Adaptive Sliding Mode Control Design based on Disturbance Compensator for Controlling Multi-Agent Robots

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ABSTRACT:
In this research, the goal is to develop a sliding mode control strategy based on the disturbance compensator to control the arrangement of a multi-agent system. For this purpose, the exponential access law is used to derive chattering-independent sliding mode control laws. In this design method, the sliding level information and its sign are used simultaneously, and by properly adjusting the sliding gain so that it is relatively larger than the switching gain, chattering effects can be removed significantly. On the other hand, since the adjustment of the switching gain is closely related to the changes of uncertainty and external disturbances, an adaptive approach is used to determine it. This is done using the Lyapunov stability theory and it is expected that the switching gain matching law is directly dependent on the instantaneous information of the sliding surface. In addition, to improve the consistency of the closed loop and adaptability to the environmental conditions and parameter changes of the system, a perturbation observer such as the developed mode observer is used.

KEYWORDS: Multi-agent System, Arrangement Control, Sliding Mode Control, Adaptive Disturbance Observer.

1. INTRODUCTION

The problem of controlling the arrangement of multi-agent systems has attracted a lot of attention due to its wide applications in many fields such as unmanned vehicles and so on. The purpose of arrangement control is to design control rules to move the agents towards their desired state and thus achieve the target arrangement. Arrangement approaches can be divided into leaderless, single-leader and multi-leader. In the multi-leadership challenge, the goal is to direct followers to some desired space surrounded by leaders. This improves flexibility and maneuverability; Because the configuration can be easily controlled by controlling a small part of it. To realize the arrangement problem in multi-agent systems, the dynamics of the agents and the leader must be determined first. In these models, state variables, control signals and their descriptive parameters such as dynamic coupling coefficients between factors should be specified.

In addition, various performance objectives can be explored in this field, among which can be mentioned the arrangement in the presence of model uncertainties, external disturbances, fault of stimuli and delay in received data. In addition, another important issue is to avoid the collision of agents in different operating environments, which, of course, is related to the nature of the arrangement control algorithm. In other words, the control method should be able to properly by designing a suitable guidance and tracking program for the followers so that the agents always have a suitable relative distance from their neighbors. Therefore, the structure of a control algorithm in this field depends on

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the nature of predetermined performance goals, the type of agents and leaders used, and the conditions of the agents' functional environment.

In practical applications, individual equipment cannot achieve high efficiency and low cost target control. To improve efficiency, increase execution accuracy, reduce costs and reduce maintenance cost, several small devices with low cost, simple structure and easy assembly and maintenance are employed to work together to achieve the desired goals. The control objective is to replace a single-factor complex agent. Compared to single-agent systems, multi-agent systems have advantages:

1) Cooperation between agents can greatly increase the ability to perform the work of the automation device. Based on the extension of task performance capability, multi-agent systems can perform many complex tasks that are difficult to achieve by a single agent.

2) Multi-agent systems have lower energy costs and are easier to construct and maintain, which lead to better economic returns.

3) Multi-agent systems have better performance and higher efficiency.

A multi-agent system is a system that consists of a group of agents and can solve problems that are difficult for an individual agent through communication, consultation and cooperation between agents and the environment. Multiple agents cooperating with each other can complete work beyond the capacity range of an individual agent and manage the capacity of the entire system better than a single agent. Applications of multi-agent systems have increased in recent years, and control models and theories related to multi-agent systems have been used in engineering fields day by day. In aerospace technology, spacecraft can be considered as an agent. Tasks such as system cost reduction, system stability improvement, and performance scalability can be achieved by developing coordinated attitude control and multiple spacecraft formation control [1]–[2]. Using multi-agent technologies, multiple spacecraft systems, where spacecraft have simple structures and processes, can deal with collective targets that are difficult for a single spacecraft to process[3]. In the application of military technology, the use of multiple unmanned aerial vehicles (UAVs) [4]– [5] to perform reconnaissance and combat, the use of multiple robots for search, rescue, patrolling, mine clearance, etc., or the use of autonomous underwater vehicles to cruise under the sea can greatly improve overall combat capability, increase task completion and accuracy, and reduce casualties [6]–[7]. In industrial manufacturing processes, using multiple robotic arms to perform complex tasks on a production line can often improve assembly accuracy and production efficiency [8]–[9]. Research on multi-agent systems, as a new and comprehensive topic, has a wide range of applications and enormous potential value, attracting researchers in various fields and promoting the rapid development of related theories[10]–[11].

2. DYNAMICS OF THE SECOND ORDER MULTI AGENT SYSTEM

In general, graph theory is used as an effective mathematical tool to describe coordinates and relationships between agents in a multi-agent system. Suppose $\Omega = \{\phi, \psi\}$ that represents a directed graph where $\phi = \{0,1,2, \ldots, n\}$, represents the set of nodes, node i for the i-th agent, and represents the set of edges. An edge in the Ω set is an ordered pair (i, j), which means that agent i can transmit information directly to agent j, but not necessarily the other way around. In contrast to the direct graph, the pairs of nodes in an indirect graph are not ordered, which means that the edge (i, j) describes the paired information transfer between agent i and agent j. Hence, an undirected graph can be considered as a special case of a directed graph[6]. The matrix $A = (a_{i,j}) \epsilon R^{(n+1)*(n+1)}$ is a weighted adjacency matrix of the set with non-negative elements. Based on this, if there is an edge between the i-th factor and the j-th factor, $a_{i,j} = 1$ and otherwise $a_{i,j} = 0$. in other words:

$$a_{ij} = \begin{cases} 1 \ , \ if \ (i, j) \in \Omega \\ 0 \ \text{otherwise} \end{cases} \tag{1}$$

The weight of communication between the i-th agent and the leader is denoted by b_i. If here is an edge between the i-th agent and the leader, $b_i = 1$ and zero otherwise. in other words:

$$b_i = \begin{cases} 1 \ , \ \text{if agent i is connected to leader} \\ 0 \ \ \text{otherwise} \end{cases} \tag{2}$$

The adjacency matrix can be rewritten as follows:

$$A = \begin{bmatrix} 0 & 0 & \dots & 0 \\ a_{10} & a_{11} & \dots & a_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n0} & a_{n1} & \dots & a_{nn} \end{bmatrix}_{(n+1)(n+1)} \tag{3}$$

Based on the direct topology, the following points should be considered:

• Only some factors are directly related to the leader.
• Some agents must be coordinated with the leader's behavior only by following the behavior of other agents.
• Finally, all agents must be able to follow the leader's direction.

The communication between the agents or the agent with the leader is considered one-way.

The general multi-agent system used in this article includes the dynamic equation of the active leader as follows:

$$\begin{cases} \dot{x}_0 = v_0 \\ M_0 \dot{v}_0 = u_0 \end{cases} \tag{4}$$

in which, $x_0 \epsilon R$ and , $v_0 \epsilon R$ represent the momentary position and speed of the leader, respectively. $u_0 \epsilon R$ is a time-varying control input with condition $\|u_u\| \le \overline{u_0}, u_0 > 0$ and $M_0 \epsilon R$ inertial leader. The point that should be remembered is that in the general dynamic state of the leader, it keeps its changes in the whole movement process and its behavior is independent of the followers. The dynamic equation of forces is described as follows:

$$\begin{cases} \dot{x}_i = v_i \\ m_i \dot{v}_i = u_i + f_i \end{cases} \quad , \quad i = 1, 2, \dots, N \tag{5}$$

Where $x_i \epsilon R$ and $v_i \epsilon R$ represent the instantaneous position and speed of follower i, respectively. $u_i \epsilon R$ represents the time-varying control input and $m_i \epsilon R$ is the follower's inertia. Also, $f_i \epsilon R$ represents the uncertainty of the system caused by modeling errors and represents external disturbances, so that the condition $|f_i| \le F, F > 0$ is always assumed. This means that the instantaneous value of the uncertainty is not known, but the maximum range of its changes must be predetermined. N also represents the number of followers. Therefore, in the general state, the second-order general multifactorial system has $N+1$ state variables, and the dynamic behavior of the leader is somehow considered as a reference model, and the control rules of the followers are calculated from the momentary difference between the leader and the followers at the position level.

3. ADAPTIVE SLIDING MODE CONTROL BASED ON DISTURBANCE COMPENSATOR

In this section, the following exponential access condition is used to define the control rules[12]:

$$\dot{s}_i = -\eta_{1i}\,\text{sgn}(s_i) - \eta_{2i} s_i \ , \ \ i = 1, 2, \dots, N \tag{6}$$

In fact, considering relation (6) for each follower, the control system is designed with two parameters. By considering the parameters, a stable dynamic can be achieved for the slip surface derivative. This problem means that the derivative of the slip surface becomes zero with the passage of time. Similarly, with high-order sliding mode controllers, in this situation, we can expect to reduce or eliminate chattering in the control signal by increasing the sliding mode gain. In other words, the section containing the slip surface has a great influence in dealing with the switching effects caused by the section containing the sign of the slip surface. As we know, the principles of sliding mode control are based on establishing the sliding condition. In the following, we show that using the above condition, Lyapunov stability is also established. For this purpose, we consider the Lyapanov function similar to the first design equal to the square of the slip surface:

$$V_i = \frac{1}{2} s_i^2 \ , \ \ i = 1, 2, \dots, N \tag{7}$$

By deriving it, we can write:

$$\begin{aligned}\dot{V}_i &= s_i\dot{s}_i \\ &= s_i(-\eta_{1i}sgn(s_i) - \eta_{2i}s_i) \\ &= -\eta_{1i}s_i sgn(s_i) - \eta_{2i}s_i^2\end{aligned} \tag{8}$$

We know that:

$$\begin{cases} s_i \geq 0 \rightarrow \text{sign}(s_i) = 1 \rightarrow s_i\text{sign}(s_i) > 0 \\ s_i < 0 \rightarrow \text{sign}(s_i) = -1 \rightarrow s_i\text{sign}(s_i) > 0 \end{cases} \tag{9}$$

Therefore, the derivative of the Lyapunov function in relation (8) is negative and the slip condition is established. The defined slip surface guarantees that in addition to the slip surface, its derivative also converges to zero. As a result, the exponential access condition can be expressed as follows:

$$\ddot{e}_i = \lambda_{1i}\dot{e}_i + \lambda_{2i}e_i = -\eta_{1i}sgn(s_i) - \eta_{2i}s_i \quad , \quad i=1,2,\dots,N \tag{10}$$

By inserting the second derivative, we have the convergence error in the above relation:

$$\sum_{j=1}^{N} a_{ij}\left(\frac{u_i}{m_i} + \frac{f_i}{m_i} - \frac{u_j}{m_j} - \frac{f_j}{m_i}\right) + b_i\left(\frac{u_i}{m_i} + \frac{f_i}{m_i} - \frac{u_0}{M_0}\right) + \lambda_{1i}\dot{e}_i + \lambda_{2i}e_i = -\eta_{1i}sgn(s_i) - \eta_{2i}s_i \tag{(11)}$$

Therefore, the sliding mode control law is derived as follows:

$$U = B^{-1}\left(-F - K_1\,\text{sgn}\left(S\right) - K_2 S\right) \tag{12}$$

where in:

$$F = \begin{bmatrix} -\dfrac{b_1}{M_0}u_0 + \dfrac{f_1}{M_1} + \lambda_{11}\dot{e}_1 + \lambda_{21}e_1 \\ -\dfrac{b_2}{M_0}u_0 + \dfrac{f_2}{M_1} + \lambda_{12}\dot{e}_2 + \lambda_{22}e_2 \\ \vdots \\ -\dfrac{b_N}{M_0}u_0 + \dfrac{f_N}{M_1} + \lambda_{1N}\dot{e}_N + \lambda_{2N}e_N \end{bmatrix} \tag{13}$$

4. DISTURBANCE COMPENSATOR DESIGN

As can be seen in relation (12), the vector function F includes nonlinear functions and the effects of external disturbances of follower dynamics. In this paper, a disturbance compensator is used to estimate these nonlinear effects including uncertainties and external disturbances. For this purpose, first consider the dynamics of the second-order multi agent system as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \dfrac{f_1}{M_1} + \dfrac{u_1}{M_1} \end{cases}, \quad \begin{cases} \dot{x}_3 = x_4 \\ \dot{x}_4 = \dfrac{f_2}{M_2} + \dfrac{u_2}{M_2} \end{cases}, \quad \dots, \quad \begin{cases} \dot{x}_{N-1} = x_N \\ \dot{x}_N = \dfrac{f_N}{M_N} + \dfrac{u_N}{M_N} \end{cases} \tag{14}$$

Now, the nonlinear part including the uncertainty and the effects of external disturbances in the dynamics of each follower is considered as a state variable. In this case, the relation (14) can be rewritten as follows:

$$\begin{cases}\dot{x}_1 = x_2 \\ \dot{x}_2 = z_1 + \dfrac{u_1}{M_1} \\ \dot{z}_1 = h_1\end{cases}, \begin{cases}\dot{x}_3 = x_4 \\ \dot{x}_4 = z_2 + \dfrac{u_2}{M_2} \\ \dot{z}_2 = h_2\end{cases}, \ldots, \begin{cases}\dot{x}_{N-1} = x_N \\ \dot{x}_N = z_N + \dfrac{u_N}{M_N} \\ \dot{z}_N = h_N\end{cases} \quad (15)$$

where in:

$$\begin{cases}z_1 = \dfrac{f_1}{M_1} \\ h_1 = \dfrac{d}{dt}\left(\dfrac{f_1}{M_1}\right)\end{cases}, \begin{cases}z_2 = \dfrac{f_2}{M_2} \\ h_2 = \dfrac{d}{dt}\left(\dfrac{f_2}{M_2}\right)\end{cases}, \ldots, \begin{cases}z_N = \dfrac{f_N}{M_N} \\ h_N = \dfrac{d}{dt}\left(\dfrac{f_N}{M_N}\right)\end{cases} \quad (16)$$

In this case, the dynamic equations of the disturbance estimator for the first follower are described as follows[13]:

$$\begin{aligned}\dot{\hat{x}}_1(t) &= \hat{x}_2(t) + \frac{\alpha_1}{\beta^3}\left[\beta^5\left(x_1(t) - \hat{x}_1(t)\right)\right]^\eta \\ \dot{\hat{x}}_2(t) &= \hat{z}_1(x) + \frac{u_1}{M_1} + \frac{\alpha_2}{\beta}\left[\beta^5\left(x_1(t) - \hat{x}_1(t)\right)\right]^\eta \\ \dot{\hat{z}}_1(t) &= \alpha_3\beta\left[\beta^5\left(x_1(t) - \hat{x}_1(t)\right)\right]^\eta\end{aligned} \quad (17)$$

And for the second follower, we can write:

$$\begin{aligned}\dot{\hat{x}}_3(t) &= \hat{x}_4(t) + \frac{\alpha_1}{\beta^3}\left[\beta^5\left(x_3(t) - \hat{x}_3(t)\right)\right]^\eta \\ \dot{\hat{x}}_4(t) &= \hat{z}_2(x) + \frac{u_2}{M_2} + \frac{\alpha_2}{\beta}\left[\beta^5\left(x_3(t) - \hat{x}_3(t)\right)\right]^\eta \\ \dot{\hat{z}}_2(t) &= \alpha_3\beta\left[\beta^5\left(x_3(t) - \hat{x}_3(t)\right)\right]^\eta\end{aligned} \quad (18)$$

And for follower N we will have:

$$\begin{aligned}\dot{\hat{x}}_{N-1}(t) &= \hat{x}_N(t) + \frac{\alpha_1}{\beta^3}\left[\beta^5\left(x_{N-1}(t) - \hat{x}_{N-1}(t)\right)\right]^\eta \\ \dot{\hat{x}}_N(t) &= \hat{z}_N(x) + \frac{u_2}{M_2} + \frac{\alpha_2}{\beta}\left[\beta^5\left(x_{N-1}(t) - \hat{x}_{N-1}(t)\right)\right]^\eta \\ \dot{\hat{z}}_N(t) &= \alpha_3\beta\left[\beta^5\left(x_{N-1}(t) - \hat{x}_{N-1}(t)\right)\right]^\eta\end{aligned} \quad (19)$$

In the above relationships, $\beta$and η are positive design parameters. Furthermore, the relationship is $[\blacksquare]^r = |\blacksquare|^r sgn(\blacksquare)$. The components of $\alpha_{1,2,3}$ are positive and must be determined in such a way that the matrix $\begin{bmatrix}-\alpha_1 & 1 & 0 \\ -\alpha_2 & 0 & 1 \\ -\alpha_3 & 0 & 0\end{bmatrix}$ is stable. In this case, the vector function F is rewritten as below:

$$F = \begin{bmatrix} -\dfrac{b_1}{M_0}u_0 + \hat{z}_1 + \lambda_{11}\dot{e}_1 + \lambda_{21}e_1 \\ -\dfrac{b_2}{M_0}u_0 + \hat{z}_2 + \lambda_{12}\dot{e}_2 + \lambda_{22}e_2 \\ \vdots \\ -\dfrac{b_N}{M_0}u_0 + \hat{z}_N + \lambda_{1N}\dot{e}_N + \lambda_{2N}e_N \end{bmatrix} \quad (20)$$

5. EVALUATION OF AMBIGOBOT MULTI-ROBOT ARRANGEMENT CONTROL USING THE PROPOSED METHOD

In the rest of this section, a multi-agent system including a number of mobile robots is explained. As seen in Figure 1, each robot is an AmbigoBots type, the actual view of which is presented in Figure.2[14].

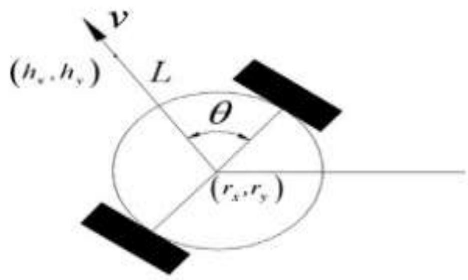

Fig. 1. Schematic view of AmbigoBots non-holonomic differential mobile robot[14].

According to Fig.1, the kinematic equations of each moving robot can be expressed as follows:

$$\begin{aligned} \dot{r}_{xi} &= v_i \cos(\theta_i), \\ \dot{r}_{yi} &= v_i \sin(\theta_i) \\ \dot{\theta}_i &= w_i \quad , i = 1, 2, ..., N \end{aligned} \tag{21}$$

Fig. 2. A view of AmbigoBots mobile robot multimedia system.

In which, r_{xi} and r_{yi} represent the position of the center of mass of the mobile robot i and θ_i represent its momentary orientation. On the other hand, the position of each follower will be equal to:

$$\begin{bmatrix} h_{xi} \\ h_{yi} \end{bmatrix} = \begin{bmatrix} r_{xi} \\ y_{yi} \end{bmatrix} + L_i \begin{bmatrix} \cos(\theta_i) \\ \sin(\theta_i) \end{bmatrix} , i = 1, 2, ..., N \tag{22}$$

By deriving equation (22) once, we can write:

$$\begin{bmatrix} \dot{h}_{xi} \\ \dot{h}_{yi} \end{bmatrix} = \begin{bmatrix} v_i \cos(\theta_i) \\ v_i \sin(\theta_i) \end{bmatrix} + L_i w_i \begin{bmatrix} -\sin(\theta_i) \\ \cos(\theta_i) \end{bmatrix} , i = 1, 2, ..., N \tag{23}$$

In simple terms:

$$\begin{bmatrix} \dot{h}_{xi} \\ \dot{h}_{yi} \end{bmatrix} = \begin{bmatrix} \cos(\theta_i) & -L_i \sin(\theta_i) \\ \sin(\theta_i) & L_i \cos(\theta_i) \end{bmatrix} \begin{bmatrix} v_i \\ w_i \end{bmatrix} , i = 1, 2, ..., N \tag{24}$$

$$\begin{bmatrix} \ddot{h}_{xi} \\ \ddot{h}_{yi} \end{bmatrix} = \begin{bmatrix} -w_i \sin(\theta_i) & -L_i w_i \cos(\theta_i) \\ w_i \cos(\theta_i) & -L_i w_i \sin(\theta_i) \end{bmatrix} \begin{bmatrix} v_i \\ w_i \end{bmatrix} + \begin{bmatrix} \cos(\theta_i) & -L_i \sin(\theta_i) \\ \sin(\theta_i) & L_i \cos(\theta_i) \end{bmatrix} \begin{bmatrix} \dot{v}_i \\ \dot{w}_i \end{bmatrix} \tag{25}$$

By deriving the equation (2٤), we have:
The relation (25) can be written as the following general relation:

$$\begin{bmatrix} \ddot{h}_{xi} \\ \ddot{h}_{yi} \end{bmatrix} = \begin{bmatrix} u_{xi} \\ u_{yi} \end{bmatrix} + \begin{bmatrix} g_{xi} \\ g_{yi} \end{bmatrix}, \; i = 1, 2, ..., N \quad (26)$$

where in:

$$\begin{bmatrix} u_{xi} \\ u_{yi} \end{bmatrix} = \begin{bmatrix} \cos(\theta_i) & -L_i \sin(\theta_i) \\ \sin(\theta_i) & L_i \cos(\theta_i) \end{bmatrix} \begin{bmatrix} \dot{v}_i \\ \dot{w}_i \end{bmatrix},$$
$$\begin{bmatrix} g_{xi} \\ g_{yi} \end{bmatrix} = \begin{bmatrix} -w_i \sin(\theta_i) & -L_i w_i \cos(\theta_i) \\ w_i \cos(\theta_i) & -L_i w_i \sin(\theta_i) \end{bmatrix} \begin{bmatrix} v_i \\ w_i \end{bmatrix} \quad (27)$$

The control rules for solving the problem of the formation of the robotic multi-agent system are briefly mentioned below:

$$e_{xi} = \sum_{j=1}^{N} a_{ij} \left(h_{xi} + \Delta_{xi} - h_{xj} - \Delta_{xj} \right) + b_i (h_{yi} + \Delta_{yi} - h_{x0} - \Delta_{x0})$$
$$e_{yi} = \sum_{j=1}^{N} a_{ij} \left(h_{yi} + \Delta_{yi} - h_{yj} - \Delta_{yj} \right) + b_i (h_{yi} + \Delta_{yi} - h_{y0} - \Delta_{y0}) \quad (28)$$

i=1,2,…,N

By deriving the equation (٢٨), we can write:

$$\begin{cases} \dot{e}_{xi} = \sum_{j=1}^{N} a_{ij} \left(\dot{h}_{x_i} - \dot{h}_{x_j} \right) + b_i \left(\dot{h}_{x_i} - \dot{h}_{x_0} \right) \\ e_{yi} = \sum_{j=1}^{N} a_{ij} \left(\dot{h}_{y_i} - \dot{h}_{y_j} \right) + b_i \left(\dot{h}_{y_i} - \dot{h}_{y_0} \right) \end{cases} \quad (29)$$

where in:

$$\begin{cases} \dot{h}_{xi} = v_i \cos(\theta_i) - L_i w_i \sin(\theta_i) \\ \dot{h}_{x0} = v_0 \cos(\theta_0) - L_0 w_0 \sin(\theta_0) \end{cases}$$
$$\begin{cases} \dot{h}_{yi} = v_i \sin(\theta_i) + L_i w_i \cos(\theta_i) \\ \dot{h}_{y0} = v_0 \sin(\theta_0) + L_0 w_0 \cos(\theta_0) \end{cases} \quad (30)$$

By re-derivation from the error signals, we have:

$$\begin{cases} \ddot{e}_{xi} = \sum_{j=1}^{N} a_{ij} \left(\ddot{h}_{x_i} - \ddot{h}_{x_j} \right) + b_i \left(\ddot{h}_{x_i} - \ddot{h}_{x_0} \right) \\ \ddot{e}_{yi} = \sum_{j=1}^{N} a_{ij} \left(\ddot{h}_{y_i} - \ddot{h}_{y_j} \right) + b_i \left(\ddot{h}_{y_i} - \ddot{h}_{y_0} \right) \end{cases} \quad (31)$$

On the other hand, for the dynamics of follower robots, we can write:

$$\begin{bmatrix} \ddot{h}_{xi} \\ \ddot{h}_{yi} \end{bmatrix} = \begin{bmatrix} u_{xi} \\ u_{yi} \end{bmatrix} + \begin{bmatrix} f_{xi} \\ f_{yi} \end{bmatrix} \quad (32)$$

where in:

$$\begin{bmatrix} f_{xi} \\ f_{yi} \end{bmatrix} = \begin{bmatrix} -v_i w_i \sin(\theta_i) - L_i w_i^2 \cos(\theta_i) \\ v_i w_i \cos(\theta_i) - L_i w_i^2 \sin(\theta_i) \end{bmatrix} \quad (33)$$

Also, for the leader robot, we can write:

$$\begin{bmatrix}\ddot{h}_{x0}\\ \ddot{h}_{y0}\end{bmatrix}=\begin{bmatrix}f_{x0}\\ f_{y0}\end{bmatrix}$$

$$\begin{cases}f_{x0}=u_{x0}-v_0w_0\sin(\theta_0)-L_0w_0^2\cos(\theta_0)\\ f_{y0}=u_{y0}-v_0w_0\cos(\theta_0)-L_0w_0^2\sin(\theta_0)\end{cases} \tag{34}$$

Therefore, the second-order dynamics of tracking error signals can be expressed as follows:

$$\begin{aligned}\ddot{e}_{xi}&=\sum_{j=1}^{N}a_{ij}\left(u_{xi}+\mathrm{f}_{xi}-u_{xj}-\mathrm{f}_{xj}\right)+b_i(u_{xi}+\mathrm{f}_{xi}-f_{x0})\\ \ddot{e}_{yi}&=\sum_{j=1}^{N}a_{ij}\left(u_{yi}+\mathrm{f}_{yi}-u_{yj}-\mathrm{f}_{yj}\right)+b_i(u_{yi}+\mathrm{f}_{yi}-f_{y0})\end{aligned} \tag{35}$$

The relative degree of error dynamics compared to the control signals is of the first order, so the slip levels are defined as follows:

$$\begin{bmatrix}\dot{s}_{xi}\\ \dot{s}_{yi}\end{bmatrix}=\begin{bmatrix}\ddot{e}_{xi}+\lambda_{1i}\dot{e}_{xi}+\lambda_{2i}e_{xi}\\ \ddot{e}_{yi}+\lambda_{1i}\dot{e}_{yi}+\lambda_{2i}e_{yi}\end{bmatrix} \tag{36}$$

Based on the access condition, we can write:

$$\begin{aligned}&\sum_{j=1}^{N}a_{ij}\left(u_{xi}+\mathrm{f}_{xi}-u_{xj}-\mathrm{f}_{xj}\right)+b_i(u_{xi}+\mathrm{f}_{xi}-f_{x0})+\lambda_{1i}\dot{e}_{xi}+\lambda_{2i}e_{xi}\le-\eta_i sgn(s_{xi})\\ &\sum_{j=1}^{N}a_{ij}\left(u_{yi}+\mathrm{f}_{yi}-u_{yj}-\mathrm{f}_{yj}\right)+b_i(u_{yi}+\mathrm{f}_{yi}-f_{y0})+\lambda_{1i}\dot{e}_{yi}+\lambda_{2i}e_{yi}\le-\eta_i sgn(s_{yi})\end{aligned} \tag{37}$$

In the matrix form, the relation $BU+F\le-\Gamma sgn(S)$ is obtained in which:

$$F=\begin{bmatrix}-b_1f_{xo}+(a_{12}+a_{13}+\ldots+a_{1N}+b_1)f_{x1}-a_{12}f_{x2}-\ldots-a_{1N}f_{xN}+\lambda_{11}\dot{e}_{x1}+\lambda_{21}e_{x1}\\ -b_1f_{yo}+(a_{12}+a_{13}+\ldots+a_{1N}+b_1)f_{y1}-a_{12}f_{y2}-\ldots-a_{1N}f_{yN}+\lambda_{11}\dot{e}_{y1}+\lambda_{21}e_{y1}\\ -b_2f_{xo}+(a_{21}+a_{23}+\ldots+a_{2N}+b_2)f_{x1}-a_{21}f_{x2}-\ldots-a_{2N}f_{xN}+\lambda_{12}\dot{e}_{x2}+\lambda_{22}e_{x2}\\ -b_2f_{yo}+(a_{21}+a_{23}+\ldots+a_{2N}+b_2)f_{y1}-a_{21}f_{y2}-\ldots-a_{2N}f_{yN}+\lambda_{12}\dot{e}_{y2}+\lambda_{22}e_{y2}\\ \vdots\\ f_{xo}+(a_{N1}+a_{N2}+\ldots+a_{NN-1}+b_N)f_{x1}-a_{N2}f_{x2}-\ldots-a_{NN-1}f_{xN-1}+\lambda_{1N}\dot{e}_{xN}+\lambda_{2N}e_{N}\\ {}_{yo}+(a_{N1}+a_{N2}+\ldots+a_{NN-1}+b_N)f_{y1}-a_{N2}f_{y2}-\ldots-a_{NN-1}f_{yN-1}+\lambda_{1N}\dot{e}_{yN}+\lambda_{2N}e_{yN}\end{bmatrix} \tag{38}$$

$$U=\begin{bmatrix}u_{x1}\\ u_{y1}\\ \vdots\\ u_{xN}\\ u_{yN}\end{bmatrix},S=\begin{bmatrix}s_{x1}\\ s_{y1}\\ \vdots\\ s_{xN}\\ s_{yN}\end{bmatrix}\Gamma=\mathrm{diag}\left(\eta_{x1},\eta_{y1},\eta_{x2},\eta_{y2},\ldots,\eta_{xN},\eta_{yN}\right) \tag{39}$$

$$B=\begin{bmatrix}\alpha_1 & 0 & -a_{12} & 0 & -a_{13} & 0 & \cdots & -a_{1N} & 0\\ 0 & \alpha_1 & 0 & -a_{12} & 0 & -a_{13} & \cdots & 0 & -a_{1N}\\ -a_{21} & 0 & \alpha_2 & 0 & -a_{23} & 0 & \cdots & -a_{2N} & 0\\ 0 & -a_{21} & 0 & \alpha_2 & 0 & -a_{23} & \cdots & 0 & -a_{2N}\\ \vdots & & \vdots & & \ddots & & \vdots & \cdots & \vdots\\ -a_{N1} & 0 & -a_{N2} & 0 & -a_{N3} & 0 & \cdots & \alpha_N & 0\\ 0 & -a_{N1} & 0 & -a_{N2} & 0 & -a_{N3} & \cdots & 0 & \alpha_N\end{bmatrix}$$

As a result, the control rules for each follower are obtained as follows:

$$U=B^{-1}\left(-F-K\,\mathrm{sgn}(S)\right) \tag{40}$$

For the robotic system including one leader and four followers, the control parameters are considered as follows:

$\lambda_1=8,\lambda_2=16,\eta_1=0.01,\eta_2=1.5,\alpha_1=15,\alpha_2=75,\alpha_3=125,\beta=2,\eta=0.8,\mu=0.002$

The same communication topology as the second-order multi agent system is considered. As seen in Fig. 3 and Fig. 4, the follower robots are located at a certain relative distance from the leader robot and follow the leader's dynamic behavior with high performance accuracy. This problem can be better understood especially in the formation presented in two-dimensional space. The control signals in Figure 6 have a large amplitude in the start-up conditions and no chattering effect is observed in them. Figure 7 and Figure 8 show that the disturbance compensator is well able to estimate the nonlinear effects of follower dynamics. The course of the switching gain changes is also presented in Figure 9, which is their time-varying nature due to their dependence on the slip surfaces.

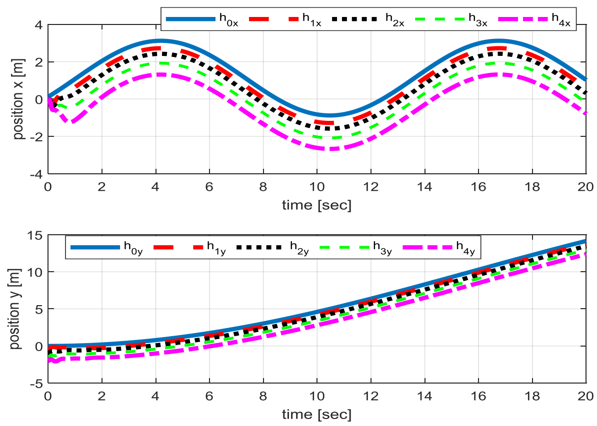

Fig. 3. Robotic system arrangement control using adaptive sliding mode control based on disturbance compensator.

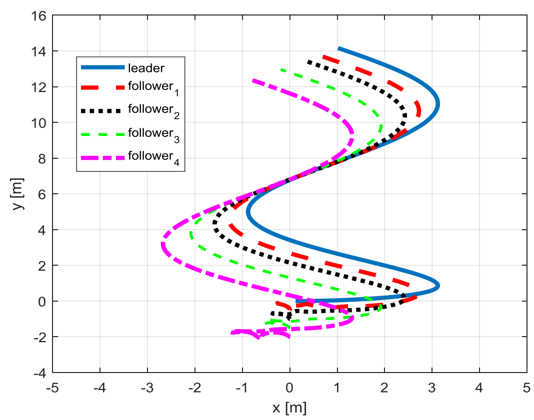

Fig.4. Robotic system arrangement control in two-dimensional space using adaptive sliding mode control based on disturbance compensator.

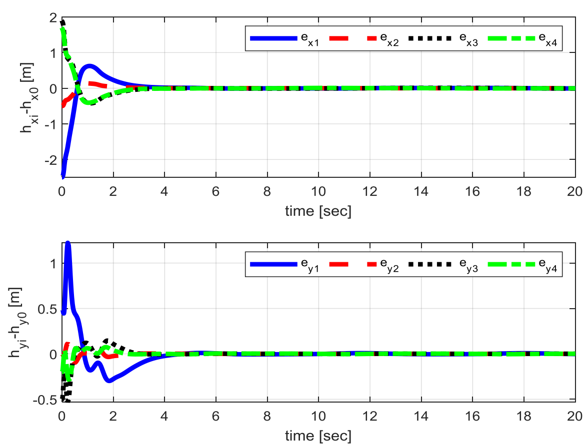

Fig.5. Robotic system alignment error using adaptive sliding mode control based on disturbance compensator.

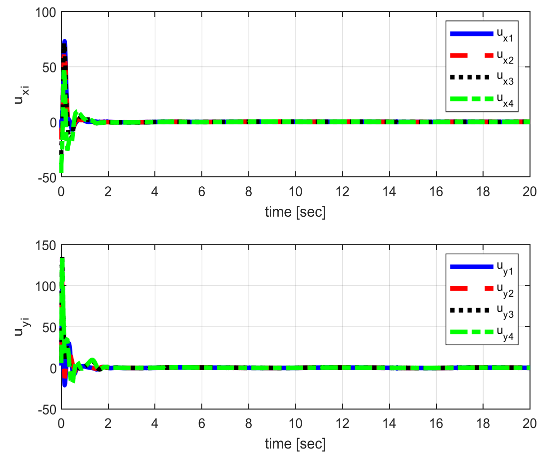

Fig. 6. Control signals for starting robotic system using adaptive sliding mode control based on disturbance compensator.

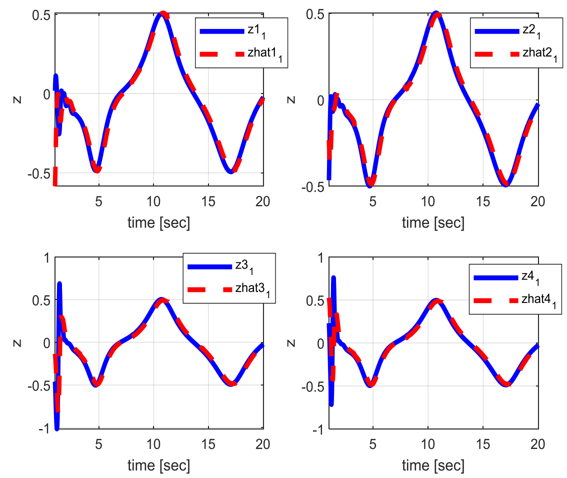

Fig. 7. Estimation of the first component of the nonlinear part of robot dynamics using the disturbance compensator.

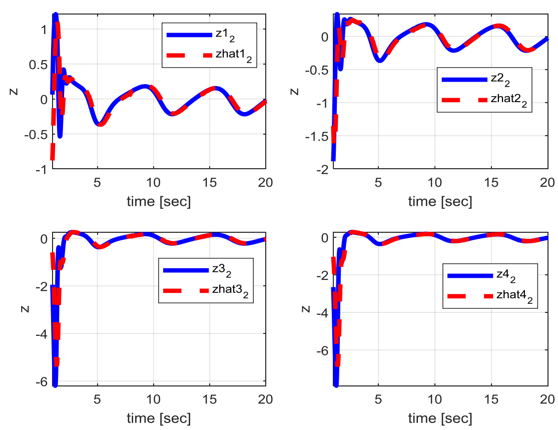

Fig.8. Estimation of the second component of the non-linear part of robot dynamics using the disturbance compensator.

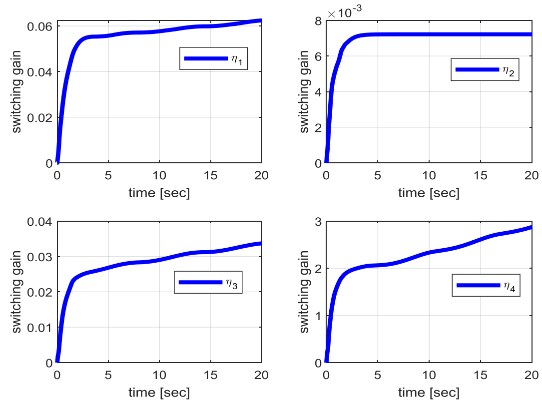

Fig. 9. The course of control gains changes with the help of switching gain adaptive algorithm.

6. COMPARISON OF RESULTS WITH REFERENCE PAPER

In this section, a comparison has been made according to the proposed method and the reference article [13], and the following results have been obtained:

In the proposed method, the movement path of the robots is much more complicated than Zhang's method, and also four robot followers are considered, while in Zhang's method, there are two followers. Observer error is much less in the proposed method. To estimate the path of the followers, the error of the proposed method is less, while in Zhang's method, the path reaches the correct value by spending a lot of time and energy.

7. CONCLUSION

In this paper, the main goal was to realize the control of the arrangement of multi-agent robots with the help of the adaptive sliding mode control approach based on the disturbance compensator. Based on this, first, the dynamic equations of the leader-follower of the robotic multi-agent system were presented. Then, considering the direct topology and a communication graph between the agents with each other and the agents with the leader, the way to formulate the classical sliding mode control rules for robots was stated. To solve the chattering problem, the sliding mode control strategy based on the exponential access condition was used. In addition, the structure of disturbance compensator for instantaneous estimation of nonlinear effects including uncertainty and external disturbances was explained analytically. Also, an adaptive algorithm was derived for instantaneous estimation of switching gain in control rules. In evaluating the performance of the proposed algorithm, it can be stated that the control approach presented in this research is able to realize the multi-agent arrangement in the presence of uncertainty by eliminating the chattering phenomenon. In this paper, sliding mode control method based on adaptive viewer was used to remove chattering and disturbances. As a suggestion, we can consider obstacles in the path of the agents, in this situation, all the agents should communicate with the leader and share their information with the leader, and the leader should use another path to avoid the obstacles by consensus with all the followers.

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