ISSN: 2414-1895 DOI: 10.6919/ICJE.202104_7(4).0052

Robust Formation Control for Multi-robot Networks Via Synergetic Control

Chuangchuang Wang[1,2], Sheng Gao[1,2], Jinyu Tian[1,2] and Han Tang[1,2]

[1]Artificial Intelligence Key Laboratory of Sichuan Province, Zigong, 643000, China;

[2]School of Automation and Engineering, Sichuan University of Science & Engineering, Yibin, 644000, China.

Abstract

This paper investigates the formation consensus for multi-robot networks subject to synergetic control (SC). The dynamics of multi-robot networks are modeled by the Euler-Lagrange (EL) equations. With the use of the synergetic control, the finite-time convergence properties and chattering free phenomena of multi-robot networks under directed topologies are addressed by using the Lyapunov stability theory. Simulation results are provided to prove the validity of proposed control approaches.

Keywords

Multi-robot Networks; Euler-Lagrange system; Synergetic Control; Finite-time Control; Nonchattering Phenomena.

1. Introduction

1.1 Motivation

In recent years, there has been a extensive exploration of the formation control problem in advanced multi-robot networks [1-3]. Because of the certain engineering goals, implementing formation control of a flock of robots based on nonlinear networks has resulted in a lot of concern among increasing researches. Moreover, compared to single robot, multi-robot networks have higher fault tolerance, flexible reconfgurability and higher work efficiency [4]. Among a great deal of research on multi-robot formation control algorithms, the distributed tracking problem needs to be considered and there is a leader node in the networked systems, which serves as a command generator to generate specifed trajectories required for robot activities. Consequently, the follower robot systems need to track the curve of the leader node [5]. Secondly, the EL equations can usually be demanded to model quantities of mechanical structures, such as aircraft, manipulator, military industrial vehicle and helicopter [6-8]. In this paper, the SC strategy of networked EL systems is discussed. Thirdly, the research in this paper involving the formation on networked EL systems is taken very seriously because of the need of overcoming chattering phenomena in applications, such as cooperative control on the robot formation or synchronous coordinating multi-motor systems. Therefore, the purpose of this paper is to derive SC strategies applied in the formation control for multi-robot networks based on EL systems with model uncertainties.

1.2 Brief summary of prior literature

The formation control problems of multi-robot networks have been extensively investigated. There exist the asymptotical convergence stability conditions in most published papers [9-11]. However, most results based on linear multi-robot dynamics cannot be fully applied to deal with the formation control issue for multi-robot systems based on EL model, which are used to describe a great deal of complex nonlinear networks[12-14]. As a result, the formation consensus of the EL multi-robot systems has been widely studied [15-17]. Compared with multiple asymptotical control methods,

ISSN: 2414-1895 DOI: 10.6919/ICJE.202104_7(4).0052

finite-time control is prevailing for its higher control accuracy, faster convergence speed and stronger robustness [18-20]. Different from the traditional sliding mode control schemes, SC generates a smooth and non-switching continuous synergetic term [29]. Then a new approach law with property of finite-time convergence without chattering phenomena is obtained. In contrast to the previous results about synergetic control [21-23], it may be a first attempt to handle the formation control problem for multi-robot networks by the SC scheme while the finite-time stability is also necessary. Further, the advantages of the proposed controller are derived in this paper, in comparison to other finite-time formation control laws using SC, are that it can deal with multi-robot networks composed of nonlinear manipulators with dynamical EL-systems and the interconnection of the network is assumed to be modeled by a connected, directed, graph with fixed topology.

1.3 Contribution of this paper

In view of preceding literatures as far as the author knows, SC for synchronization of nonlinear multi-robot networks based on EL model with time-delay and external disturbances is seldom investigated. The present paper aims to deal with this problem by using the SC scheme, directed topology graph theory and the Lyapunov stability theory. The main challenge is that the introduction of SC scheme to multi-robot systems represents a relatively big difficulty to the solution of this issue. The core contributions of this work can be listed as follows:

1.The finite-time synergetic controller of nonlinear multi-robot networks based on EL model are obtained by distributed finite-time formation control schemes.

2.The SC scheme mentioned in this paper generates a smooth and non-switching continuous synergetic term, which will overcome chattering phenomena.

1.4 Organization

The remainder of this work is structured as follows. Section 2 reviews the model of the EL system and related preliminaries in detail. In Section 3, the design of synergetic controller is elaborated, on basis of which the characteristics of finite-time convergence and nonchattering phenomena can be achieved. In Section 4, finite-time consensus control scheme for multi-robot networks is investigated by SC. Then the simulation results are described to achieve the effectiveness of the given distributed control algorithms in Section 5. Concluding conclusions are presented in Section 6 in the end.

2. Preliminaries

2.1 Algebraic graph theory

Consider the multi-robot network that consists one leader and N followers. In order to reach the formation control consensus and realize the information exchange among multiple robots, we introduce the communication graph theory in the following. Let $\mathcal{G} = (\mathcal{V}, \mathscr{E})$ be defined as the directed graph, where $\mathcal{V} = \{v_1, v_2, \ldots, v_N\}$ acts as the set of nodes. The edge $(v_i, v_j) \in \mathscr{E}$ if the robot can transfer information to the robot directly, but not necessarily vice versa. Define the weighted adjacency matrix A = [aij] of $\mathcal{G}$, where aij > 0 if there is an information channel between the i_{th}robot and the j_{th} robot and aij = 0 otherwise. Define the diagonal matrix $B = diag\{b_1, b_2, \ldots, b_N\}$ and $b = [b_1, b_2, \ldots, b_N]^T$ with elements bi= 1 if there is an information channel between the i_{th} follower robot and the leader, otherwise bi = 0. A directed spanning tree is a directed graph. Define Laplacian matrix of $\mathcal{G}$as $L = [l_{ij}]$ whose elements is defined as

$$l_{ij} = \begin{cases} a_{ij}, i \neq j \\ -\sum_{k=1,k\neq i}^{N} a_{ik}, i = j \end{cases}.$$

2.2 Networked Euler-Lagrange systems

Considering the multi-robot dynamics with model uncertainties defined by [24]

$$M_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + G_i(q_i) = u_i + \delta_i(t, q_i, \dot{q}_i, \tau_i) \tag{1}$$

ISSN: 2414-1895 DOI: 10.6919/ICJE.202104_7(4).0052

where $q_i = [q_{i1}, q_{i2}, \cdots, q_{in}]^T$ $(i = 1, \cdots, N)$ represents joint positions, $C_i(q_i) \in R^{n\times n}$ is the Coriolis and centripetal matrix and $G_i(q_i) \in R^n$ is the gravitational torques. The inertia matrix $M_i(q_i) \in R^{n\times n}$ is denoted as the symmetric and positive-definite matrix, whereas $u_i \in R^n$ represents the input torques and $\delta_i \in R^n$ includes the external disturbances and system uncertainties. Matrices $M_i(q_i) \in R^{n\times n}$ and $C_i(q_i) \in R^{n\times n}$ and vectors $G_i(q_i) \in R^n$ are assumed to change depending on $1 \le i \le N$. In fact, the behavior of the leader is in dependent of the followers, which means that leader's state keeps changing freely throughout the entire process. Suppose that q_0 is the leader robot's desired input and the dynamic of the leader is defined by

$$M_0(q_0)\ddot{q}_0 + C_0(q_0, \dot{q}_0)\dot{q}_0 + G_0(q_0) = u_0. \tag{2}$$

Throughout subsequent analyses, the dynamics were assumed to satisfy the following assumptions [25,26]:

Assumption 1. $M_i(q_i) \in R^{n\times n}$in (1) is defined as positive definite symmetric and bounded matrix, that is, $M_m \le \| M_i(q_i) \| \le M_M$ for constants $M_m > 0$ and $M_M > 0$.

Assumption 2. δ_i in (1) and $u_0$in (2) are assumed to be bounded as follows: $\|\delta_i\| \le \bar{d} < \infty$and $\|u_0\| \le \bar{u}_0 < \infty$. Define $\bar{d}$and $\bar{u}_0$ are positive constants.

Remark 1. When designing control protocols for the uncertain EL systems, the information about matrix $M_i(q_i)$, input torques $u_0$is not needed to be precisely achieved. Therefore, it just need to know the upper bound or an estimation in advance, which can be obtained in practical application.

Assumption 3. The directed communication topology $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ has a directed spanning tree if $(\mathcal{V}, \mathcal{E})$ exists one node at least in presence of a directed path to all other nodes.

Remark 2. [27] A directed spanning tree of $\mathcal{G}$ is a directed tree that contains all nodes of $\mathcal{G}$, where each node contains accurately one parent exclusive of the root which contains a directed path to the other nodes. A directed graph contains a directed spanning tree on condition that one exists as a subset of a directed graph.

2.3 Synergetic control procedure

Consider the dynamic of nonlinear systems of the form

$$\dot{x} = f(x, u, t) \tag{3}$$

Where $x \in R^n$ is the generalized state vector, $u \in R^n$ represents the control torque.

The main steps of design procedure for synergetic controller may be summarized as follows [28]:

A macro variable ψ defined for constructing a manifold in a nonlinear system yields: $M = \{x : \psi(x) = 0, \psi \in R^n\}$ where the macro variable ψ acts as a function of states in nonlinear system. Basically, for simplicity, we chose a linear combination of the states of the system.

A controller is synthesized that drives the system state exponentially to a specifed manifold whose dynamic evolution can be represented as

$$T\dot{\psi} + \psi = 0 \tag{4}$$

where T denotes a nonsingular positive definite diagonal matrix, satisfying $T = diag\{\tau_1, \cdots, \tau_n\}$.

The chain rule of differentiation is given by $\dot{\psi} = \frac{d\psi}{dx}\dot{x}$. Combining equations (3) and (4), it follows that $T\frac{d\psi}{dx}f(x, u, t) + \psi = 0$. Then equation (4) is ultimately carried out to design the control protocol u.

2.4 Synergetic control design

Define the error variable as

$$e_i(t) = \sum_{j=1, j\ne i}^{N} a_{ij}\left[q_i - q_j\left(t - T_{ji}\right)\right] + b_i(q_i - q_0) \tag{5}$$

ISSN: 2414-1895 DOI: 10.6919/ICJE.202104_7(4).0052

where T_{ji} acts as a positive real constant, representing time-delay of information exchange between i_{th} and j_{th} robot.
Define the manifold as follows:

$$M_{\varepsilon_i} = \{\varepsilon_i : \sigma_i = \psi(\varepsilon_i) = 0, \psi \in R^n\}$$

where $\psi(\varepsilon_i) = \lambda_i e_i + \dot{e}_i$, $\varepsilon_i = \dot{e}_i$.
Further, it follows that

$$\ddot{e}_i = \dot{\varepsilon}_i = -\left(\tau_i \psi_{\varepsilon_i}\right)^{-1} \psi(\varepsilon_i) \tag{6}$$

According to equation (1) and equations (5) -(6), we can obtain the SC laws:

$$\begin{aligned} u_i &= C_i \dot{q}_i + G_i + \left(\sum_{j=1, j\neq i}^{N} (a_{ij} + b_i) \right)^{-1} M_i \left[\ddot{e}_i + \sum_{j=1, j\neq i}^{N} a_{ij}\, \ddot{q}_j(t - T_{ji}) + b_i \ddot{q}_0 \right] \\ &= C_i \dot{q}_i + G_i + \left(\sum_{j=1, j\neq i}^{N} (a_{ij} + b_i) \right)^{-1} M_i \left[\sum_{j=1, j\neq i}^{N} a_{ij}\, \ddot{q}_j(t - T_{ji}) + b_i \ddot{q}_0 \right] \\ &\quad -\left(\textstyle\sum_{j=1,j\neq i}^{N} (a_{ij} + b_i)\right)^{-1} M_i {\tau_i}^{-1} (\lambda_i e_i + \dot{e}_i) \end{aligned} \tag{7}$$

Remark 3. Compared with the existing design schemes of distributed controller in the works like [29] which were confined to the single system, the controller designed in this paper is an effective compensation for formation control applied to a network of N EL systems. More precisely, in the networked EL system, only a few algorithms adopt SC methods to approximate the desired time-varying trajectory. In addition, the method can also be applied to more general directed communication topology.

Remark 4. Compared with communication topologies in the multi-robot networks about finite-time formation control algorithms which were undirected, the finite-time control methods proposed are based on directed graphs, which can contribute significantly to reducing the burden of information exchange.

Remark 5. Different from traditional sliding mode control schemes, the SC provides a smooth, nonswitching continuous synergetic term which is continuous without abrupt change such that overcomes chattering phenomena. The controller can make the system state exponentially asymptotically reach the manifold. Once states reach manifolds, the synergetic controller will retain them thereafter.

Definition 1. Assume that there exist the networked EL systems modeled by (1). Our goal is to ensure that all robots outputs can follow a time-varying reference trajectory generated by a leader, replaced with 0. The systems are said to synchronize in finite time T if $q_i \to q_0$, $\dot{q}_i \to \dot{q}_0$, for all i = 1, 2, N, as t >T.

3. Main results

In view of above discussions, we know that the control scheme achieved in this paper is introduced by combining the matrix properties of graph theory and SC design techniques. To illustrate the consensus of formation control and feasibility of the considered control protocol in this section, one gives necessary and sufficient derivation of main theorems in detail in Section 4.

4. Synergetic control for multi-robot networks

When Tji = 0, according to SC laws (7), we can obtain

ISSN: 2414-1895 DOI: 10.6919/ICJE.202104_7(4).0052

$$u_i = C_i\dot{q}_i + G_i + \left(\sum_{j=1,j\neq i}^{N}(a_{ij}+b_i)\right)^{-1} M_i\left[\sum_{j=1,j\neq i}^{N} a_{ij}\,\ddot{q}_j + b_i\ddot{q}_0\right]$$
$$-\left(\sum_{j=1,j\neq i}^{N}(a_{ij}+b_i)\right)^{-1} M_i{\tau_i}^{-1}(\lambda_i e_i + \dot{e}_i) \quad (8)$$

Theorem 1. Consider the N EL robots model (1) in the absence of disturbances. The errors and error rates in multi-robot system will guarantee convergence asymptotically to zero exponentially under the speed of convergence rate τi if dynamic controller is selected as (8), where τi is element of the nonsingular positive definite diagonal matrix T.

Proof : Choose a Lyapunov candidate function V=½ ψ(ε)T ψ (ε) where

$$\psi(\varepsilon) = (\psi(\varepsilon_1)^T, \ldots, \psi(\varepsilon_N)^T)^T.$$

Using the fact that $T$is a nonsingular positive definite diagonal matrix, then T^{-1} is also positive definite.

Differentiating V along (4) yields

$$\dot{V} = \frac{d}{dt}\left(\frac{1}{2}\psi(\varepsilon)^T\psi(\varepsilon)\right) = -T^{-1}\|\psi(\varepsilon)\|^2 \le 0$$

In view of inequality V, it can be guaranteed that the stability of the N robots cooperative systems (1) with the control input (8) when δi = 0. The errors and error rates in system will ensure convergence exponentially.

The errors and error rates in system will ensure convergence exponentially asymptotically to zero, namely, $\lambda_i e_i + \dot{e}_i \to 0$. We can easily get the properties of asymptotical convergence about e_i and $\dot{e}_i$. When ei = 0, it holds that

$$[(\overline{\mathcal{L}}+\overline{\mathcal{B}})\otimes E_n]\begin{bmatrix} q_1 \\ \vdots \\ q_N \end{bmatrix} = [(\overline{\mathcal{L}}+\overline{\mathcal{B}})\otimes E_n](1_N \otimes q_0).$$

In light of Lemma 2, $\overline{\mathscr{L}}+\overline{\mathscr{B}}$ is invertible. Therefore, it is clear that $[q_1,\cdots,q_N]^T = 1_N \otimes q_0$ and it follows that $[\dot{q}_1,\cdots,\dot{q}_N]^T = 1_N \otimes \dot{q}_0$.

5. Numerical simulation

Considering the nominal model of networked EL systems, a group of two-link robot manipulators may be simulated for validating tracking performance of the proposed controller strategies in this section [25, 30]. Assume that we take four two-link robot manipulators as followers and the remaining manipulator as a leader for the multi-robot systems. The internal structure of a two-link revolute manipulator is depicted in Fig. 1. The parameters of manipulators are set as follows: the

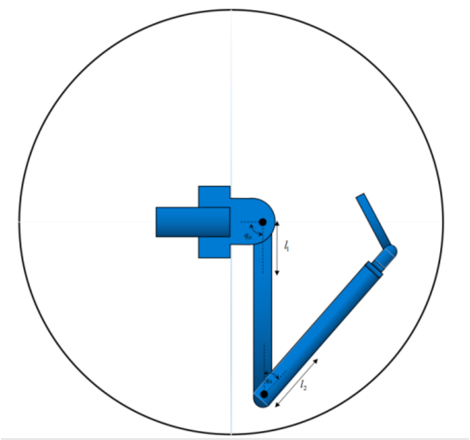

Fig. 1 two-link manipulator platform

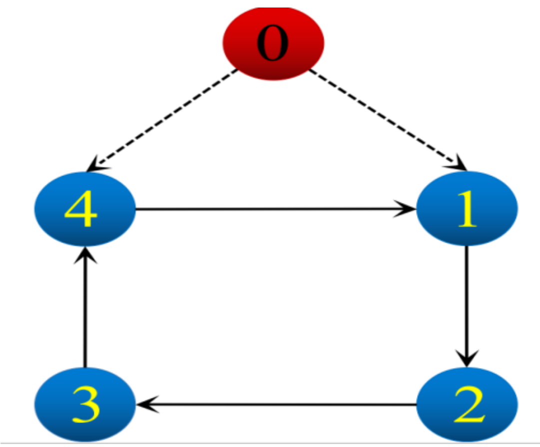

Fig. 2 Communication topology

ISSN: 2414-1895
DOI: 10.6919/ICJE.202104_7(4).0052

acceleration of gravity is $g = 9.8m/s^2$; the masses of links 1 and 2 are $m_{i1} = m_{i2} = 1kg$; the lengths of links 1 and 2 are $l_{i1} = l_{i2} = 1m$; the moments of inertia of links 1 and 2 are $J_{i1} = 0.2kgm^2$ and $J_{i2} = 0.4kgm^2$, respectively. Suppose the directed communication topology used to model the information communication among robots is depicted in Fig. 2, where node 0 denotes the leader manipulator and others denote the followers. For easy of plotting, we assume that each manipulator keeps the state value uniformly. It is clear that the communication topology is directed and the information exchange occurs only between the leader and followers 1 and 4.

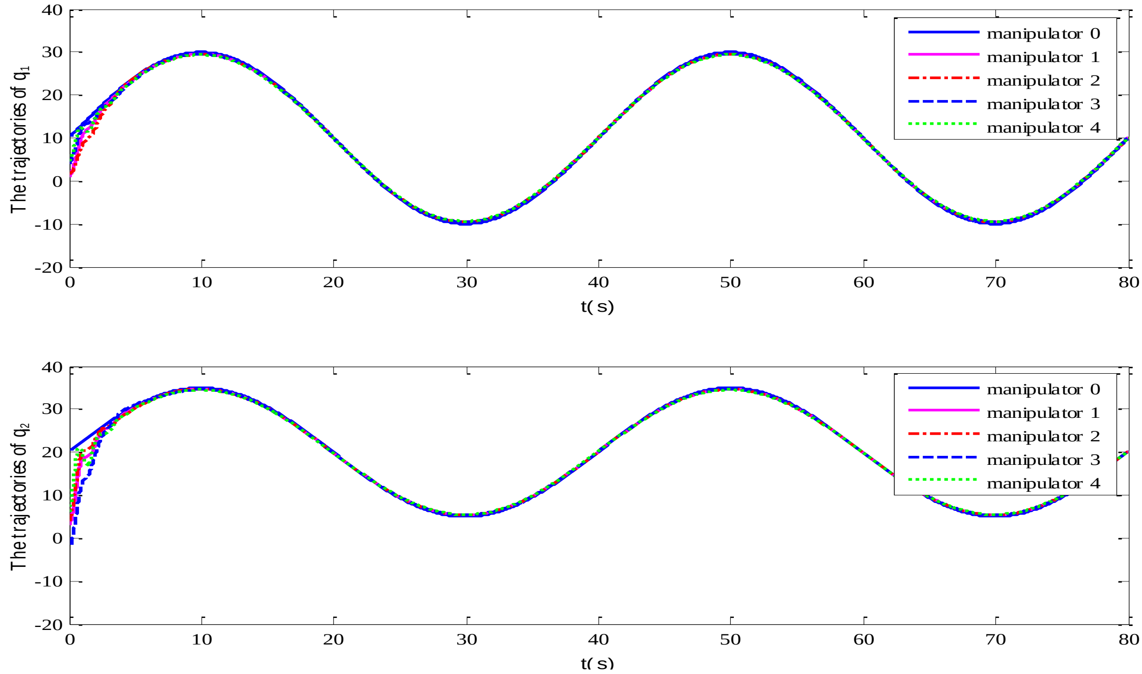

Fig. 3 Joint 1 and 2 positions of all manipulators

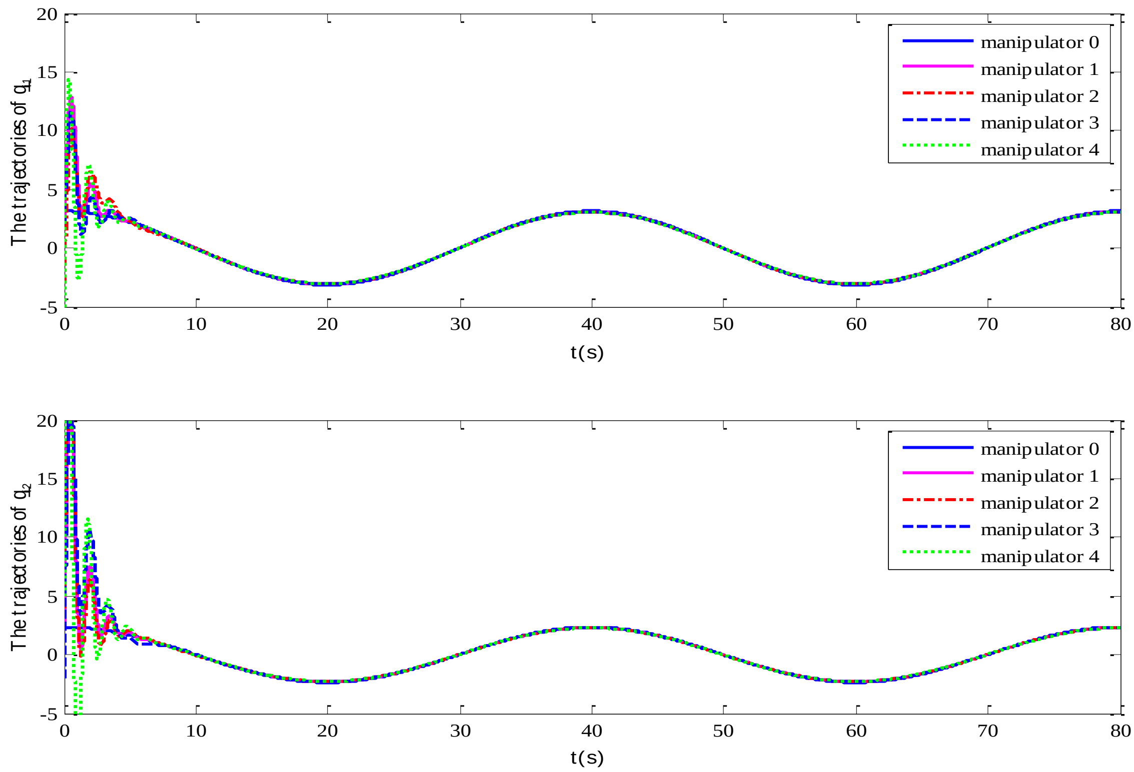

Fig. 4 Joint 1 and 2 velocities of all manipulators

ISSN: 2414-1895 DOI: 10.6919/ICJE.202104_7(4).0052

5.1 Example

Let the leader track the curves of $q_0(t) = \left(20\,sin\left(\frac{\pi t}{20}\right) + 10{,}15\,cos\left(\frac{\pi t}{20}\right) + 20\right)^T$. $q_0(0) = (10{,}20)^T$. Let the initial conditions of the four follower manipulators be $q_1(0) = (1{,}3)^T$, $q_2(0) = (2{,}4)^T$, $q_3(0) = (4,-2)^T$, $q_4(0) = (5{,}6)^T$, respectively. Here, we select $\tau_1 = \tau_2 = 1$ and $\lambda_1 = \lambda_2 = 1$. In the following, the sufficient results are represented in Fig. 3 to Fig. 4 with the SC scheme (8) in Theorem 1. Fig. 3 and Fig. 4 show the trajectories of the angle positions and angle velocities for the manipulators, respectively. It is easy to find that each manipulator follower can converge to the leader in finite time.

It can be concluded that the amplitude of control input tends to zero smoothly when the multi-robot networks achieves formation consensus, so that the validity of the chattering-free can be verified.

6. Conclusion

This paper mainly investigates the the robust formation control for multi-robot networks via synergetic control. Based on SC scheme, distributed networked control algorithms are provided under finite-time formation and directed topologies. As claimed in numerical results simulated, it can be derived that the effectiveness of the proposed methods and the elimination of the chattering phenomena can be reached.

7. Appendix A. Some lemmas

Lemma 1. [31] If choose states $x_i \in R$, $i = 1,2,\cdots,N$, for $0 < p < 2$, leads to $\sum_{i=1}^{N}|x_i|^p \geq (\sum_{i=1}^{N} x_i^2)^{p/2}$, especially when $p = 1$, $-\sum_{i=1}^{N}|x_i|^p \leq -(\sum_{i=1}^{N} x_i^2)^{1/2}$.

Lemma 2. [32] If there exists a directed spanning tree in topology $\mathcal{G} = (\mathcal{V}, \mathscr{E})$, yields rank($\mathcal{L}$)=N. In addition, for any elements in the last row of $\mathscr{L}$ are all zeros so as to obtain the condition where rank $[\overline{\mathscr{L}} + \overline{\mathscr{B}} - b] = N$.

Acknowledgments

This work was supported by The Innovation Fund of Postgraduate, Sichuan University of Science & Engineering (y2019018).

References

[1] J. Alonso-Mora, E. Montijano, T. Nageli, O. Hilliges, M. Schwager, and D. Rus, “Distributed multi-robot formation control in dynamic environments,” Autonomous Robots, vol. 43, no. 5, pp. 1079–1100, 2019.

[2] J. Jin, J.-P. Ramirez, S. Wee, D. Lee, Y. Kim, and N. Gans, “A switched-system approach to formation control and heading consensus for multi-robot systems,” Intelligent Service Robotics, vol. 11, no. 2, pp. 207–224, 2018.

[3] G. Antonelli, F. Arrichiello, F. Caccavale, and A. Marino, “Decentralized time-varying formation control for multi-robot systems,” The International Journal of Robotics Research, vol. 33, no. 7, pp. 1029–1043, 2014.

[4] M.-Y. Chow, S. Chiaverini, and C. Kitts, “Guest editorial introduction to the focused section on mechatronics in multirobot systems,” IEEE/ASME Transactions on Mechatronics, vol. 14, no. 2, pp. 133–140, 2009.

[5] G. Chen and F. L. Lewis, “Cooperative control of unknown networked lagrange systems using higher order neural networks,” in Artificial Higher Order Neural Networks for Modeling and Simulation. IGI Global, 2013, pp. 214–236.

[6] R. Huang, Z. Cao, B. Hu, and Z. Ding, “Synchronization tracking of a class of uncertain nonidentical networked euler-lagrange systems on directed graphs,” in IEEE 15th International Conference on Control and Automation. IEEE, 2019, pp. 869–874.

[7] C. H. F. d. Santos, M. U. Cildoz, M. H. Terra, and E. R. De Pieri, "Backstepping sliding mode control with functional tuning based on an instantaneous power approach applied to an underwater vehicle," International Journal of Systems Science, vol. 49, no. 4, pp. 859–867, 2018.

[8] G. V. Raffo, M. G. Ortega, and F. R. Rubio, "Nonlinear H_∞ controller for the quad-rotor helicopter with input coupling," IFAC Proceedings Volumes, vol. 44, no. 1, pp. 13834–13839, 2011.

[9] Z. Peng, S. Yang, G. Wen, A. Rahmani, and Y. Yu, "Adaptive distributed formation control for multiple nonholonomic wheeled mobile robots," Neurocomputing, vol. 173, pp. 1485–1494, 2016.

[10] X. Ge and Q.-L. Han, "Distributed formation control of networked multi-agent systems using a dynamic event-triggered communication mechanism," IEEE Transactions on Industrial Electronics, vol. 64, no. 10, pp. 8118–8127, 2017.

[11] X. Dong and G. Hu, "Time-varying formation control for general linear multi-agent systems with switching directed topologies," Automatica, vol. 73, pp. 47–55, 2016.

[12] Q. Zhang, J. Zhou, H. Wang, and T. Chai, "Output feedback stabilization for a class of multi-variable bilinear stochastic systems with stochastic coupling attenuation," IEEE Transactions on Automatic Control, vol. 62, no. 6, pp. 2936–2942, 2017.

[13] X. Yin, Q. Zhang, H. Wang, and Z. Ding, "Rbfnn-based minimum entropy filtering for a class of stochastic nonlinear systems," IEEE Transactions on Automatic Control, vol. 65, no. 1, pp. 376–381, 2020.

[14] Y. Zhou, Q. Zhang, H. Wang, P. Zhou, and T. Chai, "Ekf-based enhanced performance controller design for nonlinear stochastic systems," IEEE Transactions on Automatic Control, vol. 63, no. 4, pp. 1155–1162, 2018.

[15] L. Liu and J. Shan, "Distributed formation control of networked euler–lagrange systems with fault diagnosis," Journal of the Franklin Institute, vol. 352, no. 3, pp. 952–973, 2015.

[16] M. R. Rosa, S. Baldi, X. Wang, M. Lv, and W. Yu, "Adaptive hierarchical formation control for uncertain euler–lagrange systems using distributed inverse dynamics," European Journal of Control, vol. 48, pp. 52–65, 2019.

[17] J. Yu, J. Ji, Z. Miao, and J. Zhou, "Adaptive formation control of networked lagrangian systems with a moving leader," Nonlinear Dynamics, vol. 90, no. 4, pp. 2755–2766, 2017.

[18] X. Li, D. W. Ho, and J. Cao, "Finite-time stability and settling-time estimation of nonlinear impulsive systems," Automatica, vol. 99, pp. 361–368, 2019.

[19] O. Mofid and S. Mobayen, "Adaptive sliding mode control for finite-time stability of quad-rotor uavs with parametric uncertainties," ISA transactions, vol. 72, pp. 1–14, 2018.

[20] K. Lu and Y. Xia, "Adaptive attitude tracking control for rigid spacecraft with finite-time convergence," Automatica, vol. 49, no. 12, pp. 3591–3599, 2013.

[21] K. Mokhtari, A. Elhadri, and M. Abdelaziz, "A passivity-based simple adaptive synergetic control for a class of nonlinear systems," International Journal of Adaptive Control and Signal Processing, vol. 33, no. 9, pp. 1359–1373, 2019.

[22] A. A. Sklyarov, G. E. Veselov, and S. A. Sklyarov, "The method of synergetic control for a group of homogeneous transport robots to solve formation tasks," in IEEE II International Conference on Control in Technical Systems. IEEE, 2017, pp. 220–223.

[23] S. Zhai, Q. Chen, and X. Tang, "Finite-time synergetic control of mechanical system based on model-free friction compensa- tion," in Proceedings of the 2015 Chinese Intelligent Automation Conference. Springer, 2015, pp. 275–284.

[24] G. Chen, Y. Yue, and Y. Song, "Finite-time cooperative-tracking control for networked euler–lagrange systems," IET Control Theory & Applications, vol. 7, no. 11, pp. 1487–1497, 2013.

[25] G. Chen, "Cooperative controller design for synchronization of networked uncertain euler–lagrange systems," International Journal of Robust and Nonlinear Control, vol. 25, no. 11, pp. 1721–1738, 2015.

[26] S. Khoo, L. Xie, and Z. Man, "Robust finite-time consensus tracking algorithm for multirobot systems," IEEE/ASME Transactions on Mechatronics, vol. 14, no. 2, pp. 219–228, 2009.

[27] W. Ren, "Multi-vehicle consensus with a time-varying reference state," Systems & Control Letters, vol. 56, no. 7-8, pp. 474–483, 2007.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202104_7(4).0052

[28] E. Santi, A. Monti, D. Li, K. Proddutur, and R. Dougal, “Synergetic control for power electronics applications: a comparison with the sliding mode approach,” Journal of Circuits, Systems, and Computers, vol. 13, no. 04, pp. 737–760, 2004.

[29] C.-H. Liu and M.-Y. Hsiao, “A finite time synergetic control scheme for robot manipulators,” Computers & Mathematics with Applications, vol. 64, no. 5, pp. 1163–1169, 2012.

[30] Y. Sun, G. Ma, M. Liu, C. Li, and J. Liang, “Distributed finite-time coordinated control for multi-robot systems,” Transactions of the Institute of Measurement and Control, vol. 40, no. 9, pp. 2912–2927, 2018.

[31] M. P. Aghababa, S. Khanmohammadi, and G. Alizadeh, “Finite-time synchronization of two different chaotic systems with unknown parameters via sliding mode technique,” Applied Mathematical Modelling, vol. 35, no. 6, pp. 3080–3091, 2011.

[32] W. Ren and R. W. Beard, “Consensus seeking in multiagent systems under dynamically changing interaction topologies,” IEEE Transactions on Automatic Control, vol. 50, no. 5, pp. 655–661, 2005.