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Control of an Under-Actuated X4-flyer using Integral Backstepping Controller

Abstract. *This paper presents the study of stabilization with motion planning of the four rotors mini-flying robot (helicopter with four rotors). The dynamic model involves four control inputs which are computed to stabilize the engine with predefined trajectories path. The tracking feedback controller is based on receding horizon point to point steering. It is clear that our device belongs to families of under-actuated systems. Our aim is to obtain control algorithms using Integral Backstepping approach in order to stabilize the engine and to generate its trajectory.*

Streszczenie. *W artykule przedstawiono badania stabilizacji w planowaniu ruchu czterowirnikowego robota (helikopter z czterema wirnikami).Dynamiczny model obejmuje cztery wejsćia sterujqce, które sq; obliczane w celu stabilizacji silnika dla zdefiniowanej ścieżeki trajektorii. Celem jest uzyskanie algorytmów sterowania. (Sterowanie robotem czterowirnikowym przy użyciu kontrolera Integral Backstepping)*

Keywords: Helicopter, Dynamical systems, Backstepping control
Słowa kluczowe: Helikopter, Uklady dynamiczne, Backstepping kontroli.

Introduction

Recently the merit and application of small-sized UAVs (Unmanned Aerial Vehicles) have been being increased explosively as the design and control technologies for the small flying objects have been combined with various high technologies. Small-sized UAVs have wider operation range and better mobility in the environment with many obstacles than on-the-ground mobile robots. Further, small-sized UAVs are much cheaper and safer in dangerous tasks than piloted aircrafts. These kinds of UAVs can be widely applied in various tasks from calamity observation such as wood and building fires, meteorological observation, patrol, and spraying agricultural chemicals to military purpose such as reconnaissance, monitoring, and communication.

Small-sized UAVs are classified into two categories, fixed and rotary wing types. The rotary wing type UAVs are more advantageous than the fixed wing type ones in the sense of VTOL(Vertical Take-off and Landing), omnidirectional flying, and hovering performances, and can be divided into QRTs (Quad-Rotor Types), same axis reverse rotation types, and helicopter types as their shapes. QRTs have the simplest mechanical structures among them, and that is the reason why the QRT is considered in this study as a flying platform for calamity observation such as indoor fire spots etc. is one of the stochastic algorithms. Such methods are simple to implement, they search for globally best solution and they may be applied for practically any cost function: even discontinuous and multimodal. QRT small-sized UAVs with various shape and size have been developed for commercial and research purposes, and some models are being sold as RC (Radio Control) toys. Autonomous QRT UAVs equipped with high technology sensors are also being developed for special purposes, and researches for analysis and control of the flying robots are being done vigorously [17].

Modeling and controlling aerial vehicles are the principal preoccupation of our laboratory. The aerial flying engine could not exceed $2kg$ in mass, a wingspan of $50cm$ with a $30mn$ flying-time (see Fig. 1). Within this optic, it can be held that our system belongs to family of mini-UAV. It is an autonomous hovering system, capable of vertical takeoff, landing, lateral motion and quasi-stationary (hover or near hover) flight conditions. Compared to helicopters [1], the four rotors called (X4-flyer) has some advantages [10] [14] [4]: given that two motors rotate counter clockwise while the other two rotate clockwise, gyroscopic effects and aerodynamic torques tend, in trimmed flight, to cancel. An X4-flyer operates as an omni directional UAV. Vertical motion is controlled by collectively increasing or decreasing the power for all motors. Lateral motion, in x direction or in y direction, is achieved by differentially controlling the motors generating a pitching/rolling motion of the airframe that inclines the collective thrust (producing horizontal forces) and leads to lateral accelerations.

Several recent works were completed for the design and control in pilotless aerial vehicles domain such that Quadrotor [1, 14, 20]. Also, related models for controlling the Vertical Take-Off and Landing (VTOL) aircraft are studied by Hauser et al [11]. A model for the dynamic and configuration stabilization of quasi-stationary flight conditions of a four rotors VTOL, based on Newton formalism, was studied by Hamel et al [9] where the dynamic motor effects are incorporating and a bound of disturbing errors was obtained for the coupled system. Castillo et al [8] performed autonomous take-off, hovering and landing control of a four rotors by synthesizing a controller using the Lagrangian model based on the Lyapunov analysis.

The stabilization problem of a four rotors is also studied and tested by Castillo [7] where the nested saturation algorithm is used, the input/output linearization procedure [11], in [6] a proportional integral derivative (PID) controller and a linear quadratic (LQ) controller were implemented and proved capable of regulating the system and application of the theory of flat systems by Beji et al [3]. Mokhtari et al [13] proposed an attempt to apply linear H_∞ outer control of helicopter quadrotor with plant uncertainty combined with a robust feedback linearization inner controller. Hanford et al [12], presented a simple closed loop equipped with MEMS (Micro-Electro-Mechanical Systems) sensors and PIC based processing unit.

Tayebi and McGilvray [15] proposed a new quaternion-based feedback control scheme for exponential attitude stabilization of a quadrotor. The proposed controller is based upon the compensation of the Coriolis and gyroscopic torques and the use of a PD^2 feedback structure, where the proportional action is in terms of the vector quaternion and the two derivative actions are in terms of the airframe angular velocity and the vector quaternion velocity. In [2] Benzemrane et al, adressed the classical problem of speed estimation of an Unmanned Aerial Vehicle when the acceleration, the angles and the angular speeds are available for measurement. A solution has been provided for a class of systems via the tools of adaptive observation theory with promissing results. Bestaoui et al [5] addressed the problem of characterizing maneuvers paths on the group of rigid body motions in 3D for a quadrotor. The role of the trajectory generator is to generate a feasible time trajectory for the UAV.

Flight control methods utilizing vision systems are also studied by [16], which exploits the Moirtterns. Hamel and Mahony [10] proposed a vision based controller which performs visual servo control by positioning a camera onto a fixed target for the hovering of a quadrotor.

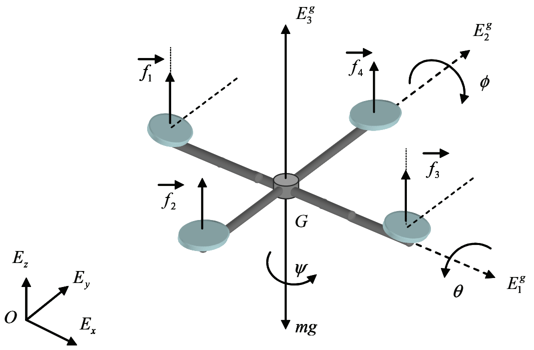

Fig. 1. 3D X4-flyer model

In this paper, the Integral backstepping controller and motion planning are combined to stabilize the helicopter by using the point to point steering stabilization. After having presented the study of modeling and the description of the configuration in the second section. Integral backstepping controllers is described for the model of the X4-Flyer in the third section. Motions planning and simulations results are presented in fourth section. The robustness of the proposed controller is evaluated in the fifth section. Finally, conclusion and future work are given in the last section.

Configuration description and modeling

Unlike regular helicopters that have variable pitch angles, an engine that has fixed pitch angle rotors and the rotor speeds are controlled to produce the desired lift forces. Basic motions of the four rotors are described by Fig. 2. Vertical motion is controlled by collectively increasing or decreasing the power for all motors. Lateral motion, in x direction or in y direction, is achieved by differentially controlling the motors generating a pitching/rolling motion of the airframe that inclines the collective thrust (producing horizontal forces) and leads to lateral accelerations (case of the X4-flyer).

A body fixed frame is assumed to be at the center of gravity of the X4-flyer, where the z axis is pointing upwards. This body axis is related to the inertial frame by a position vector (x, y, z) and three Euler angles (θ, ϕ, ψ) representing pitch, roll and yaw respectively. A XYZ Euler angle representation given in Eq. (1) has been chosen for the representation of the rotations.

(1)
$$R = \begin{pmatrix} C_\psi C_\theta & C_\theta S_\psi & -S_\theta \\ S_\phi C_\psi S_\theta - S_\psi C_\phi & S_\theta S_\psi S_\phi + C_\psi C_\phi & C_\theta S_\phi \\ S_\theta C_\psi C_\phi + S_\psi S_\phi & C_\phi S_\theta S_\psi - C_\psi S_\phi & C_\theta C_\phi \end{pmatrix}$$

where C_θ and S_θ represent $cos\ \theta$ and $sin\ \theta$ respectively.

Each rotor produces moments as well as vertical forces. These moments have been experimentally observed to be linearly dependent on the forces for low speeds. There are four input forces and six output states $(x, y, z, \theta, \phi, \psi)$ therefore the X4-flyer is an under-actuated system. The rotation direction of two of the rotors are clockwise while the other two are counterclockwise, in order to balance the moments and produce yaw motions as needed.

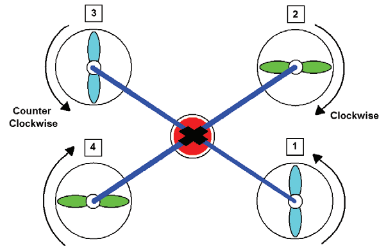

Fig. 2. Upper view to the four rotors rotorcraft.

0.1 Dynamics motion

We consider the translation motion of $\Re_G$ with respect to (wrt) $\Re_O$. The position of the center of mass wrt $\Re_O$ is defined by $\overline{OG} = (x\ y\ z)^T$, its time derivative gives the velocity wrt to $\Re_O$ such that $\frac{d\overline{OG}}{dt} = (\dot{x}\ \dot{y}\ \dot{z})^T$, while the second time derivative permits to get the acceleration $\frac{d^2\overline{OG}}{dt^2} = (\ddot{x}\ \ddot{y}\ \ddot{z})^T$. Currently, the model is a simplified one's. The constraints and the gyroscopic torques are neglected. The aim is to control the engine vertically $z-$axis and horizontally according to $x-y$ axes. Applying the first Newton equation of mechanics, we obtain the following compact expression of the translation motion:

(2)
$$m\vec{\gamma_G}|_{\Re_O} = -mg\vec{e_z} + R(\psi, \phi, \theta)\ \vec{u_3}$$

Where m is the total mass of the vehicle. The vector u_3 combines the principal non conservative forces applied to the engine airframe including forces generated by the motors and drag terms.The gyroscopic due to motors effects will be not considered in this work. The lift (collective) force u_3 is the sum of the four forces, such that

(3)
$$\vec{u_3} = \vec{f_1} + \vec{f_3} + \vec{f_2} + \vec{f_4}$$

with $\vec{f_i} = k_i\omega_i^2\vec{e}_3$ and $\vec{e}_3$ the unit vector along E_3^g. $k_i > 0$ is a given constant and ω_i is the angular speed resulting of motor i.

The dynamics of the vehicle, represented by Fig.1, is modeled by the system of equations (4).

(4)
$$\begin{aligned} m\ddot{x} &= -S_\theta u_3 \\ m\ddot{y} &= C_\theta S_\phi u_3 \\ m\ddot{z} &= C_\theta C_\phi u_3 - mg \end{aligned}$$

0.2 Rotational motion

The rotational motion of the X4-flyer will be defined wrt to the local frame but expressed in the inertial frame. According to Classical Mechanics, and knowing the inertia matrix $I_G = diag\,(I_{xx}, I_{yy}, I_{zz})$ at the center of the mass.

(5)
$$\begin{aligned} \ddot{\theta} &= \frac{1}{I_{xx}C_\phi}\left(\tau_\theta + I_{xx}S_\phi\dot{\phi}\dot{\theta}\right) \\ \ddot{\phi} &= \frac{1}{I_{yy}C_\theta C_\phi}\left(\tau_\phi + I_{yy}S_\phi C_\theta\dot{\phi}^2 + I_{yy}S_\theta C_\phi\dot{\theta}\dot{\phi}\right) \\ \ddot{\psi} &= \frac{\tau_\psi}{I_{zz}} \end{aligned}$$

with the three inputs in torque

(6)
$$\begin{aligned} \tau_\theta &= l\,(f_2 - f_4) \\ \tau_\phi &= l\,(f_1 - f_3) \\ \tau_\psi &= lk\,(f_1 - f_2 + f_3 - f_4) \end{aligned}$$

where l is the distance from G to the rotor i and k is the actuator torque coefficient. The equality from (6) is ensured, meaning that

(7) $$\ddot{\eta} = \Pi_G(\eta)^{-1}\left[\tau - \dot{\Pi}_G(\eta)\dot{\eta}\right]$$

With $\tau = (\tau_\theta, \tau_\phi, \tau_\psi)^T$ as an auxiliary inputs.
and

(8) $$\Pi_G(\eta) = \begin{pmatrix} I_{xx}C_\phi & 0 & 0 \\ 0 & I_{yy}C_\phi C_\theta & 0 \\ 0 & 0 & I_{zz} \end{pmatrix}$$

as a first step, the model given above can be input/output linearized by the following decoupling feedback laws.

(9) $$\begin{aligned} \tau_\theta &= -I_{xx}S_\phi\dot{\phi}\dot{\theta} + I_{xx}C_\phi u_4 \\ \tau_\phi &= -I_{yy}S_\phi C_\theta\dot{\phi}^2 - I_{yy}S_\theta C_\phi\dot{\theta}\dot{\phi} + I_{yy}C_\theta C_\phi u_5 \\ \tau_\psi &= I_{zz}u_6 \end{aligned}$$

and the decoupled dynamic model of rotation can be written as:

(10) $$\ddot{\eta} = u$$

with $u = (u_4\ u_5\ u_6)^T$ using Eq. (4) and Eq. (10), the dynamic of the system is defined by:

(11) $$\begin{aligned} m\ddot{x} &= -S_\theta u_3 \\ m\ddot{y} &= C_\theta S_\phi u_3 \\ m\ddot{z} &= C_\theta C_\phi u_3 - mg \\ \ddot{\theta} &= u_4 \\ \ddot{\phi} &= u_5 \\ \ddot{\psi} &= u_6 \end{aligned}$$

Integral backtepping controller design

In this section, controller design for the quadrotor UAV is proposed by using integral backsteppig technique. Our objective is to ensure the onvergence of the positions $\{x(t), y(t), (z(t), \psi(t)\}$ to the desired trajectories $\{x_d(t), y_d(t), z_d(t), \psi_d(t)\}$ respectively and stabilize the pitch and the roll angles $\{\phi(t), \theta(t)\}$.

0.3 Integral backstepping control of the Linear Translations

0.3.1 Altitude control

The altitude, can be controlled by the integral backstepping controller. With through the equation of the following movement (z).

(12) $$m\ddot{z} = C_\theta C_\phi u_3 - mg$$

The first step in control design is to consider the tracking error signal:

(13) $$e_1 = z_{ref} - z$$

Then its error dynamics is:

(14) $$\dot{e}_1 = \dot{z}_{ref} - \dot{z} = \dot{z}_{ref} - v_z$$

The linear speed v_z is not our control input and has its own dynamics. So,we set for it a desired behavior and we consider it as our virtual control:

(15) $$v_{zref} = c_1e_1 + \dot{z}_{ref} + \lambda_1\chi_1$$

with c_1 and λ_1 positive constants and $\chi_1 = \int e_1(\tau)\partial\tau$ the integral of altitude tracking error. Since v_z has its own error e_2 , we compute its dynamics using Eq.(15) as follows:

(16) $$\dot{e}_2 = c_1(\dot{z}_{ref} - v_z) + \ddot{z}_{ref} + \lambda_1e_1 - \ddot{z}$$

where e_2, the linear velocity tracking error defined by :

(17) $$e_2 = v_{zref} - v_z$$

Using Eq.(15) and Eq.(17) we rewrite the altitude z tracking error dynamics as:

(18) $$\dot{e}_1 = -c_1e_1 - \lambda_1\chi_1 + e_2$$

By replacing $\ddot{z}$ in Eq.(16) its corresponding expression the control input u_3 appears in Eq.(19):

(19)
$$\dot{e}_2 = c_1(-c_1e_1 - \lambda_1\chi_1 + e_2) + \ddot{z}_{ref} + \lambda_1e_1 - \frac{1}{m}(C_\theta C_\phi u_3 - mg)$$

The desirable dynamics for the velocity tracking error is:

(20) $$\dot{e}_2 = -c_2e_2 - e_1$$

So that is result the output command of the altitude is:

(21)
$$u_3 = \frac{m}{C_\theta C_\phi}(g + (1 - c_1^2 + \lambda_1)e_1 + (c_1 + c_2)e_2 - c_1\lambda_1\chi_1 + \ddot{z}_{ref})$$

where c_2 is positive constant which determines the convergence of the linear speed loop.

0.3.2 Stability analysis

Stability analysis is performed using Lyapunov theory. The following condidate Lyapunov function is chosen :

(22) $$V = \frac{1}{2}\left[\lambda_1\chi_1^2 + e_1^2 + e_2^2\right]$$

It includes the position tracking error e_1 and velocity tracking error e_2. Deriving Eq. (22) and using Eqs. (18) and (20) gives:

(23) $$\dot{V} = -c_1e_1^2 - c_2e_2^2 \leq 0$$

Global Asymptotic Stability is also ensured from the positive definition of V and the fact that $\dot{V}(e_1, e_2) < 0$, $\forall(e_1, e_2) \neq 0$ and $\dot{V}(0) = 0$ and by applying LaSalle theorem.

0.3.3 Linear x and y motion control

From the model (11) one can see that the motion through the axes x and y depends on u_3. In fact u_3 is the total thrust vector oriented to obtain the desired linear motion. If we considered $u_x = s_\theta$ and $u_y = c_\theta s_\phi$ the orientations of u_3 responsible for the motion through x and y axis respectively, we can then extract the roll and pitch angle necessary to compute the control u_x and u_y.

The control law is then derived using integral backstepping technique. Positions tracking errors for x and y are defined as:

$$\left\{\begin{array}{l} e_3 = x_{ref} - x \\ e_5 = y_{ref} - y \end{array}\right. \tag{24}$$

according speed tracking error are:

$$\left\{\begin{array}{l} e_4 = c_3 e_3 + \dot{x}_{ref} + \lambda_2 e_3 - \dot{x} \\ e_6 = c_5 e_5 + \dot{y}_{ref} + \lambda_3 e_3 - \dot{y} \end{array}\right. \tag{25}$$

The control laws are then:

(26)
$$\left\{\begin{array}{l} u_x = \frac{m}{u_3}((1 - c_3^2 + \lambda_2)e_3 + (c_3 + c_4)e_4 - c_3\lambda_2\chi_2 + \ddot{x}_{ref}) \\ u_y = \frac{m}{u_3}((1 - c_5^2 + \lambda_3)e_5 + (c_5 + c_6)e_6 - c_5\lambda_3\chi_3 + \ddot{y}_{ref}) \end{array}\right.$$

With (c_3,c_4,c_5,c_6,λ_2,λ_3)$\succ$ 0 and (χ_2,χ_3) the integral position tracking error of x and y position respectively.

0.4 Integral backtepping control of the rotations subsystem

0.4.1 Attitude control

Attitude control is the heart of the control system, it keeps the 3D orientation the desired value. The first step in integral backstepping control design is to consider the tracking error $e_7 = \phi_{ref} - \phi$ and its dynamics:

$$\dot{e}_7 = \dot{\phi}_{ref} - \dot{\phi} = \dot{\phi}_{ref} - w_x \tag{27}$$

the angular speed w_x is not our control input and has its own dynamic. So, we set for it a desired behavior and we consider it as our virtual control.

$$w_{xref} = c_7 e_7 + \dot{\phi}_{ref} + \lambda_4 \chi_4 \tag{28}$$

With c_7 and λ_4 positive constants and $\chi_4 = \int e_7(\tau)\partial\tau$ the integral of roll tracking error. Since w_x has its own error e_8 , we compute its dynamics using Eq. (28) as follows:

$$\dot{e}_8 = c_7(\dot{\phi}_{ref} - w_x) + \ddot{\phi}_{ref} + \lambda_4 e_7 - w_x \tag{29}$$

where e_8 is the angular velocity tracking error defined by:

$$e_8 = w_{xref} - w_x \tag{30}$$

Using Eq. (27) and Eq. (28) we rewrite the altitude ϕ tracking error dynamics as:

$$\dot{e}_7 = -c_7 e_7 - \lambda_4 e_7 + e_8 \tag{31}$$

$$u_5 = (1 - c_7^2 + \lambda_4)e_7 + (c_7 + c_8)e_8 - c_7\lambda_4\chi_4 + \ddot{\phi}_{ref} \tag{32}$$

where c_8 is positive constant which determines the convergence of the angular speed loop.

0.4.2 Pitch and yaw control (θ, ψ)

The same steps are followed to extracted u_4 and u_6.

$$u_4 = (1 - c_9^2 + \lambda_5)e_9 + (c_9 + c_{10})e_{10} - c_9\lambda_5\chi_5 + \ddot{\theta}_{ref} \tag{33}$$

(34)
$$u_6 = (1 - c_{11}^2 + \lambda_6)e_{11} + (c_{11} + c_{12})e_{12} - c_{11}\lambda_6\chi_6 + \ddot{\psi}_{ref}$$

Simulations results

The drone is tested in simulation in order to validate some motion planning algorithm considering the proposed Integral backstepping control laws. We have considered a total mass equal to $m = 2kg$. We solve the tracking control problem using the point to point steering stabilization see [18] [19] for more details.

Figure 3 and 7 shows the tracking of desired trajectory by the real one and the evolution of the quadrotor and its stabilization in 3D displacement for the circle and helical trajectory.

Figure 4 illustrate the controlled positions zxy using Integral backstepping controller where u_3, u_4 and u_5, denote the command signals for z, x and y directions respectively. Note that the input $u_3 = mg$ at the equilibrium state is always verified. The inputs u_4 and u_5 tend to zero after having carried out the desired orientation of the vehicle. Figure 5 shows displacement errors according to all the directions. It is noticed that the error thus tends to zero toward the desired positions.

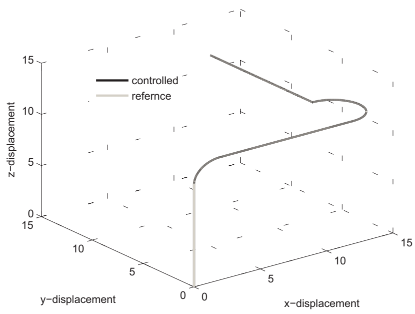

Fig. 3. Realization of a circle corners.

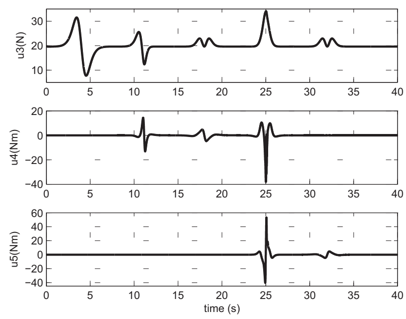

Fig. 4. Control inputs ($u_3,\ u_4\ and\ u_5$).

On the Fig. 6, we notice that the angles θ and ϕ control the engine for displacements along the axes x and y. These angles tend to zero value.

controllers robustness

The robustness of the developed controllers are evaluated regarding external disturbances and performance degradations in the case of wind influence. In the case of the XSF, a resistance or a drag force is opposed to its movement in flight. The work produced by this force involve an

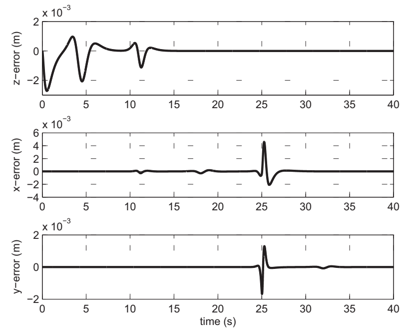

Fig. 5. Position error (x, y, z).

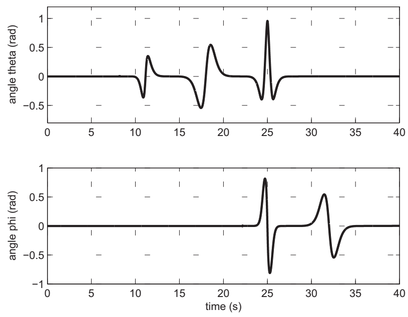

Fig. 6. The pitch θ and the roll ϕ.

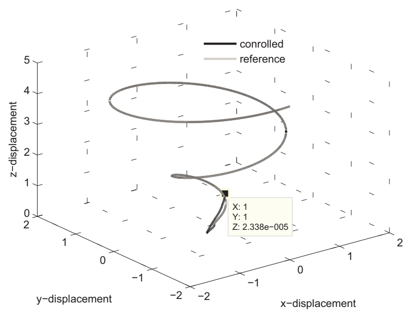

Fig. 7. Realization of cone corners.

additional energy consumption at the actuators levels which limits its maneuvering capacities in flight. This force can be expressed as follow:

$$F_i = \frac{1}{2} C_x \rho A V_i^2 \tag{35}$$

Where $F_i[N]$ is the drag force following the i axis, V_i [m/s] is the drone velocity, $A[m^2]$ is the coss-sectional area perpendicular to the force flow and $\rho[Kg/m^3]$ is the body density. The equation (35) induced the drag coefficient C_x which is a dimensionless quantity that describes a characteristic amount of aerodynamic drag depending on the UAV structure and which is experimently determined by wind tunnel tests. This coefficient is equal to 0.5 for the x and y directions and 0.08 for the z displacement. The surface characteristic $A = 0.031m^2$ and it density is considered equal to $\rho = 1.22Kg/m^3$.

To test the controller robustess the simulations have been executed considering external disturbances: $F_z = 3[N]$ at t=15s, $F_x = 3[N]$ at t=20s and $F_y = 3[N]$ at t=27s

The simulations results are dipicted in Figs. 8-11. These figures show that the control stratgies present a robust path following when abrupt changes of references and sustained disturbaces are applied to the quadrotor.

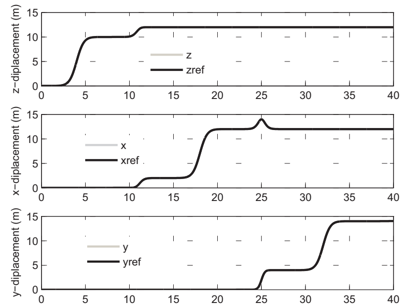

Fig. 8. Position (x, y, z).

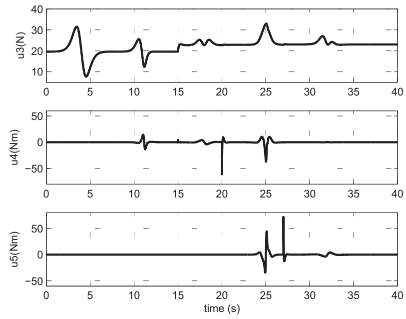

Fig. 9. Control inputs($u_3,\ u_4\ and\ u_5$).

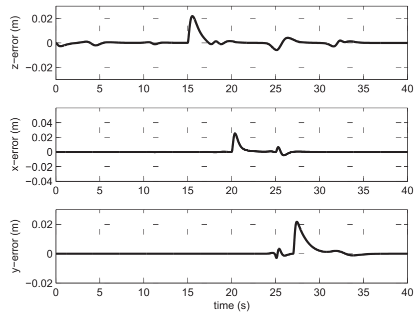

Fig. 10. Position error (xyz).

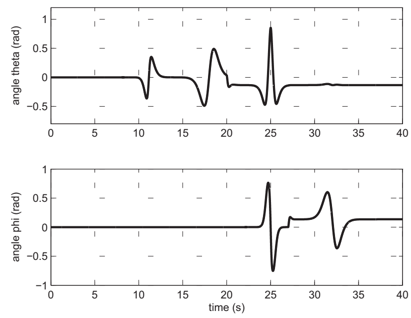

Fig. 11. The pitch θ and the roll ϕ.

Figure 12 show the tracking of desired trajectory by the real one and the evolution of the quadrotor and its stabilization in 3D displacement helical trajectory when disturbances are applied to the system.

Conclusion

In this paper, The four rotors helicopter is studied and controlled using the integral backstepping control. In this work the stabilizing/tracking control problem for the three decoupled displacements of a X4-flyer has been considered. The objectives are to test the capability of the engine to fly

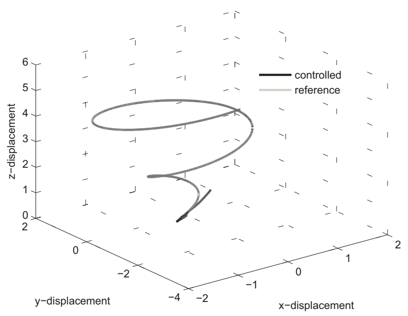

Fig. 12. Realization of cone corners with disturbance.

with circle and helical intersections trajectories. This technique was successfully applied and allows us to design algorithms of control ensuring the vehicle displacement from an initial position to a desired position. An analysis of the Integral backstepping controller and their robustness regarding disturbance shows the effectiveness of the proposed controller. Future works will essentially investigate the real time implementation of this technique. A realization of a control system based on engine sensors information is envisaged.

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