Multi-UAV Formation Control Method Based on Modified Artificial Physics

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Abstract: This paper proposed a formation control method based on the modified artificial physics for the multiple Unmanned Aerial Vehicles(UAVs) formation control problem.The formation control method based on basic artificial physics has a shortcoming of easily plunging into a local optimal solution,which will result in some unexpected formation.So we improved the existing artificial physics method using interaction scheme to avoid the local optimum.In our formation control method based on modified artificial physics, interaction forces are applied on the UAVs to make the system escape from local optimum and achieve global optimum. Meanwhile we have constructed a distributed multi-UAVs coordination simulation framework based on the Robot Operating System(ROS) and Gazebo 3D simulator. The simulation results using our simulation framework are presented to verify the effectiveness of our formation control method.

Key Words: unmanned aerial vehicle(UAV), formation control, artificial physics, Gazebo, ROS

1 INTRODUCTION

Research in the formation of multi-UAV systems have attracted growing interest in recent years, due to its extensive applications in both civilian and military domains. The capability of keeping multiple unmanned vehicles in a designed geometric pattern provides favorable capability multiplying effects for tasks where a single vehicle is difficult to accomplish or too costly[1]. In recent decades, various methods have been proposed to solve the formation control problems, such as the leader-follower strategy, the virtual structure strategy, the behavior-based strategy, the artificial field strategy and the graph-based strategy[2][3].

The artificial physics method proposed by William M.Spears is a new research direction in the multi-agent coordination problem. It is used to self-organize swarms of mobile robots into hexagonal and square lattices[4]. Inspired by the law of universal gravitation, they define the virtual force between two agents. Through the attractive and repulsive forces between two agents, the swarms can exhibit the convergence and avoidance behavior[5][6]. As many advantages such as self-assembly, fault-tolerance, self-repairs, briefness and distribution as there may be, the artificial physics method also has shortcomings such as easily plunging into a local optimal solution, longer settling time and rough trajectories[7].

In order to overcome some shortcomings of traditional artificial physics, we have modified the artificial force law of the traditional artificial physics, and designed a new artificial-physics-based formation control strategy in our previous work[8]. However it still has the problem of the local optimum. So a main contribution of this paper is that we extend our previous work to overcome the local optimum problem by introducing an interaction scheme into our formation control method. Another contribution of this work is that a simulation platform is constructed based on the ROS and Gazebo simulator to verify theories in the research of multi-UAV coordination problems. Main advantages of the proposed simulation framework are that the environment is very close to reality, the control is entirely distributed, and the system is easy to expand.

The rest of this paper is organized as follow: In Section 2, we introduce the basic principles of traditional artificial physics and construct our desired standard formation, and the modified artificial force law in our previous work is also introduced. Section 3 gives a detailed description of the local optimum problem of the artificial physics. Section 4 introduces our interaction scheme to solve the local optimum problem. And our simulation results based on the ROS and Gazebo 3D simulator are given and analyzed in Section 5. And our concluding remarks are contained in the final section.

2 ARTIFICIAL PHYSICS FRAMEWORK

In this section, we will introduce some basic notions of the artificial physics framework. In the artificial physics approach, the virtual physics forces are defined to drive a swarm robotics system to a desired configuration, which is one that minimizes overall system potential energy, and the system acts as a molecular dynamics($\overrightarrow{F} = m\overrightarrow{a}$)simulation[9].

2.1 The Standard Formation Model

The standard formation is defined as a regular polygon with n sides. The robots are deposited on the circumcircle evenly,and the length of each side is equal to L. The circum-

This work is supported by the National Natural Science Foundation of China under No.61403406.

center of the polygon is in a desired position x_c. R is the redius of the circumcircle of the polygon.In the rest of the paper we use six UAVs as an example to build the formation controller and carry out the simulations. Our aim is to drive the six UAVs to form a standard formation shown in Figure 1,with five UAVs positioned on the circumcircle and one on the circumcenter to act as the leader of the formation.

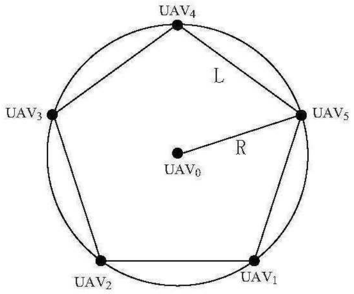


Figure 1 The standard formation

2.2 The Artificial Physics Force Law

In the traditional artificial physics framework, each agent will exert virtual forces upon others. Imitating the Newtonian gravitational force law, the artificial force can be defined as:

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

where F is the magnitude of force between two agents i and j, m_i is the mass of the i_{th} agent, r represents the range between two agents, p is some power, and the "gravitational constant" G is set at initialization. The force is repulsive if r < R and attractive if r > R. Each agent has a visual range of only 1.5R. Thus each agent can be considered to have a circular "potential well" around itself. Finally, under this force law,seven agents will form a hexagon formation shown in Figure 2(a), and the agents will form a hexagonal lattice with the number of the agents increasing, as Figure 2(b) shows.

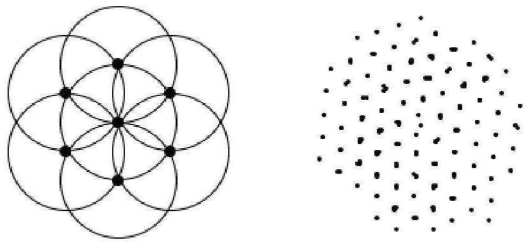


Figure 2 (a)The hexagon formation.(b)The hexagonal lattice.

Actually,by the traditional artificial physics force law, the agents cannot form the desired formation like the standard formation shown in Figure 1, because in the standard formation, the distance between two adjacent UAVs on the circumcircle does not equal R.

So the artificial physics force law in our previous work is modified. In order that the six UAVs form the standard formation shown in Figure 1, firstly, we define the force law between UAV_0 at the circumcenter and $\text{UAV}_i(i = 1,2,3,4,5)$ on the circumcircle. The mass of each UAV is 1 by default. The force is defined as follows:

$$f_{ic} = G\frac{(||\overrightarrow{r}_i|| - R)\overrightarrow{r}_i}{||\overrightarrow{r}_i||} \tag{2}$$

where f_{ic} is the force between UAV_0 and $\text{UAV}_i(i = 1,2,3,4,5)$; $\overrightarrow{r}_i = \overrightarrow{p}_i - \overrightarrow{p}_c$ is the relative position vector; $\overrightarrow{p}_i$ is the position vector of UAV_i; and $\overrightarrow{p}_c$ is position vector of UAV_0. As we can see, if $||r_i|| > R$, it will produce an attractive force to drive the $\text{UAV}_i(i = 1,2,3,4,5)$ toward the UAV_0; to the contrary, if $||r_i|| < R$, a repulsive force will work. So the $\text{UAV}_i(i = 1,2,3,4,5)$ will be deposited on the circumcircle eventually.

In order to avoid collision, we define the repulsive force between two UAVs among the $\text{UAV}_i(i = 1,2,3,4,5)$ as follow:

$$f_{ij} = \begin{cases} G\frac{(||\overrightarrow{r}_{ij}|| - L)\overrightarrow{r}_{ij}}{||\overrightarrow{r}_{ij}||} & \text{if } ||\overrightarrow{r}_{ij}|| < L \\ 0 & \text{if } ||\overrightarrow{r}_{ij}|| \geqslant L \end{cases} \tag{3}$$

where f_{ij} is the repulsive force between the UAV_i and UAV_j, $\overrightarrow{r}_{ij} = \overrightarrow{p}_i - \overrightarrow{p}_j$, and $\overrightarrow{p}_i$ and $\overrightarrow{p}_j$ are the position vectors of the UAV_i and UAV_j respectively.

The force defined above can make the $\text{UAV}_i(i = 0,1,2,3,4,5)$ form the standard formation. In fact, there are infinite possible polygons lying on the same circumcircle due to the freedom of rotation. So we add the attractive point X^* with an attractive range of L^* to eliminate the freedom of rotation as Figure 3 shows.

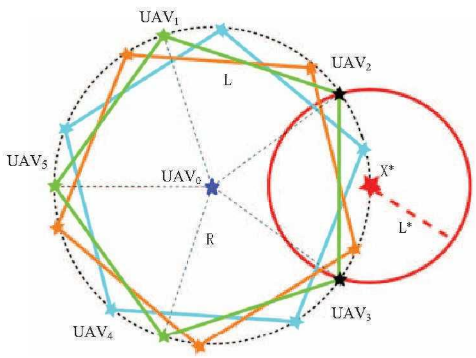


Figure 3 The standard formation with an attractive point

If the distance between the UAV_i and X^* is less than L^*, the attractive point will exert an attractive force on the UAV. Meanwhile, other UAVs will adjust their positions to maintain the standard formation. The force between the UAV in the attractive range and X^* is :

$$f_{io} = G(\overrightarrow{p}_i - \overrightarrow{X}^*) \tag{4}$$

Combining (2), (3) and (4), we can get the sum force applied on the UAV_i:

$$f_i = \sum_{j=1, j\neq i}^{5} f_{ij} + f_{ic} + f_{io} \tag{5}$$

Finally, we can make the six UAVs form the exclusive standard formation shown in Figure 1. In order to simplify the simulation and observe the course of formation control, we set the six UAVs at the same desired altitude range, and the virtual force exerted on each UAV is set as their desired velocity. The system adopts the distributed pattern, and each UAV runs the same formation control algorithm. The process for each UAV is summarized in Algorithm 1.

Algorithm 1 Formation control algorithm based on artificial physics

Input: the desired altitude range $h - e < H < h + e$, the parameter of the standard formation(i.e., the radius of the circumcircle R, the length of the side of the polygon L)

Output: the flight control command for the UAV

The process is iteratively run as follows:

(1) Obtain the positions of the UAVs. While the UAVs are not all in the desired altitude range, do as follow:

(a)Compute the altitude command for the current UAV so that it is in the the desired altitude range.

(b) Set the flight control command in the horizontal direction for the current UAV as 0.

(2)While all the UAVs get to the desired altitude range, do as follow:

(a)Compute the altitude command to keep the UAV in the altitude range.

(b)Compute the virtual forces for the current UAV according to our definition, and get the flight control command in the horizontal direction.

(3)Send the flight control command to the current UAV.

3 PROBLEM OF THE LOCAL OPTIMAL SOLUTION

In this section, the problem of the local optimal solution of the artificial physics will be introduced. We use our formation control method based on the artificial physics introduced in section 2 as the example. In order to form the standard formation and eliminate the freedom of rotation, we have defined three kinds of virtual force, the repulsive force between two UAVs on the circumcircle, the force between UAV_0 and $UAV_i (i = 1, 2, 3, 4, 5)$, and the attractive force between the attractive point X^* and the UAV which locates itself in its attractive range.

In most situation, the six UAVs can form the standard formation shown in Figure 1. But in some cases, when two UAVs enter the attractive range of X^* before the formation is formed due to the initial position of the UAVs, the formation control method based on artificial physics will plunge into a local optimal solution shown in Figure 4.

As we can see, UAV_0 acts as the leader of the formation, and there is no force exerted on it. UAV_1, UAV_4 and UAV_5 are located on the circumcircle, and the distance between them and their neighbor UAVs is no less than L. UAV_2 and UAV_3 are located outside the circumcircle and both in the attractive range of X^*, the distance between them is clearly less than L, and they are symmetric with respect to the straight line through UAV_0 and X^* .

For UAV_1, UAV_4 and UAV_5 ,the force from UAV_0 is 0 according to our definition. The repulsive force between them will be 0 too, because the distance between them and their neighbor UAVs is no less than L. Clearly, they are not

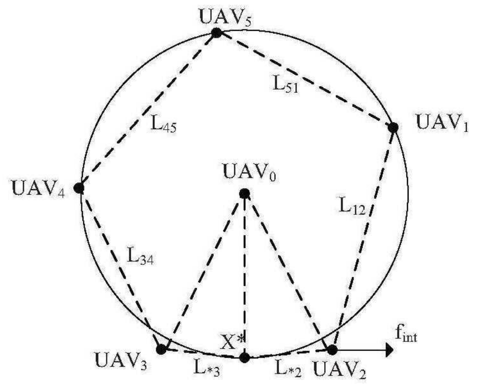


Figure 4 The local optimal solution of the formation control method based on artificial physics

in the attractive range of the X^*, so the total force exerted on each of them is 0.

As for UAV_2 and UAV_3, the forces exerted on them are shown in Figure 5.

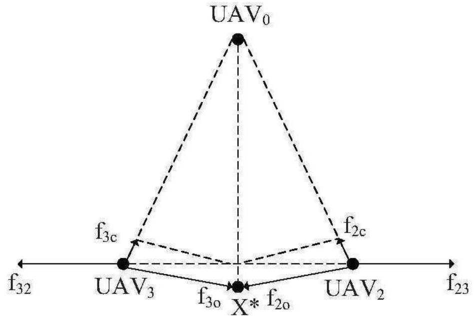


Figure 5 The force exerted on UAV_2 and UAV_3

For UAV_3, the repulsive force f_{32} produced by UAV_2 is balanced by the sum of the attractive force f_{3c} produced by UAV_0 and the attractive force f_{3o} from X^*. The situation for UAV_2 is similar to UAV_3.

So all six UAVs achieve an equilibrium condition of forces, which makes them unable to continue the travel, and the system become stable but the formation is not the desired standard one. So we consider that the system has plunged into a local optimal solution.

4 MODIFIED ARTIFICIAL PHYSICS METHOD

In this section we will introduce our modified artificial physics method to solve the local optimum problem. As we have discussed in section 3, the formation control method based on basic artificial physics has a shortcoming of easily plunging into a local optimal solution, and we have introduced the situation of the local optimum we met in the simulation. So we modify the artificial physics method to solve the local optimum problem by applying the interaction force f_{int} to drive the system out of the local optimal solution.

The interaction force is applied on one of the two UAVs which have the smallest distance between them. We set

Figure 4 as an example, where the interaction force applied on UAV_2 is defined as below:

$$f_{int} = k_{int}\frac{(L^* - ||\overrightarrow{r}_{23}||)\overrightarrow{r}_{23}}{||\overrightarrow{r}_{23}||} \tag{6}$$

where k_{int} is the interaction coefficient, determined by the sampling interval of the system and the attractive range of X^* to ensure that the interaction force can make the UAV escape from the attractive range. The interaction force process is summarized in Algorithm 2.

Algorithm 2 The interaction force scheme

The process is iteratively run as follows:

(1)While the system is not labelled as plunging into a local optimal solution, do as follow:

(a)Record the velocities of all the UAVs. If the velocity is less than a specified value ε, then it is UAV's Bas value plus one.

(b)If every Bas value of the UAVs is larger than a certain threshold Limit M, then the system is considered to be stable.

(c)If the system is considered stable ,compute the distance among the UAVs , then we determine if the formation is our desired standard formation according to the distances and the geometric principle of regular polygon. If not, then the system is labelled as plunging into an optimal solution.

(2)While the system is labelled as plunging into a local optimal solution, do as follow:

(a)Set the interaction time as t_{int}.

(b)Find two UAVs with the smallest distance between them , and apply the interaction force on one of them during t_{int}. The direction of the interaction force is, as Figure 4 shows, parallel to the straight line through the two UAVs and points to the direction away from each other.

(c)Set the Bas value as 0.

When the system plunges into the local optimum like Figure 4 shows, with the interaction scheme above, UAV_2 will try to move away from X^*, meanwhile, with the effect of Algorithm 1, UAV_3 will get to the attractive point, and the other UAVs will also adjust their own positions to get the new equilibrium points, so the system will achieve globe optimum eventually.

5 EXPERIMENTAL RESULTS

In this section, we will introduce our distributed multi-UAV coordination simulation framework and present the simulation results for a group of six quadrotors to form the standard formation shown in Figure 1.

5.1 The Simulation Framework

As we aim at comprehensive simulation of the formation control method and making the simulation experiments as close as possible to reality, we construct our simulation framework using ROS and the Gazebo 3D simulator. Gazebo is a well-designed robot simulator, which provides a multi-robot simulation environment including dynamics simulation. The simulator considers gravity, contact forces and friction by its own. The whole system is integrated with ROS that has become a defacto standard in robotics research and facilitates integration of contributions by other researchers[10].

In our system, the quadrotor model we use is provided by the hector_quadrotor package on the ROS official website. It has provided the geometry model, the dynamics model including flight dynamics and motor dynamics, trust calculation etc. So the model is very close to the real quadrotor. Based on the publish/subscribe mechanism, the system adopts a distributed structure. The control is entirely distributed, the number of the UAVs can be adjusted according to the requirement of the experiment by adding or removing a UAV node, and we can also add some obstacles and design a varied topography. So the simulation framework is very easy to expand, and can be used to do various simulation experiments to verify different theories in the multi-UAV coordination research.

In the rest of this section, we set six UAV nodes as an example due to the need of our experiment. The architecture of our simulation framework is shown in Figure 6. As we can see, each UAV has a Gazebo UAV model and a corresponding ROS node including the UAV world model and its formation control method to subscribe the state information of the UAVs in Gazebo and publish the flight command back through the ROS topics.

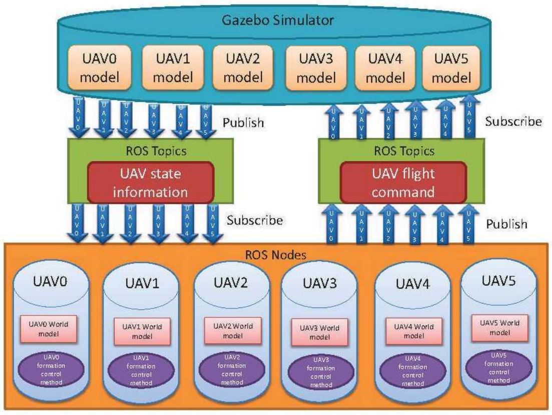
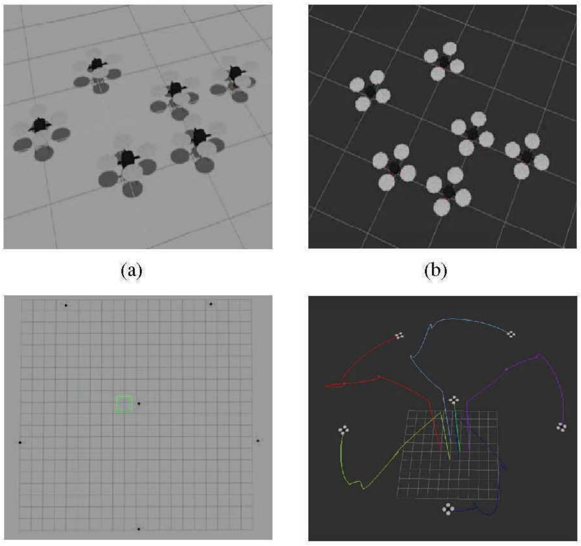


Figure 6 The architecture of the system

In order to observe the experiments more directly and analyze the movement process of the UAVs, we have also drawn the trajectories of the UAVs using Rviz, a 3D visualization tool for ROS.

5.2 Simulation Results of the Proposed Formation Control method

To demonstrate the effectiveness of our formation control method based on modified artificial physics, we have done three sets of experiments, one without the local optimum problem, one with the local optimum problem but not using our modified artificial method with the interaction scheme, and one with the local optimum problem using the modified artificial method with the interaction scheme. Figure 7(a) and Figure 7(b) show the initial state of the quadrotors in Gazebo and Rviz. The desired length of the regular pentagon of the standard formation is set as 10m. In this case, the system does not meet a local optimum. Figure 7(c) shows the final state in Gazebo. It can be seen that the six quadrotors has formed our desired standard formation. Figure 7(d) shows the final state in Rviz, with the trajectories of the six quadrotors showing the forming process of the standard formation.



(a) (b)

(c) (d)

Figure 7 (a)Initial state in Gazebo.(b)Initial state in Rviz.(c)Final state in Gazebo.(d)Final state in Rviz with the trajectories of the quadrotors

To save space, we set UAV_2 as an example. Figure 8(a) shows the evolution of distances between UAV_2 and UAV_0, UAV_3, X^*. From it we can conclude that UAV_2 gets to the attractive point X^* which is located on the circumcircle, and keeps the desired distance 10m from its neighbor quadrotor UAV_3. The same as UAV_2, our simulation results shows that other UAVs also get to the desired positions. And we define the system error as below:

$$e = 5L + 5R - (\sum_{i=1}^{5} d_{ic} + \sum_{i=1}^{5} d_{ij} + d_{X^*}) \tag{7}$$

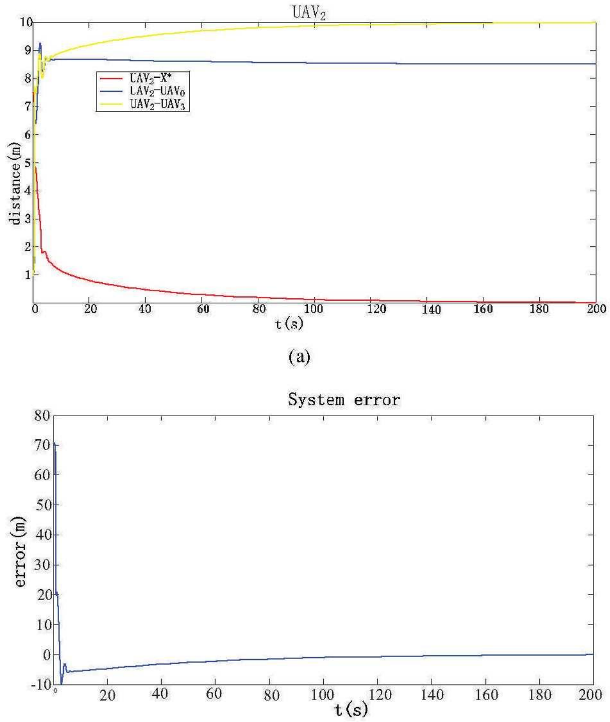
where e represents the system error, d_{ic} is the distance between $UAV_i (i = 1, 2, 3, 4, 5)$ and UAV_0, d_{ij} is the distance between each UAV on the circumcircle and its next neighbor, and d_{X^*} is distance between the UAV which gets to the attractive point X^* at last and X^*. Figure 8(b) shows that the system error has approached 0 eventually, and the standard formations is considered to be formed.

But with the change of initial positions of the quadrotors shown in Figure 9(a), the system plunges into the local optimum without our modified artificial physics method using the interaction scheme shown in Figure 9(b) as we discussed above.

Figure 10(a) and Figure 10(b) show the evolution of the distances between UAV_2 and UAV_0, UAV_3, X^* and that of distances between UAV_3 and UAV_0, UAV_4, X^* without our modified artificial physics respectively. It can be seen that UAV_2 and UAV_3 reach the equilibrium points but not our desired positions. Figure 10(c) shows the evolution of the system error, indicating that the system error has approached a certain value but not 0, and the system has plunged into the local optimum.

Figure 11 shows the final state and the trajectories using our formation control method based on modified artificial physics. It can be seen that with the initial position shown in Figure 9(a), the system plunges into the local optimum at the beginning, and then with our modified artificial physics method, UAV_2 escapes from the local optimum position, and other UAVs adjust their own positions to arrive at the new equilibrium points and form the standard formation.

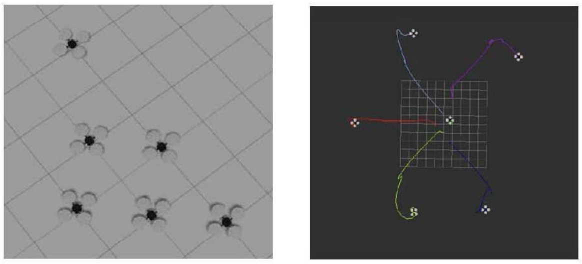
Figure 12(a) and Figure 12(b) show the evolution of the distances between UAV_2 and UAV_0, UAV_3, X^* and that of distances between UAV_3 and UAV_0, UAV_4, X^* with our modified artificial physics respectively. From the change of the distances, we can see that the system has plunged into local optimum before 20s, but as the time increases, UAV_2 escapes from the attractive range of X^*, and reaches the new equilibrium point. Meanwhile, UAV_3 reaches the X^*, and the other UAVs also adjusts their own positions. Figure 12(c) shows the evolution of the system error, from



(a)

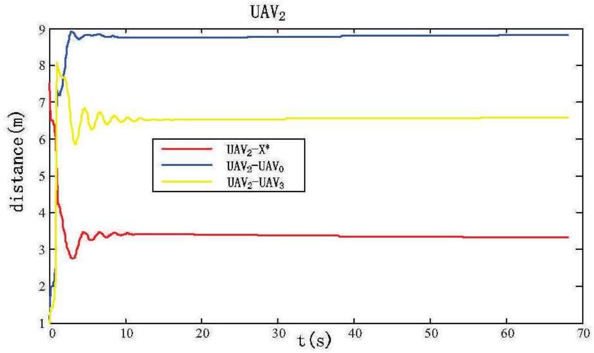
(b)

Figure 8 (a)Evolution of distances between UAV_2 and UAV_0, UAV_3, X^*.(b)Evolution of the system error.

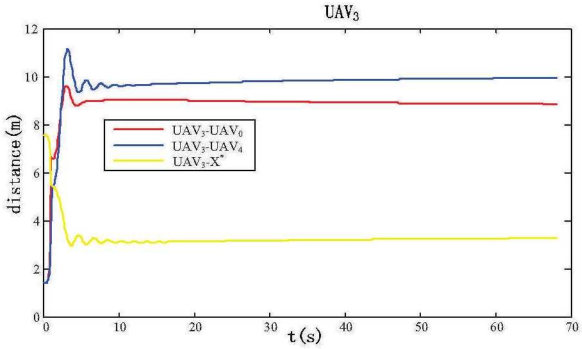


(a) (b)

Figure 9 (a)Initial state in Gazebo.(b)Local optimum state in Rviz with the trajectories of the quadrotors



(a)



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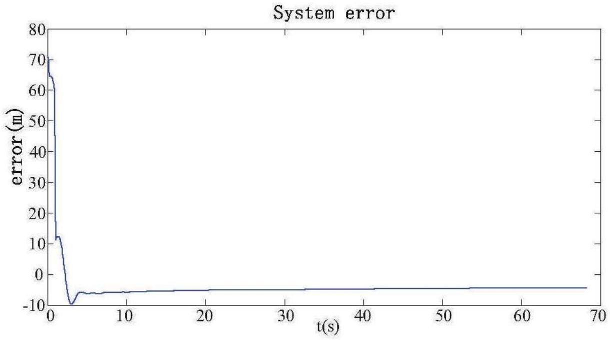


(c)

Figure 10 (a)Evolution of distances between UAV_2 and UAV_0, UAV_3, X^*.(b)Evolution of distances between UAV_3 and UAV_0, UAV_4, X^*.(c)Evolution of the system error.

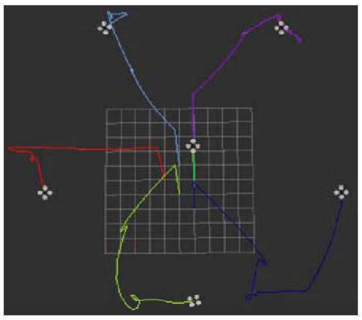
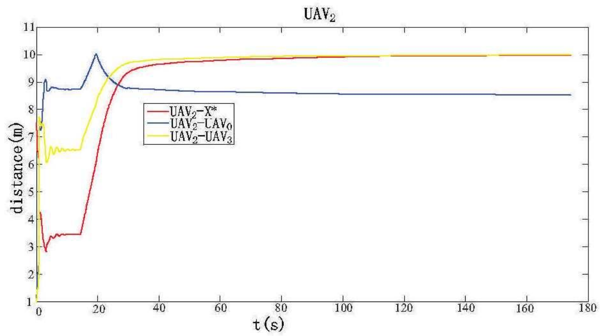
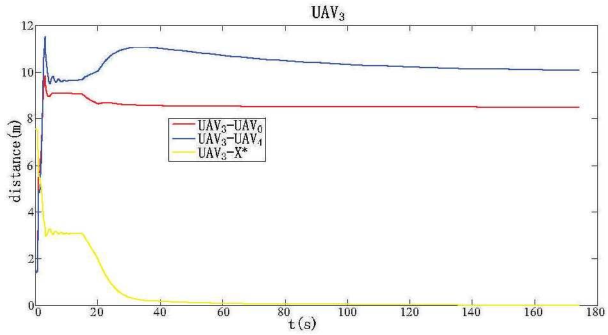


Figure 11 The system escape from local optimum



(a)



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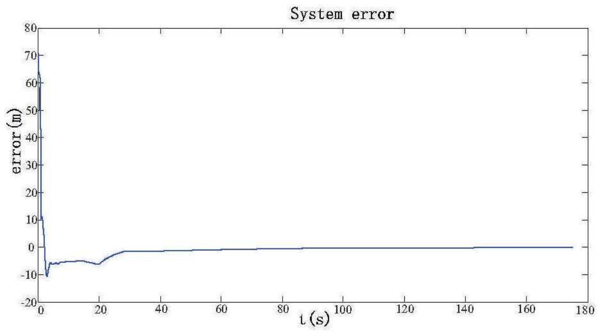

(c)

Figure 12 (a)Evolution of distances between UAV_2 and UAV_0, UAV_3, X^*.(b)Evolution of distances between UAV_3 and UAV_0, UAV_4, X^*.(c)Evolution of the system error.

which it can be seen that with the time increase the system error approaches 0 eventually, finally, the desired standard formation is formed.

Based on the simulation results and analysis, it is obvious that our proposed formation control method based on modified artificial physics is advantageous over the basic artificial physics when facing the problem of local optimum, thereby greatly improving the overall system performance.

6 CONCLUSIONS

In this paper, we have proposed a control method based on modified artificial physics to solve the multi-UAV formation problem. Driven by the designed controller, UAVs can form the standard formation which can overcome the shortcoming of the local optimum problem in the basic artificial physics method. Some simulation experiments were conducted using the ROS and Gazebo simulator, and the simulation results demonstrated the performance of our proposed formation control method in solving the local optimum problem and forming the standard formation. As a future work, we will continue our efforts to find better solutions in order to shorten the settling time, make the trajectories smoother, and try to apply this method to real quadrotors so as to form the desired formation.

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