

Stabilization Position of Quadcopter Using Vision-Based Corner Detector from Top-Down Footage of Camera

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ABSTRACT

Quadcopter is a kind of robot which is popularly used in both academic and industrial environments. In this paper, we present and implement a method to stabilize a quadcopter prototype's position using feature extraction and tracking from camera footage. The quadcopter's position and linear velocity are determined from images which are captured by a downward-facing camera - Logitech C270. First, the Shi-Tomasi technique is used to detect corners in the images and from this method, displacement of the quadcopter is yielded. Linear velocity is then calculated by using the quadcopter's displacement. Once the linear velocity of the quadcopter has been estimated, the cascade PID controller is proposed to stabilize the hovering quadcopter's position. Simulation results prove the ability of the controller on Matlab/Simulink. Then, a real quadcopter prototype is built to evaluate the proposed method and the experimental results recorded in approximately 70 seconds show that the quadcopter remained in its position with minimal error.

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1. Introduction

With its simple and flexible structure, quadcopter is an unmanned aerial vehicle that attracts many interests in academic researches. The application of control algorithms for quadcopter has been studied in recent years [1], [2]. However, in order for the controller to work properly, values such as position, angle, and angular velocity measured from the sensor must be accurate. Tilt angle and angular velocity can be easily measured from Inertia Measurement Unit (IMU). However, in terms of quadcopter's linear velocity, IMU poses many challenges.

Usually, Global Positioning System (GPS) is integrated into quadcopter to determine the coordinates of quadcopter (Longitude and Latitude). In [3], a method of measuring position of quadcopter by GPS with Extend Kalman Filter was introduced. However, the drawback of this approach is the GPS only works in open spaces. In different studies, IMU is used to measure position of quadcopter in an indoor or GPS-denied environment by using the "integrating twice" formula [4], but this method is easily affected by noises. In addition, a method of measuring position for quadcopters using radio frequency and ultrasonic signal was introduced in [5].

The strategy of combining a camera to control quadcopter is a potential, flexible area, and there are many articles released in this area. [6] uses Simultaneous Localization and Mapping (SLAM) to estimate quadcopter position, [7] uses SLAM for navigation, mapping, and combine SLAM with IMU to improve the quantification position of quadcopter. Inspired by the research [8] and [9], authors aim to hover quadcopter in GPS-denied or indoor areas by using the optical flow method to estimate linear velocity and position of quadcopter.

In this paper, the process of displacement estimation for quadcopter consists of 5 steps. First, a downward-facing camera captures images from the field of view. Next, Shi-Tomasi corner detector [10] is applied to extract features because of its fast and reliable performance on uniformly distributed structures before Pyramid Lucas-Kanade (PLK) [11] is used to calculate the displacement of features between two consecutive frames. Eventually, pixel's displacement in image frame is converted into actual quadcopter's displacement. Intermediate results of this strategy are illustrated in Fig. 1.

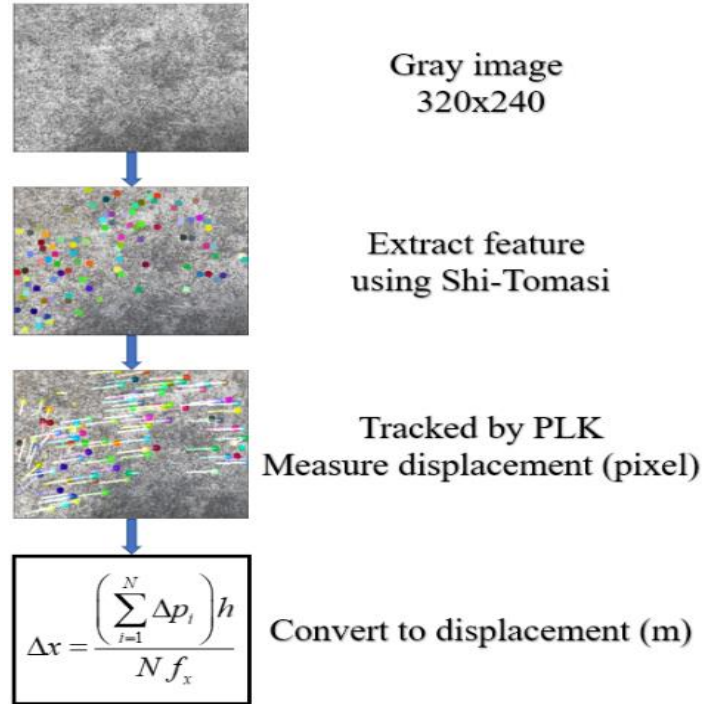


Figure. 1. Measure position scheme

Besides, authors use a cascade PID controller consisting of two stages. The first stage controls quadcopter in hovering and then uses linear velocity measured from the camera to stabilize position for quadcopter. To evaluate the algorithms and related methods, an experimental model is built in which these algorithms are deployed.

2. Measure position based optical flow

First, Shi-Tomasi method [10] is applied to detect good features. For a 2-dimensional gray image, Sum of squared differences of all pixels in window W is shifted (u,v) as follows

$$f(u,v) = \sum_{(x,y) \in W} [I(x+u, y+v) - I(x,y)]^2 \quad (1)$$

For ease of calculation, $I(x+u, y+v)$ term is approximated by Taylor series

$$I(x+u, y+v) \approx I(x,y) + I_x(x,y)u + I_y(x,y)v \quad (2)$$

Substituting (2) into (1)

$$f(u,v) = \sum_{(x,y) \in W} [I_x(x,y)u + I_y(x,y)v]^2 \quad (3)$$

Expand equation (3) and rewrite it as a matrix

$$f(u, v) = [u \ v] M \begin{bmatrix} u \\ v \end{bmatrix} \quad (4)$$

where,

$$M = \sum_{(x,y) \in W} \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix} \quad (5)$$

Our goal is to find windows where value of SSD calculated by formula (4) is large. Based on the eigenvalues of matrix M, score for Shi-Tomasi method is given by

$$R = \min(\lambda_1, \lambda_2) \quad (6)$$

where, λ_1 and λ_2 are eigenvalue of matrix M in (5).

After finding scores of all windows in image using Shi-Tomasi method, scores greater than given threshold is considered features.

Based on the position of features on image, Lucas-Kanade [12] is adopted to calculate features displacement between the previous frame and the current frame. Assumes displacement of pixel between two frames is small, equation for brightness constant is given by

$$I(x, y, t) = I(x + dx, y + dy, t + dt) \quad (7)$$

Equation (7) is linearized using a first-order Taylor series

$$I(x + dx, y + dy, t + dt) \approx I(x, y, t) + \frac{\partial I}{\partial x} dx + \frac{\partial I}{\partial y} dy + \frac{\partial I}{\partial t} dt \quad (8)$$

As mentioned, the displacement of pixels between two frames is small. Therefore, derivative term in (8) has a value of 0 and is rewritten as follows

$$I_x u + I_y v + I_t = 0 \quad (9)$$

where $u = \frac{dx}{dt}$, $v = \frac{dy}{dt}$, $I_x = \frac{\partial I}{\partial x}$, $I_y = \frac{\partial I}{\partial y}$, $I_t = \frac{\partial I}{\partial t}$

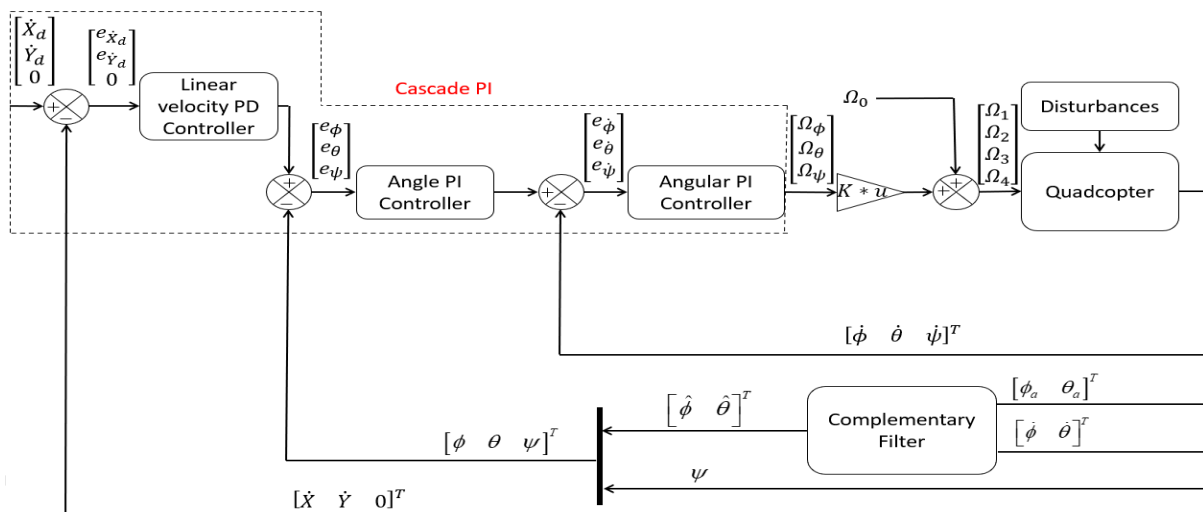


Figure. 2. Cascade PID for quadcopter

Considering in a window W $(x,y) \in W$, solution to equation (9) given by LK based on the least squared method is obtained

$$\begin{bmatrix} u \\ v \end{bmatrix} = - \begin{bmatrix} \sum_{(x,y) \in W} I_x I_x & \sum_{(x,y) \in W} I_x I_y \\ \sum_{(x,y) \in W} I_x I_y & \sum_{(x,y) \in W} I_y I_y \end{bmatrix}^{-1} \begin{bmatrix} \sum_{(x,y) \in W} I_x I_t \\ \sum_{(x,y) \in W} I_y I_t \end{bmatrix} \quad (10)$$

In reality, the pixel shift between two sequential frames is large. Therefore, the pyramidal implementation of Lucas-Kanade [11] is used instead to solve this problem.

Roughly, PLK changes large movements into small and small movements are ignored.

After calculating the displacement of features in image frame, displacement in reality is derived based on the geometry of similar triangles. Assuming tilt angle of quadcopter in hovering condition is small. Translation operation is used to convert displacement in pixels to displacement in meters and rotation operations is eliminated.

$$\Delta d = \frac{\left(\sum_{i=1}^N \Delta p_i \right) h}{N f_x} \quad (11)$$

where, $\Delta d = \begin{bmatrix} \Delta d_x \\ \Delta d_y \end{bmatrix}$ is displacement along x and y axes (meters), $\Delta p_i = \begin{bmatrix} \Delta p_{ix} \\ \Delta p_{iy} \end{bmatrix}$ is displacement along x and y (pixels). h is height of quadcopter from the ground, f_x is focal length of the camera and N is number of features.

Linear velocity is derived from displacement found in equation (11) and fed into cascade PID controller to control position for quadcopter.

The structure of cascade PID consists of 3 separate PID controllers. Whereas, the highest level is Linear velocity PD, followed by Angle PI and finally Angular PI. Initially, cascade PI is used for hovering control consisting of two stages, Angle PI and Angular PI. For stabilization position, a linear velocity controller is incorporated into cascade PID. Block diagram of cascade PID controller for quadcopter is shown in Fig. 2.

The complementary filter in Fig. 2 is expressed as follow

$$\begin{bmatrix} \hat{\phi}_t \\ \hat{\theta}_t \end{bmatrix} = \alpha \begin{bmatrix} \hat{\phi}_{t-1} + \dot{\phi} \\ \hat{\theta}_{t-1} + \dot{\theta} \end{bmatrix} + (1-\alpha) \begin{bmatrix} \phi_a \\ \theta_a \end{bmatrix} \quad (12)$$

Whereas, ϕ_a and θ_a are the raw angles calculated by accelerometer, $\hat{\phi}_t$ and $\hat{\theta}_t$ are the estimated angles, $\alpha = 0.98$ is filter gain.

For convenience, the estimated angles, $\hat{\phi}_t$ and $\hat{\theta}_t$, will be written as ϕ and θ in the rest of the paper

The state variables $\begin{bmatrix} \dot{X} & \dot{Y} & \dot{Z} & \dot{\phi} & \dot{\theta} & \dot{\psi} & \phi & \theta & \psi \end{bmatrix}^T$ of quadcopter are linear velocity along x, y and z axes, angular speed around x, y and z axes, roll, pitch and yaw angles, respectively. In Fig. 2, input of Linear velocity PD is linear velocity in x, y axis and output are the desired pitch, roll angle for Angle PI controller. Angle PI controller output produces the desired angular speed around the x, y, and z axes for

Angular PI controller. Since X-configuration quadcopter is adopted, angular speeds w.r.t roll, pitch and yaw movement are transformed to each propeller speed by equation (13)

$$\begin{bmatrix} \Omega_1 \\ \Omega_2 \\ \Omega_3 \\ \Omega_4 \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 \\ 1 & 1 & 1 \\ -1 & 1 & -1 \\ -1 & -1 & 1 \end{bmatrix} \begin{bmatrix} \Omega_\phi \\ \Omega_\theta \\ \Omega_\psi \end{bmatrix} \quad (13)$$

3. Experimental Results

Hardware model is shown in Fig. 4. Camera Logitech C270 is used for a downward-facing camera with angle camera of 60 degrees, resolution of 720p, frame rate of 30FPS. Computation is processed by Raspberry Pi 3B+ board with ARM Cortex-A53 1.4GHz CPU, 1GB. SRAM. Execution program uses OpenCV library to execute image processing operations. To speed up computation, image size is chosen at 320x240. For Shi-Tomasi method, the threshold for determining feature (corner) is 0.3, shift window is 7x7. For PLK method, the pyramid consist of 3 levels, a considered window is 15x15. In addition, during features tracking, features that fall out of frame are discarded, and if number of features is less than 10, features are re-detected.

According to measurement sensors and actuators (brushless motors), the Euler angle is measured by Inertia Moment Unit (MPU6050) and the height of the quadcopter is calculated through a pressure sensor BMP180. However, with low-cost IMU, a complementary filter is utilized to estimate tilt angles because of its simplicity. Regarding the actuators and relevant drivers, DJI Phantom 3 motors are controlled by electronic speed controllers (EMAX BLHeli 30A), hence, the relationship between PPM and motor's angular rate is modeled by the first-order transfer function within linear region.

The method which is used to measure motor's (propeller) angular speed is referenced by [11]. However, in this research, an infrared sensor is utilized instead of a microphone as proposed in [11] to measure period between each passage of the propeller blades T_p . Based on this measured period, the angular speed of motor is computed by the following equation

$$\omega = \frac{\pi}{T_p} \quad (14)$$

Through trial and error, control parameters for linear velocity in x and y, angle, angular rate are selected to make quadcopter takes off upright, stabilize hovering and position as well as possible. These parameters are chosen as follows

$$\begin{aligned} \begin{bmatrix} K_{p\dot{x}} & K_{d\dot{x}} \end{bmatrix}^T &= [1 \quad 0.1]^T; \quad \begin{bmatrix} K_{p\dot{y}} & K_{d\dot{y}} \end{bmatrix}^T = [1 \quad 0.1]^T; \\ \begin{bmatrix} K_{p\phi} & K_{i\phi} & K_{p\theta} & K_{i\theta} & K_{p\psi} & K_{i\psi} \end{bmatrix}^T &= [1 \quad 0.1 \quad 1 \quad 0.1 \quad 1 \quad 0]^T; \\ \begin{bmatrix} K_{p\dot{\phi}} & K_{i\dot{\phi}} & K_{p\dot{\theta}} & K_{i\dot{\theta}} & K_{p\dot{\psi}} & K_{i\dot{\psi}} \end{bmatrix}^T &= [0.5 \quad 0.6 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.3]^T \end{aligned} \quad (15)$$

The reason behind why the control parameters are chosen is according to [12]. The control terms are selected by the strategy proposed in Fig. 3. Since more damped response is not required, the D term is eliminated in quadcopter's stabilization

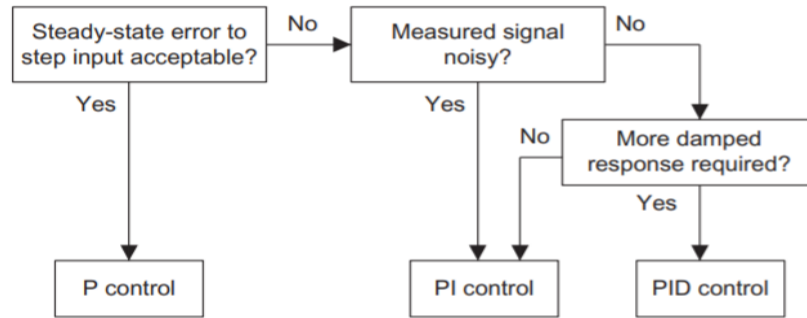


Figure 3. Strategy for choosing control terms [12]

About quadcopter’s stabilization, the procedure of control parameter calibration is that the P term is chosen sufficiently to make quadcopter stabilized around its setpoint, then, the I term is chosen for eliminating the residual error.



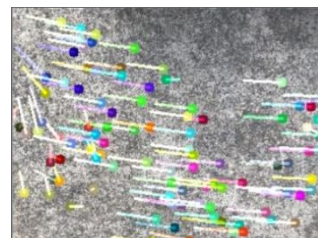
Figure 4. Implemented hardware



Figure 5. Quadcopter is hovering and holding position



(a)



(b)

Figure 6. Test-ground

Experimental results for quadcopter in 70s when hovering and holding position are shown in Fig. 7-12.

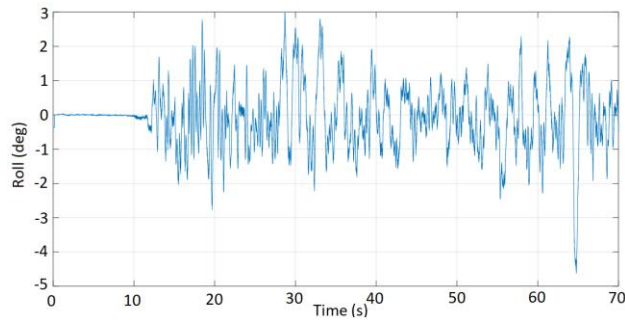


Figure 7. Response of roll angle

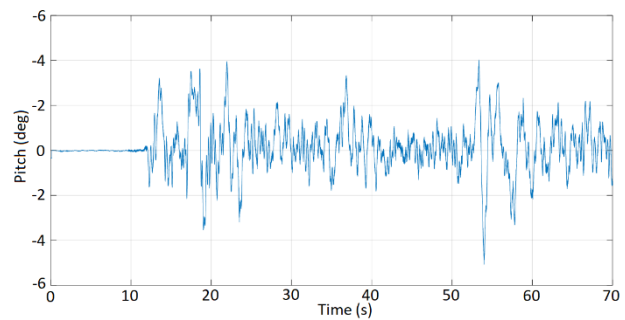


Figure 8. Response of pitch angle

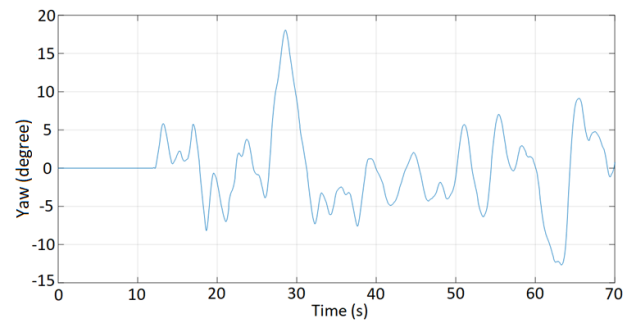


Figure 9. Response of yaw angle

The results of roll, pitch and yaw angle show that quadcopter hovered and not rotated around body. Due to the controller, roll angle and pitch need to respond quickly to keep quadcopter hovering and oscillate from -4 to 4 degrees.

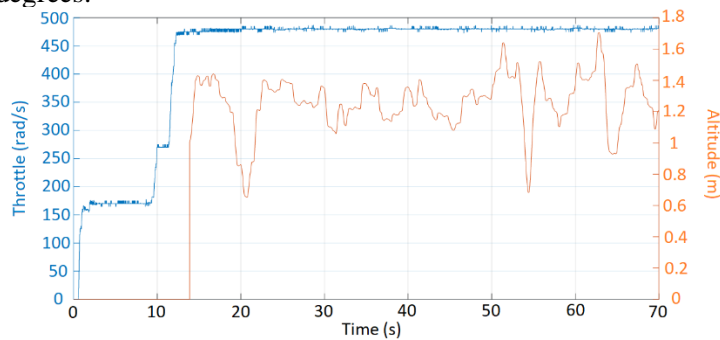


Figure 10. Throttle and respective altitude

Fig. 10 shows that when angular speed of four motors (throttle or Ω_0) reached 475rad/s, quadcopter took off from the ground and reached an altitude of about 1.3 m.

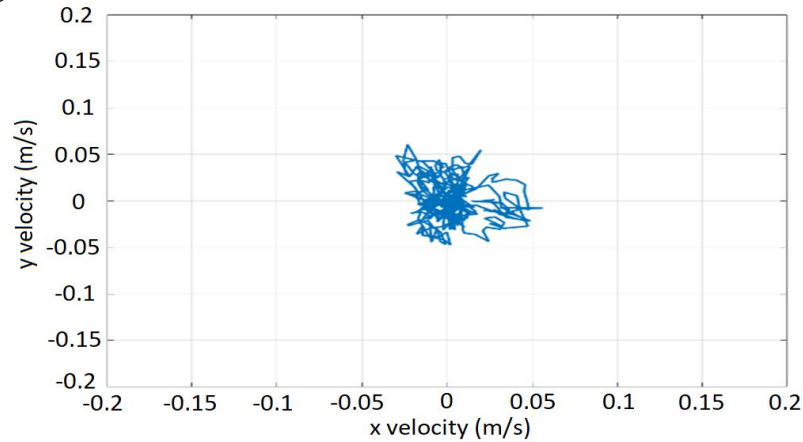


Figure. 11. Linear velocity of quadcopter

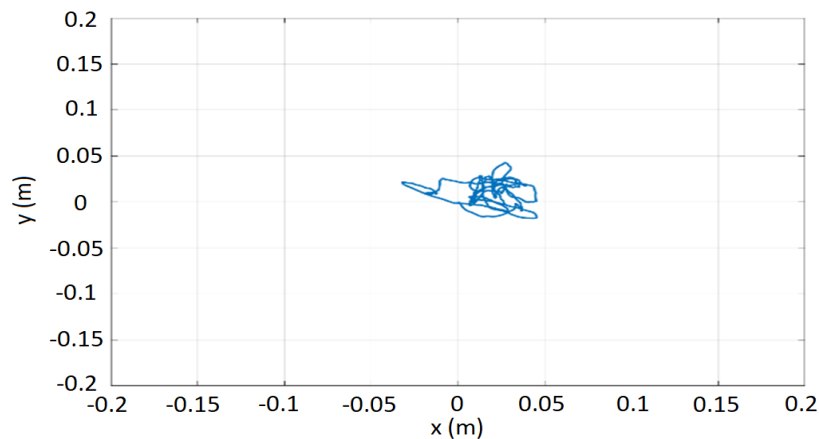


Figure. 12. Position of quadcopter in x and y-axis

Results of linear velocity and position in x, y axis (Fig. 11 and Fig. 12) show that quadcopter holds position in Earth-frame (velocity ranges from -0.08 to 0.08 m/s for both axes). However, Fig. 12 shows that quadcopter slowly drifts but not significantly (0.05m from x axis and 0.04m from y axis).

4. Conclusions

By extracting features from captured image, the position and velocity of quadcopter are successfully estimated with PLK method. Authors also present methods and processes for performing the calculation of this method in pixel and converting the pixel to meter. Furthermore, the proposed structure of cascade PID is shown with sub-blocks, the order of these sub-blocks, its' input, output and task description. In experimental stage, authors found consistent parameters for velocity estimation and cascade PID controller, which regulate the stability of real-time quadcopter and experimental results are demonstrated to prove that.

With the goal of stabilizing position of quadcopter, feature extraction method has not yet incorporated RANSAC for matching features. Moreover, experimental results have not been tested in more test-ground.

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