University of Groningen

Stress-matrix-based formation scaling control

Yang, Qingkai; Sun, Zhiyong; Cao, Ming; Fang, Hao; Chen, Jie

Published in:
Automatica

DOI:
[10.1016/j.automatica.2018.11.046](https://doi.org/10.1016/j.automatica.2018.11.046)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2019

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Yang, Q., Sun, Z., Cao, M., Fang, H., & Chen, J. (2019). Stress-matrix-based formation scaling control. *Automatica*, 101, 120-127. <https://doi.org/10.1016/j.automatica.2018.11.046>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Brief paper

Stress-matrix-based formation scaling control[☆]Qingkai Yang^{a,b}, Zhiyong Sun^c, Ming Cao^b, Hao Fang^{a,*}, Jie Chen^a^a School of Automation, Beijing Institute of Technology, Beijing 100081, China^b Faculty of Science and Engineering, University of Groningen, Groningen 9747 AG, The Netherlands^c Department of Automatic Control, Lund University, Sweden

ARTICLE INFO

Article history:

Received 31 August 2017

Received in revised form 21 October 2018

Accepted 15 November 2018

Available online 14 December 2018

Keywords:

Formation control

Stress matrix

Universal rigidity

Multi-agent systems

ABSTRACT

This paper investigates the formation scaling control problem for multi-agent systems by utilizing the stress matrix associated with a universally rigid framework. Compared with the existing results on formation scaling control, we consider a more challenging scenario where only one agent has the knowledge of the desired formation size. To cope with this constraint, we first propose a distributed estimator for the remaining agents to estimate the scaling parameter. Then by employing the outputs of the estimator, we design a new class of formation scaling control algorithms for universally rigid frameworks such that the overall formation converges to the prescribed shape with the desired scaling. Numerical simulations are carried out to validate the theoretical results.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

In recent years, the research on cooperative control of multi-agent systems has attracted increasing attention from the control community. A fundamental task for cooperative control is formation control, which has found a wide range of applications, including networked mobile sensors performing ocean sampling tasks, a group of mobile robots enclosing a target, and unmanned aircraft imaging in space (Bullo, Cortés, & Martinez, 2009; Chen, Gan, Huang, Dou, & Fang, 2016; Leonard, Paley, Lekien, Sepulchre, Fratantoni, & Davis, 2007). The main objective of distributed formation control is to design control laws using only local information to realize a given prescribed formation shape.

In general, the shape of a formation can be specified by various types of variables: absolute position, relative position (or displacement), distance, bearing (Zhao & Zelazo, 2017), or complex Laplacian (Lin, Wang, Han, & Fu, 2014) (where agents' positions in the 2-D space are described by complex variables in the complex plane and a target formation is identified by a Laplacian matrix with entries of complex numbers). In position-based control, each agent is informed of its absolute position and desired position with respect to a global coordinate system, where agents can be controlled individually without any interaction with their neighbors.

Therefore, any information exchange among agents, e.g., relative position measurement or communication, is not required but a global coordinate system for all agents is needed (Oh, Park, & Ahn, 2015). When relative position becomes the sensed and controlled variable, the desired realizable formation can be achieved based on consensus algorithms using only measurements from local coordinate systems. However, the orientations of local coordinate systems for all individual agents are required to be the same as that of a global coordinate system. In recent years, researchers have thoroughly studied the relative-position-based formation control from various aspects: agents' models with linear, holonomic dynamics or nonlinear, nonholonomic dynamics (Liu & Jiang, 2013; Wen, Duan, Ren, & Chen, 2014); undirected and directed switching interaction graphs (Ji & Egerstedt, 2007; Olfati-Saber & Murray, 2004); continuous- and discrete-time models (Cortés, 2009), to name a few.

In comparison, it is allowed in distance-based formation control that the sensed variable, i.e., relative position, can be measured in an arbitrary local coordinate system for each agent (Oh et al., 2015; Summers, Yu, Dasgupta, & Anderson, 2011). However, using the gradient control protocols, only local stability is guaranteed for distance-based control systems under general graphs. In this scenario, rigidity graph theory has been shown to be an effective tool for analyzing the equilibrium formations up to translations and rotations. In Krick, Broucke, and Francis (2009), infinitesimal rigidity is shown to be a sufficient condition for locally asymptotically stabilizing an equilibrium formation under gradient control laws. To investigate global stability for triangular formations in the plane, it is shown in Cao, Morse, Yu, Anderson, and Dasgupta (2011) that properly initialized formations can be controlled to exponentially converge to a desired formation with proper orientation.

[☆] The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Dimos V. Dimarogonas under the direction of Editor Christos G. Cassandras.

* Corresponding author.

E-mail addresses: qingkai.yang@bit.edu.cn (Q. Yang), sun.zhiyong.cn@gmail.com, zhiyong.sun@control.lth.se (Z. Sun), m.cao@rug.nl (M. Cao), fangh@bit.edu.cn (H. Fang), chenjie@bit.edu.cn (J. Chen).

Note that to implement gradient control laws, relative positions are measured. The paper (Cao, Yu, & Anderson, 2011) proposes a stop-and-go cyclic strategy, which can stabilize a generically minimally rigid formation using only inter-agent distances. More recently, researchers have investigated the formation robustness issues, and have established formation movements in the presence of measurement mismatches (Mou, Belabbas, Morse, Sun, & Anderson, 2016; Sun, Mou, Anderson, & Morse, 2017).

In this paper we focus on designing distributed controllers to achieve a target formation with different scales. Formation scaling control is a major concern in multi-agent formation systems and has been motivated by various practical scenarios. A formation with flexible and different sizes can dynamically adapt to changing environments in practice, e.g. avoiding obstacles for a group of mobile vehicles. In Park, Jeong, and Ahn (2015), in addition to formation stabilization, the size of the formation can also be controlled by adjusting the leader edge of an acyclic minimally persistent graph. In Coogan and Arcak (2012), via a projection operator approach, two strategies are designed for the case when the scaling parameter is known to some of the agents. However, for the single-link method developed in Coogan and Arcak (2012), the monitoring graph (a subgraph that is a directed spanning tree rooted at the leader) needs to be chosen to contain all the vertices in the sensing graph. Later, the projection operator is also employed in Zhao and Zelazo (2017), where bearing-based control frameworks are established. In addition, Han, Wang, Lin, and Zheng (2016) address the formation scaling problem for both single- and double-integrator agent dynamics in the context of complex Laplacians.

It is worth noting that for the multi-agent consensus problem, it is meaningful to incorporate negative weights in the network to model diverse behaviors. In Altafini (2013), by employing the Laplacian-like control scheme under a structurally balanced graph, it has been shown that state agreement can be reached on the same modulus value except for the sign, which is termed as *bipartite consensus*. However, the positive definiteness of the corresponding Laplacian matrix, while useful to guarantee convergence, restricts the degrees of freedom for motion. In this paper we adopt a stress-matrix-based approach to control a formation with desired scaling, where stresses between neighboring agents in the underlying graph are weights that encode the information of the target formation, and contain positive and negative elements. The stress matrix, which generalizes the conventional Laplacian matrix, is widely used to represent the stresses of edges and their connection relationships in a framework. Stress can be interpreted physically as the force per unit length, whose sign indicates the direction of the force. Hence, the stress matrix implicitly captures the features of a framework, e.g., rigidity, stability, and robustness (Connolly & Guest, 2016). Our early efforts on formation scaling control using the stress matrix can be found in Yang, Sun, Cao, Fang and Chen (2017) and Yang, Cao, Sun, Fang and Chen (2017), where some basic control laws were proposed to deal with the constraints that a small number of agents (d pairs in Yang and Sun et al. (2017), and one pair in Yang and Cao et al. (2017), respectively) knows the desired scaling size. We have proposed an algorithm in Yang, Cao, Fang, and Chen (2018) for constructing a positive semidefinite stress matrix, in which the weights of the edges associated with the resultant universally rigid framework are explicitly given. The latest results on stress-matrix-based formation control have been reported in Zhao (2018), where formation control laws are presented to realize transformations of a given nominal configuration under the framework of *affine transformation* (defined as a linear transformation plus a translation). This problem has also been interpreted as homogeneous transformation of particles of a continuum body (Rastgoftar & Jayasuriya, 2014), which gives new insights into the collective motion of multi-agent systems.

Motivated by these results, the goal of this paper is to solve the formation scaling problem in the case where only *one* agent knows the prescribed size, which is more challenging than the existing results (Yang & Cao et al., 2017; Yang & Sun et al., 2017; Zhao, 2018). We first design distributed estimators for each agent in a subgraph in order to infer the prescribed scaling information. Then based on the outputs of the estimator, a new type of formation scaling control laws is proposed by invoking the stress matrix associated with a universally rigid framework. By employing the stress-matrix-based formation control scheme, one can incorporate negative weights in the interaction network, which allows us to model more complex behaviors of autonomous agents. Moreover, more diverse forms of motions (such as translation, rotation, scaling and shearing) can be obtained due to the fact that the dimension of the null space of the stress matrix associated with a universally rigid framework is $d + 1$ (d denotes the dimension of the working ambient space), which thus provides more freedom in formation motion control. In comparison with Zhao (2018), by using the proposed estimator, the formation scaling control can still be achieved even only one agent knows the precise scaling information.

Notations: Denote by I_n the identity matrix with dimension n . Let $\mathbf{1}_n$ be the n -dimensional column vector with all ones. The symbol $\text{span}(x_1, \dots, x_n)$ represents the linear span of vectors $x_1, \dots, x_n$. The cardinality of the set X is written as $|X|$. We use $\|x\|$ to represent the 2-norm of a vector x . The symbol $\otimes$ denotes the Kronecker product.

2. Background

In this section, we introduce basic concepts on stress and formulate the formation scaling control problem. In addition, some preliminary results on stress-matrix-based formation control are reviewed.

2.1. Basic notations

Let $\mathcal{V} = \{1, 2, \dots, n\}$ and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ be, respectively, the vertex set and the edge set of an undirected graph $\mathcal{G}$ representing the neighboring relationships between n vertices. An edge (i, j) exists in $\mathcal{G}$ if and only if vertices i and j are neighbors of each other. The set of vertices that are adjacent to i is denoted by $\mathcal{N}_i = \{j | (i, j) \in \mathcal{E}\}$. The adjacency matrix $A = [a_{ij}] \in \mathbb{R}^{n \times n}$ associated with the graph $\mathcal{G}$ is defined in such a way that $a_{ij} = 1$ if $(i, j) \in \mathcal{E}$ and $a_{ij} = 0$ otherwise. We assume that the graph studied in this paper is finite and simple, i.e., without loops or multiple edges. By assigning an arbitrary orientation to $\mathcal{G}$, the *incidence matrix* $H = [h_{ij}] \in \mathbb{R}^{n \times |\mathcal{E}|}$ is defined by

$$h_{ij} = \begin{cases} 1, & \text{if the } j\text{th edge enters node } i, \\ -1, & \text{if the } j\text{th edge leaves node } i, \\ 0, & \text{otherwise.} \end{cases}$$

In this paper, we assume $|\mathcal{E}| = m$ for simplicity, namely, there are m edges in the graph. The *Laplacian matrix* L can be defined by $L = HH^T \in \mathbb{R}^{n \times n}$.

A *configuration* is a finite collection of n labeled points in $\mathbb{R}^d$, denoted by $q = [q_1^T, \dots, q_n^T]^T$. We say a configuration q is generic if the entries of q are algebraically independent over the rational numbers, namely, there is no non-zero polynomial with rational coefficients that vanishes at the entries of q . A *framework* $(\mathcal{G}, q)$ is obtained by embedding an undirected graph $\mathcal{G}$ in $\mathbb{R}^d$ together with its corresponding configuration q . Given a framework $(\mathcal{G}, q)$ in $\mathbb{R}^d$, if there exists another framework $(\mathcal{G}, p)$ in $\mathbb{R}^d$ such that $\|p_i - p_j\| = \|q_i - q_j\|$, $\forall (i, j) \in \mathcal{E}$, then we say that $(\mathcal{G}, p)$ is *equivalent* to $(\mathcal{G}, q)$. Furthermore, they are *congruent* if $\|p_i - p_j\| = \|q_i - q_j\|$, $\forall i, j$.

$j \in \mathcal{V}$. With these concepts, we follow [Connelly and Guest \(2016\)](#) to introduce rigidity graph theory. A framework $(\mathcal{G}, q)$ in $\mathbb{R}^d$ is said to be *rigid*, if all the frameworks $(\mathcal{G}, p)$ in $\mathbb{R}^d$ equivalent to $(\mathcal{G}, q)$ and sufficiently close to $(\mathcal{G}, q)$ are congruent to $(\mathcal{G}, q)$. If all the frameworks $(\mathcal{G}, p)$ in $\mathbb{R}^d$ equivalent to $(\mathcal{G}, q)$ are congruent to $(\mathcal{G}, q)$, we call it *globally rigid*. Finally, if this congruent relationship holds in any higher-dimensional space $\mathbb{R}^D \supset \mathbb{R}^d$ (where D is a positive integer satisfying $D > d$), it is said to be *universally rigid*.

Mathematically, a *stress* ω_{ij} is a scalar assigned to each edge (i, j) , and there holds $\omega_{ij} = \omega_{ji}$. We use $\omega \in \mathbb{R}^m$ to denote the concatenated vector $\omega = (\dots, \omega_{ij}, \dots)^T$. Given a framework $(\mathcal{G}, q)$, if for each vertex i , we have

$$\sum_{j \in \mathcal{N}_i} \omega_{ij}(q_j - q_i) = \mathbf{0}, \quad (1)$$

then we call ω an *equilibrium stress* with respect to the configuration q . The corresponding *stress matrix* $\Omega = [\Omega_{ij}] \in \mathbb{R}^{n \times n}$ is defined by

$$\Omega_{ij} = \begin{cases} -\omega_{ij}, & i \neq j, \\ \sum_{j \in \mathcal{N}_i} \omega_{ij}, & i = j. \end{cases} \quad (2)$$

Remark 1. Non-zero off-diagonal elements of a Laplacian are positive and a Laplacian matrix is positive semi-definite; however, a stress ω_{ij} can be either positive or negative. Therefore, a stress matrix is usually indefinite.

2.2. Problem formulation

Consider a group of $n \geq d + 2$ mobile agents, each of which is modeled by single integrator dynamics

$$\dot{q}_i = u_i, \quad i = 1, \dots, n, \quad (3)$$

where $q_i \in \mathbb{R}^d$ is the position of agent i and $u_i \in \mathbb{R}^d$ is the control input. Given a generic universally rigid framework $(\mathcal{G}, q^*)$ with an equilibrium stress ω , the objective of formation scaling control is, by using the stress ω , to design distributed control laws $u_i(q_i^* - q_j^*, q_i - q_j), j \in \mathcal{N}_i$, such that

$$\lim_{t \rightarrow \infty} (q_i(t) - q_j(t)) = \kappa(q_i^* - q_j^*), \quad \forall (i, j) \in \mathcal{E}, \quad (4)$$

where κ is a positive constant indicating the size of the formation. Here, by mapping the multi-agent system to the virtual universally rigid framework, we have assigned each edge of the formation with a weight (or stress), which can be either positive or negative.

Remark 2. The formation scaling problem becomes trivial if each agent knows the scaling parameter κ but is much more challenging to solve if the scaling parameter is known to only a limited number of agents ([Yang & Cao et al., 2017](#); [Yang & Sun et al., 2017](#)). In this paper, we show formation scaling can still be achieved using the proposed algorithms even if only one agent knows κ .

2.3. Revisit stress-based formation scaling control

Formation scaling control based on the stress matrix has been partly solved in our recent papers under different scenarios. In this section we review some existing results and detail their differences that motivate the current problem. In [Yang and Sun et al. \(2017\)](#), a class of distributed stress-based control laws has been proposed as follows:

$$u_i = - \sum_{(i,j) \in \mathcal{E}} \omega_{ij}(q_i - q_j) - \sum_{(i,j) \in \mathcal{E}_l^a} a_{ij} [(q_i - q_j) - \kappa(q_i^* - q_j^*)], \quad (5)$$

where ω_{ij} is the stress of edge (i, j) for the underlying graph. Denote by $\mathcal{E}_l^a$ the edge set consisting of d edges whose corresponding relative position vectors linearly span $\mathbb{R}^d$. The subgraph formed by $\mathcal{E}_l^a$ and its associated nodes is connected. Then we have the following result.

Lemma 3. Under the assumption that the given generic framework $(\mathcal{G}, q^*)$ is universally rigid with an equilibrium stress ω , consider a group of agents modeled by (3), and employ the stress-matrix-based control law (5) for each agent. Then the target formation with the prescribed size κ is globally exponentially stabilized.

This lemma was proved in [Yang and Sun et al. \(2017\)](#).

Remark 4. An algorithm on designing positive semidefinite stress matrices for constructing universally rigid frameworks is proposed in [Yang et al. \(2018\)](#) (also see [Yang and Sun et al. \(2017\)](#)). The construction approach is based on matrix SVD and Multiplicative Inverse Eigenvalue (MIE) algorithms, in which global information (i.e., configuration) of the graph is required. However, the implementation of the proposed formation control law based on the stress matrix is completely distributed and no global information is required. We note that this is consistent with the control design strategy “centralized design, distributed implementation”, often used in the literature of distributed control (see e.g., [Oh et al. \(2015\)](#), [Ren and Cao \(2010\)](#)).

Aiming at further reducing the number of agents knowing κ , we have designed another class of distributed control laws by utilizing orthogonal projection ([Yang & Cao et al., 2017](#)). For the sake of clear presentation and without loss of generality, we assume that the edge linking agents 1 and 2 is labeled as the first edge. The control inputs for agents 1 and 2 are designed as

$$u_i = - \sum_{(i,j) \in \mathcal{E}} \omega_{ij}(q_i - q_j) - h_{i1}(z_1 - \kappa z_1^*) - \sum_{\iota=2}^{d+1} h_{i\iota}(z_\iota - \kappa_\iota z_\iota^*), \quad i = 1, 2, \quad (6)$$

where ω_{ij} is the stress associated with edge (i, j) , $z_\iota = q_i - q_j$, $\iota = 1, \dots, m$, with agents i and j being the head and tail of the ι th edge, respectively, and $h_{i\iota}$ is the entry of the incidence matrix H . The scaling estimation κ_ι is defined by

$$\kappa_\iota = \frac{1}{\|z_\iota^*\|^2} (z_\iota^*)^T z_\iota, \quad \iota = 2, \dots, d+1. \quad (7)$$

For the remaining agents, their control inputs $u_i, i = 3, \dots, n$, are given by

$$u_i = - \sum_{(i,j) \in \mathcal{E}} \omega_{ij}(q_i - q_j) - \sum_{\iota=2}^{d+1} h_{i\iota}(z_\iota - \kappa_\iota z_\iota^*). \quad (8)$$

It is assumed that the stresses in (6) and (8) admit a universally rigid framework. To implement the above control law, a subgraph $\mathcal{G}_l^b(\mathcal{V}_l^b, \mathcal{E}_l^b)$ with $|\mathcal{E}_l^b| = d + 1$ is chosen such that the dimension of the convex hull spanned by any d pairs of nodes is d . The projection technique (7) is also employed in [Coogan and Arcak \(2012\)](#), [Zhao and Zelazo \(2017\)](#), where the projection operator is used to ‘estimate’ the scaling parameter ([Coogan & Arcak, 2012](#)) and to realize the bearing-based control ([Zhao & Zelazo, 2017](#)).

One of the main results of [Yang and Cao et al. \(2017\)](#) is as follows.

Lemma 5. For a group of agents modeled by (3), the formation scaling control task (4) is achieved globally using the proposed distributed control laws (6) and (8).

Fig. 1. An example of selecting the sub-framework $(\mathcal{G}_l, q_l^*)$ from a universally rigid framework in the plane.

3. Main results

In this section, we consider the scenario where only one agent knows the desired formation size represented by the scaling parameter κ . In practice, it is very possible that only a small number of agents (or possibly only one agent) in a multi-agent group is able to receive limited information from outside world or interact with environment due to physical constraints or certain task requirements. For example, the agents knowing the predefined information are not equipped with communication devices, or they are vulnerable to attacks causing physical damages. These scenarios motivate the formation scaling problem that will be solved in this section. First, distributed estimators are proposed for a subset of the agents to get the precise knowledge of κ . Then we design a new type of stress-matrix-based control algorithms by using the outputs of the proposed estimators to realize formation scaling control.

To facilitate the system design, we choose d pairs of nodes together with d edges from the given generic universally rigid framework $(\mathcal{G}, q^*)$ to construct a sub-framework $(\mathcal{G}_l, q_l^*)$ with an underlying connected graph $\mathcal{G}_l(\mathcal{V}_l, \mathcal{E}_l)$, such that the dimension of the convex hull spanned by the nodes in $\mathcal{V}_l$ is d . It is worth noting that the chosen d pairs of nodes can involve less than $2d$ nodes, due to the common endpoint shared by distinct edges. For simplicity, it is assumed that $|\mathcal{V}_l| = n_l$. The edge set $\mathcal{E}_l$ is defined as $\mathcal{E}_l = \{(i, j) \in \mathcal{E} \mid i \in \mathcal{V}_l, j \in \mathcal{V}_l\}$. Fig. 1 shows an example of the setup for the sub-framework $(\mathcal{G}_l, q_l^*)$ in the plane, where the stresses of dashed and solid lines are positive and negative, respectively.

Remark 6. For a general framework, there might be multiple choices for constructing the sub-framework $(\mathcal{G}_l, q_l^*)$. Since the given framework $(\mathcal{G}, q^*)$ is generic, no $d + 1$ nodes of V lie in a $(d - 1)$ -dimensional affine space (Connolly & Guest, 2016). In other words, any d relative position vectors for d edges associated with at least $d + 1$ nodes are linearly independent, and thus the dimension of the convex hull spanned by the d relative position vectors is d . In view of the fact that there must exist a spanning tree in a connected graph, one can choose a sub-tree with d edges and $d + 1$ nodes to guarantee the connectivity of the subgraph $\mathcal{G}_l(\mathcal{V}_l, \mathcal{E}_l)$. An example of choosing the subgraph from a universally rigid framework in the plane is shown in Fig. 1.

3.1. Estimator-controller design

Without loss of generality, we assume only agent 1 knows the scaling parameter κ among all the agents. Motivated by Lemma 3 indicating the size of the formation can be controlled by d pairs of agents, estimators are designed for the other agents in $\mathcal{V}_l$.

We propose the following estimator for agent 2

$$\begin{cases} \dot{\theta}_2 = -\Lambda_2 \xi_2^T \zeta_2 \\ \dot{\hat{\kappa}}_2 = -\theta_2 - \Lambda_2 \xi_2^T (q_2 - q_1) \end{cases}, \quad (9)$$

and for agent $i, i = 3, \dots, n_l$,

$$\begin{cases} \dot{\theta}_i = -\Lambda_i \xi_i^T \zeta_i \\ \dot{\hat{\kappa}}_i = \hat{\kappa}_{i-1} - \theta_i - \Lambda_i \xi_i^T (q_i - q_{i-1}) \end{cases}, \quad (10)$$

where $\hat{\kappa}_i$ is agent i 's estimation of κ , θ_i is an intermediate variable, and Λ_i is a positive scalar. For agent $i, i = n_l + 1, \dots, n$, we assign

$$\hat{\kappa}_i = 0. \quad (11)$$

The variables ξ_i and ζ_i in (9) and (10) are respectively given as follows.

$$\xi_i = |\mathcal{N}_{i-1}^l| (q_{i-1}^* - q_i^*) + \sum_{j \in \mathcal{N}_{i-1}^l \cap \mathcal{N}_i^l} (q_i^* - q_j^*), \quad (12)$$

and

$$\begin{aligned} \zeta_i &= \hat{\kappa}_i (|\mathcal{N}_{i-1}^l| + 1) (q_{i-1}^* - q_i^*) - \sum_{j \in \mathcal{N}_i^l} \omega_{ij} (q_i - q_j) \\ &\quad - \sum_{j \in \mathcal{N}_i^l} a_{ij} (q_i - q_j) + \sum_{k \in \mathcal{N}_{i-1}^l} \omega_{(i-1)k} (q_{i-1} - q_k) \\ &\quad + \sum_{k \in \mathcal{N}_{i-1}^l} a_{(i-1)k} (q_{i-1} - q_k), \quad i = 2, \dots, n_l, \end{aligned} \quad (13)$$

where $\mathcal{N}_i^l$ denotes the set of neighbor agents of agent i in the subgraph $\mathcal{G}_l(\mathcal{V}_l, \mathcal{E}_l)$. For the estimation of an unknown parameter in a multi-agent system, the leader–follower consensus-based estimation method has been commonly used in the literature, see e.g., Cao, Ren, and Meng (2010), Ren (2007) and many recent papers citing them. The successful estimation in these works is built upon active communication. In comparison, it can be seen from the proposed relative-position-based estimator (9) and (10) that κ is not used to establish the estimation, which implies that the accurate information of κ can be estimated even when the agent that knows κ does not have the capability of broadcasting because of some physical constraints, such as the absence of communication device or failure of transmission due to e.g. a long communication range.

Based on the estimator, the control inputs for the multi-agent system are given by

$$\begin{cases} u_1 = - \sum_{j \in \mathcal{N}_1^l} \omega_{1j} (q_1 - q_j) \\ \quad - \sum_{j \in \mathcal{N}_1^l} a_{1j} ((q_1 - q_j) - \kappa (q_1^* - q_j^*)) \\ u_i = - \sum_{j \in \mathcal{N}_i^l} \omega_{ij} (q_i - q_j) \\ \quad - \sum_{j \in \mathcal{N}_i^l} a_{ij} ((q_i - q_j) - \hat{\kappa}_i (q_i^* - q_j^*)), \quad i = 2, \dots, n, \end{cases} \quad (14)$$

where ω_{ij} is the stress of edge (i, j) , and the stress ω admits a generic universally rigid framework $(\mathcal{G}, q^*)$. We recall that a_{ij} is the entry of the adjacency matrix with respect to the subgraph $\mathcal{G}_l(\mathcal{V}_l, \mathcal{E}_l)$. The symbol $\hat{\kappa}_i$ is the estimation of κ by agent i . The first part of the control law for each agent is used to confine the agents to the null space of the stress matrix $\mathcal{Q}$, and the second part aims to scale the formation to the prescribed size. It can be observed from (14) that only agent 1 knows the desired size of the formation, and the others employ the estimation variable $\hat{\kappa}_i, i = 2, \dots, n_l$, in their control inputs.

3.2. Stability analysis

We present our main result as follows.

Theorem 7. *Given a generic universally rigid framework $(\mathcal{G}, q^*)$, the formation scaling for a group of agents modeled by (3) is achieved globally asymptotically using the proposed control laws (14) and estimators (9) and (10). In addition, for agent i , $i = 2, \dots, n_l$, the convergence of estimations holds that $\lim_{t \rightarrow \infty} \hat{\kappa}_i = \kappa$.*

Proof. In the proof, we will first show that the estimation errors converge to zero, followed by the analysis that the formation scaling problem can be solved. Considering the control inputs for the first two agents, we obtain their dynamics from (14) as

$$\begin{aligned} \dot{q}_2 - \dot{q}_1 = & - \sum_{j \in \mathcal{N}_2} \omega_{2j}(q_2 - q_j) + \sum_{k \in \mathcal{N}_1} \omega_{1k}(q_1 - q_k) \\ & - \sum_{j \in \mathcal{N}_2^l} a_{2j}((q_2 - q_j) - \hat{\kappa}_2(q_2^* - q_j^*)) \\ & + \sum_{k \in \mathcal{N}_1^l} a_{1k}((q_1 - q_k) - \kappa(q_1^* - q_k^*)). \end{aligned} \quad (15)$$

Define the estimation error for agent 2 by

$$\tilde{\kappa}_2 = \hat{\kappa}_2 - \kappa, \quad (16)$$

and denote the quantity associated with κ and $\hat{\kappa}$ in (15) by q_{2r}^* , i.e.,

$$q_{2r}^* \triangleq \sum_{j \in \mathcal{N}_2^l} a_{2j} \hat{\kappa}_2 (q_2^* - q_j^*) - \sum_{k \in \mathcal{N}_1^l} a_{1k} \kappa (q_1^* - q_k^*). \quad (17)$$

By invoking the fact that $q_1^* - q_k^* = q_1^* - q_2^* + (q_2^* - q_k^*)$, we have

$$\begin{aligned} q_{2r}^* = & \sum_{j \in \mathcal{N}_2^l} a_{2j} \hat{\kappa}_2 (q_2^* - q_j^*) - \sum_{k \in \mathcal{N}_1^l} a_{1k} \kappa (q_2^* - q_k^*) \\ & - \sum_{k \in \mathcal{N}_1^l} a_{1k} \kappa (q_1^* - q_2^*) \\ = & \sum_{j \in \mathcal{N}_1^l \cap \mathcal{N}_2^l} (\hat{\kappa}_2 - \kappa) (q_2^* - q_j^*) + a_{21} \hat{\kappa}_2 (q_2^* - q_1^*) \\ & - \sum_{k \in \mathcal{N}_1^l} a_{1k} \kappa (q_1^* - q_2^*) + \sum_{k \in \mathcal{N}_1^l} a_{1k} \hat{\kappa}_2 (q_1^* - q_2^*) \\ & - \sum_{k \in \mathcal{N}_1^l} a_{1k} \hat{\kappa}_2 (q_1^* - q_2^*) \\ = & \tilde{\kappa}_2 \sum_{j \in \mathcal{N}_1^l \cap \mathcal{N}_2^l} (q_2^* - q_j^*) + \tilde{\kappa}_2 |\mathcal{N}_1^l| (q_1^* - q_2^*) \\ & + \hat{\kappa}_2 (|\mathcal{N}_1^l| + 1) (q_2^* - q_1^*). \end{aligned} \quad (18)$$

Substituting (18) into (15), we get

$$\dot{q}_2 - \dot{q}_1 = \xi_2 + |\mathcal{N}_1^l| (q_1^* - q_2^*) + \sum_{j \in \mathcal{N}_1^l \cap \mathcal{N}_2^l} (q_2^* - q_j^*), \quad (19)$$

where ξ_2 and ξ_2 are defined in (12) and (13). By differentiating $\hat{\kappa}_2$ in (9), and replacing $\dot{q}_2 - \dot{q}_1$ with (19), it follows

$$\dot{\hat{\kappa}}_2 = -\tilde{\kappa}_2 \Lambda_2 ||\mathcal{N}_1^l|| (q_1^* - q_2^*) + \sum_{j \in \mathcal{N}_1^l \cap \mathcal{N}_2^l} (q_2^* - q_j^*)^2. \quad (20)$$

By recalling that the scaling parameter is constant, there holds $\dot{\kappa} = 0$. Hence, it is straightforward to have

$$\dot{\tilde{\kappa}}_2 = \dot{\hat{\kappa}}_2 = -\tilde{\kappa}_2 \Lambda_2 ||\mathcal{N}_1^l|| (q_1^* - q_2^*) + \sum_{j \in \mathcal{N}_1^l \cap \mathcal{N}_2^l} (q_2^* - q_j^*)^2. \quad (21)$$

Note that the subgraph $\mathcal{G}_l$ with d edges is chosen to be connected, and thus $n_l \leq d + 1$. In light of the fact the given framework is generic, the configuration $\{q_1^*, \dots, q_{n_l}^*\}$ is affinely independent. Hence, for $i = 2, \dots, n_l$, there holds

$$|\mathcal{N}_{i-1}^l| (q_{i-1}^* - q_i^*) + \sum_{j \in \mathcal{N}_{i-1}^l \cap \mathcal{N}_i^l} (q_i^* - q_j^*) \neq \mathbf{0}_d. \quad (22)$$

Therefore, it is easy to know $\tilde{\kappa}_2$ converges to zero exponentially, namely, $\lim_{t \rightarrow \infty} \hat{\kappa}_2(t) = \kappa$.

Analogously, define the estimation error for agent i , $i = 3, \dots, n_l$, by

$$\tilde{\kappa}_i = \hat{\kappa}_i - \hat{\kappa}_{i-1}. \quad (23)$$

Similar to the calculations for agent 2, we get

$$\dot{\tilde{\kappa}}_i = -\tilde{\kappa}_i \Lambda_i ||\mathcal{N}_{i-1}^l|| (q_{i-1}^* - q_i^*) + \sum_{j \in \mathcal{N}_{i-1}^l \cap \mathcal{N}_i^l} (q_i^* - q_j^*)^2 \quad (24)$$

In light of (22), we know $\lim_{t \rightarrow \infty} \tilde{\kappa}_i(t) = 0$, which implies $\lim_{t \rightarrow \infty} \hat{\kappa}_i(t) = \hat{\kappa}_{i-1}(t)$, $i = 3, \dots, n_l$. In combination with the fact that $\lim_{t \rightarrow \infty} \hat{\kappa}_2 = \kappa$, we have

$$\lim_{t \rightarrow \infty} \hat{\kappa}_i = \kappa, \quad i = 2, \dots, n_l. \quad (25)$$

Now we consider the control law (14), which can be equivalently written as

$$\begin{cases} u_1 = - \sum_{j \in \mathcal{N}_1} \omega_{1j} (q_1 - q_j) \\ \quad - \sum_{j \in \mathcal{N}_1^l} a_{1j} ((q_1 - q_j) - \kappa (q_1^* - q_j^*)), \\ u_i = - \sum_{j \in \mathcal{N}_i} \omega_{ij} (q_i - q_j) + (\hat{\kappa}_i - \kappa) \sum_{j \in \mathcal{N}_i^l} a_{ij} (q_i^* - q_j^*) \\ \quad - \sum_{j \in \mathcal{N}_i^l} a_{ij} ((q_i - q_j) - \kappa (q_i^* - q_j^*)), \quad i = 2, \dots, n. \end{cases} \quad (26)$$

Before moving on, we define an auxiliary variable $\tilde{q}_i$ as follows

$$\tilde{q}_i = q_i - \kappa q_i^*. \quad (27)$$

Then the compact form of (26) is given by

$$\dot{\tilde{q}} = -((\Omega + \mathcal{L}_s) \otimes I_d) \tilde{q} + (\tilde{K} \mathcal{L}_s \otimes I_d) q^*, \quad (28)$$

where $\tilde{q} = [\tilde{q}_1^T, \dots, \tilde{q}_n^T]^T \in \mathbb{R}^{dn}$ is the vector form of $\tilde{q}_i$, and $\tilde{K} \in \mathbb{R}^{n \times n}$ is a diagonal matrix defined as $\tilde{K} \triangleq \text{diag}(0, (\hat{\kappa}_2 - \kappa), \dots, (\hat{\kappa}_{n_l} - \kappa), 0, \dots, 0)$.

The matrix $\mathcal{L}_s$ is given in the form of

$$\mathcal{L}_s = \begin{bmatrix} \mathcal{L}_l & \mathbf{0}_{n_l \times (n-n_l)} \\ \mathbf{0}_{(n-n_l) \times n_l} & \mathbf{0}_{(n-n_l) \times (n-n_l)} \end{bmatrix}, \quad (29)$$

where $\mathcal{L}_l$ is the Laplacian matrix associated with the subgraph $\mathcal{G}_l(\mathcal{V}_l, \mathcal{E}_l)$, defined by

$$[\mathcal{L}_l]_{ij} = \begin{cases} \sum_{j \in \mathcal{N}_i^l} a_{ij}, & i = j, \\ -a_{ij}, & i \neq j. \end{cases}$$

It follows from Lemma 3 that the autonomous part of system (28), i.e., $\dot{\tilde{q}} = -((\Omega + \mathcal{L}_s) \otimes I_d) \tilde{q}$, is globally exponentially stable. The details of the proof are omitted here due to the space limitation. In view of the facts that q^* is fixed and bounded, and $\tilde{K}$ globally converges to the zero matrix from (25), by invoking the input-to-state stability theorem (Khalil, 2002), we can conclude that

$$\lim_{t \rightarrow \infty} (q_i(t) - q_j(t)) = \kappa (q_i^* - q_j^*), \quad \forall (i, j) \in \mathcal{E}. \quad (30)$$

This completes the proof. $\square$

Fig. 2. The prescribed formation shape and one universally rigid framework.

Fig. 3. Estimation errors of agents 2 and 3 on the unknown scaling parameter.

Remark 8. As can be seen from (9) and (10), two-hop information is required to implement the relative-position-based estimator. Similar estimation problem was also addressed in Meng, Anderson, and Hirche (2016) to estimate an unknown rotation parameter, in which the estimator was designed under complete graphs. In addition, as stated in Meng et al. (2016), it is still an open problem of how to construct estimators using only relative position information with a general connected sparse graph. This can be a topic for future research.

4. Simulation results

In this section, we present simulation results to validate the effectiveness of the theoretical results. Suppose the given prescribed formation shape and one of its corresponding universally rigid frameworks in $\mathbb{R}^2$ are shown in Figs. 2(a) and 2(b), respectively. Dashed lines and solid lines indicate positive and negative stresses, respectively. The subgraph $\mathcal{G}_l(\mathcal{V}_l, \mathcal{E}_l)$ is marked in blue with $\mathcal{V}_l = \{1, 2, 3\}$ and $\mathcal{E}_l = \{(1, 2), (2, 3)\}$.

In this scenario, the stress matrix is in the form of

$$\Omega = \begin{bmatrix} 27.5 & -45 & 26.75 & -8.25 & -1 \\ -45 & 75 & -45 & 15 & 0 \\ 26.75 & -45 & 27.1250 & -9.375 & 0.5 \\ -8.25 & 15 & -9.3750 & 4.125 & -1.5 \\ -1 & 0 & 0.5 & -1.5 & 2 \end{bmatrix}.$$

The initial positions for the five agents are randomly chosen as $q_1(0) = [-0.0573, -0.9285]^T$, $q_2(0) = [-1.4483, 2.0435]^T$, $q_3(0) = [-2.053, 1.3054]^T$, $q_4(0) = [-2.3178, -1.7852]^T$ and $q_5(0) = [-1.6165, -1.5231]^T$. The scaling parameter κ is set to be 10, which is only known to agent 1. By employing the estimators (9) and (10), agents 2 and 3 can successfully estimate the accurate value of κ shown in Fig. 3.

Fig. 4. Formation evolution using the control law (14).

Fig. 5. Scaling length errors using the control law (14).

To clearly show the variations of the formation shape at different time instants, we design an additional input $[3.5, 0]^T$ for each agent. Since the extra input is constant and the same for each agent, it will not affect the stability of the closed-loop system. From Fig. 4, we can observe that the formation starts from a random initial formation shape, which is zoomed in on the left top, and finally converges to the desired one using the control law (14). The corresponding scaling length errors are shown in Fig. 5, which implies that all the edges achieve their desired ones.

5. Conclusion

In this paper, we have addressed the formation scaling problem for multi-agent systems for the scenario where only one agent knows the desired scaling size of the overall formation. To infer the scaling information for the agents in the set $\mathcal{V}_l$ of a chosen subgraph, we have constructed a relative-position-based estimator, with which the scaling parameter κ is effectively estimated. Then by mapping the multi-agent system into a virtual universally rigid framework, we have proposed a new class of stress-matrix-based control algorithms in combination with the estimation, such that all the agents converge to the predefined formation globally. Along this line, we will investigate the formation scaling problem when the scaling parameter is time-varying or state-dependent (instead of being constant or piecewise constant) in the future. In addition,

the effect of time-delay transmission on the convergence will also be of great interest for further study.

Acknowledgments

Q. Yang is partially supported by the Ubbo Emmius scholarship of the University of Groningen. Z. Sun was supported by the Prime Minister's Australia Asia Incoming Endeavour Postgraduate Award from Australian Government. The work of H. Fang and J. Chen was supported by Projects of Major International (Regional) Joint Research Program NSFC (Grant No. 61720106011), NSFC (Grant Nos. 61621063, 61573062, 61873033), Beijing Advanced Innovation Center for Intelligent Robots and Systems (Beijing Institute of Technology), Key Laboratory of Biomimetic Robots and Systems (Beijing Institute of Technology), Ministry of Education, Beijing, 100081, China.

References

- Altafini, C. (2013). Consensus problems on networks with antagonistic interactions. *IEEE Transactions on Automatic Control*, 58(4), 935–946.
- Bullo, F., Cortés, J., & Martinez, S. (2009). *Distributed control of robotic networks: a mathematical approach to motion coordination algorithms*. Princeton University Press.
- Cao, M., Morse, A. S., Yu, C., Anderson, B. D. O., & Dasgupta, S. (2011). Maintaining a directed, triangular formation of mobile autonomous agents. *Communications in Information and Systems*, 11(1), 1.
- Cao, Y., Ren, W., & Meng, Z. (2010). Decentralized finite-time sliding mode estimators and their applications in decentralized finite-time formation tracking. *Systems & Control Letters*, 59(9), 522–529.
- Cao, M., Yu, C., & Anderson, B. D. O. (2011). Formation control using range-only measurements. *Automatica*, 47(4), 776–781.
- Chen, J., Gan, M., Huang, J., Dou, L., & Fang, H. (2016). Formation control of multiple Euler-Lagrange systems via null-space-based behavioral control. *Science China. Information Sciences*, 59(1), 1–11.
- Connelly, R., & Guest, S. D. (2016). *Frameworks, tensegrities and Symmetry: Understanding Stable Structures*. Cambridge University Press.
- Coogan, S., & Arcak, M. (2012). Scaling the size of a formation using relative position feedback. *Automatica*, 48(10), 2677–2685.
- Cortés, J. (2009). Global and robust formation-shape stabilization of relative sensing networks. *Automatica*, 45(12), 2754–2762.
- Han, Z., Wang, L., Lin, Z., & Zheng, R. (2016). Formation control with size scaling via a complex Laplacian-based approach. *IEEE Transactions on Cybernetics*, 46(10), 2348–2359.
- Ji, M., & Egerstedt, M. (2007). Distributed coordination control of multi-agent systems while preserving connectedness. *IEEE Transactions on Robotics*, 23(4), 693–703.
- Khalil, H. K. (2002). *Nonlinear systems* (3rd ed.). Upper Saddle River, NJ: Prentice Hall.
- Krick, L., Broucke, M. E., & Francis, B. A. (2009). Stabilisation of infinitesimally rigid formations of multi-robot networks. *International Journal of Control*, 82(3), 423–439.
- Leonard, N. E., Paley, D. A., Lekien, F., Sepulchre, R., Fratantoni, D. M., & Davis, R. E. (2007). Collective motion, sensor networks, and ocean sampling. *Proceedings of the IEEE*, 95(1), 48–74.
- Lin, Z., Wang, L., Han, Z., & Fu, M. (2014). Distributed formation control of multi-agent systems using complex Laplacian. *IEEE Transactions on Automatic Control*, 59(7), 1765–1777.
- Liu, T., & Jiang, Z. (2013). Distributed formation control of nonholonomic mobile robots without global position measurements. *Automatica*, 49(2), 592–600.
- Meng, Z., Anderson, B. D. O., & Hirsche, S. (2016). Formation control with mismatched compasses. *Automatica*, 69, 232–241.
- Mou, S., Belabbas, M. A., Morse, A. S., Sun, Z., & Anderson, B. D. O. (2016). Undirected rigid formations are problematic. *IEEE Transactions on Automatic Control*, 61(10), 2821–2836.
- Oh, K. K., Park, M. C., & Ahn, H. S. (2015). A survey of multi-agent formation control. *Automatica*, 53, 424–440.
- Olfati-Saber, R., & Murray, R. M. (2004). Consensus problems in networks of agents with switching topology and time delays. *IEEE Transactions on Automatic Control*, 49(9), 1520–1533.
- Park, M. -C., Jeong, K., & Ahn, H. -S. (2015). Formation stabilization and resizing based on the control of inter-agent distances. *International Journal of Robust and Nonlinear Control*, 25(14), 2532–2546.
- Rastgoftar, H., & Jayasuriya, S. (2014). Evolution of multi-agent systems as continua. *Journal of Dynamic Systems, Measurement, and Control*, 136(4), 041014.
- Ren, W. (2007). Multi-vehicle consensus with a time-varying reference state. *Systems & Control Letters*, 56(7–8), 474–483.
- Ren, W., & Cao, Y. (2010). *Distributed coordination of multi-agent networks: emergent problems, models, and issues*. Springer Science & Business Media.
- Summers, T. H., Yu, C., Dasgupta, S., & Anderson, B. D. O. (2011). Control of minimally persistent leader-remote-follower and coleader formations in the plane. *IEEE Transactions on Automatic Control*, 56(12), 2778–2792.
- Sun, Z., Mou, S., Anderson, B. D. O., & Morse, A. S. (2017). Rigid motions of 3-d undirected formations with mismatch between desired distances. *IEEE Transactions on Automatic Control*, 62(8), 4151–4158.
- Wen, G., Duan, Z., Ren, W., & Chen, G. (2014). Distributed consensus of multi-agent systems with general linear node dynamics and intermittent communications. *International Journal of Robust and Nonlinear Control*, 24(16), 2438–2457.
- Yang, Q., Cao, M., Fang, H., & Chen, J. (2018). Constructing universally rigid frameworks with application in multi-agent formation control. *IEEE Transactions on Automatic Control*, <http://dx.doi.org/10.1109/TAC.2018.2829687>.
- Yang, Q., Cao, M., Sun, Z., Fang, H., & Chen, J. (2017). Formation scaling control using the stress matrix. In *Proc. of the 56th IEEE conference on decision and control* (pp. 3449–3554).
- Yang, Q., Sun, Z., Cao, M., Fang, H., & Chen, J. (2017). Construction of universally rigid frameworks and their applications in formation scaling control. In *Proc. of the 36th chinese control conference* (pp. 163–168).
- Zhao, S. (2018). Affine formation maneuver control of multi-agent systems. *IEEE Transactions on Automatic Control*, 1–16. <http://dx.doi.org/10.1109/TAC.2018.2798805>.
- Zhao, S., & Zelazo, D. (2017). Translational and scaling formation maneuver control via a bearing-based approach. *IEEE Transactions on Control of Network Systems*, 4(3), 429–438.

Qingkai Yang received his first Ph.D. degree from Beijing Institute of Technology, Beijing, China, and the second one from University of Groningen, Groningen, the Netherlands, in 2018. He is currently an associate professor with the School of Automation, Beijing Institute of Technology. His research interest is in cooperative control of multi-agent systems and autonomous agents.

Zhiyong Sun received the Ph.D. degree from Australian National University (ANU), Canberra, ACT, Australia, in 2017. He was a Research Fellow/Lecturer with the Research School of Engineering, ANU, from 2017 to 2018. In June 2018, he joined the Department of Automatic Control, Lund University, Lund, Sweden, as a postdoctoral researcher. His current research interests include graph rigidity theory, control of autonomous formations, and networked systems.

Dr. Sun was a recipient of the Australian Prime Minister's Endeavor Postgraduate Award from the Australian Government in 2013, the Outstanding Overseas Student Award from the Chinese Government in 2016, and the Springer Ph.D. Thesis Prize from Springer in 2017. He was a finalist of the Best Student Paper (BSP) Award in the 54th IEEE Conference on Decision and Control (CDC 2015).

Ming Cao received the Bachelor and Master degrees from Tsinghua University, Beijing, China, in 1999 and 2002, respectively, and the Ph.D. degree from Yale University, New Haven, CT, USA, in 2007, all in electrical engineering.

He is currently a Professor of systems and control with the Engineering and Technology Institute (ENTEG), University of Groningen, Groningen, The Netherlands, where he started as a tenure-track Assistant Professor in 2008. From September 2007 to August 2008, he was a Postdoctoral Research Associate with the Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, USA. He worked as a Research Intern during the summer of 2006 with the Mathematical Sciences Department, IBM T. J. Watson Research Center, Yorktown Heights, NY, USA. His main research interest include autonomous agents and multiagent systems, mobile sensor networks, and complex networks.

Prof. Cao is the 2017 and inaugural recipient of the Manfred Thoma medal from the International Federation of Automatic Control (IFAC) and the 2016 recipient of the European Control Award sponsored by the European Control Association (EUCA). He is an Associate Editor for the IEEE TRANSACTIONS ON AUTOMATIC CONTROL, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS, and Systems & Control Letters, and for the Conference Editorial Board of the IEEE Control Systems Society. He is also a member of the IFAC Technical Committee on Networked Systems.

Hao Fang received the B.S. degree from the Xi'an University of Technology, in 1995, and the M.S. and Ph.D. degree from the Xi'an Jiaotong University, in 1998 and 2002, respectively. He held two postdoctoral appointments at the INRIA/France research group of COPRIN and at the LASMEA (UNR6602 CNRS/Blaise Pascal University, Clermont-Ferrand, France). Since 2011 he has been a professor at Beijing Institute of Technology. His research interests include control of multi-agent systems, unmanned systems, and robotics.

Jie Chen received the B.S., M.S., and Ph.D. degrees in control theory and control engineering from the Beijing Institute of Technology, Beijing, China, in 1986, 1993, and 2000, respectively. He is currently a Professor of Control Science and Engineering with the Beijing Institute of Technology. His current research interests include intelligent control and decision in complex systems, multiagent systems, and optimization methods.