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Formation Control of Multi Agent System in Cyclic Pursuit with Varying Inter-Agent Distance

Galib Rahaman Mallik[1] and Arpita Sinha[2]

Abstract— **This paper is concerned with formation control of multi-agent system under cyclic pursuit strategy. The object is to control inter-agent distance between the agents heterogeneously. We propose a control algorithm based on bearing angle information of the pursuing agent. The algorithm consist of heading control only. The control law is simple and easy to implement in real world application. The effectiveness of the proposed control law are demonstrated through various simulations**

I. INTRODUCTION

In recent year, formation control has become one of the well-known problems in multi-agents systems. In formation control, the task is to control a group of mobile agents to follow a predefined path or trajectory, while maintaining a desired formation pattern. Compared with a single mobile robot, several advantages of a network of mobile robots working together have been shown in the literature. Formation control is an important cooperative behavior used in wide range of applications, such as security patrols, search and rescue in hazardous environments, area coverage, reconnaissance in military missions and object transportation.

In cyclic pursuit, the control strategy in which n agents are placed in such a way that the agent i pursues agent $i+1$ modulo n. Cyclic pursuit strategy involve interactions based on local information. In [1], authors proposed the linear cyclic pursuit algorithm for a system of identical agents under which all the agent will converge to a point. In [2], authors generalized the problem of formation of group of autonomous agents by considering nonlinear cyclic pursuit. They derived a necessary condition at equilibrium formation by considering different speed and controller gain. In [3], authors extended the classic cyclic pursuit to a system of wheeled vehicles of each having unicycle model. They showed formations are generalized regular polygons at equilibrium and analyzed the local stability of those equilibrium polygons. There are many applications based on cyclic pursuit strategy. In [4], authors proposed control strategy to track stationary target with multiple agent. In [5], authors presented a pursuit based approached to achieve formation of group of agents with having both single-integrator kinematics and double-integrator dynamics on directed acyclic graphs. The above-mentioned research mainly concentrates on the two-dimensional pursuit problem. In [6], authors proposes control strategy for a group of n agents to achieve target-capturing task in 3D space. They applied cyclic pursuit algorithms to control the yaw angle. The control scheme involve only one other agent and the target. In [7], authors develop control laws that only require relative measurements of position and velocity with respect to the two leading neighbors in the ring topology of cyclic pursuit. Hence they showed, with the help of proposed control law the spacecraft to form the evenly spaced circular and elliptic formation and also evenly spaced Archimedes spirals. In [8], authors proposed cyclic spacecraft formations algorithm based on line of sight (LOS) measurements. In [9], authors present a combined cyclic pursuit and virtual beacon guidance for the spacecraft formation control.

Another important approach to multi-agent coordinated navigation is based on the imitation of animal flocking and swarming. Much of this work is based on Reynolds [10], where he develops three basic rules - separation, alignment and cohesion for the simulation of flocking behavior. [11], [12], [13], the authors develop a decentralized control law that emulates the three flocking rules and describe three flocking algorithms:- two for flocking in free-space and the third one for flocking in presence of multiple obstacles. All three algorithm are based on collective potential function. Authors also show that with these algorithms the agents can navigate through obstacles using split/rejoin and squeezing maneuvers, while maintaining the group together.

To achieve autonomous formation flight of UAVs, the idea from missile guidance strategies have been used extensively. [14], showed the formation of unmanned air vehicles (UAV) based on guidance laws. The proposed guidance law regulates the distances between vehicles and the heading angles with respect to angle subtend between them called lines of sight (LOS). Similarly, in [15], authors discuss formation guidance laws for formation flight using only line of sight (LOS) information. They were able to achieve formation by controlling the flight path angle and velocity.

[16] proposes control law for three agents based on bearing-angle information. The strategy is to maintain a specified angular separation between two neighboring agents. Similarly, in their subsequent paper [17], they propose a control law for quadrilateral formation with bearing angle measurements. They also establish strong convergence result which ensures the desired formation is globally asymptotically stable.

There has been some considerable amount of research over the last few decades on distance-based formation control and potential function based control laws. Whereas angle based

[1]Galib Rahaman Mallik is a graduate student at Systems and Control Engineering, Indian Institute of Technology, Bombay, India. gmallik@sc.iitb.ac.in

[2] Arpita Sinha is with Faculty of Systems and Control Engineering, Indian Institute of Technology, Bombay, India. asinha@sc.iitb.ac.in

formation control is not commonly address in the existing literature. In [3], authors shows inter-agent distance can be vary by varying velocity and controller gain. The changes are homogeneous i.e. all the inter-agents distance will vary in equal proportion. There are many applications where some of the vehicles may required to place close enough to each other for monitoring or complex task processing where complementing with each other is an utmost important. This motivates us to consider this problem which consists of only angular measurements under cyclic pursuit strategy. In this paper, we are concerned with heterogeneous inter-agent distance under cyclic pursuit strategy. In other word, controlling the inter-agent distance to the different values.

This paper organized as follows. Section II gives the problem formulation and formation control strategy of multiple agents with each having unicycle model. In section III, we have extend our control strategy to a system MAVs of each having 6-DOF model. In section IV, simulation results are provided to validate the above mention control algorithm. Finally, conclusions and future works are given in section V.

II. Problem Formulation

In this paper, we are considering n agents of each having a unicycle model. The kinematic of unicycle model is given by

$$\begin{aligned} \dot{x}_i &= V_i \cos\alpha_i \\ \dot{y}_i &= V_i \sin\alpha_i \\ \dot{\alpha}_i &= u_i \end{aligned} \tag{1}$$

where $(x_i, y_i) \in \mathbb{R}^2$ is the position of agent i and α_i is the heading angle of the agent i. V_i and $\dot{\alpha}_i$ is the linear velocity and angular velocity of agent i respectively. u_i is the heading angle control input of agent i.

The following assumptions are consider through out the paper. Equation (1) represent a point mass model. The agents are ordered from 1 to n and agent i pursues agent i+1 modulo n. All agents have the same controller gain k. All agents are moving with the same and constant linear velocity, that is

$$V_i = V \qquad \text{for} \qquad i = 1, 2 \ldots n \tag{2}$$

We are considering the following problem in this paper. The object is to control the inter-agent distance between agents under cyclic pursuit strategy. In other word, varying inter-agent distance heterogeneously.

Consider figure 1, where agent i pursuing agent i+1 and agent i+1 pursuing agent i+2 and so on in cyclic fashion. Where p_i, p_{i+1}, p_{i+2}... denote the position of the agent i, $i+1$, $i+2$ ...respectively. Our objective is to control the respective inter-agent distance r_1, r_2,..., r_n. Where r_i denote distance between agent i and $i+1$. Let ϕ_i be the deviation angle between heading angle of the i th agent and line of sight (LOS) angle between i and $i+1$ th agent. These deviation angle ϕ_i can be easily obtained from the sensor. θ_i is the line of sight angle between i and $i+1$. The motion of the agent i is controlled through its heading angle and is given as

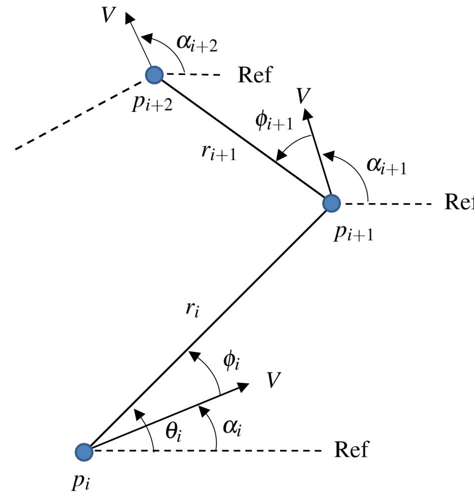


Fig. 1. Formation geometry under cyclic pursuit

$$\omega_i = k(\phi_i - \delta_i) \qquad \text{for} \qquad i = 1, 2 \ldots n \tag{3}$$

where $\delta_i \in \mathbb{R}$, $\forall i$ and $k > 0$ is constant.

Kinematics equations of i agent pursuing i+1 in polar coordinate is given as follows:

$$\begin{aligned} \dot{r}_i &= V\cos(\alpha_{i+1} - \theta_i) - V\cos(\alpha_i - \theta_i) \\ \dot{\theta}_i &= \frac{V\sin(\alpha_{i+1} - \theta_i) - V\sin(\alpha_i - \theta_i)}{r_i} \\ \dot{\alpha}_i &= k(\phi_i - \delta_i) \end{aligned} \tag{4}$$

A. Formation in equilibrium

In this section we will discuss formation of n agent at equilibrium. The desired formation will be achieved if the following conditions hold

$$\dot{r}_i = 0 \tag{5}$$

$$\dot{\phi}_i = 0 \qquad \text{for} \qquad i = 1, 2 \ldots n \tag{6}$$

Using the formation strategy at equilibrium as in [2], we propose the following theorem

Theorem 1: A system consist of n agents with kinematics (4) at equilibrium, will move in a circular trajectory of having same center with identical radius.

Proof: $\dot{\phi}_i = 0 \implies \phi_i$=constant $\implies$ $\omega_i = k(\phi_i - \delta_i)$, $\forall i$ is constant as k, δ_i is constant. Therefore, all agents will move in circular trajectory. As ϕ_i is constant implies $\angle Cp_iE = \pi/2 - \phi_i$ is also constant as shown in figure (2). Rest of the proof is in same line with [2]. Therefore position of agent p_{i+1} should be on the line p_i E. The line p_iE is determine from $\dot{r}_i = 0$ which implies r_i is constant. Hence, triangle Cp_ip_{i+1} forms a rigid triangle. Thus, agent i+1 also has the same center as that of agent i. Since, formation of the triangle Cp_ip_{i+1} remain rigid at equilibrium. Then we must have the

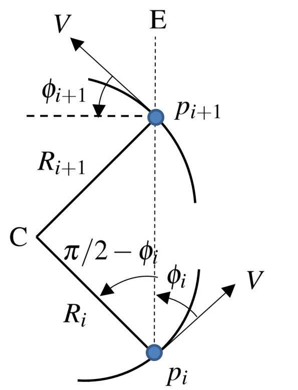


Fig. 2. Formation at equilibrium

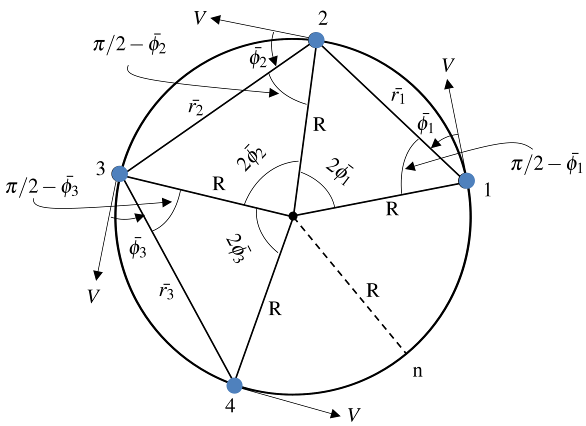


Fig. 3. Formation of multi-agent at equilibrium

following condition,

$$\omega_i = \omega_{i+1} \quad \text{for} \quad i = 1, 2 \ldots n$$
$$\frac{V}{R_i} = \frac{V}{R_{i+1}} \tag{7}$$
$$R_i = R_{i+1} = R \quad \forall \quad i = 1 \ldots n \tag{8}$$

Therefore all agents are move in a circle of having same radius R. ■

Next we will calculate the inter-agents distances and deviation angle of the respective agent.

Consider a situation where all agents ($i = 1 \ldots n$) are moving in a circular path of having radius R at equilibrium as shown in figure (3). Let $\bar{r}_1, \bar{r}_2, \ldots, \bar{r}_n$ be the distances between the respectively agents at equilibrium. $\bar{\phi}_1, \bar{\phi}_2, \ldots, \bar{\phi}_n$ be deviation angle of respective agent at equilibrium.

From figure 3, we get

$$2\bar{\phi}_1 + 2\bar{\phi}_2 + 2\bar{\phi}_3 + \ldots\ldots + 2\bar{\phi}_n = 2\pi d$$

where d is define as $d = 0, \pm 1, \pm 2, \ldots$.

$$\Rightarrow \bar{\phi}_1 + \bar{\phi}_2 + \bar{\phi}_3 + \ldots\ldots + \bar{\phi}_n = \pi d \tag{9}$$

At equilibrium, equation (3) becomes,

$$\bar{\omega}_i = k(\bar{\phi}_i - \delta_i) = \frac{V}{R} \quad \text{for} \quad i = 1, 2 \ldots n \tag{10}$$

From equation (9) and (10), we get

$$\begin{aligned} &\frac{V}{kR} + \delta_1 + \frac{V}{kR} + \delta_2 + \ldots + \frac{V}{kR} + \delta_n = \pi d \\ &\frac{nV}{kR} + \{\delta_1 + \delta_2 + \ldots + \delta_n\} = \pi d \\ &\frac{nV}{kR} = \pi d - \{\delta_1 + \delta_2 + \ldots + \delta_n\} \end{aligned} \tag{11}$$

Hence, the radius of the circular trajectory is given as

$$R = \frac{V}{k[\frac{\pi d}{n} - \frac{\sum_{i=1}^{n} \delta_i}{n}]} \tag{12}$$

δ_i are the design parameter and hence the selection of δ_i must satisfy the following condition

$$\sum_{i=1}^{n} \delta_i < \pi d \tag{13}$$

With equation (12), equation (10) becomes as follows

$$\bar{\phi}_i = [\frac{\pi d}{n} - \frac{\sum_{i=1}^{n} \delta_i}{n}] + \delta_i \quad \text{for} \quad i = 1 \ldots n \tag{14}$$

Inter-agents distance between agents are given as

$$\bar{r}_i = 2R\sin(\bar{\phi}_i) \quad \text{for} \quad i = 1 \ldots n \tag{15}$$

where R and $\bar{\phi}_i$ is given in equation (12) and (14) respectively.

***Remark** 1:* From (15), we can infer that the inter-agents distance are depends on $\delta' s$. For a given set of (V, k, n and d), we can have the control over the inter-agents distance with the help of δ. Therefore inter-agents can be vary heterogeneously.

***Remark** 2:* When $\delta_i = 0$ for all i, then we get the results obtained in [3].

III. 6-DoF Dynamics of Miniature autonomous Vehicles (MAVs)

The above proposed control law is implemented on realistic 6-DOF MAV models. The states vector consists of components of the position vector, components of the Euler angles, components of the velocity vector and components of the angular rate vector respectively. The model is taken from [18], and is given as

$$
\begin{aligned}
\dot{x}_p &= [u\cos\theta + (v\sin\phi + w\cos\phi)\sin\theta]\cos\phi \\
&\quad - (v\cos\phi - w\sin\phi)\sin\psi \\
\dot{y}_p &= [u\cos\theta + (v\sin\phi + w\cos\phi)\sin\theta \\
&\quad + (v\cos\phi - w\sin\phi)\cos\psi] \\
\dot{z}_p &= -u\sin\theta + (v\sin\phi + w\cos\phi)\cos\theta \\
\dot{\theta} &= q\cos\phi - r\sin\phi \\
\dot{\phi} &= p + (q\sin\phi + r\cos\phi)\tan\theta \\
\dot{\psi} &= \frac{(q\sin\phi + r\cos\phi)}{\cos\theta} \\
\dot{u} &= rv - qw + \frac{1}{m}f_x - g\sin\theta \qquad (16) \\
\dot{v} &= pw - ru + \frac{1}{m}f_y + g\cos\theta\sin\phi \\
\dot{w} &= qv - pv + \frac{1}{m}f_z + g\cos\theta\cos\phi \\
\dot{p} &= \Gamma_1 pq - \Gamma_2 qr + \Gamma_3 l + \Gamma_4 n \\
\dot{q} &= \Gamma_5 pr - \Gamma_6(p^2 - r^2) + \Gamma_7 m \\
\dot{r} &= \Gamma_8 pq - \Gamma_2 qr + \Gamma_4 l + \Gamma_9 n
\end{aligned}
$$

where

$$
\Gamma = J_x J_z - J_{xz}^2, \quad \Gamma_1 = \frac{(J_x - J_y + J_z)J_{xz}^2}{\Gamma}, \quad \Gamma_2 = \frac{(J_y - J_z)J_z - J_{xz}^2}{\Gamma},
$$

$$
\Gamma_3 = \frac{J_z}{\Gamma}, \quad \Gamma_4 = \frac{J_{xz}}{\Gamma}, \quad \Gamma_5 = \frac{(J_z - J_x)}{J_y}, \quad \Gamma_6 = \frac{J_{xz}}{J_y},
$$

$$
\Gamma_7 = \frac{1}{J_y}, \quad \Gamma_8 = \frac{J_x(J_x - J_y) + J_{xz}^2}{\Gamma}, \quad \Gamma_9 = \frac{J_x}{\Gamma}
$$

where $[x_p \;\; y_p \;\; z_p]$ denote position of the MAV. $[\phi \;\; \theta \;\; \psi]$ are roll, pitch and yaw angle respectively and they are commonly referred to as *Euler angles*. $[u \;\; v \;\; w]$ represents velocity component of the MAV and $[p \;\; q \;\; r]$ are the angular rate component in the body axes frame. J_x, J_y and J_z are the inertia about x-axis, inertia about y-axis and inertia about z-axis respectively. J_{xy}, J_{xz}, J_{yz} are cross product of inertia.

$$
[f_x \;\; f_y \;\; f_z] = \frac{1}{2}\rho V^2 S[C_X \;\; C_Y \;\; C_Z] \qquad (17)
$$

$$
[l \;\; m \;\; n\;] = \frac{1}{2}\rho V^2 S[bC_l \;\; cC_m \;\; cC_n] \qquad (18)
$$

where ρ, V, S, b and c are air density, velocity of MAV, wing surface area, wing span and M.A.C respectively. To derive the eqns of motion along body axis, transformation from wind axis coefficients C_D , C_L and C_Y to body axis C_X, C_Y and C_Z has to be applied. Where C_D, C_L and C_Y are the total drag coefficient, total lift coefficient and side force coefficient respectively. C_l, C_m and C_n are rolling moment coefficient, pitch moment coefficient and yaw moment coefficient respectively. These are called dimensionless coefficients and are given as

$$
\begin{aligned}
C_L &= C_{L_0} + C_{L_{\delta_e}}\delta_e + \frac{C_{L_q} qc}{2V} \\
C_D &= C_{D_{min}} + |C_{D_{\delta_\alpha}}\delta_\alpha| + |C_{D_{\delta_e}}\delta_e| + k(C_L - C_{L_{min}})^2 \\
C_Y &= C_{y_\beta}\beta + C_{y_{\delta_\alpha}}\delta_\alpha + \frac{(C_{y_p} p + C_{y_r} r)b}{2V} \\
C_m &= C_{m_0} + C_{m_\alpha}\alpha + C_{m_{\delta_e}}\delta_e + \frac{C_{L_q} qc}{2v} \\
C_l &= C_{l_\beta}\beta + C_{l_{\delta_\alpha}}\delta_\alpha + \frac{(C_{l_p} p + C_{l_r} r)b}{2V} \\
C_n &= C_{n_\beta}\beta + C_{n_{\delta_\alpha}}\delta_\alpha + \frac{(C_{n_p} p + C_{n_r} r)b}{2V}
\end{aligned}
$$

Autopilot of each MAV has three control loops to regulate heading, speed and altitude using proportional-integral-derivative (PID) controllers. The autopilot design is the same as in [19]. There are two separate autopilots for the longitudinal and lateral control. Lateral and longitudinal motions of the aircraft and their corresponding control loops are decoupled by linearizing. The control loops implemented are as follows

Heading command is implemented by giving a roll command which is proportional to the difference between the heading error (commanded heading - actual heading) and turn rate. Therefore roll command is generated

$$
\phi_{i_c} = K_p\{\chi_c - \chi_m\} - K_d\dot{\chi}_i \qquad (19)
$$

where χ_c and χ_m are the command and measured heading angle respectively. K_p and K_d are proportional and derivative constant. The turn rate $(\dot{\chi}_i)$ is calculated as

$$
\dot{\chi}_i = -p\sin\theta + q\cos\theta\sin\phi + r\cos\phi\sin\theta
$$

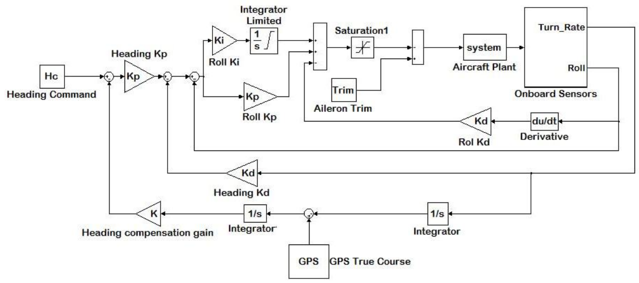
The roll command is implemented through block diagram shown in figure 4(a). Altitude and airspeed command are held constant and implemented through block diagram shown in figure 4(b) and 4(c).

IV. Simulation Results

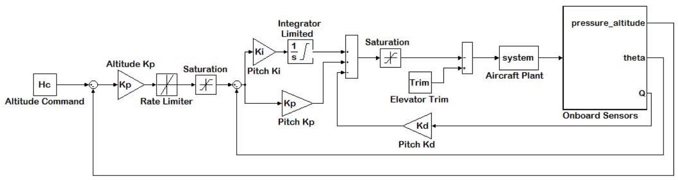
In this section, we presents various simulation results to test the effectiveness of the proposed control law. We considered group of $n = 5$ agents moving with linear velocity $V = 15m/s$. Other simulation parameters are : $k = 0.2$, initial positions and heading angle of the agents are random. For $\delta = [3^\circ \;\; 4^\circ \;\; 2^\circ \;\; 0^\circ \;\; -5^\circ]$.

With unicycle model, agents achieved $\{5/1\}$ and $\{5/2\}$ formation configuration as shown in figure 5(a) and figure 6(a) respectively. Figure 5(b) and 6(b), shows the inter-agent distances for the respective configuration.

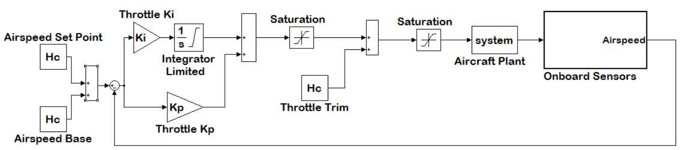
The proposed control strategy is extended to Miniature Autonomous Vehicles (MAVs), each vehicle is represented by a 6-DOF model. The flight model considered is based on the wind tunnel data provided by nation Aerospace Laboratories, Bangalore, India [20]. Figure 7(a) shows the trajectories of agents which are similar to that observed with unicycle model and figure 7(b) shows corresponding inter-agent distances. Also from Table 1, we can observed that the



(a) Heading control command



(b) Altitude control command



(c) Speed control command

Fig. 4. Autopilot control commands

TABLE I

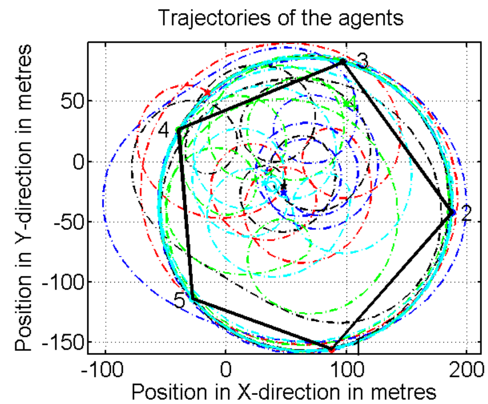
COMPARISION OF $\bar{r}_i$ BETWEEN UNICYCLE AND 6 DOF MODEL

		$\bar{r}_i$	
Formation	δ	**Unicycle**	**6-DOF**
{5/2}	3	117.8	126.6
	10	121.6	130.7
	−5	111.8	120.0
	0	116.2	124.7
	5	119.2	127.9
{5/2}	3	116.5	124.7
	−4	111.4	119.4
	2	115.9	124.2
	0	114.8	122.9
	5	117.9	125.9

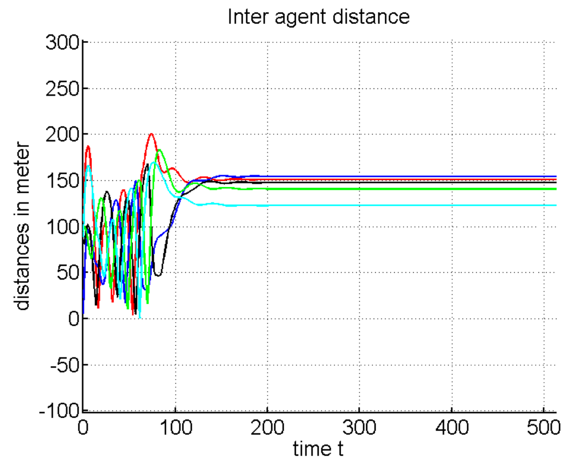
simulation results of inter-agent distances are very close to that of unicycle model results.

V. CONCLUSIONS

In this paper, we have proposed an algorithm to maintain the desired inter-agent distance under cyclic pursuit strategy. Firstly, we are able to derive the heterogeneous distance between the agents and verified with the help of simulations results. The control algorithm is simple and its required only bearing angle information. Secondly, the proposed algorithm is extended to a system of MAVs of each having 6-DOF model. The simulation results of the 6-DOF model shows similarly behavior with the unicycle model. We are under process of further more analysis about the whole systems and its stability.



(a) Trajectories of the vehicles



(b) Inter-agent distances

Fig. 5. {5/1} formation configuration with unicycle model

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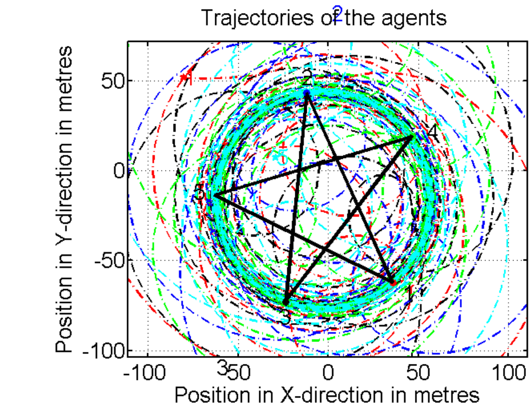
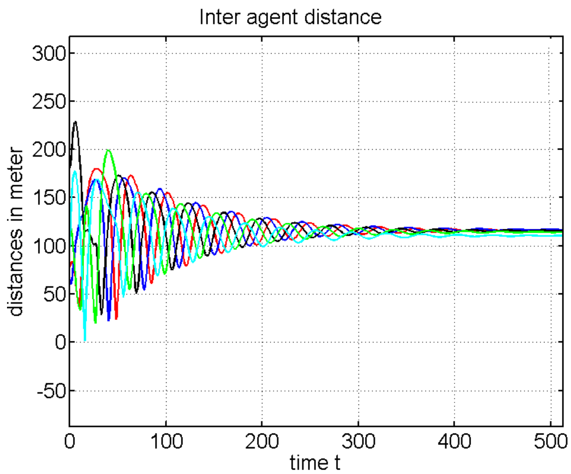


(a) Trajectories of the vehicles



(b) Inter-agent distances

Fig. 6. {5/2} formation configuration with unicycle model

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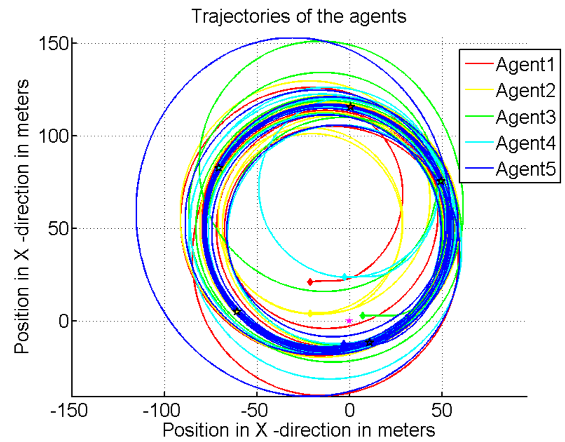
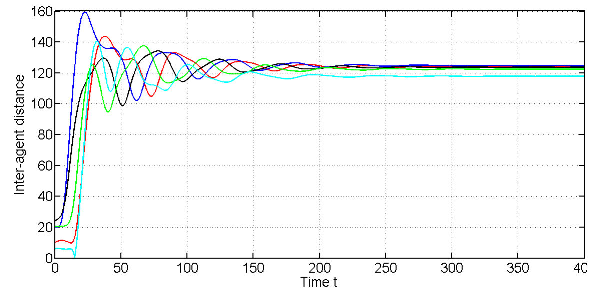


(a) Trajectories of the vehicles



(b) Inter-agent distances

Fig. 7. {5/1} formation configuration with 6-DOF model

Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Orlando, Florida, 2011.