Physical Experimental Realization of Modified Artificial Physics Method Based on UAVs Formation Control

Yinbo Xu, Yongwei Zhang, Yajing Wang, Xiangke Wang
College of Mechatronic Engineering and Automation
National University of Defense Technology
Changsha, Hunan, China
xkwang@nudt.edu.cn

***Abstract* - This paper provided the physical experiments of formation flights based on the modified artificial physics for the multiple Unmanned Aerial Vehicles (UAVs) formation control problem. This control method that using modified artificial physics force law to build up UAV formation is verified not only in theory but also in simulation environment in our previous work. To further verify the method in physical experiment, we have introduced a high precision indoor positioning system (VICON system) and mini quad-rotors (crazyflies) to construct our real experimental platform. The result shows the reliability of the experimental platform and the effectiveness of our control method based on modified artificial physics.**

Keywords-UAV; formation control; artificial physics; VICON system; crazyflies

I. INTRODUCTION

In recent years, researchers have paid more and more attention to the UAVs formation control problem. As we all know, formation control is widely applied to express logistics, agriculture, emergency rescue and light or firework show etc. A lot of methods have been studied to solve the formation control problem, such as the leader-follower strategy, the virtual structure strategy, the behavior-based strategy, the artificial field strategy and the graph-based strategy [1]. The strategy based on artificial physics is put forward by Willian M.Spears [2]. Through the attractive and repulsive forces between the agents, the swarm can conduct convergence and avoidance behavior [3][4]. In spite of many advantages like self-assembly, fault-tolerance, the artificial physical method cannot avoid some weaknesses. Our previous work proposed the modified artificial physics method to overcome some shortcomings such as non-uniqueness of standard formation [5] and local optimal problem [6]. We have done simulation experiment on ROS and Gazebo to verify the control method based on modified artificial physics, but have not conducted real physical experiments yet. So the main contribution of this paper is to build a real experimental platform which consists of VICON system, an indoor positioning system with infrared high-speed camera, and crazyflie UAVs to verify the theories. This real experimental platform has high positioning precision which can eliminate the disturbance brought by large positioning error. Besides, the experimental crazyflie UAV is a mini-UAV, which makes our experiments safer and more repeatable.

The rest of this paper is organized as follow: In section Ⅱ, we construct our standard formation model with three UAVs, and bring the modified artificial physics force law up. Section Ⅲ is mainly about building up the experimental platform, conducting verification experiments and showing the experimental result. The final section is the concluding remarks of this paper.

II. METHODOLOGY

In this part, the definitions of the multi-UAV standard formation model and control method base on modified artificial physics are introduced.

A. Standard Formation Model

The standard formation we defined is an equilateral polygon such as equilateral triangle, square, regular pentagon and so on. Those regular polygons have a circumcircle on which the UAVs are evenly distributed to form the standard formation, which is shown in Figure 1. Each point represents one UAV.

Given that this paper will show the physical experimental realization of three UAVs formation flight, we will use three UAVs as an example to illustrate the model. As shown in Figure 2, R represents the radius of the circumcircle of the regular polygon. Three UAVs are positioned on the circumcircle evenly. The length of each side between two UAVs is same which is denoted by L. The position of circumcenter is supposed to be x_c. And there is assumed to a virtual UAV at the central position to play the formation leader role. The goal of our work is to drive the UAVs to form the standard formation around the circumcenter.

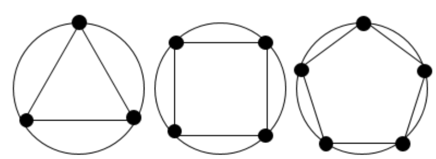


Figure 1. The standard formation of UAVs

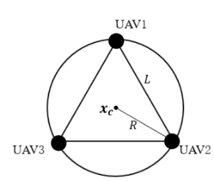


Figure 2. The standard formation model

B. The Force Law of Modified Artificial Physics

978-1-5386-3022-8/17 $31.00 © 2017 IEEE

DOI 10.1109/IHMSC.2017.116

The modified artificial force law has the basis of the traditional artificial physics, but some essential improvements are proposed. In the traditional artificial physics [2], every experimental subject is treated as a mass point. And each one will exert virtual force upon others. This kind of force obeys the following law:

$$F = G\frac{m_i m_j}{r^p} \tag{1}$$

F is the magnitude of the force between two subject i and j, m_i and m_j represent the mass of i_{th} and j_{th} subject respectively. G denotes a constant which is set at initialization, r is the range between two subject. Repulsive force is generated if $r \le R$ while the force is attractive if $r > R$. Consequently, each subject owns a circular “potential well” around itself. Eventually, seven subjects, for example, will form a hexagon formation as Figure 3(a) [5] shows. With the number of the subjects increasing, a hexagonal lattice will come into being like Figure 3(b) [5].

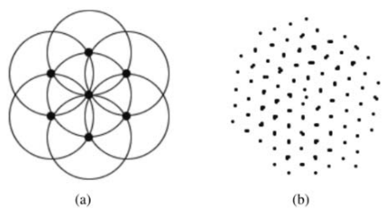


Figure 3. (a)The hexagon formation. (b)The hexagonal lattice

However, under the traditional artificial physics force law, the subjects cannot form the anticipant standard formation actually. Because the distance L between two neighboring UAVs does not always equal R. So the modification of the traditional artificial law is expected.

To demonstrate the modifications, the subjects UAVs are still regarded as mass points. We define the attractive force law between two UAVs as follows:

$$f_{ija} = \begin{cases} G\frac{(\|r_{ij}\|-L)r_{ij}}{\|r_{ij}\|}, & if \ \|r_{ij}\| > L \\ 0, & if \ \|r_{ij}\| \le L \end{cases} \tag{2}$$

where the mass of every UAV is set to 1 as default, and $r_{ij} = X_j - X_i$ is the relative position vector. X_j and X_i are the positions of the j_{th} UAV and the i_{th} UAV. As the expression of attractive force law reveals, if $\|r_{ij}\| > L$, the attractive force will be produced to drive the i_{th} UAV to approach the j_{th} UAV; if $\|r_{ij}\| \le L$, the attractive force will disappear, and the repulsive force will appear. Like the definition of f_{ija}, we give the formula of the repulsive force as follows:

$$f_{ijr} = \begin{cases} G\frac{(\|r_{ij}\|-L)r_{ij}}{\|r_{ij}\|}, & if \ \|r_{ij}\| \le L \\ 0, & if \ \|r_{ij}\| > L \end{cases} \tag{3}$$

Obviously, we can integrate the equations of f_{ija} and f_{ijr} into one:

$$f_{ij} = G\frac{(\|r_{ij}\|-L)\overrightarrow{r_{ij}}}{\|r_{ij}\|} \tag{4}$$

If we want to form the standard formation at the desired position where the center of the formation is located at x_c, another force between the circumcenter and the surrounding UAVs is needed. The formula of the force law goes as follows:

$$f_{ic} = G\frac{(\|r_{ic}\|-R)\overrightarrow{r_{ic}}}{\|r_{ic}\|} \tag{5}$$

where f_{ic} is the force between UAV_i and the circumcenter; $\overrightarrow{r_{ic}} = x_c - x_i$ is the relative position vector. x_c and x_i represent the position of the center and the UAV_i separately. Similarly, if $\|r_{ic}\| > R$, it will produce an attractive force to attract the UAV_i towards the circumcenter, while the repulsive force will come into being to prevent UAV_i from approaching the center closer if $\|r_{ic}\| \le R$.

Synthesizing (4) and (5), we can get the sum forces exerted on UAV_i:

$$f_i = \sum_{j=1,j\neq i}^{N} f_{ijr} + f_c \tag{6}$$

The force f_i can drive the UAVs to form the standard formation at the desired position x_c. In fact, although the number of the UAV is determined, the shape of the formation is not exclusive. Because of the rotation, there are infinite possible polygons lying on the same circumcircle. To eliminate the uncertainty, another force should be added to f_i.

We place an attractive point X^* with an attractive range of L^* as Figure 4 demonstrates.

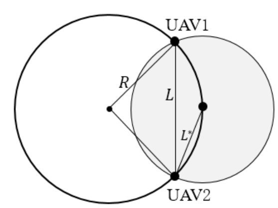


Figure 4. The value of L^*

The value of L^* can be calculated by following formula:

$$L^* = \frac{L}{2\cos\left[\frac{\sin^{-1}(L/2R)}{2}\right]} \tag{7}$$

If the distance between X^* and the UAV_i is less than L^*, the attractive point will exert an attractive force on the UAV. At the same time, the rest of UAVs will alter their own position to the new balance point to structure the standard formation. The force between the UAV which is in attractive range and the attractive point X^* is:

$$f_{io} = G * (\overrightarrow{x_i} - \vec{x}^*) \tag{8}$$

Combing (6) and (8), the final force acting on the UAV_i is:

$$f_i = \sum_{j=1,j\neq i}^{N} f_{ijr} + f_c + f_{io} \tag{9}$$

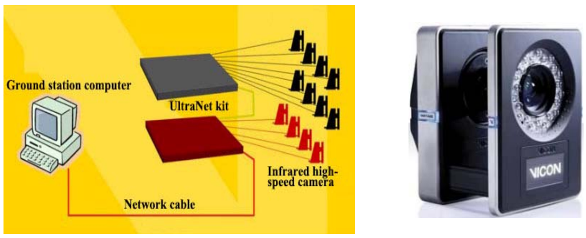
Eventually, with each UAV observing the force law above, we can drive three UAVs to form the standard formation shown in Figure 2.

III. Experimental Verification and Results

This part will show our physical experimental framework and conduct physical experiment based on simulation work. Finally, the experimental results will be analyzed and demonstrated.

A. Multi-UAV Experimental Platform Setup

VICON system is a set of high precision optical movements capture system [8][9]. The structure is shown in Figure 5(a).



(a) (b)

Figure 5. The VICON system

The core component of this system is infrared high-speed camera shown in Figure 5(b). It can capture luminous mark points attached to UAV subjects.

The captured position data are transmitted to ground station computer via UltraNet kit by network cable. The matched software named VICON Tracker utilizes the data to build three-dimensional rigid-body model of UAV, and calculate its position data. The position data are exactly what we need to locate the UAV.

Gauge points which can reflect infrared light are supposed to stick on UAV asymmetrically as shown in Figure 6. The asymmetry of gauge points guarantees that VICON system can distinguish every subjects and discern their orientation correctly.

Figure 6. Subject with gauge point attached asymmetrically

After placing the subjects in the experimental region, we can build the rigid-body model of every subjects, which is shown in Figure 7. The rigid-body model has its certain center of mass; therefore, it can be tracked as a mass point by VICON system.

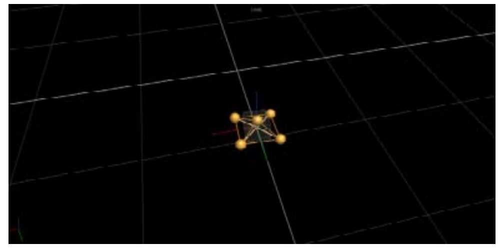


Figure 7. Building the rigid-body model of subject

We use crazyflie, a mini quad-rotor UAV [10], as our experimental subjects, which is shown in Figure 7. Crazyflie is small in size and light. So comparing to traditional UAV, crazyflie is flexible, safer, more resistant to fall off and more durable. Besides, all the parts of crazyflie are replaceable. So it is quite suitable for indoor UAV research.

To use crazyflie under ROS, we need to install relevant ROS driver package "crazyflie_ros". The whole control process is demonstrated in Figure 8.

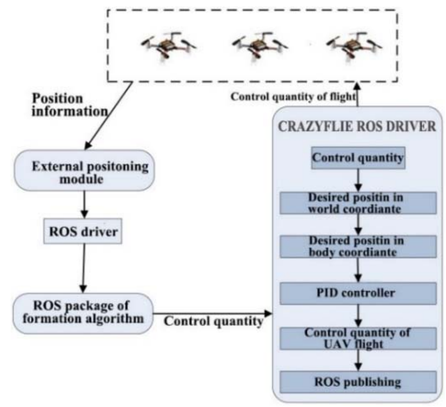


Figure 8. The process of controlling crazyflie

The framework of real experimental platform is shown in Figure 9.

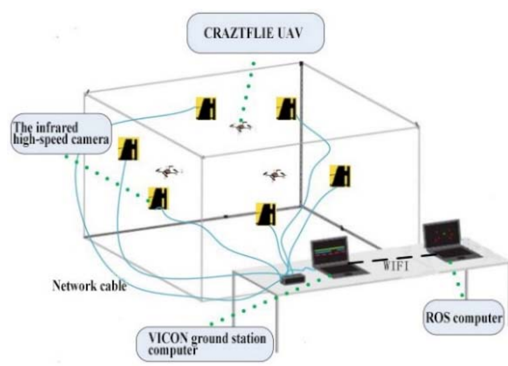


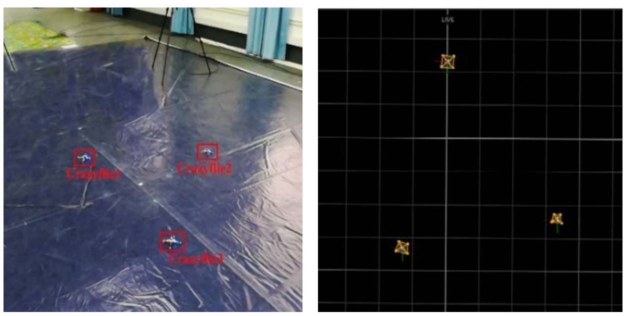
Figure 9. The framework of experiment platform

Real-time data captured by infrared high-speed camera are transmitted to terminal via network cable, then entering ground station computer with Windows system to be analyzed and processed. Another computer with ROS system is connected to the Windows computer by network cable. The ROS driver package, “Vicon_bridge”, runs on the ROS computer so that the position data of crazyflies can be obtained to calculate control quantity with formation control law based on modified artificial physics. In the end, control quantity is delivered to each crazyflie to structure the standard formation via Crazyradio PA.

B. Experimental Result

To focus our attention on studying the formation change, we only consider the axis X and axis Y of crazyflies. So we will make them stay 800mm high before beginning formation.

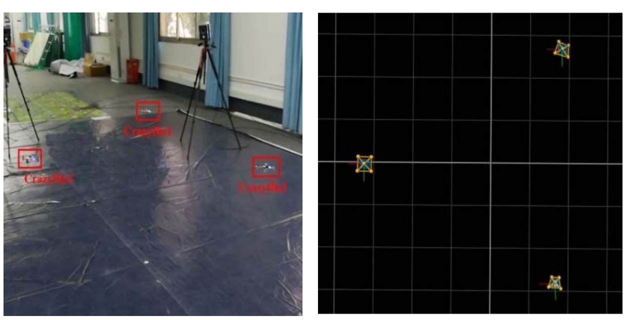
Figure 10(a) shows the initial state of three crazyflies, and Figure 10(b) shows the initial planform of the UAVs’ rigid model in VICON Tracker. The initial positions of three UAVs are (0, -600), (-771, 611), (379, 806). It is apparent that the formation is not an equilateral triangle. We set the coordinates of the vertexes of our standard formation are (-400, -692.8), (-400, 692.8), (800, 0). The length unit we use is millimeter.



(a) (b)

Figure 10. The initial state of three crazyflies

Figure 11(a) shows the state when the standard formation is finished, and Figure 11(b) is corresponding planform of the UAVs’ rigid model in VICON Tracker.



(a) (b)

Figure 11. The state when the standard formation is finished

We record the position of the crazyflie continuously and depict their trajectories in Matlab. From the trajectories shown in Figure 12 we can see that after taking off and undergoing the period of adjustments, three crazyflies are approximately stabilized at (-400, 692.8), (-400, -692.8), (800, 0). The errors between present positon of UAVs and the desired ones are less than 50mm. So we think these three have formed the expected standard formation.

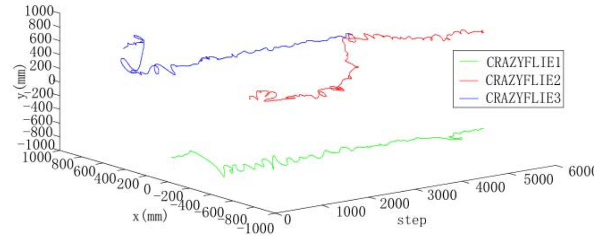


Figure 12. The trajectories of three UAVs

IV. Conclusion

In this paper, we have realized the physical experiment of UAVs’ formation flight to validate a formation control method based on modified artificial physics law. We use VICON system and crazyflie UAVs to build a real experimental platform. We use three crazyflies to conduct the physical experiments, and the result has validated the good performance of our formation control method. The result also reflects the high precision, ease of use and reliability of our physical experimental platform. In our future work, we will increase the number of UAVs to conduct more complicated standard formation flight and random formation flight.

ACKNOWLEDGMENT

This work is supported by National Natural Science Foundation (NNSF) of China under Grant 61403406.

REFERENCES

[1] Wang X K, Zeng Z W, Cong Y R. Multi-agent distributed coordination control: Developments and directions via graph viewpoint. Neurocomputing, 2016, 199: 204-218.

[2] Spears W M, Gordon D F, “Using artificial physics to control agents,” In: Proceedings of the IEEE Conference on Information, Intelligence, and System. Bethesda MD: IEEE, pp.281–288,1999.

[3] W.Spears, D.Spears, J.Hamann, and R.Heil, “Distributed, physics-based control of swarms of vehicles,” Autonomous Robots,vol.17,no.2-3,2004.

[4] Spears W M, Spears D F, Heil R, et al, “An overview of physicomi - Metics,” Lecture Notes in Computer Science. Berlin: Springer-Verlag Press, pp. 84–97,2005.

[5] Liu H, Wang X, Zhu H. Multi-UAVs arbitrary formation control based on artificial physics [C]. In Chinese Automation Congress. 2015.

[6] SHEN L C, WANG X K, ZHU H Y, et al. UAVs flocking and reconfiguration control based on artificial physics[J]. SCIENTIA SINICA Technologica, 2017.

[7] Fu Y, Wang X K, Huan L, et al. Multi-UAV formation control method based on modified artificial physics[C]//Control and Decision Conference (CCDC), 2016 Chinese. IEEE, 2016: 2523-2529.

[8] Al Habsi S, Shehada M, Abdoon M, et al. Integration of a Vicon camera system for indoor flight of a Parrot AR Drone [C]. In International Symposium on Mecha-tronics and ITS Applications. 2015: 2801–2804.

[9] Goodarzi F A, Lee D, Lee T. Geometric Adaptive Tracking Control of a Quadrotor Unmanned Aerial Vehicle on SE(3) for Agile Maneuvers [J]. Journal of Dynamic Systems Measurement & Control. 2015, 137 (9): 393–398.

[10] Bandala A, Nakano R C S, Faelden G E, et al. Implementation of an Artificial Neural Network in Recognizing in-flight Quadrotor Images [C]. In IEEE Region 10 Conference. 2015: 1–5