Implementation of a Quad-Rotor Robot Based on SoPC

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Abstract — This work uses a SoPC platform as the flight controller of a quad-rotor aircraft. By CAD/CAM technologies the fuselage of the aircraft is built. The posture of the aircraft is stabilized according to the sensory data from a three-axle gyroscope and a tri-axia accelerometer. Additionally, a CMOS camera mounted on the bottom of the aircraft and an ultra-sonic sensor enables it to detect and track the object of interest on the ground while the aircraft is flying.

Keywords — FPGA, CAD, CAM, gyroscope, accelerometer

I. INTRODUCTION

With the progress of science and technology in recent decades, it is possible for scholars to develop small UAVs (Unmanned Aerial Vehicles). Among which the four-rotor unmanned aerial vehicle (Quad-rotor) has drawn a lot of research attention.

A Quad-rotor helicopter is able to take off and land vertically as well as hanging and horizontally flying, making it becomes an ideal monitoring tool in the sky. It can be utilized in various civil and military operations, for example: search and rescue operation, monitoring the air pollution and traffic condition, etc.

A quad-rotor vehicle has equipped with four brushless motors which divided into two pairs rotated in opposite directions. Contrasting to standard helicopter, the quad-rotor has advantages in security and efficiency, and there even have been remote control toys of quad-rotor helicopters on the market, but they are still lack of stability [1-2]. Many research groups have begun developing quad-rotor vehicles as the targets for robotics research [2-10], and several groups have studied to build quad-rotor UAVs serving as general unmanned aircraft [11-12].

As shown in Figure 1, quad-rotor helicopters have two pairs of propellers (1, 3) and (2, 4) rotating in opposite directions in order to compensate the phenomenon that the helicopter spins, and through changing the turning speed of the motors, the helicopter can create and change lifting force as well as its posture and moving direction. Changing rotational speed of propeller 2 and 4 vary the roll rotation and lateral movement, whereas changing the speed of propeller 1 and 3 produce the pitch rotation. The yaw rotation is the joint result of the forces of the four propellers. For example, Figure 1(c) shows the counterclockwise effect caused by the motors (1, 3) rotate in moderate speed and the motors (2, 4) rotated in a relative high speed.

In this paper, a SoPC (System on a Programmable Chip) is utilized as the flight control system, on which a three-axis gyro and a tri-axial accelerometer are being the flying robot gesture detector, and an ultra-sonic sensor can estimate the flying height of the aircraft. Furthermore, a CMOS camera mounted on the quad-rotor is employed to enhance the quad-rotor with the function of detecting and tracking objects on the ground. The flight controller adopts the PID control law to do closed-loop control of the flying robot to achieve self-balancing, hovering flight, and object tracking missions.

II. QUAD-ROTOR DYNAMIC MODEL

An ideal dynamic model contains the gyroscopic effect caused by hardware, or rotation caused by propeller, and etc. [4]. The coordinate system E and the body frame B are shown in Figure 2. The center of mass and the origin of the body frame are assumed to be coincident.

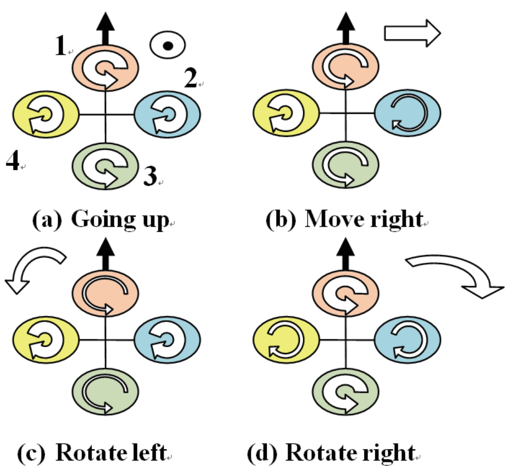

Figure 1. Quad-rotor concept motion description, the arrow width is proportional to propeller rotational speed

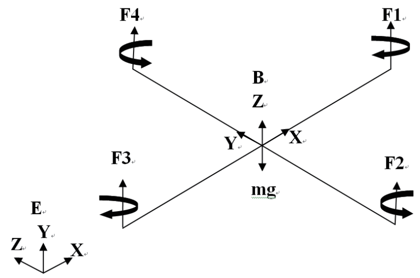

Figure 2. The coordinate system E and the body frame B of the aerial robot quad rotor.

TABLE I. SYMBOL DEFINITIONS IN EQUATIONS

Symbol	Definition
ζ	position vector
ν	speed vector (expressed in E)
R	rotation matrix
$\hat{\omega}$	skew symmetric matrix
ϕ	roll angle
θ	pitch angle
ψ	yaw angle
Ω	rotor speed
$I_{x,y,z}$	body inertia
J_r	rotor inertia
F_b	forces on airframe body
τ_b	torques on airframe body
b	thrust factor
d	drag factor
l	lever
e1, 2, 3	standard basis in R^3
g	acceleration due to gravity

Perform parameterization with Euler angles; in the given space, the rotation matrix for frame B with respect to coordinate E is $R_{B\ni E}$.

$$R_{B\ni E} = \begin{pmatrix} c\psi c\theta & s\varphi s\theta c\psi - c\varphi s\psi & c\varphi s\theta c\psi + s\varphi s\psi \\ s\theta s\psi & s\varphi s\theta s\psi + c\theta c\psi & c\varphi s\theta s\psi \\ -s\theta & s\varphi c\theta & c\varphi c\theta \end{pmatrix} \quad (1)$$

Where c=cos, s=sin.

Sastry[13] and Chriette[14] proposed that the force exerted by the external and acted on the center of the mass in rigid-body dynamics, as shown by the definition of Newton-Euler method:

$$\begin{bmatrix} mI_{3*3} & 0 \\ 0 & J \end{bmatrix}\begin{bmatrix} \dot{V} \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} \omega \times mV \\ \omega \times J\omega \end{bmatrix} = \begin{bmatrix} F \\ \tau \end{bmatrix} \tag{2}$$

$I \in \Re^{(3*3)}$ is the inertial matrix; V is linear velocity vector of the body; ω is the angular velocity of the body; J is moment of inertia.

The equation [15] of motion of the helicopter can be written as:

$$\begin{cases} \zeta = v \\ m\dot{v} = RF_b \\ J\dot{\omega} = -\omega \times J\omega + \tau_b \end{cases} \tag{3}$$

The first stage model of a quad-rotor can be written roughly as:

$$\begin{cases} \zeta = v \\ \dot{v} = -ge_3 + R_{e3}(\frac{b}{m}\sum \Omega_i^2) \\ I\dot{\omega} = -\omega \times I\omega - \sum J_r(\omega \times e_3)\Omega_i + \tau_b \end{cases} \tag{4}$$

Propellers on different axes and different moment differences act on the body.

$$\tau_b = \begin{bmatrix} lb(\Omega_4^2 - \Omega_2^2) \\ lb(\Omega_3^2 - \Omega_1^2) \\ d(\Omega_2^2 + \Omega_4^2 - \Omega_1^2 - \Omega_3^2) \end{bmatrix} \tag{5}$$

The symbol definitions are shown in Table 1.

The integrated dynamic model of the quad-rotor is shown as (6); except yaw, for motion in x, y and z axes, friction is ignored for all body movement.

$$\begin{cases} \ddot{x} = (\cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi)\frac{1}{m}U_1 \\ \ddot{y} = (\cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi)\frac{1}{m}U_1 \\ \ddot{z} = -g + (\cos\varphi\cos\theta)\frac{1}{m}U_1 \\ \ddot{\varphi} = \theta\psi(\frac{I_y - I_z}{I_x}) - \frac{J_r}{I_y}\dot{\theta}\Omega + \frac{1}{I_x}U_2 \\ \ddot{\theta} = \dot{\varphi}\psi(\frac{I_z - I_x}{I_y}) + \frac{J_r}{I_x}\dot{\varphi}\Omega + \frac{1}{I_y}U_3 \\ \ddot{\psi} = \dot{\varphi}\dot{\theta}(\frac{I_x - I_y}{I_z}) + \frac{1}{I_z}U_4 \end{cases} \tag{6}$$

Suppose U1, U2, U3, U4 and Ω serve as input of the system and a disturbance, we get:

$$\begin{cases} U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ U_2 = b(\Omega_4^2 - \Omega_2^2) \\ U_3 = b(\Omega_3^2 - \Omega_1^2) \\ U_4 = d(\Omega_2^2 + \Omega_4^2 - \Omega_1^2 - \Omega_3^2) \\ \Omega = \Omega_2 + \Omega_4 - \Omega_1 - \Omega_3 \end{cases} \tag{7}$$

III. SIMULATION

The model derived in section II has been simulated, the quad-rotor flying from coordinate (0, 0, 0) to (40, 50, 3). As can be seen in Figure 3, it has taken about 20 seconds for the quad-rotor to reach the destination and about 40 seconds to reach stable (roll, pitch, yaw) angle, (0, 0, 0).

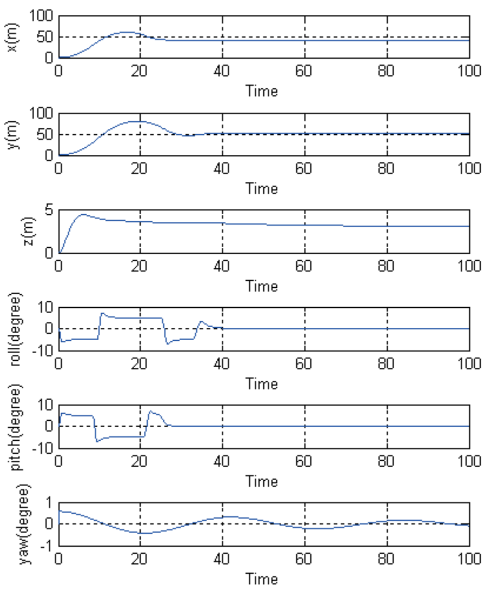

Figure 3. Simulation results of Quad-rotor

IV. MECHANISM DESIGN

This research employs the computer added design and manufacture (CAD/CAM) technologies to produce the fuselage. First, the skeleton consisting of two aluminium bars with a crossing structure are made. The four terminals of the cross are mounted with legs which are made of glass fibreboard material in order to reduce the weight while maintaining the strength. Shown in Figure 4 is the completed structure.

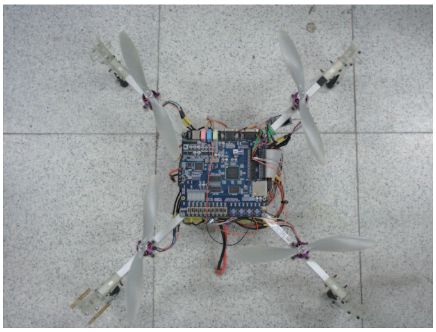

Figure 4. Quad-rotor fuselage

V. SYSTEM ARCHITECTURE

The flight control system of the quad-rotor combines the remote control and automatic stable functions. The aircraft receives remote control commands from the operators together with the multi-sensor signals to perceive its posture and to tune the flying automatically. The system adopts the PID control method to control the vehicle. Systematic structure of the quad-rotor is shown as in Figure 5, consisting of the following sub-system:

A. SoPC

A platform with a FPGA (Field Programmable Gate Array) being its major chip, the user can design and implement his idea in hardware approach as well as in software approach or both on the platform.

B. Sensors

A CMOS camera, a three-axis gyroscope, a tri-axil accelerometer, and an ultra-sonic are the sensors being used for the quad-rotor.

C. Remote control receiving module

The remote control signals received from the PPM (Pulse Position Modulation) module are demodulated and put into the SoPC for control values calculation.

D. Electric Speed Controller

A module transforms control signals from the FPGA into tri-phase signals to control the rotational speed of the motors.

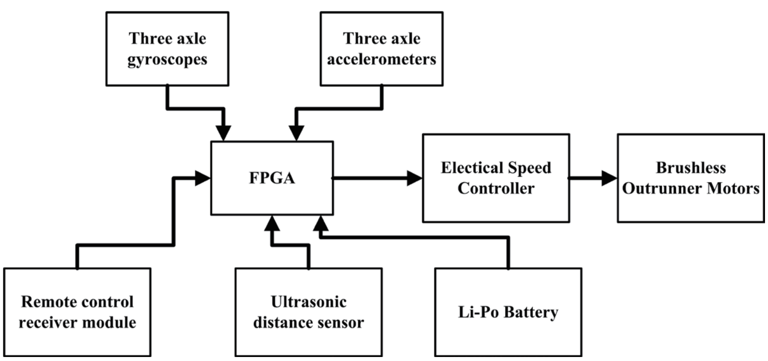

Figure 5. Quad-rotor system

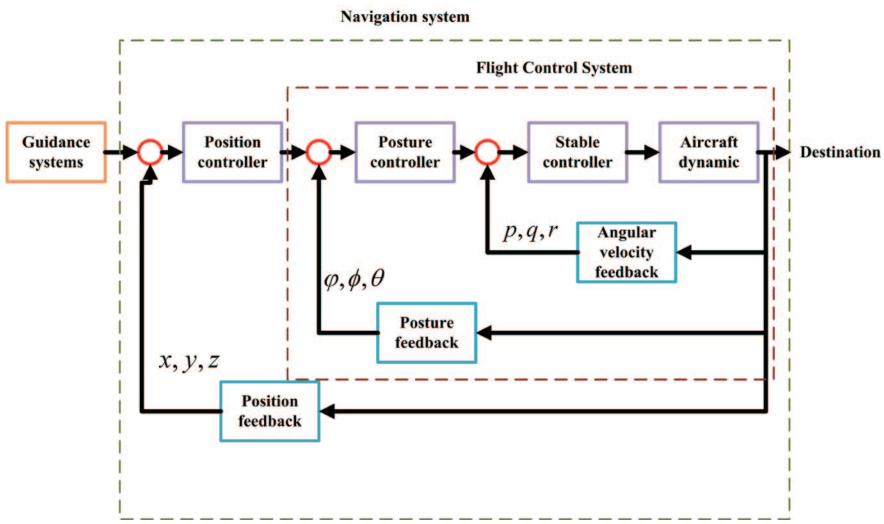

Figure 6. Quad-rotor control system

VI. CONTROL SYSTEM AND SOFTWARE DESIGN

The flight control system, as depicted in Figure 6, is the sour of the quad-rotor. The software design is more complicated than the hardware design for the quad-rotor. Good flight control software makes the quad-rotor flying stably and reliably and being easy to control and tune. The three main control loops are as follows.

A. Angular velocity feedback

The three-axis gyroscope provides the feedback of angular velocities (p, q, and r) to maintain stable flight of the aerial robot and avoid oscillation.

B. Posture feedback

The three rotational angles (θ, ϕ, and ψ) provided by integrating the gyroscope or from the tri-axles accelerometer can be corrected by the flight controller to maintain a stable flight of the quad-rotor.

C. Position feedback

The three-dimensional coordinates (x, y, and z) are getting from image processing unit of the SoPC, (x, y), and ultra-sonic sensor, z, and through the position controller, the position error of the aerial robot can be reduced.

VII. EXPERIMENTS

A. Image processing

In order to detect and track the object on the ground, the system uses a CMOS camera to capture images and performs image processing to find the object location related to the aircraft. Additionally, the system uses an ultra-sonic sensor for measuring the altitude from the ground so the quad-rotor has the coordinate (x, y, z) information about the object of interest from the perspective of the quad-rotor.

Demonstrated in Figure 7 is the image processing experimental result for locating an apron. On the right figure, the coordinate (x, y) of the midpoint of the blue LED and the red LED is successfully located after the image processing process.

Figure 7. Results of Image processing

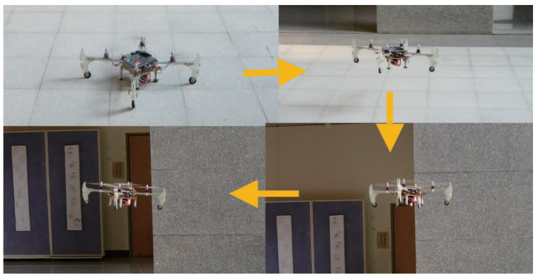

Figure 8. Outdoor flight tests

B. Flying test

The pictures for basic outdoor flying test have been taken and shown in Figure 8. The flying test was performed under the remote control mode and exhibited that the resulting quad-rotor system meets the design goal to some extent.

CONCLUSIONS

A quad-rotor, mounted with a CMOS camera, a three-axil gyroscope, a tri-axle accelerometer, and an ultra-sonic, being capable of performing object detecting and tracking tasks, has been designed and implemented on a SoPC. The critical functions of the aircraft including image processing, feedback of angular velocities (roll, pitch, yaw), PID control, remote control, and hovering, have finished.

However, the resulting system has only met some of the functions of the design goal, i.e. image processing for locating the object of interest, remote control flying. The PID controller of the system exhibits a bit unstable when the vehicle is remotely controlled and causing the automatic flying fails. The problem should be caused by the fact that the three-axil gyroscope is not accurate enough. Hopefully, by replacing the gyroscope with a more accurate one can resolve the control problem and realize the rest of the functions of the deign goal.

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