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Integral Backstepping for Attitude Tracking of a Quadrotor System

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Introduction

Unmanned Aerial Vehicles (UAVs) have been designed in the military field since more than one half century. The main objective was to replace human pilot in a painful tasks and when the environment became hostile where the security of pilots is not ensured.

The firsts UAV's date from the Second World War; they have the dimensions of planes and fly at a high altitudes [1].

Nowadays, researches in this field know a large progress with the advance development of electronic and digital systems. This progress has given birth to low cost very small and accurate electronic components, a powerful calculators, and sensors. All these progress, allowed the development of small autonomous UAVs, able to perform missions in constrained area with more effectiveness and reliability.

Many universities and research's centers have been interested to the modeling, the control, and the design of a four rotors helicopter commonly known as a quadrotor [2–10]. The most part of these works use commercially platforms like UFO4, HMX4 and Draganflyer and modify its embedded control systems by adding more sensors and calculators in order to give them more reliability and intelligence [8]. While others work deal with the design and control of new platforms, like the STARMAC project [9] and Mesicopter Project [10].

In this work, we use the Draganflyer four rotors helicopter of RCTOYS [11] as a test bench. Its electronic part is replaced by another control system containing a control unit based on a dsPIC microcontroller from Microchip [8]. However, instead of PICO25 power circuit, a speed controller card is realized based on a Mosfet *IRLZ44NS* to improve the motor control. It receives four *PWM* motor control signals from the control unit. An inertial measurement unit 3DM-GX1 of MicroStrain is used as an attitude sensor. In addition, an internal speed motor controller is added.

The integral backstepping approach proposed in [12] for a class of nonlinear system is designed for the attitude tracking problem in order to improve the performances of the quadrotor system comparing with the backstepping approach presented in [8]. The developed control algorithm is implemented in real time for the attitude tracking of the quadrotor platform by using the developed embedded control system. The system stability analysis is conducted through the Lyapunov theory and global asymptotic angular tracking stability is demonstrated. Several robustness tests are carried out, to highlight the advantages of the proposed approach.

Physical model of the quadrotor

A Quadrotor is an aircraft that is propelled by four rotors. This allows a vertical taking-off and landing.

The motion of this vehicle is controlled by varying the rotation speed of the four rotors to change the thrust and the torque produced by each one (Fig. 1). The front and rear motors rotate counter clockwise, while the two other motors rotate clockwise in order to control the yaw angle. The pitch and roll torques are derived respectively from the differences $(F_1 - F_3)$ and $(F_2 - F_4)$, with F_i is the thrust force generated by the rotor "i" (Fig. 1). The roll and pitch inclination create the translational motion along X and Y axis respectively.

The yaw torque is the sum of the reaction (Drag) torques generated of each rotor produced by the shaft acceleration and the blade's drag $M_1 - M_2 + M_3 - M_4$ with $M_i = k_d\omega_i^2$ and k_d is the drag coefficient [2, 13].

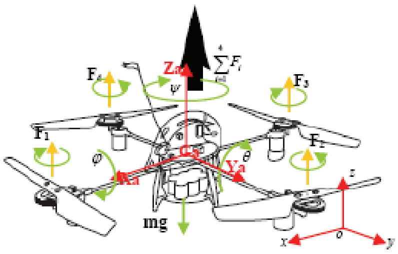

Fig. 1. Quadrotor helicopter

The lift F_i produced by the rotor *"i"* is proportional to the square of the rotation speed, $F_i = b\omega_i^2$ with b is the proportionality constant of the thrust force.

The quadrotor is a six degrees of freedom system. Its dynamic is related to the position (x, y, z) and the attitude described by the Euler angles(φ, θ, ψ). These six coordinates are related to the centre of masse. The Euler angles are defined as follows:

- Roll angle $\varphi: -\frac{\pi}{2} < \varphi < \frac{\pi}{2}$;
- Pitch angle $\theta: -\frac{\pi}{2} < \theta < \frac{\pi}{2}$;
- Yaw angle $\psi: -\pi < \psi < \pi$;

The rotation transformation matrix (DCM: Direct Cosinus Matrix) from the inertial fixed frame to the body fixed frame is given by:

$$R = \begin{bmatrix} C_\theta C_\psi & C_\psi S_\theta S_\varphi - C_\varphi S_\psi & C_\varphi C_\psi S_\theta + S_\varphi S_\psi \\ C_\theta S_\psi & S_\theta S_\varphi S_\psi + C_\varphi S_\psi & C_\varphi S_\theta S_\psi - C_\psi S_\varphi \\ -S_\theta & C_\theta S_\varphi & C_\theta C_\varphi \end{bmatrix}, \quad (1)$$

where S and C represent the Sinus and Co-sinus functions respectively.

To derive the dynamic model of the quadrotor (position and attitude); the Newton Euler formalism is used. Therefore the following equations are obtained [2, 8]:

$$\begin{cases} \dot{\xi} = v, \\ F_t + F_{dt} + F_g = m\ddot{\xi}, \\ \tau_c - \tau_{af} - \tau_g = J\dot{\Omega} + \Omega \wedge J\Omega, \end{cases} \quad (2)$$

where $F_{dt} = k_{dt}\dot{\xi}$ – the vector of the drag forces, $k_{dt} = diag(k_{dtx}, k_{dty}, k_{dtz})$ – a diagonal matrix with the drag coefficients of translation in the diagonal, F_t – the vector of the thrust force given by

$$F_t = R.[0 \quad 0 \quad \textstyle\sum_{i=1}^{4} F_i\,]^T \,, \quad (3)$$

F_g – the vector of the gravity forces given by

$$F_g = [0 \quad 0 \quad mg]^T, \quad (4)$$

where m – the total masse of the quadrotor and g is the gravity acceleration, $J = diag(J_x, J_y, J_z)$ – the inertia matrix (it is diagonal if we suppose a symmetrical structure of the quadrotor), $\wedge$ – denote the vector cross-product, Ω – the angular speed of the quadrotor expressed in the body fixed frame given by:

$$\Omega = \begin{bmatrix} 1 & 0 & -S_\theta \\ 0 & C_\varphi & C_\theta S_\varphi \\ 0 & -S_\varphi & C_\varphi C_\theta \end{bmatrix}, \quad (5)$$

where τ_c – the control torques applied on the quadrotor body and generated by the rotors of the quadrotor according to the body fixed frame defined as:

$$\tau_c = \begin{bmatrix} d(F_3 - F_1) \\ d(F_4 - F_2) \\ M_1 - M_2 + M_3 - M_4 \end{bmatrix}, \quad (6)$$

where d is the distance from the rotor center to the quadrotor airframe mass center.

In (2) τ_{af} – the aerodynamic friction torque, τ_g – the gyroscopic torque. They are described as follows:

$$\tau_{af} = k_{af}\Omega \,, \quad (7)$$

$$\tau_g = \textstyle\sum_{i=1}^{4} \Omega \wedge J_r\, \omega_i, \quad (8)$$

where $k_{af} = diag(k_{afx}, k_{afy}, k_{afz})$: a diagonal matrix of the coefficients of the aerodynamic friction and ω_i is the rotation speed of the rotor *"i"*. J_r is the rotor inertia.

This work is mainly focused to the attitude dynamic and a reduced dynamical model of the attitude is considered to simplify the control design and is given by the following equations [3, 8]:

$$\begin{cases} \ddot{\varphi} = \frac{1}{I_x}\{\dot{\theta}\dot{\psi}(I_y - I_z) - k_{fax}\dot{\varphi}^2 - J_r\bar{\Omega}\dot{\theta} + dU_2\}, \\ \ddot{\theta} = \frac{1}{I_y}\{\dot{\varphi}\dot{\psi}(I_z - I_x) - k_{fay}\dot{\theta}^2 - J_r\bar{\Omega}\dot{\varphi} + dU_3\}, \\ \ddot{\psi} = \frac{1}{I_z}\{\dot{\varphi}\dot{\theta}(I_x - I_y) - k_{faz}\dot{\psi}^2 + U_3\} \end{cases} \quad (9)$$

and

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ -b & 0 & b & 0 \\ 0 & -b & 0 & b \\ k_d & -k_d & k_d & -k_d \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix}. \quad (10)$$

The rotors are driven by DC-motors with the well known equations [4]:

$$\begin{cases} L\frac{di}{dt} = V - Ri + k_e\omega_i, \\ I_r\dot{\omega}_i = \tau_i - Q_i. \end{cases} \quad (11)$$

And the reactive torque generated by the rotor i, in free air, due to rotor drag is given by $Q_i = k_d\omega_i^2$.

Embedded control system architecture

The embedded control system used to implement the attitude stabilization of the quadrotor is composed of four elements: the attitude sensor (IMU), the on board control unit, the speed controllers and the wireless communication device. Each element is detailed below.

A. Attitude sensor (IMU). The attitude sensor used in our study is the 3DM-GX1 Inertial Measurement Unit from MicroStrain (Fig. 2). It contains three magnetometers, three gyroscopes, three accelerometers and a digital processor which performs the Kalman filter calculations and returns sensor orientations in several formats (Euler angles, quaternion, Direct Cosinus Matrix) over a high speed serial link.

Fig. 2. IMU 3DM-GX1 from MicroStrain

B. Onboard control unit. We have developed an embedded control board (Fig. 3) based on the microcontroller dsPIC30F6010A from Microchip.

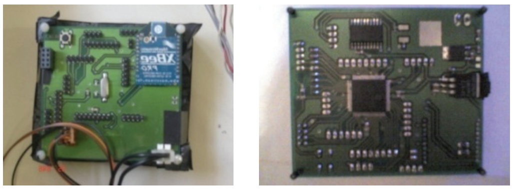

Fig. 3. Realized embedded control system

The first task of this unit is to acquire measurements from different sensors through its input/output ports and uses several modules of communication like UART module for the serial communication RS232, CAN, I²C and SPI Buses. It runs at 10MHZ with 144Kbyte on chip flash program memory and includes 8 PWM outputs channels, five 16 bits timers, output-compare module and input-capture module [8].

The second task of this unit is to run the control algorithms for the stabilization of the platform and generate PWM (Pulse Width Modulation)) control signals to control its four DC motors.

C. Speed controller. To be able to stabilize the quadrotor, we must independently control the speed of the four propellers, and thus of the four D.C. motors. However, controlling motors starting from the microcontroller directly is impossible. The current drawn by a motor is quite higher than the current delivered by a PWM pin of a microcontroller, which is of 25mA. Hence, a speed controller card based on the IRLZ44N Mosfet is realized (Fig. 4). The IRFZ44 in a D2 pack has very small resistance and high power dissipation, which makes them ideal for H-Bride situation. This interface receives the PWM control signals from a microcontroller at a frequency of 200Hz.

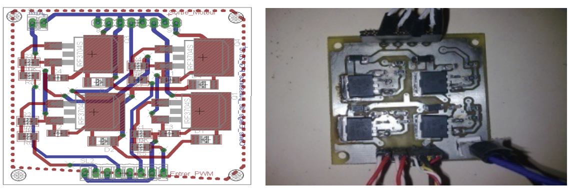

Fig. 4. Speed controllers board based on a Mosfets IRLZ44N

D. Hall Effect Sensor. The propellers speeds are obtained from Hall Effect sensors in combination with little magnets (Fig. 5). Two magnets are mounted under each main rotor gear. The magnets pass above the sensor as the gear rotates. The normally high (+5V), output signal pulses switch to low (0V), as each magnet passes above.

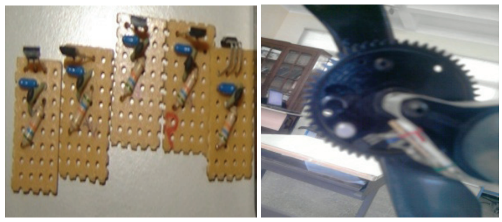

Fig. 5. Hall effect sensor

The rotation speed is then obtained by measuring the time T_{Period}(s) between two falling edges; it's the time for one rotor revolution in seconds (Fig. 6). Finally the rotation speed ω for one rotor is given by: $\omega = {}^{2\pi}/_{T_{Period}}$ (rad/s)

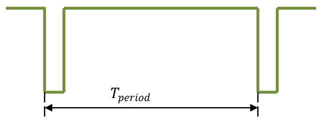

Fig. 6. Hall Effect Sensor Timing Diagram

E. Wireless communication device. To perform wireless communication with a remote computer, we have used two XBee Modems from Maxstream. This wireless device contains an intelligent electronic which allows to perform both a simple point to point communication and a real multi points transmission network.

Data transmission is very simple and seems as a serial transmission along a virtual serial link.

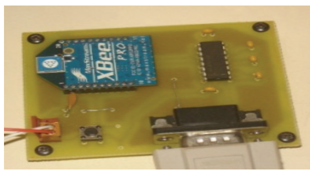

Fig. 7. Wireless Serial adaptation board with XBee device

The quadrotor system with embedded control system, speed controller card and sensors is presented in Fig. 8.

Fig. 8. The quadrotor with the embedded electronic and sensors

For real time implementation of the attitude stabilization control laws of the quadrotor system; the test-bench in Fig. 8 is used. The standard RS232 interface is used to ensure the communication between an embedded control system based on a dsPic30F6010A µc and a PC which is considered as ground station. An user interface is developed on the PC ground station for tuning the controller parameters, to generate a Euler angles desired trajectory, and to show the outputs and the inputs controls of the quadrotor (torque inputs controls, propellers speeds, Euler angles). The microcontroller allows the sensors signal acquisition and the control algorithm calculus. The control algorithm implemented on the control unit runs at a predefined sampling time (30ms), generated by a timer's interruption.

Control laws synthesis

The control algorithm developed can be divided in two loops, an internal loop to control the propellers speeds and an external loop to stabilize the attitude of the quadrotor.

A. Speed Controller Design. The desired speed ω_{di} for the propeller is determined from (10). To ensure the convergence of the speed errors for the four propellers, the torques τ_i, $i = 1,2,3,4$ are used as a control inputs.

We define the propeller speed error as: $\varpi_i = \omega_i - \omega_{di}$.

Using model equation in [4] and the above equation we have $I_r\dot{\varpi}_i = \tau_i - Q_i - I_r\dot{\omega}_{di}$. Therefore, a control law may be developed from the above equation as follows

$$\tau_i = Q_i + I_r\dot{\omega}_{di} - \kappa_i\varpi_i, \tag{12}$$

where κ_i ,*i = {1, 2, 3, 4}* are a controllers parameters. Applying the above controller one obtains

$$\dot{\varpi}_i = -\frac{k_i}{I_r}\varpi_i. \tag{13}$$

This last demonstrate an exponential convergence of ω_i to ω_{di}.

The physical quadrotor under consideration is powered by four voltage controlled permanent magnet DC motors. Assuming negligible armature inductance

$$V_i = RI_a + k_e\omega_{mi}. \tag{14}$$

The equation for the motor torque is given by

$$\tau_m = k_c I_a. \tag{15}$$

The rotor torque τ_i can be related to the motor torque τ_{mi}, using the gear ratio N as follows: $\tau_{mi} = \frac{\tau_i}{N}$.

Similarly, the propeller speed ω_i can be related to the motor speed ω_{mi} using the gear ratio *N*: $\omega_{mi} = N\omega_i$; hence one can obtain

$$V_i = R\frac{\tau_i}{Nk_c} + Nk_e\omega_i. \tag{16}$$

Assuming no losses, the electrical power must be equal to the mechanical output power, i.e.

$$V_i I_a = \tau_{mi}\omega_{mi} \Rightarrow \frac{V_i}{\omega_{mi}} = k_e = \frac{\tau_{mi}}{I_a} = k_c. \tag{17}$$

B. Control Design. The attitude stabilization objective is achieved using the Integral Backstepping control method. The benefit within the use of the integral term is to improve the system steady state output errors performances comparing with backstepping approach [4].

Recall that, the Backstepping approach is a recursive control methodology for nonlinear systems in strict feedback form. If we consider the reduced model of the quadrotor attitude, the system can be written in state space form as [3, 8]:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = a_1x_4x_6 + a_2\bar{\Omega}x_4 + b_1U_2, \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = a_3x_2x_6 + a_4\bar{\Omega}x_2 + b_2U_3, \\ \dot{x}_5 = x_6, \\ \dot{x}_6 = a_5x_4x_2 + b_3U_4, \end{cases} \tag{18}$$

where the state vector is defined by: $\underline{\boldsymbol{X}} = [\boldsymbol{x_1}\ \boldsymbol{x_2}\ \boldsymbol{x_3}\ \boldsymbol{x_4}\ \boldsymbol{x_5}\ \boldsymbol{x_6}] = [\boldsymbol{\varphi}\quad \dot{\boldsymbol{\varphi}}\quad \boldsymbol{\theta}\quad \dot{\boldsymbol{\theta}}\quad \boldsymbol{\psi}\quad \dot{\boldsymbol{\psi}}]$.

The above model can be rewritten as:

$$\begin{cases} \dot{x}_i = x_{i+1}, \\ \dot{x}_{i+1} = f_i(x_i, x_{i+1}) + g_iU_j, \end{cases} \quad i = 1,2,3,\ j = 2,3,4. \tag{19}$$

The most common way to include integral action is to augment the plant dynamics with the integral state $\dot{\xi}_i = x_{id} - x_i$ [12]. The resulting system is still in strict feedback form; however, the vector relative degree is increased to 3 and two steps of Backstepping are therefore necessary.

$$\begin{cases} \dot{\xi}_i = x_{id} - x_i, \\ \dot{x}_i = x_{i+1}, \\ \dot{x}_{i+1} = f_i(x_i, x_{i+1}) + g_iU_j, \end{cases} \quad i = 1,2,3,\ j = 2,3,4. \tag{20}$$

<u>*Step 1.*</u> The first subsystem is considered:

$$\begin{cases} \dot{\xi}_i = x_{id} - x_i, \\ \dot{x}_i = x_{i+1}, \end{cases} \tag{21}$$

where x_{i+1} is a virtual control, we definite a new state z_i such as: $z_i = x_{id} - x_i$, and we introduce the first Lyapunov function $V_1 = \frac{1}{2}z_i^2 + \frac{1}{2}\xi_i^2$.

Its time derivative is given by

$$\dot{V}_1 = z_i(\xi_i - x_{i+1} + \dot{x}_{id}). \tag{22}$$

If we apply the Lyapunov theorem, i.e. by imposing $\dot{V}_1 \leq 0$ condition, the stabilization of z_i and ξ_i can be obtained by introducing a new virtual control input x_{i+1} and a positive constant $(\alpha_i > 0)$, where

$$x_{i+1} = \dot{x}_{id} + \xi_i + \alpha_i z_i. \tag{23}$$

<u>*Step 2.*</u> Let us make the following change of variable

$$\Phi = x_{i+1} - \dot{x}_{id} - \xi_i - \alpha_i z_i. \tag{24}$$

Now one considers a new subsystem given by:

$$\begin{cases} \dot{\xi}_i = z_i, \\ \dot{z}_i = -\xi_i - \alpha_i z_i - \Phi, \\ \dot{\Phi} = F_i(\xi_i, z_i, \Phi) + g_iU_j, \end{cases} \tag{25}$$

where U_j is the real control of the subsystem *j*. We define the second Lyapunov function as

$$V_2 = V_1 + \frac{1}{2}\Phi^2. \tag{26}$$

Its time derivative is

$$\dot{V}_2 = \alpha_i z_i{}^{\angle} + \Phi\big(f_i(x_i, x_{i+1}) + g_i U_j + (\alpha_i^2\text{-}2)z_i\text{-}\,\text{-}\ddot{x}_{id} + \alpha_i \xi_i + \alpha_1 z_2\big). \quad (27)$$

The real control input U_j chosen to force $\dot{V}_2$ to be negative definite is given by

$$U_j = g_i{}^{-1}(-f_i(x_i, x_{i+1}) + (2 + \alpha_i\alpha_{i+1})z_i + \alpha_{i+1}\xi_i - -(\alpha_i + \alpha_{i+1})(x_{i+1} - \dot{x}_{id}) + \ddot{x_{id}}). \quad (28)$$

Hence, the resulting control inputs for the quadrotor system are given by:

$$\begin{cases} U_2 = b_1{}^{-1}\begin{pmatrix} a_1 x_4 x_6 + a_2 x_2^2 + a_3 \bar{\Omega} x_4 + (2 + \alpha_1\alpha_2)z_1 + \\ +\alpha_2\xi_1 - (\alpha_1 + \alpha_2)(x_2 - \dot{x}_1) + \ddot{x}_1 \end{pmatrix}, \\ U_3 = b_2{}^{-1}\begin{pmatrix} -a_4 x_2 x_6 + a_5 x_4^2 - a_6 \bar{\Omega} x_2 + (2 + \alpha_3\alpha_4)z_2 + \\ +\alpha_4\xi_2 - (\alpha_3 + \alpha_4)(x_4 - \dot{x}_3) + \ddot{x}_3 \end{pmatrix}, \\ U_4 = b_3{}^{-1}\begin{pmatrix} a_7 x_2 x_4 + a_8 x_6^2 + (2 + \alpha_5\alpha_6)z_3 + \alpha_6\xi_3 + \\ -(\alpha_5 + \alpha_6)(x_6 - \dot{x}_5) + \ddot{x}_5 \end{pmatrix}. \end{cases} \quad (29)$$

Hence, in addition to stability; these controls ensure also a trajectories tracking and disturbances rejection [12].

Real time implementation

In order to validate the control law developed in the previous section, we implemented the controller on the embedded control unit. The sampling period of the algorithm is fixed at 30ms. We carried out several experiments to stabilize the orientation of quadrotor. The altitude was then fixed by the operator. We have implemented the Integral Backstepping controllers on the real system, the controllers parameters were tuned by trial and error, until obtaining a best performance of the system.

In the first experiment, the controller is used to stabilize the system and maintain the roll, pitch and yaw angles in zero. The values of the desired U_1 and gain κ_i used in the speed controller are fixed U_1=2.6, κ_i=0,004. The controllers Parameters are taken: $\alpha_1 = 8.56$, $\alpha_2 = 11.6$, $\alpha_3 = 8.96$, $\alpha_4 = 9.03$, $\alpha_5 = 3.92$, $\alpha_6 = 2.96$. The results show the aircraft angles (Fig. 9), the control inputs and the propeller rotation speed for each rotor (Fig. 10).

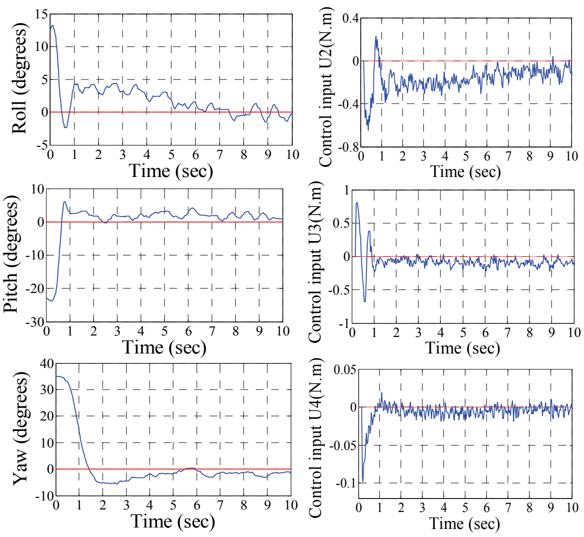

Fig. 9. Outputs angles and their control inputs

These results show that the integral backstepping approach stabilize the attitude of the qaudrotor in a reasonable time with a good steady state errors for the three angles and with smooth control inputs.

Now, in order to test the robustness of the proposed approach to external disturbances rejection; in the second experiment, and after having stabilized the quadrotor in horizontal plane, we added a mass of 50mg as a disturbance on one of the end of the roll axis (Fig. 10)

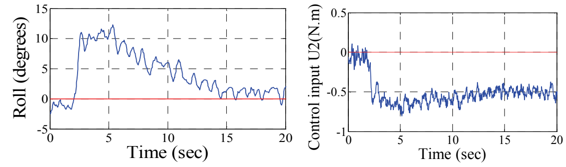

Fig. 10. Roll with disturbance (left), its control torque

In the third experiment we make the same for the pitch angle (Fig. 11).

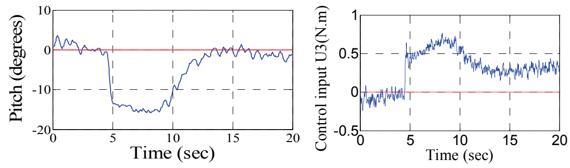

Fig. 11. Pitch with disturbance (left), its control torque

As we can see in Fig. 10 and Fig. 11, The results obtained show the ability of the proposed controller to handle the disturbances effects in a reasonable time.

In the fourth experience, the control algorithm developed were tested for a cycloid reference with $t_f = 10ms$,$D_i = x_{di}(t_f) - x_{di}(0)$ and $x_{d1}(t_f) = x_{d2}(t_f) = \mp 8$, $x_{d3}(t_f) = \mp 20.$

$$x_{di}(t) = \begin{cases} x_{di}(0) + \frac{D_i}{2\pi}\left[2\pi\frac{t}{t_f} - \sin\left(2\pi\frac{t}{t_f}\right)\right], & if\ 0 \le t \le t_f, \\ x_{di}(t_f), & if\ t > t_f \end{cases} \quad (30)$$

and for a sinusoidal reference with $x_{di}(t) = x_{di}(0)\sin\left(\frac{2\pi}{T=0.036}t\right)$,$x_{d1}(0) = x_{d2}(0) = 8$,$x_{d3}(0) = 20.$

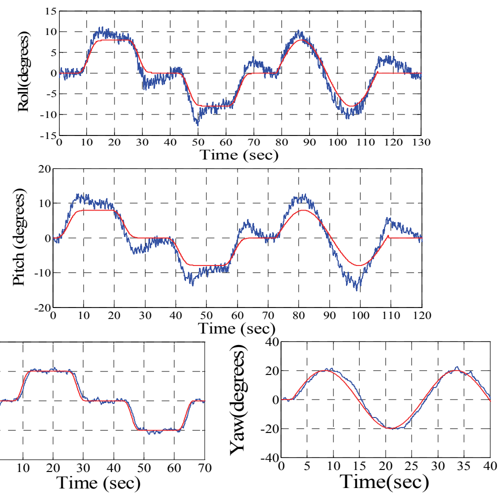

Fig. 12. Desired Angles (Red) and real Angles outputs (Blue)

The results obtained (Fig. 12) show a good performance tracking for the three angles.

Conclusions

This paper presents the design of an embedded control system for the attitude tracking of quadrotor based on integral backstepping methodology. The embedded control unit is developed to acquire measurements from several sensors and performs control algorithms to stabilize the attitude of the platform. An IMU 3DM-GX1 is used as an attitude sensor. The rotation speed of the propeller for each rotor is obtained from Hall Effect sensors in combination with little magnets. An internal propellers speeds controllers are added to improve the performance stabilization. The integral backstepping algorithm is designed and implemented in real time using the developed embedded control system for the attitude tracking of the quadrotor helicopter. The obtained experimental results demonstrate the good performance stabilization, tracking, and disturbances rejection.

References

1. **Brisset P.** Drones civils Perspectives et réalités // Ecole Nationale de l'Aviation Civile Report, 2004.
2. **Hamel T., Mahony R., Lozano R., Ostrowski J.** Dynamic modelling and configuration stabilization for an X4–flyer // Procedding of the IFAC World Congress. – Barcelona, Spain, 2002.
3. **Bouabdallah S., Murrieri P., Siegwart R.** Design and control of an indoor micro quadrotor // Proceeding of the 2004 IEEE International Conference on Robotics & Automations. – New Orleans, LA, 2004.
4. **MC Gilvray S. J.** Attitude stabilization of a quadrotor aircraft. – A thesis submitted in partial fulfillment of the requirements for the degree of Master Science, in control Engineering. – Lakhead University, Thunder Bay, Ontario, Canada, 2004.
5. **Bouabdallah S., Siegwart R.** Backstepping and Sliding Mode Techniques Applied to an Indoor Micro Quadrotor // Proc. of the 2005 IEEE, International Conference on Robotics and Automation. – Barcelona, Spain, 2005.
6. **Castillo P., Lozano R., Dzul A.** Modelling and Control of Mini–Flying Machines. – Springer–Verlag, London, 2005.
7. **Escareño J., Salazar–Cruz S., Lozano R.** Embedded control of a four–rotor UAV // Proceedings of the 2006 American Control Conference. – Minneapolis, Minnesota, USA, 2006.
8. **Osmani H., Bouchoucha M., Bouri M.** Design of an embedded control system for an UAV quadrotor system // Proc. of the IFAC 9th Portuguese conference on automatic control (CONTROLO'2010). – Coimbra, Portugal, 2010.
9. **Hoffmann G. M., Huang H., Waslander S. L., Tomlin C. J.** Quadrotor Helicopter Flight Dynamics and Control: Theory and Experiment // AIAA Guidance, Navigation and Control Conference. –Hilton Head, South Carolina, 2007.
10. **Kroo I., Prinz F.** The Mesicopter: A miniature rotorcraft concept –phase ii interim report. – Stanford university, USA.
11. **Draganflyer V TI.** Online: www.rctoys.com.
12. **Skjetne R., Fossen T. I.** On Integral Control in Backstepping Analysis of Different Techniques // Proceeding of the 2004 American Control Conference. – Boston, Massachusetts, 2004.
13. **Scott D. H.** A small semi–autonomous rotary–wing unmanned air vehicle. – A thesis in Aerospace Engineering. – The Pennsylvania State University, the Graduate School, 2005.

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This work aims to redesign an embedded control system for an autonomous quadrotor. This embedded control system is developed based on a *DsPic* microcontroller. A wireless communication between the ground station and the system is insured via an *Xbee* device and an inertial measurement unit is used for attitude measurement. The integral backstepping approach is designed and its algorithm is implemented in real time on the realized embedded control system for the attitude stabilization of the quadrotor system. The results obtained show good performance stabilization, demonstrates superior angles tracking response as well as rejection to the load disturbance. Ill. 12, bibl. 13 (in English; abstracts in English and Lithuanian).

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Atliktas įterptinės valdymo sistemos, skirtos autonominiams kvadrorotoriams, tobulinimas. Sistema suprojektuota naudojant mikrovaldiklį *DsPic*. Bevielis ryšys tarp antžeminės stebėjimo stoties ir sistemos užtikrinamas naudojant modulį *Xbee*. Suprojektuota valdymo sistema buvo įdiegta realioje kvadrorotorinėje sistemoje. Ji užtikrina gerą stabilizaciją, puikų valdymo sistemos kampų išlaikymą pasikeitus apkrovai. Il. 12, bibl. 13 (anglų kalba; santraukos anglų ir lietuvių k.).