TECHNICAL REPORT of CIVIL DRONE for IARC 2018

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Contents

Abstract

The seventh generation mission of the IARC has increased many difficulties with respect to the previous six-generation missions and mainly has three new challenges: Firstly, the aircraft need to interact with ground-based autonomous mobile robots. Secondly, in an open environment with no external navigation assistance, GPS or walls, the aircraft need to navigate by itself. Thirdly, the aircraft games with other competing aerial robots. To accomplish the mission, all numbers of our team have made a lot of effort. In this report, we describe the approach of the drone systems and perception-to-cognitive process that our team designed to complete the seventh-generation mission. And the aerial robot of our team shall be introduced in detail.

Keywords: Markov Prediction; Perception ; Situation Estimation ; Decision-making

1 Introduction

1.1 Problem Statement

In order to complete the seventh generation mission, the participating teams need to construct a fully autonomous multi-rotor drone. The aircraft can interact with the ground robot through autonomous flight. In the interaction process, the ground robots change their movements by slight touching on the top or front of them so that they are driven across the green boundary of the arena. Simultaneously, it is required that at least 4 ground robots are driven out of the green boundary within 10 minutes of the game time.

The task will change teams to develop two behaviors of the air drone. Firstly, the interaction with ground robot challenges perception and control ability of the aerial robot. Secondly, navigation in a sterile environment without external navigation aids such as GPS or large stationary points of reference challenges the aerial robot to get a reliable navigation performance based on visual processing only. And in the 10 minutes of flight time, as many ground robots are driven out of bounds from the green boundary, which challenges the mission planning to be smart enough to make an acceptable decision.

1.2 Markov Prediction Model

Markov predicted that the transition probability matrix between states is used to predict the state of the event and its development trend, and it is also a time series analysis method. It is based on the Markov chain, according to the current situation of the event to predict their future time (or period) changes. We list the state variables and the state transition matrix, according to the Markov model to the robot at the next moment the state of the optimal estimate, so as to determine the movement of the UAV.

1.2.1 Model Hypothesis

Assume that the ground target robot is R_a, $a=1\sim 10$,the ground obstacle robot is B_c, $c=1\sim 4$, the UAV is D.

State transition state quantity: 200 times in 10 minutes. (Due to the robot movement speed of 1/3 meters per second, move one meter about 3s).

Site assumptions: green side for the first column, red edge for the first 21 columns, white from top to bottom for the first 1 to 20 lines.

1.2.2 Model Establishment

In this paper, the Markov state transition matrix model is used to obtain the *k*th state transition matrix according to Markovian property:

$$P^k(X)=\begin{pmatrix} P_{11} & P_{12} & \mathrm{L} & P_{1j} & \mathrm{L} & P_{1n} \\ P_{21} & P_{22} & \mathrm{L} & P_{2j} & \mathrm{L} & P_{2n} \\ \mathrm{M} & \mathrm{M} & \mathrm{O} & \mathrm{M} & \mathrm{O} & \mathrm{M} \\ P_{i1} & P_{i2} & \mathrm{L} & P_{ij} & \mathrm{L} & P_{in} \\ \mathrm{M} & \mathrm{M} & \mathrm{O} & \mathrm{M} & \mathrm{O} & \mathrm{M} \\ P_{n1} & P_{n2} & \mathrm{L} & P_{nj} & \mathrm{L} & P_{nn} \end{pmatrix}_{n\times n} \quad (1)$$

Where n=20.

We divide the site into three areas:

$$\alpha_j=\begin{cases} 3;\ j=1\sim 8, & \text{Optimum Flight Area} \\ 2;\ j=9\sim 16, & \text{Preliminary Flight Area} \\ 1;\ j=17\sim 20, & \text{Course Reversal Area} \end{cases} \quad (2)$$

In order to optimize the model, the aerial robot in the optimal area and the preparatory area to drive the ground target robot while avoiding the ground obstacle robot. This leads to the k-th state transition optimization matrix:

$$P^k\left(X^*\right)=\begin{pmatrix} P_{11} & P_{12} & \mathrm{L} & P_{1j} & \mathrm{L} & P_{1n} \\ P_{21} & P_{22} & \mathrm{L} & P_{2j} & \mathrm{L} & P_{2n} \\ \mathrm{M} & \mathrm{M} & \mathrm{O} & \mathrm{M} & \mathrm{O} & \mathrm{M} \\ P_{i1} & P_{i2} & \mathrm{L} & P_{ij} & \mathrm{L} & P_{in} \\ \mathrm{M} & \mathrm{M} & \mathrm{O} & \mathrm{M} & \mathrm{O} & \mathrm{M} \\ P_{n1} & P_{n2} & \mathrm{L} & P_{nj} & \mathrm{L} & P_{nn} \end{pmatrix}_{n\times n} \begin{pmatrix} \alpha_1 & 0 & \mathrm{L} & 0 & \mathrm{L} & 0 \\ 0 & \alpha_2 & \mathrm{L} & 0 & \mathrm{L} & 0 \\ \mathrm{M} & \mathrm{M} & \mathrm{O} & \mathrm{M} & \mathrm{O} & \mathrm{M} \\ 0 & 0 & \mathrm{L} & \alpha_j & \mathrm{L} & 0 \\ \mathrm{M} & \mathrm{M} & \mathrm{O} & \mathrm{M} & \mathrm{O} & \mathrm{M} \\ 0 & 0 & \mathrm{L} & 0 & \mathrm{L} & \alpha_n \end{pmatrix}$$

(3)

1.2.3 Initial State

Ground target robot initial state, near the green side of the ground target robot is R_1, for the initial state, there are the following:

Table1 Ground target robot initial state

R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
$P_{11,10}=1$	$P_{10,10}=1$	$P_{10,11}=1$	$P_{10,11}=1$	$P_{10,12}=1$	$P_{11,12}=1$	$P_{11,12}=1$	$P_{11,11}=1$	$P_{11,11}=1$	$P_{11,10}=1$

The corresponding other state probability of each ground target robot is 0.

Ground condition Robot initial state, near the green side of the ground target robot is B_1, for the initial state, there are the following:

Table2 Ground condition Robot initial state

B_1	B_2	B_3	B_4
$P_{11,6}=1$	$P_{6,11}=1$	$P_{11,16}=1$	$P_{16,11}=1$

The corresponding other state probability of each ground target robot is 0.

The initial state of the UAV, the UAV from the white side take off, for the initial state, you can get:

$$P_{1,j}=P_{20,j}=\frac{1}{16} \tag{4}$$

The corresponding initial state probability of the UAV is 0.

4.4 Consequence

The number of the target robot after entering the ground from the green side after the kth state transition is:

$$N=\sum_{m=1}^{10}\left\lfloor P_{i1}^{(k)}\left(R_a\right)+P_{i1}^{(k)}\left(D\right)-\sum_{c=1}^{4}P_{ij}^{(k)}\left(B_c\right)-1\right\rfloor \tag{5}$$

Where i = 1 ~ 20, j = 1 ~ 20; in formula 5, the symbol is rounded down.

2 Hardware Introduction

2.1 Drone Platform

Our team choose a four-rotor UAV as the flight platform that is built by ourselves (Figure 1). The platform adopts carbon fiber tube and carbon fiber plate. The connecting pieces are made of aluminum alloy materials. The materials we use are as solid and light as possible. So it can save power and increase drone flight time.

Figure 1. the flight platform

The items and parameters of the accessories that make up the quadrotor UAV are shown in Table 3:

Table 3 Drone accessories parameters

Items	parameters
motor	V3508　kv：580
propeller	1238 carbon fiber propeller
ESC	30A
battery	8000mah 25C
flight control	Pixhawk

2.2 Hardware Devices

The other hardware devices that make up the system are connected by an onboard airborne computer. They mainly include industrial computer, cameras, laser radars, optical flow sensors, etc. The specific hardware system is shown in Figure 2. Intel's NUC microcomputer as industrial computer to process and program data. The main function of the selected two-dimensional laser radar is to avoid obstacles. A wide-angle USB camera is used to identify ground robots. Optical flow sensor using px4flow sensor, is capable of navigation and positioning of drones. Then, ground station monitors real-time flight status of drones. In order to switch the drone flight mode and prevent drones from landing control in emergency, the remote control play an important role.

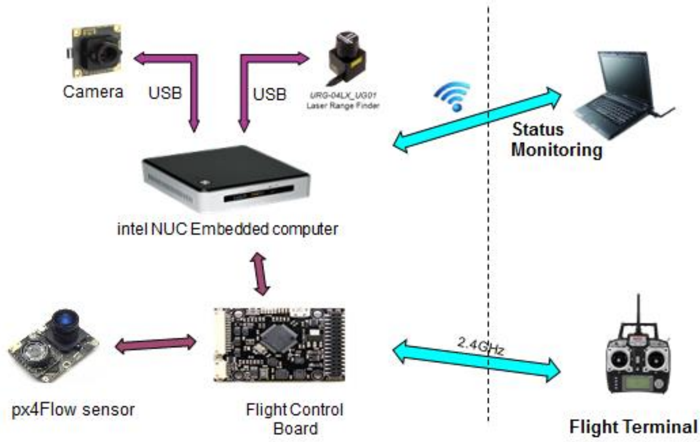


Figure 2. The hardware devices

2.3 Touch and Interception Mechanism

During the interaction with the ground robot, the touch behavior of the drone requires the navigation accuracy on the hand. On the other hand, it tests whether the touch and interception mechanism design is reasonable. The contact mechanism designed by us uses a mesh structure made of carbon fiber sheet. The carbon fiber rod installed around the drone can accurately intercept the ground target robot, as shown in Figure 3.

Figure 3. interception and touch mechanism

3 System Framework

For the features of the Mission 7, we divide the UAV system into four levels: the perception layer, the situation assessment layer, the decision layer, and the behavior layer. The overall framework of the system is shown in Figure 4.

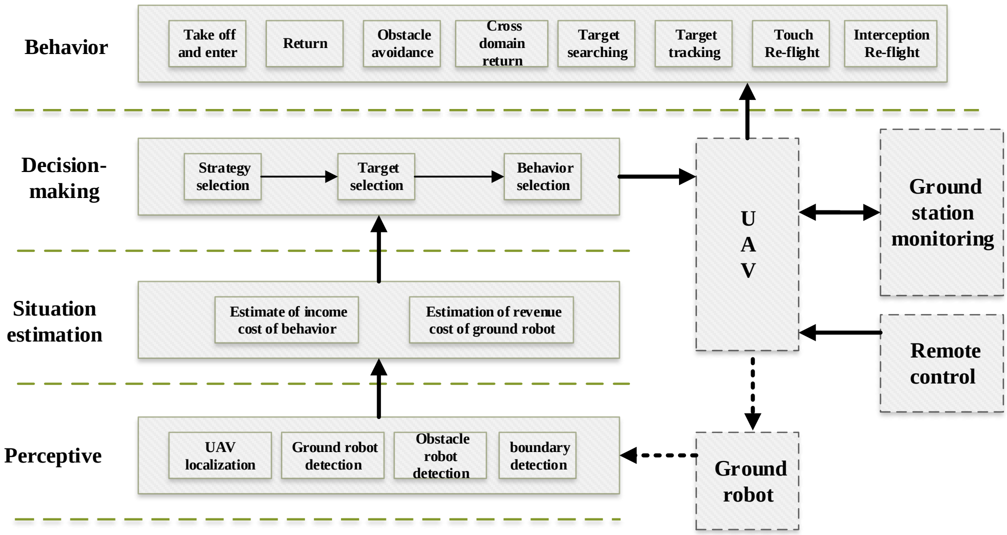


Figure 4. The overall framework of the system

The main functions of the sensing layer are the positioning of the drone itself, the detection of ground robots, the detection of obstacle robots, and the detection of borders. Then the data obtained transfers to the situation assessment layer after processing. In the situation estimation layer, we analyze the cost and profit of each ground robot in the site through the established mathematical model. At the same time, we estimate their costs and benefits. Then the preliminary sorted costs and benefits transfer to the decision-making layer. In the decision-making stage of the sequential decision, we eventually make decisions about the strategy adopted, the control targets and the control actions, according to the situation. After that, the result of each decision is passed to the behavior layer. Based on the decision result, the behavior layer controls the drone to perform the corresponding behavior. Finally, through the change of the ground robot's movement state execution, behavior results are evaluated at the situation assessment level. So, it allows us to more accurately estimate the next behavior of the drone.

3.1 Vision-based Perception

3.1.1 Perception for Ground Robots

A wide-angle camera mounted on a drone, as shown in Figure 5, gets environmental information in the arena. The robot operating system (ROS) is combined with OpenCV vision library to extract the color and shape information of the board above the ground robot to fusion and filter. Then, the distance and direction of the target robot relative to the drone are obtained. The obtained data transfer to the next stage after preprocessing. It can provide a basis for decision making.

Figure 5. A wide-angle camera

3.1.2 Perception for Site Boundaries

We judge boundary information by the rate of change of the H component of the color histogram。As we all know, boundary information includes whether there is a boundary in the field of view. And then, if there is a border, it is in which direction for the drone.

3.2 Drone Positioning Based on Improved Optical Flow Method

The aerial drone positioning adopts the method of optical flow sensor and inertial navigation fusion. Therefore, we propose a drone positioning based on improved optical flow method. First of all, we use median filtering to filter out common noise. And at the same time, the effect of light intensity on the optical flow is reduced by adopting a gradual approach. Then we introduce the Hessian matrix to remove the outliers. Afterwards, we use the three-step search block matching method for optical flow calculation. Finally, using discrete Kalman filter fuses optical information and rate gyro information to estimate the height, attitude, and speed of UAVs and perform drone positioning. The positioning flow chart of drone using improved optical flow method is shown in Figure 6.

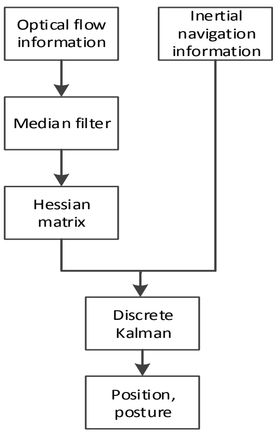


Figure 6. Positioning flow chart based on improved optical flow method

3.3 Situation Assessment for Ground Robots

3.3.1 Trajectory Prediction and Confidence Analysis

(1) By analyzing the rules of the game, it can be seen that the ground target robot does regular reciprocating motion without colliding with obstacles. So we can build a kinematic model of a ground target robot. A global coordinate system with the green edge as the x-axis is established, and the site is distributed throughout the first quadrant. So the ground target robot's motion model is $S_t^n = S_{t-1}^n + V_t^n \times \Delta t$, The variation of V_t^n in one cycle is:

$$\begin{cases} V_t^n = \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \times V_{t-1}^n & (t = 5k, t \neq 20k) \\ V_t^n = \begin{bmatrix} \cos\pi & \sin\pi \\ \sin\pi & \cos\pi \end{bmatrix} \times V_{t-1}^n & (t = 20k) \\ V_t^n = V_{t-1}^n & (t \neq 5k, t \neq 20k) \end{cases}$$

In the formula, θ =[0°,20°] is the random noise of the ground target robot. S_t^n is the position of the nth ground target robot at time t. V_t^n is the velocity vector of the nth ground target robot, at time t.

(2) Based on the motion model of each robot, we can estimate the trajectory of each robot in the field.

According to the regular pattern of motion, the trajectory of the ground robot can be predicted as shown in Figure 7.

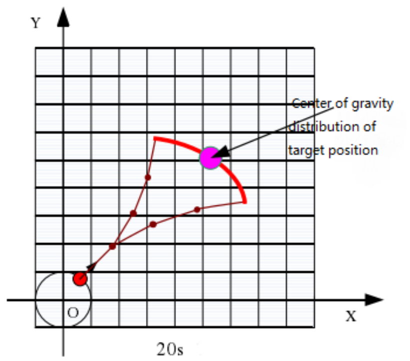


Figure 7. Trajectory prediction of a single robot within one beat

According to the ground sweeping robot movement program provided by the official website. It can be seen that the noise is generated by the random function in C++. So θ obeys Gaussian distribution. Therefore, the trajectory probability of the ground robot can be obtained.

（3）Calculate the credibility of estimates based on D-S evidence theory

The basis for credibility is as follows: The time that we can't observe the robot. The gap between the data of each sensor updating and the predicted estimated data.

3.3.2 The Value of Operating Each Ground Target Robot

The whole process of situation assessment is very complicated. Firstly, we need to get the position information of the drone collected by the drone in the flight control, the position and orientation information of the ground robot within the field of the drone vision and the position and orientation information of other ground robots predicted based on the historical information. Then, based on the revenue function, the UAV's revenue from each ground robot is calculated. After that, according to the time cost function, we can calculate the time cost of the aircraft to operate each ground robot. At the same time, the energy cost of the aircraft to operate each ground robot is calculated based on the energy cost function. Ultimately, we can transform this issue into a multi-objective optimization problem. We use the particle swarm optimization algorithm to optimize the target and finally get the value of the UAV's operation of each ground robot. The algorithm flow is shown in Figure 8:

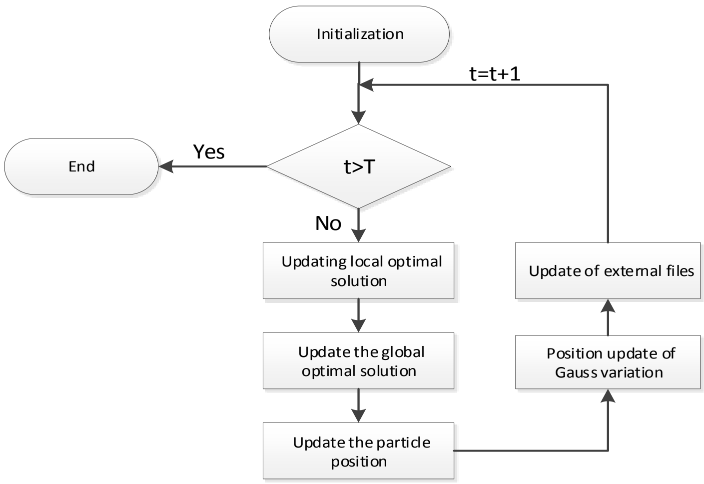


Figure 8. Improved Particle Swarm Optimization Algorithm for Target Optimization Algorithm Flow

3.4 Drone Decision-making

In the mission 7, the decision-making problem can be divided into three major areas: strategic decision-making, goal decision-making, and decision-making for manipulation. And the sequence of these three decisions is Sequential Decision (SD) problem. SD is an optimal decision method of dynamic systems with randomness or uncertainty. Its features are that the system is dynamic and sequential, but The next possible state is random or uncertain.

The process of sequential decision is: Starting from the initial state, we need to make optimal decisions at every moment. And then, we can observe the actual state of the next step,that is, collecting new information. After that, we can make new optimal decisions. The process need to repeat until the last.

In the decision process of selecting the strategy in mission 7, first of all, we make decisions on strategies to drive off the ground robot. That is, according to the situation assessment results in the current arena, we select the strategy that maximizes the overall revenue. Secondly, in the selected strategy, the greatest gains from ground robots are used as manipulative targets. Finally, the selected control target is driven according to its direction of movement and the corresponding time-rhythm to select the corresponding control target to drive the target until the target is driven out from the green side. Finally, according to its direction of movement and in conjunction with the time tempo, we can select the appropriate control target to be driven until it is out of the green side. The overall process of decision making is shown in Figure 9.

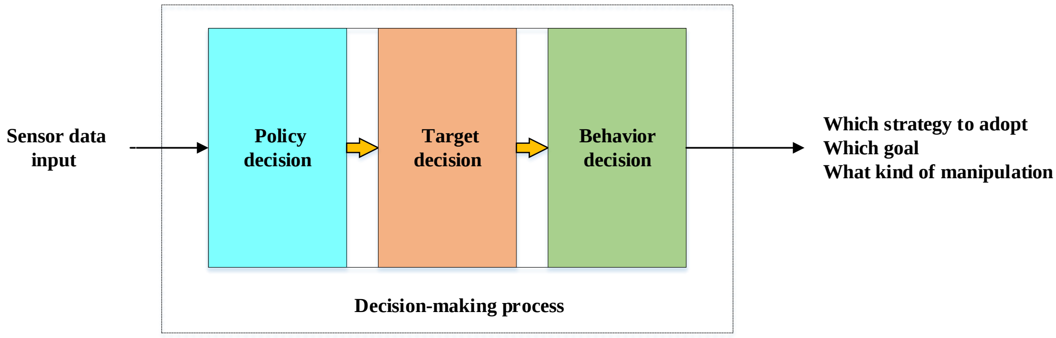


Figure 9. The overall process of decision making

In the process of driving ground robots, we need to estimate current benefits and costs in real time. The so-called revenue is related to the state of the drone in the current state, the remaining time, the number of ground robots in the ground and the position and movement status of the ground robot.

When the time of the game and the energy of the drone are relatively sufficient and the state of the ground robot is good, drone can gain much revenue and then choose a global strategy. That is, priority is given to ground robots that go out of non-green boundaries. Then, the ground robots in the field are moved from the rear half (half field near the red boundary) to the green edge through the touch or interception of the drone.

This process is called "rational direction". Then drones drive all of the ground robots away. When the revenue is smaller, drone can choose the local strategy. That is, the drone does the " rational direction" within the visual field. When the revenue is very small, it can choose the maximum revenue strategy. That means the ground robot in the field of view that are closest to the UAV is driven until they are driven out of green side.

When the strategy is selected, selecting the suitable target ground robot to be controlled is very important. Through the position and direction of movement of the ground robot, we can choose the control target that maximizes the profit.

Under the given goal, we need to choose manipulation behavior. The selection of manipulative behavior is based on the target ground robot movement direction and time rhythm and the touch and intercept properties of the ground robot. There is no doubt that we choose to track the target within the defined direction of safe movement. The target is intercepted in the second half of the time rhythm, such as 18 seconds. If it is not in the defined range of safe motion, the drone will need to adjust the direction of motion of the target to a safe direction of motion by intercepting or touching as soon as possible. The direction of safe movement of the target robot is defined in Figure 10:

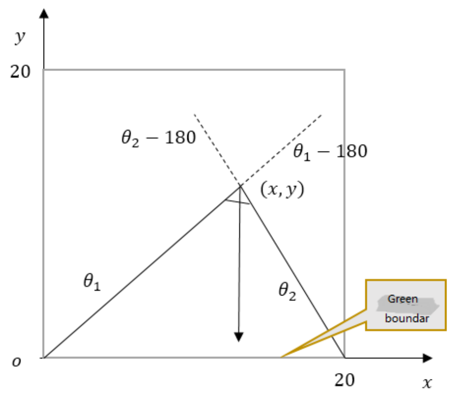


Figure 10. The direction of safe movement of the target robot

As shown in Figure 10, when the ground target is in the position (x, y),we build a Cartesian coordinate system with the current (x, y) as the origin of the coordinate. The direction of motion in the range of (θ_1, θ_2) is considered that the direction of motion of the current target is safe. Among them, $\theta_1 = 270 - arctan\frac{x}{y}$, $\theta_2 = 270 + arctan\frac{20-x}{y}$.

In addition, when a drone encounters an obstacle robot in the course of driving a target or it reaches the boundary of the arena (including the height boundary), the UAV prioritizes obstacle avoidance or transboundary return behavior until the drone reaches the safe area and then re-searches for the target. Figure 11 shows the flow chart of the drone drives a ground target robot.

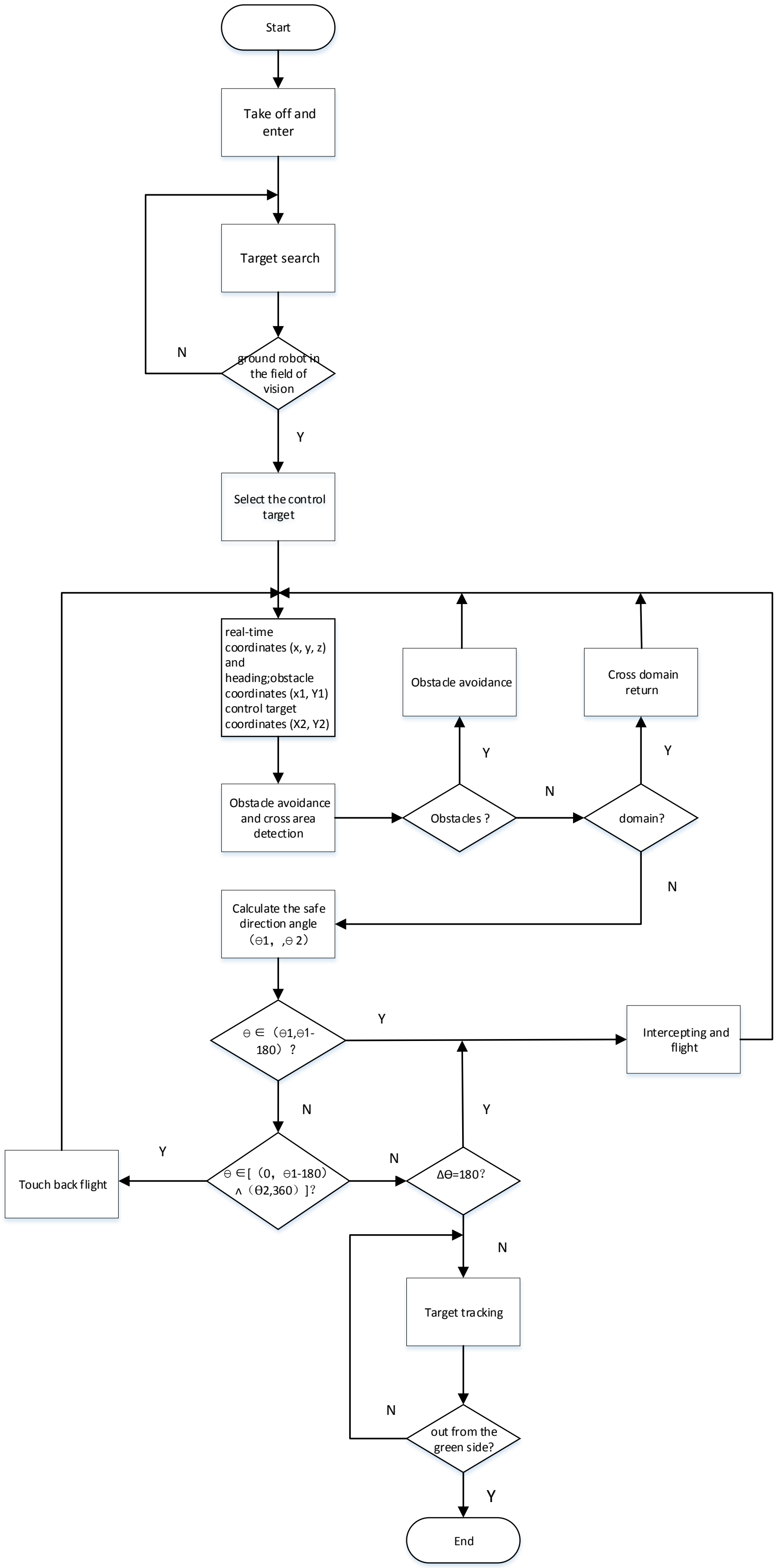


Figure 11. The flow chart of the drone drives a ground target robot

3.5 Drone Behavior Control

According to the game mission, the drone's behavior is divided into 8 basic behaviors: taking off to admission, returning flight, obstacle avoidance, overland return, target searching, target tracking, interception re-flight and touching re-flight. Some typical behaviors are analyzed below.

3.5.1 Interception Re-flight

There are four stages in drone autonomous interception re-flight: the stage of closing t1、Tracking stage t2、Interception stage t3 and the stage of re-flight. The schematic diagram of interception re-flight process is shown in Figure 12. The total time for intercepting re-flight is T=t1+t2+t3+t4.

The first stage is closing. After the drone find the target, it combines the characteristics of the drone itself and approaches the target with a smooth trajectory. The Sigmoid function curve is a typical "S" curve. So at this stage, the flight trajectory is fitted to the function curve in order to smoothly approach the ground robot. The second stage is visual tracking. The third stage is the parabolic curve fitting. The fourth stage is to take off again when the interception is successful.

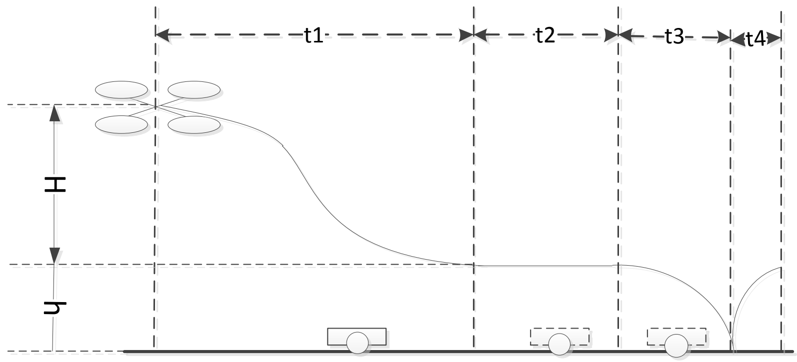


Figure 12. The schematic diagram of taking off after interception process

3.5.2 Touching Re-flight

There are four stages in drone autonomous touching re-flight: the stage of closing t1、Tracking stage t2、touching stage t3 and the stage of taking off again. The schematic diagram of touching re-flight process is shown in Figure 13. The total time for Touching re-flight is T=t1+t2+t3+t4.

Touching re-flight is similar to intercepting re-flight. Only in the third stage, touching re-flight requests the drone to land on the target robot and touch the switch to make the ground robot rotate clockwise by 45 degrees.

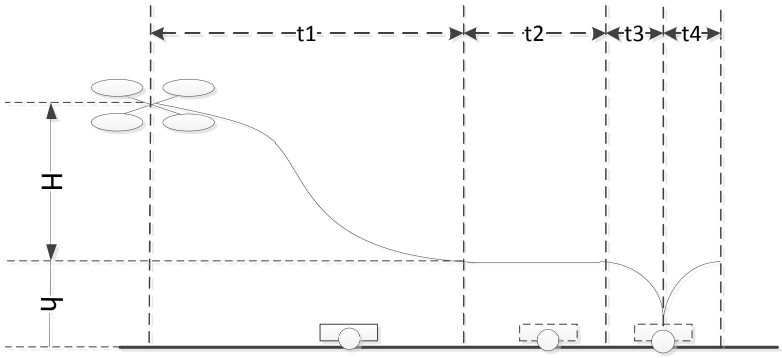


Figure 13. The schematic diagram of touching re-flight process

3.5.3 Target Search Behavior

The RRT algorithm searches fast and is suitable for planning with kinematic and dynamic constraints, so we apply this algorithm idea to the drone target search process. After estimating the approximate location of the ground target robot and the drone flying to this location if no target is found, the RRT algorithm strategy is used to search the area until a target is found or the next instruction is received. The RRT search diagram is shown in Figure 14.

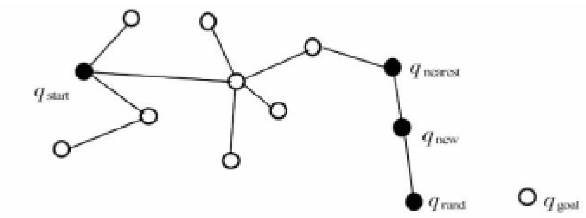


Figure 14. the RRT search diagram

RRT searching steps:

Step1. Select the starting point q_{start} as the root node;

Step2. Randomly select sampling points q_{rand} in space;

Step3. Search for a point $x_{nearest}$ closest to the sampling point on the generated random tree;

Step4. On the connection between q_{near} and q_{rand}, select a new node q_{new} with a certain step;

Step5. Repeat the above steps until reaching the target point or less than the given distance from the target threshold.

3.5.4 Obstacle Avoidance

1、Obstacle Avoidance—— Detour

One obstacle　　　　　　Two nearby obstacles

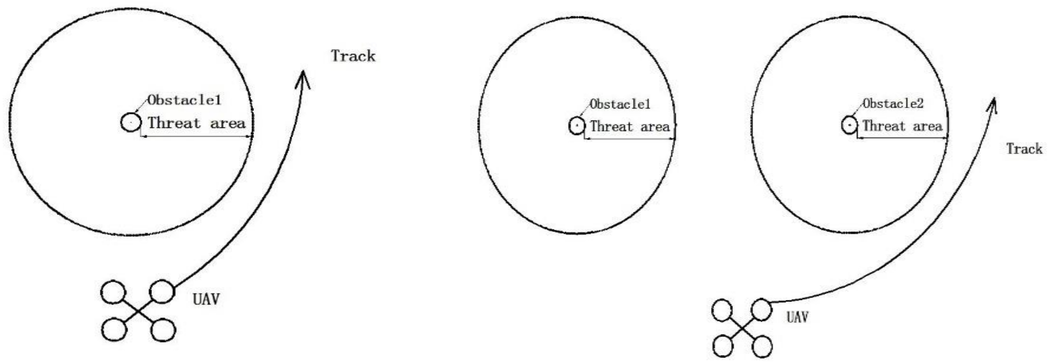


Figure 15. drone bypasses obstacle avoidance

As shown in Figure 15, the drone encounters one or two obstacles to choose to bypass. That is, in order to achieve obstacle avoidance, the UAV continues to perform other actions in accordance with the set threat zone to bypass.

2、Obstacle Avoidance—— Cross

Two distant obstacles　　　　　　Two of the three obstacles are distant

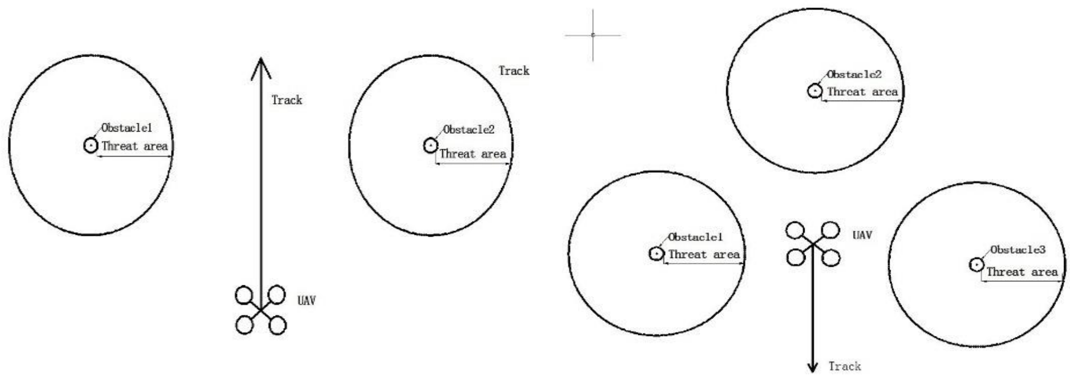


Figure 16 drone go through obstacle avoidance

As shown in Figure 16, when the drone detects two or more obstacles and the distance between the obstacles is greater than the set threat area, the drone will choose to avoid obstacles by crossing.

3、Obstacle Avoidance—— Lift

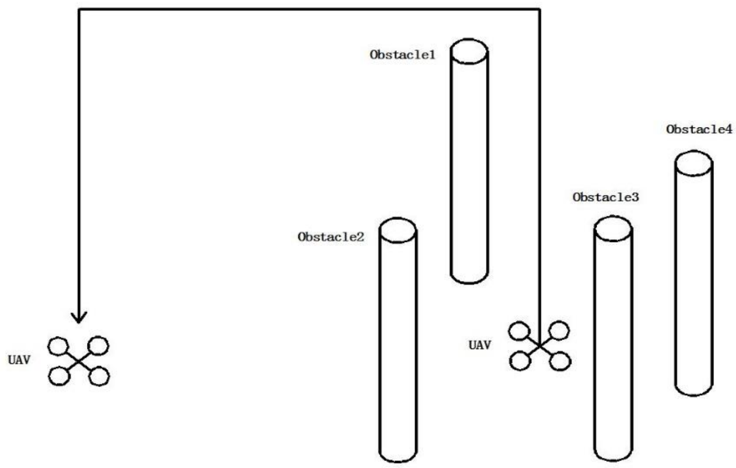


Figure 17. Drone flying high to achieve obstacle avoidance

As shown in Figure 17, when the drone is surrounded by a plurality of obstacles, and the distance between the obstacles is less than the set threat range, the drone will perform obstacle avoidance in the form of flying height.

4. Experimental Measurement

4.1 Visually Detecting Ground Robot

After the drone systems are built, we do some test experiments. Currently, we use vision tracking of ground robots in real time and identifying the pixel coordinates and direction of movement of the ground robot. The camera mounted on the drone detects the direction of the ground moving robot in real time. As shown in Figure 18, Blue box indicates that the target has been detected and locked. The green arrow indicates the direction of the target robot's movement.

Figure 18. Detecting the movement direction of the ground robot

In addition to the above, we can use the vision to get some other data, such as the number of frames processed, the direction of the real-time movement direction, and the coordinates of the center point of the ground robot, as shown in Figure 19.

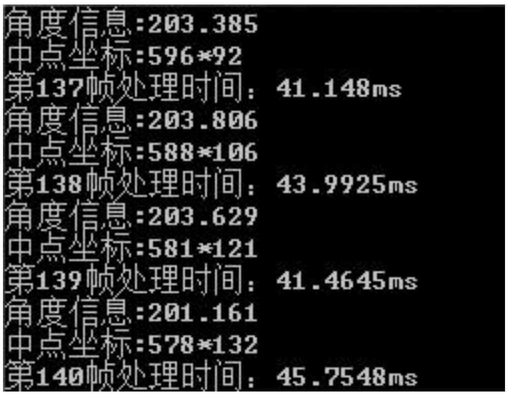


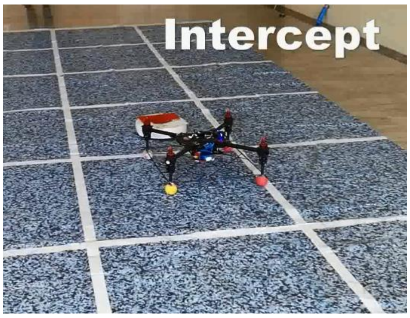
Figure 19. Ground Robot Detection Results

4.2 Flight Test Experiment

According to the set behaviors. We have done some basic experiments, including Autonomous takeoff, target tracking, intercepting, Re-flight, and so on. The results of the experiment are shown in Figure 20 (a to f)

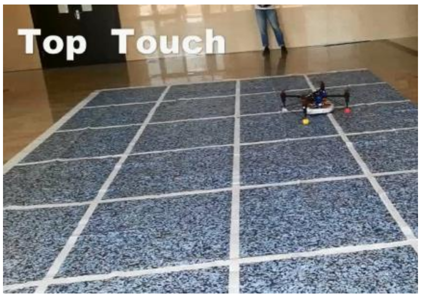
(a) Autonomous Takeoff

(b) Target Tracking



(c) Intercept

(d) Re-flight



(e)Top Touch

(f) Cross the Line

Figure 20. Some Basic Experiments

5 Conclusion

In this paper, we present the technical details of self-design drone system. It is feasible to verify from the hardware platform to the system architecture by experiments. It can achieve autonomous flight in an unknown environment. Simultaneously, the drone can autonomously make decisions to complete specific actions, based on environmental information, such as obstacle avoidance, target tracking, touched re-flight, etc. In the later period, our direction is that the drone can make decisions more quickly and accurately and perform corresponding actions. Furthermore, we can successfully complete this competition

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