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Research Article

Investigation on the Airworthiness of a Novel Tri-Rotor Configuration for a Fixed Wing VTOL Aircraft

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Abstract

In this paper, a novel tri-rotor configuration is proposed with the goal of granting vertical take-off and landing capabilities to a future concept of tiltrotor, fixed-wing, aircraft while minimizing the overall mass of the propulsive system and the amount of aerodynamic drag developed during horizontal flight. The novelty of the presented configuration is related not only to the thrust vectoring capabilities of all three rotors but also to the constraints surrounding the action of the rear rotor, which will be required to provide thrust during both vertical and horizontal flight stages while drawing power from an internal combustion engine fixed inside the aircraft's fuselage. Another distinctive feature of the proposed configuration is related to the 20/80 thrust distribution which exists between the front and rear rotors respectively in vertical flight, unlike the more conventional approach of having all three rotors evenly loaded. The proposed rotorcraft configuration was then translated into a test vehicle which was subjected to several stages of ground and flight testing, with the ultimate goal of evaluating the airworthiness of this multi-rotor configuration as a concept. This process also encompasses the development of a custom flight control firmware in PX4, required to operate not only this vehicle but also any other multi-rotor or Vertical Take-Off and Landing system with such configuration. Finally, a frequency-response based system identification technique is applied to the collected flight data as to obtain a suitable flight dynamics model for future autopilot tuning

Keywords

Unmanned Aerial Vehicle
Vertical Take-Off and Landing
Tilt-rotor
Tri-rotor
System Identification

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1. Introduction

One of the most prominent topics within the current aerospace engineering paradigm revolves around the development of hybrid aircraft concepts which combine the horizontal flight speed and efficiency of fixed-wing (FW) vehicles with the flexibility of executing Vertical Take-Off and Landing (VTOL) and steady hovering manoeuvres, attributes that were, until recently, reserved for rotary wing vehicles such as helicopters and multicopters. As the topic of Urban Air Mobility gains momentum, and with a growing interest, especially by the military, in unmanned aircraft which incorporate the aforementioned characteristics, investigation into the development of novel configurations of VTOL aircraft designs presents an unprecedented level of relevance.

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Several possible platforms of hybrid (FW+VTOL) aircraft have been proposed over the years through concepts for both manned and unmanned aviation. The multiple suggested configurations can, in general, be grouped in two broad categories (Saeed et al., 2018): tail-sitters and convertiplanes. Tail-sitters usually present a fixed propulsion system, i.e., without thrust vectoring capabilities, relying on a complete change of the airframe's orientation throughout the different mission segments. As so, aircraft of this kind usually take-off and land with the airframe in a vertical stance and then, to achieve forward flight, execute a complete tilting maneuver of the aircraft's body. On the other hand, the usually called convertiplanes maintain their airframe orientation throughout the mission (usually horizontal or at a pitch angle within the flight envelope of the aircraft), relying on propulsion systems with thrust vectoring capabilities (e.g.: tilt-rotor, tilt-wing, tilt-prop) or separate, segregated systems to deal with the vertical and horizontal flight stages of the mission as happens with Lift+Cruise configurations (Goetzendorf-Grabowski et al., 2020).

The multi-rotor propulsive system configuration proposed in this paper is the result of a series of design constraints which were imposed during the conceptual design of the new, canard configuration, fixed-wing, unmanned aerial vehicle (UAV) for which such a system is being devised (Fig. 1). The main requirement and motivation for this investigation is that the vehicle should be capable of performing VTOL manoeuvres, as well as being able to hover steadily upon request. With respect to the categorization presented above, this vehicle shall be classified as a convertiplane.

The propulsive system was conceptualized in a way that the two front rotors are to be powered by electric motors, with the frontal arms on which these are mounted retrieving into the fuselage of the aircraft during horizontal flight to optimize the aerodynamic efficiency of the vehicle (note that the design of the fixed-wing aircraft is out of the scope of this work and has already been explored previously in Pedro et al., 2021). The front rotors are meant to operate only in the vertical flight stages and are responsible for generating, in nominal flight conditions, around 10% of the total vertical thrust required to hover (i.e., enough thrust to balance 10% of the total aircraft's weight each). The third, rear tilting rotor, which will provide thrust in both the vertical and horizontal stints of the aircraft's mission should, in its term, be powered by an internal combustion engine. This engine is to be fixed inside the aircraft's fuselage, in such a way that the rear rotor, responsible for generating enough thrust to balance the remaining 80% of the vehicle's weight in vertical flight, shall assume a tilt-shaft configuration. To achieve this, a tilting 90° gearbox system will be used. The tilting axis of said gearbox shall be aligned with the motor's output shaft (gearbox's input shaft) in order to allow for the proper transmission of power between motor and propeller regardless of the angle assumed by the propeller shaft.

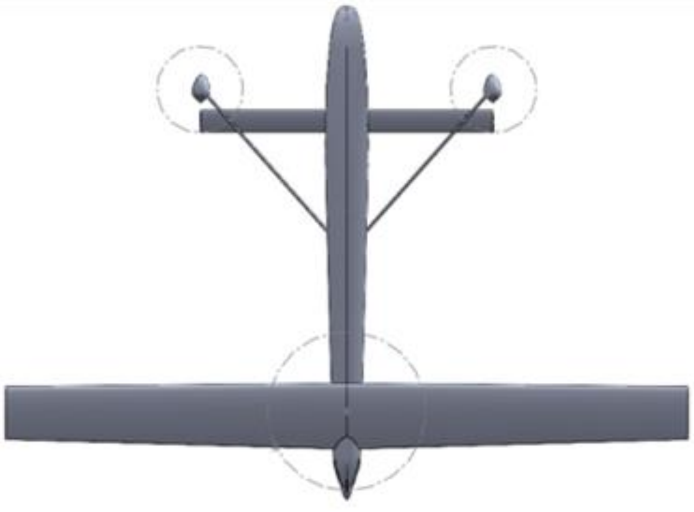

Fig. 1. Preliminary CAD model of the VTOL UAV first conceptualized in Pedro et al., 2021.

When dealing with a multi-rotor configuration where the number of propellers is not even, and thus propeller pairing cannot be accomplished, a problem arises regarding the balance of the drag torques developed by each rotating propeller. While in multi-rotors with an even number of propellers these are usually paired between them (same number of vertically pointing propellers rotating clockwise as counterclockwise) yielding that a balance of torques along the yaw axis is achievable as long as the rotational speed of any given clockwise rotor is matched to the one of a counterclockwise one. Furthermore, in such cases, these rotational speeds can be manipulated by the flight controller, as is often, to manoeuvre the aircraft in yaw. Tri-rotor configurations however, having an uneven number of rotors, must achieve yaw stability through other means, the most common one being thrust vectoring. This approach requires that one of the rotors (usually the aft one in a y configuration) is capable of tilting laterally, thus developing a lateral thrust component and an associated torque along the yaw axis (Salazar-Cruz & Escareño, 2009; Mohamed & Lanzon, 2012; Papachristos & Tzes, 2012; Gu et al., 2021). However, in the proposed configuration, the aft rotor shaft will already be required to tilt between the initial vertical stance and a longitudinal orientation during the forward flight stages. As so, it was decided that the yaw attitude should be managed by a similar thrust vectoring approach but performed by the two frontal rotors. These will thus tilt along the longitudinal axis of the frontal arms of the tri-rotor simultaneously, which allows to minimize the tilting angle that is required from each front rotor to achieve the necessary equilibrium of torques in yaw. Furthermore, the sense of rotation of the frontal rotors (counterclockwise) shall be opposite to the one of the rear one (clockwise) as shown in Figure 2. This will allow to minimize the natural torque imbalance and consequently the lateral thrust vector needed to achieve equilibrium, the tilting angle of the frontal rotors (assuming that the required vertical thrust is constant) and thus the amount of power required to operate the front rotors.

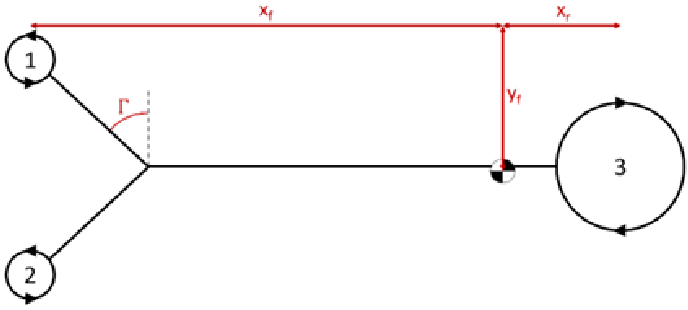

Fig. 2. Schematic representation of the proposed tri-rotor configuration (not to scale).

Γ :Arms' opening angle

x_f :longitudinal distance between front rotors and aircraft center of gravity

x_r :longitudinal distance between rear rotor and aircraft center of gravity

y_f :lateral distance between each front rotor and aircraft center of gravity

Given that the objective of the present study was to explore a new multi-rotor configuration for application to a VTOL, fixed-wing aircraft, it was deemed necessary to start the process by deducting the equations which would later support the development of a preliminary flight dynamics model (FDM) for vertical flight stages. Once these equations were obtained, equilibrium condition studies were performed as to establish the conditions under which this multi-rotor aircraft configuration could perform stable, hovering flight. Once an initial understanding of the configurations' capabilities was gained, the development of the test vehicle commenced with particular focus on the development of the mechanisms required to perform thrust vectoring with all three rotors. These mechanisms, when built, were, in their term, tested to map their actuation and to explore their performance. In parallel, a personalized PX4 autopilot firmware was devised to control this novel configuration aircraft in the subsequent test flights. Once the vehicle was concluded, it was subjected to a battery of test flights to assert the airworthiness of both the vehicle itself and of the configuration as a concept. Finally, with the collected data, a frequency-response system identification method was applied to obtain a suitable dynamics model from experimental data.

In the following subsections, this sequence of steps is to be explored in more detail.

2. Configuration Study

2.1 Flight Dynamics Model

With the goal of better comprehending the expected vertical flight dynamics of the future FW vehicle which encompasses the proposed multi-rotor configuration, it was first necessary to derive the appropriate flight dynamics model (FDM).

The dynamic equations, which describe the motion of the aircraft, were derived from the typical Newton-Euler equations (Roskam, 1998; Phillips, 2009; Beard & McLain, 2012). Given that the current iteration of the vehicle is electric (despite the final one having a hybrid electric propulsion system), it is possible to manipulate the equations in such a way that a constant mass and inertia tensor are considered. The main distinction between the derived FDM and a common multi-rotor FDM will reside in the formulation of the propulsive forces and moments which act on the aircraft (alongside the contributions of gravity and aerodynamics). For the presented multi-rotor configuration, the formulation of the propulsive forces and moments will take the form shown in Equation 1. In these expressions, “T_n” and “τ_n” represent the thrust and drag torque magnitudes generated by rotor n, according to the numbering provided in figure Fig. 2 while “x_f”, “x_r” and “y_f” represent the distances portrayed in the same figure. Furthermore, “δ_{arms}” stands for the tilting angle of the front rotors (0° for vertical) and “μ” for the rear rotor tilting angle (90° at vertical). Furthermore, the contributions of aerodynamics (Pedro et al., 2021), gravity, and gyroscopic effects (Phillips, 2009) towards the aircraft's vertical flight dynamics were also considered.

$$\left\{\begin{aligned}
F_{x_{prop}} &= (-T_1 + T_2)\sin\delta_{arms}\cos\Gamma + \\
&\quad +T_3\cos\mu \\
F_{y_{prop}} &= (T_1 + T_2)\sin\delta_{arms}\sin\Gamma \\
F_{z_{prop}} &= -(T_1 + T_2)\cos\delta_{arms} - T_3\sin\mu \\
M_{x_{prop}} &= (-T_1 + T_2)y_f\cos\delta_{arms} + \\
&\quad +(\tau_1 - \tau_2)\sin\delta_{arms}\cos\Gamma + \\
&\quad +\tau_3\cos\mu \\
M_{y_{prop}} &= (T_1 + T_2)x_f\cos\delta_{arms} - \\
&\quad -T_3\, x_r\sin\mu - \\
&\quad -(\tau_1 + \tau_2)\sin\delta_{arms}\sin\Gamma \\
M_{z_{prop}} &= (T_1 + T_2)x_f\sin\delta_{arms}\sin\Gamma + \\
&\quad + (T_1 + T_2)y_f\sin\delta_{arms}\cos\Gamma + \\
&\quad +(\tau_1 + \tau_2)\cos\delta_{arms} - \tau_3\sin\mu
\end{aligned}\right. \tag{1}$$

2.2 Equilibrium Condition Analysis

Once the dynamics equations were derived, an equilibrium condition analysis was carried out through the use of a non-linear solver algorithm with the purpose of determining the attitude and actuator outputs required for the conceptualized test vehicle to hover steadily under various constant wind conditions.

This algorithm, being based on an optimization approach, required the definition of a cost function. The methodology which was considered consisted of minimizing the sum of the mechanical power developed by the three rotors (P_i). As so, the program was to find values for a set of pre-defined variables, regarding the vehicle's attitude (roll angle – ϕ; pitch angle – θ) and actuation (rotational speed of the i rotor – Ω_i; tilt angle of front rotors – δ_{arms}) which would enable for said minimization to happen. The optimization problem was thus defined as shown in Equation 2.

$$min \sum_{i=1}^{3} P_i \tag{2}$$

$$w.r.t.\ \ [\phi, \theta, \Omega_1, \Omega_2, \Omega_3, \delta_{arms}]$$

$$\begin{cases} F_{x_a} + F_{x_{prop}} + F_{x_g} = 0 \\ F_{y_a} + F_{y_{prop}} + F_{y_g} = 0 \\ F_{z_a} + F_{z_{prop}} + F_{z_g} = 0 \\ M_{x_a} + M_{x_{prop}} = 0 \\ M_{y_a} + M_{y_{prop}} = 0 \\ M_{z_a} + M_{z_{prop}} = 0 \end{cases}$$

Here, F stands for forces, M for moments and subscripts a, prop and g stand for the contributions of aerodynamics, propulsive system and gravity towards the system, respectively.

As for the values in between which the optimization variables could vary, these are provided in Table 1.

Table 1. Study variables' boundaries.

Variable	Lower Bound	Upper Bound
ϕ	-30°	30°
θ	-30°	30°
Ω_1	0 rpm	8200 rpm
Ω_2	0 rpm	8200 rpm
Ω_3	0 rpm	6374 rpm

Once the algorithm had been established, several simulations were performed where the magnitudes and directions of (constant) incoming wind gusts were varied and the attitude of the aircraft and expected actuation registered. This allowed to conclude on the expected tendencies of this novel configuration under different hovering flight scenarios as well as to obtain an initial vertical flight envelope. This flight envelope contains the maximum allowable gust magnitudes for each direction based on the actuation and attitude limits that were established, namely the allowable roll and pitch angles, maximum tilt angle that the frontal rotors can achieve and maximum allowable rotational speed of all three rotors, as provided on Table 1.

The first study which was carried out using the developed optimization tool had the objective of determining the attitude and actuation assumed in vertical flight by the future fixed-wing vehicle (FW VTOL) for which the explored multi-rotor configuration was conceptualized under zero-wind conditions. The results obtained from such simulations are available in Table 2.

Table 2. Attitude and actuation during steady hovering flight under zero-wind conditions.

Variable	FW VTOL
ϕ	-0.338°
θ	0°
Ω_1	6047 rpm
Ω_2	6047 rpm
Ω_3	4909 rpm

From the analysis of these results, it is possible to reach some conclusions regarding the behaviour of the configuration in hover. Even though this may not prove truthful for all vehicles which assume this multi-rotor configuration, for the present study case it was concluded that the drag torque developed by the rear rotor of the vehicle surpassed the accumulated drag torques developed by the front rotors in hovering flight conditions. This is translated, considering the sense of rotation defined for the various propellers in Figure 2, into an accumulated drag torque which is different from zero in magnitude and that assumes negative values along the vertical (yaw) axis of the aircraft's local referential. As so, from the need to counterbalance this phenomenon through the tilting action of the frontal rotors, to obtain a thrust vectoring such that this torque imbalance is neutralized, the frontal rotors will have to tilt to the right. This allows for the development of a lateral (Y-positive) thrust component and an associated, positive, torque along the yaw axis which will thus balance the accumulated drag torques. This tilting action is then translated by a positive value of the δ_arms variable. Such a thrust vectoring action, however, despite allowing to achieve a balance of torques in yaw, creates an imbalance of forces along the local Y axis in levelled flight. As so, and in order for the aircraft not to drift to the right as a consequence of this imbalance, the vehicle will also reveal a tendency to roll to the left, which allows for this lateral thrust to be balanced by a local component of the aircraft's weight. The pitch angle will expectedly remain null while the rotational speeds of the different rotors are dependent on the specific powertrain characteristics for each vehicle. In the hypothetical case of the balance of torques along the yaw axis revealing a greater equilibrium of drag torques or even a reversal of the verified situation (accumulated drag torques of the frontal rotors surpassing in magnitude the one of the rear one), the stationary hovering flight attitude and actuation will change. Nevertheless, the underlying logic as to why the aircraft assumes such attitude/actuation will remain unchanged.

The devised optimization tool was also used to obtain a preliminary vertical flight envelope regarding the gust magnitudes (and directions) under which the conceptualized vehicle would be able to operate, in hovering flight, while respecting the operational boundaries defined in Table 1 and maintaining a fixed position. Such results are provided in Table 3.

Finally, an additional study on the relation between the angle assumed by the rear rotor and the forward speed achieved by the future FW VTOL vehicle during a hypothetical transition manoeuvre was also carried out using a modified version of the tool which allowed to obtain the results previously presented.

Table 3: Maximum allowable gust magnitudes by direction and study case.

Variable	FW VTOL
Front	>10
Rear	>10
Left	4
Right	4
Up	7
Down	4

The optimization process for this study case was identical to the one presented earlier, with the distinction of considering an additional optimization variable regarding the tilting angle of the rear rotor. The results relative to the optimal transition scenario (where the total mechanical power required to maintain levelled flight at a constant altitude is minimized and wind gusts are null across all directions) are thus presented in Figure 3. The aerodynamic model which was used assumed that the transition was performed with a null pitch angle and with the canard incidence set at the same value as in trimmed flight at cruise speed.

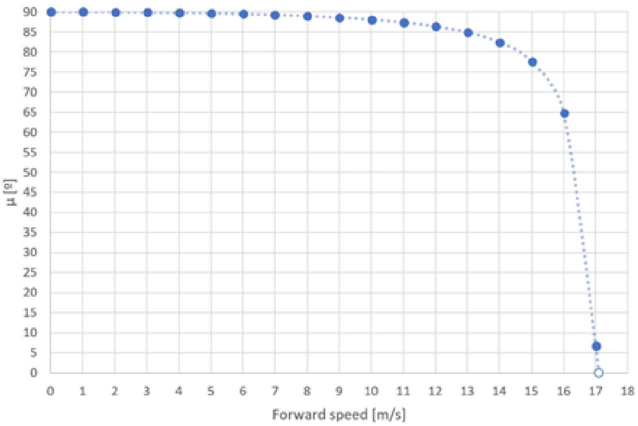

Fig. 3. Relation between rear rotor tilting angle and forward speed achieved by the aircraft for optimal transition scenario.

μ : Rear rotor's tilting angle.

Considering that the theoretical stall speed for the conceptualized FW VTOL aircraft has been established at 13 m/s (Pedro et al., 2021), it was deemed possible that such forward flight condition could be achieved with a rear rotor tilting angle as low as 5° (considering that the required time is provided for the vehicle to acquire such forward velocity). From the analysis of the provided graph, it is also noticeable that once the theoretical stall speed is achieved, a ramp-up in the progression of the rear rotor's tilting angle with the forward speed is also verified. This result was expected, given, firstly, the increase in the contribution of the aerodynamic surfaces (wing and canard) in the generation of lift, which reduces the need for the rotors to generate vertical thrust (in fact, throughout the transition process, a gradual decrease in rotational velocity is also verified for all rotors) and secondly, since the increasing forward speed also brings an increase in horizontal drag, the demand for horizontal thrust is simultaneously enlarged, hence the reduction of the tilting angle of the rear rotor in the later stages of this transition process.

3. Vehicle Design

3.1 Flight Controller Development

In order to perform the proof-of-concept flights which could attest to the airworthiness of the proposed configuration, a test vehicle was built, and a custom flight control firmware was developed. This later step was done in the PX4 environment, through the development of a custom airframe configuration. Even though there were two pre-existent Y-shaped tri-rotor flight controllers available in the PX4 repository, neither of them was applicable to the proposed configuration. There were three reasons for this: 1) Both of these models assumed that all three rotors were equidistant from the aircraft's centre of gravity (CG), which does not apply to the presented case that presents a 20/80 thrust distribution between the front and rear rotors; 2) The sense of rotation of the rotors was different from the ones envisioned for the proposed configuration; 3) The pre-existent controllers presumed that yaw control was dependent on the laterally tilting action of the rear rotor while for our configuration this task is assigned to the frontal rotors tilting mechanism instead.

Once the characteristics of the proposed configuration were translated into the required files and the compilation of the firmware took place, the obtained autopilot was flashed into a PixHawk 4 board. Communication with the hardware was done through QGroundControl.

One of the main aspects of concern during said development was the neutralization of possible coupled dynamics. This is of particular interest given the fact that the sense of rotation of the frontal rotors is opposite to the sense of the rear one. Although this design aspect was intended, for minimization of the natural drag torque imbalance along the yaw axis and thus of the lateral thrust vector required to achieve said balance (minimizing overall power to achieve stable, stationary, hovering flight), it brought up a possible undesirable effect. This effect was associated to the typical approach of multi-rotor flight controllers towards yaw attitude management. The common approach consists of changing the rotational speed of specific rotors, depending on the defined sense of rotation, to perform yaw attitude changes. However, given the proposed configuration, the application of a similar yaw control methodology would derive in a coupled action along the pitch axis. The solution which was found, and that took advantage of the fact that the proposed configuration grants thrust vectoring capabilities to the frontal rotors, was to assign full control over the yaw attitude to the front tilt mechanism while preventing the flight controller from changing the rotational velocities of the rotors when yaw attitude changes were required. As so, one can say that control over the pitch and roll axis, as well as of heave actions, were deemed dependent on the manipulation of the rotational velocities of the different rotors, as is usual, while authority over the yaw attitude was attributed solely to the front tilt mechanism action.

3.2. Tilt Mechanisms Development

Regarding the design of the test vehicle, the two subsystems which present particular interest due to their novelty and fundamentality to the functioning of the proposed multi-rotor concept are the front and rear rotors' tilt mechanisms. These were developed from an initial conceptual drawing until the final prototyping stage during the course of this investigation.

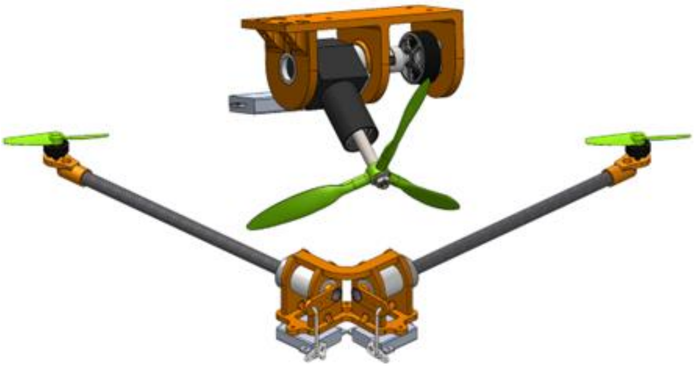

Fig. 4. CAD models for both the rear (top) and front (bottom) rotors' tilting mechanisms.

The rear rotor design was developed with the ever-present intention of simulating the introduction of an internal combustion engine to power the rear rotor, as will be required in the future larger-scale version of the fixed-wing VTOL aircraft. It was also determined that such power unit should be fixed relative to the airframe, in a way that a 90° gearbox is required to transfer the mechanical power between the fixed power source and the tilting output shaft of the system, where the propeller is mounted on. As in any mechanical system, however, this gearbox will present losses, which will influence the overall efficiency of the rear rotor system. This phenomenon shall be studied in a later stage of this work.

Regarding the frontal rotors' tilting mechanism, one of the main considerations that were taken into account was that the chosen design should allow for the future modification of the system, as to allow for the retracting action of the frontal arms of the tri-rotor during the horizontal flight stages of the future FW-VTOL vehicle. As so, it was deemed necessary that each arm was fitted with a dedicated actuator (servo). This choice would not only provide redundancy to the yaw attitude management system, in the case of a failure occurring, but also allow for the separation of the designed tilt mechanism support (in orange, at the bottom of Fig. 4) into two symmetrical parts, capable of rotating independently and thus allowing for the future development of an adequate retraction mechanism based on this design. This additional mechanism was, however, not developed for the current test multi-rotor due to not having any real influence on the dynamics of the vehicle apart from the additional weight contribution.

3.3 Ground Testing

Once the different mechanisms were built, their actuation was mapped before their fitment onto the airframe. This allowed to update the previously devised FDM and to gather valuable data for future interpretation of the flight logs. Static thrust testing was also conducted for both the front and rear rotors' systems with the same objective. The aforementioned study on the loss of performance caused by the introduction of a 90° gearbox between the rear electric motor and propeller shaft was also conducted, allowing to compare the power required to obtain similar thrust values both in direct drive and with the complete rear tilt mechanism system. To collect said results, firstly, static thrust tests where the rear rotor's propeller was mounted, as is usual, on the rear motor's shaft were performed. Then, after the assembly of the rear rotor tilting mechanism had been completed, the gearbox was fixed using two wedges, as to align the output propeller shaft with the static thrust test bench and additional thrust tests were carried out, with the obtained results being displayed graphically on Figure 5.

These results show that there is a clear increase in the electrical power required by the motor for the case of the complete rotor tilt system, as expected. From the obtained values it was possible to estimate, for example, that to generate the amount of thrust required from the rear rotor under hovering flight conditions, the increase in power that would be required to drive the complete rear rotor system when compared with the direct drive case would be of around 19%. This loss in efficiency is mainly due to the energy losses associated with the introduction of the 90° gearbox in the system. In fact, the efficiency (loss) curve which was obtained also proved consistent with the typical gearbox efficiency.

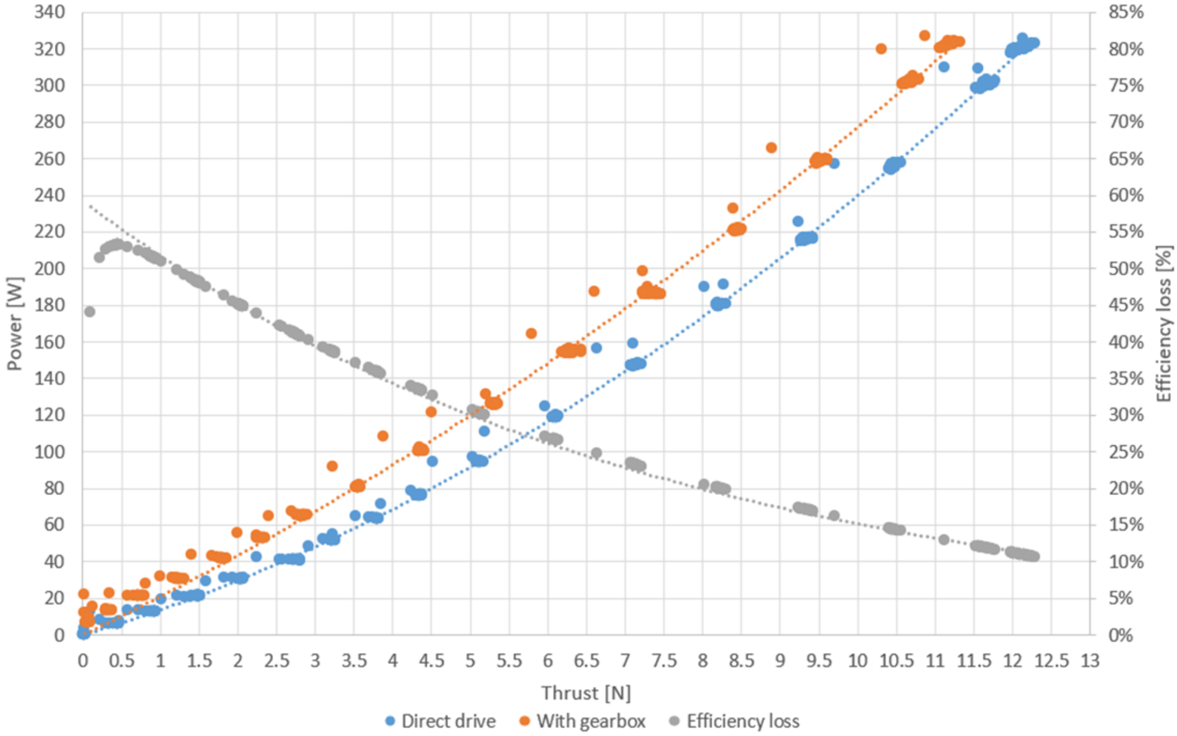

Fig. 5. Static thrust test results for the rear ESC/motor/ propeller system in direct drive and when fitted to the rear tilting mechanism.

Behaviour registered by several authors (Bogdan & Zoltan, 2017; Sekar, 2019), who have previously verified marked tendencies of such mechanical systems to minimize their losses when an increase in the loading conditions is verified.

Other ground tests which were performed involved continuous operation static thrust testing of the rear rotor system. These were done for temperature survey of the gearbox's gears and particularly of the electric motor's temperature when exposed to such continuous operating conditions. The main driver for this test was the concern that the motor, not being directly in the wake of the propeller as it was designed to be during its operation, would overheat and experience a loss in performance due to magnet demagnetization (Zhou et al., 2012; Ruoho et al., 2010). However, it was found that the temperatures achieved were considerably lower than the maximum allowable ones stated by the manufacturer, in a way that the subsystem could then be considered safe and thus mounted on the vehicle's airframe.

4. Flight Testing

After all the subsystems were tested individually and the multi-rotor prototype completed, flight testing could then commence. The first flights were performed indoors, with the prototype tethered, as to ensure the safety of the intervenient and of the vehicle itself in these early stages of testing. These tests allowed to tune the different aircraft systems, from the controller to the airframe and power distribution system, which were objects of continuous upgrades during this preliminary testing stage. Once the vehicle's performance and controllability were deemed satisfactory, the tethers were removed, and the team proceeded to perform the first untethered flight (Fig. 6). During this test, the aircraft proved capable of performing stable hovering flight while maintaining position, as required during a vertical take-off or landing manoeuvre, and also to perform manoeuvres across all three attitude axis, with the pilot reporting that the vehicle was easily controllable and that its dynamics were fairly predictable despite being a novel aircraft configuration.

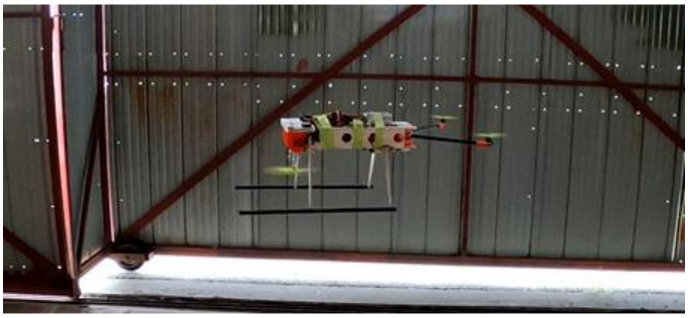

Fig. 6. Test vehicle during indoor, untethered flight testing.

Based on these results, the team felt confident in proceeding with the following flight tests outdoors (Fig. 7).

The first set of exterior tests consisted of five flights encompassing manoeuvres such as chirps, doublets, and periods of static hovering flight, which were done with the purpose of collecting data for later system identification. As so, an initial practice flight was carried out for the pilot to be familiarized with the different manoeuvres and associated tendencies of the aircraft. This was followed by three other flights, one dedicated to each of the local attitude axis (roll, pitch and yaw). In each of these flights, the pilot commanded the vehicle to perform various sets of chirps and doublets, always on the same axis during each test, intercalating these manoeuvres with periods of hovering flight. After this, another flight was performed (the validation flight), where sets of chirps and doublets were performed once again but this time across alternating axes, in a way that there was at least one example of each manoeuvre across each of the three axes for later validation of the flight dynamics models obtained from system identification. Having data from this final validation flight allows to assess the robustness of the model when replicating a different flight from the ones used to generate the dynamics model.

Finally, the only capability of the configuration that had not been tested until this moment was the ability to initiate and maintain stable forward flight by tilting the rear rotor system. Considering that the developed experimental vehicle lacked the traditional lifting surfaces of a fixed-wing aircraft, it was obvious that a complete transition between vertical and horizontal flight could not take place. However, the objective which was defined for this test was solely the evaluation of the capability of this multi-rotor configuration and of the flight controller to initiate a simulated transition manoeuvre. As so, a final test flight where the aft rotor was tilted by 5° was performed. Previous parametric studies yielded that the thrust vectorization that would derive from this actuation would allow for the aircraft to maintain a levelled attitude and a constant altitude while also gaining forward momentum as would be required during a transition flight manoeuvre.

Fig. 7. Test tri-rotor during outdoor flight testing.

The results obtained were very satisfactory, with the aircraft revealing itself as capable of initiating and maintaining stable forward flight with minimal to no pilot intervention for attitude correction being required.

5. System Identification

Upon collection of the required flight data from the previously mentioned flight tests, the following objective was to obtain a dynamics model from said experimental data.

The chosen system identification approach used in this work was based on a frequency-response model (Tischler & Remple, 2012). This approach, translated into a custom transfer-function estimation tool, took as inputs the rate setpoints of the flight controller during the test flights performed for each of the different attitude axes and the angular rate response registered by the gyroscope for that same axis. At the same time, and for each file of flight test data, the user was required to provide the program with the time intervals where the different manoeuvres took place during the respective test. Then, with this information, the flight data of the three SID flights (one relative to each attitude axis) was partitioned in a way that each sample was composed of one manoeuvre on one axis. Next, all possible combinations of these manoeuvres for a given axis were obtained, yielding a certain number of simulated flight examples. Each of these simulated flights would then be used to estimate one transfer function, which related the inputs and outputs for the set of manoeuvres encompassed by that flight. After this point, each of the obtained transfer functions would be tested against the additional validation flight data (which had not been used in the estimation of said transfer functions) for the respective axis. Then, the transfer functions which provided the highest fitting, or in other words that best replicated the validation flight outputs when provided with the same inputs, were said to represent the aircraft's dynamic behaviour for that axis.

It should be noted that the provided model is linear, which means that the coupled dynamics are neglected. This can be reflected in an undesirable reduction of the fitting of the replicated dynamics to the original ones, considering that the proposed concept presents some marked couplings. Even though, as explained in subsection 3.1., some of these coupling tendencies were dealt with when defining the flight controller, others could not be neutralized. One of the most prominent couplings occurred between the variation of the pitch attitude and a subsequent reflection on the yaw attitude. This effect showed itself particularly during high-frequency pitching manoeuvres, where the rapid variation of the thrust developed by the front rotors, required to achieve the desired chirp manoeuvre along this axis, would cause an unrequested chirp along the yaw axis of equal frequency and smaller amplitude (Fig. 9 and Fig. 10). This was caused by the thrust vectoring of the thrust developed by the front rotors, which while allowing to manage the yaw attitude of the vehicle during the vertical flight stages, also exposes it to such coupled dynamics.

Nevertheless, the dynamics model retrieved from such an approach presents itself as a capable tool when it comes to the replication of the relation between inputs and outputs for the same axis and can be used in, for example, autopilot optimization tasks. Furthermore, when applied to vehicles with configurations less prone to dynamic couplings, the obtained models prove even more accurate in the replication of the overall behaviour of the vehicle, yielding superior fittings between simulated and real flight dynamics to the ones verified for the current application. The goodness of fitment values obtained for the presented case study are provided in the figures below ("G").

6. Conclusions

The work presented in this paper characterizes the airworthiness of the proposed multi-rotor configuration for future application on the VTOL system of a fixed-wing aircraft.

During the course of the reported work, an initial study on the expected behaviour of a future fixed- wing VTOL aircraft fitted with the proposed tilt tri-rotor propulsive system configuration in vertical flight was carried out.

Such study culminated in the comprehension of the attitude and actuation that would be expected of said aircraft during hovering, stationary flight under several wind conditions; in the obtention of a preliminary vertical flight envelope regarding the maximum acceptable gust magnitudes for various directions that would still allow for the vehicle to maintain hovering, stationary flight; and on the expected attitude and actuation of the conceptualized vehicle when transitioning from vertical to horizontal flight by means of the tilting action of the rear rotor.

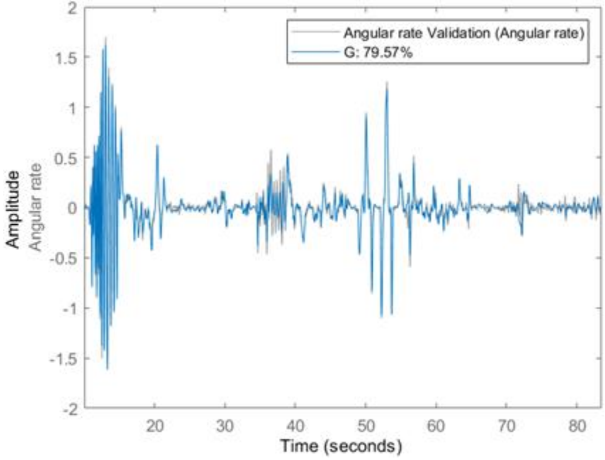

Fig. 8. Comparison between replicated and recorded roll dynamics during the validation flight.

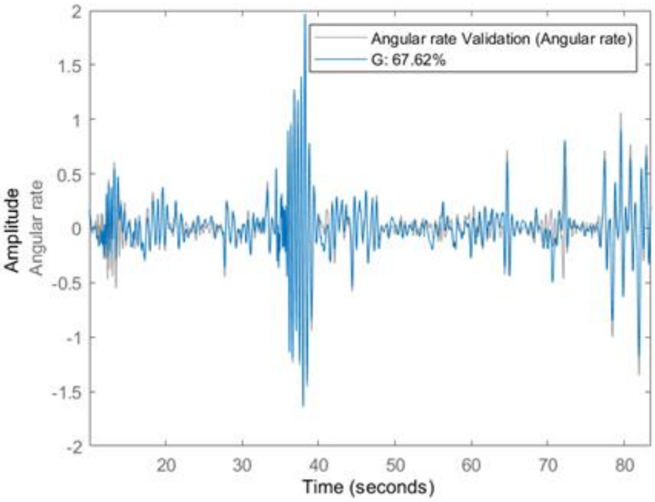

Fig. 9. Comparison between replicated and recorded pitch dynamics during the validation flight.

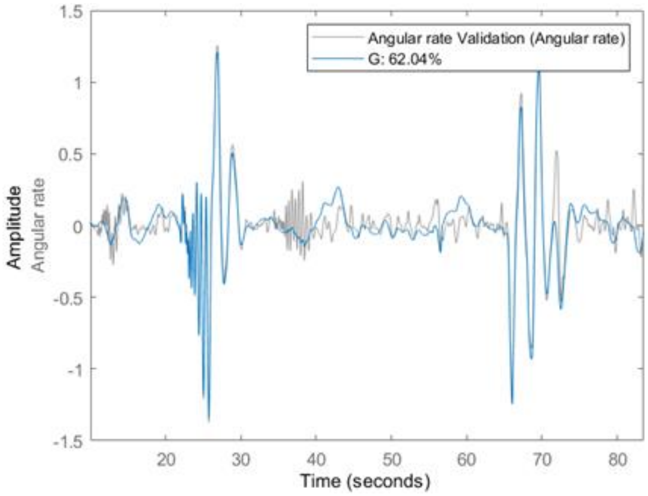

Fig. 10. Comparison between replicated and recorded yaw dynamics during the validation flight.

Furthermore, the solutions proposed for both the front and rear rotor tilting mechanisms were successfully developed and tested.

Next, the multi-rotor prototype that was developed during the course of this investigation was flight tested successfully, both indoors and outdoors, proving not only the ability of the aircraft and thus of the configuration to sustain continuous and stable hovering flight when exposed to external disturbances but also the ability to manoeuvre adequately along all attitude axis with various frequencies. Moreover, the important milestone of initiating and performing stable forward flight through the action of the rear tilting mechanism was also achieved, paving the way for future transition condition studies of the fixed-wing aircraft that is being developed to be made.

Finally, a newly developed, frequency-response based, SID tool was applied to the collected data, providing a model which yielded satisfactory results when it came to the replication of the real flight test dynamics, despite neglecting some of the coupled dynamics associated with the proposed configuration.

Nomenclature

VTOL : Vertical Take-Off and Landing
UAV : Unmanned Aerial Vehicle
FDM : Flight Dynamics Model
SID : System Identification

CRediT Author Statement

António Arco: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization. **José Lobo do Vale**: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing – Review & Editing, Supervision. **Sean Bazzocchi:** Conceptualization, Software, Writing – Original Draft. **Afzal Suleman:** Conceptualization, Resources, Writing – Review & Editing, Supervision, Project Administration, Funding Acquisition.

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