Design and Control of a Quad-Rotor Flying Robot For Aerial Surveillance

Kong Wai Weng, Mohamad Shukri b. Zainal Abidin
Center for Artificial Intelligence And Robotic (CAIRO)
Universiti Teknologi Malaysia, City Campus,
Jalan Semarak 54100, Kuala Lumpur, Malaysia
Email: waiweng83@gmail.com, shukri@fke.utm.my

Abstract – **This paper presents the control of a Quad-Rotor VTOL (Vertical Take Off and Landing) Flying Robot as an experimental flying platform. The flying robot is to be controlled by a pilot using radio frequency. A wireless CCTV camera is installed on the robot to perform aerial surveillance and inspection operation. Due to the naturally unstable behavior of the flying robot, PID control system is implemented with the aid of accelerometer, compass sensor and gyro sensors to stabilize the flying robot and make it easier to be controlled by the operator. The fusion between the accelerometer, compass sensor and also the gyro sensors is done by the complementary filter.**

I. INTRODUCTION

The concept of quad-rotor aircraft has been around for a long time. One of the earliest quad-rotor aircraft, the *Gyroplane No. 1*, was built by Breguet-Richet in 1970 [14]. The quad-rotor aircraft is changing the flight direction by manipulating the fixed-pitch rotors' speed. Thus, it does not require a complicated mechanical structure like conventional helicopter and potentially it is easier to be controlled. Furthermore, recent progress in miniature electric motor and lightweight battery has made the development of the battery powered miniature Quad-Rotor Flying Robot possible.

The Quad-Rotor Flying robot has four rotors arranged in a '+' shape. Being the front and back rotors are rotating counter-clockwise and the left and right rotors are rotating clockwise. This type of counter-rotating rotor-pairs setup will cancel out the rotating force produced by the rotating rotor where the conventional helicopter is using the tail rotor to counter it. The flight direction control of the Quad-Rotor Flying Robot is described below.

To increase the altitude of the flying robot, all the rotors' speed will be increased to produce more thrust and vice versa. The front and back rotors are used to control the pitch of the flying robot. To fly forward, the front rotor's speed is decreased while the back rotor's speed is increased and vice versa. The left and right rotors are used to control the roll of the flying robot. To fly to the right, the left rotor will rotate faster while the right rotor will rotate slower and vice versa. The CW and the CCW rotor pairs are used to control the yaw action of the flying robot. To rotate the robot counter-clockwise, the CW rotor pairs have to rotate faster while the CCW rotor pairs have to rotate slower and vice versa [8].

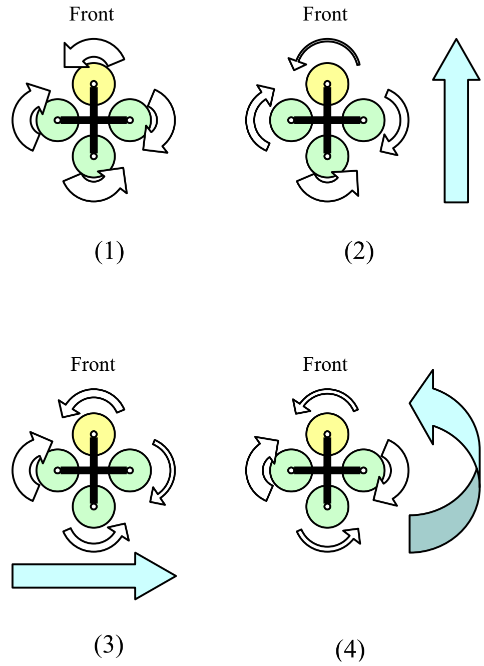

Fig 1: The concept of controlling the direction of the Quad-Rotor Flying Robot. The arrow's size is proportional to the corresponding rotor's speed. (1) Going up, (2) Move forward, (3) Move to right, (4) Rotate counter-clockwise.

II. DESIGN AND FABRICATION

Hardware Structure

The structure of the Quad-Rotor Flying Robot is modified from a popular quad-rotor RC toy, the *Draganflyer* [9].

Fig 2: The popular quad-rotor RC toy, the *Draganflyer*.

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The main frame of the Quad-Rotor Flying Robot is constructed from a strong but lightweight material. The 5mm carbon fiber tubes are used and they are connected together by a center PVC hub which is available as a spare part for the *Draganflyer*. The 2mm carbon fiber rods are connected to the main frame using epoxy to strengthen the structure of the flying robot.

The motors and rotors used for the flying robot are the power system for the commercial RC hobby aircraft. They are available at any RC hobby shop as a spare part for the RC aircraft. The motors chosen are the GWS/EPS-350C-CS motor with 5.33:1 gearbox while the rotors used is the 10" diameter EPP1045 counter rotating propeller pair. It is available in a CW and CCW pair.

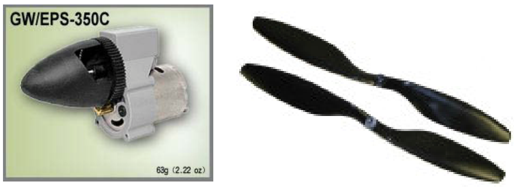

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Fig 3: The power system for the Quad-Rotor Flying Robot. (1) GWS/EPS-350C-CS motor with 5.33:1 gearbox, (2) EPP1045 counter rotating propeller pair.

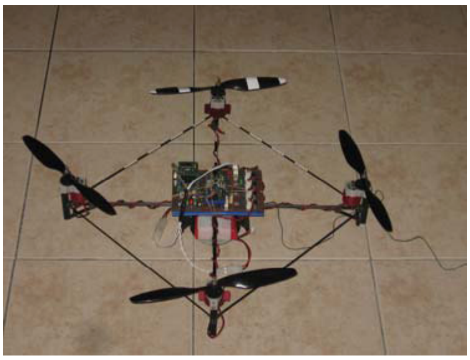

Fig 4: The Quad-Rotor Flying Robot

Sensors

In order to implement the control system to stabilize the Quad-Rotor Flying Robot, the attitude of the robot such as pitch, roll and yaw angle need to be measured. Compass sensor, accelerometer, together with three gyro sensors, are used in this robot for this purpose.

Compass Sensor

The purpose of using compass sensor is to measure the yaw angle of the flying robot. CMPS03 Robot Compass Module which contains two units of Philips KMZ51 magnetic field sensors mounted at right angles is used to each other to detect the earth magnetic field. This sensor will output a number in the range of 0 – 255 which represent the direction of the robot. However, the reading of the sensor is not calibrated. Thus, the exact number which represents North, South, East and West are unknown. In the application, knowing the exact direction is not important. The important is to maintain the robot orientation no matter which direction it faces.

However, using the compass sensor alone is not enough to know the exact yaw angle of the robot. This is because the motors of the robot will generate the magnetic field which can be detected by the compass sensor. As a result, the output from the compass sensor will be very noisy.

Fig 5: The CMPS03 Robot Compass Module

Gyro Sensor

The gyro sensor measures the rate of rotation along the corresponding axes. Three units of NEC-TOKIN CG-L43 piezoelectric gyro sensors are used to measure the rate of rotation along pitch, roll and yaw axes of the robot.

To get the absolute orientation angle of the robot, the signal from the gyro sensors need to be integrated. The problem is when the signal of gyro sensor is integrated, the noise will also be integrated. Besides that, the reading of the gyro sensor will drift over time and temperature. As a result, the small constant offset may cause the integrated angle grows to infinity [2].

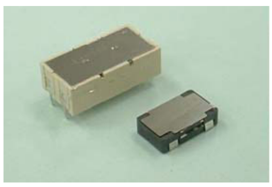

Fig 6: The Piezoelectric Gyro Sensor

Accelerometer

By measuring the gravity force, the accelerometer is used to measure the absolute tilting angle along pitch and roll axes of the flying robot. However, the measurement is only accurate when the robot is static. If the robot is moving, the acceleration and deceleration of the robot will affect the reading of the accelerometer [2].

Electronic Circuit

In Quad-Rotor Flying Robot, the dsPIC30F6014A DSP controller running at 96MHz is selected as the main processor due to its high speed capability, large memory space and it includes lot of peripherals. The electronics circuit is designed to integrate the accelerometer, compass sensor, gyro sensor, RC receiver and motor driver with the dsPIC. The compass sensor is interfaced with the dsPIC by using I^2C. While the output pulse from the RC receiver will be detected and decoded by the Input Capture peripheral of the dsPIC. For the gyro sensor and the accelerometer, the output is low passed filtered at approximately 33Hz before feeding the ADC of the dsPIC.

Sensor Fusion Using Complementary Filter

As discussed earlier, the orientation angle of the flying robot can be known either by integration of the signal from gyro sensors or using the accelerometer/compass sensor. However, the integration of the gyro sensors will drift over time, the accelerometer will be affected by the acceleration of the robot while the compass sensor can be affected by the motors' magnetic field. In solving this problem, the output from the gyro sensors needs to be combined together with the reading from accelerometer/compass sensor by using Complementary Filter [17].

Although the integration of gyro sensors signal will drift over time, but the drift rate is quite slow. The integrated angle still can be considered valid over a short period. For the accelerometer and the compass sensor, although the reading is quite noisy, the average reading of the sensor over some period of time does actually represent the actual orientation angle of the robot. Therefore, the integrated gyro signal for short period of time and the reading from the accelerometer/compass sensor is used to correct the gyro drift over long period. The block diagram in figure 7 shows how the gyro sensor and accelerometer/compass sensor are fused together.

There are two parameters in the Complementary Filter that need to be tuned. *K1* is the weighting factor that determines how important the reading from accelerometer/compass sensor compared to the integrated angle of the gyro sensor. *K2* determines how fast the drift of the gyro sensor need to be corrected. The value of *K1* and *K2* are obtained by using trial and error method.

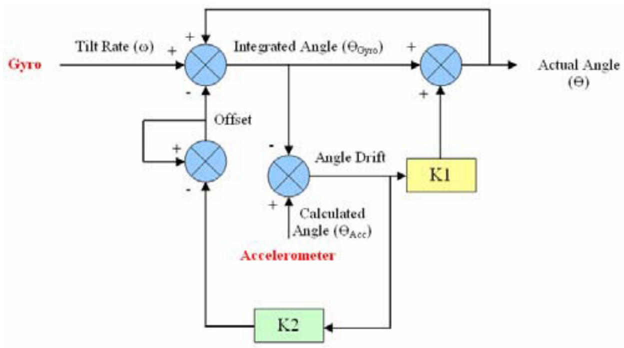

Fig 7: Block Diagram of the Complementary Filter.

The complementary filter is updated every 5mS (Sampling Rate). The equation to calculate the output of the complementary filter is simplified as follow:

$$\Theta_{Gyro} = (\omega - Offset) + \Theta \quad (1)$$

$$\Theta = \Theta_{Gyro} + (\Theta_{Acc} - \Theta_{Gyro}) * K1 \quad (2)$$

$$Offset = Offset - (\Theta_{Acc} - \Theta_{Gyro}) * K2 \quad (3)$$

Where:

ω = *Tilt rate*
Θ_{Gyro} = *Integrated angle from gyro*
Θ_{Acc} = *Calculated angle from accelerometer*
Θ = *Actual Angle*

PID Control Algorithm

The purpose of this project is to make a flying robot which can be controlled by a human operator using the RC transmitter. Due to the naturally unstable dynamic behavior of the flying robot, the robot is impossible to be controlled without a proper control system. In this project, the PID control system is implemented to slow down the dynamic respond of the flying robot to a level that can be controlled by a human operator.

There are three separate PID control systems implemented to stabilize the Quad-Rotor Flying Robot. The pitch, roll and yaw action require an individual PID control. The following diagram shows the PID control system of Quad-Rotor Flying Robot.

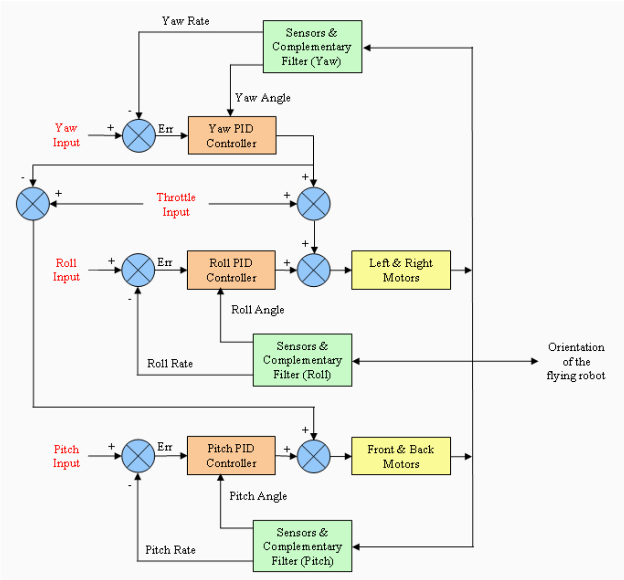

Fig 8: Block Diagram of the PID control system.

The PID controller is updated every 5mS (Sampling Rate). The equation to calculate the PID controller output is simplified as follow:

$$Err = RC\ receiver - Tilting\ Rate \quad (4)$$

$$Integral = Integral + Err + Tilting\ Angle \quad (5)$$

$$P_{Term} = K_P * Err \quad (6)$$

$$I_{Term} = K_I * Integral \quad (7)$$

$$D_{Term} = K_D * (Err - Err_{Old}) \quad (8)$$

The output of the PID controller will be:

$$Output = P\ Term + I\ Term + D\ Term \quad (9)$$

We can see from the PID equation, the main parameter that is being controlled is the tilting rate of the robot but not the tilting angle. This is because the resolution of the tilting angle is not fine enough after the Complementary filter. Thus, the PID is used to control the tilting rate and the tilting angle is added to the integral term to correct any slow drift that may occur. The limitation of doing this is the robot still needs to be controlled and corrected by the human operator through the RC link. The robot is not possible to achieve fully autonomous flight.

To tune the PID controller, the Quad-Rotor Flying Robot is attached to a Test Bed, which allows the flying robot to only tilt around one axis. The PID controller must be tuned separately for pitch, roll and yaw axis. First, K_P, K_I and K_D are set to zero. The throttle input is set to about 50%. Then the K_P is slowly increased until the flying robot just start to oscillate forth and back. Set the K_P to 0.7 * current K_P. The flying robot should not be oscillating now. Next, the K_I is slowly increased until the flying robot start to oscillate again. Then the K_D is slowly increased until the flying robot is stable and is not oscillating. Then the PID controller is tuned [13].

Although the tuning method used is not optimized, but it does stabilized the flying robot to a level that can be easily controlled by a human operator.

III. RESULT AND CONCLUSION

The Quad-Rotor Flying Robot has successful been flown by a human operator. However, it has some drawbacks.

The flying robot is quite hard to be controlled by a human operator. The operator must be concentrate and some training is required to control and hover the flying robot. Another drawback of the flying robot is it consumes much current. It only has the flight time for approximately 5 minutes with a fully charged 7.4V 2200mAH Lithium-Polymer battery.

Fig 9: The Quad-Rotor Flying Robot is hovering high

IV. ACKNOWLEDGEMENTS

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