RESEARCH ARTICLE OPEN ACCESS

Stability Control of an Autonomous Quadcopter through PID Control Law

Nicolas Ives Roque Pacheco*, Daniel de Castro Ribeiro Resende **, Pedro Américo Almeida Magalhães***
*(Graduate of Mechatronic Engineering, Pontificia Universidade Católica de Minas Gerais, Brazil)
** (Graduate of Mechatronic Engineering, Pontificia Universidade Católica de Minas Gerais, Brazil)
***(Department of Mechanical Engineering, Pontificia Universidade Católica de Minas Gerais, Brazil)

ABSTRACT
In the recent years the world has seen a astonishing ascendance of non tripulated vehicles, and among these is the quadrotors aircrafts or quadcopters. These types of aircraft have been of particular interest due to its easy maneuverability in closed and open spaces and somewhat simplified dynamics. In these paper is presented an first attempt in the built model, to control the 4 DOF(Degrees of freedom) of an soon to be autonomous quadcopter through PID law in an controlled environment.
Keywords – Quadcopter, PID law, Autonomous flight

I. Introduction

The first quadcopter model to be developed was called the Breguet-Richet aircraft dated from1907. This mechanism was a simple cross structure (fig.1) with a motor-propeller in the end of each bar, for lift, and additional propellers to make it translate in the space [1]. After many years of development Mark Adam Kaplan developed the enhanced the Breguet-Richet machinery, birthing the actual model known as quadcopter [2] which used the roll-pitch yaw angles of the vehicle to make translations on the space. Although Kaplan model was capable of successful flight, it was obsolete when it came to speed, load and obtained height, when compared to the others aircraft models from the period.

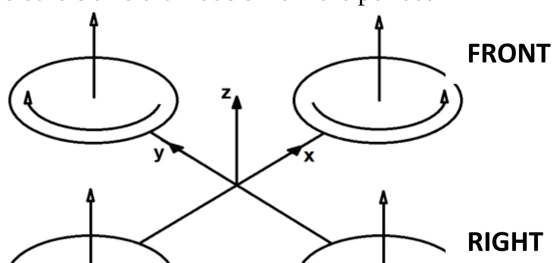

Fig. 1- Quadcopter Body-frame.

In the 90’s with the advent of robotics and microcontrollers, enthusiasts of air-modeling and robotics resurrected the quadcopter model that presented for flying robots the advantage of maneuverability, simple rotor dynamics, reduced gyroscopic effects and capability of load increase [3].

The quadcopter is a 6 degree of freedom (DOF) platform capable of rotations and translations in the space. Although the quadcopter can perform all of these actions, it’s inputs are limited to four, being these the lift produced by each rotor, making the quadrotor a sub-actuated system. Beyond this complication, such system has a non-linear dynamic that contributes to the challenge of the implementation of control that will allow it to perform stable flight.

As said before the quadcopter is a system with four inputs with six outputs, but due to its simple structure it’s almost easy to pick the four observable variables that will make the feedback of the system [4]. These being:

- Height: this output is controlled through the increase or decrease of the rotors lift by the same amount making it translate in the Z-axis of the earth frame.
- Roll: X body-frame rotation by θ. This movement is caused by making the rotors lift in the Y-axis in the body frame differ by an finite amount in finite time interval.
- Pitch: Y body-frame axis rotation by Φ. This action is performed exactly as the roll, but instead the rotors in the Y-axis is the ones in the X-axis that have a different lift.
- Yaw: as show in fig.1 the rotors have different spin directions, being the pair in the X-axis direction counter-clockwise and in the ones in the Y-axis direction clockwise. By making the rotation of the propeller between these pairs different a Z-axis rotation is induced.

For each one of these DOF was elaborated a PID controller. This type of controller is thoroughly used in the control of robotics system due to its characteristics of [5]:

- Having a simple structure.

- Having a good performance in many processes.
- Having the possibility of tuning the parameters without an exact modeling of the system.

In this article is presented the elaboration of linear PID control, and the simulation results for a indoors controlled flight of the system.

II. Quadcopter modeling.

For the modeling of the quadcopter was assumed the following to be true:

- The quadcopter structure is rigid and symmetric.
- The geometric, mass center and body-frame of the quadcopter are coincident.

Through equations (1) and (2) we relate the concatenated vector that contains the linear and angular velocities of the body-frame (subscript B) and earth-frame (subscript E).

$$\boldsymbol{v}_E = \boldsymbol{J}_\Theta \boldsymbol{v}_B \quad (1)$$

$$\boldsymbol{J}_\Theta = \begin{bmatrix} \boldsymbol{R}_\Theta & \boldsymbol{0}_{3x3} \\ \boldsymbol{0}_{3x3} & \boldsymbol{T}_\Theta \end{bmatrix} \quad (2)$$

Where $\boldsymbol{R}_\Theta$ (3) is the rotation operator, $\boldsymbol{T}_\Theta$ (4) is the transfer operator for the system rotations and $\boldsymbol{0}_{3x3}$ is a 3 by 3 null matrix.

$$\boldsymbol{R}_\Theta = \begin{bmatrix} c_\psi c_\theta & -s_\theta c_\phi + c_\psi s_\theta s_\phi & s_\psi s_\phi + c_\psi s_\theta c_\phi \\ s_\psi c_\psi & c_\psi c_\phi + s_\psi s_\theta s_\phi & -c_\psi s_\phi + s_\psi s_\theta c_\phi \\ -s_\theta & c_\theta s_\phi & c_\theta c_\phi \end{bmatrix} \quad (3)$$

$$\boldsymbol{T}_\Theta = \begin{bmatrix} 1 & t_\theta s_\phi & t_\theta c_\phi \\ 0 & c_\phi & -s_\phi \\ 0 & s_\phi / c_\theta & c_\phi / c_\theta \end{bmatrix} \quad (4)$$

The system dynamics in the body frame were equated through the Newton-Euler (6) formalism where in the left-hand-side of the equation is the resultant force $\boldsymbol{M}_B \dot{\boldsymbol{v}}_B$ summed with the Coriolis and centripetal force $\boldsymbol{C}_B(\boldsymbol{v})\boldsymbol{v}$. In the right-hand-side are the gravitational force $\boldsymbol{G}^B$, the gyroscopic effects $\boldsymbol{O}_b(\boldsymbol{v})$ and the forces and torques $\boldsymbol{U}_b(\Omega)$ originated from the propellers.

$$\boldsymbol{M}_B \dot{\boldsymbol{v}}_B + \boldsymbol{C}_B(\boldsymbol{v})\boldsymbol{v} = \boldsymbol{G}^B + \boldsymbol{O}_b(\boldsymbol{v}) + \boldsymbol{U}_b(\Omega) \quad (5)$$

Rewriting the equation above in an system of equations, we can isolate the body-frame accelerations on the left-hand-side, allowing us to describe therefore the aircraft dynamics through (6)

$$\begin{cases} \dot{u} = (vr - wq) + g \sin\theta \\ \dot{v} = (wp - ur) - g\cos\theta \sin\phi \\ \dot{w} = (uq - vp) - g\cos\theta \sin\phi + \dfrac{b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2)}{m} \\ \dot{p} = \dfrac{I_{YY} - I_{ZZ}}{I_{XX}} qr - \dfrac{J_{TP}}{I_{XX}} q(-\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4) + \dfrac{b\, l\, (\Omega_4^2 - \Omega_2^2)}{I_{XX}} \\ \dot{q} = \dfrac{I_{ZZ} - I_{XX}}{I_{YY}} pr + \dfrac{J_{TP}}{I_{YY}} p(-\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4) + \dfrac{b\, l\, (\Omega_4^2 - \Omega_2^2)}{I_{YY}} \\ \dot{r} = \dfrac{I_{XX} - I_{YY}}{I_{ZZ}} pq + \dfrac{d(\Omega_2^2 + \Omega_4^2 - \Omega_1^2 - \Omega_3^2)}{I_{ZZ}} \end{cases} \quad (6)$$

III. QUADCOPTER DATA

The constructed quadcopter (Fig.2) consists of a two perpendicular aluminum axis fixed in a nylon board, with 4 brushless E-Max CF2822 motors, each connected in a (Electronic Speed Controller) Mistery Simonk 30A and propellers GWS Slow-flyer 8'x4.3'.

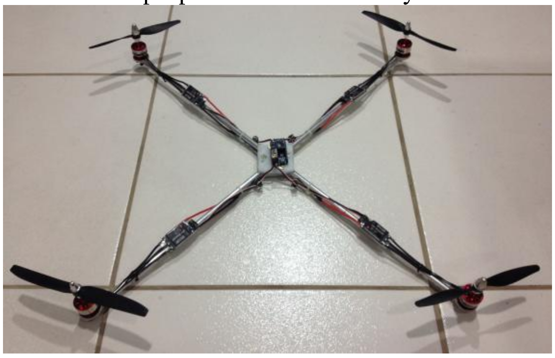

Fig. 2 Modeled quadcopter

A reproduction of the model in the CAD (Computer Aided Design) Solidworks allowed an estimation of the mass properties of the system, giving as output an mass of 695g and and the inertia tensor given by (7).

$$\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} 0.022 & 0.000 & 0.000 \\ 0.000 & 0.022 & 0.000 \\ 0.000 & 0.000 & 0.04389 \end{bmatrix} \quad (7)$$

For the set consisting of propeller, motor and ESC's were used an dynamometer that gave the output lift of the rotating propeller in gram-force for a given PWM (Pulse Wave Modulation). The resulting curves can be seen in figures 3 to 6.

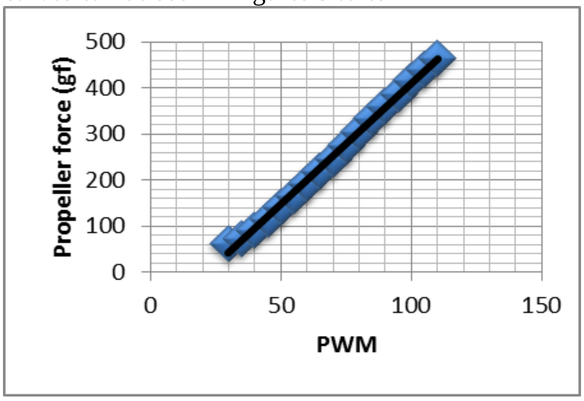

Fig. 3 – Back Rotor

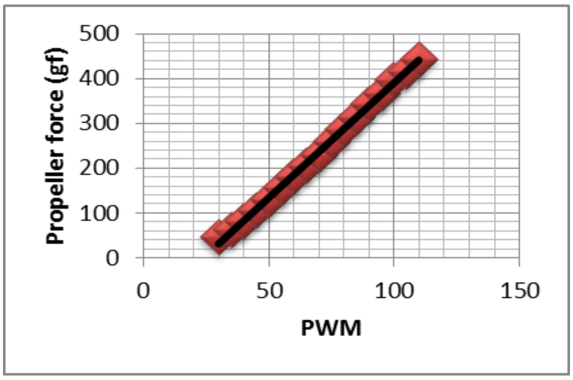

Fig. 4 Right Rotor

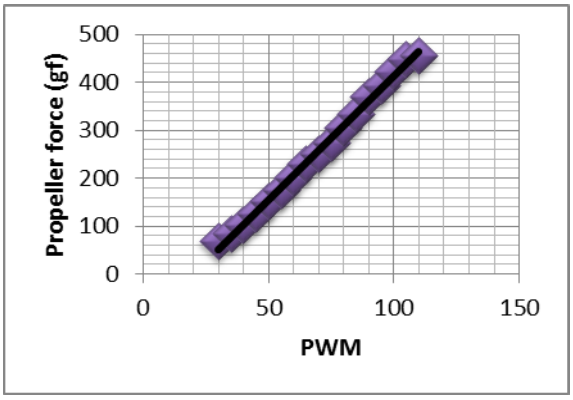

Fig. 5 Left Rotor

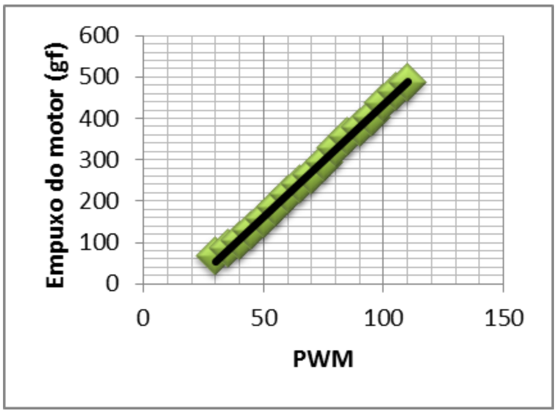

Fig. 6 Front Rotor

For the used range of PWM a line seemed a good approximation yielding the following equations for the front (8), right (9), left (10) and back(11) motor.

y= 5.426x – 97.84 (8)
y = 5.276x – 109.3 (9)
y = 5.426x – 97.84 (10)
y = 5.487x – 106.7 (11)

Where y is the force and x is the PWM. The linear correlation coefficient for the equations 8 to 11 were 0.999, 0.999, 0.998 e 0.999 respectively, showing that the fitted curve gives a reasonable approximation for the motor dynamics.

The thrust and drag coefficient of the propeller were obtained from an available database [6], allowing then a full elaboration of the quadcopter main dynamics.

IV. Simulation

With the given data for the quadcopter system, an implementation of the model in block diagram, fig. 7 was made in the MATLAB toolbox system simulation, Simulink.

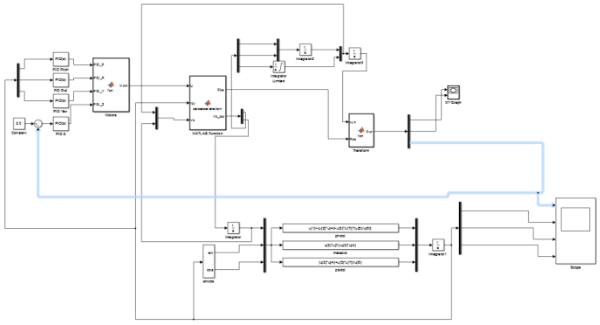

Fig. 7 Simulink block diagram.

The simulation reproduced a take-off flight and hovering flight in sequence for the modeled quadcopter. Since the microcontroller allows only integer values for the PWM a quantization block was inserted between the controllers output and the motor block, giving a quantized response as show in fig.8

The controllers were tuned using the Ziegler Nichols method, yielding the following results for the height in meters and roll pitch and yaw in radians shown in fig.9.

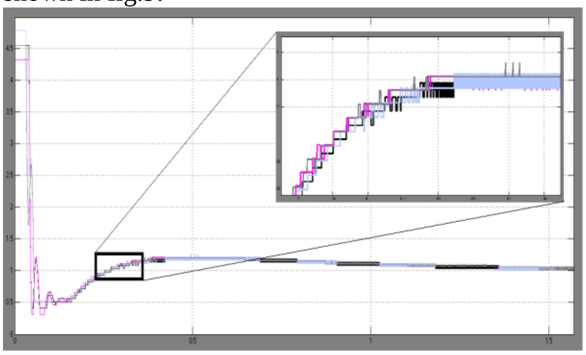

Fig. 8 Propellers response.

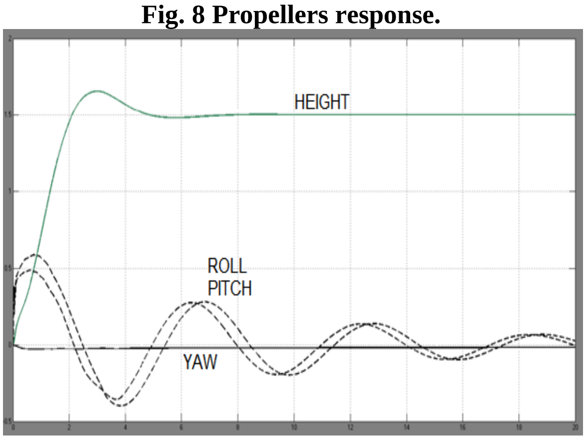

Fig. 9 Simulation results.

V. CONCLUSIONS

The results from the simulation showed that flight for the quadcopter controlled through PID is possible, but the achieved results were somewhat poor. Even though the yaw can be easily stabilized with the PID controller, for the roll and pitch curve is easily seem that the quadcopter passes more time above the desired angle of 0 than below it, causing a undesirable translation on the Y and X axis of the earth-frame., showing that the tuned PID controller is incapable to account for the motor thrust differences given by the as can be seen in equations 8 to 11.

For this problem a Kalman filter implementation seems to be capable of estimating the X and Y translation and feeding it to the controllers allowing the removal of this issue, or yet a visual system capable of giving the translations for feedback control system for the X and Y coordinates of the body frame.

REFERENCES

This heading is not assigned a number.

[1] BOUAHBDALLAH, Samir; NOTH, André; SEIGWART, Roland. . PID vs LQ Control Techniques Applied Indoor Micro Quadrirotor. In: Proceedings of 2004 IEEE/RSJ International Conference On Intelligent Robots and Systems. P. 2451-2456, 2004.

[2] BASTA, Peter O. Quad Copter Flight. California State University, Northridge. Thesis Electric Engineering, 2012, p. 60.

[3] JIANG, Jun et al. Control Platform Design and Experiment of a Quadrirotor. Proceedings of the 32nd Chinese Control Conference. 2013. p. 2974-2979.

[4] BRESCIANI, Tommaso. **Modelling, Identification and Control of a Quadrirotor Helicopter**. Universidaty of Lund, Thesis Automation Engineering, 2008, p. 184.

[5] LEONG, Bernard Tat Meng; LOW, Sew Ming; OOI, Melanie Po-Leen. Low-Cost Microcontroller-based Hover Control Design of a Quadcopter. Procedia Engineering. V. 41, p. 458-464, 2012.

[6] BRANDT, John B.; SELIG, Michael S. Propeller Performance Data at Low Reynolds Numbers. 49th AIAA Aerospace Sciences Meeting, Orlando, FL, 2011.