International Journal of Applied Science and Engineering Review

ISSN: 2582-6271

Vol. 3, Issue.3, May-June 2022, page no. 47-58

To cite this article: Jie Wang (2022). HIGH GAIN FEEDBACK ROBUST CONTROL FOR FLOCKING OF MULTI-AGENT SYSTEM WITH UNKNOWN PARAMETERS, International Journal of Applied Science and Engineering Review (IJASER) 3 (3): 47-58

HIGH GAIN FEEDBACK ROBUST CONTROL FOR FLOCKING OF MULTI-AGENT SYSTEM WITH UNKNOWN PARAMETERS

Jie Wang

Basic Teaching Department, Shandong University of Engineering and Vocational Technology, Jinan 250200, P.R. China.

DOI: http://dx.doi.org/10.52267/IJASER.2022.3307

ABSTRACT

In this paper, the control that has high gain feedback robust control with un- known parameters is designed. By the boundedness theorem and the Lyapunov stability theory, the velocity error is bounded and no collision occurs between the multi-agent is proved. Flocking of multi-agent system can be formed under the action of the high gain feedback robust control with unknown parameters. In the simulation, the feasibility of high gain feedback robust control for flocking of multi-agent system is verified.

KEYWORDS: flocking of the multi-agent system, high gain feedback robust con- trol, unknown parameters

1. INTRODUCTION

Flocking is a common phenomenon in nature [1]. Scholars [2, 3, 4] have con- ducted fruitful researches on flocking systems. Such as, Reynolds [5] proposed the Boid model which was deemed as a computer model employed to simulate the aggregation behavior of animals. A adbabie et al. [6, 7] conducted rele- vant analysis on the consistency of flocking in undirected switched networks. J Tanner [8, 9] allowed the system to reach a stable state through the design of the controller. Zhang et.al [10] studied flocking of heterogeneous multi-agents' systems and Zhang et.al [11] studies flocking of high frequency feedback robust control with unknown parameters.

High gain feedback robust control [12, 13, 14, 15] can adjust parameters based on sliding mode control which has good robustness. Jin[16] studies formation and containment control of multi-agent systems based on high-frequency feed- back robust control.

The innovation of this paper lies in the study conducted for the flocking of multi-agent system with high gain feedback robust control with unknown parameters. A controller with high gain feedback robust control is designed. It is proved that under the action of the controller, the speed of the flocking of the multi-agent system is consistent and no collision occurs. The feasibility of the system is verified by simulation, and the unknown parameters are identified.

2. Preliminaries

A set of $N+1(N \geq 1)$ agents moving in an n-dimensional Euclidean space are considered.
The virtual leader of the multi-agent is described by

$$\dot{x}_0(t) = v_0(t), \qquad (1)$$
$$\dot{v}_0(t) = a_0,$$

$x_0(t) \in R^n$ is the position vector of the virtual leader, $v_0(t) \in R^n$ is the velocity vector of the virtual leader, $a_0 \in R^+$ is the acceleration of the virtual leader.

The dynamic of the following agent is depicted by

$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = f(x_i(t), t) + u_i(t), i = 1, 2, \cdots, N \end{cases} \qquad (2)$$

$x_i(t) \in R^n$ is the position vector of the agent i, $v_i(t) \in R^n$ is the velocity vector of the agent i, the unknown nonlinear dynamic property $f(x_i(t), t)$ of the follower which is bounded, which satisfies Assumption 1 and Assumption 2.

Assumption 1 The nonlinear function $f(x_i(t), t) \in R^n$ can be linearly parameterized: $f(x_i(t), t) = g(x_i(t), t) + \phi_i^T(x_i(t), t)\theta_i$, $g(x_i(t), t)$ is the known nonlinear function, $\phi_i(x_i(t), t) \in R^{m \times n}$ is a known basis vector function, $\theta_i \in R^m$ is unknown constant parameter.

Assumption 2 The nonlinear vector-valued continuous function $f(x_i(t), t)$ is not determined, exists an upper bound function $\rho(\cdot) \in R^+$, make it satisfy $\|f(x_i(t), t)\| \leq \rho(\cdot)$.

International Journal of Applied Science and Engineering Review

ISSN: 2582-6271

Vol. 3, Issue.3, May-June 2022, page no. 47-58

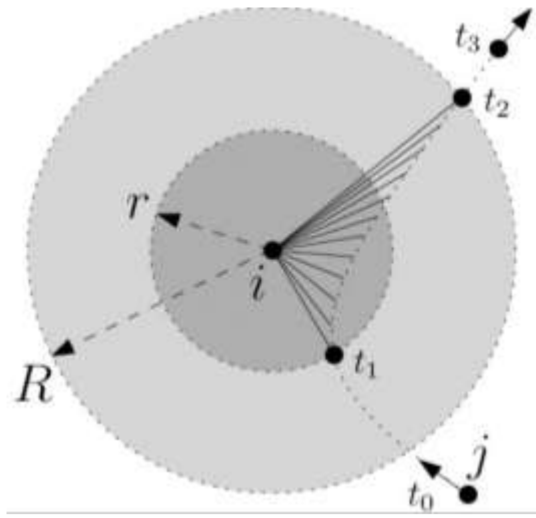

Figure 1: Switching process of dynamic graphs.

The directed graph G describe the topology between agents. The directed graph G is composed of a vertex set V and edge set E, $V = \{1,2,...,N\}$, $E = \{(i, j) | i, j \in V\}$. If agent i can receive the information of agent j, then $(j,i) \in E$, otherwise $(j,i) \notin E$.

The adjacency matrix $A = [a_{ij}] \in R^{n \times n}$ of graph G, where a_{ij} satisfies

$$a_{ij} = \begin{cases} 1, & \text{follower i can receive information from follower j,} \\ 0, & \text{follower i does not receive information from follower j,} \end{cases} \quad (3)$$

The Laplace matrix of graph G is defined as $L = [l_{ij}] \in R^{n \times n}$. The element in L satisfies $l_{ii} = \sum_{j=1}^{N} a_{ij}, l_{ij} = -a_{ij}, i \neq j.$

Definition 1 [17] For G, if there is a path in G from every node i in G to node 0, we say that node 0 is globally reachable in G, which is much weaker than strong connectedness.

Definition 2 [7] A group of mobile agents is said to be asymptotically flocking. When all agents have the same velocity vector, and collision among each agent are always avoid.

Lemma 1 [18] For the function $N_d(x, y) = \Omega(x)xy - k_n \Omega^2(x)x^2$, k_n is a positive constant, $\Omega(x)$ is a function than has nothing to do y, $N_d(x, y)$ has an upper bound function $N_d(x, y) \leq \frac{y^2}{k_n}$.

Lemma 2 [18] If the real matrix $A \in R^{n\times n}$ is a positive definite symmetric, for any vector $x \in R^{n\times n}$ satisfy : $\underline{\lambda}(A)x^T x \le x^T Ax \le \overline{\lambda}(A)x^T x$, $\overline{\lambda}(A)$ is the upper bound of the eigenvalues of matrix A, $\underline{\lambda}(A)$ is the lower bound of the eigenvalues of matrix A.

Lemma 3 [18] If the function $V(t): R^+ \to R^+ \ge 0$, and $\dot{V}(t) \le -\theta V(t) + \zeta$, $\theta, \zeta \in R^+$, we have $V(t) \le V(t_0)e^{-\theta t} + \frac{\zeta}{\theta}\left(1 - e^{-\theta t}\right)$.

3. Design of control based on high-gain feedback robust control with unknown parameters

we can define the set of control laws,

$$u_i(t) = 2K_1 \sum_{j=1, j\ne i}^{N} a_{ij}(t)(v_j - v_i) - 2\sum_{j=1}^{N} a_{ij}(t)\nabla_{x_i} V_{ij}(x_{ij}(t)) - \gamma\rho^2(\cdot)e_i - \phi_i^T \hat{\theta}_i, i, j = 1,2,\ldots,N \quad (4)$$

$$\hat{\theta}_i = \frac{K_2}{K_1}\phi_i e_i(t), i, j = 1,2,\ldots,N \quad (5)$$

control parameters $K_1 > 0, K_2 > 0$, γ is unknown parameter , $\hat{\theta}_i$ is the estimated value of agent i on θ_i, $\rho(\cdot)$ is the upper bound function of the unknown nonlinear function $f(x_i(t), t)$.

$\nabla_{x_i} V_{ij}(x_{ij}(t))$ is a direction vector of the negative gradient of an artificial potential function defined by the following equation:

$$V_{ij}(x_{ij}(t)) = \frac{1}{R^2 - \|x_{ij}(t)\|^2} + \frac{1}{\|x_{ij}(t)\|^2}, \|x_{ij}(t)\| \in (0, R) \quad (6)$$

with $x_{ij}(t) = x_i(t) - x_j(t)$, which allows both collision avoidance and maintaining links in the network. R represents the maximum distance within which multi-agents are able to obtain information from other agents. when $\|x_{ij}\| \to R^+$ or $\|x_{ij}\| \to 0^-$, $V_{ij}(x_{ij}(t))$ is unbound.

Based on the definition of $V_{ij}(x_{ij}(t))$,

$$\nabla_{x_{ij}} V_{ij}(x_{ij}(t)) = \nabla_{x_i} V_{ij}(x_{ij}(t)) = -\nabla_{x_j} V_{ij}(x_{ij}(t)), i, j = 1,2,\cdots,N \quad (7)$$

Define the velocity error as: $e_i(t) = v_i(t) - v_0(t), i = 1,2,\cdots,N$.

According to the definition of $e_i(t)$, we can get the following formula:

$e_i(t) - e_j(t) = (v_i(t) - v_0(t)) - (v_j(t) - v_0(t)) = v_i(t) - v_j(t), i, j = 1,2,\cdots,N$.

For convenience, $x=\begin{pmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_N(t) \end{pmatrix}$, $v=\begin{pmatrix} v_1(t) \\ v_2(t) \\ \vdots \\ v_N(t) \end{pmatrix}$, $v_0=\begin{pmatrix} v_0(t) \\ v_0(t) \\ \vdots \\ v_0(t) \end{pmatrix}$, $e=\begin{pmatrix} e_1(t) \\ e_2(t) \\ \vdots \\ e_N(t) \end{pmatrix}$, $\hat{\Theta}=\begin{pmatrix} \hat{\theta}_1 \\ \hat{\theta}_2 \\ \vdots \\ \hat{\theta}_N \end{pmatrix}$, $\bar{f}(\cdot)=\begin{pmatrix} f_1(x_1,t) \\ f_2(x_2,t) \\ \vdots \\ f_N(x_N,t) \end{pmatrix}$,

$$F=\begin{pmatrix} \sum_{j=1}^{N} a_{1j}\nabla_{x_1}V_{1j}(x_{1j}(t)) \\ \sum_{j=1}^{N} a_{2j}\nabla_{x_2}V_{2j}(x_{2j}(t)) \\ \vdots \\ \sum_{j=1}^{N} a_{Nj}\nabla_{x_N}V_{Nj}(x_{Nj}(t)) \end{pmatrix}, \Phi = diag\{\phi_1,\phi_2,\ldots,\phi_N\}.$$

The vector form of derivative of the velocity error: $\dot{e}=\dot{v}-\dot{v}_0$.

By (1), $\dot{v}_0(t)=a_0$ is bounded. $\bar{f}(\cdot)$ and $\dot{v}_0(t)$ satisfy both bounded at the same time. a_0 has no effect on system analysis. Assume $a_0=0$.

4. The main theory results

Theorem 1 In the multi-agent systems (1) and (2), under the control laws (3), velocity error variable satisfies $\|e\|\le\sqrt{\dfrac{M_2}{4K_1\underline{\lambda}(L)}}$. The speed of the multi-agent is gradually stable, and there will be no collision between agents.

Proof: Construct Lyapunov function $V_G(t)$

$$V_G(t)=\frac{1}{2K_1}\sum_{i=1}^{N}e_i^Te_i+\frac{1}{2K_2}\sum_{i=1}^{N}\hat{\theta}_i^T\theta_i+\frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)V_{ij}(x_{ij}(t)) \tag{8}$$

The generalized time derivative of $V_G(t)$ is

$$\dot{V}_G(t)=\frac{1}{K_1}\sum_{i=1}^{N}e_i^T\dot{e}_i+\frac{1}{K_2}\sum_{i=1}^{N}\dot{\hat{\theta}}_i^T\theta_i+\frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)\dot{V}_{ij}(x_{ij}(t)) \tag{9}$$

The first part of (9) can be written as

$$\begin{aligned}\frac{1}{K_1}\sum_{i=1}^{N}e_i^T\dot{e}_i &= \frac{1}{K_1}\sum_{i=1}^{N}e_i^T[\,f(x_i,t)+2K_1\sum_{j=1,j\ne i}^{N}a_{ij}(t)(v_j-v_i)-2\sum_{j=1}^{N}a_{ij}(t)\nabla_{x_i}V_{ij}(x_{ij}(t))-\gamma\rho^2(\cdot)e_i-\phi_i^T\hat{\theta}_i] \\ &= 2\sum_{i=1}^{N}e_i^T\sum_{j=1,j\ne i}^{N}a_{ij}(t)(v_j-v_i)+\frac{1}{K_1}\sum_{i=1}^{N}e_i^T[\,f(x_i,t)-2\sum_{j=1}^{N}a_{ij}(t)\nabla_{x_i}V_{ij}(x_{ij}(t))-\gamma\rho^2(\cdot)e_i-\phi_i^T\hat{\theta}_i]\end{aligned} \tag{10}$$

International Journal of Applied Science and Engineering Review

ISSN: 2582-6271

Vol. 3, Issue.3, May-June 2022, page no. 47-58

The first part of (10) can be written as

$$
\begin{aligned}
2\sum_{i=1}^{N} e_i^T \sum_{j=1, j\neq i}^{N} a_{ij}(t)(v_j - v_i) &= -2\sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} a_{ij}(t) e_i^T (v_i - v_j) \\
&= -2\sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} a_{ij}(t) e_i^T (e_i - e_j) \\
&= -2\sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} a_{ij}(t) e_i^T e_i + 2\sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} a_{ij}(t) e_i^T e_j \\
&= -2e^T Le
\end{aligned}
\tag{11}
$$

The last item of (10) can be written as

$$
\begin{aligned}
\frac{1}{K_1}\sum_{i=1}^{N} e_i^T [f(x_i,t) - 2\sum_{j=1}^{N} a_{ij}(t) \nabla_{x_i} V_{ij}(x_{ij}(t)) - \gamma\rho^2(\cdot) e_i - \phi_i^T \hat{\theta}_i] &= \frac{1}{K_1} e^T [\bar{f}(\cdot) - 2F - \gamma\rho^2(\cdot) e - \Phi^T \hat{\Theta}] \\
&= \frac{1}{K_1} [e^T \bar{f}(\cdot) - 2e^T F - \gamma\rho^2(\cdot) e^T e - (\Phi e)^T \hat{\Theta}]
\end{aligned}
\tag{12}
$$

By Assumption 2 and take the norm of the first term,

$$e^T \bar{f}(\cdot) \leq \rho(\cdot)\|e\|. \tag{13}$$

By Lemma 1, we have

$$e^T \bar{f}(\cdot) - \gamma\rho^2(\cdot) e^T e \leq \rho(\cdot)\|e\| - \gamma\rho^2(\cdot)\|e\|^2 \leq \frac{1}{\gamma} \tag{14}$$

By (12) and (14), we have

$$\frac{1}{K_1}\sum_{i=1}^{N} e_i^T \dot{e}_i \leq -2e^T Le + \frac{1}{K_1\gamma} - \frac{1}{K_1} 2e^T F - \frac{1}{K_1} (\Phi e)^T \hat{\Theta} \tag{15}$$

For the second item of (9), we have

ISSN: 2582-6271

Vol. 3, Issue.3, May-June 2022, page no. 47-58

$$
\begin{aligned}
\frac{1}{K_2}\sum_{i=1}^{N}\dot{\hat{\theta}}_i^T\theta_i &= \frac{1}{K_2}\sum_{i=1}^{N}\left(\frac{K_2}{K_1}\phi_i e_i\right)^T\theta_i \\
&= \frac{1}{K_1}\sum_{i=1}^{N}(\phi_i e_i)^T\theta_i \qquad (16)\\
&= \frac{1}{K_1}(\Phi e)^T\hat{\Theta}
\end{aligned}
$$

By (7), the last item of (9) can be written as

$$
\begin{aligned}
\frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)\dot{V}_{ij}(x_{ij}(t)) &= \frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)\dot{x}_{ij}^T(t)\nabla_{x_{ij}}V_{ij}(x_{ij}(t)) \\
&= \frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)\left(\dot{x}_i^T(t)-\dot{x}_j^T(t)\right)\nabla_{x_{ij}}V_{ij}(x_{ij}(t)) \\
&= \frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)\left(v_i^T(t)-v_j^T(t)\right)\nabla_{x_i}V_{ij}(x_{ij}(t)) \qquad (17)\\
&= \frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)\left(e_i^T(t)-e_j^T(t)\right)\nabla_{x_i}V_{ij}(x_{ij}(t)) \\
&= \frac{2}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)e_i^T(t)\nabla_{x_i}V_{ij}(x_{ij}(t)) \\
&= \frac{1}{K_1}2e^T F
\end{aligned}
$$

Above all, we have

$$
\begin{aligned}
\dot{V}_G(t) &\le -2e^T Le + \frac{1}{K_1\gamma} - \frac{1}{K_1}2e^T F - \frac{1}{K_1}(\Phi e)^T\hat{\Theta} + \frac{1}{K_1}(\Phi e)^T\hat{\Theta} + \frac{1}{K_1}2e^T F \\
&\le -2e^T Le + \frac{1}{K_1\gamma} \qquad (18)
\end{aligned}
$$

By Lemma 2, we have

$$
\dot{V}_G(t) \le -2\underline{\lambda}(L)e^T e + \frac{1}{K_1\gamma} \qquad (19)
$$

Assume $M_1 = \frac{1}{2K_2}\sum_{i=1}^{N}\hat{\theta}_i^T\theta_i + \frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)V_{ij}(x_{ij}(t))$.

ISSN: 2582-6271

Vol. 3, Issue.3, May-June 2022, page no. 47-58

Because $V_G(t)=\frac{1}{2K_1}\sum_{i=1}^{N}e_i^T e_i+\frac{1}{2K_2}\sum_{i=1}^{N}\hat{\theta}_i^T\theta_i+\frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)V_{ij}(x_{ij}(t))$,

we have $e^T e=2K_1\left(V_G(t)-\frac{1}{2K_2}\sum_{i=1}^{N}\hat{\theta}_i^T\theta_i-\frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{ij}(t)V_{ij}(x_{ij}(t))\right)=2K_1(V_G(t)-M_1)$.

$$\begin{aligned}\dot{V}_G(t)&\le -2\underline{\lambda}(L)e^T e+\frac{1}{K_1\gamma}\\&=-2\underline{\lambda}(L)2K_1(V_G(t)-M_1)+\frac{1}{K_1\gamma}\\&=-4K_1\underline{\lambda}(L)(V_G(t)-M_1)+\frac{1}{K_1\gamma}\\&=-4K_1\underline{\lambda}(L)V_G(t)+4K_1\underline{\lambda}(L)M_1+\frac{1}{K_1\gamma}\\&=-4K_1\underline{\lambda}(L)V_G(t)+M_2\end{aligned}\tag{20}$$

$M_2=4K_1\underline{\lambda}(L)M_1+\frac{1}{K_1\gamma}$.

According to Lemma 3, by solving the above differential inequality, we can get the upper bound of $V_G(t)$

$$V_G(t)\le V_G(t_0)e^{-4K_1\underline{\lambda}(L)t}+\frac{M_2}{4K_1\underline{\lambda}(L)}\left(1-e^{-4K_1\underline{\lambda}(L)t}\right)\tag{21}$$

The limit of $V_G(t)$ is

$$\lim_{t\to\infty}V_G(t)\le\lim_{t\to\infty}\left(V_G(t_0)e^{-4K_1\underline{\lambda}(L)t}+\frac{M_2}{4K_1\underline{\lambda}(L)}\left(1-e^{-4K_1\underline{\lambda}(L)t}\right)\right)=\frac{M_2}{4K_1\underline{\lambda}(L)}\tag{22}$$

By $V_G(t)$, we have $e^T e\le 2K_1V_G(t)$, then $\lim_{t\to\infty}\|e\|\le\sqrt{2K_1V_G(t)}=\sqrt{\frac{M_2}{4K_1\underline{\lambda}(L)}}$.

Above all, it can be concluded that the velocity error of the multi-agent is bounded by the feedback robust control of high gain with unknown parameters.

Theorem 2 There will be no collision occurring between the multi-agent under the control of the high gain feedback robust with unknown parameters.

ISSN: 2582-6271

Vol. 3, Issue.3, May-June 2022, page no. 47-58

Proof: If there is a collision occurs between the agent i and the agent j, we have $\|x_{ij}\|^2 \to 0$. Based on the definition of $V_{ij}(x_{ij}(t))$. if $\|x_{ij}\|^2 \to 0$, we have $V_{ij}(x_{ij}(t)) \to \infty$. If $V_{ij}(x_{ij}(t)) \to \infty$, and $V_G(t) = \frac{1}{2K_1}\sum_{i=1}^{N} e_i^T e_i + \frac{1}{2K_2}\sum_{i=1}^{N} \hat{\theta}_i^T \theta_i + \frac{1}{K_1}\sum_{i=1}^{N}\sum_{j=1}^{N} a_{ij}(t) V_{ij}(x_{ij}(t))$, we have $V_G(t) \to \infty$. According to the formula (21), we can get the upper bound of the $V_G(t)$. This is contradictory. We can get that there will be no collision occurs between agents.

5. Simulation Results

In this section, we use an example to verify the feasibility of the algorithm. The unknown nonlinear function f is assumed as

$$\begin{cases} f_x(\cdot) = 10(v_y - v_x) \\ f_y(\cdot) = -v_x v_z - v_y + 28 v_x \\ f_z(\cdot) = v_x v_y - \frac{8}{3} v_z \end{cases} \tag{23}$$

and it easily knows that the function f satisfies the assumption condition.

We assume $\rho(\cdot) = 60$. Assuming that 20 agents are randomly distributed on a circle with a radius of 1, the initial speed of the agent is chosen at randomly. Arrows indicate the direction of agent's movement.

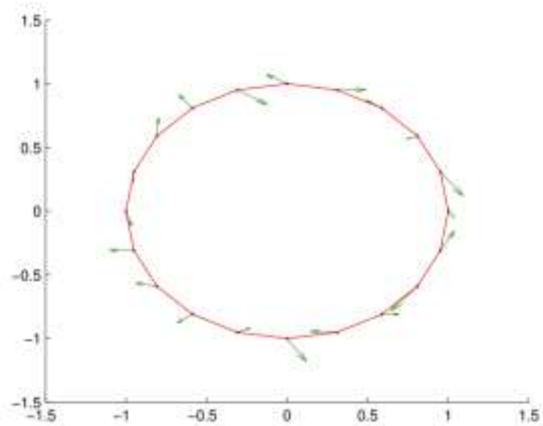

Figure 2: Flocking of N = 20 agent's initial state.

Figure 2 depicts the initial state of 20 agents. 20 agents are evenly distributed on a circle with a radius of 1, and the initial movement direction of the agents are inconsistent.

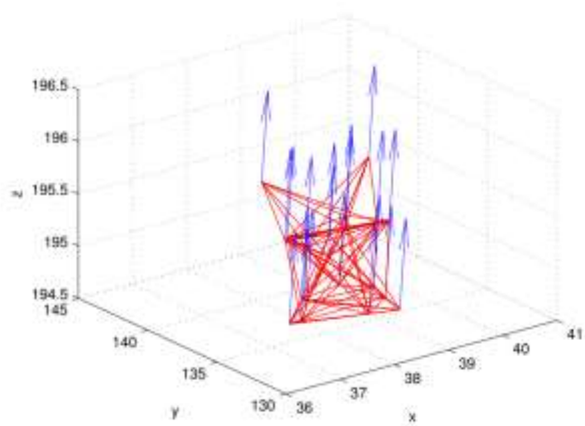

Figure 3: Flocking of N = 20 agent's final state.

Figure 3 shows the final states of flocking of the multi-agent under the multi-agent under the control of high gain feedback robust control with unknown parameters. The speed directions of the multi-agent are consistent, and no collision occurs between the multi-agent.

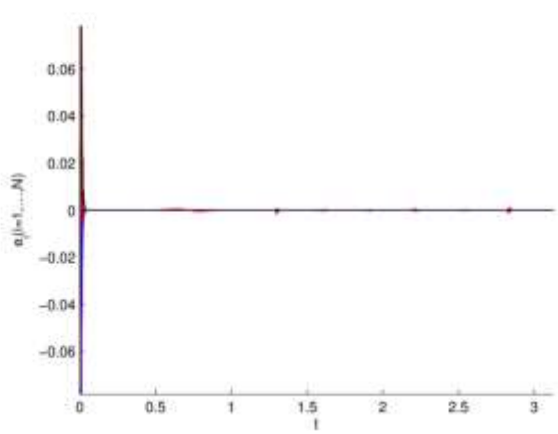

Figure 4: Velocity error of flocking of the multi-agent of high gain feedback robust control with unknown parameters.

Figure 4 shows the speed error of the multi-agent is 0, velocity error of flocking of the multi-agent of high gain feedback robust control with unknown parameters is bounded.

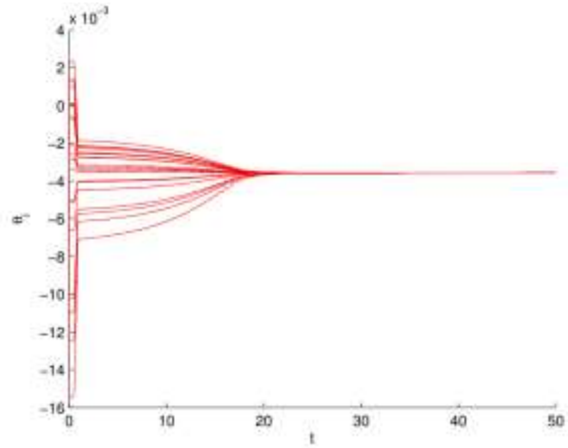

Figure 5: Unknown parameter identification.

Figure 5 shows that the flocking of the multi-agent system under the action of the controller can identify the unknown parameters.

6. CONCLUSIONS

In this paper, the flocking of the multi-agent of high gain feedback robust control with unknown parameters is proposed. It is proved that the velocity error of the multi-agent is bounded, and no collision occurs. In the simulation, under the action of high gain feedback robust control with unknown parameters, the flocking of the multi-agent is obtained. Simulation results show that under the action of the controller, the multi-agent system can achieve the same speed, the same direction of motion, and the unknown parameters can be identified.

REFERENCES

[1] J. K. Parrish, L. Edelstein-Keshet, Complexity, pattern, and evolutionary trade-offs in animal aggregation, Science 284 (1999) 99–101.

[2] X. L. Tang, L. M. Li, B. J. Jiang, Mobile robot slam method based on multi-agent particle swarm optimized particle filter, Journal of China Universities of Posts and Telecommunications 21 (2014) 78–86.

[3] R. Olfati-Saber, J. A. Fax, R. M. Murray, Consensus and cooperation in networked multi-agent systems, Proceedings of the IEEE 95 (2007) 215– 233.

[4] G. Wen, Z. Duan, G. Chen, W. Yu, Consensus tracking of multi-agent systems with lipschitz-type node dynamics and switching topologies, IEEE Transactions on Circuits and Systems I: Regular Papers 61 (2014) 499–511.

[5] A. Ferrara, C. Vecchio, Collision avoidance strategies and coordinated control of passenger vehicles, Nonlinear Dynamics 49 (2007) 475–492.

[6] A. Jadbabaie, J. Lin, A. S. Morse, Coordination of groups of mobile autonomous agents using nearest neighbor rules, IEEE Transactions on Automatic Control 48 (2003) 988–1001.

[7] M. M. Zavlanos, A. Jadbabaie, G. J. Pappas, Flocking while preserving network connectivity, in: 2007 46th IEEE Conference on Decision and Control, 2007, pp. 2919–2924.

[8] H. G. Tanner, A. Jadbabaie, G. J. Pappas, Stable flocking of mobile agents, part i: fixed topology, in: 42nd IEEE International Conference on Decision and Control (IEEE Cat. No.03CH37475), 2003, pp. 2010–2015.

[9] H. G. Tanner, A. Jadbabaie, G. J. Pappas, Stable flocking of mobile agents part ii: dynamic topology, in: 42nd IEEE International Conference on Decision and Control (IEEE Cat. No.03CH37475), 2003, pp. 2016–2021.

[10] Q. Zhang, Y. Hao, Z. Yang, Z. Chen, Adaptive flocking of heterogeneous multi-agents systems with nonlinear dynamics, Neurocomputing 216 (2016) 72–77.

[11] Q. Zhang, J. Wang, Z. Yang, Z. Chen, High-frequency feedback robust control for flocking of multi-agent system with
unknown parameters, Automatika 60 (2019) 28–35.doi:10.1080/00051144.2019.1570630.

[12] X. Geng, C. Li, F. Liu, Low complexity robust linear transceiver design for mimo interference channel, Journal of China Universities of Posts and Telecommunications 23 (2016) 76–81.

[13] M. Katebi, M. Grimble, Y. Zhang, H∞ robust control design for dynamic ship positioning, IEE Proceedings - Control Theory and Applications 144 (1997) 110–120.

[14] H. J. Lee, J. B. Park, G. Chen, Robust fuzzy control of nonlinear systems with parametric uncertainties, IEEE Transactions on Fuzzy Systems 9 (2001) 369–379.

[15] I. R. Petersen, R. Tempo, Robust control of uncertain systems: Classical results and recent developments, Automatica 50 (2014) 1315 – 1335.

[16] Q. Jin, Formation and containment control of multi-agent systems based on high-frequency feedback robust control, Ph.D. thesis, Nankai university (2015).

[17] Z. Yang, Z. liu, Z. Chen, Z. Yuan, Tracking control for multi-agent consensus with an active leader and directed topology, in: 2008 7th World Congress on Intelligent Control and Automation, 2008, pp. 1037–1041.

[18] Y. Fang, G. Lu, Nonlinear System Theory, Tsinghua University Press, Beijing, 2009.