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Design and analysis of a mode-switching micro unmanned aerial vehicle

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Abstract

In this study, design and analysis of a mode-switching vertical take-off and landing (VTOL) unmanned aerial vehicle (UAV) with level flight capability is considered. The design of the platform includes both multirotor and fixed-wing (FW) conventional airplane structures; therefore named as VTOL–FW. The aircraft is modeled using aerodynamical principles including post-stall conditions. Trim conditions are obtained by solving constrained optimization problems. Linear analysis techniques are utilized for trim conditions in examining stability and controllability. The proposed method for control includes implementation of multirotor and airplane mode controllers and an algorithm to switch between them in achieving transitions between VTOL and FW flight modes. Thus, VTOL–FW UAV's flight characteristics are expected to be improved by enlarging operational flight envelope through enabling mode-switching, agile maneuvers, and increasing survivability. Simulations and flight tests showed that VTOL–FW UAV demonstrates multirotor and airplane flight characteristics with extra benefits.

Keywords

Analysis, control, design, mode switching, unmanned aerial vehicle

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Introduction

Aerial vehicles have proved themselves in military and civil areas of different applications over a hundred years, by enhancing their capabilities over time, and adapting to new mission requirements. Unmanned aerial vehicles (UAVs) offer a unique set of advantages compared to piloted aircrafts with smaller, safer, and lighter platforms. Future UAVs are expected to perform much more extended missions with higher maneuverability and higher degrees of autonomy.

Different capabilities like vertical take-off and landing (VTOL), hover, level flight, switching between hover and level modes, high endurance, long range, and mechanical simplicity are expected from UAV platforms as the mission demands. Comparison of capabilities of different types of UAV platforms (Table 1) provides insight about its mission profile. When VTOL and hovering are required, then rotary-wing aircraft such as helicopters, multirotors, ducted fans, tiltrotors, and tailsitters are most optimal. However, if level flight, endurance or range is of priority, then a fixed-wing (FW) airplane type will most likely be preferred due to its efficiency. When all of these features are desired in one platform, then VTOL–FW platforms become the best option, as an in-between solution. VTOL capability removes the need for runway or launch/recovery equipment and provides flexibility to operate in any theatre, whereas level flight capability allows efficient range and endurance flight. An aerial vehicle designed to possess the strengths of both a rotary and FW aircraft would provide advantages of both types in one platform, with acceptable tradeoffs in some capabilities.

Available studies[1–10] in VTOL–FW UAV platform category include tailsitters, tiltrotors, and tiltwings. Although all of these platforms can perform hover and level flight, the main difference comes from the method of transition method (Table 2) between flight

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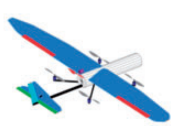
Table 1. Comparison of UAV platform types.

Capability	Multirotor	Helicopter	Airplane	VTOL–FW
VTOL	Good	Good	Bad	Good
Hover	Good	Good	Bad	Good
Level flight	Bad	Bad	Good	Good
Mode switching	Bad	Bad	Bad	Good
Endurance	Bad	Good	Good	Neutral
Range	Bad	Bad	Good	Neutral
Simplicity	Good	Bad	Good	Neutral

Table 2. VTOL–FW UAV platforms' transition methods.

Photograph	Type	Transition method
	Tailsitter	Tilts fuselage by control surfaces through stalling the aircraft.
	Tiltrotor	Tilts fuselage by tilting rotors that stalls wings.
	Tiltwing	Tilts wings that operate in stall region, while the fuselage remains parallel to earth surface.
	VTOL–FW	Switches active control elements between VTOL and FW control surfaces, without stalling the aircraft.

modes. These types of platforms suffer from difficult transition maneuvers that operate the aircraft out of trim conditions and increase susceptibility to disturbances in transitions. However, a hybrid VTOL–FW platform asserted in this study allows smooth transitions, by being operated in an enlarged flight envelope.

Transition maneuvers between hover and level flight is of primary concern for VTOL aircrafts that are capable of level flight. T-wing tailsitter UAV with two counter rotating propellers was one of the pioneering studies; Stone[11] has developed a flight control system including low-level and mid-level guidance controllers, utilizing linear quadratic regulator and classical controllers, which were verified in flight tests.[3] Kubo[12] showed that a tailsitter UAV could achieve transitions between level flight and hover in shorter time using slats and flaps by using an optimal controller. Hogge[13] demonstrated transition maneuvers of a UAV with only one propulsion system using control surfaces. Tumble-stall maneuvers are implemented in achieving transitions by Green and Oh,[6] Anathkrishnan and Shim,[14] and Jung and Shim[15] utilizing dynamic inversion methods. A state machine is designed by Osborne[16] for transitions between the flight modes, where the states are defined as hover, level, hover-to-level, and level-to-hover. Back-stepping control technique is studied by Wang and Lin[4] for a coaxial-rotor tailsitter UAV and successfully simulated hover, level flight, and transitions. Cory and Tedrake[17] and Johnson et al.[18] performed transition maneuver of a FW aircraft from level flight to hover by tilting the fuselage of the aircraft through utilizing large control surfaces. Although available studies in this field are successfully implemented on different platform types, an aircraft that has physically separated multirotor and airplane control surfaces is not examined in demonstrating transition maneuvers.

In this study, design, analysis, and implementation of control system of a VTOL aircraft with level flight capability is considered. The design of the platform includes both multirotor and FW conventional airplane structures; therefore named as VTOL–FW. The proposed control method includes implementation of multirotor and airplane controllers and design of an algorithm to switch between them in achieving transitions between VTOL and FW flight modes. Thus, VTOL–FW UAV's flight characteristics are expected to be improved by enabling agile maneuvers, increasing survivability, providing redundancy, and exploiting enlarged flight envelope capabilities.

VTOL–FW UAV platform

VTOL–FW UAV platform is constructed by four-propeller multirotor modification applied to a model airplane (Figure 1). Then, the platform is converted into an UAV by adding an autonomous flight controller (Pixhawk) and sensors like GPS, magnetometers, accelerometers, gyros, and pitot-static system as defined by Çakıcı et al.[19] The physical properties of the prototype aircraft are given in Table 3.

Main components of the aircraft (Figure 2) contribute to forces and moments acting on the vehicle in flight. Fuselage experiences drag in negative direction of airflow, caused by linear motion. FW propulsion system (Prop.0) provides thrust to balance drag, while main wing provides lift to overcome gravitational force and ailerons, rudder and elevator provide roll, pitch, and yaw motions as in a conventional airplane. VTOL propulsion systems (Prop.1-4) provide lift, roll,

Figure 1. VTOL–FW UAV platform.

Table 3. Physical properties of VTOL–FW UAV.

Property	Unit	Value
Wing span	m	2.05
Mass	kg	1.52
Inertia Tensor	kg·m^2	$\begin{bmatrix} 0.14 & 0 & 0 \\ 0 & 0.04 & 0 \\ 0 & 0 & 0.17 \end{bmatrix}$

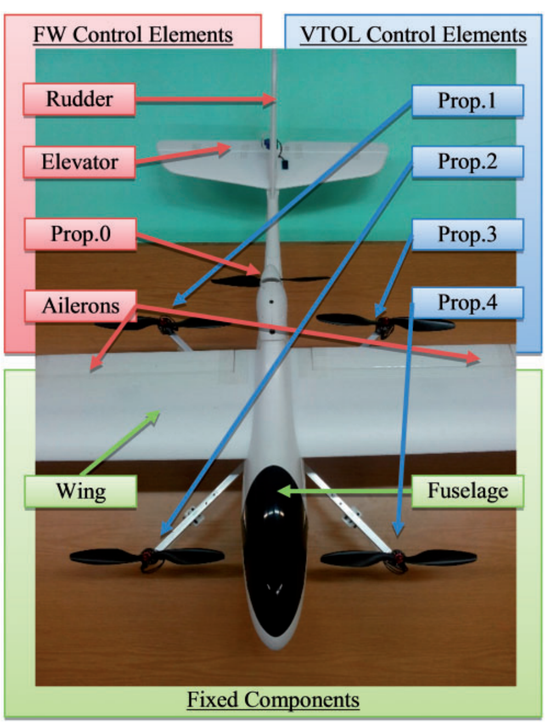


Figure 2. Control elements of VTOL–FW UAV.

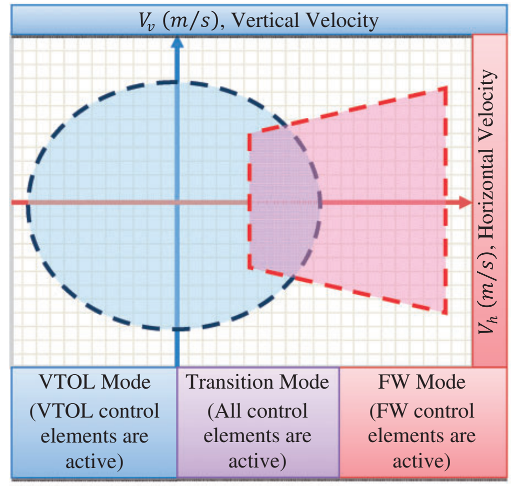


Figure 3. Flight envelope of VTOL–FW UAV platform.

pitch, and yaw motions by changing the rotational speeds of the propellers, as in a multirotor.

Flight mode of VTOL–FW UAV is determined according to vertical and horizontal velocities of the aircraft in an enlarged flight envelope (Figure 3), which covers both VTOL and FW regions. When both of the vertical and horizontal velocities are small in magnitude, the aircraft operates in VTOL mode with VTOL control elements activated. As horizontal velocity is increased the aircraft enters the FW mode by enabling FW control elements. Intersectional region is used for switching between VTOL and FW modes, by changing active control elements. Activation of control elements are handled by a control mixer, that distributes controller commands to control elements.

Mathematical modeling

The complexity of dynamics of aerial vehicles makes obtaining accurate mathematical models for a large portion of flight envelope a difficult problem. VTOL–FW UAV platform is modelled by using the real physical specifications of the aircraft in a MATLAB graphical user interface (Figure 4) environment, that is specifically developed for the preliminary design, analysis, control system design, mission planning, and flight simulations of aircrafts. Initially, every main component like fuselage, wings, control surfaces, and propellers are modelled using aerodynamical principles (blade element theory and momentum theory for propellers) stated by McRuer et al.,[20] Leishman,[21] and Allerton,[22] for the whole flight envelope including post-stall conditions.[23] Then, these models' outputs are combined considering aircraft's geometry in calculating total forces $\left({}^{B}F\right)$ and moments $\left({}^{B}M\right)$. Equations of motion, defined by Craig,[24] are formed as a set of nonlinear equations (1), using Newton's second law of

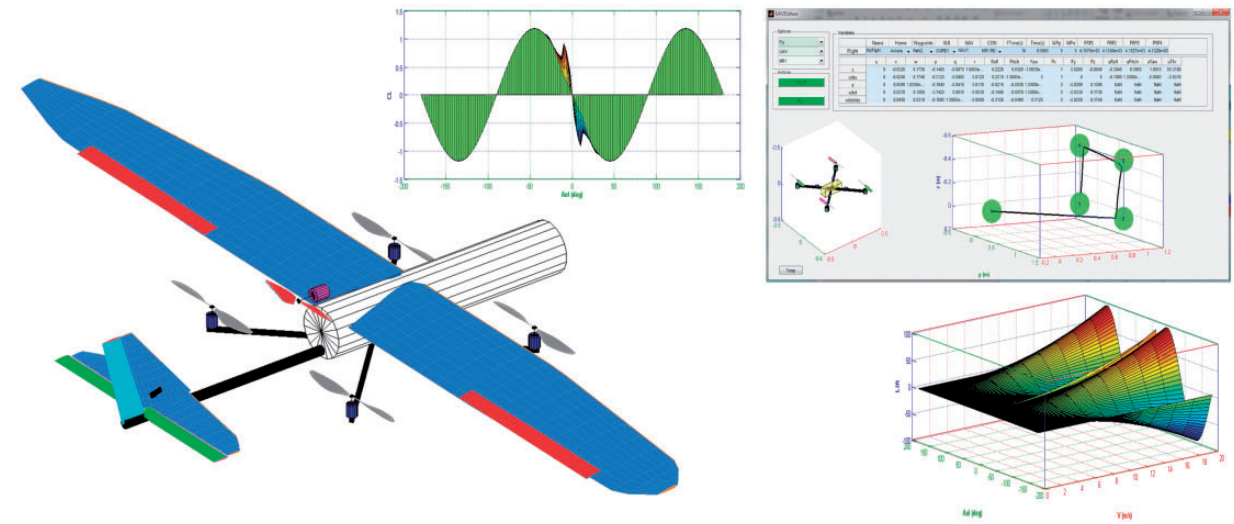


Figure 4. Model of VTOL–FW UAV.

forces, Euler's formula for moments, and kinematic relationships defined in body frame.[25]

$$\dot{x} = f(x, u, t) = f\left({}^{B}F(x, u), {}^{B}M(x, u), t\right) \quad (1)$$

Total forces and moments acting on the aircraft are obtained by summing forces and moments of the components according to center of gravity as in equations (2) and (3).

$$\begin{aligned} {}^{B}F = {}^{B}R_{FU} \cdot {}^{FU}F + {}^{B}R_{WI_i} \cdot {}^{WI_i}F + {}^{B}R_{CS_j} \cdot {}^{CS_j}F \\ + {}^{B}R_{PR_k} \cdot {}^{PR_k}F \end{aligned} \quad (2)$$

$$\begin{aligned} {}^{B}M = {}^{B}P_{FU} \times {}^{B}R_{FU} \cdot {}^{FU}F + {}^{B}R_{FU} \cdot {}^{FU}M \\ + {}^{B}P_{WI_i} \times {}^{B}R_{WI_i} \cdot {}^{WI_i}F + {}^{B}R_{WI_i} \cdot {}^{WI_i}M \\ + {}^{B}P_{CS_j} \times {}^{B}R_{CS_j} \cdot {}^{CS_j}F + {}^{B}R_{CS_j} \cdot {}^{CS_j}M \\ + {}^{B}P_{PR_k} \times {}^{B}R_{PR_k} \cdot {}^{PR_k}F + {}^{B}R_{PR_k} \cdot {}^{PR_k}M \end{aligned} \quad (3)$$

Linear analysis

The mechanics of aircraft flight analysis can be described in terms of three aspects—trim, linearization, and stability. These three make up the flying characteristics of the aircraft. Linear analysis of VTOL–FW UAV is performed by examining stability and controllability of the linearized system dynamics for trim states.

Trim conditions

A trim state is defined as the equilibrium point, where the rates of the aerodynamic state variables are zero, when the resultant forces and moments are in balance. The trimming problem concerns the determination of control commands $[u_{rol},\ u_{pit},\ u_{yaw},\ u_{thr}]$, which maps to control variables $[\theta_{ail},\ \theta_{ele},\ \theta_{rud},\ \Omega_0,\ \Omega_1, \Omega_2, \Omega_3, \Omega_4]$, and aerodynamical variables $[u,\ v,\ w,\ p,\ q,\ r,\ \phi,\ \theta]$ that are required to hold the aircraft in equilibrium for a set of prescribed variables $[\dot{\psi},\ \dot{x}_e,\ \dot{y}_e,\ \dot{z}_e]$. The trim conditions are obtained by solving a constrained optimization problem, defined by Nocedal[26] as the following:

$$\begin{aligned} &\text{Minimize} \|\ \dot{x}_a\ \| \text{ for } x_p,\ u \\ &\text{subject to } \dot{x}_a = f(x_a,\ x_p,\ u), \text{given } \dot{x}_p \end{aligned} \quad (4)$$

where $x_a = [u,\ v,\ w,\ p,\ q,\ r,\ \phi,\ \theta]$, $x_p = [\psi,\ x_e,\ y_e,\ z_e]$, and $u = [u_{rol},\ u_{pit},\ u_{yaw},\ u_{thr}]$.

Inspection of all prescribed operation points reveals that the trim conditions could not be established for all of the points of interest, which reveals the limits of the flight envelope for each flight mode (Figure 5). An important observation is that the trim conditions of VTOL and FW flight modes intersect at level velocities between 12 and 16 m/s. This intersection region is used for transition maneuvers between modes.

Pitch angle (θ) of the aircraft plays significant role in aircraft dynamics, by determining angle of incidence of the wings with the airflow. Operating in VTOL mode, the aircraft pitches down to gain forward velocity. This motion is typical to multirotors reaching larger magnitudes of pitch angles as the aircraft's level velocity increases. Having wings provides lift and extra moment, resulting in smaller pitch angles compared to a multirotor. When the aircraft is operated in FW mode, pitch angle reduces slowly so that the lift provided by the wings is sufficient for countering

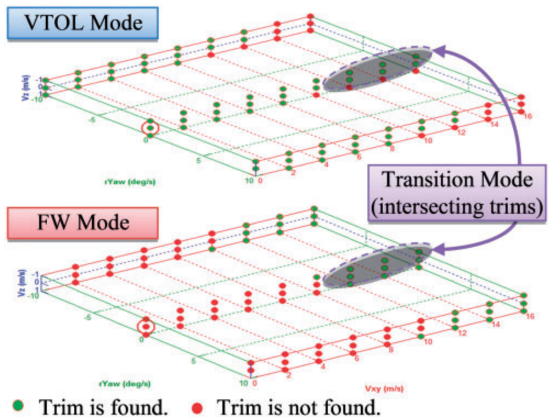


Figure 5. Trim conditions of VTOL–FW UAV.

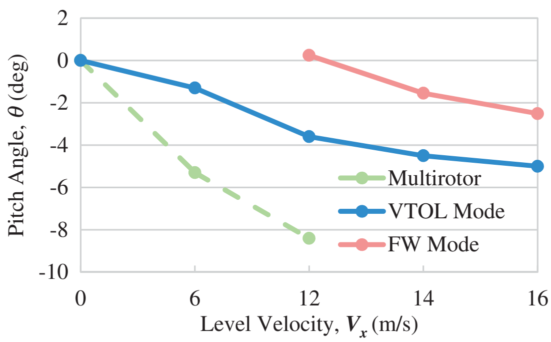


Figure 6. Pitch angle changes of VTOL and FW modes.

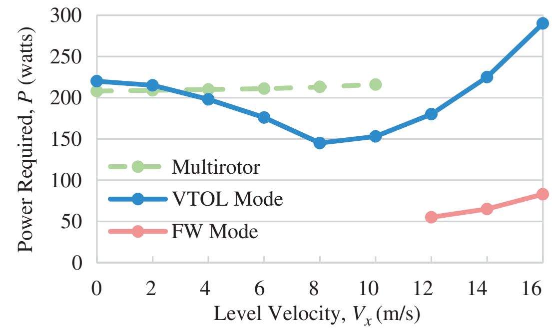


Figure 7. Power requirements of VTOL and FW modes.

gravitational force. Small differences of pitch angles for level velocities between 12 and 16 m/s of both modes (Figure 6) imply that the mode transition can be performed by a small change in pitch angles.

Analysis of power requirements for an aircraft is important for achieving efficient flight. Assuming power dissipated on control surface servos is negligible and having lossless motors, electronic speed controllers, the major power consuming elements can be considered as propellers. Calculations of power required to fly (Figure 7) show that VTOL–FW UAV power consumption is similar to a comparable multirotor for hover. As level velocity is increased, multirotor power consumption increases due to the drag of the fuselage. As for VTOL–FW UAV in VTOL mode, power requirement decreases when wings start to provide lift. The required power starts to increase after a point since more lift indicates more moment provided by aerodynamical surfaces, where VTOL propellers consume more power in balancing moment. The steep increase in the power in VTOL mode, as the velocity is increased, is one of the major reasons of the need for transition to the FW mode.

Another observation regarding trim conditions is the position of center of gravity (cg) of the aircraft. VTOL mode requires cg at the geometrical center of propellers, so that rotational speeds of the propellers are close to each other allowing large control authority. On the other hand, FW mode requires cg to be placed close to the nose of the aircraft for stability and adequate control authority. Thus, the position of cg determines the available control authority as a tradeoff in both modes.

Linearization

The equations of motion are nonlinear in nature. Thus, in order to utilize linear system analysis, linearization around trim points is required. For linearization, aerodynamical state variables $[u, v, w, p, q, r, \phi, \theta]$ are of primary concern that describe the dynamics of the system. Linearized system dynamics[25] are obtained in state-space form (5), for the trim points using small perturbation theory and Taylor's series expansion of equations of motion (1):

$$\dot{x} = Ax + Bu \tag{5}$$

where $x = [u, v, w, p, q, r, \phi, \theta]$, $u = \left[u_{rol}, u_{pit}, u_{yaw}, u_{thr}\right]$, A : 8 x 8 matrix and B : 8 x 4 matrix.

Linearized dynamical models are constructed for all of the trim conditions, for stability and controllability analysis.

Stability

Following a general approach,[27] stability of linearized models of VTOL–FW UAV are examined in terms of stability in the sense of Lyapunov (all of the eigenvalues of A matrix have non-positive real parts and those with zero real parts are distinct roots of the minimal polynomial of A.) and asymptotic stability (all of the eigenvalues of A matrix have negative real parts.). Stability analysis (Figure 8) shows that the aircraft is unstable in both modes. When a measure of stability is defined as

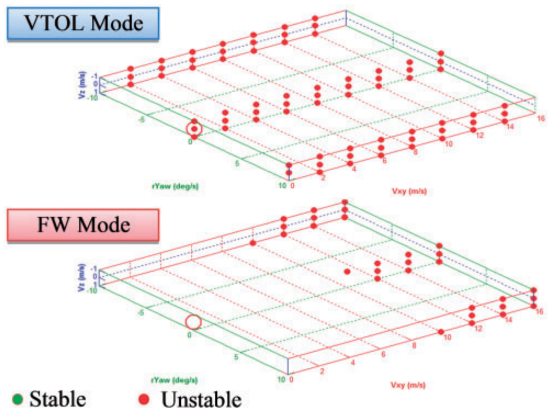


Figure 8. Stability of VTOL and FW modes.

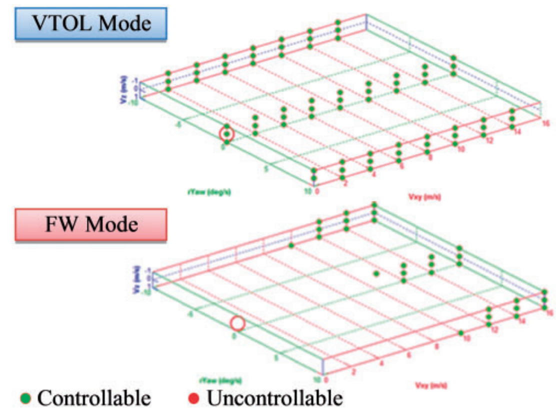


Figure 9. Controllability of VTOL and FW modes.

the distance of the largest unstable pole in the right-hand s-plane to marginal stability line, the aircraft becomes more unstable in VTOL mode and less unstable in FW mode, as the horizontal velocity is increased. Analysis of the aircraft's dynamic modes proves that the aircraft demonstrates similar characteristics to an airplane in FW mode and to a multirotor in VTOL mode. Eventually, stability analysis shows that VTOL–FW UAV demonstrates conventional aircraft characteristics in FW mode, and common multirotor characteristics in VTOL mode.

Controllability

A dynamical system is controllable if a control input trajectory for a limited time can be found that takes the system from an arbitrary initial state to an arbitrary final state. For linear systems, controllability requires that the controllability matrix has full rank.[27] Controllability analysis (Figure 9), performed by examining the rank of the controllability matrix, shows that the linearized systems of all of the trim points are controllable.

Control system

A closed loop-control system is expected to stabilize the system, reject disturbances, reduce sensitivity to parameter variations, track reference, provide robustness to uncertainties, and be implementable for real world applications. A control system architecture (Figure 10) is proposed that controls the aircraft in different flight modes. The inputs of the control system are obtained from guidance, and the outputs are defined as $[u_{rol},\ u_{pit},\ u_{yaw},\ u_{thr}]$ which tell the aircraft to roll, pitch, yaw or change throttle, regardless of the active operation mode, which are then transformed into control element's commands through a control mixer.

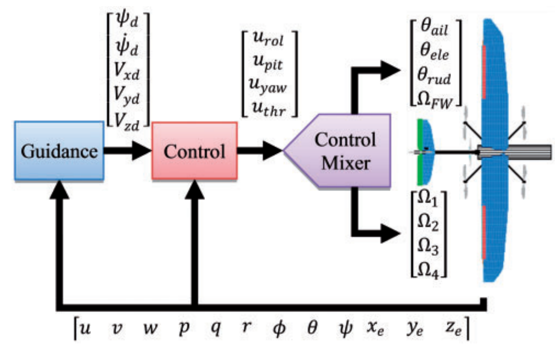


Figure 10. Control system architecture of VTOL–FW.

Although different control techniques could be used in designing a controller for VTOL–FW UAV, proportional-integral-derivative (PID) controller design technique is utilized, for its ease of applicability on the real world problems. Also, PID controller relies on measurements, which are made available through sensors, and does not rely on the underlying process which often contains unknowns, uncertainties, and disturbances. Major drawback of this method is that it does not guarantee optimal control or closed-loop system stability, requiring tuning for satisfactory performance.

Since VTOL–FW UAV is a multi-input multi-output dynamical system, single-input single-output PID controllers are designed with sequential loop closure technique having three major loops:

- Inner loop is the fastest loop and responsible for the fastest dynamics of the aircraft which tell the aircraft to roll, to pitch, to yaw or to change throttle through acceleration commands in body frame,
- Medium loop is responsible for controlling the orientation of the aircraft in vehicle carried frame, where the inputs are the desired attitudes that depend on the mode of operation and the outputs

are the desired angular rates, which are transformed into body frame, as inputs for the inner loop.

- Outer loop, being the slowest loop, takes its inputs from guidance as desired velocities in the Earth frame and calculates desired accelerations in vehicle carried frame, which are then converted into desired angles and throttle commands according to mode of operation. A mode selector is defined in order to determine the mode of operation according to current state of the aircraft in the whole flight envelope (Figure 3). If the aircraft is operating in VTOL region then the desired commands are determined by equations (6), (7), and (8), and by equations (9), (10), and (11) when it is operating in the FW region:

$$\phi_d = \phi_{\text{trim}} + a\tan(a_{td},\ g) \tag{6}$$

$$\theta_d = \theta_{\text{trim}} - a\tan(a_{hd},\ g) \tag{7}$$

$$u_{thr} = -a_{vd} \tag{8}$$

$$\phi_d = \phi_{\text{trim}} + a\tan(a_{td},\ g) \tag{9}$$

$$\theta_d = \theta_{\text{trim}} - a\tan(a_{vd},\ g) \tag{10}$$

$$u_{\text{thr}} = a_{\text{hd}} \tag{11}$$

Tuning a PID control loop is the adjustment of its control parameters $[k_p,\ k_i,\ k_d]$, to the optimum values for the desired controlled response. The performance of the closed-loop system depends on the transient as well as the steady-state behavior and is usually specified in terms of the rise time, settling time, percent overshoot, and steady state error. When tuning a controller, a step change in the desired variable is applied to the closed-loop system and the performance is evaluated by the integral of time accumulated error of the response. In order to account for all of the performance criteria, an optimization problem is defined (12) in tuning PID controller parameters as:

$$\begin{aligned} &\text{Minimize } \int_{t_0}^{t_f} t\,\left|e_i(t)\right|\mathrm{d}t \text{ for } k_p,\ k_i,\ k_d \\ &\text{subject to } \dot{x} = f(\mathrm{x}, \mathrm{u}, \mathrm{t}) \end{aligned} \tag{12}$$

where $e_{\mathrm{i}} = x_{\mathrm{id}} - x_{\mathrm{i}}$, $x_{\mathrm{id}} = x_{i,\text{trim}} + h(t)$, $h(t) = \begin{cases} 1, & t \geq t_0, \\ 0, & t < t_0, \end{cases}$, and i is the index of state variable.

VTOL–FW UAV has three basic modes of flight. The first one being the VTOL mode is essential for vertical take-off and landing. When the aircraft's total velocity is small, then it is operated in VTOL mode. When the aircraft's velocity is high enough, FW mode is turned on for achieving efficient level flight. Also, the controller has an AUTO mode, where the mode selector decides on the mode of operation by monitoring state variables.

Flights

Flight tests are performed in real-world and simulation environments, in order to verify VTOL–FW UAV's flight characteristics. A flight course of desired waypoints (Figure 11), forming a rectangle, is planned flight testing. Initiating flight from waypoint 1, the aircraft took off vertically in VTOL mode and started ascending towards waypoint 2. After reaching waypoint 2, level velocity is increased in order to reach waypoint 3. As the velocity is increased further, the autopilot changed the mode to FW for level flight. When the aircraft approaches to waypoint 3, the autopilot changed the mode to VTOL again and the final waypoint is reached by vertical landing.

Analysis of flight test (Figure 12) shows that the aircraft performs VTOL mode as a multirotor, FW mode as a plane and mode-switching successfully. Having a

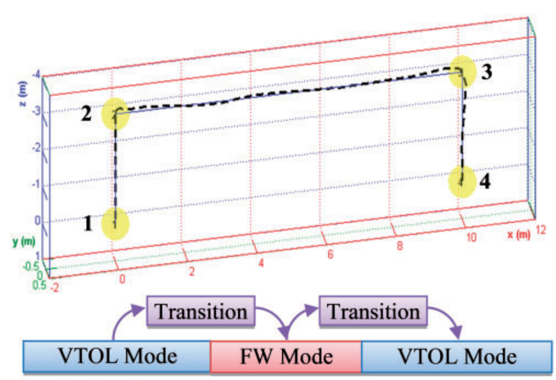


Figure 11. Flight test of VTOL–FW.

Figure 12. VTOL–FW UAV in flight.

total electrical current drawn from the battery around 40 A in VTOL mode, the power consumption is decreased as the aircraft gained level velocity, which allowed the main wings to provide lift. The current is measured around 15 A when the aircraft is operated in FW mode, which reveals advantage of efficient level flight.

Conclusion

In this study, design and analysis of a UAV with VTOL, hover, level flight and mode switching capabilities, VTOL–FW, is considered. Incorporating multirotor and airplane structures in the same platform, the aircraft demonstrated distinct flight characteristics of a multirotor and a FW airplane according to flight mode of operation both in simulations and in real flights. The aircraft is modeled using aerodynamical principles for analysis, simulation, and controller design phases. Different PID controllers tuned for VTOL and FW modes performed well in flying the aircraft like a multirotor and an airplane. Transitions between these modes are achieved through mode switching by applying smoothed control commands to control elements of different modes of flight.

One of the major problems in designing an air vehicle with VTOL and level flight capabilities is the determination of center of gravity. An airplane requires center of gravity in front of the aerodynamical center, and a multirotor requires center of gravity close to aerodynamical center. Thus, this problem becomes a trade-off between better hover and better level flight.

The aircraft's fuselage remains mostly parallel to the Earth's surface with small pitch angles, in a large portion of its flight envelope. This allows both VTOL and FW mode flight envelopes intersect with each other, which makes the transition between these modes easier by having close trim state conditions. Also, the enlargement of flight envelope provides redundancy, increases survivability, and allows various mission profiles.

Power consumption of VTOL–FW UAV in different modes reveals the necessity of switching modes for achieving overall efficient flight. When operated in VTOL mode, the power requirement is close to a comparable multirotor, and as the linear velocity is increased it requires less power due to its wings, which provides a significant benefit. As the linear velocity is increased more, required power starts to increase for balancing the moment provided by the aerodynamical surfaces. This condition indicates the necessity of switching to FW mode, which requires much less power.

Simulation and real-world flight experiments proved the applicability of the proposed platform. VTOL–FW UAV is expected to find usage areas in missions requiring VTOL, hover, and efficient level flight capabilities without the need for a runway and launch-recovery equipment.

Declaration of conflicting interests

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Appendix

Nomenclature

a	acceleration, m/s^2
B	body
CS_j	jth control surface (1: ailerons, 2: elevator, 3: rudder)
e	error
$f(\,)$	function of equations of motion
^aF	force vector in a-frame, N
FU	fuselage
g	gravitational acceleration, m/s^2
^aM	moment vector in a-frame, Nm
^aP_b	position vector of b in a-frame
PR_k	kth propeller (0: FW propeller, 1-4: VTOL propellers)
^aR_b	rotation matrix from b-frame to a-frame
t	time, s
u	control commands
WI_i	ith wing (1: main wing, 2: horizontal tail, 3: vertical tail)
x	state variables vector
θ	pitch angle, degrees
ϕ	roll angle, degrees
ψ	yaw angle, degrees

Subscripts

d	desired
h	horizontal
t	tangential
v	vertical