Unmanned aerial vehicle design for pressure washing building facades in Lima Metropolitan Area using hydrogen fuel cell

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***Abstract*—The following paper has the purpose of presenting an innovative solution for building facade cleaning using an unmanned aerial vehicle (UAV) that employs pressure washing technique and hydrogen fuel cell (HFC) technology to enhance flight autonomy. Indeed, the main design stages are both stated and explained within the paper. However, the design is separated in two stages: Conceptual and Preliminary. Thus, it begins with the research statement, state of the art revision and conceptual design proposal. Then, it continues with the development of the propulsion system, which uses a proposed recursive methodology for estimating, selecting, and then confirming all the inter-dependent elements such as motors, propellers, fuel cell and hydrogen amount. As the drone is treated as a mechatronic machine, the following design explores certain domains that help build it, such as: Mechanical, Electrical and Control. The Mechanical domain emphasizes on frame design, material selection, resistance calculations, pressure washing gun recoil analysis, and finite element and aerodynamic simulations. The Electrical domain focuses on component selection and power consumption verification while the last domain proposes flow diagrams and a PID control diagram based on an hexacopter mathematical modelling. Finally, the main flight parameters are simulated on SIMULINK, obtaining appropriate stabilizing and response times according to limitations cited.**

Keywords—UAV, HFC, pressure washing, frame design, SIMULINK.

I. INTRODUCTION

As a result of continuous migration from Peruvian external regions towards the capital Lima, a boom of vehicle dependence has arisen, having a vast amount of 1'752,919 registered vehicles in 2016 [1]. This has led to an overall increase in smog contamination along Lima Metropolitan Area, with alarming results of approximately 15'432,105 tons of CO_2, which covers around 12% of all national territory [1]. As known, increased smog levels entail building facades acidification, degradation, and loss of structural properties. In addition, the Peruvian public cleaning program does not face this issue. On the contrary, the private sector leads the cleaning endeavor. However, the use of traditional cleaning methods, such as harness, manlifts, scaffolding, etc, put the workers' life exposed to sudden falls and injuries.

It should be noted that the main cleaning technique is via pressure washing or hydro washing, which employs a pressure gun attached through a hose to a ground station, delivering water jets up to 140 bar (2000 PSI) commercially. Nowadays, there are alternative solutions to carry the hose and aim for the target area. One of them is the use of UAVs. Although they are mainly focused on agricultural washing tasks, brands such as Lucid Drone Technologies with the C1 Cleaning drone and AERONES with AD28 Heavy Lift UAS can seamlessly fulfill a cleaning operator's job.

Therefore, the main objective of this project is to design a UAV capable of pressure washing building facades up to 6 stories high with an energetic autonomy destined to keep in flight the aerial vehicle at least for 1 hour. For this reason, HFC technology is brought, as it is a clean solution and provides long flight spans in contrast with traditional LiPo batteries. Hence, the main requirements are the following:

- Frame and chassis must withstand wind gusts up to 25 km/h up to 15 m (6 stories high)
- Pressure washing system must withstand up to 69 bar (soft washing technique) [2].
- Frame and control strategy must consider the recoil generated by pressure release during flight.
- Energy source must provide at least 1 hour flight autonomy.

II. CONCEPTUAL DESIGN AND METHODOLOGY

A. Conceptual description of UAV

Firstly, the conceptual product is achieved using VDI 2221 methodology. Indeed, the proposed UAV consists of an hexacopter configuration with carbon fiber as the main fuselage's material. To achieve flight autonomy, a hydrogen fuel cell is being used along with a hydrogen tank mounted on top. Besides, a V- shaped carbon fiber extension is installed below the base to mount a pressure washer wand and a solenoid valve.

B. Methodology for propulsion system

The main stage of this project is developing the propulsion system, which is considered indeed as a mechatronic system since it relies both on mechanical items (Propellers, Hydrogen tank), electrical-electronic items (HFC, Brushless motors) and control items (ESC, Electronic Speed Controller). Thus, these are interdependent, and an iterative design method is needed for optimal results, such as the one proposed in figure 1.

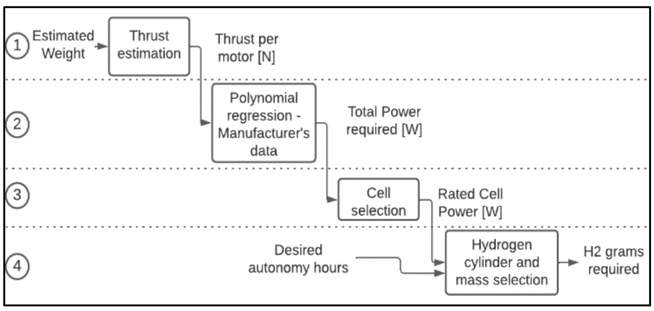

Fig. 1. Propulsion system design methodology.

As seen, the process begins with an initial weight estimation that is used consequently to determine the thrust required per motor. Then, a polynomial regression is done with the manufacturer's data on brushless motors' tests with different propellers obtaining a formula which returns the power per motor required based on the thrust exerted. With the power per motor obtained, one can have the total power required, which is a direct input for cell selection since the rated power cell must be of higher value. Finally, HFC's manufacturers bring a formula to calculate H_2 cylinder and mass required. It is noted that after the engineering design, a reweighing must obtain a lower value than the initial estimated.

III. Preliminary Design

A. Propulsion system

Based on Quan Quan recommendations on the ratio of total weight on payload used (1:1/3), an estimation of 8.2 kg is made [3]. Therefore, thrust per motor is obtained.

$$\text{Thrust} = 8200/6 = 1366.66 \text{ g } (13.39 \text{ N})$$

Since it is a UAV of considerable weight, T-Motor's "Antigravity Type" category will be used. The MN5008 range is chosen due to its optimal performance for higher load applications in quadcopters and hexacopters. The KV170 model is then chosen as it is the one with the lowest consumption. Following T-Motor's standardized tests sheets with propeller P18*6.1"CF, a polynomial regression is made as seen in figure 2.

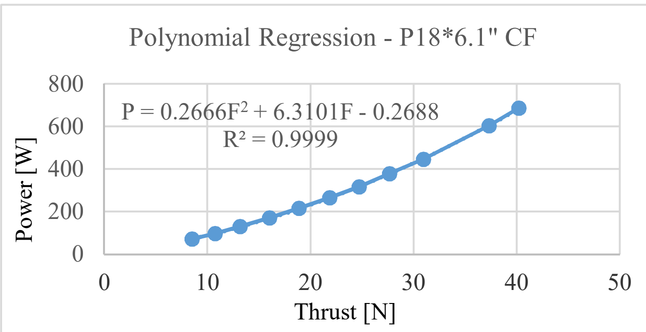

Fig. 2. Polynomial regression of propeller P18*186.1"CF

The optimal power per motor value is obtained for a KV170 model and it is 132.02 W, which adds up for 792.12 W for total power (6 motors). Then, an HFC with a higher rated power must be selected. Within commercial options, the best economically and physically suited is IE-SOAR 800W from Intelligent Energy, who directly provides a formula for obtaining the fuel consumption as seen in (1) and autonomy hours in (2) [4].

$$\text{Fuel consumption } \left(\frac{g}{h}\right) = \frac{\text{Power (W)}}{H_2 \text{ energy content } \left(\frac{Wh}{g}\right) \times \text{Efficiency}} \quad (1)$$

Considering 33 Wh/g energy content and 0.53 efficiency:

$$\text{Fuel consumption } \left(\frac{g}{h}\right) = \frac{800}{33.3 \times 0.53} = 45.33 \left(\frac{g}{h}\right)$$

$$\text{Autonomy (h)} = \frac{H_2 \text{ mass (g)}}{\text{Fuel consumption } \left(\frac{g}{h}\right)} \quad (2)$$

$$H_2 \text{ mass (g)} = 1\text{h} \times 45.33 \frac{g}{h} = 45.33 \text{ g}$$

Intelligent Energy provides a catalog for commercial H_2 cylinders suitable for SOAR 800W. The AMS Composite MC3 model is selected with a total weight of 1.7 kg and can contain up to 61.9 g of H_2, storing 1030 Wh of electrical energy. Thus, a second method for obtaining a better estimated value for autonomy is by the stored energy Wh. Knowing that 1Wh is 3600 J, then:

$$\text{Energy (J)} = 1030 \times 3600 = 3.708 \times 10^6 \text{ J}$$

$$800 \text{ W} \rightarrow 800 \ \frac{J}{s}$$

$$\text{Final autonomy} = \frac{3.708 \times 10^6 \text{ J}}{800 \ \frac{J}{s}} = 4635 \text{ s} = 1.2875 \text{ h}$$

B. Frame design

The frame's construction consists of one lower 12-sided base where the arms are attached via clamps and then closed by an upper same sided base. Also, electronic parts are housed inside the inner space created by polycarbonate windows. As mentioned, the frame follows a hexagonal distribution of 25 mm carbon fiber (CF) tubes as arms to enhance aerodynamical performance (figure 3). In addition, a commercial payload rail is installed below the lower base, and it holds the pressure wand and the HFC (figure 4). In contrast, CF molds support the hydrogen cylinder above the upper base and on the sides to prevent it from falling. Finally, two CF legs are used as undercarriage and a back section is reserved for a 10 kg Foxtech Parachute Ejector System. CF stands as the main building material for larger parts while Aluminum 6061-T6 is used for complex assemblies such as clamps and sheet metal parts for parachute and HFC integration.

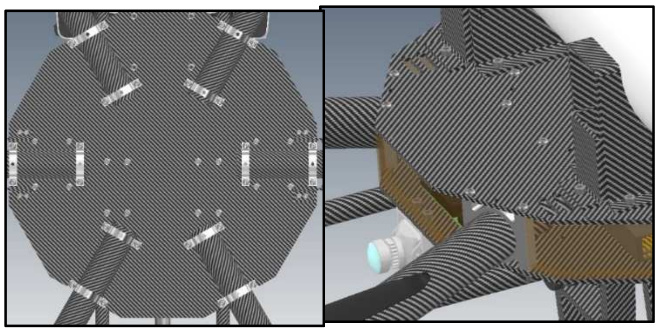

Fig. 3. Base distribution and electronics housing.

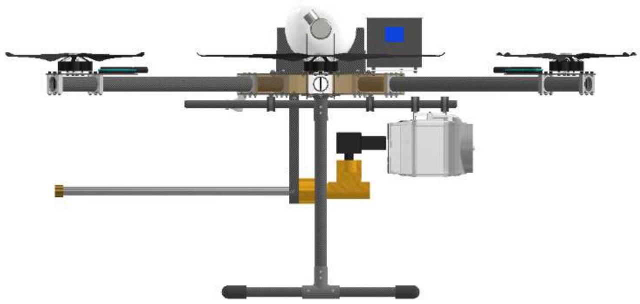

Fig. 4. Payload rail and wand integration for HFC.

C. Mechanical simulations

Regarding mechanical simulations, they were all done using software such as Autodesk Inventor and Nastran. The key evaluations were arm bending and pressure water release effect on the structure.

Arm bending is evaluated as a net force representing thrust exerted by a single motor (13.39 N). The strength analysis resulted in 40.97 MPa, below CF yield strength of 570 MPa, having a security factor of 7.32. Moreover, this caused a maximum deformation of 0.2362 mm, as seen in figure 5, which is negligible and therefore, it is certain to conclude no harm is done to the arms due to thrust.

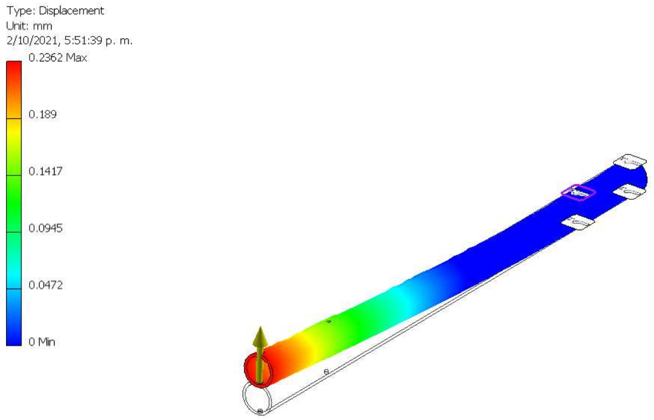

Fig. 5. Arm deformation due to motor thrust.

On the other hand, the recoil generated by releasing pressurized water is critical to maintaining stability during flight as seen as a red force in figure 6. Therefore, a flow of 12.2 L/min (2.03 x 10^{-4} m^3/s) from pressure washer Barovo HL 701-2 – 100 bars is considered; as well as an internal diameter of the selected hose of 10 mm (0.010 m) with an area of 7.85 x 10^{-5} m^2. Then. following the steps suggested by Al Jaber et al. for a firefighting drone project, fluid velocity is calculated through the flow expression [5].

$$Q = A \times v \rightarrow v = \frac{Q}{A} = \frac{2.03\times10^{-4}}{7.85\times10^{-5}} = 2.59 \text{ m/s}$$

Since the maximum height is 15 m, the required volume of water is calculated.

$$V = \pi \times h \times \frac{D^2}{4} = \pi \times 15 \times \frac{0.010^2}{4} = 1.178\times10^{-3} m^3$$

The generated moment P is defined as (3):

$$P = \rho_{water} \times V \times v \tag{3}$$

$$1000\times\left(1.178\times10^{-3}\right)\times2.58=3.039 \ \frac{kg{\cdot}m}{s}$$

Fig. 6. Force exerted due to water release.

Assuming that water is released for safety reasons one meter from the building:

$$t = \frac{1}{2.59} = 0.386 \text{ s}$$

Finally, the force exerted by the pressurized water is obtained using Newton's second law (4):

$$F = \left(\frac{Dp}{Dt}\right) = \frac{3.039}{0.386} = 7.87 \text{ N}$$

The lower base - wand distance is 155 mm. A torque is created at the base of:

$$T=7.87\times0.155=1.22 \text{ Nm}$$

Both F and T are used as simulation parameters in Nastran (figure 7) resulting in 56.4 MPa (SF = 5.32) and 0.1381 mm maximum deformation. Thus, the base is compromised.

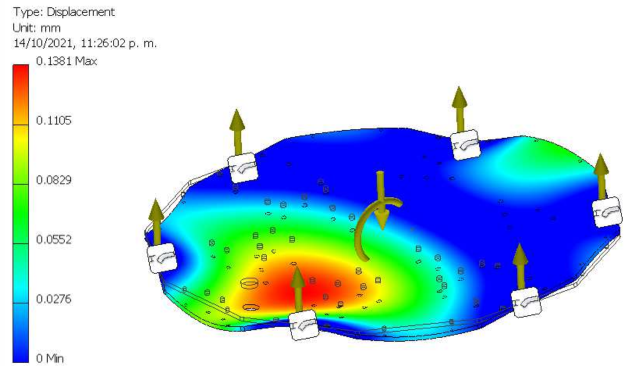

Fig. 7. Effect on lower base due to water release.

D. Electrical-electronics layout

As seen in figure 8, there are two main groups:

- Control – Supplied by a LiPo battery and governed by a Pixhawk PX4 Controller, who both enables flight control and water release action.
- Power – Supplied by the HFC and distributed over 6 ESCs capable of controlling 6 brushless motors.

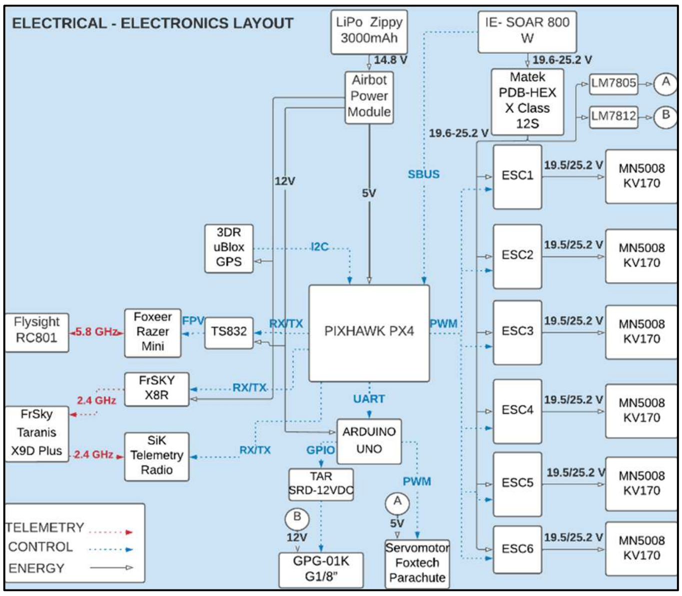

Fig. 8. Electrical – electronics layout.

E. Control strategy

The control strategy employs a closed loop control diagram with a PID controller as seen in figure 9.

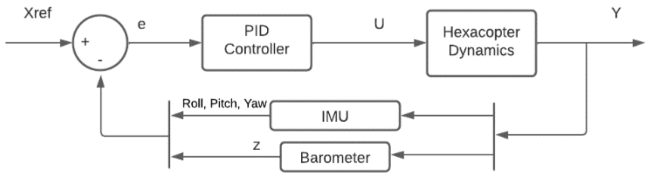

Fig. 9. Control strategy diagram.

In general, the diagram tries to emulate the change of a current position $(z,\emptyset,\theta,\psi)$ towards a desired position $X_{ref}=(z_d,\phi_d,\theta_d,\psi_d)$, which is achieved by estimating the error between the desired state and the current one. Indeed, the controller oversees processing the error between the desired and current state variables, obtaining the control variables $(T,\tau_\phi,\tau_\theta,\tau_\psi)$. These are then converted in the 'hexacopter dynamics' block into the 6 respective angular velocities W_i. Moreover, the Euler parameterization is used where the orientation of the body of an aircraft is described with the 3 Euler angles and the modelling is based on Alaimo et al. proposal [6]. On the other hand, the control model will have 6 PID controllers in accordance with each of the state variables $(x,y,z,\emptyset,\theta,\psi)$. This way, the difference between the desired values and the currents provided by the sensors is carried out. The PID algorithm receives this difference to convert it into $(T,\tau_\phi,\tau_\theta,\tau_\psi)$ as seen in figure 10 [7].

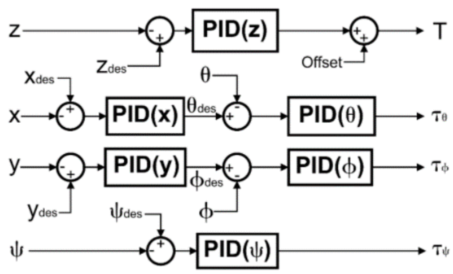

Fig. 10. Controller diagram.

For simulation purposes, the inherent hexacopter properties were required. These are summarized in table I.

TABLE I. FLIGHT PARAMETERS

g	Gravity	9.81	m/s^2
m	Mass	8.2	kg
l	Distance center of gravity - rotor	0.459	m
k	Lift coefficient	1.1584×10^{-6}	-
b	Drag coefficient	0.97	-
I_{xx}	Inertia with respect to x axis	0.02063	$kg.m^2$
I_{yy}	Inertia with respect to y axis	0.02715	$kg.m^2$
I_{zz}	Inertia with respect to z axis	0.02126	$kg.m^2$
I_r	Rotational inertia	84.6×10^{-7}	$kg.m^2$

Using Simulink, a response can be obtained for altitude (Z) and Pitch (θ) as seen in figure 11, obtaining stabilizing times under 5 s and response times under 2 s in accordance with Singh's limitations [8].

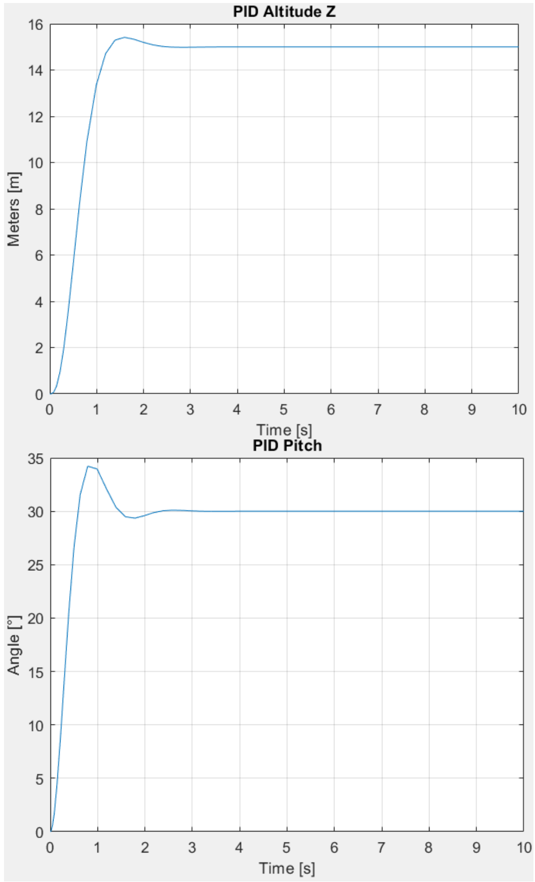

Fig. 11. Simulation results on Simulink.

IV. Conclusion

The results obtained from the preliminary design enable the possibility for this project to be further developed into a prototype for testing and data acquisition. Indeed, the present drone is capable of theoretically fulfilling its task while maneuvering in the air. This is supported by both mechanical analysis and control system design. Finally, this study represents an innovative solution to carry in cleaning solutions for larger buildings, complicated for human labor.

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