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Control Platform Design and Experiment of A Quadrotor

JIANG Jun[1,2], QI Juntong[1], SONG Dalei[1], HAN Jianda[1]

1. State Key Laboratory of Robotics, Shenyang Institute of Automation Chinese Academy of Sciences, Shenyang 110016

2. University of Chinese Academy of Sciences, Beijing 100049

E-mail: qijt@sia.cn

Abstract: Quadrotor helicopter control is nowadays a hot issue in the field of unmanned aerial vehicle (UAV) research due to its unique advantages compared with traditional helicopters. However, the complex structure and low loading ability make control platform building and control algorithm verifications very hard. To solve this problem, this paper starts with brief review of the quadrotor history after which the development of quadrotors is analyzed. The advantages of the quadrotor are narrated logically due to their inner relationship. Then, the frameworks of several famous quadrotor UAV are enumerated and the design of an autonomous quadrotor helicopter SIAQR(SIA QuadRotor) is introduced. The paper further elaborated the structure of the whole system and components of the flying robot, and the detail design of the critical subsystems is also discussed. The dynamics of the flying robot in the near hovering mode is analyzed based on Newton-Euler equation. This paper further verified the performance of the control system by implementing the PID control algorithm on the quadrotor platform. The experiments showed the efficiency of the designed control system for SIAQR. Hover flying is achieved through the above mentioned control approach, and the performance is analyzed through the data recorded onboard. At the end of this paper, a conclusion is drawn and we believe that this experimental system paves way for further research.

Key Words: Quadrotor, control platform design, flight experiments

1 Introduction

The quadrotor has been an eye-catching flying robot during the last decade，but the history of the quadrotor is much longer than that. In 1907, the first quadrotor Bréguet-Richet Gyroplane No. 1 lifted off the ground in France. The brief flight attained an altitude of only two feet [1]. Several other tries on flying quadrotors were executed in early years of early 1920s, but due to the limitation of technology at that time, none of these succeeded. Between 1920 and 1990, quadrotors seldom showed up except in 1956 and 1958 when the attitude control of quadrotor was refined by applying using differential thrust between pairs of rotors. The early attempts of controlling quadrotor stopped in the middle of 20th century.

People restarted researching on quadrotor control from the late 1990s thanks to the rapid growth of MEMS(micro electro mechanical systems)[2], which make design of micro controller possible. Initial attempt to build micro quadrotor was launched by hobby production. One of the most famous products is the Draganflyer series of quadrotor (http://www.draganfly.com/), DraganflyerIII is a classic version among the series, whose tip-to-tip length is 76.2cm, and weighs 481.1g. Its propeller diameter is 28cm and payload is up to 113.2g, the duration of flying is 16~20min. Due to its outstanding performance, Draganflyer was widely used in research field. For instance, the Draganflyer series of quadrotor has been refined to be test-beds at Stanford [3] and the Massachusetts Institute of Technology[4]. Some research groups opt for designing their own quadrotor instead of modifying commercial RC quadrotors as their test-beds. For example, Australian National University designed and built an X4-Flyer[5]. Pennsylvania State University tried to build a quadrotor with off-the-shelf components, and replaced the commercial controller with the self-designed 8-bit microcontroller[6]. Stanford University detailedly and successfully developed their test-bed Mesicopter, including aerodynamic design, fabrication, power systems[7]. In [8]Swiss Federal Institute of Technology developed OS4 with total weight up to half kilo.

In the middle of the first decade in the 21th century, most pioneers in the quadrotor research field had finished their prototypes and tried many kinds of existing control algorithm on their separate test-beds. From that time on, research on the quadrotor diversified. MIT and Technische Universität München[9] developed a three-level sensing hierarchy indoor navigation system, and tested the algorithm on a developed quadrotor. Chiba University[10] presented a visual navigation system as an alternative pose estimation method for environments and situations in which GPS is unavailable. GRASP in [11] developed a formation control algorithm, and in [12], it considered the planning and control of multiple aerial robots manipulating and transporting a payload in three dimensions via cables. Y. Bouktir in[13] researched on the path planning problem for the quadrotors and simulation. Gabriel M. Hoffmann[14] developed a trajectory tracking algorithm through cluttered environments for the STARMAC platform.

One most promising direction can be summarized as ‘aggressive maneuver’. Three groups pioneer in this field. Pennsylvania in [15] designed a learning algorithm control algorithm for perching maneuver. Lupashin from ETH developed a simple and intuitive policy gradient method for improving parameterized quadrotor multi-flips in [16]. Due to the inner characters of quadrotors, aggressive maneuver

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has becoming a promising direction for quadrotor control research.

Aggressive maneuver calls for stricter demand of the platform, which is discussed in the following 4 aspects. Firstly, in aggressive maneuver, low control frequency increases error in trajectory tracking. Secondly, more powerful computational ability is required because of the complexity of dynamics in this scenario. Thirdly, reliability is emphasized in aggressive maneuver, otherwise the out-of-control high speed flying robot may severely injured people around. Last but not the least, mechanical structure should be tough, light, small inertial, and easy to repair. To this end, an aggressive-maneuver-oriented quadrotor system was designed and built. A simple control algorithm was implemented to testify the system.

The next section discusses the characters and principles of the quadrotor. In section III, our platform design is introduced in detail. The dynamics of the quadrotor is deduced in section IV. To verify the capability of the system, we tested the flying robot which is discussed in section V. At the end of the paper, we introduced the plan for future work.

2 Characters and Principle of Operation

Compared with traditional helicopters, quadrotors are simpler in mechanical composition. A quadrotor typically has a rigid frame with four motors at each end. Four propellers are mounted on each motor directly without any transmission mechanism in between. This greatly reduces the nonlinear component when analyzing the dynamic model. Fig. 1 shows the advantages and disadvantages of the quadrotors compared to traditional helicopters. The colored represents the disadvantages and the non-colored ones represents the advantages of the quadrotors compared to traditional helicopters. The arrows show the relationship of the two components which it connects, with the pointed being the result of the other one. From this diagram we can see that the structure simplicity of the quadrotor contributes most of its advantages while the layout of this kind of helicopter is so controversial that contributes both advantages and disadvantages.

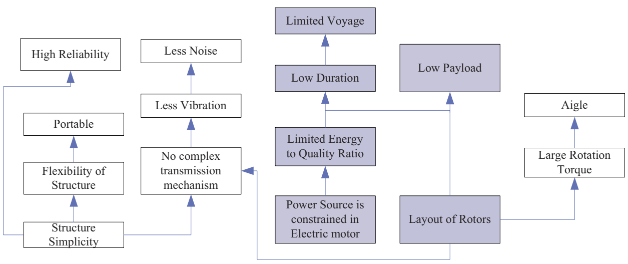
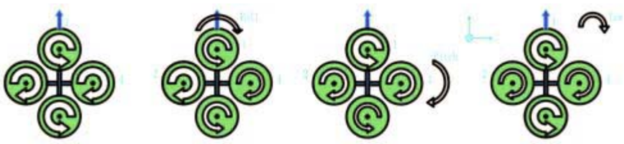


Fig. 1 Advantages and disadvantages of quadrotor



(a) (b) (c) (d)

Fig. 2 Operational principle of quadrotor

Like any other mobile robot, a quadrotor has 6 DOF (degree of freedom). However, the quadrotor has only four inputs, which makes an under-actuated and nonlinear system. To drive a quadrotor to move, three torques must be implemented along the according axis, and a collective thrust should be implemented along the hub. For convenience, we number the front, left, rear, right rotors with 1, 2, 3, and 4 respectively. For each propeller, the thrust is proportional to the square of the rotation speed, and the torque is also proportional to the square of the rotation speed. By driving rotor 1 and rotor 3 in clockwise and rotor 2 and rotor 4 in anti-clockwise Fig. 2 (a), the reaction torque generated from the first pair of motors is exactly cancelled off by the reaction torque from the second pair of motors, the yaw angle is held. Ideally, if each actuator produces one-fourth of the vehicle's weight, the quadrotor will achieve a stationary hover. The torque imposed on each rotor is also proportional to the square of the rotation speed. If rotor 2's speed is increased and 4's speed is reduced in the same magnitude, then rotor 2 produces more lifts than rotor 4 without changing the total torque imposed on the body, because the torque change on 2 and 4 is cancelled by each other (see Fig. 2 (b)). The performance of pith action is the same with above (see Fig. 2 (c)). Increasing speed of rotor 1 and 3, and reducing the speed of rotors 2 and 4 at the same time cause rotation around z axis (see Fig. 2 (d)).

3 The Construction of the System

The helicopter group from SIA (Shenyang Institute of Automation, China) has been concentrating on research in helicopter design and control algorithm for more than 10 years. Great efforts have been put into these research, and a handful amount of research outcomes can be studied in[17-20]. The building of quadrotor in our group took its first step in late 2010, a quick progress has been made thanks to the prior endeavor within this group.

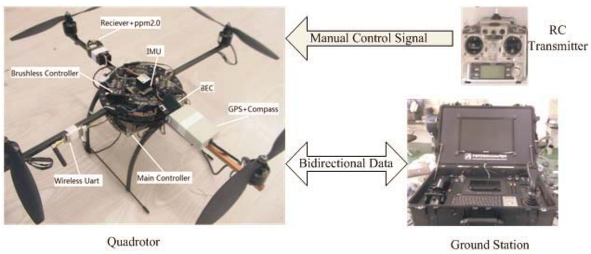


Fig. 3 Overview of the whole system

Typical quadrotor system contains a flying robot (the quadrotor), a ground station (GS), a RC Transmitter, and additional equipments aims at respective purposes in different groups. We divide the whole system into the following 3 subsystems as is shown in Fig. 4. The flying robot is the most important component in the whole system. It holds most parts of the whole system except for the communication subsystem. Fig.3 shows the whole system we developed.

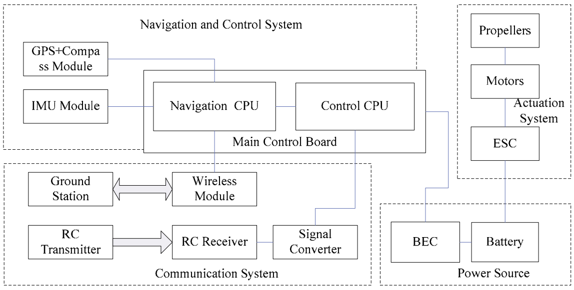


Fig. 4 The whole system

3.1 The Body of the Quadrotor

For aggressive maneuver, the body is supposed to be light, strong, and small inertial. We traded off the above mentioned factors and finally chose the MK's design for our quadrotor body for the following reasons. 1) Commercial bodies helps fast carry out of our research. 2) The rigidness of the frame is highlighted. 3) Considering the quadrotor may crash from now and then, the replacement of its frame parts should be easy, cheap, and time-saving. The frame of MK quadrotor is the perfect candidate, for it is rigid enough because of the four aluminum pipes, and takes advantage of industrial part which ensures the low-price and achievable of the material.

3.2 The Actuator System

Typically it includes the following components: the brushless motor, the propeller, the ESC (electronic speed controller) and the battery, as can be seen in the Fig.5. Aggressive maneuver requires high thrust-quality ratio, fast respond.

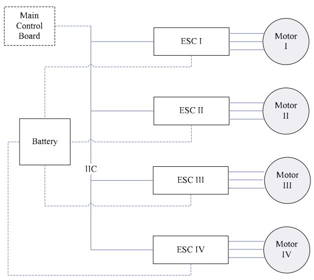


Fig. 5 Actuation system

We reserved the original design of the actuator of the MK system, for the actuators behaved well during our trials of the original system. Special made propellers are more efficiency, but these propellers are too expensive to be our choice. The reserved propeller is 1205 in dimension and is able to produce 2 kilogram thrust under the motor's 200W maximum power which ensured large thrust-quality ratio. Though pan-shaped motors are considered as more efficiency, we reserved the original ones for fast respond. Original battery was replaced for purchase reasons. This combination ensures 15 minute flying. The actuation subsystem receives signal through IIC bus with the speed of 400k which ensure the respond speed.

3.3 The Communication Subsystem

The aggressive-oriented controller features large data exchange, which imposes heavy burden on the communication system. The typical structure of this kind of communication is illustrated in Fig. 6. There two channels in the communication system. The GS and the main controller exchange data through bidirectional wireless module, while the RC transmitter sends data to the controller without receiving any information from it.

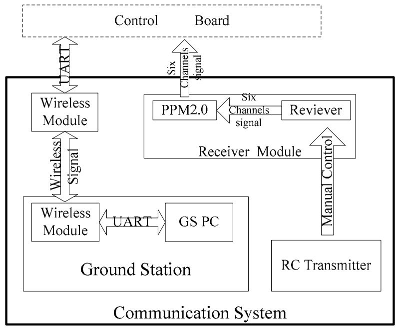


Fig. 6 Communication system diagram

Wireless Module

Currently used small communication modules includes: wireless UART and industrial wireless modem. We chose a cheap, small and light module which is shown in the picture, this module each is 37.5mm×23mm×5mm in dimension and weights 10g, the maximum operation range is 1500m. We chose 11520bps again with a little discount of communication distance. Wireless transferring consumes great current, this module costs 5-100mw that is less than 1/100 the total consumption.

RC Transmitter and Ground Station

We chose FF9 as our transmitter. The widely use of this old but powerful transmitter proved its reliability. This transmitter has 9 channels, enough for our experiments. The buttons and switches on the body provided enough flexibility for future experiment.

The ground station is previously designed and manufactured by colleagues in our group, it is a powerful ground station and has many useful functions such as: monitoring the sates of the flying robot through home-developed software, controlling the flying robot and the equipment on it through operating the sticks on the station, setting parameters to the flying robot using mouse and keyboard on it.

3.4 The Navigation and Control Subsystem

The navigation and control system is the core of the whole system. To meet the demand of fast control speed, two CPU structure is applied. Fig.7 shows the composition of our navigation and control system design.

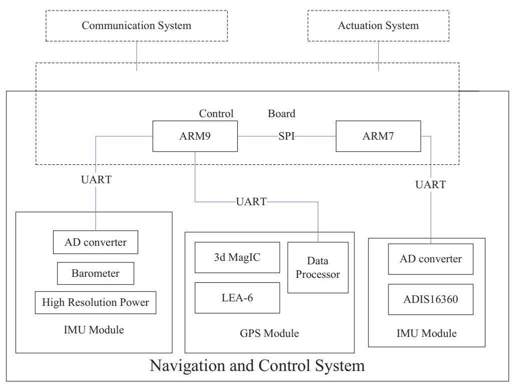
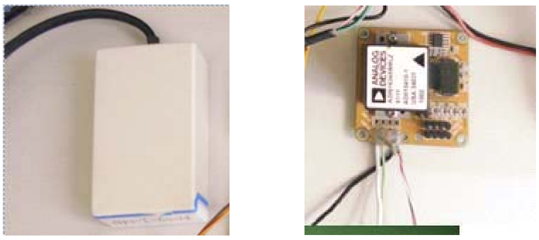


Fig. 7 Navigation and control system diagram

Sensor and Data Acquisition Modules

Typically, outdoor-oriented navigation system needs gyros, accelerators, GPS, compass, barometer to get enough data for state estimation. In this design, the sensors are organized in a reasonable way. Two modules are built, and barometer is installed on the main board.



(a) GPS module (a) IMU module

Fig. 8 GPS and IMU modules

GPS Module

The navigation system needs absolute position information and heading information. Typical UMAV navigation system use GPS module and magnetic compass to provide this information. A GPS+compass module was built in our group (See Fig. 8 (a)), which is proved to be reliable. There are four reasons for this design: 1) Compass is an electromagnetic interference sensitive part which is not supposed to be on the main board where electromagnetic interference is server. 2) Like the IMU, the GPS and compass needs special mounting direction. 3) Being together in a small package makes it easy for the two parts to be mounted. 4) GPS module is not supposed to be mounted in the body of the flying robot where them main control board is usually built.

IMU Module

Dispersive parts of gyros and accelerators are cheaper in price but the position accuracy is not guaranteed, especially when large acceleration is imposed to the quadrotor. To make relatively more reliable IMU, we chose ADIS16360. It is a six-degree of freedom inertial sensor, and provides a simple, cost-effective method for integrating accurate, multiaxis inertial sensing into industrial systems. This compact module is approximately 23 mm × 23 mm × 23 mm and provides a flexible connector interface that enables multiple SPI-compatible serial interfaces. Its bandwidth is 330 Hz, enough for our scenario. Triaxis digital gyroscope with digital range scaling ±75°/sec, ±150°/sec, ±300°/sec settings, and orthogonal alignment is less than 0.05°. Triaxis digital accelerometer: ±18 g mounting orientation options, large enough for aggressive maneuver. Again we made an independent module for the IMU ((See Fig. 8 (b))). By installing the module in on the CoG(Centre of Gravity), we achieve better IMU performance. We implemented a filter algorithm to preprocess the data from the sensors and further pass the processed data to the main control board though UART. The data transfer rate is 115200 bps equal to other home-made modules'.

Barometer

Barometer is sensitive altitude sensor and responds fast to altitude change, and it compensates the GPS which respond slow and work at low frequency. As a barometer is easily disturbed by the winds and temperature, it is built on the main controller board where wind does not exit and sunshine is avoided. We consider the accuracy as the most important thing in the choice of the barometers. The accuracy of MPX6115 (0 to 85°C) is ±1.5 %VFss, relatively high than other products at this price grade. To take advantage of its high accuracy, AD7790 is used to convert analog signal from the sensor. Test results shows the accuracy is up to 0.4m.

Main Controller

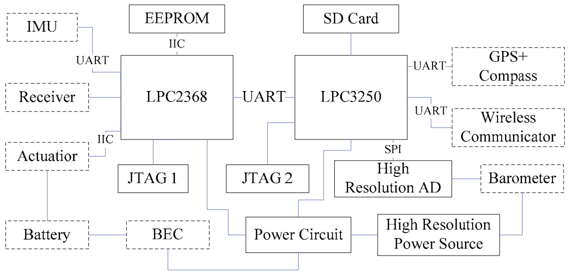


Fig. 9 The main control board

1) Auxiliary design for the control board:

Power source: In order to minimize the weight and simplify the complexity of the system, a BEC is used to shunt electricity from the power battery and, supply current to the main control board. The BEC weighs 36g, and saves 177g for the whole system. Debug Interface: To easy the debug process, we saved Jtag debug interface for both of the CPUs. As has been introduced before, UART is widely used in the independent modules. Instruction LEDs are also designed for interactive. SD card: a SD card adapter is soldered on the main board to record flight data for off-line analysis. Fig.9 depicts the configuration of the main board, and Fig.10 is a real controller.

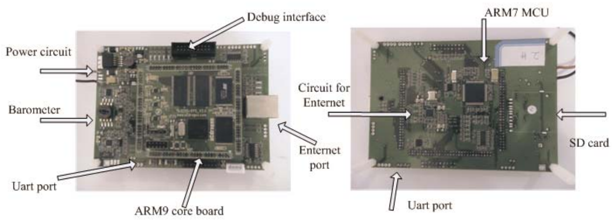


Fig. 10 Main control board

2) CPU cooperation:

The main control board has two CPUs both of which belong to LPC series controllers because of their reliable performance in industrial application. The dual CPU design aims at fully use the computing capacity of the chips. LPC2368 (ARM7) is used for regular computations such as: IMU data acquisition, the ESC command sending, LPC2368 is based on a 32-bit ARM7TDMI-S CPU which runs at up to 72 MHz. The high computing rate ensures the control algorithm running in the CPU which has been verified in the earlier controller. Actuation system is also instructed by the lower level controller, the communication speed is set to 400k for fast respond of the control system. Instruction from the receiver is preprocessed by the ppm2.0 module which combined six channels information into one. The periodicity for this manual instruction is approximately 17 ms, shorter than the control periodicity. All the parameters are recorded in AT24C256 on this board at the same frequency of the control instruction. To ensure high reliability, no more burden is imposed on this chip.

To become a powerful candidate for changeful experiments, Operation system is considered to deal with potentially complex work, uCosII is a powerful and reliable real-time system that is a heavy burden for LPC2368 so we applied an LPC3250 for running uCosII. Three missions have been imposed on to this controller, namely running the calculation of the attitude codes and coping with stochastic missions. Data acquisition is also partly done by this chip, for example, the barometer data and the GPS module data are all processed in this chip. This is mainly because of former work on this design, and this saved a lot of time. We chose the commercial core board YL3250, which contains SDRAM 64M, NAND Flash 32MB, NOR Flash 2MB；High frequency leads to difficulty, The choice of commercial core board saves troubles in the circuit design. This is proved by the stable performance of the new system.

4 The Overview of the Flying Robot Dynamics

In this section we present a classic PID controller for the attitude control of the system, this controller verified the feasibility of the system. Normally, two approaches lead to model a quadrotor dynamic equation. One is to use Lagrangian and the derived formula for the equations of motion, the other is Newton-Euler Formalism. In this paper, the second way is applied as showed in formula (1). The derivation of the dynamic of our test-bed follows North-East-Down (NED) inertial coordinate, in the following text, subscript E denotes the Earth coordinate which in our case is considered as the inertial coordinate, subscript B denote the body coordinate with the origin coincident with the CoG of the test-bed. x_B , y_B , z_B respectively denotes the unit vectors along the front , the right , and down direction. Euler angles of the body axes are [21] with respect to the e_N , e_E and e_D axes, respectively, and are referred to as roll, pitch and yaw. Rotation matrix R can be presented by roll, pitch, and yaw as can be seen in formula (2). To simplify the problem, CoG (centre of the gravity) is assumed to be coincident with the centre of the collective thrust, and other external forces are also assumed to be at the same point. The following equation describes the relationship between the force imposed on a rigid body and the movement the body takes.

$$\begin{bmatrix} mI_{3\times3} & 0 \\ 0 & I \end{bmatrix}\begin{bmatrix} \dot{V} \\ \dot{\omega} \end{bmatrix}+\begin{bmatrix} \omega\times mV \\ \omega\times I\omega \end{bmatrix}=\begin{bmatrix} F \\ \tau \end{bmatrix} \quad (1)$$

Where $I_{3\times3}$ represents the inertial matrix, V represents for the translational velocity, and ω stands for the angular speed of the main body. In our application, there exists no coriolis acceleration，so the second phase of the left hand of the equation is zero. According the coordination we use, the rotation matrix is shown as below.

$$R=\begin{pmatrix} c\phi c\theta & c\phi s\theta s\varphi - s\phi c\varphi & c\phi s\theta c\varphi + s\phi s\varphi \\ s\phi c\theta & s\phi s\theta s\varphi + c\phi c\varphi & s\phi s\theta c\varphi - c\phi s\varphi \\ -s\theta & c\theta s\varphi & c\theta c\varphi \end{pmatrix} \quad (2)$$

where c represents $\cos$ and s represents $\sin$ .Gary Fay in[22] derivated aerodynamic forces for the Mesicopter Simulation in detail. Each rotor produces thrust T_i along the axis of the rotor, according to aerodynamic, $T_i = k_1 \times \Omega_i^2$, and the moment it produces is $M_i = k_2 \times \Omega_i^2$, where k_1 and k_2 are positive coefficient. so for a rotor the ratio from T_i to M_i would be γ. We currently focus on the hover scenario, so the first line of the Newton-Euler equation which represents the translation movement is neglected. The second can be written as formula (3).

$$I\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix}=\begin{bmatrix} l(F_2-F_4) \\ l(F_3-F_1) \\ M_1-M_2+M_3-M_4 \end{bmatrix}-\begin{bmatrix} p \\ q \\ r \end{bmatrix}\times I\begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (3)$$

Where l represents the distance from the according actuator to the CoG, p, q ,r are the rotation speeds. Again in hovering condition, the angular velocity is negligible, so the right item in the above equation is omitted. Let $u_1 = F_1 + F_2 + F_3 + F_4$; $u_2 = (F_2 - F_4)\times l$; $u_3 = (F_1 - F_3)\times l$; $u_4 = \gamma(F_1 - F_2 + F_3 - F_4)\times l$

As the roll and pitch angle are small, the transformation matrix (shown in formula (2)) from the body coordination to the Earth coordination is assumed to be I, so the relationship between the Euler angles and body rotation angles are decoupled. We assume u_2 control roll rotation, u_3 control pitch rotation, u_4 control the yaw rotation, the inputs are calculated by formula (4), (5), and (6).

$$u_2 = k_{p1}(\phi_{des}-\phi)+k_{d1}(\dot{p}^{des}-\dot{p})+k_{i1}\int(p^{des}-p)dt \quad (4)$$

$$u_3 = k_{p1}(\theta_{des}-\theta)+k_{d1}(\dot{q}^{des}-\dot{q})+k_{i1}\int(q^{des}-q)dt \quad (5)$$

$$u_4 = k_{p2}(\varphi_{des}-\varphi)+k_{d2}(\dot{r}^{des}-\dot{r})+k_{i2}\int(r^{des}-r)dt \quad (6)$$

In our test, the total thrust is manually controlled, the operator gives the instruction through manipulating the stick on the transmitter.

5 Experiments

Class PID control algorithm is implemented and parameters are fine adjusted to achieve high hover flying performance. The upper window in Fig. 11 shows the roll angle in hover mode, and the lower presents the according control input. Roll angle is restricted within 1 degree, and small disturbance occurred around 5000 is restrained in a short time. Fig. 12 shows the quadrotor in flight.

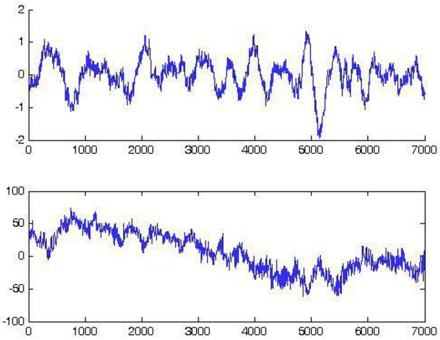


Fig. 11 Roll stabilization

Fig. 12 Quadrotor in-flight

6 Conclusion and Future Work

This paper shows the history of quadrotor briefly, and analysis the development of the quadrotors. A full function quadrotor test-bed is designed and tested. A PID algorithm is implemented on the platform and attitude stability is obtained by flight experiments. The results from the experiments show that the whole system is reliable and effective for control experiments. In the future, we will focus on aggressive flight control research and do some flight tests bade on the designed quadrotor platform.

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