Development of a Micro Quad-Rotor UAV for Monitoring an Indoor Environment*

B.C. Min, C.H. Cho, K.M. Choi, and D.H. Kim

Department of Electrical Engineering, Kyung Hee University,
Seocheon-Dong, Giheung-Gu, Yongin-Si, 449-701, Korea
{minbc,movielove61,donghani}@khu.ac.kr
sm20s@naver.com

Abstract. The purpose of this paper is to develop a micro UAV (Unmanned Aerial Vehicle) as the platform for monitoring an indoor environment, more specifically, a quad-rotor aircraft that has strong advantages of its small size, stable hovering and precise flight. To begin with, we analyze the dynamics of a quad-rotor aircraft, and introduce control strategies based on the PD control. Then, the developed micro quad-rotor UAV, equipped with micro controllers, various sensors, and a wireless camera, is presented and is compared with the DraganFlyer commercial quad-rotor aircraft. Finally, experimental results are also provided so as to illustrate stable flight performances.

Keywords: UAV, quad-rotor aircraft, hovering, DraganFlyer.

1 Introduction

The UAV (Unmanned Aerial Vehicle) is widely used in many practical application e.g. research, surveillance and reconnaissance in specific regions or in dangerous regions which are inaccessible or hard to reach for other types of vehicles [1]. The UAV, which has such tremendous advantages, can be classified into two categories – fixed-wing aircraft and rotary-wing aircraft. When compared with fixed-wing aircrafts, rotary-wing aircrafts (rotorcrafts, helicopters) have specific characteristics like landing vertically in a limit space. Furthermore, such types are able to hover that make them suitable for applications that may be impossible to be performed using fixed-wing aircrafts [8].

Depending on their shape, rotary-wing aircrafts comprise several types of aircrafts. A single rotor aircraft, known as a standard helicopter, is one of the rotary-wing type aircrafts. This type aircraft is very hazardous to humans and other objects in an indoor environment due to the possibility that exposed rotor blades may collide with obstacles and cause the aircraft to crash. On the other hand, a quad-rotor aircraft is much safer in terms of the rotors, which are smaller and can be enclosed [3].

The most prevalent quad-rotor type UAV is DraganFlyer depicted as Fig.1, which is a radio-controlled quad-rotor aircraft commercially available from RCtoys[11]. Because of its tremendous advantages during flying, a number of research groups

* This work was supported in part by the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MEST) (R01-2008-000-20352-0).

J.-H. Kim et al. (Eds.): FIRA 2009, LNCS 5744, pp. 262–271, 2009.

have used it as the platform in order to implement experiments on their research [1] [2]. However, some groups often complain an outrageous price and hardware, which is very large and heavy when used in indoor environments [10].

For all these reasons, we develop a platform with a low cost quad-rotor type UAV for monitoring an indoor environment by means of light frames, and compact circuits. To begin with, it is obvious that UAV should be equipped with stable hovering and precise flight: this is essential for an application like data acquisition using an on-board wireless camera for taking distinct images of the indoor environment. Accordingly, we have primarily focused on analyzing the dynamics of the quad-rotor aircraft and designing controllers for its stable flight.

The rest of the paper is organized as followed: Section 2 presents the dynamics of the quad-rotor aircraft. Section 3 introduces a PD controller for assuring a stable and optimal system. Section 4 presents a description of the platform that we have designed for the micro quad-rotor UAV and shows the summary results of the experimental operations of the quad-rotor UAV. Finally, Section 5 summarizes our finding and future scope of work to improve the capabilities of the UAV.

Fig. 1. DraganFlyer, from www.rctoys.com

2 Dynamic Modeling of the Quad-Rotor Aircraft

Deriving mathematical modeling or differential equations is necessary for the control of the quad-rotor position and altitude. However, it is hard for the complicated structure of the quad-rotor type to express its motion with only a simple modeling. In addition, since the quad-rotor type aircraft includes highly nonlinear factors, we need to consider several assumptions in order to get a desired model [6].

1) The body is rigid and symmetrical.
2) The rotors are rigid, i.e. no blade flapping occurs.
3) The difference of gravity by altitude or the spin of the earth is minor.
4) The center of mass and body fixed frame origin coincide.

These assumptions can be formed because of slower speed and lower altitude of the quad-rotor aircraft whose body is rigid having 6 DOF (Degree of Freedom) as compared to a regular aircraft. Under these assumptions, it is possible to describe the fuselage dynamics. Therefore, to mathematically illustrate the fuselage dynamics of the quad-rotor type aircraft, a coordinate system should be defined. The coordinate system can be divided into an earth frame {E} and a body frame {B} as shown in Fig. 2.

The rotational transformation matrix between the earth frame and the body frame can be obtained based on Euler angles in Fig. 2 [1].

$$R_{EB} = R_\psi R_\theta R_\phi = \begin{bmatrix} C_\theta C_\psi & C_\psi S_\theta S_\phi - C_\phi S_\psi & C_\phi S_\theta C_\psi + S_\phi S_\psi \\ C_\theta S_\psi & S_\theta S_\phi S_\psi - C_\phi C_\psi & C_\phi S_\theta S_\psi - C_\psi S_\phi \\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi \end{bmatrix} \tag{1}$$

where C and S indicate the trigonometric cosine and sine functions, respectively.

The transformation of velocities between the earth frame and body frame can be derived from Eq. (1).

$$\begin{bmatrix} \upsilon \\ v \\ \omega \end{bmatrix} = R_{EB} \begin{bmatrix} \upsilon_B \\ v_B \\ \omega_B \end{bmatrix} \tag{2}$$

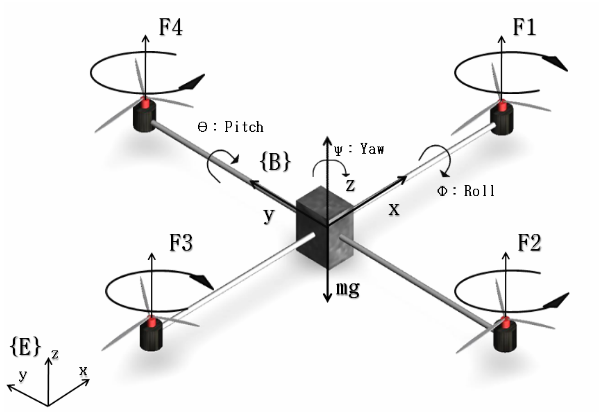


Fig. 2. The coordinate system with an earth frame {E} and a body frame {B}

Similarly, positions, forces, moments, accelerations and rotational velocities can be transformed based on R_{EB} between coordinate systems. In the body frame, the forces are presented as

$$F_B = \begin{bmatrix} F_{xB} \\ F_{yB} \\ F_{zB} \end{bmatrix} = \begin{bmatrix} 0\ 0\ 0\ 0 \\ 0\ 0\ 0\ 0 \\ 1\ 1\ 1\ 1 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} \tag{3}$$

Accordingly, in the earth frame, the forces can be defined as

$$F_E = \begin{bmatrix} F_{xE} \\ F_{yE} \\ F_{zE} \end{bmatrix} = R_{EB} F_B = \begin{bmatrix} C_\phi C_\psi S_\theta + S_\phi S_\psi \\ C_\phi S_\theta S_\psi - C_\psi S_\phi \\ C_\phi C_\theta \end{bmatrix} (\sum_{i=1}^{4} F_i) \tag{4}$$

Therefore, equations of motion in the earth frame are derived by the Newton's laws.

$$m \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} F_{xE} \\ F_{yE} \\ F_{zE} \end{bmatrix} - \begin{bmatrix} K_{fx} & 0 & 0 \\ 0 & K_{fy} & 0 \\ 0 & 0 & K_{fz} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} = \begin{bmatrix} F_{xE} - K_{fx}\dot{x} \\ F_{yE} - K_{fy}\dot{y} \\ F_{zE} - K_{fz}\dot{y} - mg \end{bmatrix} \tag{5}$$

where K_{fx}, K_{fy}, K_{fz} are the drag coefficients, which can be ignored at low speeds.

By extending the Newton's law on rotational dynamics, its equation can be written as [1]

$$\ddot{\theta} = \frac{l(K_l(\omega_3^2 - \omega_1^2))}{I_y} \tag{6}$$

$$\ddot{\phi} = \frac{l(K_l(\omega_4^2 - \omega_2^2))}{I_x} \tag{7}$$

$$\ddot{\psi} = \frac{K_d(\omega_1^2 + \omega_3^2 - \omega_2^2 - \omega_4^2)}{I_z} \tag{8}$$

where l is the distance from the center of rotors to the quad-rotor aircraft center of mass. K_l and K_d indicate the lift coefficient and drag coefficient respectively and w_i is the angular rotor speed. I_x, I_y, I_z are moments of inertia of the quad-rotor.

As a consequence, the complete dynamic model which governs the quad-rotor aircraft is as follows:

$$\begin{cases} \ddot{x} = \dfrac{(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)u_1 - K_{fx}\dot{x}}{m} \\ \ddot{y} = \dfrac{(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)u_1 - K_{fy}\dot{y}}{m} \\ \ddot{z} = \dfrac{(\cos\phi\cos\theta)u_1 - K_{fz}\dot{z}}{m} - g \\ \ddot{\phi} = \dfrac{l(u_2 - K_l\dot{\phi})}{I_x} \\ \ddot{\theta} = \dfrac{l(u_3 - K_l\dot{\theta})}{I_y} \\ \ddot{\psi} = \dfrac{(u_4 - K_d\dot{\psi})}{I_z} \end{cases} \tag{9}$$

where u_i (i=1, 2, 3, 4) are control inputs of the model.

$$\begin{cases} u_1 = F_1 + F_2 + F_3 + F_4 \\ u_2 = F_4 - F_2 \\ u_3 = F_3 - F_1 \\ u_4 = F_1 + F_3 - F_2 - F_4 \end{cases} \tag{10}$$

3 Control of the Quad-Rotor Aircraft

The PD controllers, which are widely used in the process industries, are implemented on each of the four axes of the quad-rotor aircraft, namely altitude, roll, pitch and yaw as depicted in Fig. 3 [5].

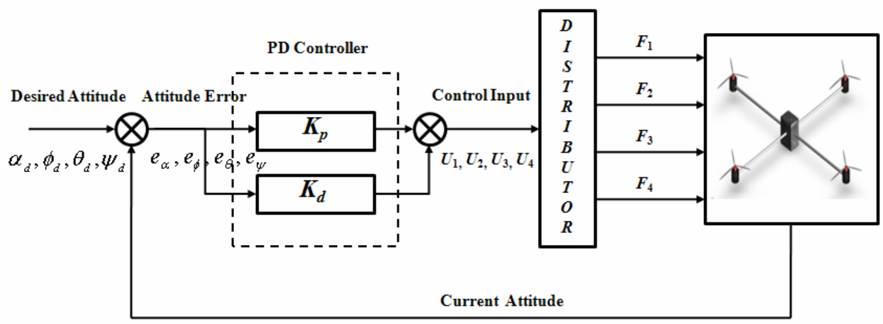


Fig. 3. A structure of the PD controller for controlling the altitude and the attitude of the micro quad-rotor UAV

3.1 Altitude Control

U_1, which is the control input with respect to the desired altitude a_d, is obtained from the PD controller [2] [7].

$$U_1 = \frac{K_{p1}(\alpha_d - \alpha) + K_{i1}\int_0^t (\alpha_d - \alpha)_{d\tau} + K_{d1}(\dot{\alpha}_d - \dot{\alpha}) + mg}{\cos\theta\cos\phi} \tag{11}$$

In Eq. (11), K_{p1}, K_{i1} and K_{d1} indicate a proportional, integral, and differential positive gains respectively. However, since effects causing a steady-state error like wind are not considered in this paper, integral terms can be eliminated. Hence, Eq. (11) can be simplified as

$$U_1 = \frac{K_{p1}(\alpha_d - \alpha) + K_{d1}(\dot{\alpha}_d - \dot{\alpha}) + mg}{\cos\theta\cos\phi} \tag{12}$$

3.2 Attitude Control

The motion along the x-axis and y-axis are related to the pitch and roll angles, respectively [4]. Hence, U_2 is given by

$$U_2 = K_{p2}(\phi_d - \phi) + K_{d2}(\dot{\phi}_d - \dot{\phi}) \tag{13}$$

The desired roll angle, in terms of the error between the desired angle and the actual angle, can be written as

$$\phi_d = \arcsin(K_p(y - y_d) + k_d(\dot{y} - \dot{y}_d)) \tag{14}$$

Similarly, the control input U_3, the desired pitch angle and the desired pitch angle velocity can be written as follows:

$$U_3 = K_{p3}(\theta_d - \theta) + K_{d3}(\dot{\theta}_d - \dot{\theta}) \tag{15}$$

$$\theta_d = \arcsin(K_p(x - x_d) + K_d(\dot{x} - \dot{x}_d)) \tag{16}$$

Furthermore, the control input U_4 for the control of the yaw can be derived as

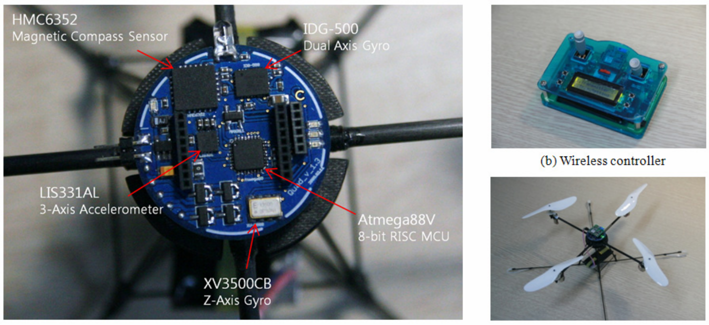
$$U_4 = K_{p4}(\psi_d - \psi) + K_{d4}(\dot{\psi}_d - \dot{\psi}) \tag{17}$$

4 Experimental Setup and Results

4.1 Experimental Setup

Main board. The main board architecture of the developed micro quad-rotor UAV is shown in Fig. 4 (a). The developed quad-rotor UAV has a 8-bit micro controller (Atmega88V) which is in charge of managing sensors, controlling four dc geared motors and communicating with a controller by a wireless. It is thus equipped with compact on-board sensors composed of two gyro modules, an accelerometer for attitude control of the UAV and a magnetic compass sensor for the control of its heading directions. Moreover, to receive the command data from the wireless controller (Fig. 4 (b)), a zigbee module allowing the wireless communication via a serial port, is also composed.

Hardware. To reduce the weight of the platform, carbon fiber robs were used for the whole body as depicted in Fig 4 (c). In addition, we have tried to keep the micro quad-rotor UAV as small as possible so that it performs well in an indoor environment. As a result, its specification, briefly given in Table 1, strikingly differs with the DraganFlyer. In Table 1, the lighter total weight of the developed quad-rotor UAV with batteries, which is almost one tenth of the DraganFlyer, means that it can be an efficient system compared with the DraganFlyer in terms of energy. Furthermore, the smaller size, which is a half of the DraganFlyer, signifies that it will be helpful to utilize it in an indoor environment.



(b) Wireless controller

(a) The designed circuit board for operating the quad-rotor UAV (c) The finalized platform for UAV

Fig. 4. The scheme of the developed micro quad-rotor UAV system

Table 1. Comparisons between the developed micro quad-rotor UAV and the DraganFlyer

Parameter	Developed micro quad–rotor UAV	DraganFlyer
total weight	41 g	482 g
height	85 mm	110 mm
diameter	300 mm	760 mm
blade	4″	12.375″

Table 2. Parameter values used in PD controllers

Parameter	Value	Parameter	Value
K_{p1}	0.32	K_{d1}	2.21
K_{p2}	7	K_{d2}	0.8
K_{p3}	17	K_{d3}	4.42
K_{p4}	1.23	K_{d4}	0.73

4.2 Experiments and Results

Fig. 5 shows that measured angle data from the accelerometer sensor, which is attached on the circuit board, are mixed with noise when speeding up motors. To eliminate the noise arising from vibrations of the body, we designed the RC filter composed with several resistors and capacitors.

The performance of the proposed control approach is illustrated in Fig. 6 through 8. Fig. 6 and Fig. 7 show the response of the PD controllers to stabilize the micro quad-rotor UAV, which was implemented from the tilted body at 40 degrees on the test bench as depicted in Fig. 9 on the lower right. In addition, we ignored any disturbances like wind during experiments because we assumed that the developed UAV is only used indoors.

Parameters that have been used for PD controllers are given in Table 2. Most parameters were derived by tuning gains until obtaining a better response of the system on the test bench [9]. However, PD gains of yaw control were nakedly obtained without the test bench because the test bench only allows UAV to roll from side to side.

In Fig. 6 and Fig. 7, left columns display the late response of roll and pitch angle with inaccuracy parameters, and right columns present the faster response of roll and pitch angle with adequate parameters. Thus, Fig. 8 shows the roll and pitch angles during hovering indoors. Accordingly, the rotational subsystem of the micro quad-rotor UAV seems to be completely controllable and observable. Finally, Fig. 9 shows an indoor flying test of the developed micro quad-rotor UAV with the designed wireless controller depicted in Fig. 4(b). Although it was not fully autonomous flight, we verified the effectiveness of its performance in the real indoor environments.

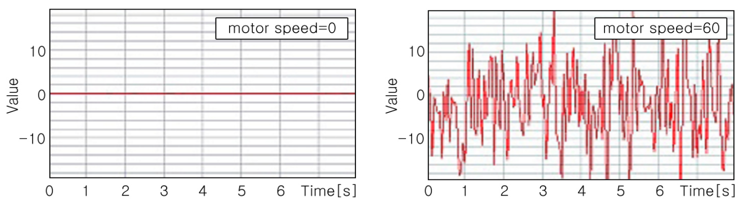


Fig. 5. Measured sensor data with noise when speeding up motors

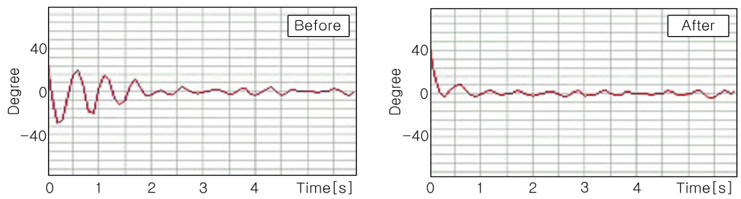


Fig. 6. Variations of roll angles with PD control

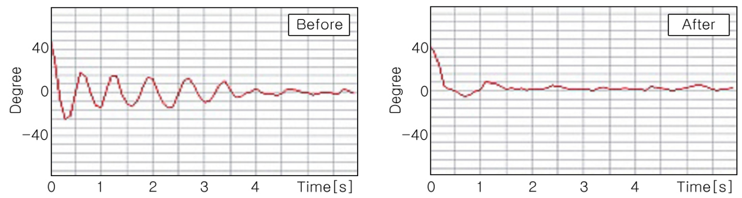


Fig. 7. Variations of pitch angles with PD control

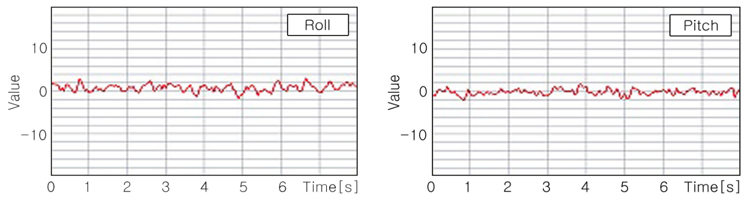


Fig. 8. Experimental results of the quad-rotor at hover

Fig. 9. The figure on the lower right is the designed test bench for experiments, and the figure on the center is the developed micro quad-rotor UAV during flight indoors

5 Conclusion

Since DraganFlyer, which is commercially the quad-rotor type UAV, has tremendous advantages as the platform, a number of research groups have used it so as to implement experiments on their research. However, some groups often complain that it is outrageous price and large size.

Accordingly, in this paper, we have presented the platform composed of the developed the micro quad-rotor UAV and the designed stabilization control algorithm. The developed quad-rotor UAV was built with light frames, compact circuits as small as possible. Furthermore, it was implemented with low cost, within the premise that its specification is outstanding compared with DraganFlyer.

As a result, the experimental results have shown that the designed platform is performing well in terms of stable flight. However, we did not verify the control of the altitude because the developed quad-rotor UAV is not yet equipped with an ultrasonic sensor measuring the distance between the ground and it even though the control strategy is designed in this paper. Hence, we will use various sensors in future research in order to improve the flight performance, and further study will be focused on autonomous flight. To be specific, a navigation system and the control strategies for avoiding obstacles will be studied.

References

1. Castillo, P., Lozano, R., Druz, A.: Modelling and Control of Mini-Flying Machines, 1st edn. Springer, London (2005)
2. Lara, D., Sanchez, A., Lozano, R., Castillo, P.: Real-Time Embedded Control System for VTOL Aircrafts: Application to stabilize a quad-rotor helicopter. In: 2006 IEEE Symposium Intelligent Control, pp. 2553–2558 (2006)
3. Valavanis, K.P.: Advances in Unmanned Aerial Vehicles, 1st edn. Springer, Heidelberg (2007)
4. Erginer, B., Altuġ, E.: Modeling and PD Control of a Quadrotor VTOL Vehicle. In: IEEE explore of Intelligent Vehicles Symposium, pp. 894–899 (2007)
5. Park, S., Won, D.H., Kang, M.S., Kim, T.J., Lee, H.G.: RIC (Robust Internal-loop Compensator) based flight control of a quad-rotor type UAV. In: 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1015–1020 (2005)
6. Bouadi, H., Bouchoucha, M., Tadjine, M.: Sliding Mode Control based on Backstepping Approach for an UAV Type-Quadrotor. International Journal of Applied Mathematics and Computer Sciences 4(1), 12–17 (2008)
7. Kuo, B.C., Golnaraghi, F.: Automatic Control Systems, 8th edn. John Wiley & Sons. Inc., Chichester (2003)
8. Bouabdallah, S., Murrieri, P., Siegwart, R.: Design and control of an indoor micro quadrotor. In: Proceedings of IEEE International Conference on Robotics and Automation, vol. 5, pp. 4393–4398 (2004)
9. Ledin, J.: Simulation Engineering, 1st edn. CMP Books (2001)
10. Lillywhite, K., Lee, D.J., Tippetts, B., Fowers, S., Dennis, A., Nelson, B., Archibald, J.: An embedded vision system for an unmanned four-rotor helicopter. Robotic Vision Laboratory, Department of Electrical and Computer Engineering, BrighamYoung University
11. DraganFlyer, `http://www.rctoys.com/draganflyer3.php`