w & L_u \end{pmatrix} = \begin{pmatrix} R_{31} & R_{32} \end{pmatrix} \begin{pmatrix} R_{11} & 0 \\ R_{21} & R_{22} \end{pmatrix}^{\dagger}, \quad (12)$$

where $L = \begin{pmatrix} L_w & L_u \end{pmatrix}$ and $\dagger$ denotes the Penrose $-$ Moorepseudo$-$inverse. We adopt the receding window method, the measured data are collected over a sliding (receding) window and only the newest date sequences are used to develop the control protocol at each sampling instant.

Definition 1: The discrete-time multi-agent system in (8) with a given network topology G and a distributed control protocol $u_i(k) = f_i(y_i(k); y\_i(k))$ is said to achieve consensus if $\lim_{t\to\infty} \|y_i(k) - y\_i(k)\| = 0, j = 1, 2, \ldots, M$, where $y\_i(k)$ represents reference value [36].

In the paper, the agent i can get neighbors information of the agent $i+1, i+2, \ldots, M$. The network topology of the looper tension system composed of M ($M = 6$) agents is shown in Fig.2. We are interested in developing the consensus control protocol using subspace identification method. The consensus control protocol can be obtained by solving optimization Problem 1.

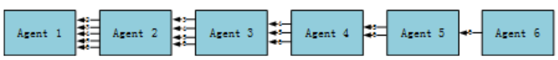

FIGURE 2. Looper tension system topology for a platoon of six agents.

Problem 1:

$$\arg\min_{u_i(k)} J_i(y_i(k), u_i(k)). \quad (13)$$

Subject to

$$y_{i\_f} = L_w w_{i\_p} + L_u u_{i\_f}, \quad (14)$$

and

$$J_i(k) = \sum_{j\in N_i} \beta_{ij} a_{ij} \|y_{i_f} - y_{j\_f}\|^2_{P_i} + \|u_{i\_f} - u_{j\_f}\|^2_{Q_i} \quad (15)$$

Due to the effect weight numerical of the downstream rolling stands on the current looper tension control system is different, weighting factor $\beta_i = [\beta_{i,i+1}, \beta_{i,i+2}, \ldots, \beta_{i,j}]$ is employed, where $i < j \leq M$, and $\sum_{j=i+1}^{M} \beta_{ij} = 1$, $P_i > 0$ and $Q_i > 0$ are symmetric matrices. At each sampling instant k, solving Problem 1 we can achieve the consensus control protocol.

Remark: In Problem 1, the term

$$\sum_{j\in N_i} \beta_{ij} a_{ij} \|y_{i\_f} - y_{j\_f}\|^2_{P_i} \quad (16)$$

is employed to achieve consensus.

Theorem 1: For the system (8) with the network topology G the optimal solution is given as:

$$u_i(k) = -\Phi_i \sum_{j\in N_i} \beta_{ij} a_{ij} L_u^T P_i [L_w \delta_i - L_u u_j(k)], \quad (17)$$

where $\Phi_i = [I, 0, \ldots, 0][\sum_{j\in N_i} \beta_{ij} a_{ij} L_u^T P_i L_u + Q_i]^{-1}$ and $\delta_i = L_{wu}(u_{i\_p} - u_{j\_p}) + L_{wy}(y_{i\_p} - y_{j\_p})$.

Proof 1: Let

$$\frac{\partial J_i(k)}{\partial \Delta u_{i\_f}} = 0, \quad (18)$$

we can get the optimal solution as follows

$$u_{i\_f} = -[\sum_{j=1}^{N} \beta_{ij} a_{ij} L_u^T P_i L_u + Q_i]^{-1} [\sum_{j=1}^{N} \beta_{ij} a_{ij} \cdot L_u^T P_i (L_w (W_{i\_p} - W_{j\_p}) - L_u u_j], \quad (19)$$

and only the first one is adopted as the current control law. The proof is completed.

IV. STABILITY ANALYSIS

The sufficient conditions for reaching consensus with the proposed control protocol are as follows.

Theorem 2: For the multi-agent system (8) with the consensus control protocol and digraph G, the consensus can be reached if and only if all the eigenvalues of $T(z^{-1})$ are inside the unit circle. Let $z : f(k) \to f(k+1)$ be a time shift operator. The function $T(z^{-1})$ can be expressed by

$$T(z^{-1}) = a_0 + a_1 z^{-1} + a_2 z^{-2} +, \ldots + a_l z^{-l}, \quad (20)$$

where $\begin{pmatrix} a_0 & a_1 & \ldots & a_{l-1} \end{pmatrix} = \begin{pmatrix} 1 & L_{wy} \end{pmatrix}$.

Proof 2: The neighborhood error is defined as

$$e_i(k) = \sum_{j\in N} \beta_{ij} a_{ij} (y_i(k) - y_j(k)). \quad (21)$$

So

$$\begin{aligned} e_i(k+1) &= \sum_{j\in N} \beta_{ij} a_{ij} (y_i(k+1) - y_j(k+1)) \\ &= \sum_{j\in N} \beta_{ij} a_{ij} (L_{wu}(u_{i\_p} - u_{j\_p}) \\ &\quad + L_{wy}(y_{i\_p} - y_{j\_p}) + L_u(u_i(k) - u_j(k))). \end{aligned} \quad (22)$$

Substituting the equation (14) into (22), we have that

$$\begin{aligned} e_i(k+1) - L_{wy} e_{i\_p}(k) &= \sum_{j\in N} \beta_{ij} a_{ij} L_{wu} (u_{i\_p} - u_{j\_p}) \\ &\quad + \sum_{j\in N} \beta_{ij} a_{ij} (L_u (u_i(k) - u_j(k)), \end{aligned} \quad (23)$$

where $e_{i\_p} = (e_i(k-1), e_i(k-2), \ldots, e_i(k-l))$, $u_{i\_p} = (u_i(k-1), u_i(k-2), \ldots, u_i(k-l))$.

To further facilitate the analysis, we design the parameters as $Q_i = Q$ and $R_i = R$ for all $i = 1, \ldots, M$, where $R > 0$ and $Q > 0$. It is worth noting that all the agents have the same dynamics, that is, all the agents are homogeneous, which is reasonable and of practical meanings. Let $e(k) = (e_1(k), e_2(k), \ldots, e_M(k))^T$, $e_i(k) = (e_i(k), e_i(k-1), \ldots, e_i(k-l))^T$, $\Pi_i = (1, -L_{wy})$, and $u(k) = (u_1(k), u_2(k), \ldots, u_M(k))$. Writing the above equations in an augmented form, one gets

$$\Pi e(k) = \Xi (L_{wu} \otimes I \Delta u_p - L_u \otimes I \Delta u(k)) \quad (24)$$

where $\Pi = diag\{\Pi_1, \Pi_2, \ldots, \Pi_M\}$, $\Delta u_p = (\Delta u_{1\_p}, \Delta u_{2\_p}, \ldots, \Delta u_{M\_p})^T$, $\Delta u_{i\_p}(k) = u_{i\_p} - u_{j\_p} = (\Delta u_i(k), \Delta u_i(k-1), \ldots, \Delta u_i(k-l))^T$. As a result, we have the function (23), and the eigenvalues of Π are inside one circle, for all $i = 1, \ldots, M$. That is, the consensus can be reached if and only if $T(z^{-1})$ are stable. The proof is completed.

V. CONSENSUS CONTROL PROTOCOL WITH TIME DELAY

Theorem 3: For the multi-agent system (8) with directed digraph G, we can assume that there is one step of communication time delays between two neighboring agents, the optimal solution is given as

$$u_i(k) = -\Phi_{i\_d}[\sum_{j=1}^{N_i} \beta_{ij} a_{ij} L_u^T P_{i\_d}(\delta_{i\_d} - z^{-(j-i)} L_u u_j(k))], \quad (25)$$

where $\Phi_{i\_d} = [\sum_{j=1}^{N_i} \beta_{ij} a_{ij} L_u^T P_{i\_d} L_u + Q_{i\_d}]^{-1}$, $\delta_{i\_d} = L_{wu} u_{i\_p} + L_{wy} y_{i\_p} - z^{-(j-i)}(L_{wu} u_{j\_p} + L_{wy} y_{j\_p})$.

Proof 3: Similar to Proof 2, the cost function can be written as follows

$$J_{i\_d}(k) = \sum_{j=1}^{N_i} \beta_{ij} a_{ij} \|y_i(k) - q^{-(j-i)} y_j(k) - r_{ij}\|^2_{P_{i\_d}} + u_i^T(k) Q_{i\_d} u(k). \quad (26)$$

Let $\frac{\partial J_i(k)}{\partial \Delta u_i(k)} = 0$, the consensus control protocol for the looper tension control system with communication time delays can be written as follows

$$u_{i\_d}(k) = [\sum_{j \in N} \beta_{ij} a_{ij} L_u^T P_{i\_d} L_u + Q_{i\_d}]^{-1} \times [\sum_{j=1}^{N_i} \beta_{ij} a_{ij} L_u^T P_{i\_d}(\delta_{i\_d} - z^{-(j-i)} L_u u_j(k)]. \quad (27)$$

The proof is completed. Similarly, the method of stability analysis of Theorems 2 can be extended to the case of time delay.

VI. SIMULATION RESULTS

We consider a looper control system of hot strip mills with 6 rolling stands. The parameters of the looper tension system are as follows.

$E_i = 1.4 * 10^5 \mathrm{Mpa}$, $l_i = 5.5\mathrm{m}$, $1/T_{i\_v} = 0.091$, $T_{i\_i} = 0.0182$, $G_{i\_R} = 11.638$, $f_i = 0.0687$, $\beta_{i+1} = 0.1595$, $C_{i\_m} = 8.2404(\mathrm{Nm/A})$, $v_i = 6.6445\mathrm{m/s}$, $v_{i+1} = 8.4034\mathrm{m/s}$, $J_i = 74.1342\mathrm{Nm}^2$, $\frac{\partial \beta_i}{\partial \tau_i} = -0.08304$, $\frac{\partial f_i}{\partial \tau_i} = -0.1075$, $\frac{dloop_i}{d\theta_i} = 1.2312$, $\frac{1}{G_{i\_R}} \frac{\partial M_{i\_T}}{\partial \theta_i} = 6.7652$, $\frac{1}{G_{i\_R}} \frac{\partial M_{i\_T}}{\partial \tau_i} = 209.6705$.

We assumed that the six agents are homogeneous, and the initial value of looper tension and rolling speed are, $s_1 = \begin{bmatrix}1 & 0.2\end{bmatrix}$, $s_2 = \begin{bmatrix}0.8 & 0.4\end{bmatrix}$, $s_3 = \begin{bmatrix}0.6 & 0.3\end{bmatrix}$, $s_4 = \begin{bmatrix}0.3 & -0.1\end{bmatrix}$, $s_5 = \begin{bmatrix}0.6 & 0.1\end{bmatrix}$, and $s_6 = \begin{bmatrix}0.1 & 0.4\end{bmatrix}$, respectively. To design the data driven control protocol, open loop input-output data are requied, which can be obtained based on the model of looper tension control model(7). The simulations are carried out with the MATLAB, and sampling time is 4ms. We try to maintain the tension of stand i at their desired values and all agents work cooperatively, which can prevent the strip steel from sliding forward or backward and improve the stability of the multi-agent system.

The effects of the neighbouring agents on the current looper control system are different. For comparison, three numerical simulations cases are considered. In the first case, the information of leader agent is emphasized. We let $\beta_1 = [0.05, 0.05, 0.2, 0.1, 0.6]$, $\beta_2 = [0.1, 0.1, 0.2, 0.6]$, $\beta_3 = [0.2, 0.2, 0.6]$, $\beta_4 = [0.4, 0.6]$, $\beta_5 = [1]$. The simulation results are shown in Fig 3.

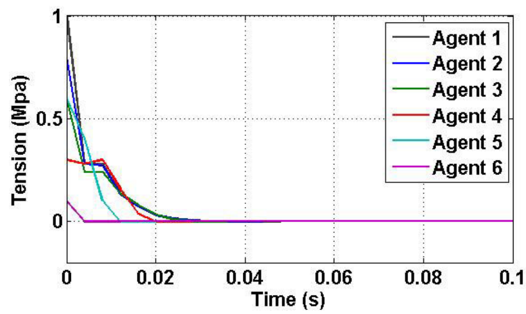

FIGURE 3. Output of looper systems that leader agent is emphasized.

In the second case that the information of the nearest neighbor is emphasized, we let $\beta_1 = [0.6, 0.2, 0.1, 0.05, 0.05]$, $\beta_2 = [0.6, 0.2, 0.1, 0.1]$, $\beta_3 = [0.6, 0.2, 0.2]$, $\beta_4 = [0.6, 0.4]$, $\beta_5 = [1]$, and the simulation results are shown in Fig.4.

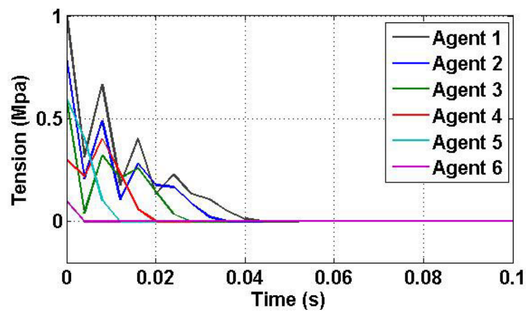

FIGURE 4. Output of looper systems that the nearest neighbor is emphasized.

In the third case, the simulation results of the average consensus control strategy is proposed, where no neighbouring agents are emphasized,that is, $\beta_{i,1+1} = \beta_{i1} =, \ldots, = \beta_{i,M}]$. The cost function (14) in Problem 1 is rewritten as follows.

$$J_i(k) = \sum_{j \in N_i} \tilde{a}_{ij} \left\| y_i(k+1) - y_j(k+1) \right\|^2_{P_i} + u_i^T(k) Q_i u_i^T(k) \quad (28)$$

The simulation results are shown in Fig.5.

Comparing the above three simulation results as shown in Fig.3, Fig.4 and Fig.5, one can observe that the consensus

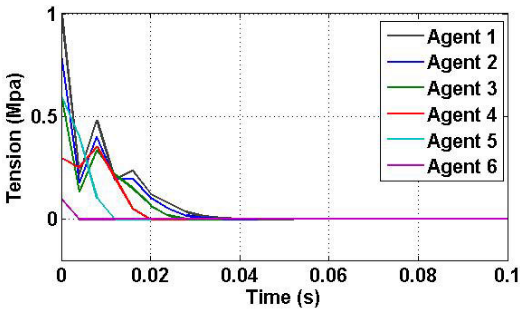

FIGURE 5. Output of looper systems that average consensus control strategy.

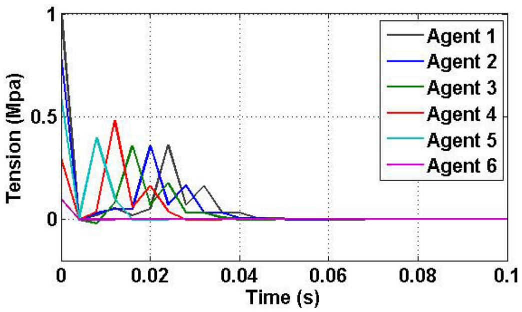

FIGURE 6. Output of looper systems that leader agent is emphasized.

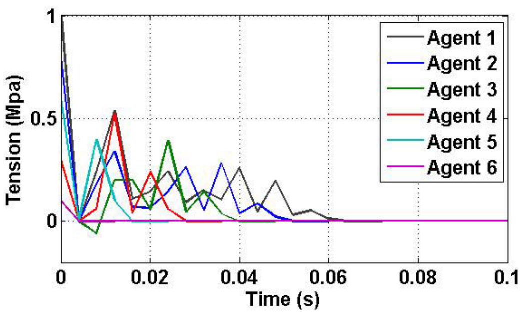

FIGURE 7. Output of looper systems that the nearest neighbor is emphasized.

of the looper tension control system is improved substantially with the developed control protocol for achieving more information through their neighbors, the coupling effects of the neighboring agents are compensated well, and the agents can work cooperatively. In addition, better simulation results can be obtained by selecting proper weighting parameters.

Another three simulation results are carried out when communication time delays is considered, where the weighting numerical values are same to the above three simulation cases,respectively. In the first case that the information of leader agent is emphasized, the simulation results are shown in Fig,6. In the second case that the information of the nearest neighbor is emphasized, the simulation results are shown in Fig.7. In the third case, $\beta_{i,i+1} = \beta_{i,i+2} =, \ldots, = \beta_{i,M}$, the simulation results are shown in Fig.8. The simulation results show that the proposed consensus control protocol based on the subspace identification method is effective and feasible for the communication time delays system, and consensus of the multi-agent system can be improved by selecting appropriate weighting parameters.

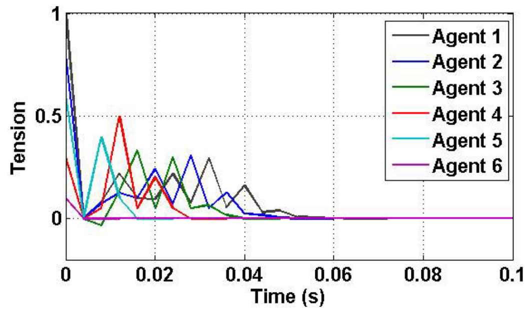

FIGURE 8. Output of looper systems that average consensus control strategy.

VII. CONCLUSIONS

For the looper tension control system of the hot strip mills, the stability and the coordination are high-priority issues. The model of looper tension system becomes more complex and hard to be obtained, when the coupling effects are considered. Conventional model-based control methods can not meet the request of production. In the paper, the consensus control protocol is developed for the multi-agent system using subspace identification method with completely unknown dynamics. The data of neighboring agents are used to design the consensus control protocol to improve the coordination of the looper tension control system. Sufficient conditions for reaching consensus of the multi-agent system are proposed. Furthermore, communication time delays between agents is considered and corresponding control protocol is developed. Simulation results are provided to show the effectiveness. In the future, we will investigate the multi-agent system with unknown disturbance and the input constraint.

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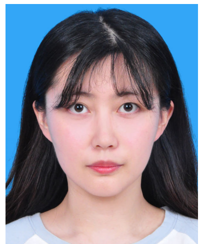

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