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Implementation of Formation Flight of Multiple Unmanned Aerial Vehicles

Xiangxu Dong, Guowei Cai, Feng Lin, Ben M. Chen, Hai Lin, Tong H. Lee

***Abstract*—We present in this paper the actual implementation results of flight formation of multiple unmanned helicopters. More specifically, we consider a leader-follower formation flight behavior with two scenarios: 1) the flight formation test with the leader being a manned helicopter following a zigzag-like trajectory, and 2) the flight test with the leader being an unmanned system following circle and raceway paths. Experimental results show that our design is very successful.**

***Index Terms*—Unmanned aerial vehicles, formation flight, cooperative control.**

I. INTRODUCTION

In recent years, more research efforts have been focused on the development of cooperative behaviors among multiple unmanned aerial vehicles in both military and civilian applications. The multiple vehicles possess more powerful capability when executing certain tasks in a cooperative way than in the single UAV. The potential application scenarios may include urban collaborative surveillance, geographic mapping, mobile sensor network, emergent rescue and fire detection, etc. And the formation flight forms an necessary and integrated part in all the cooperative behaviors.

The theoretic research in the field of cooperative control of multiple vehicles has made great progress. However, the implementation of the cooperative behaviors is not a trivial task. To integrate both theory and implementation, many research institutes and universities worldwide have developed the experimental testbeds. A hybrid system approach is incorporated in [1] to modeling both the UAV dynamics and way point switching logic. In [4], the information driven method is deployed among vision-based UAV to realize cooperative ground feature gathering task. Also in [6], the receding horizon control is used for task assignment and path planning. Most of the aerial vehicles are fix-wing based due to its easy modeling and control. The rotorcraft platform developed at the National University of Singapore presents more robust and reliable cooperative behaviors in the outdoor flight tests.

This paper first describes the overall system architecture for coordination and control in Section II. Section III gives a detailed formulation of formation flight under the proposed framework. Section IV presents the formation flight results of two UAVs both in indoor simulation and outdoor tests, with conclusions given in section V.

The authors are with Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576.

Fig. 1. HeLion and SheLion, the UAV helicopters in formation.

II. SYSTEM DESCRIPTION AND ARCHITECTURE

The UAV platform developed at the National University of Singapore is shown in Fig. 1, with the name of HeLion and SheLion. Interested readers on the construction of the UAV are referred to [3].

The architecture of the coordination and control for multiple UAVs determines the overall performance of the system, such as efficiency, stability, scalability, modularity and etc. Thus, the coordinate architecture should be organized in hierarchical layers to accommodate requirements as much as possible. There are three abstract layers. The highest layer coordinates the dynamic transitions from one state to another in the overall coordination task. For example, in the formation flight, all the UAVs will first finish the rendezvous action before being ready for the following formation flight task. The next abstract layer is for coordination task dispatch based on the coordination mechanism: to assign the proper task to the corresponding UAV. The bottom level is to realize full automatic control based on its assigned task. The idea of the adopted architecture for our application-oriented project comes from [2]. Fig. 2 illustrates the block diagrams of the proposed architecture in our multiple-UAV system. In this architecture, $\mathcal{S}_i$ represents the dynamic model of the ith UAV, with the control input vector $\mathbf{u}_i$ and the measurable output vector $\mathbf{y}_i$.

The higher layer of the local UAV is the coordinator $\mathcal{C}$. It receives coordinate performance input vector from all or selected UAVs, then process and encapsulate the performance evaluation result vector z_C to the top layer according to the

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coordination mechanism. And it will adjust its coordination mechanism based on the performance feedback $\mathbf{y}_G$ from top layer. The output of coordinator ξ_i behaves as the interaction between the local UAV and the global team and can be broadcast or multicast to the UAV team. In the case of leader-follower based formation flight, the information of the leader is the coordination mechanism. In other words, the coordinator will dispatch the tasks to each follower based on the leader information update. The system $\mathcal{G}$ locating at the highest level is a discrete-event system, which acts as a supervisor to regulate the performance of coordination for the multiple-UAV system. The current design of the supervisor is a finite state machine which regulates the overall states of multiple UAVs. In formation flight, the states of the multiple UAVs consist of formation keeping, formation reconfiguration. Events like collision avoidance detection, new task allocation will trigger the state transitions.

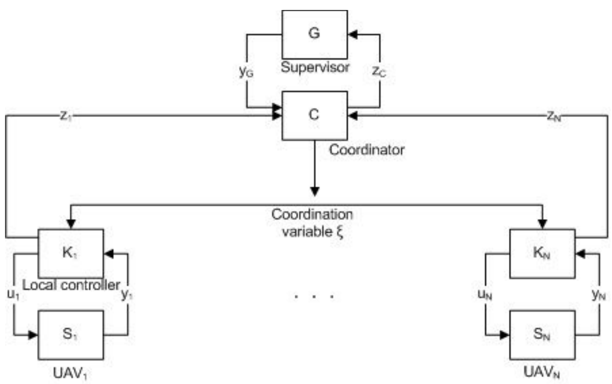

Fig. 2. Architecture for coordinated control among multiple UAVs.

III. Formation Flight

In the formation flight, the overall behaviors of the team consist of formation keeping and formation reconfiguration. Formation keeping refers to the situation when the leader and followers are at their designated position and keep pre-defined interval distance in the flight duration. On the other hand, formation reconfiguration refers to the transition phrase from one formation to another formation in case of collision avoidance, task change, etc. For each UAV in the team, the tasks for individual include specific behaviors such as hovering, path tracking, heading to. The combinations of these basic behaviors on individual UAV contribute to the overall cooperative control.

In formation flight, the coordinator encapsulates the performance vector and feeds it to the supervisor. The supervisor decides the next task (state) for the team and sends the output to the coordinator for it to dispatch the corresponding task to each local controller for execution. The supervisor and coordinator can be implemented in centralized or decentralized depending on the applications. For small number of UAVs, centralized approach is preferred since the centralized node has sufficient computation ability and makes decisions based on the performance index derived from the global information update. At present, the supervisor and coordinator reside in the centralized ground station.

A. Formation Geometry

Fig. 3 illustrates the formation geometry relationship between the leader and the follower in 3D plan. As the leader information is the coordination mechanism, the coordinates of the followers are converted into that of the leader for convenience. For 2D plane, we define the requirements for formation as follows: in the leader's coordinate, the follower lags the leader in longitudinal and lateral axis, f_c and l_c, respectively. On the other hand, the height constraint for the follower is set independently on the leader to minimize the risk of collision. Note that there are two coordinates in Fig. 3, the NED (North-East-Down) frame and the body frame of the leader. Suppose the angle difference between the north and the leader is ψ, then the desired reference position for the follower can be easily calculated in (1). Details of the geometry formulation of the formation can be seen in [7].

$$\begin{cases} x_f = x_l + l\sin\psi - f\cos\psi \\ y_f = y_l - l\cos\psi - f\sin\psi \end{cases} \tag{1}$$

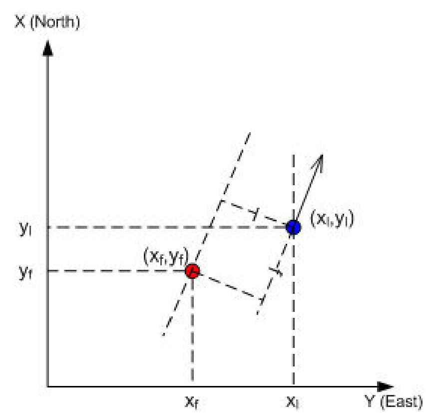

Fig. 3. Leader-follower formation geometry in 2D.

B. Coordinator

As explained, the coordination variable is the leader's update(position and heading angle) in formation flight. Thus, we incorporate the states consisting of position(x, y, z) and yaw angle(c) both in NED frame. Define the state of ith UAV in formation flight to be:

$$\mathbf{x}_{iF} = [x, y, z, c]^T \tag{2}$$

Thus, the formation state vector of the UAV team can be defined as the combination of each UAV:

$$\mathbf{x}_F = [\mathbf{x}_{1F}, \mathbf{x}_{2F}, ..., \mathbf{x}_{NF}]^T \tag{3}$$

For the performance index, we initially consider the constraints like inter-vehicle distance in formation flight. As such, the Euclidean distance between one UAV and the other is

TABLE I
PERFORMANCE EVALUATIONS IN SUPERVISOR $\mathcal{G}$.

Performance	True	False
G1	$\mathbf{E}_b > \epsilon_1$	otherwise
G2	$\epsilon 2 < \mathbf{E}_a < \epsilon_3$ and $\alpha_1 < \mathbf{A} < \alpha_2$	otherwise
G3	$\mathbf{E}_a < \epsilon_4$	otherwise
G4	$\mathbf{z}_C(t) = \mathbf{z}_C$	otherwise

defined as the interval distance constraints, $E_a(\mathbf{x}_{iF}, \mathbf{x}_{jF})$. And the consistency in heading angle is another performance index, denoted as $A(\mathbf{x}_{iF}, \mathbf{x}_{jF})$. Also, the norm distance between the current position and reference position for follower is the third performance index, $E_b(\mathbf{x}_{iF}, \mathbf{x}^r_{iF})$. Hence the performance triplet can be defined as:

$$\begin{cases} E_{ai}(\mathbf{x}_{iF}, \mathbf{x}_{jF}) = \|\mathbf{x}_{iF} - \mathbf{x}_{jF}\| \\ E_{bi}(\mathbf{x}_{iF}, \mathbf{x}^r_{iF}) = \|\mathbf{x}_{iF} - \mathbf{x}^r_{iF}\| \\ A_i(\mathbf{x}_{iF}, \mathbf{x}_{jF}) = |c_i - c_j| \end{cases} \quad (4)$$

where $\mathbf{x}^r_{iF}$ is the reference position for the ith UAV.

Consider the case where two UAVs are performing the formation flight, i.e. N=2. The performance vector encapsulated $\mathbf{z}_C$ in the coordinator is:

$$\mathbf{z}_C : \begin{cases} \mathbf{E}_a = [\mathbf{E}_{a1}]^T \\ \mathbf{E}_b = [E_{b1}, E_{b2}]^T \\ \mathbf{A} = [\mathbf{A}_{a1}]^T \end{cases} \quad (5)$$

After deriving the performance vector $\mathbf{z}_C$, the coordinator will send it to the supervisor for further analysis and decision making.

C. Supervisor

The supervisor receives the formation performance update from coordinator and performs state transitions based on the formation flight requirements such as the tolerable Euclidean distance, time resource allocated to reach the reference position.

The supervisor will first reside in the formation initialization state, during which it will make the coordinator to send rendezvous command to each UAV. Once the updated formation performance indicates that both leader and follower have reached their desired position, it will transfer to the next state, and start the formation flight. During this process, collision avoidance is constantly checked from the updated performance. If collision alarm detected, the supervisor will command the UAVs to hover at the same time. And once the alarm of collision avoidance disappears, it will continue performing the formation flight until the formation flight task is successfully finished. Fig. 4 is the state transition diagram in supervisor when performing a leader-follower formation flight.

And the conditions are listed in Table I, where ϵ_1 is the tolerance distance in hover state, ϵ_2 is the tolerance of distance between leader and follower, and ϵ_3 is the tolerance(largest) distance for detecting the collision avoidance. And α_1 and α_2 are the lower and upper bound of the difference in the heading angle.

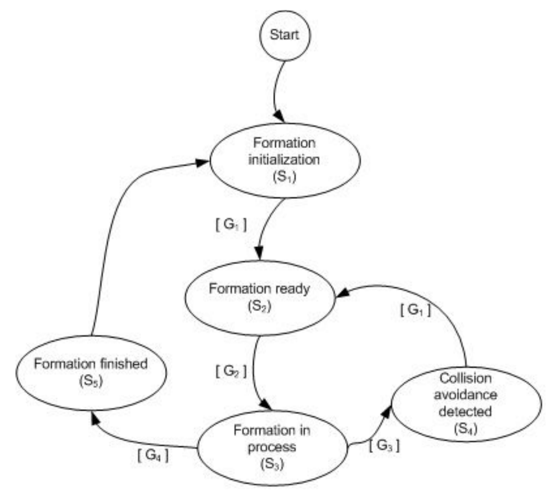

Fig. 4. State transition diagram in supervisor $\mathcal{G}$

The output $\mathbf{y}_G$ of the supervisor to the coordinator includes the tasks for each UAV to perform. In the case of performing formation flight, the leader and follower are both assigned the task of doing path tracking. While in case of collision avoidance detected, the leader and follower are simultaneously assigned to perform hovering. Table II lists the output of the supervisor in different states. The output $\mathbf{y}_G$ is the coordination vector consisting the ID of the UAVs, assigned task for each UAV and task parameters. The first row of $\mathbf{y}_G$ in Table II specifies UAV1 and UAV2 to perform "headto" commands, and $\mathbf{x}^r_i$ and $\mathbf{x}^r_j$ specifies the position where they should head to. Details on the behavior-based control approach for the UAV can be seen in [5].

D. Formation Implementation

In the formation flight, the leader is commanded to perform a predefined path tracking, and the task of the follower is to follow the leader with a 10 m distance offset both in the axis of longitudinal and lateral in the coordinate of the leader. In this two-UAV cooperative situation, HeLion is assigned as the leader, while SheLion is the follower. The final overall formation flight scenario with a circle path is demonstrated in Fig. 5, where L_0 and F_0 are the initial reference rendezvous positions for the leader and the follower respectively. The points L_i $(i = 1, 2, ..., N)$ refer to the predefined trajectory for the leader, and the points F_i $(i = 1, 2, ..., N)$ refer to the reference points for the follower.

The information update rate of the leader is set to 5 Hz. Every time the GCS receives the leader update, it transforms the position and heading into the coordinate of the follower and then sends the reference points to the follower. Considering the flight velocity of the leader is about 1 m/s, the update rate and round trip transmission delay is acceptable in this case.

IV. FORMATION FLIGHT EXPERIMENTS

In this section, the actual flight tests are performed to verify our designed leader-follower control and coordination

TABLE II
SUPERVISOR OUTPUT $\mathbf{y}_G$.

States(S_i)	Output($\mathbf{y}_G$)
S_1	$(i = 1, j = 2, BEHAVIOR\_HEADTO, BEHAVIOR\_HEADTO, \mathbf{x}_i^r, \mathbf{x}_j^r)$
S_2	$(i = 1, j = 2, BEHAVIOR\_HOLD, BEHAVIOR\_HOLD, \mathbf{x}_i^r, \mathbf{x}_j^r)$
S_3	$(i = 1, j = 2, BEHAVIOR\_PATH, BEHAVIOR\_PATH, \mathbf{x}_i^r(t), \mathbf{x}_j^r(t))$
S_4	$(i = 1, j = 2, BEHAVIOR\_HOLD, BEHAVIOR\_HOLD, \mathbf{x}_i^r, \mathbf{x}_j^r)$
S_5	$(i = 1, j = 2, BEHAVIOR\_HOLD, BEHAVIOR\_HOLD, \mathbf{x}_i^r, \mathbf{x}_j^r)$

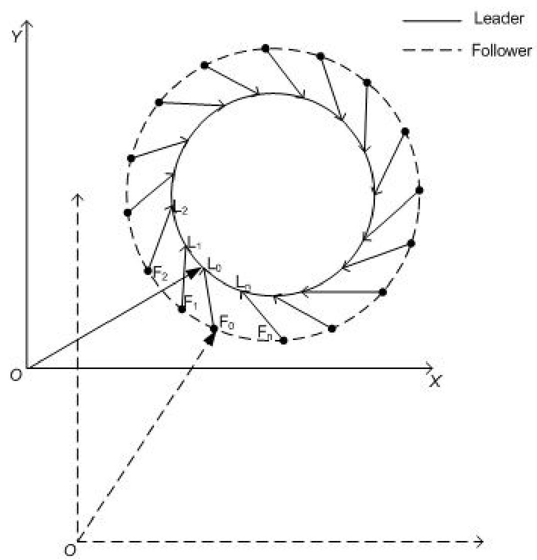

Fig. 5. Leader-follower circle formation scenario.

approach. We perform two kinds of tests: Manned aerial vehicle lead (MAV-lead) formation flight and unmanned aerial vehicle lead (UAV-lead) formation flight.

A. MAV-lead Formation Flight

The formation flight of the UAV helicopter led by an MAV helicopter has various advantages. The most distinguished character is that it can make full use of (1) the intelligence and flexibility of piloted control and (2) the unique properties of UAVs (such as ultimate precision and hazard immunity), and greatly improve the possibility and feasibility to complete designated missions. A zigzag-like trajectory flight example is presented in this section for the MAV-lead formation flight.

In this experiment, the ground pilot remotely controls the leader to perform a zigzag like path with a low velocity of about 1m/s. The procedures to conduct safe flight tests are as follows:

i. Both the leader and the follower are driven to their designated hovering points via manual control issued by two pilots. Their relative positions are adjusted by the pilots. With respect to leader's body frame, the follower is required to maintain a position with 15 m behind in longitudinal direction, 15 m right in lateral direction, and 7 m higher in vertical direction. Such distance offsets are necessary for safety. Their heading angles are roughly trimmed to be in the same direction;

ii. While the leader is maintaining the manual hovering, the follower is switched to the automatic mode. Its avionic system takes the control authority and conducts the initial hovering at the current point;

iii. After the automatic hovering of the follower is stable, the ground station uploads the formation command. The follower then automatically adjusts its position and heading angle to achieve the required distance offset with the leader;

iv. Next, the leader flies forward following a straight line trajectory. Both the velocity and trajectory are determined by the manual pilot. During this procedure, the follower will follow the manned leader to complete the formation flight, while ensuing the requirements on 3D position and heading angle. The experimental results are shown in Fig. 6. It can be noted that all of the key requirements are perfectly satisfied. The flight test results can even compete with the simulation results conducted in an ideal situation, which indicates that the flight control law designed for formation flight of UAV led by MAV is feasible for practical implementation.

B. UAV-lead Formation Flight

Due to various reasons such as (1) the limited range of radio control, (2) the hazardous environment where the human pilots can not oversee, and (3) the long time but continuous flight which is difficult for human pilot to endure, the formation flight of UAVs led by MAV may not be proper in some practical situations. Instead, they can be efficiently completed by the formation flight of a group of UAVs, in which one UAV is selected as the leader. Another big advantage of the formation flight led by a UAV is that the precision and accuracy during the flight can be greatly improved. Therefore, we conducted two UAV-lead formation tests.

1) UAV-lead Circle Path based Formation Flight: Cruising following a circle path in a confined area is greatly common in many practical implementations. As such, we choose this scenario in the first UAV-lead formation flight test. The experiment has been performed as follows:

i. Both the leader and the follower are driven to their designated hovering points via manual control issued by two pilots. Their relative positions and heading angles are adjusted by the pilots, following the expected offset distance requirements;

ii. After both UAVs have achieved steady manual hover, the leader is first switched to automatic mode and performs automatic hovering at the current point. Next, the follower is switched to the automatic mode and also conducts the automatic hovering at its current point;

iii. When automatic hovering is realized for both UAV helicopters, the ground control station upload the formation command, which is a 30-second adjusting period concatenated by the pre-defined circle path. The follower SheLion then automatically adjusts its position and heading angle to form the required formation style;

iv. Next, HeLion carries out the automatic flight following the inside circle path. The follower SheLion then tracks the online generated reference path broadcasted by HeLion to complete the formation flight, whiling ensuing the constant lateral distance gap and the same heading angles.

2) UAV-lead Circle Raceway Path based Formation Flight: Another experiment we conduct is the raceway path based formation flight. The implementation details are similar to that in the circle path based one. Flight test results are shown in Fig. 8.

From Fig. 7 and Fig. 8, it can be concluded that the follower successfully tracked the leader in position and heading angle and the performance is much better compared with the MAV-lead formation. Interested readers may visit our video link at: http://uav.ece.nus.edu.sg/video.html.

V. Conclusion

The framework of coordination and control among multiple UAVs is presented. A leader-follower based formation flight under this framework is analyzed. The actual implementation of MAV-lead and UAV-lead formation flight tests are successfully conducted to verify the proposed approach of control and coordination. Our future work includes the formation flight with automatic take off and landing, split, merge and optimal path planning.

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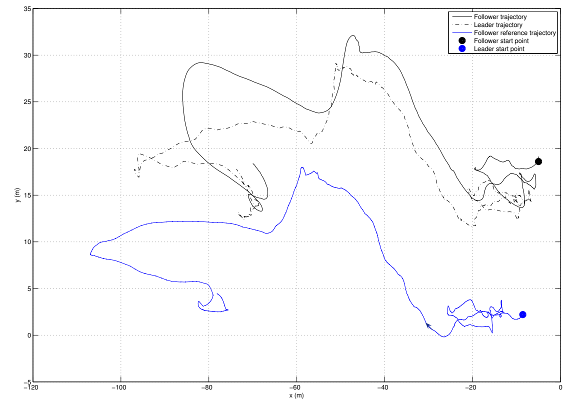
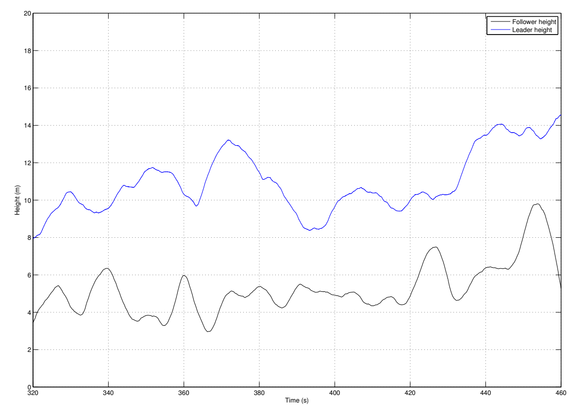


(a) x-y plane



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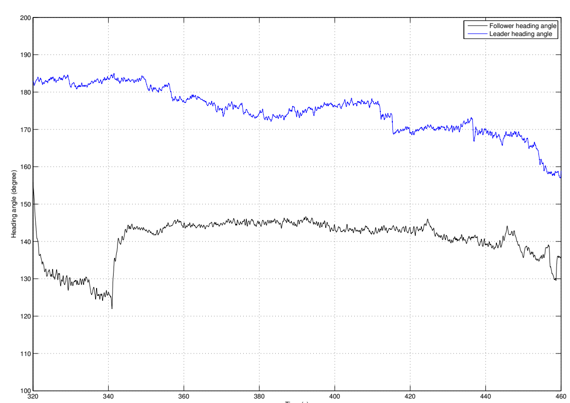
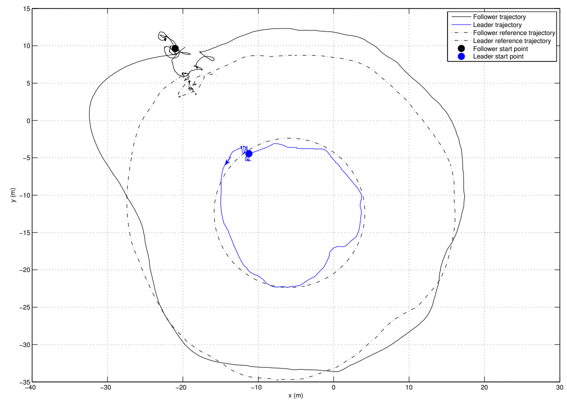


(c) Heading angle

Fig. 6. Leader-follower in a MAV-lead zigzag path based formation flight.



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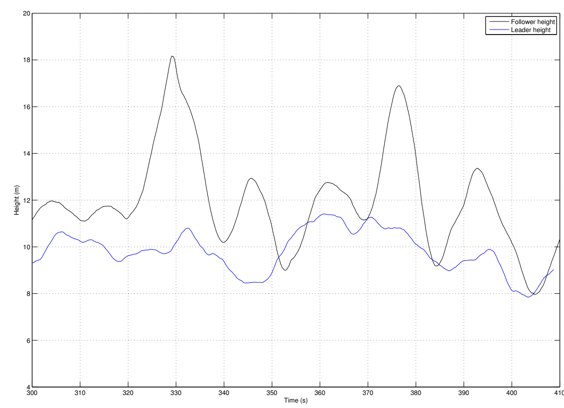

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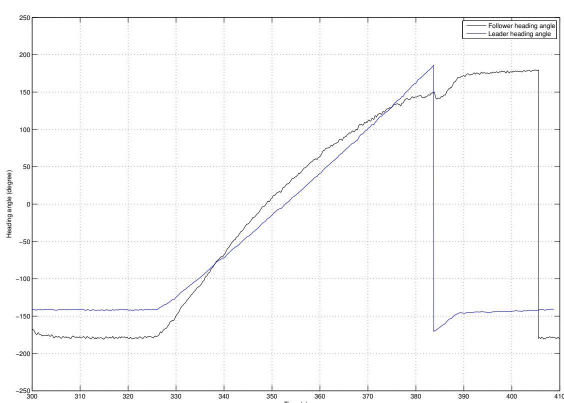
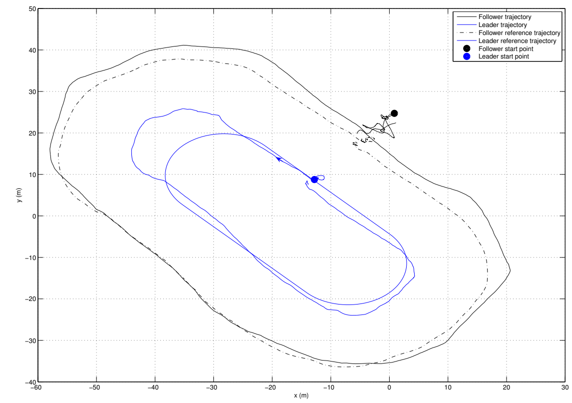


(c) Heading angle

Fig. 7. Leader-follower in a UAV-lead circle path based formation flight.



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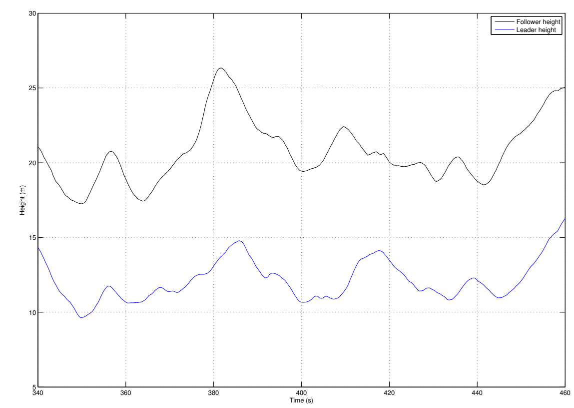

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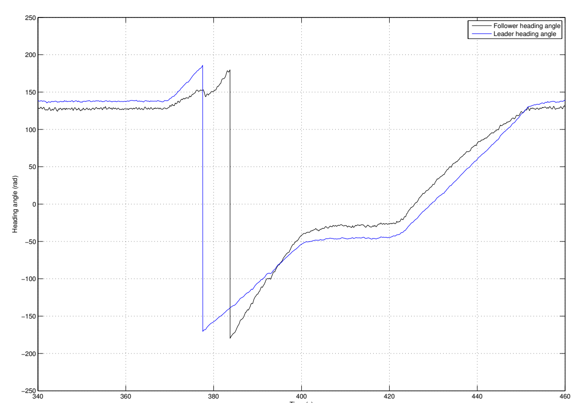

(c) Heading angle

Fig. 8. Leader-follower in a UAV-lead raceway path based formation flight.