Automatic Take-Off and Landing of a Quad-rotor Flying Robot

Wenhui Xiang, Yang Cao, Zengfu Wang

University of Science and Technology of China, Hefei 230027
E-mail: forrest@ustc.edu.cn

Abstract: In recent years, miniature quad-rotor unmanned aerial vehicles developed rapidly. Compared with the helicopter, the quad-rotor aircraft has more compact structure and greater lift force. One of the key aspects in autonomous behavior is take-off and landing. To achieve autonomy for this kind of aircraft, novel sensors are required. Those sensors need to cope with strictly limited onboard processing power. Our visual tracking system not using expensive cameras but a Wii remote camera, it belongs to commodity consumer hardware. The camera is capable of tracking infrared blobs in the case of no direct sunlight. The rate of the sensor's data refresh can reach 250Hz. Combined infrared cameras with IMU, our system can completely tracking and positioning of the aircraft. Then, we choose PID algorithm to control the aircraft, and the Quad-rotor flying robot successfully achieved automatic takeoff and landing at last.

Key Words: quad-rotor UVA; Wii remote; Visual tracking; Infrared camera

1 INTRODUCTION

The unmanned aerial vehicles (UVAs) became smaller and smarter over the past decades. They are being used in more and more areas such as traffic, military investigation, etc. But fully automatic takeoff and landing is always a hot issue. A lightweight camera should be used in visual tracking system since the Aircraft's load capacity is limited.

In this paper, we described a lightweight and extendable onboard vision-based tracking solution. The primary optical sensor of our system is dismantling from Wii Remote, the controller of Wii. It is capable of tracking infrared light and can provide the pixel position of each tracked light. The key ideal of our approach is to track a pattern formed by infrared LEDs. We can control the UAV automatically take-off and landing or hovering above the pattern after the UAV locations obtained. However, pattern alone cannot access to accurate position coordinates. We use the inertial measurement unit (IMU) of the aircraft to correct errors in the positioning process.

The control algorithm is running on an onboard DSP, we choose PID controller as Bouabdallah et al. demonstrated in [1] and Gurdan et al. described in [2]. The PID controller has the ability to control a quad-rotor and this simple algorithm can run on an onboard DSP at a high frequency.

2 RELATED WORK

Onboard vision-based tracking and navigation have been done on different aircrafts by using industrial cameras and high performance processors. Shakernia et al. [3] and [4] described a large, signal rotor helicopter system. To a known landing target, the aircraft's position and velocity was estimated by a vision system. Saripalli et al. [5] introduced a vision-based landing algorithm for an autonomous helicopter. These projects have some points in common that are the use of large aircraft and a maximum payload of 30 kg.

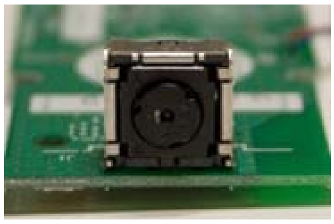
Herisse et al. [9] presented a nonlinear controller using optical flow for hovering flight and vertical landing control. Guenard et al. [10] shows a visual servo control which is capable of stationary or quasi-stationary flight. In these projects, data processing is completed by ground station.

As described by Mak et al. [6], they achieved a low-cost 6 Degrees-of-Freedom visual tracking technique with three onboard LEDs and a signal on-ground camera. Wenzel et al. [7] and [8] described a work of autonomous hovering above and landing on a stationary target with the Wii remote sensor and onboard microcontroller. All of those UAVs are miniature and the elements of visual tracking systems are cheap and easy to obtain.

3 THE CHARACTERISTICS OF THE WII REMOTE INFRARED CAMERA AND PATTERN

The Wii remote is the primary controller for Nintendo's Wii console. A main feature of the Wii Remote is its motion sensing capability through the use of accelerometer and IR camera tracker sensor technology. When communicating with the PC via Bluetooth, data refresh rate is about 100Hz; when communicating with the microcontroller through IIC protocol, the refresh rate up to 250Hz, sufficient to meet the control frequency.

(a) The Wii remote



(b) The internal camera sensor

Fig.1 The IR camera of the Wii remote

The Wii Remote includes a 128*96 monochrome camera with built-in image processing. The image processing is capable of tracking up to 4 moving objects and uses 8* subpixel analysis to provide 1024*768 resolution for the points. The IR Camera can return different sets of data describing the tracked objects. When in Basic Mode, the IR camera returns the data corresponding to the x and y locations of each of the four dots. Sreedharan et al. [11] analyses the motion by interpreting the acceleration sensor information. Shou et al. [12] integrates this controller into a game environment in a multi-wall virtual reality theatre.

We disassembled the Wii remote and separated the infrared camera from circuit. The camera is just 8*8*5mm, weighs only 0.4 grams and communicates with the microcontroller board using IIC protocol. With 20~25MHz external crystal, 3.3V voltage supply, number of simple components such as resistors and capacitors, the camera can be used as an ideal miniature on-board sensor. With the IR-pass filter intact, 940nm sources are detected by sensor with approximately twice the intensity of equivalent 850nm sources.

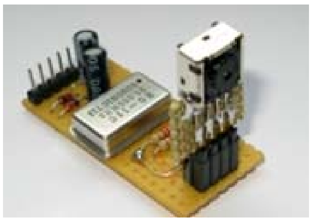


Fig.2 The on-board sensor Fig.3 IR pattern

We used four 940 nm wavelength infrared LEDs making a robust pattern and the four LEDs was on each four corners of the square. In this case, the pattern will be detected completely even one of the LEDs was covered. The side length of the pattern is 70 mm. This configuration has proven to be a good size for landing pad tracking. Larger patterns would obtain more precise position information, but it also lead to no longer fit the field of view when getting closer.

4 THE UAV SYSTEM AND MODEL

The X650 is a remote control multi-rotor mini helicopter designed for the model aircraft enthusiasts, the energy of which is provided by lithium battery, the thrust of which is provided by propellers direct-driven from four brushless motors. It is made by carbon fiber weighting only 850g.

The X650 platform equipped with a nine degree inertial measurement unit (IMU) and a GPS sensor. The IMU contains a three-axis accelerometer, gyroscope and electronic compass. GPS allows aircraft hover at a given point or fly to the location specified.

During the course of this experiment, we programmed at a TI F28335 Digital signal processor to achieve good scalability. All of the data processing is done on this board. At the same time, sensor information is sent to the ground control station (GCS) via zigBee module. The IR camera mounted in the center of the UAV frame, so we can obtain the exact position of UAV relative to IR pattern easily.

Takeoff and landing are composed of xz plane and yz plane motion. Fig4.b shows the model of quad-rotor in the z plane. Equations of motion are given by:

$$\ddot{z}(t) = f(t)cos\theta(t) - g \quad (1)$$

$$\ddot{x}(t) = f(t)sin\theta(t) \quad (2)$$

$$\dot{\theta}(t) = u(t) \quad (3)$$

The equations in the yz plane are same to xz plane:

$$\ddot{z}(t) = f(t)cos\varphi(t) - g \quad (4)$$

$$\ddot{y}(t) = f(t)sin\varphi(t) \quad (5)$$

$$\dot{\varphi}(t) = r(t) \quad (6)$$

Where $\theta(t)$ is the pitch angle, $\varphi(t)$ is the roll angle, and g is the gravitational constant. The unit of input $f(t)$ is m/s2 and the unit of the angle rate $u(t)$ is rad/s.

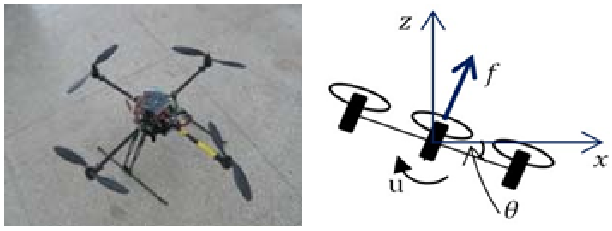


Fig.4 (a) X650D (b) Schematic of the 2D UAV model

5 RETRIEVING THE POSITION FROM IR CAMERA AND IMU

A position vector $\boldsymbol{p} = (x, y, z, \psi)$ is used to express the parameters required for vehicle control. x, y and z are the coordinates of the camera relative to the center of the pattern and ψ is the orientation in yaw. In this section, we described how to estimate the position vector by using the IR sensor and the IMU.

5.1 Pattern Analysis

When the quad-rotor flying over the pattern, the positions of the four points are obtained by the onboard DSP and the data is forwarded to the base station at the same time. Figure 5b shows a typical image received from the camera at a distance of 50 cm.

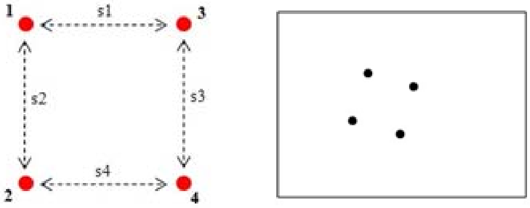


Fig.5 (a) The designed pattern (b) Image received from camera

In order to get position information, the center of the disordered points should be identified. When the four points are all covered by the camera, the coordinate of the center point $\mathbf{C}(x_c, y_c)$ can be easily calculated:

$$(x_c, y_c) = \frac{1}{4}\left(\sum_{i=1}^{4} x_i, \sum_{i=1}^{4} y_i\right) \quad (7)$$

If only three points were detected, the left one can be calculated according to the geometrical constraint and the position of the other three points.

Then, the center point $\mathbf{C}(x_c, y_c)$ can be calculated as:

$$(x_c, y_c) = \frac{1}{2}(x_1 + x_4, y_1 + y_4) \quad (8)$$

5.2 Estimating the z, x and y position

The distance from the camera to the pattern, that is the height of the aircraft, able to be calculated using geometric information. The viewing angle per pixel of the camera is given as $\rho = 7.16 * 10^{-4}$. The s_i represent of the physical distances between two LEDs and d_i are the pixel distances of the corresponding points. By using the mean value, the noise caused by shaking can be decreased. So the distance z can be measured by the follow equation:

$$z = \frac{1}{4}\sum_{i=1}^{4}\frac{s_i}{tan\ (d_i\rho)} \quad (9)$$

If the orientation of the camera is provided by the IMU, x and y position relative to the center of the pattern can be obtained.

First, we assume that the aircraft's airframe keeps horizontal when hovering above the IR pattern (Fig.7a).Let **M** be the center position of the image: $\mathrm{M} = (x_m, y_m)^T = (512, 384)^T$. $\mathbf{C}(x_c, y_c)$ is the center point of pattern, so the angle of vision θ_g and φ_g can be calculated by:

$$\theta_g = (c_x - m_x)\rho \quad (10)$$

$$\varphi_g = (c_y - m_y)\rho \quad (11)$$

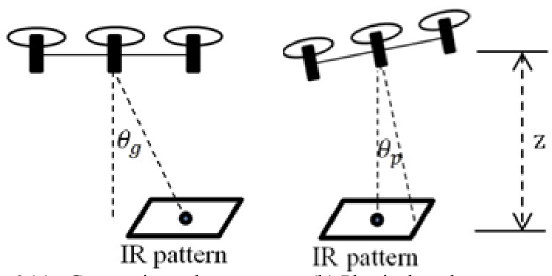


Fig.6 (a) Geometric angle (b) Physical angle

However, the aircraft will exist small roll and pitch angles when adjusting attitude (Fig.7b). This angle is defined as physical angle: φ_p, θ_p . At the same time, camera has the potential inaccuracies in positioning. Let φ_c and θ_c be the calibration angles and will be measured after attaching the camera to the aircraft.

So the second step is to correct the view angle via combing physical angles and calibration angles:

$$\varphi = \varphi_g + \varphi_p + \varphi_c \quad (12)$$

$$\theta = \theta_g + \theta_p + \theta_c \quad (13)$$

The real displacement of the pattern can be calculated by:

$$x = tan(\varphi)\, z \quad (14)$$

$$y = tan(\theta)\, z \quad (15)$$

6 FLIGHT CONTROL ALGORITHM

The goal of the controller is to stabilize the quad-rotor at a desired attitude and all other elements of position vector $\boldsymbol{p}$ should keep zero. In order to achieve this goal, first we control the quad-rotor in xz plane, then assume a constant height, and keep the quad-rotor in yz plane. The motion in the xz plane can be described as:

$$x_d = 0 \quad (16)$$

$$z_d(t) = z_d = constant \quad (17)$$

The movement in yz plane is same to xz plane:

$$y_d = 0 \quad (18)$$

$$z_d(t) = z_d = constant \quad (19)$$

6.1 Height Stabilization Controller

The movement of quad-rotor flying in xz plane is achieved by a cascaded controller design: the z direction is stabilized first and, assuming a constant height, the $x$direction controller is designed.

The thrust control value $f(t)$ in (1) is chosen such that a linear second-order system:

$$f(t) = \frac{1}{cos\theta(t)}\left(g - 2\delta_z\omega_z\dot{z}(t) - \omega_z^2(z(t) - kz_d)\right) \quad (20)$$

Using the (20), the close-loop system is given by:

$$\ddot{z}(t) + 2\delta_z\omega_z\dot{z}(t) + \omega_z^2 z(t) = \omega_z^2 z_d \quad (21)$$

The damping ratio δ_z between 0.5 and 1 is a reasonable choice in most cases. ω_z is natural frequency and k is steady-state gain.

6.2 Point Stabilization Controller

Assuming a constant height z_d and k=1, the x-dynamics (3) reduce to

$$\ddot{x}(t) = gtan\theta(t) \quad (22)$$

The pitch angle $\theta(t)$ is assumed to be small, so $tan\theta = \theta$ and the equation can be written as:

$$\ddot{x}(t) = g\dot{\theta}(t) = gu(t) \quad (23)$$

The input $p(t) = gu(t)$ is composed of a desired value and a feedback component:

$$p(t) = k_1\ddot{e} + k_v\dot{e} + k_3 e \quad (24)$$

Where $e = x_d - x(t)$ and k_1, k_2, k_3 are using the following parameters:

$$k_1 = \omega_x(1 + 2\delta_x), k_2 = \omega_x^2(1 + 2\delta_x),\ k_3 = \omega_x^3 \quad (25)$$

$\ddot{e}, \dot{e}, e$ represent the acceleration, velocity, and position errors respectively. The damping ratio δ_x is also between 0.5 and 1, ω_z is natural frequency and remains to be chosen in the actual experiments.

With the (25), the characteristic polynomial of the close-loop system can be written:

$$(s + \omega_x)(s^2 + 2\delta_x\omega_x + \omega_x^2) = 0 \quad (26)$$

Therefore, the input of x direction controller applied to the quad-rotor is:

$$\mathrm{u(t)} = \frac{1}{g}p(t) \quad (27)$$

Without considering the yaw angle, the control strategy of y direction is the same as x.

7 EXPERIMENTAL RESULTS

An accurate attitude estimate is essential for calculate the position of quad-rotor with our approach. So, we measured the position error first, and record the following example data. These data represents typical experimental results and should show the performance of the system.

7.1 Positioning Accuracy

A Wii remote camera, heading to the front, mounted on the bottom of the aircraft. The aircraft placed on a lift platform stationary and an IR pattern placed on platform below.

Then, changed the height of platform manually and measured the distance from the IR pattern to the IR camera with a rule. At the same time, record the position data obtained by the IR camera. Table 1, 2, 3 show the result and accuracy:

Table1. Position accuracy

Position	Rule/cm	Sensor/cm	Error Rate
x	5.6	5.8	3.4%
y	2.0	2.1	5%
z	31.3	30.6	2.2%

Table2. Position accuracy

Position	Rule/cm	Sensor/cm	Error Rate
x	11.5	10.9	5.5%
y	6.4	6.7	4.6%
z	62.1	64.2	3.4%

Table3. Position accuracy

Position	Rule/cm	Sensor/cm	Error Rate
x	21.3	22.6	6.1%
y	15.2	14.8	2.6%
z	125.6	122.4	2.5%

IR camera can detect all of the LEDs when the aircraft's height is from 0 to 160cm, and all of those tracking errors are less than 7%. When the aircraft is higher than 160 cm, the data from sensor became unreliable.

7.2 Flight Control Result

In flight control experiments, IR pattern was fixed on the ground and aircraft put directly over the pattern. Before the test, adjust their orientation to be consistent and keep x and y zero. Since the camera position estimation is of good quality, the position coordinates was used as actual value in the experiments.

For starting and landing, the GCS sent commands to DSP controller and received the UAV position data. The control frequency is about 30 Hz.

Figure 7 represents the performance of the controllers over one autonomous flight. Figure 7a represents the desired position and the actual measured position in x and y. Some oscillations still remain and more accurate PID parameters for flying should be found.

Figure 7b shows the trajectory tracking result of z. Aircraft's take-off spends more time since it is harder than landing. There are also some oscillations in the hovering state. The parameters of the height controller may be slightly adjusted.

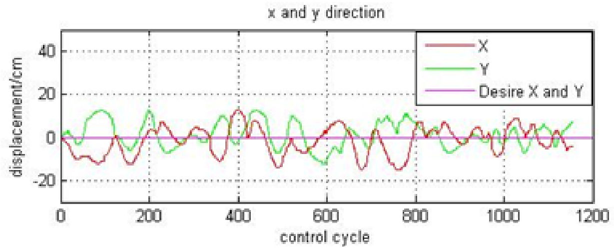


Fig.7 (a) Measured position of x and y

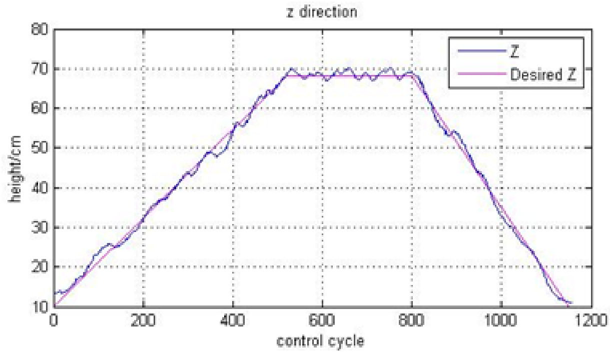


Fig.7 (b) The trajectory of z

Throughout all experiments $\delta_z = \delta_x = \delta_y = 1$ and $\omega_z = 1.5, \omega_x = 3, \omega_z = 3$. The results are not sensitive to changes in these parameters. One problem we encountered is the reflection of sunlight. It will lead to wrong pattern interpretation, as sunlight contains a strong infrared light.

8 CONCLUSION AND FUTURE WORK

This paper presents a quad-rotor achieving automatic movements of take-off and landing by using low-cost and lightweight IR camera. Actual experimental results show that the Wii remote camera is able to provide accurate position information. By running on DSP processor, the PID controller is capable of estimating the position relative to the IR pattern and controlling the aircraft flying in accordance with the trajectory.

The inadequacies of this system are that the infrared filter in front of the IR camera cannot filter out the interference of sunlight and, the distance to the target is limited. Therefore, this system can only be used for indoor low-attitude flight. Higher and more complex actions should be using other sensors.

Increase the pattern size, using multiple LEDs per point or a more powerful LED, can increase the detection distance. However, the pitch and roll angle provided by the IMU are essential for computing the exact position. In future work, we intend to design a more accurate pattern, or use multiple IR cameras to obtain the attitude information of aircraft. If the achieved accuracy is sufficient, this will be able to control the aircraft without the IMU.

REFERENCES

[1] Bouabdallah, S., Noth, A., Siegwart, R.: PID vs LQ control techniques applied to an indoor micro quadrotor. In: IEEE International Conference on Intelligent Robots and Systems (IROS), pp. 2451–2456 (2004)

[2] Gurdan, D., Stumpf, J., Achtelik, M., Doth, K.M., Hirzinger, G., Rus, D.: Energy-efficient autonomous four-rotor flying robot controlled at 1 kHz. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 361–366. Roma, Italy (2007)

[3] Shakernia, O., Ma, Y., John, T., Sastry, K.S.: Landing an unmanned air vehicle: Vision based motion estimation and nonlinear control. Asian J. Control **1**, 128–145 (1999)

[4] Sharp, C.S., Shakernia, O., Sastry, S.S.: A vision system for landing an unmanned aerial vehicle. In: IEEE International Conference on Robotics and Automation (ICRA), Seoul, Korea, pp. 1720–1727 (2001)

[5] Saripalli, S., Montgomery, J.F., Sukhatme, G. S.: Vision-based autonomous landing of an unmanned aerial

vehicle. In: IEEE International Conference on Robotics and Automation. (ICRA), pp. 2799–2804. Washington, DC, USA (2002)

[6] Mak, L.C., Furukawa, T.: A 6 DoF visual tracking system for a miniature helicopter. In: 2nd International Conference on Sensing Technology (ICST), pp. 32–37 (2007)

[7] Wenzel, K.E., Zell, A.: Automatic take off, hovering and landing control for miniature helicopters with low-cost onboard hardware. In: Proceedings of AMS'09, Autonome Mobile Systeme 2009, pp. 73–80. Karlsruhe, Germany (2009)

[8] Wenzel, K.E., Zell, A.: Low-cost visual tracking of a landing place and hovering flight control with a microcontroller. J. Intell. Robot. Syst. 57(1-4), 297–311 (2009).

[9] Herisse, B., Russotto, F.X., Hamel, T., Mahony,R.E.: Hovering flight and vertical landing control of a VTOL unmanned aerial vehicle using optical flow. In: IEEE International Conference on Intelligent Robots and Systems (IROS), pp. 801–806 (2008)

[10] Guenard, N., Hamel, T.: A practical visual servo control for an unmanned aerial vehicle. In:IEEE International Conference on Robotics and Automation (ICRA), pp. 1342–1348 (2007)

[11] Sreedharan, S., Zurita, E.S., Plimmer, B.: 3d input for 3d worlds. In: OZCHI '07: Proceedings of the 2007 conference of the computer-human interaction special interest group (CHISIG) of Australia on Computer-human interaction: design, activities, artifacts and environments, pp.227–230. ACM, New York (2007)

[12] Schou, T., Gardner, H.J.: A Wii remote, a game engine, five sensor bars and a virtual reality theatre. In: OZCHI '07: Proceedings of the 2007 conference of the computer-human interaction special interest group (CHISIG) of Australia on Computer-human interaction: design, activities, artifacts and environments, pp. 231–234. ACM, New York (2007)