Optik 124 (2013) 3296–3300

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Implementation of autonomous visual tracking and landing for a low-cost quadrotor

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ARTICLE INFO

Article history:
Received 15 May 2012
Accepted 13 October 2012

Keywords:
Visual tracking
Landing
Quadrotor
RGB filter
PID controller

ABSTRACT

This paper presents an implementation of a hybrid system consisting of a low-cost quadrotor and a small pushcart. The quadrotor is controlled with classical Proportional–Integral–Derivative (PID) controller for autonomous visual tracking and landing on the moving carrier. The vision-based tracking and landing approach utilizes enhancement of red, green and blue (RGB) color information rather than grayscale information of the helipad on the carrier, which shows fast and robust performance in different lighting conditions. This work is characteristic with utilizing the off-the-shelf affordable quadrotor and accomplishing the complex task using only the relative pixel position in image plane without communication between the quadrotor and carrier. The quadrotor's relative position to helipad is estimated with a frequency up to 30 Hz from the video stream, which enables the quadrotor to fly autonomously while performing real-time visual tracking and landing on the carrier. Series of experiments show that our system is easy to deploy and tune, simple and robust, also low-cost.

1. Introduction

Unmanned Aerial Vehicles (UAVs) have recently aroused great interests in both industrial and military fields. UAV is a type of very complex system which integrates different hardware components, such as camera, Global Positioning System (GPS), Inertial Management Unit (IMU), controller, and different software components, such as image processing, path planning and inner loop control [1]. Due to the ability to perform dangerous and repetitive tasks in remote and hazardous environments, UAV is very promising to play more important roles in many applications and recent developments have proven the benefits in different ways [2].

Computer vision is a field that includes methods for acquiring, processing, analyzing, and understanding images and high-dimensional data from the real world in order to produce numerical or symbolic information [3]. Computer vision is an excellent solution as a low-cost and information-rich source complementing the sensor suite for control of UAVs [4]. For fully autonomous UAV, the ability of autonomous visual tracking and landing is of vital importance for a complete mission in case of GPS signal lost [5,6]. Many researches have designed various types of UAVs that are quite large and expensive. Shakernia et al. propose a novel multiple view algorithm to improve the motion and structure estimation for vision-based landing of UAV [7]. Saripalli et al. present a real-time vision-based landing algorithm for an autonomous unmanned helicopter [8], and they also implement the landing of a helicopter on a moving target [9]. Zeng et al. design a vision system for helicopter landing by using image registration [10]. Wang et al. designed another type of vision system for UAV landing in complex environments [11].

In our work, the quadrotor is controlled to track a moving carrier by holding a constant position overhead, and land on the helipad autonomously. Quadrotor is a type of rotorcraft that consists of four rotors and two pairs of counter-rotating, fixed-pitch blades located at the four corners of the body. The idea of using four rotors is realized as a full-scale helicopter as early as 1920s [12]. However, quadrotor is dynamically unstable and not widely developed in applications until the advance in computers and micro sensors.

There are several advantages to quadrotors over traditional helicopters. Quadrotors simplify the design and maintenance of the vehicle because of simple mechanical structure. Furthermore, the use of four rotors allows each individual rotor to have a smaller diameter. In this way, the damage caused by the rotors can be reduced greatly. Herisse et al. make use of optical flow algorithm for hovering flight and vertical landing control of the quadrotor developed at French Atomic Energy Commission [13]. Wenzel et al. utilize a low-cost commodity consumer hardware-Wii remote

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http://dx.doi.org/10.1016/j.ijleo.2012.10.060

camera as optical sensor to accomplish hovering and landing onboard for a quadrotor from Ascending Technologies [14,15].

This paper presents a new solution for autonomous tracking and landing, which is implemented in a type of low-cost off-the-shelf quadrotor-AR.Drone. The autonomous tracking and landing scheme is realized by using the monocular camera onboard with ground control station for off-board image processing.

The rest of this paper is organized as follows. The test-bed including the quadrotor and pushcart is introduced in the next section. Then, the proposed vision algorithms are given in Section 3, which can estimate the relative position between the quadrotor and the known helipad. In Section 4, our control architecture for tracking and landing are designed. The ground control station and experimental results are given in Section 5. Our concluding remarks are contained in the final section.

2. The quadrotor and carrier test-bed

The hybrid test-bed system includes the quadrotor and ground carrier realized by a pushcart. A ground control station is developed to perform image processing and position controlling. It is also used for monitoring and parameter variation in the experiments.

2.1. The quadrotor

AR.Drone is a WiFi-controlled quadrotor with cameras attached to it (one facing forward, the other vertically downward). AR.Drone is developed by Parrot Inc. It is an affordable (usually under \$300) commercial quadrotor platform offering an open Application Programming Interface (API) and freely downloadable Software Development Kit (SDK) for developers [16]. Many useful pieces of development information can be found on the developers' websites or the official forum.

AR.Drone uses an ARM9 468 MHz embedded microcontroller with 128 M of RAM running the Linux operating system. The onboard downward Complementary Metal Oxide Semiconductor (CMOS) color camera provides RGB images in size of 320×240. The inertial system uses a 3-axis accelerometer, 2-axis gyro and a single-axis yaw precision gyro. An ultrasonic altimeter with a range of 6 m provides vertical stabilization. With a weight of 380 g or 420 g (with "indoor hull") it can maintain flight for about 12 min with a speed of 5 m/s. Fig. 1(a) shows the top view of the quadrotor and Fig. 1(b) shows the side view of the flying quadrotor.

2.2. The carrier and helipad

The carrier in our system is a common pushcart (see Fig. 2). The pushcart is powered by man, and can move according to a specific path, which is like a moving automobile. The helipad is with a green shape "H", which is a concise copy of standard helipad for helicopter.

The color pattern is printed on a standard A4 paper and fixed on the carrier. We also designed two rectangles in red and blue for the helipad pattern. The helipad is used to determine the position error between the quadrotor and carrier. The two rectangles can help to determine the bearing of the quadrotor by calculating the relative position of the two rectangles.

3. Computer vision algorithm

3.1. RGB filtering and thresholding

In this work, a simple and fast red, green and blue (RGB) filter [17] is adopted to implement filtering of the noisy signals. The RGB filter uses three values (red, green and blue) to focus the attention

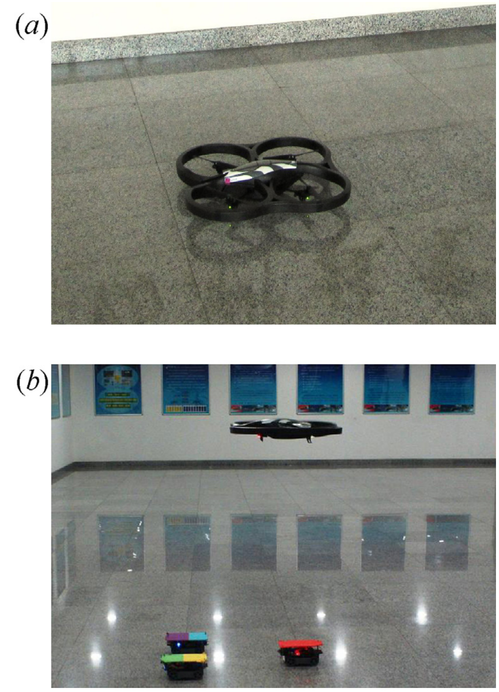


Fig. 1. Quadrotor AR.Drone picture from different views: (a) top view and (b) side view.

toward the specific color. RGB filter can diminish all pixels that are not the selected color. This filter is different from direct RGB channel comparison. The white pixels are diminished even though they may contain the color selected. Our helipad is pure green, so the RGB filter is accomplished eliminating the red and blue channels by using the following equation

$$\begin{cases} G=(G-B)+(G-R) \\ B=0 \\ R=0 \end{cases} \tag{1}$$

where G is the green value, B is the blue value, and R is the red value. Based on Eq. (1), it is obvious that the value of the white pixel results in zero, and the pure green pixel ($R=0$, $G=255$, $B=0$)

Fig. 2. Pushcart carrier with the green helipad and two color rectangles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

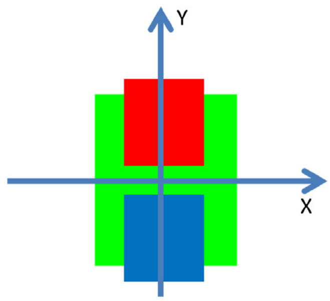


Fig. 3. Defined image coordinates.

doubles its value. G will be normalized to 0-255 after Eq. (1). This filter performs better than direct RGB channel comparison in filtering for a particular color as white pixels are removed. It is much robust under different lighting conditions.

The threshold algorithm can produce a binary image after using the RGB filter. A robust implementation is to set the image threshold at a fixed percentage between the minimum and the maximum green value. The percentage is 80% for default value in our implementation. The threshold can also be manually adjusted according to the different experimental conditions.

3.2. Position estimation

The 2-D $(p+q)$th order moment [18] of a density distribution function $f(x, y)$ can be described as

$$m_{pq} = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} x^p y^q f(x,y) dx dy \quad p, q = 0, 1, \ldots \tag{2}$$

An image can be represented as a discrete function $f(i, j)$. For the $(p+q)$th order moment of an image, Eq. (2) can be rewritten as

$$m_{pq} = \sum_i \sum_j i^p j^q f(i,j) \tag{3}$$

where i, j correspond to the coordinates in axis x, y respectively. The center of gravity of an object can be specified as

$$\bar{x} = \frac{m_{10}}{m_{00}} \tag{4}$$

$$\bar{y} = \frac{m_{01}}{m_{00}} \tag{5}$$

The obtained continuous images are processed on the ground control station for quadrotor. Fig. 3 shows the defined image coordinate system.

In Fig. 3, the origin point is the center of helipad and the relative position error is represented in pixels. The x axis means pitch channel, and y axis means roll channel. The calculated relative position errors in this coordinates are used to generate the control command, and the command is sent to the controller of the quadrotor. The onboard camera and off-board vision algorithms allows the quadrotor to track and land fully automatically without communication between the quadrotor and the carrier.

4. Control architecture for tracking and landing

The quadrotor position controller is designed as hierarchical control architecture. The low-level attitude control has already been realized in the quadrotor inner-loop controller by the developer. The high-level position control is implemented in our developed ground control station. A finite state machine controls the high-level behavior of the quadrotor. The desired behavior consists of four phases: taking off, hovering, tracking and landing. The control architecture of quadrotor is shown in Fig. 4.

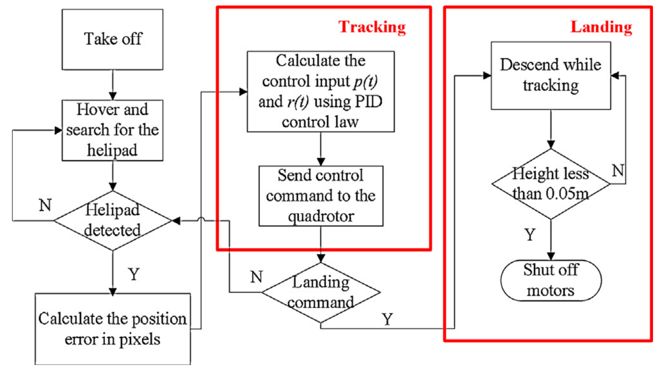


Fig. 4. Control architecture of our quadrotor.

The quadrotor takes off from the helipad on the carrier and holds a fixed height of 0.5 m in our experiments. Commands from the ground control station start the autonomous visual tracking and landing of the quadrotor. While the carrier is stationary, the quadrotor will hover overhead the helipad. The quadrotor must hover right over the center of the helipad in our task. When the carrier is moving, the quadrotor must track overhead the center of the helipad.

The precise autonomous position control is achieved by two independent Proportional–Integral–Derivative (PID) controllers [5]. One PID controller is for the pitch channel, and the other for the roll channel. The input of the controller is the position errors, which can be obtained by our proposed computer vision algorithms. The output of the controller is the attitude angle commands. The position error for the corresponding roll and pitch channel can be denoted with $e_r(t)$ and $e_p(t)$. Fig. 5 shows the PID controllers for our quadrotor's position control with real-time visual feedback.

The roll angle $r(t)$ and pitch angle $p(t)$ can be obtained by

$$r(t) = K_p e_r(t) + K_i \int_0^t e_r(\tau) d\tau + K_d \frac{d}{dt} e_r(t) \tag{6}$$

$$p(t) = K_p e_p(t) + K_i \int_0^t e_p(\tau) d\tau + K_d \frac{d}{dt} e_p(t) \tag{7}$$

When the quadrotor is in the landing phase, it will maintain a constant descending velocity while keeping tracking of the helipad. As the position errors in pixels are adopted as the inputs of controllers, height compensation must be considered during landing process. In actual experiments, the landing phase can be separated into three circumstances, which can compensate for the controller outputs. When the quadrotor's height is between 0.3 m and 0.5 m, the controller outputs calculated by Eqs. (6) and (7) can be used directly. When the quadrotor's height is between 0.05 m and 0.3 m,

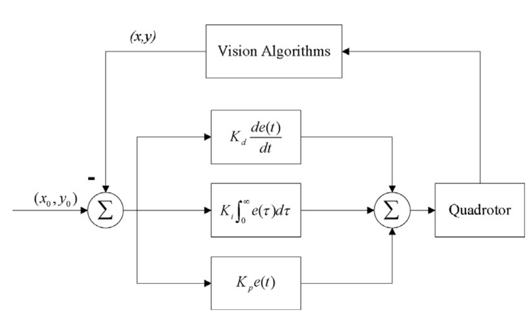


Fig. 5. Position PID controller with visual feedback.

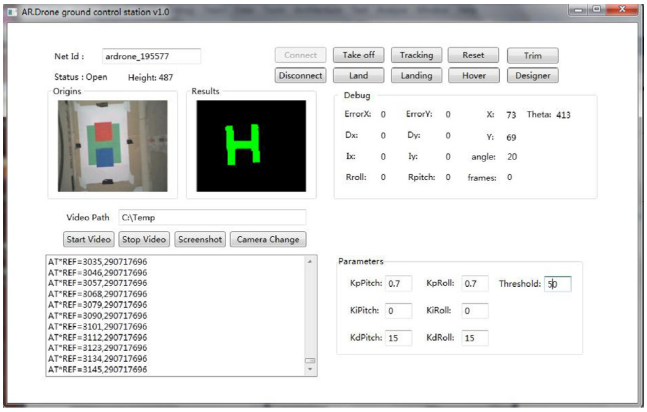


Fig. 6. Custom ground control station for our quadrotor.

the controller outputs can be reduced according to the two following equations:

$$r(t) = \frac{r(t)}{1.5} \tag{8}$$

$$p(t) = \frac{p(t)}{1.5} \tag{9}$$

If the quadrotor's height is under 0.05 m, the helipad region in the image is too large to use for navigation. The quadrotor will directly shut off motors, and land on the helipad quickly. This proposed strategy can avoid the influence of the ground effect, and better performance can be guaranteed effectively.

5. Experiments

In order to verify the feasibility and effectiveness of our proposed approaches, a custom ground control station for the quadrotor is developed. Fig. 6 shows the main interface of our developed ground control station.

The ground control station can receive/send signals, and process images transferred from the quadrotor's downward camera at 30 Hz. The station can send control commands at 33 Hz according to the recommendation in the development guide. The ground station is developed in C#, which is referring to the open source .NET DroneController [19] developed by Wilke.

Different operation modes can be chosen on our ground control station, including "take off", "land", "tracking", and "landing". "land" means ordinary landing of the quadrotor while "landing" means the touching down on the specific helipad. "tracking" starts the process of the quadrotor automatically following the carrier. All the states for monitoring the system are displayed on the ground control station. The PID parameters for the two channels and the threshold for detecting the helipad can also be set on our developed ground control station.

Our computer vision algorithms are implemented on the ground control station. Fig. 7 shows effect of the proposed vision algorithms. Fig. 7(a) is the original image of helipad captured from the on-board camera, and Fig. 7(b) shows the resulting image after filtering and thresholding.

The resulting image is displayed in green for user friendliness. The helipad is extracted effectively from the sample image, which demonstrates that the computer vision algorithms meet requirements of the quadrotor system.

The threshold for helipad detection can be tuned manually if the default value cannot perform effective helipad extraction, which varies according to different lighting conditions. A specific threshold was set, and over 90% of the helipad region is detected. After setting a threshold, the ground control station starts the tracking and landing procedure. The PID parameters for the pitch and roll channel are the same because of the symmetry of quadrotor's dynamics. In our experiments, the PID parameters can be set as $\{K_p = 0.7, \quad K_i = 0, \quad K_d = 15\}$. The proportional term produces an output value that reduces the current position error. The derivative term helps to slow the velocity of the quadrotor, and reduce the magnitude of the overshoot by considering both acceleration and velocity.

Following a large number of flights, the system has proven a good tracking and landing ability. The experimental video's screenshots are shown in Fig. 8.

(a)

(b)

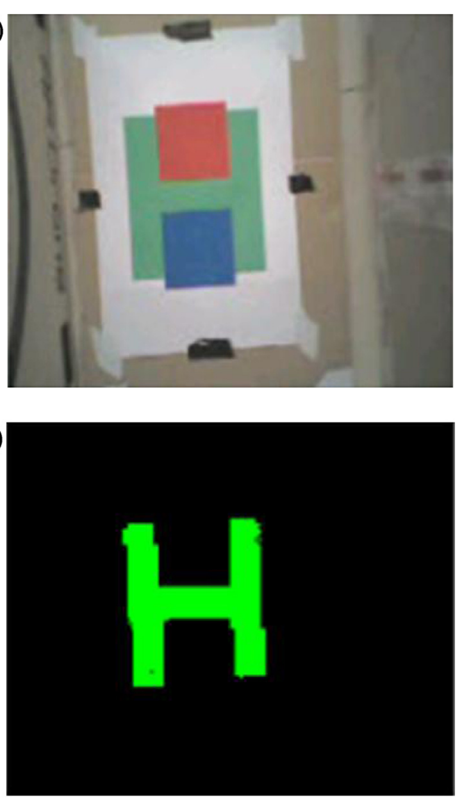
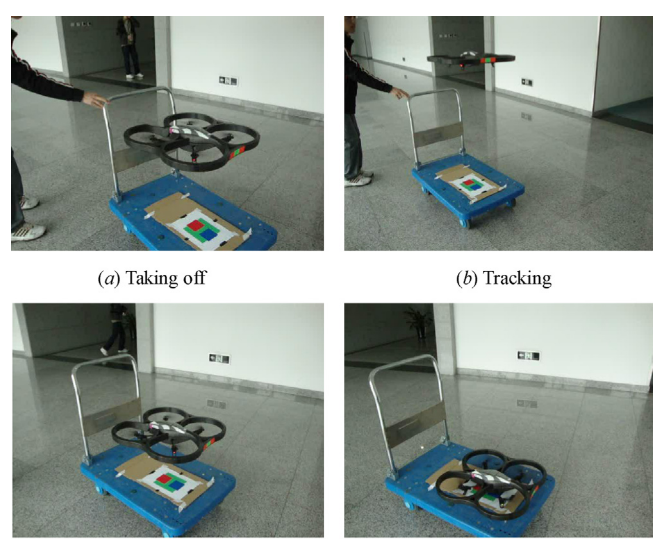


Fig. 7. Effect of the vision algorithm: (a) original image of helipad and (b) resulting image of helipad.



(a) Taking off (b) Tracking

(c) Landing (d) Landing finished

Fig. 8. Process of our quadrotor tracking and landing on helipad: (a) taking off, (b) tracking, (c) landing, and (d) landing finished.

(a)

(b)

Fig. 9. Process of the quadrotor following a toy car: (a) following start and (b) following successfully.

Fig. 8(a) shows the taking-off process of our quadrotor from the moving carrier. Fig. 8(b) shows the tracking process of our quadrotor after successful detection of the helipad. Fig. 8(c) shows the descending of height while keeping tracking the helipad during the landing process. Fig. 8(d) shows the precise landing of our quadrotor. The experimental results show the quadrotor using our proposed approaches can complete the tracking and landing on the helipad precisely while the carrier moving at the speed below 0.5 m/s.

Furthermore, we also apply the quadrotor to follow a remote-controlled toy car by using our computer vision algorithms and position controller. Fig. 9 shows the successful heterogeneous following process.

6. Conclusions

This paper mainly focused on the exact implementation of a hybrid system consisting of quadrotor and pushcart carrier. The adopted computer vision algorithms are rather simple, fast and effective under different lighting conditions. The rich vision information can guarantee excellent performance of our designed tracking and landing system.

Most of the experiments including UAVs are rather expensive and need a large experimental area. The AR.Drone is a low-cost miniature quadrotor and supports secondary developments. We have implemented an autonomous visual tracking and landing system with the low-cost quadrotor. The designed hybrid system demonstrates the usability and fast deployment ability of the miniature quadrotors.

The tracking and landing task is still challenging while the carrier is moving fast and rocking like a naval carrier. Next, we will focus on more new and effective control methods for quadrotor [20,21], and how to implement bio-inspired vision tracking algorithms in complicated environments is another challenging issue in our future work.

Acknowledgements

This work was partially supported by Natural Science Foundation of China (NSFC) under grant #61273054, #60975072 and #60604009, Program for New Century Excellent Talents in University of China under grant #NCET-10-0021, Aeronautical Foundation of China under grant #20115151019, and Opening Foundation of State Key Laboratory of Virtual Reality Technology and Systems of China under grant #VR-2011-ZZ-01.

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