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Roll Control of a Tail-Sitter VTOL UAV

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Abstract **:—This paper deals with the development of a flight controller in order to stabilize the roll motion of a vertical take-off and landing unmanned air vehicle (VTOL-UAV) during hover flight. Using Newton Euler approach, a dynamic model is firstly described then a Proportional-Integral and Derivative regulator for the stabilization of the VTOL aircraft in the vertical plan is synthesized. Next, simulations are carried out in order to test the regulator performances. Finally, the proposed control law is executed in real time by an AtMega2560 micro-controller which is built in an Arduino module in order to stabilize the roll motion of a balance platform.**

Keywords—VTOL aircraft; roll control; digital PID techniques.

1-Introduction:

The use of planes onboard a naval vessel is very important for the projection of the naval forces and the increase of the action range. Hence, the necessity of deploying big ships equipped with long runways that could exceeds the ship's length in order to be able to embark fixed wings planes. A remedy for this issue, is the use of vertical take-off and landing aircrafts.

Due to the transition mechanism and airframe VITOL aircrafts can be generally classified into two main types [9]: Convertiplanes and Tail-Sitters.

A convertiplane is an aerial vehicle that takes off, cruises, hovers and lands with remaining horizontal, it means that the main body configuration does not change during flight as Tilt-Rotors [10] and Tilt-Wings [11].

A Tail-sitter is an aircraft that takes off and lands vertically and the aircraft main body tilts forward using differential thrust or control surfaces to flight horizontally; as Control Surface Transitioning Tail-sitters (CSTT) [12] and Differential Thrust Transitioning Tail-sitters (DTTT) [13].

In addition to the operability onboard small platforms, VTOL aircraft offers several advantages such as high energy autonomy in comparison with multirotor aircraft.

The development of unmanned aerial vehicles (UAVs) has increased during the last few years, due to their wide range applications in both military and civilian. One of the latest trends in the UAV's technology is the development of mini aerial vehicles with vertical take-off and landing capabilities that are deployable even when no landing runway is available.

Also, many autopilot systems are designed based on classical control techniques. These control methods can be found in many flight controls studies such as [4,5]. Modern control techniques are also used in UAVs autopilot applications [6]. Fuzzy logic control was used too in order to control aircraft in [7]. Besides, in his project, Octavio Garcia [8] has presented a nonlinear control strategy based on Saturated-Proportional-Integral and Derivative technique.

The tail-sitter VTOL aircraft shows a natural unstable behavior in vertical flight according to previous projects so, the manual control is a difficult task. Therefore, this paper aims to design a regulator in order to stabilize the roll position of the tail-sitter VTOL aircraft during hover flight.

The paper is organized as follows. Section 2 presents the dynamic model obtained using the Newton-Euler approach. The roll control strategy is developed in section 3. The simulation results of the proposed roll control strategy applied to the system are given in section 4. Finally, the experimental platform and the embedded system were described and the real-time experimental results of an autonomous stabilized flight of the two-rotor mini UAV were discussed.

Figure 1: VTOL mini aircraft

2- Dynamic model of the tail-sitter VTOL aircraft:

In this section, a modeling approach of a VTOL aircraft will be presented. The VTOL aircraft is considered to be a solid plane moving in aerospace, it is submitted to torques

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and forces applied to its body depending on the type of flying object considered [3].

The VTOL aircraft requires high accuracy during landing and take-off maneuvers so these flying objects must be designed to control their roll, pitch and yaw motion in small area, the objective of this paper is to design a regulator that can stabilize the VTOL aircraft during hover flight by controlling its rolling motion. Firstly, the dynamic model for the VTOL system is described. This model is inspired from [1], and it was derived under the following approximations:

- The aircraft is assumed to be operated over a small local region on earth which justifies the utilization of the Flat-Earth model equations [2].
- The blade mass is neglected.

(Fig.2) shows the VTOL aircraft to be modeled using Newton's classic motion equations.
Let the north-east-down NED coordinate system (x, y, z) be the inertial reference frame $(n-frame)$ and let the (X, Y, Z) be the body fixed frame$(b-frame)$.

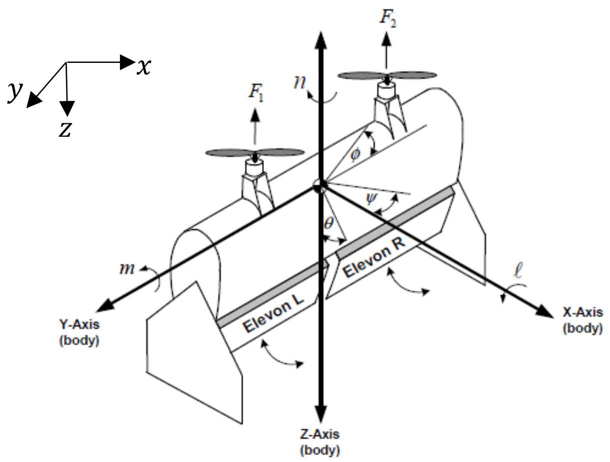

Figure 2: Studied VTOL aircraft and coordinate system

The orientation of the VTOL aircraft in the (n-frame) is given by the three Euler angles $\eta = (\phi \;\; \theta \;\; \psi)^T$ which are the classic yaw, pitch and roll Euler angles commonly used in aerodynamic applications.
The position of the center of mass of the rigid body relative to the (n-frame) is $\xi = (x, y, z)$.
Using Newton's classic equations of motion, the dynamic model of a rigid object evolving in aerospace is:

$$\dot{\xi} = RV \tag{1}$$

$$\dot{\eta} = W_\eta \Omega \tag{2}$$

$$m\dot{V} = -\Omega \times mV + F \tag{3}$$

$$J\dot{\Omega} = -\Omega \times JV + \tau \tag{4}$$

With

$$R = \begin{pmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi c_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & c_\theta s_\phi & c_\theta c_\phi \end{pmatrix}$$

: the orientation of the airframe relative to the fixed inertial frame where c_a (respectively s_a) denote *cos(a)* (respectively *sin(a)*).

$\dot{\eta} = (\dot{\phi} \quad \dot{\theta} \quad \dot{\psi})^T$: The angular velocity in the local inertial system (n-frame).

$$W_\eta = \begin{pmatrix} 1 & t_\theta s_\phi & t_\theta c_\phi \\ 0 & c_\phi & -s_\phi \\ 0 & s_\phi / c_\theta & c_\phi / c_\theta \end{pmatrix}$$

: The transformation of the angular velocity generated by a sequence of Euler rotations from the body to the local reference system during hover flight where t_a denote *tan(a).*

m: Total mass of the VTOL aircraft.
$V = (u \quad v \quad w)^T$: The speed vector of rigid body center of mass relative to body frame (b-frame).
$\Omega = (P \quad Q \quad R)^T$:The angular velocity in the body frame.
J : The inertia matrix of the flying body.
F : The external thrust applied to the VTOL aircraft center of mass in the body frame.
$\tau = (L \quad M \quad N)^T$:The torques applied to the VTOL aircraft center of mass in the body frame.
The set of attitude equations can be obtained using equations (2) and (4).
According to equation (2) we have: [1]

$$\dot{\eta} = \begin{pmatrix} P + \tan\theta\,(Q\sin\theta + R\cos\phi) \\ (Q\cos\phi - R\sin\phi) \\ (Q\sin\phi + R\cos\phi)/\cos\theta \end{pmatrix} \tag{5}$$

The inertia matrix is defined by

$$J = \begin{pmatrix} J_x & 0 & 0 \\ 0 & J_y & 0 \\ 0 & 0 & J_z \end{pmatrix} \tag{6}$$

The equation (4) can be written as:

$$\dot{\Omega} = \begin{pmatrix} \frac{(J_y - J_z)QR}{J_x} + \frac{L}{J_x} \\ \frac{(J_z - J_x)RP}{J_y} + \frac{M}{J_y} \\ \frac{(J_x - J_y)PQ}{J_z} + \frac{N}{J_z} \end{pmatrix} \tag{7}$$

Then the dynamic model is used to express and represent the behavior of the system over time, a regulation of the roll angle will be presented in the following section.

3 - roll control

This section presents the roll control of the VTOL aircraft during hover flight. The pitch and yaw motion would be stabilized with adequate control laws:

$$Q = R = 0 \tag{8}$$

Therefore, using the equations (7) and (8), the rotational dynamics for the roll angle can be represented by:

$$\ddot{\phi} = L/J_x \tag{9}$$

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where, the sum of moments L can be calculated as follows:

$$L = u_c(t)d - C_L\,\dot{\phi} \tag{10}$$

With

$u_c(t)$ = F = $f_1 - f_2$ the force difference between the right and left rotor.
d : the distance from the center of mass to each rotor.
The roll rate products an aerodynamic moment $-C_L\,\dot{\phi}$ opposing to the roll moment with a roll damping derivative C_L.
Equations (9) and (10) give us:

$$\ddot{\phi} = (u_c(t)d - C_L\,\dot{\phi})/J_x \tag{11}$$

Using (10) and applying the Laplace transform, the following transfer function for the roll angle is obtained:

$$H(s) = \frac{\phi(s)}{U_c(s)} = \frac{d/J_x}{s^2+(C_L/J_x)s} \tag{12}$$

Then, using the transfer function expressed in (11), the control loop system shown in the following Figure (Fig.3) is proposed to stabilize the roll angle.

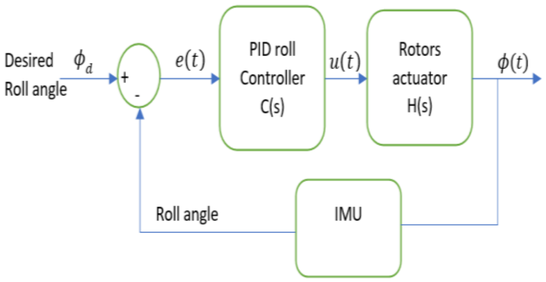

Figure 3: Roll Control Loop.

The transfer function of the control loop system is given by:

$$\frac{\phi(s)}{\phi_d(s)} = \frac{C(s)H(s)}{1+C(s)H(s)} \tag{13}$$

With
$C(s) = K_p + K_i\frac{1}{s} + K_d s$: Transfer function of the PID regulator.

4 – Simulation

To show the behavior of the system control roll stabilization, a simulation of the model has been run using Matlab and Simulink (Fig.4).
During this simulation, the K_p, K_d and K_i values are chosen by pole placement method (all poles are equal to -10):
We found that:

$$K_p = \frac{300J_x}{\mathrm{d}}\ ;\ K_i = 1000\frac{J_x}{\mathrm{d}}\ ;\ K_d = J_x\frac{30 - C_L}{d}$$

The desired roll angle was equal to 0 degrees and the initial roll angle of the system was chosen equal to -5 degrees.

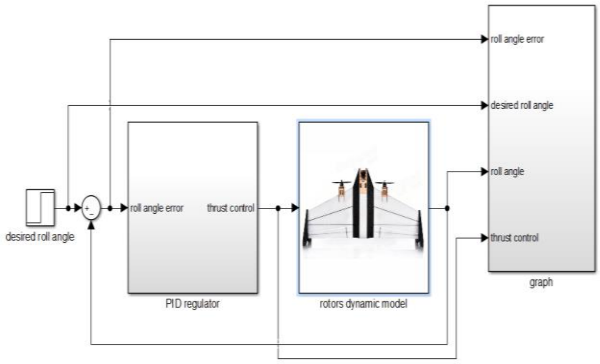

Figure 4: Block diagram

From Fig.6, the roll angle error shows a rapid convergence toward zero, hence the roll control which is based on the PID is performant.

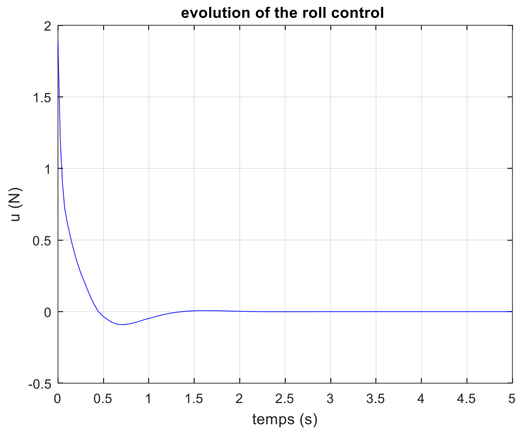

Figure 5: Evolution of the roll control

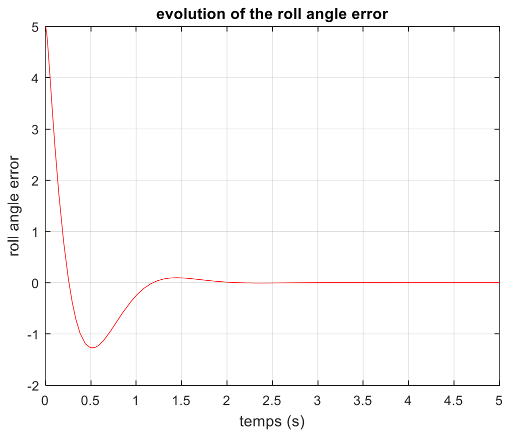

Figure 6: Evolution of the roll angle error

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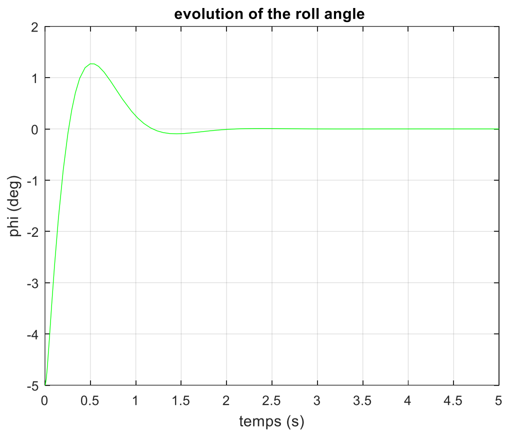

Figure 7: Evolution of the roll angle

5 - Experimental test

In this section, qualitative results of a roll stabilization test of the VTOL aircraft are discussed.

5-1- Description of used platform

A platform which is represented in (Fig.8) by a balance system with two contra-rotating brushless electric AC motors is fabricated and connected to microcontroller in order to implement and test our regulator.

Today's flight control systems have many hardware sensors like gyroscope, accelerometer modules, GPS, barometric pressure sensors and airspeed sensors which are connected on micro-controller. The gyroscope and accelerometer sensors are used together to detect any movement (roll and pitch) on each of the 3 axes, usually it gives back rotation velocity and acceleration values of the drone, using those values, the roll and pitch angle are calculated in each moment.

Our goal is to regulate the balance roll angle. In this project we will use an inertial movement unit IMU module like the MPU6050 which is a device capable of measuring the acceleration and rotation velocity. Generally, it consists of an accelerometer and gyroscope. Therefore, an IMU does not measure directly angles. However, it requires some calculations in order to obtain these angles.

Then, the use of a filter is very important to eliminate noise and error. The filter that we are going to use is known as complementary filter. It is ideal to implement with Arduino; easy to use, with low processing cost and good precision. This filter is actually a union of two different filters: a high-pass filter for the gyroscope and a low-pass filter for the accelerometer. In our case we will take just 98% of the angle obtained with the gyro data and 2% of the angle obtained with the acceleration data.

So, to get the best setting of the two motors velocity, an adequate value of P, I and D constants should be chosen. Each of these three constants will affect the PID control. The process of finding the perfect values of P, I and D is subsection below.

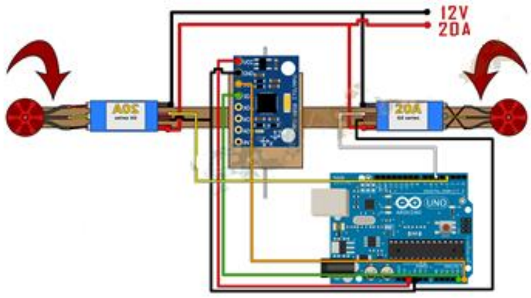

Figure 8: Platform top view

To obtain a more flexible system, the balance system architecture is controlled within only one processing unit. The control decisions that should be executed in real time are performed by a dedicated micro-controller, an AtMega2560, which is built in an Arduino module. This Arduino module is used to link actuators (two-rotors) to the sensor (IMU) through control laws (PID).

5-2- Digital PID design

A proportional-integral-derivative controller (PID controller) is a control law mechanism commonly used in industrial control systems. A PID controller continuously calculates an error $e(t)$ as the difference between a desired setpoint and a measured process variable (roll angle given by IMU) and it applies a correction based on proportional, integral, and derivative terms.

In this project we will use this mechanism to control the two-rotors in order to stabilize our mini UAV. We will control the inclination angle of the balance (the desired roll angle will be equal to zero), which means that the drone will be perfectly horizontal.

By using data from IMU, the real inclination angle of the balance was calculated. After that, we have to compare the calculated angle with the desired one which is equal to zero.

The two rotors controller is responsible for adjusting the balance inclination with respect to the desired angle. For this raison, the actual angle θ given by the IMU and the desired inclination θ_d are compared. The last one is given by radio transmitter (desired inclination). This generates an error that should be reduced at each iteration (14) of the algorithm due to the action of a PID controller. The control action u_k is calculated with the following equations:

$$\begin{aligned} e_K &= \phi_d - \phi_k \\ P &= k_p e_K \\ I_k &= I_{k-1} + k_i T e_K \\ D &= k_d (e_K - e_{K-1}) \end{aligned} \tag{14}$$

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$$u_k = p + I_k + D$$
$$e_{K-1} = e_K$$

where P, I, D, k_p, k_i and k_d are respectively the proportional action, integral action, derivative action, proportional gain, integral gain and derivative gain. e_K is the error between the desired roll angle ϕ_d and the actual roll angle ϕ_k and T is the sample time of the system, e_{K-1} is the previous error.
We could observe that the PID controller works well in the balance system and a fine tuning is performed in order to get the final values of k_p, k_i and k_d, such that the balance behaves as desired performance. After some tests, we found the values of k_p= 5, k_i = 0.01 and k_d = 2.6.
The left rotor controller is given by:

$$V_{left} = V_0 + u_k \quad (15)$$

Where V_0 is the initial rotors throttle and V_{left} is the left rotor throttle.
The right rotor controller is given by:

$$V_{right} = V_0 - u_k \quad (16)$$

With V_{right} the right rotor throttles.
The following figure (Fig.9) shows a real time response of the balance platform after a disturbance application.

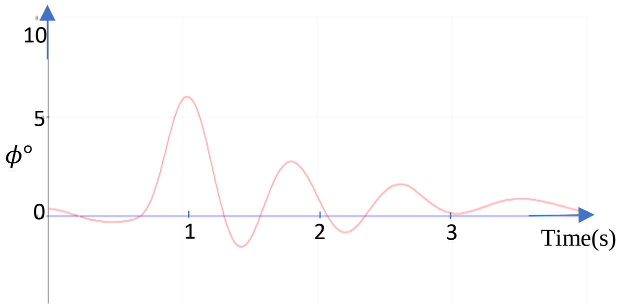

Figure 9: Real time response of the balance platform

CONCLUSION

In this paper, a mathematical model describing the dynamic motion of a tail-sitter VTOL aircraft was presented using Newton Euler formulation. This model is an adequate mathematical presentation in order to apprehend the VTOL aircraft dynamic motion during hover flight. The PID controller is employed to perform roll control for the system.

The simulation results show that the used control technique gives good results in terms of regulation. After the validation of the proposed control law through simulation, the results are supported by experimental tests. Future work in this area includes a stabilization of the pitch and yaw angle in addition to the test of the aerospace stabilization position of the mini aircraft.

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Appendix A. VARIABLE DESCRIPTION

Notation	**value**	**Description**
J_x	0.0144 kg.m^2	- x-axis moment of inertia
C_L	0.36	- roll damping derivative.
d	0.2 m	- Rotor distance from the center of mass.