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A Novel Concept for VTOL Platform Combining Variable Pitch Main Rotor and Quadrotor Configurations

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ABSTRACT

***Keywords**: Novel UAV Configuration, Conceptual Design, VTOL Drone, Helicopter, Quadrotor.*

Unmanned Aerial Vehicles (UAVs) have numerous applications in military, commercial, and hobby fields. Among these vehicles, drones with vertical take-off and landing (VTOL) capabilities have attracted more attention due to their specific capabilities, such as better maneuverability and hover flight. In recent years, numerous concepts emerged that are trying to propose new configurations to enhance UAV performance. This paper proposes a novel concept that integrates a single main rotor helicopter and quadrotor structure to overcome some difficulties in those applications. This suggested configuration includes a variable-pitch main rotor equipped with four smaller counterrotating rotors to overcome its opposite torque (instead of a tail rotor in helicopters) and sustain a portion of the UAV weight, which makes it possible to use a smaller main rotor. This design preserves the maneuverability of helicopters while eliminating tail rotor power loss and its asymmetric lateral force. It also enhances flight stability and maneuverability by properly using the other four rotors' thrusts. Preliminary dynamic modeling and control system design are presented in the text, and the results show that this idea can be investigated further. Other steps are planned to be studied in the subsequent research.

Introduction

Unmanned aircraft vehicles (UAVs) have gained much attraction in recent years. Among them, unmanned rotorcrafts are more critical due to their unique abilities, such as hover flight and vertical take-off and landing. The main configurations used in these vehicles are the single main rotor, coaxial, and multi-rotor (quadcopter, hexacopter, and octocopter) systems. Since each configuration has pros and cons compared to others, in recent years, new ideas and concepts have been proposed in the literature, including tail-sitters, hybrid flight, and VTOL UAVs. In this manuscript, we propose a novel configuration as an unmanned rotorcraft that is composed of a variable pitch main rotor and four constant pitch rotors as torque compensators (combining ideas used in single main rotor helicopters and quadrotors).

Due to the problems in utilizing each of these configurations, some prototypes have been

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developed recently, focusing on hybrid unmanned systems (transforming flight regimes from hover to forward flight). These hybrid vehicles should have the main characteristics of vertical take-off and landing vehicles (VTOL) and fixed-wing aircraft, including vertical take-off and landing and fast-forward flight. These novel vehicle designs are proposed as a concept yet and need extensive investigation to be used as mature products and technologies.

As mentioned above, numerous models and concepts are proposed in the UAV field. Especially in recent years, advancements in electronic technologies and measurement and control systems provide a better background for proposing new ideas. In these vehicles, the variety of thrust-producing mechanisms and configurations results in an enhanced possibility of designing and implementing different UAVs. For instance, different aerial robot investigations are gathered in reference [1].

This variety of configurations leads to proposing a new classification of drones. For example, we can mention categorizing UAVs by application in [2], studying hybrid flight UAVs (which can take-off and land vertically and perform cruise flight as a plane) in [3], and also technologies related to VTOL (vertical take-off and landing) UAVs in [4]. In some configurations, vehicle control and maneuvering are performed by changing the rotor axis, known as thrust vectoring, which can be found in [5]. Design methods and configurations of UAVs are introduced in [6]. Finally, the most recent advancements and concepts proposed in this field can be seen in [7].

Besides the general information given above, we can take a closer look at the detailed description of concepts based on the combination of different ideas and configurations. In recent years, combining fixed-wing UAVs and multirotor has been investigated in several works. As examples, three types of these drones have been investigated in [8], [9], and [10]. These UAVs add optimal cruise flight capability to a rotorcraft while maintaining its vertical take-off and landing capability. The main drawback of this idea would be the decreasing maneuverability and operational flight characteristics compared to rotorcraft. Another drone group based on idea combining is called "Flying Wing." In these vehicles, the main section is a wing equipped with several rotors and can perform hover flight, vertical take-off, and landing and specific maneuvers [11], [12], and [13]. The capabilities and performance of these UAVs are different from rotorcraft. Two types of these drones are shown in Figure 1.

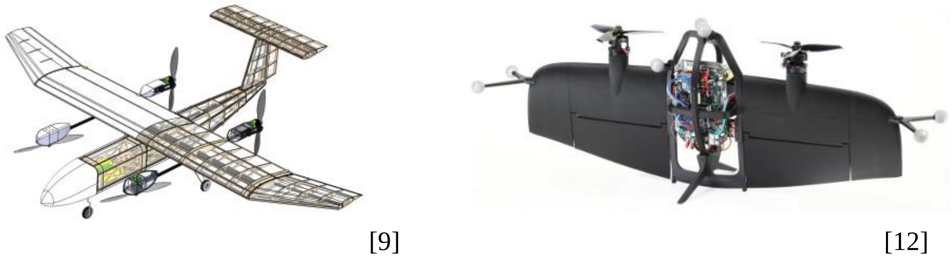
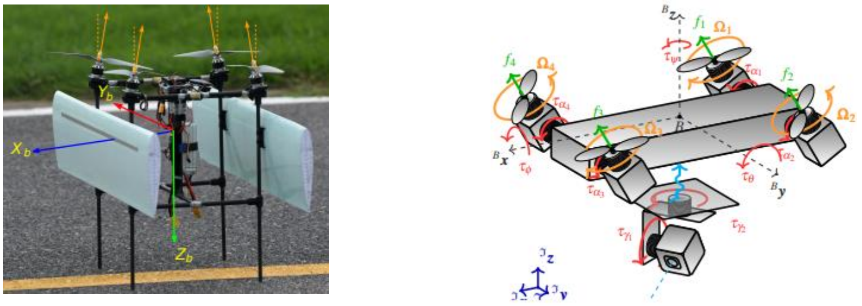

[9] [12]

Figure 1: Drones based on combining fixed-wing and multirotors (left) and flying wing (right)

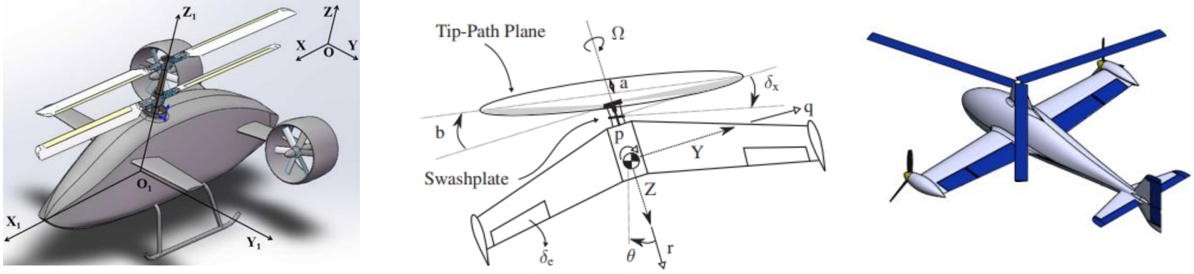
Furthermore, a quadrotor structure and adding wings to it have been proposed in the literature. In these drones, the flight performance in hover and near hover regimes is approximately the same as quadrotors [14], [15] and [16]. However, the results show enhanced wing-cruise flight and long-range routes capabilities. Of course, adding wings will lead to excess weight and drag in near hover flights, decreasing the maneuverability of these UAVs. Moreover, the addition of tilting capability for rotors in a multirotor configuration is another novel trend. These drones, known as Tiltrotors, consist of dual tilt rotors, tri tilt rotors, and quad tilt rotors [17], [18], and [19]. Although this enhancement increases the maneuverability and flight performance of these UAVs, it will increase the system's degrees of freedom and complicate its flight behavior, leading to a more complex dynamic system. Therefore, a more complicated control algorithm is needed for its guidance. The samples of these models are shown in Figure 2.



[15] [19]

Figure 2 : Drones based on wing-added quadrotors (left) and tiltrotors (right)

Finally, the most related research concerning our novel configuration is a combination of a variable-pitch main rotor with wing and other rotors. To our knowledge, three models are introduced based on this idea, shown in Figure 3. The main advantage of using a variable-pitch main rotor is the ability to generate thrust forces in a plane perpendicular to the rotor axis. Although this will increase the maneuverability and performance of the drone, it also complicates its dynamics and control mechanism. Adding a wing will improve the cruise flight ability of these UAVs. However, it will decrease near-hover flight performance.



[22] [21] [20]

Figure 3: Drones based on a single main rotor and added wings

As mentioned earlier, single-main rotor (SMR) unmanned helicopters and quadrotors are the most common UAVs used as vertical take-off and landing vehicles. There are some concepts of pentacopters [23] and [24] or triangular quadrotors, known as Y4 configuration [25], that use the main rotor and several smaller ones. Nevertheless, all the applicated rotors are fixed pitch, causing control troubles in different operation scenarios. To the author's knowledge, the idea of combining these two configurations never had been proposed before. Based on what we will describe in the following sections of this article, this idea would lead to several benefits and produce a novel drone configuration that will combine the advantages of these two classes of drones.

Proposing Novel Concept

Besides these novel configurations, standard platforms such as single-main rotor helicopters, coaxial helicopters, and multi-rotor systems are commonly used in numerous applications (Figure 4). Each one of these platforms has its pros and cons. For example, the single-main rotor configuration is an agile and high-performance platform with great maneuverability and robustness against disturbance. Its main advantage is using rotor flapping to generate in-plane forces, which is a better flight control mechanism tool. Its main weaknesses are an asymmetrical dynamic system, power loss due to tail rotor force (used to counter main rotor torque), complex nonlinear dynamics, and control system design [26]. Also, Multi-rotor systems are inherently more stable vehicles. However, they have less maneuverability and robustness. Due to the couple rotor torques used to counter each other effect, the efficiency of this configuration is about 10% higher compared to a single-main rotor configuration, as the tail rotor power is generally not useful [27]. The coaxial platforms are more stable than single-rotor systems and do not need tail rotor loss to encounter the torque of the main blade. However, mechanical complexity and lower agility are the main weaknesses of this platform.

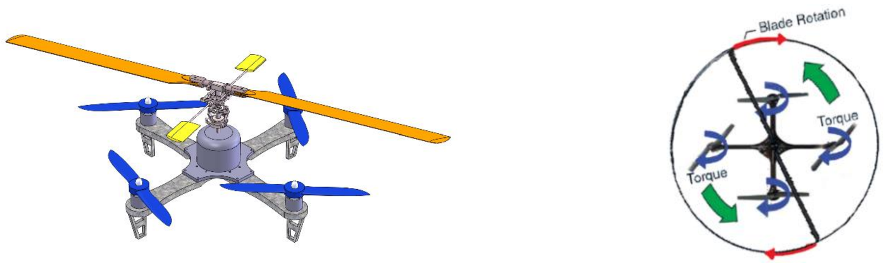
(a) Single-Main Rotor Helicopter (b) Multi-rotor Drone (c) Coaxial Drone

Figure 4: Common unmanned rotorcraft platforms working principles

This paper proposes a novel configuration that simultaneously utilizes the benefits of single-main rotor helicopters and quad-rotor. It will use a variable pitch main rotor section with collective and longitudinal and lateral cyclic inputs as it is used in radio-controlled (RC) helicopters (Fig.5). This will let the pilot trigger main rotor flapping dynamics and change the blades' tip path plane orientation. Moreover, it uses it to generate in-plane forces and moments, which will increase the agility and maneuverability of the system. The actuation mechanism will be designed based on the swash-plate mechanism and control servo motors and can be enhanced by adding a stabilizer bar to the system.

Figure 5: Swash-plate mechanism neutral position (center), collective input (right) and cyclic input (left)

Unlike the standard single-main rotor platform, the main rotor torque in the proposed concept will be encountered by 4 smaller rotor torques rotating in the opposite direction of the main rotor (Figure 6). These 4 rotors will generate thrust and lift forces and carry a portion of vehicle weight. In contrast, in a standard single-rotor configuration, the tail rotor will waste the power and create lateral unbalance force in the system. Furthermore, thrust forces generated by small rotors will increase the system's stability during flight as it is used to control a quadrotor steadily.



3-D schematic model Torque compensation principle

Figure 6: The proposed configuration

The control structure for the proposed platform is the same as the single-main rotor helicopters. The main rotor rotates at a constant RPM using an electronic governor system. In addition, the blade's angle of attack is set using a swash-plate mechanism and collective and cyclic inputs. The encountering torques of 4 small rotors are set automatically by compensating the required lift and torque based on collective input and internal yaw rate gyro controller. These modifications are performed by changing rotor RPMs. Besides, the pedal input changes the vehicle heading while performing different tasks and maneuvers. Two control strategies can be considered for this unmanned vehicle. In normal mode, all 4 small rotors RPMs are equally set, which maintains symmetrical force and moment condition and increases the stability margin of the system. In agile mode, each small motor RPM will be controlled separately by the internal intelligent control system. This will maximize the performance and maneuverability of the vehicle by generating unbalanced forces and moments.

This platform can be constructed using off-the-shelf parts available for commercial single-main rotor helicopters and quad-rotors. This will make its implementation more realistic than other mentioned novel configurations and with less time and cost. The motors and blades' sizing selection needs to be done cautiously to optimize the system's dynamic performance. Also, an internal gyro feedback controller will be used to manage small rotor thrusts to maintain constant heading or follow the desired values if required.

Preliminary Dynamic Modeling of the Proposed Configuration

Generally, a modular method is used for the dynamic modeling of unmanned rotorcrafts. The forces and moments created by different sections are calculated separately and then transferred to the center of gravity axes. After summing all forces and moments, the rotorcraft's linear and angular accelerations will be calculated using Newton-Euler equations. In the end, integrating these accelerations, translational and rotational velocities and positions will be available, and this cycle will run again for the next steps.

Space states used in modeling include CG position, translational and rotational velocities in body axes, orientation Euler angles, and an extra state considered for modeling the effect of internal gyro rate feedback of the internal PI controller. Like all other helicopters, control inputs are considered as two normalized inputs, namely collective and pedal, and two cyclic inputs, which are expressed as flapping angles of the main rotor. The definition of space states and control inputs are shown in Table 1.

Table 1: Modeling space states and inputs

Parameter	Unit	Description
$P_n = [x_n \;\; y_n \;\; z_n]^T$	m	Rotorcraft CG position vector in earth frame
$V_b = [u \;\; v \;\; w]^T$	$^{m}/_{s}$	Rotorcraft translational velocity in body frame
$\omega^b_{b/n} = [p \;\; q \;\; r]^T$	$^{rad}/_{s}$	Rotorcraft rotational velocity in body frame
$\phi\,.\,\theta\,.\,\psi$	rad	Euler angles
$Flapping\ Angles\colon a_s.\,b_s$	rad	Main rotor flapping angles
$\delta_{ped.int}$	-	State defined for yaw rate feedback PI controller
δ_{col}	-	Normalized input for collective input (-1,1)
δ_{ped}	–	Normalized input for pedal input (-1,1)
δ_{lon}	-	Normalized input for longitudinal input (-1,1)
δ_{lat}	–	Normalized input for lateral input (-1,1)

Two reference axes should be defined for the dynamic modeling of the rotorcraft: a fixed NED coordinate with arbitrary origin on the ground (the earth coordinate), and a NED coordinate attached to the helicopter center of gravity (body coordinate). The body coordinate is a non-Newtonian system in which the dynamic equations will be considered. Euler angles have been used to relate the orientation of body axes to the ground axes. According to the linear velocity components of the rotorcraft in the body axes, the kinematics of position can be written as (1):

$$\dot{P}_n = V_n = R_{n/b} V_b \tag{1}$$

Where $R_{n/b}$ is the rotation matrix between the body and earth axes:

$$R_{n/b} = \begin{bmatrix} c\theta.c\psi & s\phi.s\theta.c\psi - c\phi.s\psi & c\phi.s\theta.c\psi + s\phi.s\psi \\ c\theta.s\psi & s\phi.s\theta.s\psi + c\phi.c\psi & c\phi.s\theta.s\psi - s\phi.c\psi \\ -s\theta & s\phi.c\theta & c\,\phi\,.c\theta \end{bmatrix} \tag{2}$$

In **Error! Reference source not found.**, c and s indicate cos and sin functions, respectively. The relation between Euler angles change rates and rotorcraft angular velocity can be shown as matrix equation (2):

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}1 & tan\theta.sin\phi & tan\theta.cos\phi\\ 0 & cos\phi & -sin\phi\\ 0 & \frac{sin\phi}{cos\theta} & \frac{cos\phi}{cos\theta}\end{bmatrix}\omega_{b/n}^{b} \tag{2}$$

After calculation of applied forces and moments on CG, the rotorcraft body dynamic equations can be derived using the Newton-Euler equations (3) and (4):

$$\dot{V_b} = -\omega_{b/n}^{b} \times V_b + \frac{F_b}{m} + \frac{F_{b,g}}{m} \tag{3}$$

$$\dot{\omega}_{b/n}^{b} = J^{-1}\left(M_b - \omega_{b/n}^{b} \times \left(J\omega_{b/n}^{b}\right)\right) \tag{4}$$

In which the forces and moments are calculated using equations (5) to (7):

$$F_{b\,g} = \begin{bmatrix}-mg.sin\theta\\ mg.sin\phi.cos\theta\\ mg.cos\phi.cos\theta\end{bmatrix} \tag{5}$$

$$F_b = \begin{bmatrix}X_{mr}\\ Y_{mr}\\ Z_{mr} + \sum_{i=1}^{4} Z_{sr.i}\end{bmatrix} \tag{6}$$

$$M_b = \begin{bmatrix}L_{mr}\\ M_{mr}\\ N_{mr} + \sum_{i=1}^{4} N_{sr.i}\end{bmatrix} \tag{7}$$

In these relations, X, Y and Z are forces, and L, M and N are moments exerted on the system. These forces will be calculated for the main rotor and the small rotors and transferred to the center of gravity axes. Also, $J_{3\times 3}$ is rotorcraft inertia matrix simplified as (8):

$$J = \begin{bmatrix}J_{xx} & 0 & 0\\ 0 & J_{yy} & 0\\ 0 & 0 & J_{zz}\end{bmatrix} \tag{8}$$

Here, due to the symmetries, it is assumed that the inertial tensor is diagonal.

Modeling the main rotor is the most crucial part of the dynamic rotorcraft system, and different methods can be used for that [28]. In the most common method, flapping dynamics, containing stabilizer bar flapping dynamics, is considered a first-order dynamic system. Therefore, the dynamic model will have two states for longitudinal and lateral flapping angles. Calculation of thrust and rotor-induced velocity is carried out using the momentum theory method [27]. In the simplest case, the dynamic behavior of the main rotor is completely ignored, and it has been assumed that the inputs can directly control flapping angles and thrust force [26]. Components of the main rotor forces are obtained by thrust perpendicular to the TPP assumption. The second method is used for modeling at this stage due to its lower complexity. The small rotors flapping is neglected due to their constant pitch angle and high RPM. Therefore, they will act as a variable magnitude thrust, always normal to the body.

Generally, a rotor thrust and torque can be calculated from equations (10) and (11), respectively:

$$T_r = c_T A R^2 \Omega^2 \tag{9}$$

$$Q_r = c_Q A R^2 \Omega^2 \tag{10}$$

The blade's pitch angle is fixed for the small rotors, and the thrust and torque change are created by rotor RPM change. Each rotor RPM can be controlled separately by the flight control system. In normal mode, all the RPMs are kept equal to keep stability. Nevertheless, they can be determined separately in the agile mode to enhance that performance. For the main rotor, the motor RPM is kept constant, and thrust and torque will be changed by collective input.

The main rotor flapping dynamics can be considered a first-order coupled system controlled by longitudinal and lateral inputs. The flapping angles can be modeled by equations (12) and (13) [26]:

$$\dot{a}_s = -q - \frac{1}{\tau_{mr}} a_s + A_{b_s} b_s + \frac{1}{\tau_{mr}} \delta_{lon} \tag{11}$$

$$\dot{b}_s = -p + B_{a_s} a_s - \frac{1}{\tau_{mr}} b_s + \frac{1}{\tau_{mr}} \delta_{lat} \tag{12}$$

Based on the main rotor flapping angles, the main rotor forces are calculated using the perpendicular to TPP thrust assumption by equations (14) to (16):

$$X_{mr} = -T_{mr} a_s \tag{13}$$

$$Y_{mr} = -T_{mr} b_s \tag{14}$$

$$Z_{mr} = -T_{mr} \tag{15}$$

The opposing torque of main rotor is calculated by (16):

$$N_{mr} = Q_{mr} \qquad (16)$$

As mentioned above, an internal yaw gyro feedback PI controller will be included in the flight control system, which controls the rotorcraft's heading internally. The effect of this controller can be calculated by equation (18):

$$\bar{\delta}_{ped} = \left(K_P + \frac{K_I}{s}\right)\left(K_a \delta_{ped} - r\right) \qquad (17)$$

in which δ_{ped} is the basic input and $\bar{\delta}_{ped}$ is the applied pedal input. To consider this controller in modeling process, the dynamic equation of an extra state is defined as equation (18) which makes the applied pedal input be computed from equation (19):

$$\dot{\delta}_{ped,int} = K_a \delta_{ped} - r \qquad (18)$$

$$\bar{\delta}_{ped} = K_P\left(K_a \delta_{ped} - r\right) + K_I \delta_{ped,int} \qquad (19)$$

In hover conditions, flapping angles are zero, the sum of the thrusts is equal to the rotorcraft weight, and the main rotor torque is equal to the sum of the four small rotor torques as equations (21) and (22):

$$mg = Z_{mr} + \sum_{i=1}^{4} Z_{sr.i} \qquad (20)$$

$$N_{mr} = \sum_{i=1}^{4} N_{sr.i} \qquad (21)$$

The parameters used in dynamic modeling and their values are presented in Table 2.

Table 2: Dynamic model parameters used in simulation

Parameter	Value	Unit	Description
m	3	kg	Mass of drone
J_{xx}	0.085	$kg.m^2$	Drone moment of inertia about X axis
J_{yy}	0.185	$kg.m^2$	Drone moment of inertia about Y axis
J_{zz}	0.265	$kg.m^2$	Drone moment of inertia about Z axis
$A_b = B_a$	20	$-$	Flapping angles coupling parameter
τ_{mr}	0.1	s	Main rotor time constant
K_a	-3.8	$-$	Coefficient of internal gyro PI controller
K_P	0.4	$-$	Proportional coefficient of internal gyro PI controller
K_I	2.2	$-$	Integrator coefficient of internal gyro PI controller

For the heave motion of the rotorcraft, all thrusts increase or decrease so that the sum of torques remains zero. For yaw motion, thrusts of the main and small rotors change reversely such that the thrust sum remains equal to the weight. However, the net torque creates a heading change. Longitudinal and lateral movements are created by the main rotor flapping angles and in-plane forces generated by them. In agile mode, small rotor thrusts can also generate unbalance longitudinal or lateral torques, tilt the drone and use the balanced forces to maintain or track a desired roll or pitch angles.

Control System Design and Implementation

In order to investigate the dynamic flight behavior of the proposed idea, the model is implemented in Matlab/Simulink environment, shown in Figure 7. Also, the dynamic model block contains the equations presented above. Besides, the control system uses state feedback to generate inputs to perform the desired action. The dynamic system has 15 states and four inputs, shown in Table 1.

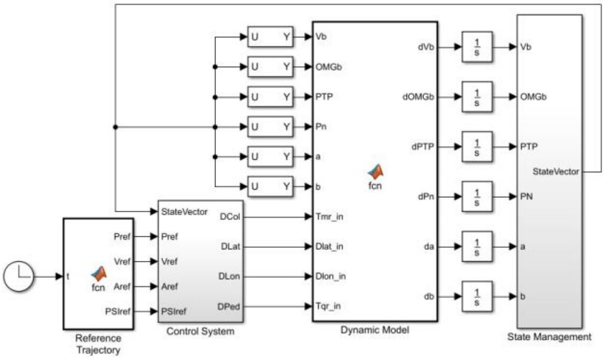


Figure 7: Drone dynamic model implemented in Matlab/Simulink environment

Moreover, a hierarchical LQR control system is designed and applied to the dynamic system. In this control scheme, the rotational dynamics, which are relatively fast, are stabilized and tracked in the inner layer. In contrast, the outer layer is concerned with linear dynamics and generates the reference values of Euler angles for the inner loop based on the desired trajectory. The inner loop contains nine states (rotational velocities, Euler angles, flapping angles, and PI gyro state), while the outer loop contains six (linear velocities and position). The control system structure (shown in Figure 8) and design processes are similar to the method described in equation [28].

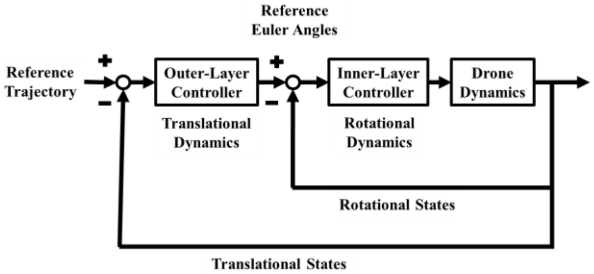


Figure 8: Schematic structure of the hierarchical LQR control system

In order to evaluate the performance of the control system, several basic scenarios were simulated. First, the control system was checked to bring the drone to hover flight from an initial condition of 5 m/s longitudinal velocities. The result shows that the controller successfully reduces the velocity and will produce stable hover flight. Due to the coupling of the system, all the states are changed during the simulation. However, the most significant changes are present in longitudinal velocity. The pitch angle is shown in Figure 9. It should be noted that the longitudinal reference position of the drone is set to its initial position, so the controller generates a negative velocity to bring the drone back.

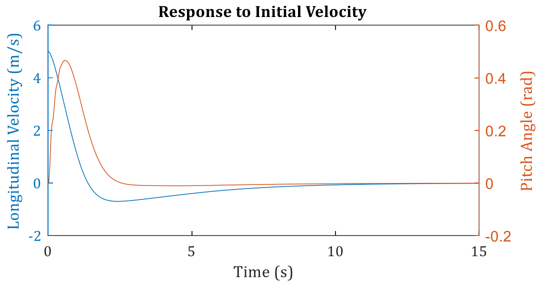


Figure 9: Response to longitudinal 5 m/s initial velocity

Next, the control system is set to follow a 10 m step change, after 1 second, in altitude (Figure 10-a) and the desired ramp displacement in the lateral direction (Figure 10-b). The reference trajectory definition is done by setting desired position, velocity, and acceleration. Since the velocity is set to zero during a step position change, the tracking performance is slow. In contrast, in ramp position change, the velocity is set to the proper value, which helps the control system to follow the trajectory faster. Again, the controller performance is acceptable in following desired trajectories.

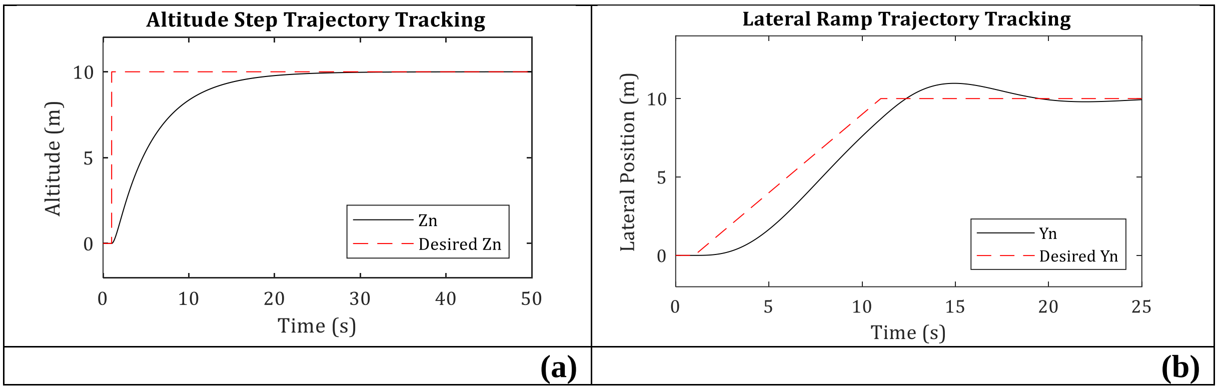


Figure 10: Single direction tracking, (a) Step altitude change, (b) Ramp lateral change

Finally, tracking a rectangular (10m x 10m) trajectory in an x-y plane with one m/s constant velocity was investigated. Figure 11 shows the desired and actual trajectory of the drone. There are some offsets when the route experiences a sudden change, which is normal due to the physics of the system. Nevertheless, the drone follows the new route section quickly, and the general performance is acceptable. The trajectory definition method is an important subject that can help the controller to follow the path more precisely.

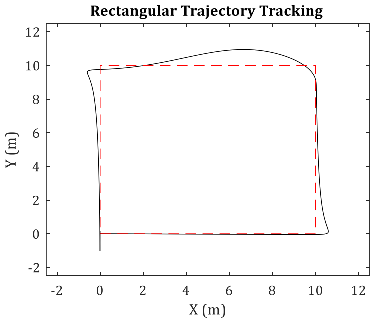


Figure 11: Rectangular trajectory tracking result

The above results are investigated to present the feasibility of the system. The control system can be improved to have a better performance. Additionally, the configuration proposed in this paper will produce different control strategies by applying the main rotor or small rotors or both in special maneuvers, which is planned to be studied in the next research.

Conclusion

This article reviewed recent developments and concepts in the unmanned aerial vehicles field. Based on various configurations, it can be concluded that research for a platform with better performance in different flight regimes is an important topic. By comparing different ideas that have already emerged, we propose a novel concept combining the advantages of single-main rotor helicopter and quadrotor systems. The main points of this novel configuration are briefly discussed in this paper, and a preliminary dynamic model is produced. A simple hierarchical LQR control system is designed and implemented, and the simulation results show its acceptable performance.

Of course, there is still a far way to design and fabricate a drone based on these assumptions. However, the idea seems to overcome some challenges in UAV capabilities and missions. Special attention should be paid to thoroughly defining expectations and missions for this drone, properly sizing the elements, predicting system behaviors through more realistic dynamic modeling, and developing control systems and algorithms. This would result in a novel UAV with superior performance. These topics will be investigated in our subsequent research.

Declaration

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References

[1] C. F. Liew and et.al., "Recent Developments in Aerial Robotics: A Survey and Prototypes Overview," *arXiv preprint arXiv:1711.10085,* 2017.

[2] S. Darvishpoor and et.al., "Configurations, flight mechanisms, and applications of unmanned aerial systems: A review," *Progress in Aerospace Sciences,* 2020.

[3] A. Saeed and et.al., "A Survey of Hybrid Unmanned Aerial Vehicles," *Progress in Aerospace Sciences,* 2018.

[4] Y. Zhou and et.al., "An evaluative review of the VTOL technologies for unmanned and manned aerial vehicles," *Computer Communications,* 2019.

[5] N. T. Hegde and et.al., "Design, dynamic modelling and control of tilt-rotor UAVs: a review," *International Journal of Intelligent Unmanned Systems,* 2019.

[6] V. Kumar and et.al., "A Review on Design Methods of Vertical take-off and landing UAV aircraft," *IOP Conference Series: Materials Science and Engineering,* 2021.

[7] C. Lee and et.al., "A Survey: Flight Mechanism and Mechanical Structure of the UAV," *International Journal of Precision Engineering and Manufacturing,* 2021.

[8] T. Ma and et.al., "Conceptual Design of a VTOL Box-wing UAV with Rotatable Duct-fans," *AIAA Scitech 2019 Forum,* 2019.

[9] M. Warren and et.al., "Design and control evaluation of a novel subscale quad-tiltrotor," *AIAA Scitech 2019 Forum,* 2019.

[10] L. Yu and et.al., "Immersion and invariance-based sliding mode attitude control of tilt tri-rotor uav in helicopter mode," *International Journal of Control, Automation and Systems,* 2019.

[11] C. Zeng and et.al., "A new tilt-arm transitioning unmanned aerial vehicle: Introduction and conceptual design," *Aerospace Science and Technology,* 2020.

[12] E. Tal and S. Karaman, "Global Trajectory-tracking Control for a Tailsitter Flying Wing in Agile Uncoordinated Flight," *AIAA AVIATION 2021 FORUM,* 2021.

[13] W. Zhou and et.al., "Position control of a tail-sitter UAV using successive linearization based model predictive control," *Control Engineering Practice,* 2019.

[14] P. Ryseck, D. Yeo, V. Hrishikeshavan and I. Chopra, "Aerodynamic and mechanical design of a morphing winglet for a quadrotor biplane tail-sitter," *Proceedings of the Vertical Flight Society 8th Autonomous VTOL Symposium,* 2019.

[15] N. Raj and et.al., "Attitude control of novel tail sitter: Swiveling biplane–quadrotor," *Journal of Guidance, Control, and Dynamics,* 2020.

[16] J. Liao and X. Song, "Mathematical modelling and model predictive controller design of a quad tiltrotor UAV," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* 2020.

[17] S. Sridhar and et.al., "Fault tolerance of a reconfigurable tilt-rotor quadcopter using sliding mode control," *Dynamic Systems and Control Conference, American Society of Mechanical Engineers,* 2018.

[18] A. Lara and et.al., "Hardware-in-the-loop simulation environment for testing of tilt-rotor uav's control strategies.," *Congresso Brasileiro de Automática-CBA,* 2019.

[19] T. Costa and et.al., "Modeling and Control of an Unmanned Aerial Vehicle with Tilt Rotors Equipped with a Camera," *19th International Conference on Advanced Robotics,* 2019.

[20] J. Muchowski, M. Szumski and A. Krzysiak, "Aerodynamic concept of the UAV in the gyrodyne configuration," *Transactions on Aerospace Research,* 2019.

[21] C. De Wagter and J. Meulenbeld, "Modeling the unstable DelftaCopter vertical take-off and landing tailsitter unmanned air vehicle in hover and forward flight from flight test data," *International Journal of Micro Air Vehicles,* 2019.

[22] Y. Chen and et.al., "Aerodynamic characteristic analysis and layout optimization design for compound UAVs by using hybrid Fuzzy–PSO algorithm," *Journal of the*

Brazilian Society of Mechanical Sciences and Engineering, 2019.

[23] N. Elmeseiry, N. Alshaer and T. Ismail, "A detailed survey and future directions of unmanned aerial vehicles (uavs) with potential applications," *Aerospace*, vol. 8, no. 12, 2021.

[24] L. N. Santhosh and T. K. Chandrashekar, "Anti-collision pentacopter for NDT applications," in *IEEE International Transportation Electrification Conference (ITEC)*, 2015.

[25] S. Driessens and P. EI Pounds, "Towards a more efficient quadrotor configuration," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2013.

[26] G. Cai and et.al., Unmanned rotorcraft systems, Berlin: Springer Science+Business Media, 2011.

[27] B. Ren, S. Ge, C. Chen and et.al., Modeling, control and coordination of helicopter systems, Berlin: Springer Science+ Business Media, 2012.

[28] M. H. Khalesi, H. Salarieh and H. Saadat Foumani, "Multilevel modeling of an unmanned rotorcraft and robust controller design for trajectory tracking," *Modares Mechanical Engineering*, vol. 17, no. 8, pp. 388-398, 2017.