Design and Construction of a Quadrotor-type Unmanned Aerial Vehicle: Preliminary Results

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Abstract—In this paper we report the stages in the construction of a quadrotor-type unmanned aerial vehicle (UAV) from scratch. This vehicle is characterized by four rotors responsible for the generation of vertical and horizontal motions. Its design should also provide capabilities for the transport of extra payload. We describe in detail the main components used for its construction, the dynamic model and the structure used for indoor flight tests. The main rationale for its construction is to have a complex realworld platform to evaluate control algorithms.

Keywords- Unmanned aerial vehicle, Quadrotor, Mechanical Design, Dynamical Modeling.

I. INTRODUCTION

A quadrotor-type UAV is a type of helicopter which is propelled by four rotors. Adjacent blades rotate in opposite directions and a tail rotor is not required in order to counteract the angular momentum of the propellers. As a coupled dynamical system, by altering the motor speed, the position is also changed. As mentioned in [1] that system is underactuated and very dynamically unstable.

In many situations it is desirable that the system to be as small as possible and to achieve large movements, being able to move both vertically and horizontally. Applications are often focused on the military areas, surveillance, inspection of transmission lines and power distribution; low cost filming and panoramic picturing for the movie industry, sport events, crop and herd monitoring, among others. Specific characteristics, such as vertical flight ability and flying at low speeds, allow quadrotors to perform tasks which are difficult to implement through other mechanisms and structures.

With demand of applications for this kind of aerial vehicle rapidly increasing, also increases the interest in research, both in industry and academia. Several studies are being conducted on the dynamics and describing methods to regulate their flight by adding automatic stability control through a diversity of hardware and software control schemes.

The objective of this work is to describe the design and the construction of the structure of a quadrotor device that can carry extra payloads (see Fig. 1). The ultimate goal of the quadrotor (not shown in this paper) is to use it for testing

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control algorithms. Initially controlled by a computer that sends commands via radio to a microcontroller contained in quadrotor, this microcontroller is responsible for sending values of the speed for each rotor.



Figure 1. A picture of the developed UAV-type quadrotor.

The remainder of the paper is organized as follows. In Section 2 we describe the structure and operation of the vehicle. The dynamic model of the quadrotor-type UAV is described in Section 3. In Section 4 we validate the structure by showing how the tests are done. The conclusions are presented in Sections 5.

II. DESCRIPTION OF THE STRUCTURE

Initially, the main issue of this work was the choice of the components to be used to build a prototype quadrotor. The choice of components was based on [2], but the structure was decided only after a detailed research in the available literature and companies as shown in Table I.

Once the final structure was defined, its dynamic model was written down and evaluated as will be shown in Section 3.

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A. Available Structures and Projects

There are some quadrotor-type UAV structures available elsewhere, some has been developed for commercial purposes (e.g. entertainment), some for research only purposes.

Just to mention a few examples, the Draganflyer quadrotor [3] is sold at the R/C Toys website and has been also used for academic research. The Parrot AR.Drone [4] is sold for entertainment, being controlled remotely by phone, containing several video games and using augmented reality. The X-4 Flyer, developed in Australia, is also used in numerous studies and several researchers [5]. The STARMAC (*Stanford Testbed of Autonomous Rotorcraft for Multi-Agent*) is already in version II. In [6] it is described the new version of their work, with modified sensors, rotors and new electronic systems. The OS4 device was developed by researchers in Switzerland, with numerous papers presented in international conferences [1].

Many other similar quadrotor-type UAV structures are being developed and used in research in various universities and companies around the world [2], [7], [8], [9], [10], [11], [12], [13]. Since there is still no widely adopted standards for the design and construction of such quadrotors, each interested research group has to build its own device, especially if the goal is to build a testbed for control algorithms.

 TABLE I.
 LIST OF QUADROTOR-LIKE AUV PROJECTS FOUND IN THE LITERATURE.

Projects	Structures
Draganflyer E4	
AR.Drone	
X-4 Flyer	
STARMAC II	
OS4	

B. Movements

A quadrotor-type UAV is driven by four actuators. The rotors are comprised of four motors and two pairs of propellers used in the reverse direction. Adjacent propellers rotate in opposite directions. In Fig. 2 we illustrate the direction of movement of the propellers with black arrows (the width is proportional to the speed of the rotors). Red arrows indicate the direction of the movement of the quadrotor structure as whole.



Figure 2. Illustrative sketches of the rotation of the propellers (black arrows) and the resulting movement of the quadrotor (red arrows).

An increase (decrease) in the speed of the rotor causes the quadrotor to move up (down) vertically. The variation of the two rotors placed on the same axis produces a torque around the axis generating an angular acceleration.

C. The Quadrotor Chassis

The starting point of the project was to set properly the suitable size and weight of the system. The chassis was constructed using aluminum profiles (bars) arranged in a cross shape. Their extremities are connected by steel cords to increase the rigidity of the structure as a whole and avoid using more aluminum profiles, which would make the structure heavier.



Figure 3. The basic aluminum structure built for the quadrotor-like AUV developed on this work. The length of the parts a, b and c highlighted in the figure are shown in Table II.

The aluminum profile has a U-shaped cross-section format for the fixation of four supporting bases located on the underside of the structure. The rotors are fixed on the bars at the end of each side and close to the steel cords. Aluminum was chosen because it is lightweight (about 1/3 the weight of steel), corrosion resistant, non-magnetic, and with the right alloying elements, very rigid. The final weight of the aluminum structure was 107 g.

The *Von Mises* test was performed using the plugin NX Nastran of the *Solid Edge ST3 CAD* software [14]. In the test it was found that the structure developed in aluminum 1060 begins to deform plastically at a yield point of 27 MPa. In this test, the extremities were fixed and its surface subjected to the force of gravity.

TABLE IL	SIZE OF THE PARTS HIGHLIGHTED	IN FIG	: 3
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Part	Length (mm)	Width (mm)	Height (mm)
а	486	6,06	6,08
b	10	2	120
с	30	6,06	6,08

D. Propulsion System

As mentioned before, the propulsion system of the quadrotor was comprised of four motor and two pairs of propellers. Brushless-type motors were used, Emax model 2822, indicated by many who work with model airplanes, with 1200 RPM/Volt. This motor weighs 39g and its current ranges from 7A to 12A in continuous use. Working together with a 9-inch propeller it may be capable of lifting loads up to 700g.

Three-bladed propellers were used, manufactured by GWS, model HD-9050x3. Two usual ones rotate in one direction and two reverse ones (with inverted angle of attack) rotate in opposite directions.

Hobby King Electronic Speed Control (ESC) devices, 30A, were used to control the motors, as commonly recommended for the kind of motors we are using. The ESCs inputs are standard aeromodelling signals with a frequency of 50 Hz, and with speed varying according to the variation in high logic in the range of 1-2 ms. At the output of each ESC three delayed (i.e. PWM) signals feed phases of each motor.

TABLE III. SIZE AND WEIGHT OF THE COMPONENTS OF THE QUADROTOR.

Component	Quantity	Dimensions(mm)	Mass (g)
Chassis	1	354x354x120	107
Propeller	4	229 (diameter)	25 (each)
Spinner	4	14 (diameter)	11 (each)
ESC	4	24x45x11	19 (each)
Motor	4	28.5x30	39 (each)
μC Board	2	80x80x25	100 (each)
Battery	1	25x35x102	179

The Table III summarizes all dimensions and masses of the components used to built the structure of the quadrotor and to control it.

E. System Architecture

Being an under-actuated system, commands for altitude and flight direction are sent via radio by a computer to another radio that is connected to a microcontroller. This receives data and sends commands to the ESCs in order to drive the motors. A basic diagram of the functioning of the system is shown in Fig. 4.



Figure 4. A basic dagram of the main parts comprising the developed quadrotor-type UAV.

F. Microcontrolled Board

The integration and optimization also depends of the ability to process sensor data and execute the control algorithms in real-time, spend little energy and save costs to the maximum.

The circuit responsible for commanding the motors of the proposed quadrotor-type UAV was developed using the dsPIC30F4011 microcontroller, Microchip family [15]. It is a 16-bit microcontroller that can execute up to 120 MIPS (Million Instructions Per Second).

Initially we decided to use only one microcontroller to execute the direction and altitude commands, both sent by radio. We then realized that the amount of information was too high for a single microcontroller to process, thus requiring the development of another microcontrolled circuit to control and receive data from the sensors. The former microcontroller then became responsible only for the implementation of the PWM signals (Pulse Width Modulation) for the motors.

G. Communication

The radio communication system is comprised of two LPRS (Low Power Radio Solutions) transceivers modules, Easy-Radio ER400TRS [16], which provide a high performance, simplicity of use and the possibility of bidirectional data transfer. The radios transmit data using digital signal at a frequency of 433 MHz, with output power and speed programmable data processing.

The radio and the microcontroller were configured to work at a transmission speed of 19200 bits per second. One radio is located at the computer and the other within the quadrotor as shown in Fig.4. The computer software send commands through the serial port, which is connected to the radio.

H. Power System

One drawback of every quadrotor-type UAV is the high energy needed to drive the four rotors. The power supply for the system was provided by one Lithium-ion Polymer (LiPo) battery of 11.1 V and 2200 mAh capacity, providing an autonomy of approximately 15 minutes of flight.

The LiPo battery is lighter than other types of commercially available batteries, having a weight of about 179 g. This battery provides power to both, the engines and the electronic circuitry.

I. Sensors

The sensors used for navigation of the quadrotor are a triaxial accelerometer, two bi-axial gyroscopes and a sonar. The gyroscopic and accelerometer are used for checking the tilting axes and sonar for checking the height flying of the structure, needed for attitude control.

The signals of the tri-axial accelerometer are processed by a support board for the integrated circuit MMA7361L type MEMS (Micro-Electro-Mechanical Systems) by Freescale [17]. The outputs X, Y and Z of the accelerometer are three separated analog voltages centered at half the supply voltage of 3.3V. Positive acceleration along an axis increases the voltage and are used to check the inclination of the structure in two axes.

The LPR510AL gyroscope biaxial also requires a MEMStype board. Each gyroscope can operate in the range of ± 100 degrees/second and ± 400 degrees/second. The sensitivity range is used for navigation of the structure to ± 100 degrees/second to check the angular velocity in three axes.

Another sensor used is the LV-MaxSonar-EZ3 ultrasonic range finder [18]. This sensor detects objects in the range 0 to 6.45 m with a resolution of 2.5 cm. The sonar possesses three output interfaces, all activated simultaneously, namely: digital pulse length output, analog voltage output, and an asynchronous serial digital output. This sensor is used in the output analog, positioned in the center of the vehicle.

III. DYNAMICS OF A QUADROTOR-TYPE UAV

A. Newton-Euler Modelling

Many researchers follows different approaches to come up with the mathematical model of a quadrotor-type UAV. In [1], the author describes mathematically the nonlinear dynamic model of a quadrotor, being adopted in the present work.

The motion about the lateral axis is the pitch (i.e. leaning forward or backward), the roll motion corresponds to movements to the left or right in the transverse axis and the yaw motion corresponds to a movement about the vertical axis.

The equations to be presented assume that the structure of quadrotor-type UAV and the propellers are rigid, that the

center of gravity lies at the center of the structure, the structure is symmetrical, the motors are identical, and that the aerodynamic thrust and drag are proportional to the square of rotation speed of the motor.



Figure 5. Sketch of the systems of coordinates used for obtaining the dynamic model of the quadrotor.

Let us consider that the coordinate system E is fixed in the floor and the coordinate system B is fixed at the center of the quadrotor. The Newton-Euler equation for rigid bodies describes the combination of rotation and translation:

$$\begin{bmatrix} mI_{3x3} & 0\\ 0 & I \end{bmatrix} \begin{bmatrix} \dot{V}\\ \dot{\tau} \end{bmatrix} + \begin{bmatrix} \omega \times mV\\ \omega \times I\omega \end{bmatrix} = \begin{bmatrix} F\\ \tau \end{bmatrix}$$
(1)

where *m* is the total mass of the system, $I \in \Re^{3\times 3}$ is the inertia matrix of quadrotor, *V* and ω are respectively the linear and angular speed of a rigid body. The force vector produced by the propeller is denoted by *F*. The torque τ that is applied along one axis can be described by the difference between the torques of each motor for each axis as follows:

$$\begin{pmatrix} \boldsymbol{\tau}_{x} \\ \boldsymbol{\tau}_{y} \\ \boldsymbol{\tau}_{z} \end{pmatrix} = \begin{pmatrix} lb \left(\Omega_{4}^{2} - \Omega_{2}^{2} \right) \\ lb \left(\Omega_{3}^{2} - \Omega_{1}^{2} \right) \\ d \left(\Omega_{2}^{2} + \Omega_{4}^{2} - \Omega_{1}^{2} - \Omega_{3}^{2} \right) \end{pmatrix}$$
(2)

where *l* is the distance between the center of the quadrotor to the center of the propeller, *d* is the drag factor, *b* is the coefficient of inclination of the propeller Ω_i , *i*=1, ...,4, denotes the angular speed of the four propellers.

The matrix R shown in (3) projects the vectors in coordinate system B into the coordinate system E for the tilt angles:

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

where C and S stand for the cosine and sine, functions, respectively.

Thus, the dynamic model of the quadrotor as a result of pitch or roll rotations, using the matrix R with the Newton's 2nd law are given by the following equations:

$$\ddot{x} = (\cos \phi . sen \,\theta. \cos \psi + sen \,\phi. sen \,\psi) \frac{1}{m} U_1 \tag{4}$$

$$\ddot{y} = (\cos\phi.sen\,\theta.sen\,\psi - sen\,\phi.\cos\psi)\frac{1}{m}U_1 \tag{5}$$

$$\ddot{z} = -g + (\cos\phi . \cos\theta) \frac{1}{m} U_1$$
(6)

$$\ddot{\phi} = \dot{\theta}\dot{\psi}\left(\frac{I_y - I_z}{I_x}\right) - \frac{J_r}{I_x}\dot{\theta}\Omega + \frac{l}{I_x}U_2$$
(7)

$$\ddot{\theta} = \dot{\phi}\dot{\psi} \left(\frac{I_z - I_x}{I_y}\right) + \frac{J_r}{I_y}\dot{\phi}\Omega + \frac{l}{I_y}U_3 \tag{8}$$

$$\dot{\psi} = \dot{\phi}\dot{\theta}\left(\frac{I_x - I_y}{I_z}\right) + \frac{J_r}{I_z}U_4 \tag{9}$$

where J_r is the inertia of the rotor, ϕ , θ and ψ are the angles of roll, pitch and yaw, respectively.

The control inputs for altitude, roll, pitch and yaw are denoted as U_1 , U_2 , U_3 , and U_4 , respectively, and are computed by the following equations:

$$U_{1} = b \left(\Omega_{1}^{2} + \Omega_{2}^{2} + \Omega_{3}^{2} + \Omega_{4}^{2} \right)$$
(10)

$$U_2 = b\left(\Omega_4^2 - \Omega_2^2\right) \tag{11}$$

$$U_3 = b \left(\Omega_3^2 - \Omega_1^2 \right) \tag{12}$$

$$U_{4} = b \left(\Omega_{2}^{2} + \Omega_{4}^{2} - \Omega_{3}^{2} - \Omega_{1}^{2} \right)$$
(13)

$$\Omega = \left(\Omega_2 + \Omega_4 - \Omega_1 - \Omega_3\right) \tag{14}$$

B. Rotor Dynamics

The brushless direct current (BLDC) motor is a type of synchronous machine commuted electronically. For our purposes, these engines are more suitable than brushed DC and induction motors, with the advantage of producing less noise.

The equation of motion that relates the developed torque, inertia and damping is given by (see [19] and [20]):

$$\tau_e - \tau_i = J_m \frac{dw(t)}{dt} + Bw(t)$$
(15)

$$\tau_e(t) = k_t i(t) \tag{16}$$

where τ_e is the electromagnetic torque, τ_l is the load torque, J_m is the inertia of the motor, *w* is the motor speed, *i* is the current, k_t is the motor torque proportionality constant and *B* is the viscous friction coefficient.

By adding propellers to the engine model and disregarding the electrical dynamics, the angular velocities of the rotors can be expressed by

$$\dot{w}_{i} = \frac{-K_{m}^{2}}{R_{m}(J_{m}+J_{r})} w_{i} - \frac{d}{J_{m}+J_{r}} w_{i}^{2} + \frac{K_{m}.V}{R_{m}(J_{m}+J_{r})}$$
(17)

where w_i is the angular velocity, K_m is the back-electromotive force constant, R_m is the internal resistance of the motor, J_m and J_r inertia of the motor and inertia of the rotor, respectively, and V is the input voltage to the motor.

IV. VALIDATION OF THE STRUCTURE

Tests conducted on the structure began to be made since the beginning of its construction. The quadrotor as a whole represents the result of design methodology and meets the requirements of size and weight.

One of the problem presented in the used components occurred with the motor. The motor shaft used in the structure has a smooth surface (in the point where the propeller is attached), so that with the continuous spinning of the propeller, it can detach eventually. Thus, it was necessary to make grooves in the shafts of the engines for a better fixation of the propellers.

Tests were performed indoors in our robotics laboratory using a test structure, made of aluminum, for safety and to avoid damage to the structure, as shown in Fig. 6. The quadrotor is fixed to the test structure by carbon fiber rods and the ends were attached to the test structure by strings. It was used 1-meter length carbon fiber rods in order to avoid, in an unfavorable situation, contact of the cords with of the propellers.

The tests aimed at verifying the flying ability of the developed quadrotor-type UAV by validating the correct functioning of each one the their main parts (transceivers, ESCs, motors, and propellers) and the throughput of signals from the computer to the UAV and vice-versa.

After a sequence of intensive tests, it was verified that 30% of the rated power of the motors the vehicle flies. And it can carry safely a payload of up to 800 g.



Figure 6. A picture of the structure to which the quadrotor is attached in order to test the movements of the quadrotor in indoor environments.

V. CONCLUSION

In this paper we presented the mechanical structure and described all the parts comprising the development of a quadrotor-type unmanned aerial vehicle.

Various control strategies have been proposed in the literature for stabilization of a quadrotor. For example, in [1] and [21], the authors used backstepping and sliding-mode control. In [22], the authors used a PID controller and integralbackstepping. In [13], it was proposed a fuzzy adaptive control. At the current stage of the development of the quadrotor, the speeds of the propellers and the altitude and flight control were implemented manually.

However, the main goal of this work is to use the developed quadrotor as a testbed of control algorithms, such as those just described.

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