2015 IEEE International Conference on Robotics and Automation (ICRA)
Washington State Convention Center
Seattle, Washington, May 26-30, 2015

Development of an unmanned helicopter automatic barrels transportation system

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***Abstract*— In the 2nd International Unmanned Aerial Vehicle (UAV) Innovation Grand Prix (UAVGP) sponsored by Aviation Industry Corporation of China (AVIC), an autonomous barrel transportation mission was proposed for Rotary-wing UAV (RUAV) which aims at validating the feasibility of marine vertical replenishment by RUAVs. The RUAV was supposed to track the movable platform, pick up barrels on the supplier platform, stack barrels on the replenishment platform, take off and land autonomously without any human interference. The final score was determined based on the mission completion time and the stacking accuracy. The main challenges involved in this mission include attitude stabilizing with varying payload, accurate movable platform tracking and task-scheduling. An unmanned helicopter (UH) automatic barrels transportation system was established by our team, and the navigation system, control system and task scheduling system will be detailed in this paper, along with the flight tests before and in the competition. The system's performance has been verified in the competition and won the first prize finally.**

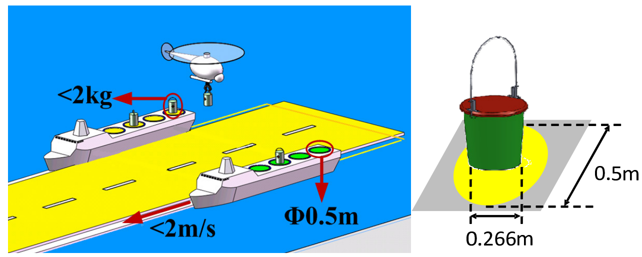

Fig. 1. Grand prix mission illustration

I. INTRODUCTION

Aerial manipulation is a newly developed research area in recent years, with a basic idea of combining traditional manipulator with unmanned aerial vehicle (UAV). The original purpose of such a combination was to extend the mission domains of UAVs from reconnaissance and surveillance to the interaction with the environment. Since vertical take-off and landing (VTOL) UAVs are much more flexible and more suitable for such kind of aerial manipulation operations, the popularly developed aerial manipulation test platforms all belong to the VTOL UAVs' category such as unmanned quadrotor [1], [2], [3], ducted-fan UAV [4], [14], and unmanned helicopter (UH) [5], [10], [11]. 涵道无人机

In ETH Zurich [1], a Flight Assembled Architecture was established using four quadrotors for cooperative construction, in which the quadrotor was equipped with a small gripper to catch the foams needed for construction. In the flight test, a great prospect of UAVs for flight assembling was demonstrated, even though the load capability of the quadrotor is quite limited. A valve turning mission was conducted by Matko Orsag [2] using a quadrotor, the quadrotor was equipped with a two degrees of freedom manipulator, a control scheme was proposed to tackle the coupling with the environment, along with a human machine interface. A flight test was finished to demonstrate the effectiveness of the whole system. A hummingbird quadrotor was used to transport a suspended load through obstacles indoors [3], this system was mainly used to validate the safety and efficiency of manipulation and transportation of load using UAVs. In Drexel University [8], [9], a control scheme was proposed to achieve dynamic stability in an aerial vehicle with dual multi-degrees of freedom manipulators. Since ducted-fan UAVs' rotor was inside the airframe, ducted-fan UAV was supposed to be relatively safer compared to the quadrotor. A ducted-fan UAV was built up to validate its applications in a service area in which a more strict security should be guaranteed [4]. Since quadrotor and ducted-fan UAVs are relatively small with a limited payload capacity for real operations, they are more suitable for indoor service-oriented applications; yet unmanned helicopter is preferred for real life applications.

The Yale Aerial Manipulator [5], [6] was a composition of UH and adaptive compliant gripper for generalized object retrieval and transport, they have analyzed and demonstrated the hovering stability of the overall aerial manipulation system, the object was grasped and rigidly affixed to the unmanned helicopter, so a stability analysis was given that identifies the influence of load location to the control loop stability, and PID controller was adopted for the analysis [7]. In this study, no specific compensation has been made about the influence of manipulation operation. A more sophisticated 7 degrees of freedom industrial manipulator was added to an unmanned helicopter by German Aerospace Center (DLR) [10], which means a more sophisticated but flexible manipulation mission can be accomplished. However, this introduced more challenges to the overall control stability. A slung load transportation test was finished by Morten Bisgaard [11] using unmanned helicopter, an estimator was designed for the slung load to provide a feedforward compensation that can significantly attenuate the influence of slung

*This work was supported by and National Natural Science Foundation of China (Project 61433016 and 61273025)

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978-1-4799-6923-4/15/$31.00 ©2015 IEEE

load to the system stability. Besides, three coupled unmanned helicopters were used for cooperative accurate deployment of loads [11], which was the first successful autonomous load transportation experiment worldwide.

In the 2nd International Unmanned Aerial Vehicle Innovation Grand Prix (UAVGP) sponsored by Aviation Industry Corporation of China (AVIC), an autonomous barrel transportation mission was proposed for Rotary-wing UAV (RUAV) which aims at validating the feasibility of vertical replenishment by unmanned helicopter [12]. The mission was illustrated in Fig.1, the RUAV was required to autonomously takeoff, track the barrels on the supplier platform, pick-up the barrels, stack the barrels on the replenishment platform and then land at the same place where it took off. The supplier and replenish platform were in uniform motion with a speed under 2m/s, the weight of the barrels was between 1.5kg to 2kg and a total of four barrels were required to be picked up and stacked. The barrels should be stacked in a circle on the replenishment platform with the diameter being 0.5m, and the diameter of the barrel was 0.266m. A stacking accuracy should be under 0.15m to obtain the full mission score. The final score was determined based on the mission completion time and the stacking accuracy. A mission completion time under 200 seconds was supposed to be perfect. The RUAV should finish the whole procedure autonomously without any human interference, and the competition was conducted outdoors in a helicopter airport near Beijing. This was the first time ever in the world that a specific mission of aerial manipulation was required by a competition, which introduced more challenges to the whole system with more strict requirements on the system's stability and robustness.

The main challenges involved in this mission include attitude stabilizing with varying payload, accurate movable platform tracking and task-scheduling. Based on the researches we have made before [15], [16], [17], [18], an unmanned helicopter automatic barrel transportation system was built up by our group in 5 months as shown in Fig.2. The development details of the navigation system, control system and task planning system will be introduced in this paper, along with the flight tests before and in the competition. This system has been verified in the competition and won the first prize.

Fig. 2. Unmanned helicopter barrel transportation system

This paper is organized as follows: the system description will be given in Section II which includes the mechanical system, electronic system and software system; control system design will be specified in Section III, along with the flight tests in Section IV and the conclusion in Section V.

II. SYSTEM DESCRIPTION

A. Mechanical System

Many rules have been given to the RUAVs in the Grand Prix to guide the system design, most of the limits were given to the airframe which was fundamental to the overall system design:

- Take-off weight: 5 to 20kg
- Barrel weight:1.5kg to 2kg
- Mission completion time: $\leq$ 1000 seconds
- Motor rated voltage: $\leq$ 44.4V
- Maximum dimension: $\leq$ 2m

Since the Barrel's weight was under 2Kg, the onboard avionics' weight was approximately 2Kg, and the grasping mechanism's weight was supposed to be around 1Kg, the total payload capacity should above 5Kg and the flight duration should be at least 10 minutes.

The UH used by our team was an electrical version of the popularly used AF25B, which was originally powered by gasoline engine, the engine used in this UH is Hacker A-100-8 with the maximum power of 7Kw and a rated power of 5Kw. Based on these limits, the UH's characteristics are illustrated in Table.I, and the UH's dimensions are shown in Fig.3. This electric flight platform is much easier to maintain compared to the gasoline powered UHs and more robust compared with the model-scale UHs.

TABLE I

THE CHARACTERISTICS OF OUR UNMANNED HELICOPTER

Takeoff Weight	30Kg	Main Rotor Diameter	1960mm
Dry Weight	12Kg	Engine Power	5Kw
Battery Weight	5Kg	Battery Voltage	44.4V
Max Payload	13Kg	Flight Duration	15 Minutes

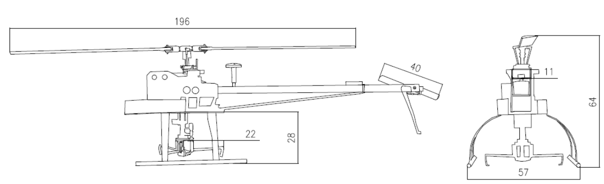

Fig. 3. Unmanned helicopter Dimensions (cm)

Based on the specific size and shape of the barrel announced by the organizing committee, a 3-DOF pick-up device was designed as shown in Fig.4. This device can move up and down to compensate the different heights of the barrels. A grasp direction adjustment and the omnidirectional mechanism can choose the best suitable grasping direction, which can guarantee the grasping performance and lower the accuracy requirements to the flight controller. Three servos were used to control the 3-DOF motions.

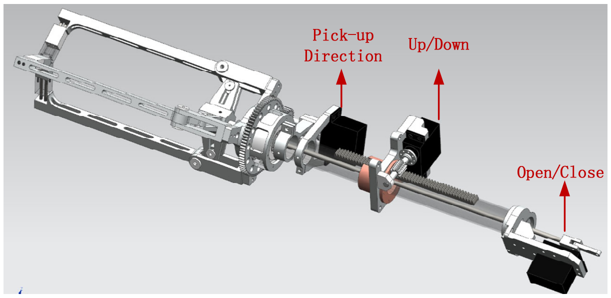

Fig. 4. Grasp Mechanism Illustration

B. Electrical System

Onboard electronics systems are composed of navigation system, flight control system, visual system, task scheduling and path planning system as shown in Fig.5.

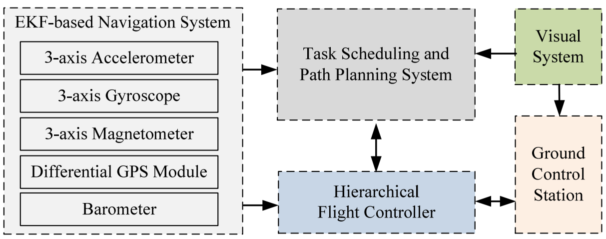

Fig. 5. Electronis Diagram

The navigation and flight control systems were built by our research group [13], with the improvement of replacing the U-blox GPS by a differential GPS to achieve the location accuracy of 2cm. Extended Kalman Filter (EKF) was used for the fusion of data from various sensors to provide more accurate navigation information. The onboard processor used was an LPC3250 ARM9 processor.

Visual system was supposed to provide relative position between barrel and UH. Shape along with color were used to identify different barrels. Even though the visual processing algorithm has been built up and tested offline using the video captured in the flight test, visual information hasn't been used in the real flight mainly because of the limited onboard processer's calculation power.

C. Software System

A state machine was built up to deal with the complicate task scheduling problem. A total of 10 states were defined through the explicit procedures needed for the whole operation are shown in Fig.6. The barrel picking-up was divided into tracking, descending, picking-up and ascending, the barrel stacking was divided into tracking, descending, stacking and ascending. Four barrels should follow the same picking-up and stacking procedures respectively.

Two critical issues should be considered in the state transition of this state machine:

- How to define the successful picking-up state: many sensors like switch or vision system can be used to detect whether the barrel was picked-up or not, but

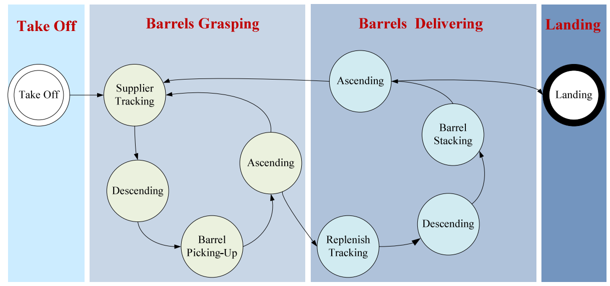

Fig. 6. Flowchart of the whole mission process

they introduced extra payload to the whole system. Here the collective pitch control quantity is used for the definition as shown in Fig.7. Since the barrel's weight is approximately 2kg which means a bigger collective pitch control should be given compared with the flight without barrel to compensate for the barrel weight. Through the experimental tests, a threshold of 80 is set as the criterion for successful picking-up state transition.
- When to abandon a barrel when picking-up is difficult or impossible: the total mission completion time is critical to the final score. In the real flight test, a barrel may deviate from the predefined area or turnover which makes the picking-up extremely difficult or impossible. A strategy should be established to avoid the tireless attempt on an impossible barrel that will significantly waste the mission time. A limitation on the number of times trying to pick-up a barrel was set as 4, and the state machine will abandon the barrel when the maximum trying times was reached.

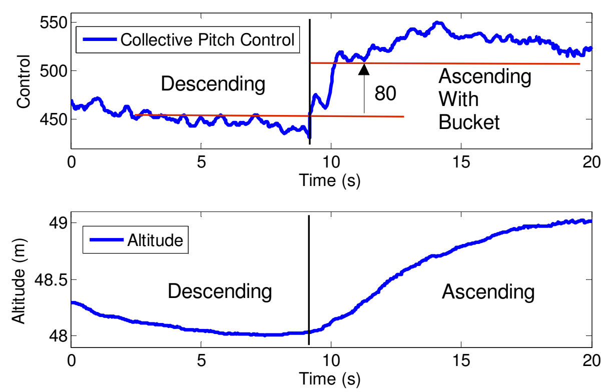

Fig. 7. Collective pitch control used for successful picking-up detection (collective pitch control range from -1000 to 1000)

III. CONTROL SYSTEM DESIGN

A hierarchical flight control algorithm architecture was adopted here for autonomous flight as shown in Fig.8, with the position and velocity controller as the outer loop and the attitude controller as the inner loop. Controller used in all these loops was the popularly used PID (proportional integration differential) controller for simplification. The adjustment of PID parameters is engineering-oriented with fewer concentration on theoretical improvement.

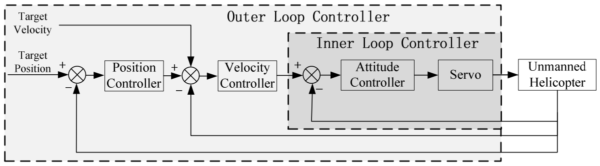

Fig. 8. Diagram of the flight controller

A. Inner-Loop Controller Design

In the inner-loop, angular velocities and attitudes were used as the feedback to attitude controller in order to stabilize the attitude of UH in various conditions. In the traditional flight controller, a fixed set of PID parameters was usually used for attitude stabilization. While in this mission, when the barrel was picked up by the UH, a variation of whole flight weight will introduce a notable disturbance to the original flight controller.

A set of barrel picked-up state scheduled PID parameters was introduced to solve this problem. The comparison of fixed and scheduled PID parameters was illustrated in Fig.9. The scheduled PID parameters controller can adjust its control parameters according to the extra barrel payload, and a better performance can be obtained compared with the fixed PID parameter controller. PID parameters were designed both upon the engineering experiences and the single loop response modeling methods, and the criterion for the PID parameters adjustment depends mainly on the mission performances and engineering experiences.

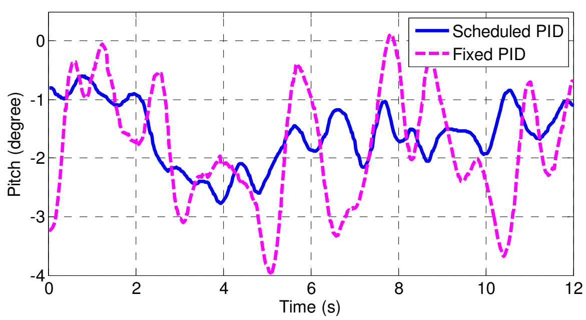

Fig. 9. Comparison of fixed and scheduled PID parameters with barrel payload

B. Outer-Loop Controller Design

In the competition, the supplier and replenishment platforms were moving at a constant speed under 2m/s in a fixed direction along the slide. A simple position loop PID controller will introduce a constant bias when tracking the moving platform. The moving platform's velocity was feed-forwarded to the velocity loop control to compensate for the constant tracking bias, an unbiased position tracking performance can be obtained when the moving platform's velocity changes slowly. The tracking performance was shown in Fig.10. The moving platform was designed to move forward at a speed near 1m/s initially and when reached the end, at a backward speed of 1.5m/s, through an adjust period of 4 seconds, the UH can track the moving platform with a position bias under 0.1m which was accurate enough for the successful barrel picking-up and stacking mission.

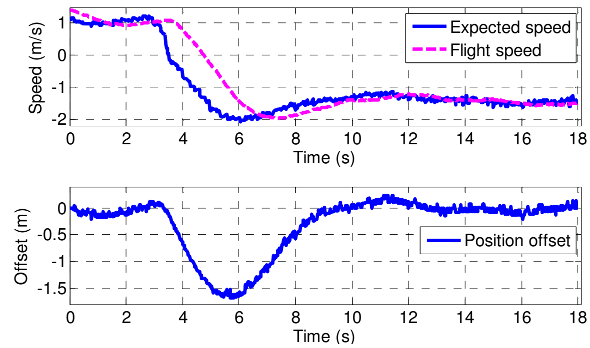

Fig. 10. Moving platform tracking performance with platform velocity feed-forward

IV. FLIGHT TEST

According to the rules designed by the Grand Prix organizing committee: in the preliminary round, the supplier and replenishment platforms were in fixed positions in order to lower the mission difficulty, this was called the stationary mission; in the final round, both of the platforms were moving which introduced more challenges to the tracking control, this was called the moving mission. In the competition, only two chances in the preliminary round and one chance in the final round were given to each team. So we had to build test environment by ourselves before the competition.

Stationary mission was much easier to be verified because no extra equipment was needed except for the barrels, a total of 15 stationary mission flight tests have been conducted before the competition. Through these flight tests, the parameters needed to finish the mission have been adjusted to improve the mission efficiency. A mission completion time of 190 seconds was derived with two barrels stacked at the centre of the circle and two barrels stacked around the centre. This mission completion result of our pre-test had almost met the best mission requirements.

Moving mission was much difficult to be verified before the competition because a moving platform was needed to conduct this flight test and the moving platform with the same size and accuracy of the competition was quite expensive to build up. A small manual controlled model car was used to simulate the moving platform with a barrel placed on it.

Next, a moving mission flight test result before the competition and a stationary mission flight test result in the competition will be given to illustrate the performance of our system.

A. Moving Mission Flight Test before the competition

Moving mission flight test was conducted using a model car. In the test, the model car was controlled by an operator in a near-uniform speed under 2m/s, the barrel was placed on the model car, the UH was supposed to track the model car and pick up the barrel on it. The flight bias was illustrated in Fig.11, a step change of the bias means the state transition of the state machine used for task scheduling because the expected position will change according to the different mission states. As we can see, the UH can track the model car with an unbiased position and pick up the barrel successfully. The flight photo gallery of the moving mission is illustrated in Fig.14.

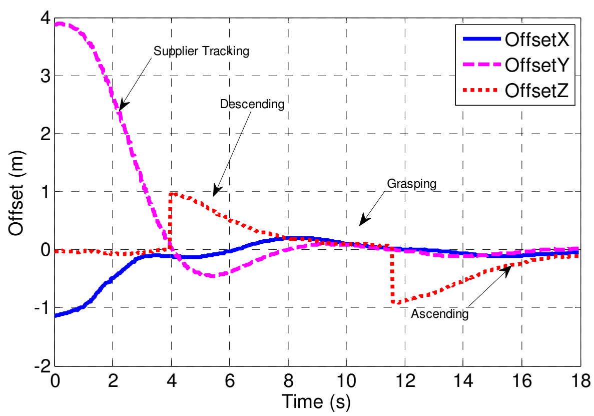

Fig. 11. Moving Mission Performance

B. Stationary mission flight test in the competition

On September 20, 2013, the flight competition was conducted in Miyun helicopter airport near Beijing. Two rounds were designed in the competition: the preliminary round was held on September 20 to select teams qualified to participate in the final round; in the final round, the platforms were moving under 2m/s at the judge's discretion.

In the preliminary round, we finished the mission successfully. A total mission completion time of 210 seconds was obtained with two barrels stacked in the circle and two barrels stacked outside the circle. We were ranked first with a score of 1025, and the full score was 1300. The flight trace of the UH is illustrated in Fig.12, and the flight photo gallery is illustrated in Fig.13.

In the final round, the UH was supposed to track the moving platform and finish the delivering task. The flight controller's PID parameters were mistakenly set wrong by the ground control station before the competition when we were conducting off-line simulation, and the UH can't achieve the accuracy needed to pick and deliver the barrels on the moving platform, we only finished the taking-off and landing mission without picking up any barrels. A score of 350 was obtained in the final round.

According to the Grand Prix rules, final ranking is based on the sum of preliminary round score and final round score. With the great advantage obtained in the preliminary round,

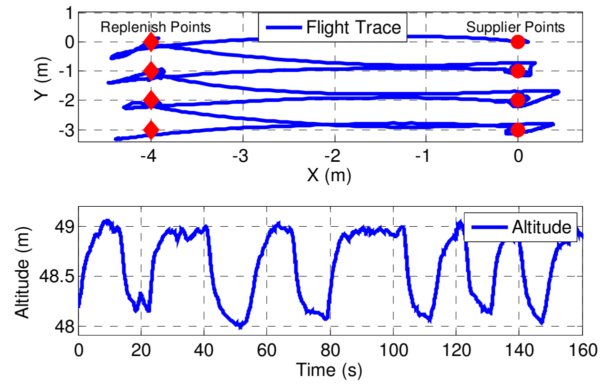

Fig. 12. Flight trace of the stationary mission competition

we won first prize with a total score of 1375, and the second highest score is 1127.

V. CONCLUSIONS

An unmanned helicopter automatic barrels transportation system had been established by our team, which was dedicated to participate the 2nd International UAV Innovation Grand Prix sponsored by Aviation Industry Corporation of China in September 2013. The navigation system, control system, task scheduling and path planning system have been introduced respectively in this paper: a specific grasping mechanism was designed to pick-up and stack the barrels; a state-machine was established to schedule the mission tasks: a scheduled PID parameter was introduced to improve the inner loop control accuracy, and a moving platform velocity feed-forward scheme was added to track the moving platform. Detailed descriptions of the results of the flight tests were given. The whole system had been verified through simulated flight tests as well as the flight tests in the competition, and our team won the first prize. Improvements on the control and visual locating accuracy will be our next focuses, the intelligence to handle complicated mission environment should also be addressed in the future.

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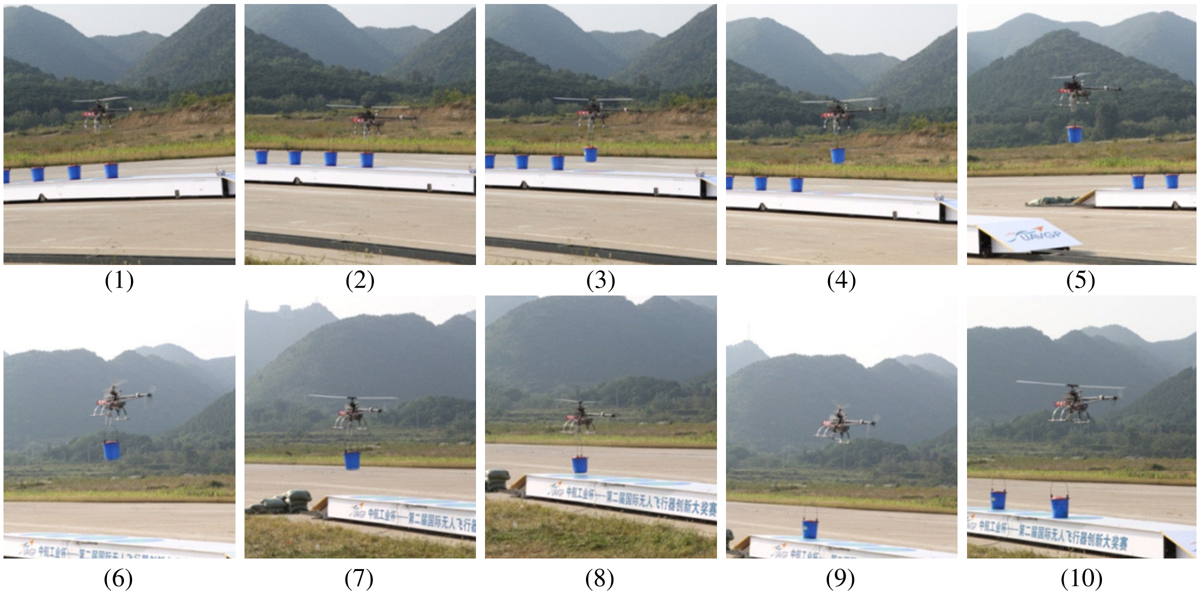

Fig. 13. Flight demonstration in the competition with stationary platform

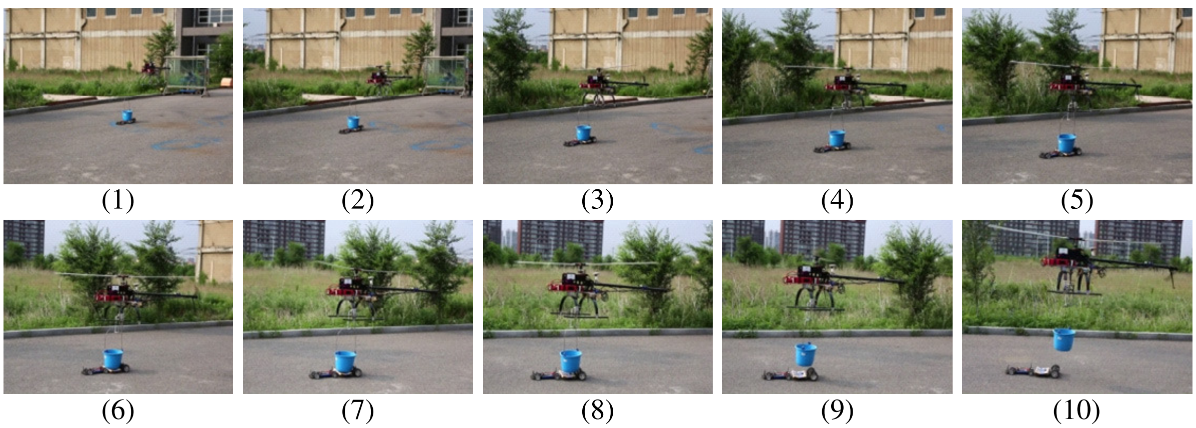

Fig. 14. Illustration of tracking the moving platform

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