# Tracking Control of Multi-Agent Systems Using a Networked Predictive PID Tracking Scheme

Guo-Ping Liu, *Fellow, IEEE*

*Abstract*—With the rapid development of network technology and control technology, a networked multi-agent control system is a key direction of modern industrial control systems, such as industrial Internet systems. This paper studies the tracking control problem of networked multi-agent systems with communication constraints, where each agent has no information on the dynamics of other agents except their outputs. A networked predictive proportional integral derivative (PPID) tracking scheme is proposed to achieve the desired tracking performance, compensate actively for communication delays, and simplify implementation in a distributed manner. This scheme combines the past, present and predictive information of neighbour agents to form a tracking error signal for each agent, and applies the proportional, integral, and derivative of the agent tracking error signal to control each individual agent. The criteria of the stability and output tracking consensus of multi-agent systems with the networked PPID tracking scheme are derived through detailed analysis on the closed-loop systems. The effectiveness of the networked PPID tracking scheme is illustrated via an example.

*Index Terms*—Coordinative tracking control, networked multi-agent systems, PID control, predictive control.

## I. INTRODUCTION

IN recent years, industrial control systems have been developed from centralised control systems, distributed control systems, fieldbus control systems and networked control systems to smart control systems. At the same time, their control units have been more and more intelligent. The control mode is increasingly moving from the individual work mode with single conventional control units to the cooperative and coordinative work mode with multiple smart control units. More and more industrial control systems are becoming multi-agent systems [1]−[3], e.g., smart grids. With the rapid development of network technology, the networked multi-agent control system is the development direction of modern industrial control systems.

The tracking control of multi-agent systems is one of key techniques in the field of the Internet of things. It will have extremely important practical significance and wide application prospects in the area of networked systems in the future.

Especially in the development and construction of distributed control systems, the autonomous tracking control and large-scale real-time communication ability of multi-agent systems can improve the management and coordination ability of various intelligent controllable plants, such as unmanned aerial vehicles, through the sensing and control of wireless signals [4]−[7]. The tracking control of networked multi-agent systems has deeply been studied in recent years [8]−[12].

For a tracking control problem of a multi-agent system with fault signals and communication delays, where the input signal of the leader agent is unknown to the follower agents, a robust tracking control protocol has been presented to eliminate the influence of the input signal combined with an unknown leader input and a fault signal, and achieve the desired tracking performance [13]. To solve the finite-time tracking problem of nonlinear multi-agent systems subject to unknown output dead zones, actuator bias and gain faults, a finite-time adaptive controller has been obtained using fault-tolerant control and neural networks, which ensures that the tracking error converges in a finite time and all system signals are bounded [14]. To investigate the distributed consensus tracking problem of nonlinear high-order multi-agent systems with mismatched unknown parameters and uncertain external disturbances, a backstepping based distributed adaptive control protocol has been presented, where an estimator is designed in each agent to handle parametric uncertainties of its neighbour's dynamics [15]. For the time-varying formation tracking problem of multi-agent systems with switching interaction topologies, a formation tracking protocol has been constructed on the basis of the relative information of the neighbouring agents so that the states of the follower agents form a predefined time-varying formation while tracking the state of the leader agent [16]. But, the impact of the communication constraints on the tracking performance of networked multi-agent control systems is often ignored.

Inspired by many research results on the predictive intelligence of natural biota, some protocols designed with predictive characteristics have been shown to speed up consensus speed, reduce sampling frequency and improve system consistency. Even if individual predictive intelligence has been considered, it cannot be used in networked multi-agent systems, which is mainly due to the influence of communication constraints caused by limited communication channel bandwidth and transmission speed [17]. The communication constraints seriously reduce the consistency of multi-agent systems, and can even completely destroy the system stability. Aimed at

addressing the communication constraints in networked multi-agent control systems, the internal mechanism of the stability and communication constraints of networked multi-agent systems has been revealed [18]. Considering how to compensate for communication constraints actively and taking advantage of characteristics of the network including its ability to transmit vector data, the networked multi-agent predictive control method was proposed [19], which is different from other existing control methods. This method adopts the predictive control strategy, generates the state or output predictions of each agent based on the information available, constructs a distributed consensus protocol with the prediction vector data, realizes the active compensation of communication constraints, and achieves the consensus of the networked multi-agent system. It solves the communication constraint problem of the networked multi-agent control system, and promotes wide applications of networked multi-agent control methods [20].

The predictive control method has been extended to various situations involving networked multi-agent systems. Normally, there exist a great number of real-time big data, heavy computing, and coordination of multiple tasks in conventional networked multi-agent systems. To overcome the problems caused by them, a cloud predictive control scheme has been proposed due to the merits of cloud computing [21]. In practice, it is often the case where the dynamics of networked multi-agent systems are unknown. For this case, a data-driven predictive control strategy has been presented [22]. For networked time-varying multi-agent systems, a learning predictive control method has been provided to adapt the time-varying dynamic characteristics of systems to maintain desired control performance [23]. The security of data propagation is a critical problem for the widespread use of networked multi-agent systems. To solve this problem, the secure predictive control protocol has been developed using blockchain techniques to improve control security under potential cyberattack [24]. Based on the high-order fully actuated (HOFA) model, a HOFA predictive control method has been proposed for the coordinative control of networked nonlinear multi-agents, which has more universality, simplicity, and flexibility for system design and analysis [25].

In spite of much research progress on the tracking control of networked multi-agent systems with communication constraints, there are still many challenges, for example, unknown information on the dynamics of neighbour agents, heavy computing load, difficult to tune parameters of control protocols, various communication constraints, difficult implementation, etc. Taking full advantage of PID control, predictive control and distributed control strategies, this paper investigates the distributed tracking of networked multi-agent systems so that computing load is significantly reduced, parameters of tracking protocols are more easily tuned, and communication delays are actively compensated for.

The main contributions of this paper are highlighted as follows: 1) A networked PPID racking scheme is proposed to achieve desired tracking performance and compensate actively for communication delays; 2) The proposed scheme is imple-

mented in a distributed way so that each agent does not need to have knowledge of the dynamics of its neighbour agents other than their output predictions, which largely simplifies parameter tuning and implementation of the scheme with much less computing load; 3) The criteria of the stability and output tracking consensus of multi-agent systems with the networked PPID tracking scheme are derived.

## II. PROBLEM FORMULATION

The structure of networked multi-agent systems appears in various different forms. The networked multi-agent control system to be studied here is shown in Fig. 1, where each agent has its own local feedback control and can also receive other agent outputs through networks. This type of networked multi-agent control systems has many applications in practice, such as mobile robots and aviation fleets.
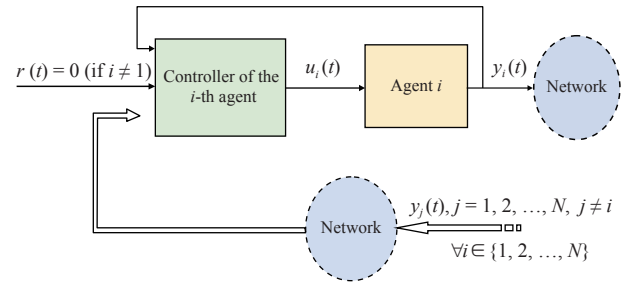


Fig. 1.   The networked multi-agent control system.

The multi-agent systems to be considered are expressed by

$$x_i(t+1) = A_i x_i(t) + B_i u_i(t) \tag{1}$$

$$y_i(t) = C_i x_i(t), \qquad i \in \mathbb{N} \tag{2}$$

where $x_i(t) \in \mathbb{R}^{n_i}, u_i(t) \in \mathbb{R}^{m_i}$ and $y_i(t) \in \mathbb{R}^l$ are the state, control input and output vectors of the $i$-th agent, respectively, $A_i \in \mathbb{R}^{n_i \times n_i}$, $B_i \in \mathbb{R}^{n_i \times m_i}$ and $C_i \in \mathbb{R}^{l \times n_i}$ are the known system matrices, $\mathbb{N} = \{1, 2, \ldots, N\}$ represents the agent set, $\mathbb{R}$ denotes the real number set, $n_i$, $m_i$, $l$ and $N$ are positive integers.

All the agents of a multi-agent system communicate via networks. The communication topology is described by a digraph $T = \{\mathbb{N}, \varepsilon, W\}$, where $\varepsilon \subseteq \mathbb{N} \times \mathbb{N}$ is the agent edge set, and $W = \{w_{ij}\}$ is the weighted adjacency matrix with $w_{ij} \geq 0$ and $w_{ii} = 0$. The directed edge $(i, j) \in \varepsilon$ means that the $i$-th agent can obtain information from the $j$-th agent via the network if $w_{ij} > 0$.

Generally, there are various communication constraints in a networked multi-agent system, for example, communication delays, data loss, attacks, bandwidth, quantisation, etc. Here, only communication delays, which are the most important communication constraint, are considered. Actually, the networked PPID tracking scheme proposed in this paper can also be used to deal with other communication constraints, such as data loss, network attacks etc. in a similar way. To consider practical applications, the following realistic assumptions are made on system (1).

*Assumption 1:*

a) The system matrix pairs $(A_i, B_i)$, $\forall i \in \mathbb{N}$ are controllable. All the state vectors $x_i(t)$, $\forall i \in \mathbb{N}$ are immeasurable, but the

system matrix pairs $(A_i, C_i)$, $\forall i \in \mathbb{N}$ are observerable.

b) Each agent knows only the outputs of its neighbour agents via communication networks and has no information on other agent dynamics.

c) The communication topology $T$ is fixed with a weighted adjacency matrix $W$.

d) The communication delay from the $j$-th agent to the $i$-th agent via networks is bounded by $\tau_{ij}$, $\forall i, j \in \mathbb{N}$, which is a given constant.

e) The desired reference $r(t) \in \mathbb{R}^l$ with constant $r(\infty)$ is known only for the first agent and unknown for other agents.

f) The data packets transmitted via networks contain time stamps, and the clocks of the system are synchronised.

The above Assumptions 1.a)−1.d) are widely employed in many research articles on networked control systems. Assumption 1.e) means that the tracking problem considered here is a leader-following problem. Assumption 1.f) implies that the controller design is based on the time-driven mode rather than the event-driven mode.

Generally, although each individual agent has its own dynamics and controller and there exist communication delays between individual agents, it is expected that all the agents track a common desired reference with coordination through networks. So, under Assumption 1, the problem to be investigated in this paper is determining how to design a distributed tracking controller for each individual agent so that communication delays are actively compensated and all the outputs of a networked multi-agent satisfy the following:

$$\lim_{t \to \infty} y_i(t) = r(\infty), \quad \forall i \in \mathbb{N} \tag{3}$$

where $r(\infty)$ is a known constant.

Let $\widehat{s_i}(t+k|t)$ denote the prediction of a signal $s_i(t)$ for time $t + k$, where $s_i(t)$ may represent the states, outputs, control inputs, errors of the agents, and

$$\tau_i = \max \left\{ \tau_{ji}, \forall j \in \mathbb{N} \right\} \tag{4}$$

where the unit of the time delay $\tau_{ji}$ from the $i$-th agent to the $j$-th agent is the sampling period of a continuous-time system.

Here, a $\Delta$ operation on a signal $s(t)$ and its prediction $s(t|t-1)$ is introduced and defined as

$$\Delta s(t) = s(t) - s(t-1) \tag{5}$$

$$\Delta s(t|t-1) = s(t|t-1) - s(t-1|t-2). \tag{6}$$

Also, let $\Omega_i^-$ represent the set of neighbour agents of the $i$-th agent without communication delays and $\Omega_i^+$ with communication delays from the neighbour agents to the $i$-th agent, respectively, and $\Omega_i^- \subset \mathbb{N}$ and $\Omega_i^+ \subset \mathbb{N}$. Normally, the sets $\Omega_i^-$ and $\Omega_i^+, \forall i \in \mathbb{N}$ determine the communication topology $T$.

### III. NETWORKED PPID TRACKING SCHEME

In industrial control applications, it is well-known that more than 95% controllers are PID controllers. Here, the PID control strategy is applied to the distributed tracking control of networked multi-agent systems so that the advantages of the PID controller are still kept. Thus, the tracking controllers of the agents are designed to be of the following form:

$$u_i(t) = K_i^P e_i(t) + K_i^I z_i(t) + K_i^D v_i(t) \tag{7}$$

$$z_i(t) = z_i(t-1) + e_i(t-1) \tag{8}$$

$$v_i(t) = e_i(t) - e_i(t-1) \tag{9}$$

$\forall i \in \mathbb{N}$, where $e_i(t)$ is the tracking error signal of the $i$-th agent to be designed in this section, which plays a key role in the tracking control, and $K_i^P, K_i^I$ and $K_i^D$ are the PID gain matrices of the $i$-th agent controller.

In this section, two communications cases are addressed: one is where there is no communication delay between agents, i.e., $\tau_{ij} = 0$, $\forall i, j \in \mathbb{N}$ and the other is where there exist communication delays between agents, i.e., $\tau_{ij} > 0$, $\forall i, j \in \mathbb{N}$, $i \neq j$. The data disorder and clock synchronisation of networked multi-agent systems would not be discussed in the controller design of the systems (1) and (2) because of Assumption 1.f).

#### 1) Without Communication Delays Between Agents

In the case of no communication delay, i.e., $\tau_{ij} = 0$, $\forall i, j \in \mathbb{N}$, a networked PID tracking scheme is presented. In this scheme, the agent tracking error signals are designed as

$$e_i(t) = \delta_i(t) + \sum_{j \in \Omega_i^-} w_{ij} \left( y_i(t) - y_j(t) \right) \tag{10}$$

$\forall i \in \mathbb{N}$, where

$$\delta_i(t) = \begin{cases} w_1 (y_1(t) - r(t)), & \text{if } i = 1 \\ 0, & \text{if } i \neq 1 \end{cases} \tag{11}$$

where $w_{ij}$ is the element of the weighted adjacency matrix $W$ and $w_1$ is the weighting factor.

Normally, the tracking error signal $e_i(t)$ in (10) is the sum of the errors between the $i$-th agent output and $j$-th agent output, $\forall j \in \Omega_i^-$. But, in terms of Assumption 1.e), the desired reference is only available for Agent 1. So, for $i = 1$, the tracking error signal $e_1(t)$ in (10) has an additional error between the first agent output and the desired reference.

In the networked PID tracking scheme, the proportional and derivative components play an important role in the transient performance of the coordination of multi-agents and the integrator component focuses on steady state coordination performance. In light of Assumption 1.a), the system matrix pairs $(A_i, B_i)$, $\forall i \in \mathbb{N}$ are controllable. So, in practice, various PID tuning techniques can be applied to the design of the PID parameters $(K_i^P, K_i^I$ and $K_i^D)$ to make the transient and state steady performance of the individual agents satisfactory. Due to Assumption 1.c), the communication topology $T$ is fixed. But, the elements $w_{ij}$ in the weighted adjacency matrix $W$ can be tuned for a networked multi-agent system to have satisfactory coordination performance between its agents using an optimisation method or the trial-and-error method.

#### 2) With Communication Delays Between Agents

When there exist communication delays between the agents, i.e., $\tau_{ij} > 0$, $\forall i, j \in \mathbb{N}$ and $i \neq j$, in a term of Assumption 1.d), only the outputs $y_j(t - \tau_{ij})$, $\forall j \in \mathbb{N} - \{i\}$ of the other agents are available at time $t$ rather than the outputs $y_j(t)$ on the $i$-th agent's side at time $t$. Clearly, the networked PID tracking scheme is not applicable because of communication delays. Thus, a networked PPID tracking scheme is proposed to compensate for communication delays. In this scheme, the predic-

tion strategy is introduced and the tracking error signal $e_i(t)$ is constructed as

$$e_i(t) = \delta_i(t) + \sum_{j\in\Omega_i^+} w_{ij}\left(y_i(t) - \widehat{y}_j\left(t|t-\tau_{ij}\right)\right) \quad (12)$$

$\forall i \in \mathbb{N}$, where $\widehat{y}_j(t|t-\tau_{ij})$ is the output prediction of the $j$-th agent.

According to Assumption 1.a), the system matrix pair $(A_i, C_i)$ is observable. The unmeasured states can be estimated using the Luenberger observer. Based on the control input $u_i(t)$ and output $y_i(t)$ at time $t$, the multi-step state predictions of the $i$-th agent are designed as

$$\widehat{x}_i(t+1|t) = A_i\widehat{x}_i(t|t-1) + B_iu_i(t)$$
$$+ K_i^L\left(y_i(t) - C_i\widehat{x}_i(t|t-1)\right) \quad (13)$$

$$\widehat{x}_i(t+2|t) = A_i\widehat{x}_i(t+1|t) + B_i\widehat{u}_i(t+1|t) \quad (14)$$

$$\vdots$$

$$\widehat{x}_i(t+\tau_i|t) = A_i\widehat{x}_i(t+\tau_i-1|t) + B_i\widehat{u}_i(t+\tau_i-1|t) \quad (15)$$

where $K_i^L$ is the gain matrix of the Luenberger observer.

Since the tracking error signal $e_i(t)$ of the $i$-th agent is related to the outputs of its neighbour agents, it is hard to estimate the control input predictions $\widehat{u}_i(t+k|t)$ using (7) without information on the neighbour agent outputs at time $t$. Due to Assumption 1.b), it is also difficult to construct the output predictions of the neighbour agents. Following the zero-order holder strategy of dealing with unpredicted factors, let the control input predictions be:

$$\widehat{u}_i(t+k|t) = u_i(t), \ k = 1, 2, \ldots, \tau_i - 1. \quad (16)$$

As a result, the state predictions of the $i$-th agent in (13)−(15) can be calculated by

$$\widehat{x}_i(t+k|t) = A_i^{k-1}\left(A_i - K_i^L C_i\right)\widehat{x}_i(t|t-1)$$
$$+ A_i^{k-1}K_i^L C_i x_i(t) + \sum_{j=1}^{k}A_i^{j-1}B_iu_i(t) \quad (17)$$

where $k = 1, 2, \ldots, \tau_i$.

Following the output equation (2), the output predictions of the $i$-th agent are constructed as:

$$\widehat{y}_i(t+k|t) = C_i\widehat{x}_i(t+k|t), \ \ k = 1, 2, \ldots, \tau_i. \quad (18)$$

The output predictions at time $t$ above will be transmitted to its neighbour agents of the $i$-th agent for coordination.

*3) Mixture With and Without Communication Delays*

In the case where some communication delays are zeros and some others are positive, i.e., $\tau_{ij} \geq 0$, $\forall i, j \in \mathbb{N}$ and $i \neq j$, the tracking error signal in the networked PPID tracking scheme is reconstructed as

$$e_i(t) = \delta_i(t) + \sum_{j\in\Omega_i^-} w_{ij}\left(y_i(t) - y_j(t)\right)$$
$$+ \sum_{j\in\Omega_i^+} w_{ij}\left(y_i(t) - \widehat{y}_j\left(t|t-\tau_{ij}\right)\right) \quad (19)$$

$\forall i \in \mathbb{N}$, where the two sets $\Omega_i^-$ and $\Omega_i^+$ have no common element, i.e., $\Omega_i^- \cap \Omega_i^+ = \emptyset$.

Clearly, the tracking error signal in (19) combines the cases in both the networked PID tracking scheme and networked PPID tracking scheme. From now on, the discussions on the networked PPID tracking scheme cover the mixture with and without communication delays in multi-agent systems.

*4) Networked PPID Tracking Control Algorithm*

The implementation of the networked PPID tracking scheme can be carried out in two steps. First, without coordination between the agents by setting the weighted adjacency matrix $W = 0$, design the PID parameters $K_i^P, K_i^I$ and $K_i^D$ of the individual agents independently utilising a PID tuning method so that the dynamic performance of the agents is satisfactory. Second, apply the coordination action in the tracking error signal $e_i(t)$ by adjusting the elements $w_{ij}$ of the weighted adjacency matrix gradually to achieve the desired coordination performance on the basis of the network topology $T$.

Following the networked PPID tracking scheme, the networked PPID tracking algorithm is proposed below.

a) The $i$-th agent receives the output predictions $\widehat{y}_j(t|t-\tau_{ij})$ from its neighbour agent set $\Omega_i^+$ and the outputs $y_j(t)$ from its neighbour agent set $\Omega_i^-$ via networks, for all $i \in \mathbb{N}$.

b) The $i$-th agent calculates the control input $u_i(t)$ using (7)−(9) and (19), based on its own output, the output predictions and outputs received from its neighbour agents and the desired reference $r(t)$ (for the first agent only), and applies the control input to its actuator, for all $i \in \mathbb{N}$.

c) The $i$-th agent estimates the output predictions $\widehat{y}_i(t+k|t)$, for $k = 1, 2, \ldots, \tau_i$, by (17) and (18) employing the available output $y_i(t)$ and control input $u_i(t)$, and sends them to other connected agents via networks, for all $i \in \mathbb{N}$.

It is clear that the networked PPID tracking algorithms is computed in a distributed manner. This makes the implementation of the networked PPID tracking scheme much more simple and highly efficient in the practical applications of multi-agent systems. However, it is shown that if the communication delays between agents become larger and larger, the difficulty of tuning controller parameters will increase slightly because the agent output predictions become less accurate.

## IV. STABILITY ANALYSIS OF CLOSED-LOOP NETWORKED MULTI-AGENT SYSTEMS

This section analyses the stability of closed-loop networked multi-agent systems with communication delays using the networked PPID tracking scheme. Since the stability of closed-loop linear systems has nothing to do with the reference input, to make the analysis simple, the reference input $r(t)$ is assumed to be constant, i.e., $r(t) = r_0$.

Using (2), the tracking error signal $e_i(t)$ in (19) can be re-expressed by

$$e_i(t) = \sum_{j\in\Omega_i^-} w_{ij}\left(C_ix_i(t) - C_jx_j(t)\right)$$
$$+ \sum_{j\in\Omega_i^+} w_{ij}\left(C_ix_i(t) - \widehat{y}_j\left(t|t-\tau_{ij}\right)\right)$$
$$+ \begin{cases} w_1\left(C_1x_1(t) - r_0\right), & \text{if } i = 1 \\ 0, & \text{if } i \neq 1. \end{cases} \quad (20)$$

Define the state estimation error as

$$\widetilde{x}_i(t) = x_i(t) - \widehat{x}_i(t|t-1). \tag{21}$$

Subtracting (13) from (1) gives

$$\widetilde{x}_i(t+1) = \left(A_i - K_i^L C_i\right)\widetilde{x}_i(t). \tag{22}$$

Utilizing the state estimation error in (21), the state prediction of the $i$-th agent in (17) becomes

$$\widehat{x}_i(t+k|t) = -A_i^{k-1}\left(A_i - K_i^L C_i\right)\widetilde{x}_i(t)$$
$$+ A_i^k x_i(t) + \sum_{j=1}^{k} A_i^{j-1} B_i u_i(t). \tag{23}$$

Let the time $t$ be shifted back by $\tau_{ij}$ and the $i$ be replaced by $j$ in (23). This leads to the state protections $\widehat{x}_j(t|t-\tau_{ij})$ of the neighbour agents of the $i$-th agent expressed by

$$\widehat{x}_j\left(t|t-\tau_{ij}\right) = -A_j^{\tau_{ij}-1}\left(A_j - K_j^L C_j\right)\widetilde{x}_j\left(t-\tau_{ij}\right)$$
$$+ A_j^{\tau_{ij}} x_j\left(t-\tau_{ij}\right) + \sum_{k=1}^{\tau_{ij}} A_j^{k-1} B_j u_j\left(t-\tau_{ij}\right)$$
$$\forall j \in \Omega_i^+. \tag{24}$$

Similar to (18), the output predictions of the $i$-th agent neighbours are

$$\widehat{y}_j\left(t|t-\tau_{ij}\right) = C_j\widehat{x}_j\left(t|t-\tau_{ij}\right), \ \forall j \in \Omega_i^+. \tag{25}$$

Substituting the following output predictions obtained from (24) and (25):

$$\widehat{y}_j\left(t|t-\tau_{ij}\right) = -C_j A_j^{\tau_{ij}-1}\left(A_j - K_j^L C_j\right)\widetilde{x}_j\left(t-\tau_{ij}\right)$$
$$+ C_j A_j^{\tau_{ij}} x_j\left(t-\tau_{ij}\right) + \sum_{k=1}^{\tau_{ij}} C_j A_j^{k-1} B_j u_j\left(t-\tau_{ij}\right) \tag{26}$$

in (20) yields

$$e_i(t) = \overline{w}_i C_i x_i(t) - \sum_{j\in\Omega_i^-} w_{ij} C_j x_j(t)$$
$$- \sum_{j\in\Omega_i^+} w_{ij} C_j A_j^{\tau_{ij}} x_j\left(t-\tau_{ij}\right)$$
$$+ \sum_{j\in\Omega_i^+} w_{ij} C_j A_j^{\tau_{ij}-1}\left(A_j - K_j^L C_j\right)\widetilde{x}_j\left(t-\tau_{ij}\right)$$
$$- \sum_{j\in\Omega_i^+} \sum_{k=1}^{\tau_{ij}} w_{ij} C_j A_j^{k-1} B_j u_j\left(t-\tau_{ij}\right)$$
$$+ \begin{cases} w_1\left(C_1 x_1(t) - r_0\right), & \text{if} \quad i = 1 \\ 0, & \text{if} \quad i \neq 1 \end{cases} \tag{27}$$

where

$$\overline{w}_i = \sum_{j\in\Omega_i^-\cup\Omega_i^+} w_{ij}.$$

Equation (27) can be simplified to

$$e_i(t) = \overline{w}_i C_i x_i(t) - \sum_{j\in\Omega_i^-} w_{ij} C_j x_j(t)$$
$$- \sum_{j\in\Omega_i^+} w_{ij} F_{ij} x_j\left(t-\tau_{ij}\right)$$
$$+ \sum_{j\in\Omega_i^+} w_{ij} G_{ij} \widetilde{x}_j\left(t-\tau_{ij}\right)$$
$$- \sum_{j\in\Omega_i^+} w_{ij} H_{ij} u_j\left(t-\tau_{ij}\right)$$
$$+ \begin{cases} w_1\left(C_1 x_1(t) - r_0\right), & \text{if} \quad i = 1 \\ 0, & \text{if} \quad i \neq 1 \end{cases} \tag{28}$$

where

$$F_{ij} = C_j A_j^{\tau_{ij}}$$
$$G_{ij} = C_j A_j^{\tau_{ij}-1}\left(A_j - K_j^L C_j\right)$$
$$H_{ij} = \sum_{k=1}^{\tau_{ij}} C_j A_j^{k-1} B_j.$$

Taking the $\Delta$ operation on the tracking error signal in (28) and replacing $t$ by $t+1$ result in

$$\Delta e_i(t+1) = \overline{w}_i C_i \Delta x_i(t+1) - \sum_{j\in\Omega_i^-} w_{ij} C_j \Delta x_j(t+1)$$
$$- \sum_{j\in\Omega_i^+} w_{ij} F_{ij} \Delta x_j\left(t+1-\tau_{ij}\right)$$
$$+ \sum_{j\in\Omega_i^+} w_{ij} G_{ij} \Delta \widetilde{x}_j\left(t+1-\tau_{ij}\right)$$
$$- \sum_{j\in\Omega_i^+} w_{ij} H_{ij} \Delta u_j\left(t+1-\tau_{ij}\right)$$
$$+ \begin{cases} w_1 C_1 \Delta x_1(t+1), & \text{if} \quad i = 1 \\ 0, & \text{if} \quad i \neq 1. \end{cases} \tag{29}$$

The $\Delta$ operation on (1), (22), (8) and (7) leads to

$$\Delta x_i(t+1) = A_i \Delta x_i(t) + B_i \Delta u_i(t) \tag{30}$$

$$\Delta \widetilde{x}_i(t+1) = \left(A_i - K_i^L C_i\right)\Delta \widetilde{x}_i(t) \tag{31}$$

$$\Delta z_i(t+1) = \Delta z_i(t) + \Delta e_i(t) \tag{32}$$

$$\Delta u_i(t) = K_i^{PD}\Delta e_i(t) + K_i^I \Delta z_i(t) - K_i^D \Delta e_i(t-1) \tag{33}$$

where $K_i^{PD} = K_i^P + K_i^D$.

The following equation can be obtained by substituting $\Delta u_i(t)$ in (30) by (33):

$$\Delta x_i(t+1) = A_i \Delta x_i(t) + B_i K_i^I \Delta z_i(t)$$
$$+ B_i K_i^{PD}\Delta e_i(t) - B_i K_i^D \Delta e_i(t-1). \tag{34}$$

Shifting $t$ backward by $\tau_{ij}$ steps in (33) and letting the index $i$ be replaced by $j$ yield

$$\Delta u_j\left(t-\tau_{ij}\right) = K_j^{PD}\Delta e_j\left(t-\tau_{ij}\right) + K_j^I \Delta z_j\left(t-\tau_{ij}\right)$$
$$- K_j^D \Delta e_j\left(t-\tau_{ij}-1\right). \tag{35}$$

Letting $\Delta x_i(t+1)$ and $\Delta u_j(t-\tau_{ij})$ on the right side in (29) be replaced by (34) and (35), respectively, gives

$$\Delta e_i(t+1) = \overline{w}_i C_i A_i \Delta x_i(t) - \sum_{j\in\Omega_i^-} w_{ij} C_j A_j \Delta x_j(t)$$

$$+ \overline{w}_i C_i B_i K_i^I \Delta z_i(t) - \sum_{j\in\Omega_i^-} w_{ij} C_j B_j K_j^I \Delta z_j(t)$$

$$+ \overline{w}_i C_i B_i K_i^{PD} \Delta e_i(t) - \sum_{j\in\Omega_i^-} w_{ij} C_j B_j K_j^{PD} \Delta e_j(t)$$

$$- \overline{w}_i C_i B_i K_i^D \Delta e_i(t-1) + \sum_{j\in\Omega_i^-} w_{ij} C_j B_j K_j^D \Delta e_j(t-1)$$

$$- \sum_{j\in\Omega_i^+} w_{ij} F_{ij} \Delta x_j\left(t-\tau_{ij}+1\right)$$

$$+ \sum_{j\in\Omega_i^+} w_{ij} G_{ij} \Delta \widetilde{x}_j\left(t-\tau_{ij}+1\right)$$

$$- \sum_{j\in\Omega_i^+} w_{ij} H_{ij} K_j^I \Delta z_j\left(t-\tau_{ij}+1\right)$$

$$- \sum_{j\in\Omega_i^+} w_{ij} H_{ij} K_j^{PD} \Delta e_j\left(t-\tau_{ij}+1\right)$$

$$+ \sum_{j\in\Omega_i^+} w_{ij} H_{ij} K_j^D \Delta e_j\left(t-\tau_{ij}\right)$$

$$+ \begin{cases} w_1 C_1 \left(A_1 \Delta x_1(t) + B_1 K_1^I \Delta z_1(t) + \right. \\ \quad \left. + B_1 K_1^{PD} \Delta e_1(t) - B_1 K_1^D \Delta e_1(t-1)\right), & \text{if } i=1 \\ 0, & \text{if } i \neq 1. \end{cases}$$

$$(36)$$

Let

$$K^{\mathrm{PID}} = \left\{K_i^P, K_i^I, K_i^D\right\}, \quad \forall i \in \mathbb{N}.$$

It is clear from (34), (31), (32) and (36) that $\Delta x_i(t+1)$, $\Delta\widetilde{x}_i(t+1)$, $\Delta z_i(t+1)$ and $\Delta e_i(t+1)$ are the linear functions of variables $\Delta x_i(t)$, $\Delta\widetilde{x}_i(t)$, $\Delta z_i(t)$, $\Delta e_i(t)$ and their delayed variables, $\forall i\in\mathbb{N}$. Thus, the closed-loop multi-agent system with the networked PPID tracking scheme can be described in a compact form below:

$$\zeta(t+1) = \Lambda\left(K^{\mathrm{PID}}, W, w_1, \tau\right)\zeta(t) \qquad (37)$$

where

$$\zeta(t) = \left[\begin{array}{cccc} \Delta X^T(t) & \Delta\widetilde{X}^T(t) & \Delta Z^T(t) & \Delta E^T(t) \end{array}\right]^T$$

$$\Delta X^T(t) = \left[\begin{array}{cccc} \Delta X_1^T(t) & \Delta X_2^T(t) & \cdots & \Delta X_N^T(t) \end{array}\right]$$

$$\Delta\widetilde{X}^T(t) = \left[\begin{array}{cccc} \Delta\widetilde{X}_1^T(t) & \Delta\widetilde{X}_2^T(t) & \cdots & \Delta\widetilde{X}_N^T(t) \end{array}\right]$$

$$\Delta Z^T(t) = \left[\begin{array}{cccc} \Delta z_1^T(t) & \Delta z_2^T(t) & \cdots & \Delta z_N^T(t) \end{array}\right]$$

$$\Delta E^T(t) = \left[\begin{array}{cccc} \Delta E_1^T(t) & \Delta E_2^T(t) & \cdots & \Delta E_N^T(t) \end{array}\right]$$

$$\Delta X_i^T(t) = \left[\begin{array}{cccc} \Delta x_i^T(t) & \Delta x_i^T(t-1) & \cdots & \Delta x_i^T(t+1-\tau_i) \end{array}\right]$$

$$\Delta\widetilde{X}_i^T(t) = \left[\begin{array}{cccc} \Delta\widetilde{x}_i^T(t) & \Delta\widetilde{x}_i^T(t-1) & \cdots & \Delta\widetilde{x}_i^T(t+1-\tau_i) \end{array}\right]$$

$$\Delta z_i^T(t) = \left[\begin{array}{cccc} \Delta z_i^T(t) & \Delta z_i^T(t-1) & \cdots & \Delta z_i^T(t+1-\tau_i) \end{array}\right]$$

$$\Delta E_i^T(t) = \left[\begin{array}{cccc} \Delta e_i^T(t) & \Delta e_i^T(t-1) & \cdots & \Delta e_i^T(t-\tau_i) \end{array}\right]$$

$\forall i\in\mathbb{N}$, $\tau$ represents all the communication delays $\tau_{ij}$, $\forall i,j\in\mathbb{N}$ and $i\neq j$, and $\Lambda(K^{\mathrm{PID}}, W, w_1, \tau)$ is a matrix function of parameters $K^{\mathrm{PID}}, W, w_1$ and $\tau$, and determined by the coefficients of variables $\Delta x_i(t)$, $\Delta\widetilde{x}_i(t)$, $\Delta z_i(t)$, $\Delta e_i(t)$ and their delayed variables in (34), (31), (32) and (36), $\forall i\in\mathbb{N}$.

Clearly, the stability of the multi-agent systems (1) and (2) with the networked PPID tracking scheme is equivalent to the one in system (37). Summarizing the above derives the following theorem:

*Theorem 1:* The multi-agent systems (1) and (2) with the networked PPID tracking scheme is stable if and only if the matrix $\Lambda(K^{\mathrm{PID}}, W, w_1, \tau)$ in (37) is Schur stable.

Also, this theorem provides the foundation of analysing the coordination performance of multi-agent systems with communication delays using the networked PPID tracking scheme in the next section.

## V. COORDINATION ANALYSIS OF NETWORKED MULTI-AGENT SYSTEMS

One of the most important features of networked multi-agent systems is coordination between agents. From (37), if the matrix $\Lambda(K^{\mathrm{PID}}, W, w_1, \tau)$ is Schur stable, it can be concluded that

$$\zeta(t) \to 0, \text{ as } t \to \infty \qquad (38)$$

which implies

$$\lim_{t\to\infty}\Delta x_i(t) = 0, \quad \forall i\in\mathbb{N} \qquad (39)$$

$$\lim_{t\to\infty}\Delta\widetilde{x}_i(t) = 0, \quad \forall i\in\mathbb{N} \qquad (40)$$

$$\lim_{t\to\infty}\Delta z_i(t) = 0, \quad \forall i\in\mathbb{N} \qquad (41)$$

and also the matrix $A_i - K_i^L C_i$ must be Schur stable because of (31). Due to (22)

$$\lim_{t\to\infty} x_i(t) = \lim_{t\to\infty}\widehat{x}_i(t|t-1), \quad \forall i\in\mathbb{N}. \qquad (42)$$

Since $y_i(t) = C_i x_i(t)$ and $\widehat{y}_i(t|t-1) = C_i\widehat{x}_i(t|t-1)$, it is clear from (42) that

$$\lim_{t\to\infty} y_i(t) = \lim_{t\to\infty}\widehat{y}_i(t|t-1) = y_i(\infty), \quad \forall i\in\mathbb{N}. \qquad (43)$$

Equation (8) can also be rewritten as

$$\Delta z_i(t) = e_i(t-1), \quad \forall i\in\mathbb{N}. \qquad (44)$$

From (41) and (44), it can be obtained that

$$\lim_{t\to\infty} e_i(t-1) = \lim_{t\to\infty} e_i(t) = 0, \quad \forall i\in\mathbb{N}. \qquad (45)$$

Considering (19), (43) and (45) leads to

$$0 = \begin{cases} w_1\left(y_1(\infty) - r(\infty)\right), & \text{if } i=1 \\ 0, & \text{if } i\neq 1 \end{cases}$$

$$+ \sum_{j\in\Omega_i^-} w_{ij}\left(y_i(\infty) - y_j(\infty)\right)$$

$$+ \sum_{j\in\Omega_i^+} w_{ij}\left(y_i(\infty) - y_j(\infty)\right) \qquad (46)$$

$\forall i \in \mathbb{N}$. The equation above can also be separated to the following equations:

$$\begin{cases} w_1 (y_1 (\infty) - r(\infty)) + \sum_{j \in \Omega_1^- \cup \Omega_1^+} w_{1j} (y_1 (\infty) - y_j (\infty)) = 0 \\ \sum_{j \in \Omega_i^- \cup \Omega_i^+} w_{ij} (y_1 (\infty) - y_j (\infty) - (y_1 (\infty) - y_i (\infty))) = 0, \\ \hspace{6cm} \forall i \in \mathbb{N} - \{1\}. \end{cases} \quad (47)$$

Thus, the above can be expressed in the following compact form:

$$\overline{W} \tilde{Y} (\infty) = 0 \quad (48)$$

where

$$\overline{W} = \begin{bmatrix} w_1 & w_{12} & w_{13} & \cdots & w_{1N} \\ 0 & -\bar{w}_2 & w_{23} & \cdots & w_{2N} \\ 0 & w_{32} & -\bar{w}_3 & \cdots & w_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & w_{N2} & w_{N3} & \cdots & -\bar{w}_N \end{bmatrix} \quad (49)$$

$$\tilde{Y} (\infty) = \begin{bmatrix} y_1 (\infty) - r(\infty) \\ y_1 (\infty) - y_2 (\infty) \\ y_1 (\infty) - y_3 (\infty) \\ \vdots \\ y_1 (\infty) - y_N (\infty) \end{bmatrix}. \quad (50)$$

From Assumption 1.c), once the elements of the weighted adjacency matrix $W$ are given, the matrix $\overline{W}$ is time-invariant. If $\overline{W}$ is an invertible matrix, (48) implies

$$\tilde{Y} (\infty) = 0 \quad (51)$$

which means

$$y_i (\infty) = y_1 (\infty) = r(\infty), \quad \forall i \in \mathbb{N}. \quad (52)$$

Therefore, the above coordination analysis results in the following theorem:

*Theorem 2:* The multi-agent systems (1) and (2) with the networked PPID tracking scheme achieves output consensus if its closed-loop system is stable and the matrix $\overline{W}$ in (49) is invertible.

This theorem indicates that there exists a certain relationship between the stability and coordination of networked multi-agent systems using the proposed PPID tracking scheme.

## VI.  AN EXAMPLE

Three agents communicating via a network are considered here to demonstrate the performance of the networked PPID tracking scheme. The system matrices used in [19] are adopted as follows:

$$A_1 = \begin{bmatrix} 1.7 & -1.3 \\ 1.6 & -1.8 \end{bmatrix}, B_1 = \begin{bmatrix} 1.0 \\ 2.0 \end{bmatrix}, C_1 = \begin{bmatrix} 1.0 \\ 0.3 \end{bmatrix}^T$$

$$A_2 = \begin{bmatrix} 1.8 & -1.4 \\ 1.8 & -1.9 \end{bmatrix}, B_2 = \begin{bmatrix} 1.7 \\ 3.4 \end{bmatrix}, C_2 = \begin{bmatrix} 0.7 \\ 0.2 \end{bmatrix}^T$$

$$A_3 = \begin{bmatrix} 1.4 & -1.1 \\ 1.3 & -1.5 \end{bmatrix}, B_3 = \begin{bmatrix} 0.8 \\ 1.6 \end{bmatrix}, C_3 = \begin{bmatrix} 1.1 \\ 0.4 \end{bmatrix}^T.$$

The eigenvalues of the three matrices $A_1$, $A_2$ and $A_3$ indicate Agent 1 is unstable, Agent 2 neutrally stable and Agent 3 stable. The initial values of the agent states are set to be

$$x_1 (0) = \begin{bmatrix} 0.1 \\ -0.4 \end{bmatrix}, \quad x_2 (0) = \begin{bmatrix} -0.2 \\ 0.3 \end{bmatrix}, \quad x_3 (0) = \begin{bmatrix} 0.3 \\ -0.2 \end{bmatrix}.$$

The desired reference input of Agent 1 is given as

$$r(t) = \begin{cases} 1, & \text{if } t \in [0, 300] \text{ or } (600, \infty] \\ -1, & \text{if } t \in (300, 600]. \end{cases}$$

To have fast transient convergence for state estimation, using the eigenvalue assignment method, the gain matrices of the three agent state observers (13) are

$$K_1^L = \begin{bmatrix} -0.0273 \\ -0.5758 \end{bmatrix}, \quad K_2^L = \begin{bmatrix} -0.0690 \\ -0.7586 \end{bmatrix}, \quad K_3^L = \begin{bmatrix} -0.0306 \\ -0.4160 \end{bmatrix}$$

so that the eigenvalues of the matrices $A_i - K_i^L C_i$, for $i = 1, 2, 3$ are 0 and 0.1, which should be chosen to provide a much faster response than the other eigenvalues of the closed-loop control system. In the case of a lack of coordination between the three agents, the PID parameters of the controller (7) are tuned employing a PID tuning method, e.g., the trial and error method, so that each agent has satisfactory control performance, e.g., no overshoot, small settling time, zero steady-state error, etc. A set of PID parameters below are obtained:

$$K_1^P = 0.004, \quad K_2^P = 0.0175, \quad K_3^P = 0.0125$$

$$K_1^I = -0.12, \quad K_2^I = -0.2, \quad K_3^I = -0.26$$

$$K_1^D = 0.001, \quad K_2^D = 0.005, \quad K_3^D = 0.008.$$

The weighted adjacency matrix $W = \{w_{ij}\}$ of the network topology is designed as

$$w_{ij} = \begin{cases} 1, & \text{if } i \neq j \\ 0, & \text{if } i = j \end{cases}, \quad \forall i, j \in \{1, 2, 3\}$$

and the weighting factor $w_1 = 1$ so that each agent has two neighbour agents and only Agent 1 has the desired reference input. At the beginning of the simulations, the control inputs of all the three agents are zeros before they receive the outputs of their neighbor agents via networks, i.e., $u_i(t) = 0$, for $t < \max\{\tau_i\}$, $i = 1, 2, 3$.

In this section, three cases are simulated: coordination without communication delays, coordination without compensating for delays, and coordination with compensating for delays.

*Case A:* Coordination without communication delays.

In this case, the three agents are connected via a network, but there exists no communication delay, i.e.,

$$\tau_{ij} = 0, \quad \forall i, j \in \{1, 2, 3\}.$$

The tracking error signal $e_i(t)$ in (10) used in the networked PID tracking scheme becomes

$$e_i(t) = \sum_{j \in \Omega_i^-} w_{ij} (y_i(t) - y_j(t)) + \begin{cases} w_1 (y_1(t) - r(t)), & \text{if } i = 1 \\ 0, & \text{if } i = 2, 3 \end{cases}$$

where

$$\Omega_i^- = \{1, 2, 3\} - \{i\}, \quad \forall i \in \{1, 2, 3\}.$$

The simulation results are shown in Figs. 2 and 3. The outputs of the three agents change rapidly at the beginning due to the initial conditions of the system. In general, the coordination performance of the networked three agents with the networked PID tracking scheme is satisfactory.
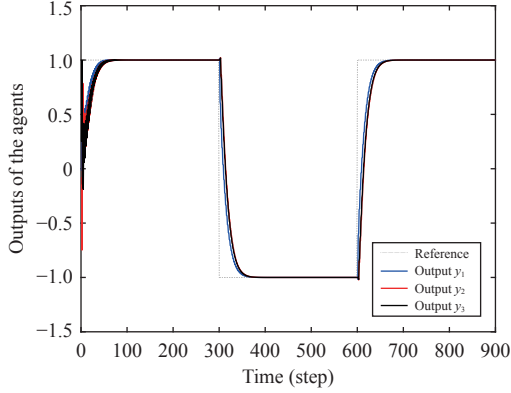


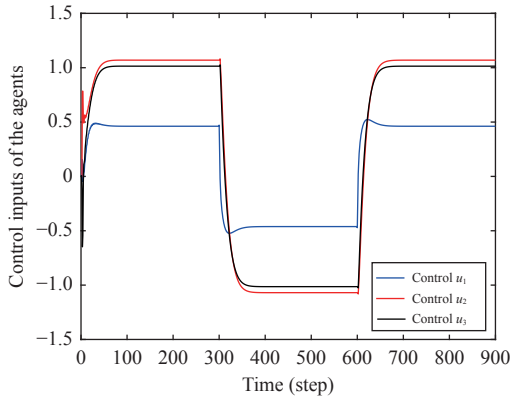Fig. 2.   The outputs of the three agents (Case A).



Fig. 3.   The control inputs of the three agents (Case A).

*Case B:* Coordination without compensating for delays.

Usually, there are communication delays when three agents exchange information via networks. Here, the communication delays between the three agents are assumed to be

$$\tau_{12} = 3, \quad \tau_{13} = 4$$
$$\tau_{21} = 0, \quad \tau_{23} = 6$$
$$\tau_{31} = 7, \quad \tau_{32} = 0.$$

Most existing control methods do not compensate for communication delays. Based on the delayed outputs received from the neighbour agents, the tracking error signal $e_i(t)$ is normally taken to be

$$e_i(t) = \sum_{j \in \Omega_i} w_{ij}\left(y_i\left(t - \tau_{ij}\right) - y_j\left(t - \tau_{ij}\right)\right)$$
$$+ \begin{cases} w_1\left(y_1(t) - r(t)\right), & \text{if } i = 1 \\ 0, & \text{if } i = 2, 3 \end{cases}$$

where

$$\Omega_i = \{1, 2, 3\} - \{i\}, \quad \forall i \in \{1, 2, 3\}.$$

The outputs and control inputs of the three agents are shown in Figs. 4 and 5. Clearly, the three-agent system is unstable. This networked three agent system is hardly stable if communication delays are not compensated for.
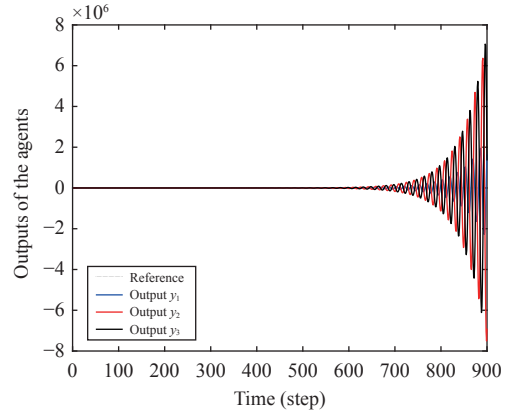


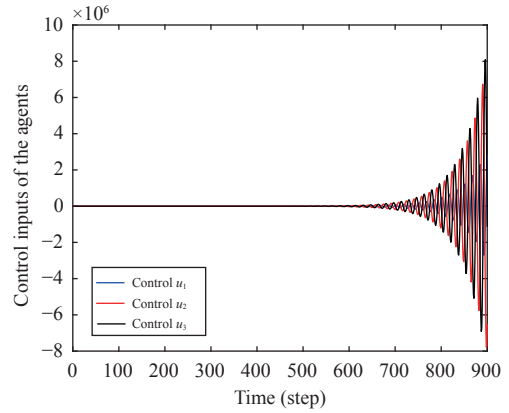Fig. 4.   The outputs of the three agents (Case B).



Fig. 5.   The control inputs of the three agents (Case B).

*Case C:* Coordination with compensating for delays.

Let the communication delays between the three agents be the same as the ones given in Case B. Hence, the sets of the neighbour agents which each agent communicates with are

$$\Omega_1^- = \emptyset, \quad \Omega_1^+ = \{2, 3\}$$
$$\Omega_2^- = \{1\}, \quad \Omega_2^+ = \{3\}$$
$$\Omega_3^- = \{2\}, \quad \Omega_3^+ = \{1\}.$$

To compensate for the communication delays actively, the tracking error signal $e_i(t)$ in (19) in the PPID tracking scheme is applied as follows:

$$e_i(t) = \sum_{j \in \Omega_i^-} w_{ij}\left(y_i(t) - y_j(t)\right)$$
$$+ \sum_{j \in \Omega_i^+} w_{ij}\left(y_i(t) - \widehat{y}_j\left(t|t - \tau_{ij}\right)\right)$$
$$+ \begin{cases} w_1\left(y_1(t) - r(t)\right), & \text{if } i = 1 \\ 0, & \text{if } i = 2, 3 \end{cases},$$
$$\forall i \in \{1, 2, 3\}.$$

The outputs and control inputs of the three agents are shown in Figs. 6 and 7. The control input of Agent 1 varies differently from the other two agents, which may be caused from its open-loop instability characteristics. The simulation results illustrate that the networked three-agent system with the networked PPID tracking scheme is not only stable but also has the similar performance to the coordination of the system without communication delays shown in Case A, and the communication delays are actively compensated.
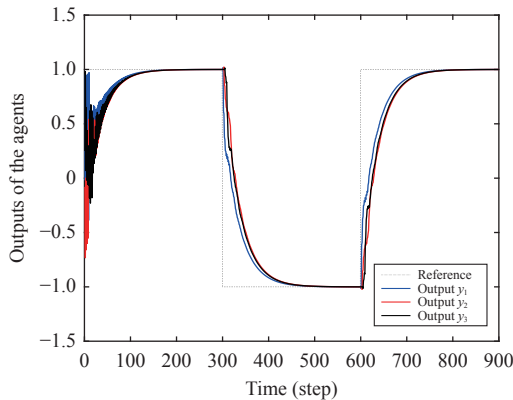


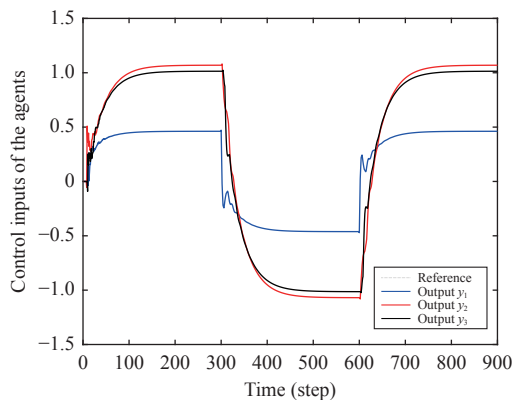Fig. 6.　The outputs of the three agents (Case C).



Fig. 7.　The control inputs of the three agents (Case C).

## VII. Conclusions

The tracking control problem of networked multi-agent systems with communication delays has been addressed using an active delay compensation strategy. The networked PPID tracking scheme has been proposed to solve the problem by taking into account past, present, and future information on the systems and networks. This scheme can provide satisfactory coordination of all the agents and active compensation for communication delays by taking advantage of predictive control and PID control strategies. The comprehensive analysis on the closed-loop networked multi-agent systems with the networked PPID tracking scheme has resulted in the stability and tracking criteria. The simulation results have shown the advantages of the proposed scheme. For practical multi-agent systems, there often exist various internal and external uncertainties and variable communication environments, for example, unmodelled system dynamics, random disturbances, time-

varying network topology, network attacks and so on, which have not been covered in this paper. Ultimately, further investigations on the networked PPID tracking scheme are needed to ensure the scheme can effectively cope with more complex practical environments.

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**Guo-Ping Liu** (Fellow, IEEE) received the B.Eng. degree in industrial automation and M.Eng. degree in control engineering from the Central South University of Technology in 1982 and 1985, respectively, and the Ph.D. degree in control systems from the University of Manchester, UK in 1992. He is a Professor with the Southern University of Science and Technology. His research interests include networked multi-agent control, nonlinear identification and intelligent control, multi-objective optimal control, and industrial advanced control applications.

Professor Liu was the General Chair of the 2007 IEEE International Conference on Networking, Sensing and Control, the 2011 International Conference on Intelligent Control and Information Processing, and the 2012 UKACC International Conference on Control. He served as an Editor-in-Chief of the *International Journal of Automation and Computing* in 2004–2021. He is a Member of the Academy of Europe, a Fellow of IET and a Fellow of CAA.