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Evaluation of Propulsion System Energy Requirements for an X-Configuration Minidrone Model

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Abstract: This article proposes a technique for evaluating energy requirements for the propulsion system of a quadcopter minidrone. This is the most energy-consuming part of the minidrone. Given the interest in energy autonomy in drones exploitation, in-depth analyzes have been made to determine the required power for propulsion. The minidrone was modeled as a rigid body of the cylinder type with a 30 cm of radius, a 1,47 kg of weight and a 20 cm of height. MATLAB-SIMULINK are used for the simulations. The powers consumed by the propulsion system of an "X-configuration" minidrone model with these parameters, are evaluated.

Keywords: propulsion system, energy autonomy, required power for propulsion, quadcopter minidrone, X-configuration model

1. INTRODUCTION

All movements of a quadcopter minidrone are the results of the combination of different forces and moments acting on the minidrone. These parameters depend on the rotation speeds of the motors. The movement of a quadcopter minidrone is therefore based on the control of each motor, which ensures its lift and its orientation in space is parameterized by the roll, pitch and yaw angles.

2. AERODYNAMIC MODELING

The torque and the thrust produced by a propeller depend on many parameters: physical parameters related to the environment status, parameters related to the propeller, and the speed of rotation of the motor that is used. These elements are essential in determining the power consumption.

2.1 Coordinate systems

Coordinate systems, composed of two systems axis, are used to study the positioning of an aircraft. The axis system (O, X, Y, Z) designates the navigation reference. The system axis (o, x, y, z), designates the mobile reference, where x is called roll axis, y is called pitch axis, and z is called yaw axis. The angles ϕ, θ, and ψ are respectively referred to as roll, pitch and yaw angles (Fig.1).

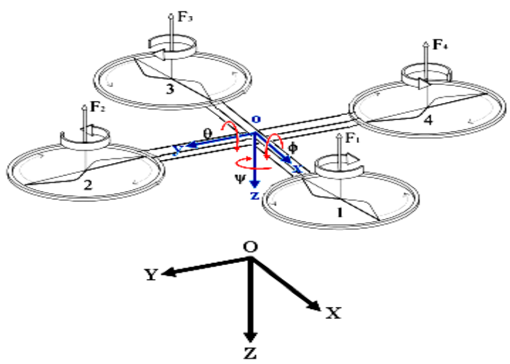

Figure. 1 Coordinate systems [1]

2.2 Thrust and moments

The thrust and moments produced by the motors depend on the configuration of the minidrone, "Plus-configuration" or "X-configuration". Figure 2 illustrates these two models.

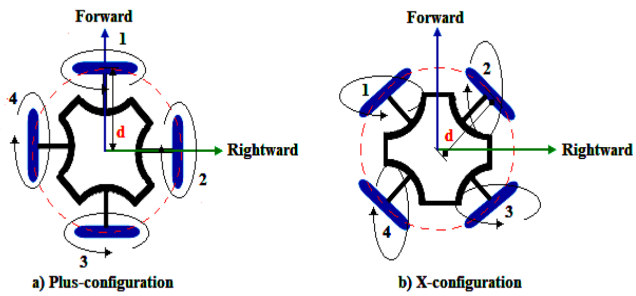

Figure. 2 Minidrone quadrotor models

Supposed that T is the total thrust, Γ_ϕ the moment in the roll axis, Γ_θ the moment in the pitch axis and Γ_ψ the moment in the yaw axis. For the "X-configuration" minidrone model, the expressions for the thrust and moments are given [2]:

$$\begin{pmatrix} T \\ \Gamma_\phi \\ \Gamma_\theta \\ \Gamma_\psi \end{pmatrix} = \begin{pmatrix} b & b & b & b \\ \frac{\sqrt{2}}{2}bd & -\frac{\sqrt{2}}{2}bd & -\frac{\sqrt{2}}{2}bd & \frac{\sqrt{2}}{2}bd \\ -\frac{\sqrt{2}}{2}bd & -\frac{\sqrt{2}}{2}bd & \frac{\sqrt{2}}{2}bd & \frac{\sqrt{2}}{2}bd \\ -k & k & -k & k \end{pmatrix} \begin{pmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{pmatrix} \quad (1)$$

where b is the thrust coefficient, k the drag coefficient, d the distance between the center of mass and the axis of the rotor, and ω_i (i = 1, 2, 3, 4), the rotation speed of the i^{th} motor.

2.3 Equations of motion

To establish the equations of motion, we use the following hypotheses:

- the structure is supposed to be rigid,
- the minidrone has a symmetrical perfect structure,

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– and the disturbances produced by the wind are neglected.

The minidrone was modeled as a rigid body of the cylinder type with a radius r=d (d is the distance between the center of mass and the axis of the rotor, see Fig. 2), a weight m and a height h.

The inertia matrix of the model is:

$$I = \begin{pmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{pmatrix} = \begin{pmatrix} \frac{md^2}{4} + \frac{mh^2}{12} & 0 & 0 \\ 0 & \frac{md^2}{4} + \frac{mh^2}{12} & 0 \\ 0 & 0 & \frac{md^2}{2} \end{pmatrix} \quad (2)$$

With these hypotheses, the equations of motion of the quadcopter minidrone are written as follows [3]:

$$\begin{cases} \ddot{x} = (cos\phi sin\theta cos\psi + sin\phi sin\psi)\frac{1}{m}T \\ \ddot{y} = (cos\phi sin\theta sin\psi - sin\phi cos\psi)\frac{1}{m}T \\ \ddot{z} = (cos\phi cos\theta)\frac{1}{m}T - g \\ \ddot{\phi} = \dot{\theta}\dot{\psi}\left(\frac{I_{yy} - I_{zz}}{I_{xx}}\right) - \frac{J_m}{I_{xx}}\dot{\theta}\Omega + \frac{1}{I_{xx}}\Gamma_\phi \\ \ddot{\theta} = \dot{\phi}\dot{\psi}\left(\frac{I_{zz} - I_{xx}}{I_{yy}}\right) + \frac{J_m}{I_{yy}}\dot{\phi}\Omega + \frac{1}{I_{yy}}\Gamma_\theta \\ \ddot{\psi} = \dot{\phi}\dot{\theta}\left(\frac{I_{xx} - I_{yy}}{I_{zz}}\right) + \frac{1}{I_{zz}}\Gamma_\psi \end{cases} \quad (3)$$

where $\Omega = \omega_1 - \omega_2 + \omega_3 - \omega_4$

With the expressions of the elements of the inertia matrix, the equations of motion of a minidrone become:

$$\begin{cases} \ddot{x} = (cos\phi sin\theta cos\psi + sin\phi sin\psi)\frac{1}{m}T \\ \ddot{y} = (cos\phi sin\theta sin\psi - sin\phi cos\psi)\frac{1}{m}T \\ \ddot{z} = (cos\phi cos\theta)\frac{1}{m}T - g \\ \ddot{\phi} = a_1\dot{\theta}\dot{\psi} - a_2 J_m\dot{\theta}\Omega + a_2 d\Gamma_\phi \\ \ddot{\theta} = -a_1\dot{\phi}\dot{\psi} + a_2 J_m\dot{\phi}\Omega + a_2 d\Gamma_\theta \\ \ddot{\psi} = a_3\Gamma_\psi \end{cases} \quad (4)$$

where

$$\begin{cases} a_1 = \frac{h^2 - 3d^2}{h^2 + 3d^2} \\ a_2 = \frac{12}{m(h^2 + 3d^2)} \\ a_3 = \frac{2}{md^2} \end{cases} \quad (5)$$

By using state variables such as:

$$[X] = [x_1\ x_2\ x_3\ x_4\ x_5\ x_6\ x_7\ x_8\ x_9\ x_{10}\ x_{11}\ x_{12}]^T = [x\ y\ z\ \phi\ \theta\ \psi\ \dot{x}\ \dot{y}\ \dot{z}\ \dot{\phi}\ \dot{\theta}\ \dot{\psi}]^T$$

the state space representation of the system is given:

$$\begin{cases} \dot{x}_1 = x_7 \\ \dot{x}_2 = x_8 \\ \dot{x}_3 = x_9 \\ \dot{x}_4 = x_{10} \\ \dot{x}_5 = x_{11} \\ \dot{x}_6 = x_{12} \\ \dot{x}_7 = (cosx_4 sinx_5 cosx_6 + sinx_4 sinx_6)\frac{1}{m}T \\ \dot{x}_8 = (cosx_4 sinx_5 sinx_6 - sinx_4 cosx_6)\frac{1}{m}T \\ \dot{x}_9 = cosx_4 cosx_5\frac{1}{m}T - g \\ \dot{x}_{10} = a_1 x_{11} x_{12} - a_2 J_m \Omega x_{11} + a_2 d\Gamma_\phi \\ \dot{x}_{11} = -a_1 x_{10} x_{12} + a_2 J_m \Omega x_{11} + a_2 d\Gamma_\theta \\ \dot{x}_{12} = a_3\Gamma_\psi \end{cases} \quad (6)$$

3. SIMULATIONS

3.1 Used parameters

Consider the non-exhaustive list of the embedded electronics equipment (Table 1).

Table 1. Embedded electronics equipment list

Equipment	Example	Weight (g)	Size (mm×mm×mm)	Power (W)
Inertial Navigation System	Ellipse 2 Micro	10	26,8×18,8×9,5	0,4
GPS	HGLRC – M80	9,4	18,5×18,5×7,1	0,3
Motor	BLDC A2212 – 1000 KV	64	27,5 × 27 × 27	-
Flight controller board	KK2.1.5 Flight Controller	20	130 × 100 × 49	-
Camera	A8 Mini Gimbal	90	55 × 55 × 70	12
Battery and other accessories	-	1000	-	-

The weight and size of each onboard equipment are used to size a minidrone. Also the minidrone was modeled as a rigid body of the cylinder type, with a 30 cm of radius, a 1,47 kg of weight and a 20 cm of height. For the motors, we used the model presented in reference [4].

3.2 Presentation of the main model

The main model is composed of four blocks. These blocks are the SIMULINK representations of equations (1) to (6). Figure 3 shows the main model used in the simulations.

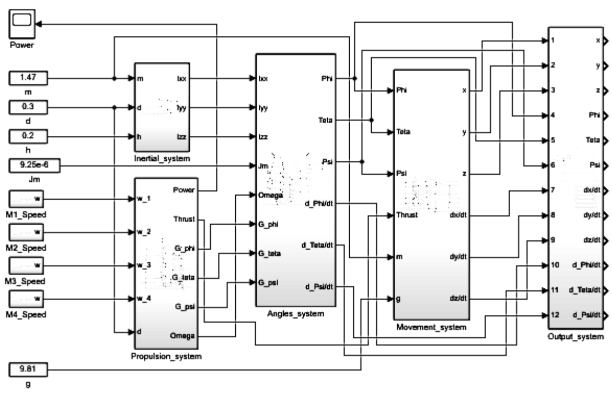

Figure. 3 The main model

3.3 Results

In our simulations, the starting time of a motor is 6 s to reach a speed of 6000 RPM. We kept this speed for the all motors during 4 minutes 24 s. To change to another speed we must wait 6 s, that is to say 4 minutes 36 s after starting.

We observed a power peak of 394,5 W when the motors started before having a stable consumption of 323,5 W for a duration of 4 min 24 s. The total thrust developed during this same duration is 24,5 N. The minidrone begins vertical takeoff 18 s after starting the motors.

3.3.1 Simulation 1

We change motor speeds 4 mn 18 s after takeoff with new values: $\omega_1 = \omega_2 = 3900$ RPM and $\omega_3 = \omega_4 = 8100$ RPM. Figure 4 shows the evolution of motor speeds and the total thrust produced.

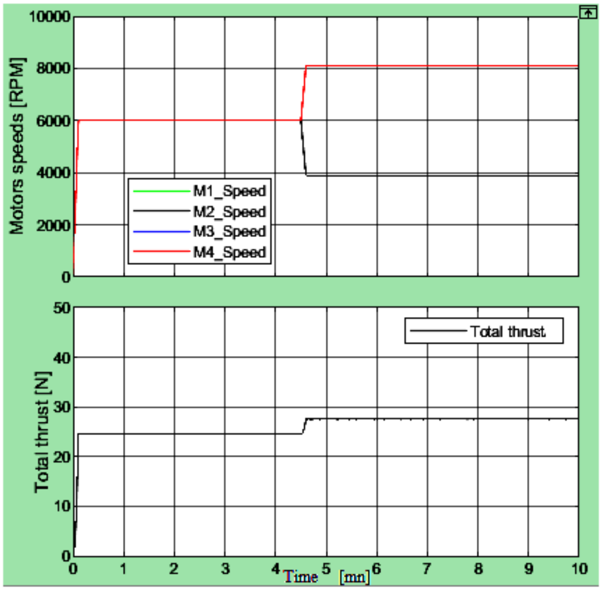

Figure. 4 Motor speeds and total thrust for the first simulation

With the new speeds, the total thrust developed increases from 24,5 N to 27,5 N.

Figure 5 represents the power consumed by the minidrone.

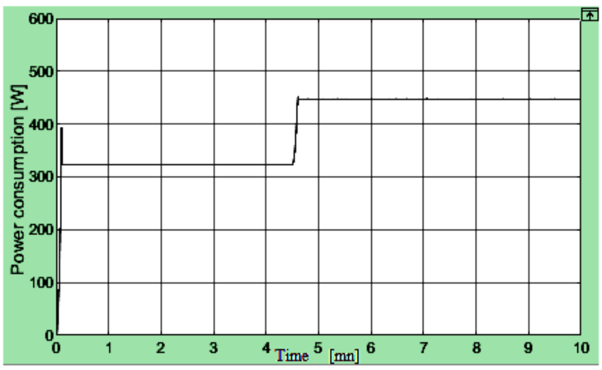

Figure. 5 Power consumption for the first simulation

After changing motor speeds, the power consumed increases from 323,5 W to 447,3 W.

Figure 6 illustrates the movements of the minidrone.

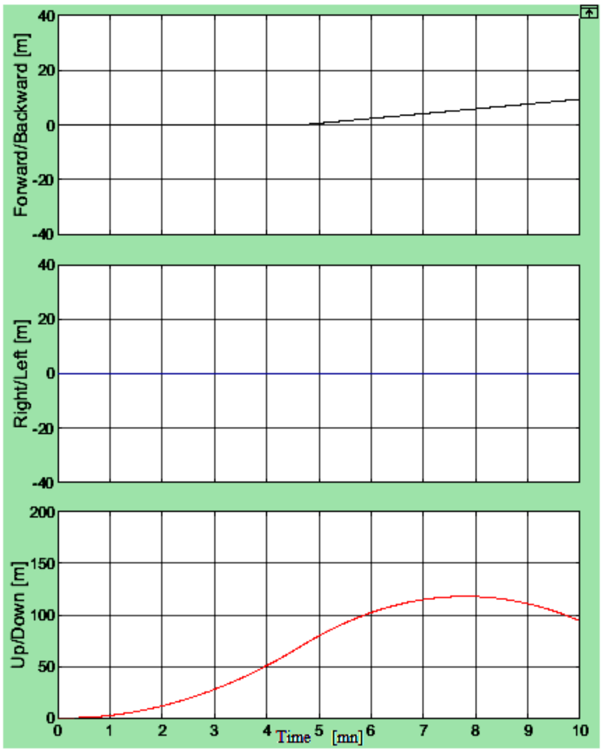

Figure. 6 Movements of the minidrone for the first simulation

After takeoff, the minidrone continues to climb and begins to move forward 4 mn 18 s later. In 5 mn 24 s, the minidrone covered a distance of 9,4 m without deviating from its trajectory. The maximum altitude of 117,9 m is reached 7 mn 30 s after takeoff.

3.3.2 Simulation 2

We change the motor speeds using the next values: $\omega_1 = 7500$ RPM, $\omega_2 = \omega_4 = 6500$ RPM and $\omega_3 = 3500$ RPM. Figure 7 shows the evolution of motor speeds and the total thrust developed.

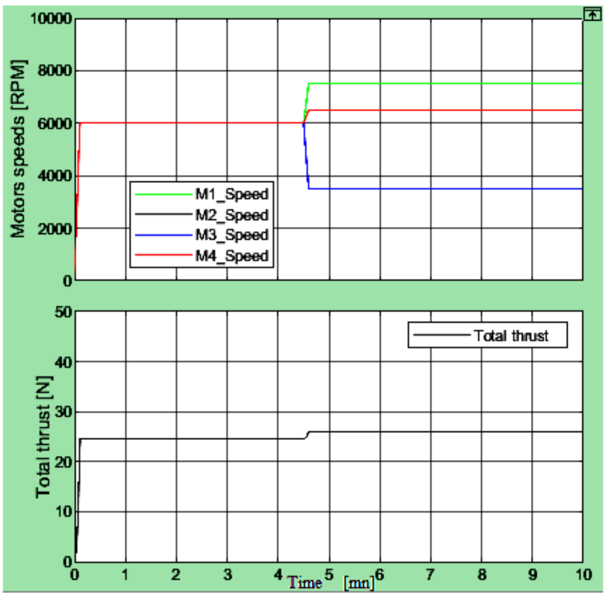

Figure. 7 Motor speeds and total thrust for the second simulation

Figure 8 illustrates the movements of the minidrone.

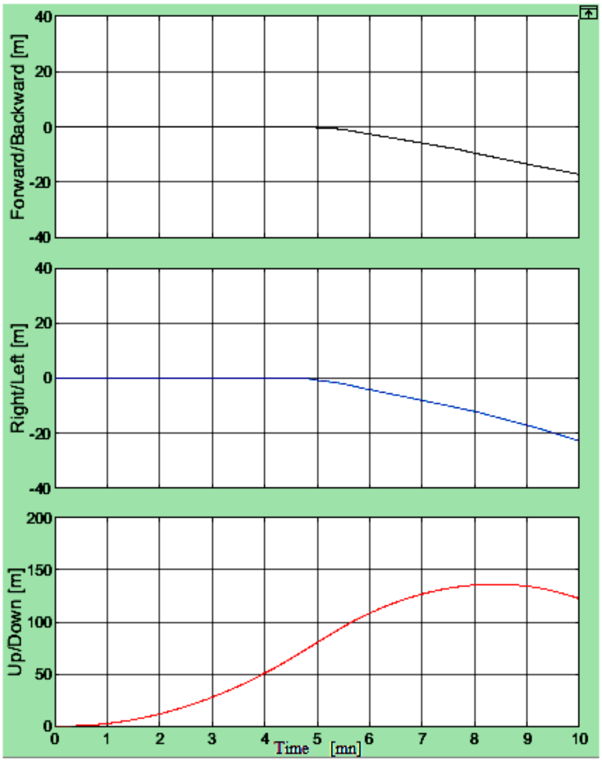

Figure. 8 Movements of the minidrone for the second simulation

The minidrone continues to climb and moves back to the left 4 mn 42 s after takeoff. Minidrone traveled a distance of 28,34 m in this direction. The maximum altitude of 136,2 m is reached 8 mn 6 s after takeoff.

Figure 9 shows the evolution of the power consumed by the minidrone.

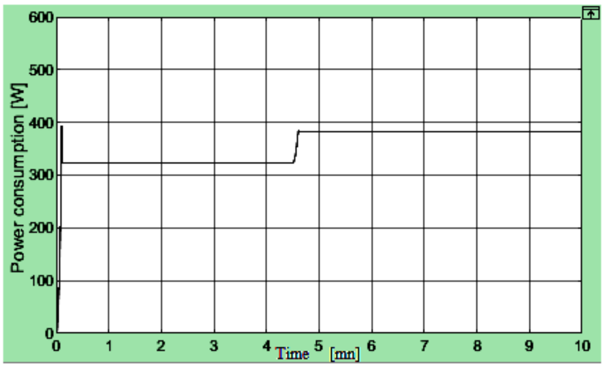

Figure. 9 Power consumption for the second simulation

After changing motor speeds, the power consumed increases from 323,5 W to 382 W.

3.3.3 Recapitulation

Table 2 recaps the results of our simulations mentioned in this article.

Table 2. Recapitulation of the simulation results

	Simulation 1	Simulation 2
Total thrust [N]	27,5	26,1
Power consumption [W]	447,3	382
Traveled distance [m]	9	28,34
Maximum altitude [m]	117,9	136,2
Takeoff after starting motors [s]	18	
Simulation duration	10	

4. CONCLUSION

The propulsion system is the most energy-consuming of a minidrone quadcopter. In this article, we presented the aerodynamic modeling of the “X-configuration” minidrone model. MATLAB-SIMULINK was used to simulate the model. For the simulations, we combined only a few values for the motor speeds, to determine the total thrust produced by the propulsion system and its power consumption. It was found that the different combinations are decisive for guiding the minidrone and determining the energy required for its propulsion.

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