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Vertical Take-off Unmanned Aerial Vehicle with Forward Flight Transition

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Abstract: *This paper presents the findings from a capstone project that was to design a drone capable of functioning as vertical take-off Unmanned Aerial Vehicle (UAV) with a conversion to horizontal flight. It could serve as stable controlled flight using a simulator based iterative design process. The vehicle was intended to work in an environment where tedious or boring jobs could be automated. The vehicle design concepts were created through research, benchmarking, design metrics, and virtual flight testing. Both the simulation model and demonstration vehicle adhered to the aim and goals of the project. This project demonstrates the acceleration in design timelines that can be achieved, even by an undergraduate engineering student, who becomes skilled in using an advanced knowledge-based simulation tool.*

Keywords: *Aerospace, Unmanned Aerial Vehicle (UAV), Vertical Take-off and Landing (VTOL), Simulation*

1. Introduction

Consider the case of pilots performing repetitive and simplistic tasks such as coastal and maritime surveillance, aerial law enforcement activities, and aerial cinematography. These tasks are often tedious and time consuming, and these pilots could be transferred to more engaging and rewarding roles, and they can be replaced with cost efficient autonomous vehicles. Commonly these take the form of “drones” or quadcopters (D'Andrea, 2014). However, there are no commercially available vehicles on the market at the time of writing which can satisfy the criteria of high speed, long range conventional flight, and vertical take-off, both of which are needed in a variety of aerial activities (Ozdemir, et al., 2014).

When one thinks of civilian drones, typically one thinks of a quadcopter. Quadcopters, also called a quad rotor helicopters, use two pairs of identical fixed pitched propellers, and use independent variation of the speed of each rotor to achieve control. Quadcopters are cheaper and more durable than conventional helicopters due to their mechanical simplicity. However, quadcopter designs possess too limited a range, and too slow a speed. For maritime operations, it may be essential for a vehicle to be able to take off from a small coastal base and subsequently travel long distances of coastline, or to be able to operate entirely from an ocean-going vessel (Stone & Clarke, 2001).

A commercially available, unmanned vehicle which is capable of high speed, long range flight as well as vertical take-off would be able to satisfy a wide range of needs and capabilities. This paper presentsc an optimal overall design, and explores the capability of knowledge-based tools to form an iterative, software based design process.

2. Background

The type of vehicles of interest for this research was those capable of Vertical Take-off and Landing (VTOL) operations and transitioning to a more efficient conventional flight mode (Sinha, et al., 2012). VTOL is a type of aircraft which can hover, take off, and land, vertically. Both fixed wing aircraft and rotary wing aircraft (such as helicopters) can be classified as VTOL’s. During the development of the XV-15, an experimental tiltrotor designed by NASA (2015) and built by Bell Helicopters, both NASA and the US Army Aeronautical Research Laboratory (AARL) developed an in-depth chart of possible VTOL configurations (see Figure 1).

The traditional way of determining vertical flight and hovering efficiency is to consider the power loading of the vehicle. This is a simple ratio between the weight of the vehicle and the power of installed engines. A more efficient vehicle requires less powerful engine to hover at a given weight. Another method of measuring hover efficiency is disc loading, i.e., (Weight of vehicle) / (Area of thrust producing structure). The thrust producing structure may be rotor area, propeller area, or jet exhaust area. A VTOL aircraft with high power loading and low disc loading is the most efficient at hovering (Markman and Holder, 2000; Warwick, 1992).

Helicopters and Gyrodynes are both rotary winged vehicles, so from a power loading and disc loading analysis perspective, they are very similar in performance. Tiltrotor, tiltwing, and gyrodyne vehicles utilise either propellers or rotors (Groenaeronautics, 2014). However, ducted fans are a potential third power plant alternative. A ducted fan is a propulsion device in which a propeller is mounted within a cylindrical shroud or duct, and they may have several advantages over standard propellers (Bensen, 2003). These are:

- Ducted fans are more efficient than a conventional propeller.
- The duct can be designed to take advantage of the Bernoulli effect to give greater high speed efficiency.
- For the same static thrust or lifting capability, a ducted fan has a smaller diameter than a standard propeller.

Figure 1. Overview of VTOL Vehicle Concept Designs
Source: Abstracted from Maisel, Giulianetti and Dugan (2000)

Vehicle categories can be analysed in terms of their hovering efficiencies. Tiltrotor and tiltwing vehicles have the highest hovering efficiencies amongst fixed-wing vehicles, with lift fan and direct lift propulsion vehicles falling behind (see Figure 2).

2. Methodology: Concepts Development and Selection

2.1 Concepts Development

The main objectives for the design of this UAV were that it be easy to control and stable through all flight phases, and that it meets the requirements of surveillance described in the Introduction.

A simple morphological table was created (see Table 1). Six aircraft design concepts were generated below.

Concept 1: Quad Tiltrotor - This aircraft design used four swivelling engines mounted on the wingtips in a quad tiltrotor configuration. The vehicle would theoretically have greater hovering performance but sacrifice horizontal flight performance.

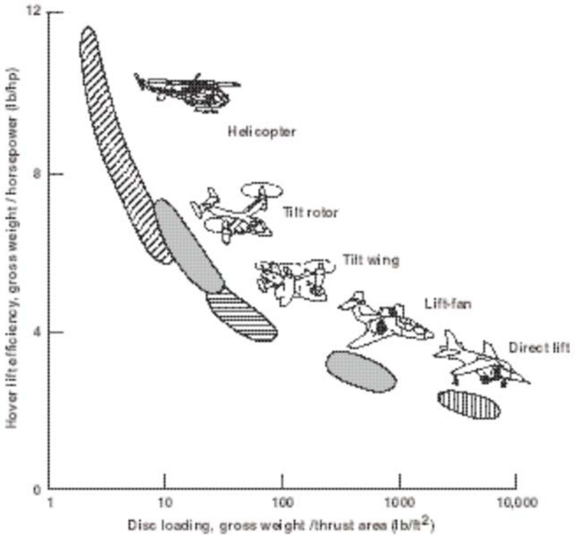


Figure 2. Comparison of Configuration Hover Efficiency

Concept 2: Dual Tiltrotor - This concept used two engines mounted on the wingtips in a dual tiltrotor configuration. To improve stability along the lateral axis, it featured a small pitch rotor mounted in the empennage. Compared to concept one this vehicle would have greater horizontal flight efficiency but have slightly lower vertical flight stability.

Concept 3: Quad Tiltwing - This design featured four engines in a tiltwing configuration. Tiltwing vehicles have superior horizontal flight efficiency compared to tiltrotors, but have slightly lower vertical flight capability. Winglets have been added to improve cruise efficiency. *Concept 4: Dual Tiltwing* - This concept vehicle uses two engines in a dual tiltwing configuration. The design had the highest theoretical horizontal flight efficiency, but the lowest vertical flight stability.

Concept 5: Quad Ducted Fan - This concept used four engines in a tiltrotor configuration. Ducted fans are more efficient than open propellers, and can lead to lower noise and higher efficiency.

Concept 6: Gydroyne - The design is a rotary wing vehicle. It would have the greatest hovering capability, and possess respectable horizontal capability.

2.2. Concept Selection and Pairwise Comparison

First, a list of required metrics was produced for concept comparison. These included: Mechanical Complexity, Software Complexity, Flight Stability, Hover Efficiency (Disc Loading), Hover Stability, Cruise Efficiency, Cruise Speed, Wing Area (Wing Loading), Durability, Reliability, Range, Portability, Agility, Ease of Maintenance, and Ease of Use. The metrics were then weighted per their relative importance using a pairwise comparison.

The six concepts were subsequently compared using a concept comparison table (see Table 2). The concept

Table 1. Morphological Table

Solutions	VTOL Type	Thrust producer	Number of Thrust Points	Tail Thruster	Structural Support Material
↓	Tiltrotor	Propeller	Four	Yes	Wood
	Tiltwing	Ducted Fan	Two	No	Carbon Fibre
	Gyrodyne	Rotor	One	-	Aluminium

Table 2. Concept Comparison Table

	Concept 1		Concept 2		Concept 3		Concept 4		Concept 5		Concept 6	
Metrics	Values	%	Values	%	Values	%	Values	%	Values	%	Values	%
Mechanical Complexity	2	0.01	1	0.00	3	0.01	2	0.01	2	0.01	1	0.00
Software Complexity	3	0.12	2	0.08	3	0.12	2	0.08	2	0.08	2	0.08
Cruise Speed	3	0.21	2	0.14	3	0.21	3	0.21	3	0.21	2	0.14
Range	1	0.09	2	0.18	2	0.18	3	0.26	2	0.18	2	0.18
Portability	2	0.03	2	0.03	2	0.03	2	0.03	2	0.03	3	0.04
Ease of Maintenance	3	0.15	3	0.15	3	0.15	3	0.15	3	0.15	3	0.15
Agility	3	0.24	3	0.24	3	0.24	3	0.24	3	0.24	3	0.24
Safety	2	0.23	3	0.35	2	0.23	3	0.35	3	0.35	2	0.23
Reliability	3	0.18	3	0.18	3	0.18	3	0.18	3	0.18	3	0.18
Wing Area (Wing loading)	3	0.12	2	0.08	3	0.12	2	0.08	2	0.08	3	0.12
Hover Efficiency (disc loading)	3	0.24	2	0.16	3	0.24	2	0.16	1	0.08	3	0.24
Hover stability	3	0.32	3	0.32	2	0.21	2	0.21	3	0.32	3	0.32
Cruise Efficiency	1	0.06	2	0.12	3	0.18	3	0.18	2	0.12	3	0.18
Durability	3	0.18	3	0.18	3	0.18	3	0.18	3	0.18	3	0.18
Ease of Use	3	0.40	3	0.40	3	0.40	3	0.40	3	0.40	3	0.40
Total:	38	2.57	36	2.60	41	2.68	39	2.71	37	2.59	39	2.68

with the highest final value of 2.71 was Concept 4, the single tiltwing. The concepts tied for 2nd and 3rd place were Concept 3 the double tiltwing, and Concept 6 the Gyrodyne. Due to the closeness of the highest scores (2.71 and 2.68), as well as the highly theoretical nature of the metrics and pairwise comparison, the three losing designs were eliminated from the selection process, and the top three concepts advanced to the next phase of concept selection.

2.3. Concept Flight Testing Comparison

Preliminary 3D models of the three concepts that performed best in initial Concept Selection were built and simulated in the Laminar Research X-Plane 10 simulation package. X-Plane uses Blade Element Theory to calculate flight dynamics, breaking the geometric shape of the aircraft down into several small components, running calculations on each section several times per second. As such, X-Plane is highly suitable for design work.

The X-Plane models were scaled so they would be capable of performing the tasks outlined in the Introduction, though the data from the planform can be scaled up or down in the software to simulate vehicles of different scales as long as Reynold's numbers, Froude numbers, and Mach numbers (in the case of compressible flow) are maintained. Tests do not completely cover all ranges of detail and similarity that full scale testing might accomplish. For example, a scale rigid model operating in a wind tunnel at full flight Mach numbers tested through a range of angles of attack will not totally portray the performance of the real full-size vehicle as this test model would not take inaccuracies such as elastic deformation into consideration. (Wolowicz and Bowman, 1979). If the scale model and full-scale model have sufficient similarity, accurate flight dynamics can be determined for one using the other.

The flight characteristics of the concepts were compared in the following phases of flight:

1) Stability and controllability during a hover
2) Ease of transition from vertical to horizontal flight
3) Stability and controllability during forward flight
4) Ease of transition from horizontal to vertical flight

The vehicles were tested in ideal atmospheric conditions. This was to obtain the raw characteristics of the vehicle without any atmospheric interference. Wind speed, precipitation, turbulence, and any other disruptive atmospheric effects were all disabled for this testing. The following parameters were consistent throughout all testing phases:

Table 3. Standard Testing Conditions

Ambient Temperature	Atmospheric Pressure	Starting Altitude	Hovering Altitude	Transitioning Altitude
31.99ºC	1.01bar (1 atm)	2.71m ASL	7-8.5m AGL	16-20m AGL

Wing and propulsion test parameters for each Concept are shown in Tables 4 and 5, respectively. Parameters were obtained through benchmarking and component data research. In some cases, engineering judgement was used to select suitable values.

Table 4. Wing Parameters Used

Parameter	Concept 3	Concept 4	Concept 6
Wing Semi length	1.29m (fore) 1.71m (aft)	1.71m (wings) 0.97m (V-Tail)	0.71m (stub wings)
RootChord	0.57m	0.57m (wings) 0.74m (V-Tail)	0.57m (stub wings)
Tip Chord	0.38m	0.38m (wings) 0.35m (V-Tail)	0.38m (stub wings)
Sweep	-9.0º (fore) 7.0º (aft)	7.0º (wings) 25º (V-Tail)	0º
Dihedral	0º	0º (wings) 45º (V-Tail)	0º
Long. Arm	0.92m (fore) 2.85m (aft)	1.80m (wings) 3.67m (V-Tail)	1.81m (stub wings)
Control Surface Deflection	20º		20º (vertical tail)
Control Surface Chord Ratio	0.3		0.3 (vertical tail)

Table 5. Performance Parameters Used

Parameter	Concept 3	Concept 4	Concept 6
Engine Power (each engine)	7.46KW (10hp)		
Engine RPM (Top of Green Arc)	1180rpm		510rpm
Engine RPM (Redline)	1950rpm		550rpm
Prop Mass Ratio to Solid Aluminium	0.3		
Prop Radius	0.5m	0.5m (engines) 0.21m (pitch rotor)	2.35m (rotor) 0.41m (other)
Prop Chord (Root/Tip)	0.11m/0.06m		0.21m/0.21m (rotor) 0.11m/0.06m (other)
Engine/Prop Gear Ratio	1.00	1.00 (engines) 0.25 (pitch rotor)	1.00 (rotor) 0.27 (other)

Each Concept UAV was tested thoroughly in hover (vertical) flight, horizontal flight and in transition between vertical and horizontal flight. For each of these phases, a detailed description of vehicle performance was recorded, and a score from 0 to 10 was assigned (with 10 being the best performance). Each UAV was tested three times in all phases and were re-analysed and re-scored each time. Analysis was repeated to ensure that the scores assigned were accurate and reasonable due to the subjective nature of this testing. The results of this testing are shown in Tables 6 and 7.

Despite having the highest score after pairwise comparison, Concept 4 has the weakest flight performance. Concept 3 emerged from the flight testing with the highest score and was selected for further development and analysis.

Table 6. Results of Subjective Flight Testing

	Hover Stability	Hover Controllability	Transition Stability	SLS	Average Score
Concept 3	9	8	8	9	8.5
Concept 4	6	6	5	10	6.75
Concept 6	5	9	9	7	7.5

SLS = Straight and Level Stability

3. Detailed Design

The strongest performer in the flight test, Concept 3, consists of four wings and engines in a tiltwing configuration. Winglets improve cruise efficiency. Transition from vertical flight to horizontal flight mode involves rotation of the entire wing with the engines mounted on them.

The design was refined with a variety of minor design improvements using the X-Plane simulator to achieve the optimal aerodynamic characteristics before detailed testing. Improvements were:

1) Selecting the most effective yaw control system. During hovering flight, the yaw stability and control of the vehicle could be achieved via two main methods: (a) Differential speeds of like-turning engines. These functions via increased thrust on clockwise engines paired with decreased anticlockwise thrust, using the resulting turning moment for yaw control; and (b) Control surfaces mounted in the airstream of the rear propellers. Extensive simulation testing of both configurations in X-Plane showed that using the flaps on the rear wing for yaw provided much faster and more accurate control response than relying on opposite engine torque.
2) The size and sweep angle of both the forward and rear wings were altered to balance mechanical feasibility (construction and internal supports) and aerodynamic characteristics. Initially the forward wing was swept forwards, but this sweep was

Table 7. Summary of Concept flight performance

Flight Characteristic	Concept 3	Concept 4	Concept 6
Hovering Performance	• Very stable, requires few control inputs, fairly quick response.	• Mixed performance, sluggish controls outside ground effect, very stable within.	• Very solid roll and pitch performance, but yaw stability is lacking nuance and response.
Vertical to Horizontal Stability	• Requires very apt inputs from pilot, but transition can be done easily.	• Slightly better than Concept 3, trimming is required for stability.	• Excellent transition performance with dead simple procedure.
Horizontal Flight Performance	• Very stable and easy to fly, minimal trim is needed to maintain stability.	• Incredibly stable, terrifically agile, banking produces minimal slip.	• Stable and responsive, but roll and pitch rates are fairly sluggish.

removed to reduce effects such as yaw instability and aero-elastic twisting of the wing. Reducing the sweep angle of the wings made them straighter and easier to manufacture.

3) The forewing was made 5% larger to adjust the centre of lift. This eliminated the requirement for slight up-pitch trimming for the UAV to remain in perfectly level flight without pilot input. Since the centre of mass cannot be moved in order without compromising hover stability, the centre of lift was instead shifted forwards. The selection of a 5% increase in wing area resulted from simulation-based experimentation with a range of areas (1%, 3%, 5% and 7%).

Throughout the design phase, the X-Plane simulator allowed for virtual experimental development that was akin to building several prototypes. Thus, the final initial design before testing was already been refined enough that most of the issues such as instability were resolved before a physical prototype was built. This is a big benefit of using a software prototyping approach.

The final specifications for the UAV are shown in Figure 3 and Figure 4. The model was to be accompanied by a physical demonstrator vehicle that was constructed using balsa wood. This concept was constructed in Blender 3D, a general 3D graphics software, then transferred to Solidworks to produce CAD drawings.

In order to determine the properties of these components, the aerodynamic forces experienced in flight had to be considered for accurate part selection. The following were calculated:

a) The estimated structural mass (using Mass = Density x Volume) was found to be 107g.
b) Vehicle performance characteristics using the eCalc RC calculator for Multicopters. From it, the estimated overall vehicle mass was 850g.
c) Vehicle performance characteristics using the eCalc RC calculator for Multicopters. From it, the estimated overall vehicle mass was 850g.

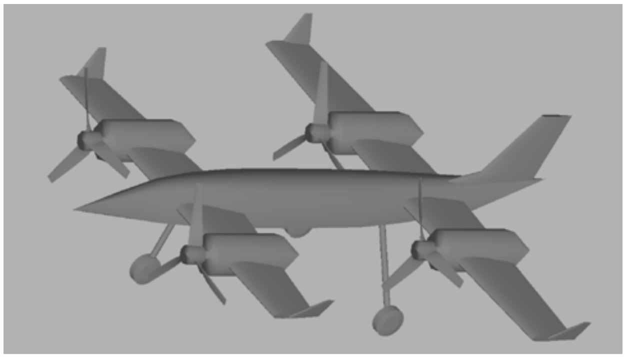
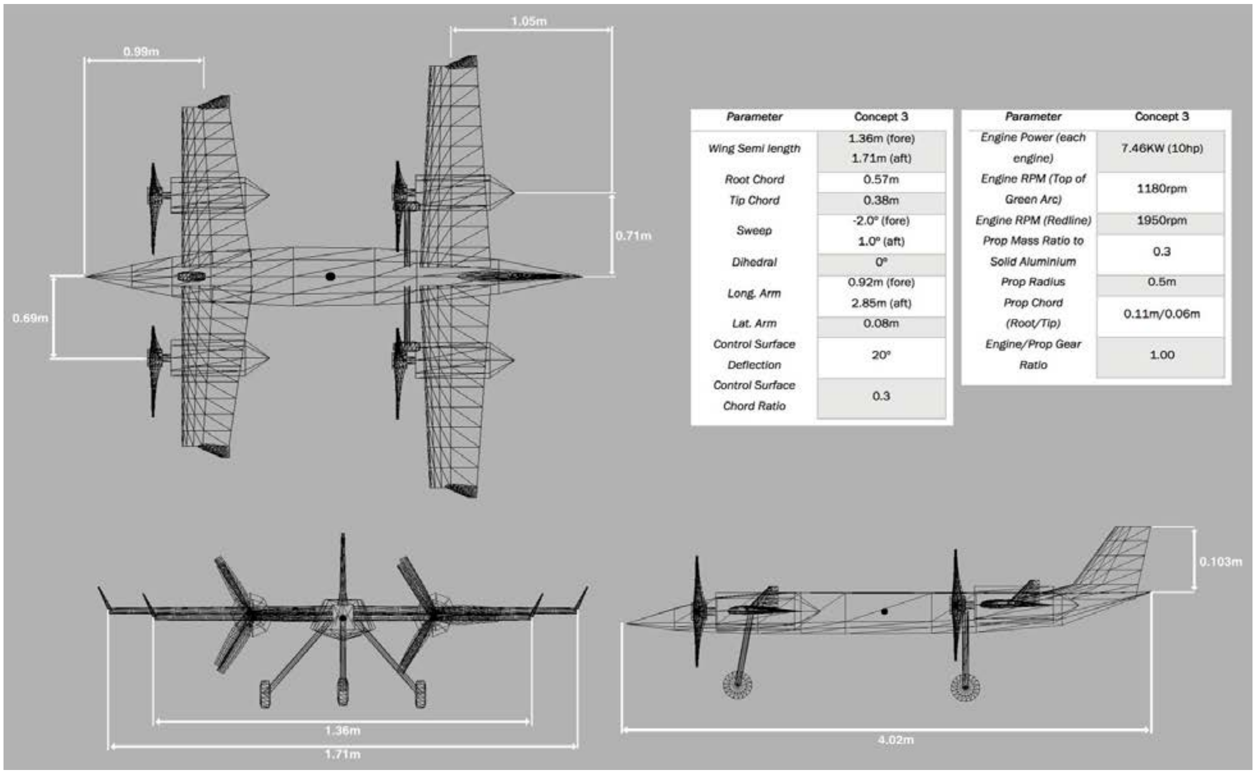


Figure 3. Overview of Final Design



Parameter	Concept 3
Wing Semi length	1.36m (fore) 1.71m (aft)
Root Chord	0.57m
Tip Chord	0.38m
Sweep	-2.0° (fore) 1.0° (aft)
Dihedral	0°
Long. Arm	0.92m (fore) 2.85m (aft)
Lat. Arm	0.08m
Control Surface Deflection	20°
Control Surface Chord Ratio	0.3

Parameter	Concept 3
Engine Power (each engine)	7.46KW (10hp)
Engine RPM (Top of Green Arc)	1180rpm
Engine RPM (Redline)	1950rpm
Prop Mass Ratio to Solid Aluminium	0.3
Prop Radius	0.5m
Prop Chord (Root/Tip)	0.11m/0.06m
Engine/Prop Gear Ratio	1.00

Figure 4. Final Design Specifications

d) Vehicle performance characteristics using the eCalc RC calculator for Multicopters. From it, the estimated overall vehicle mass was 850g.

e) The torqueing force experienced by the wings as they rotate through the airflow. This will allow appropriate servo sizing. Considering:

The force exerted on a flat plate (dynamic head) by moving air is given by:

$$P_D = \tfrac{1}{2} \rho V^2$$

where ρ is air density

The stall speed of an aircraft wing is determined by:

$$V_{stall} = \sqrt{\frac{2Wg}{2\rho S C_{Lmax}}}$$

Where S is wing area (*m*^{2}), C_{Lmax} *is the coefficient of lift at stall (dimensionless), W is aircraft weight (kg), g is gravity, and ρ is air density* (NASA, 2014).

The NACA 2412 airfoil was used for the vehicle. At 5º alpha, C_{Lmax} is 1.59 (obtained from X-Plane Simulator). Thus,

$$V_{stall} = \sqrt{\frac{2\times0.533\times9.81}{2\times1.205\times0.06171\times1.59}} = 8.40\ m/s$$

Flying just above the stall speed at 9m/s,

$$P_D = \tfrac{1}{2} \text{ x } 1.205 \text{ x } 9^2 = 48.80\ Pa$$

Thus:

$$F = 48.8 \text{ x } 0.06171 = 3.011\ N = 0.307\ kg$$

The wing when transitioning between flight phases can be approximated as a flat surface hinged at the point of the wing spar, with the motor mounted to the leading edge. Hence,

$$\sum CW = UDL \text{ across } 3.5cm$$
$$= (0.307\times3.5)\times3.5/2 = 1.88\ kgcm$$

and

$$\sum ACW = (0.307\times6.9)\times6.9/2+0.05\times4.5 = 6.31\ kgcm$$

$$\therefore \text{net moment} = 5.6\ kgcm \text{ at } 9\ m/s$$

This then is the torque requirement of the servo motor required to drive the rotation of the tilt wings.

5. Presentation and Analysis of Simulation Results

Despite the existence of a physical prototype, all analysis was conducted using Laminar Research X-Plane. Simulation results were an excellent indication of the performance of the real vehicle, if it was correctly built. Given that the main objective of the UAV design is that it be easy to control and stable through all flight phases, including transitions, to fulfil surveillance requirements, these characteristics are tested throughout the analysis. Throughout all of these tests, environmental parameters from the initial concept selection phases were held constant (see Table 3). For all vertical flight tests, the vehicle was maintained in a stable hover at 8m AGL.

5.1 Vertical Take-Off and Hovering Flight Phase

In Vertical Flight, yaw control is achieved by control surfaces aligned in the vertical airflow, which generated differential wing lift that rotates the UAV about its Centre of Lift. The vehicle's yawing response was observed and measured.

When full yaw control inputs were applied, the vehicle's yawing response was observed and measured. Figure 5 compares the rudder control input to the yaw rotation rate, or yaw response. Yaw response with the benefit of the control surfaces is deemed to be acceptable. The UAV's angular velocity changed immediately when given an input, though acceleration was slow, taking 2.05s to reach peak velocity. This relatively slow response did not hinder flight performance during the leisurely stage of hovering.

Full pitch control inputs were applied. Figure 6 compares the pitch control input to the pitch rotation rate, or pitch response, which was much faster than the yaw response. It took approximately 1.3s to reach maximum pitch rate, or approximately 63% faster. This faster response was due to the greater torque produced by the differential engine thrust compared to the control surfaces, where the delta in power was significantly greater than the difference in torqueing force in yaw control. Figure 7 shows the Engine RPM response versus pitch response.

The roll response (Figure 8) was even faster than the pitch response, as it took approximately 0.8s to reach maximum roll rate, or approximately 62% faster than pitch. Roll response was faster than pitch response due to the roll axis having a much lower mass moment of rotational inertia than the pitch axis. Figure 9 compares the asymmetrical engine thrust produced by the left and right engine pairs (engine speed as the proxy) in order to generate the roll response. In vertical flight mode, roll is generated by differential thrust between the engines on the two sides. The control algorithm must ensure that the roll response is rapid, stable and predictable in this flight mode.

During lift force analysis, the vehicle did not leave the ground until thrust reached a sufficient level. Then, it accelerated exponentially as it gained altitude. The wing lift generated increased nearly linearly as thrust increased. Based on the data from these tests, the vehicle concept demonstrates acceptable controllability and precision in a hover.

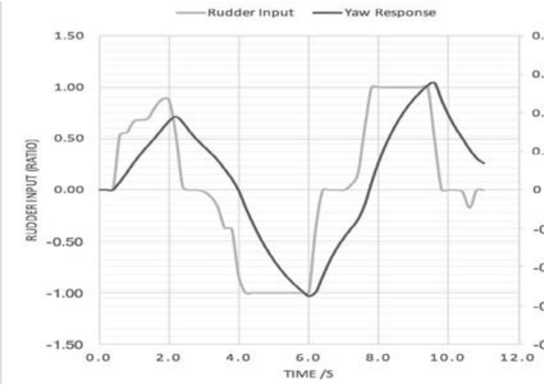


Figure 5. Yaw Response Graph

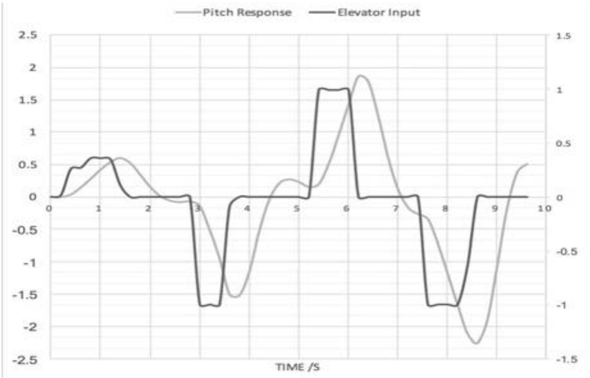


Figure 6. Hovering Pitch Response Graph

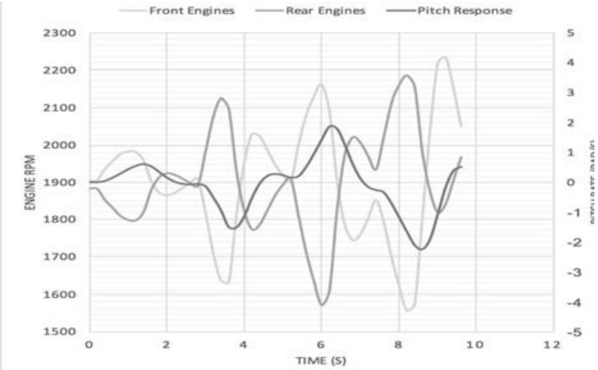


Figure 7. Engine RPM versus Pitch Response Graph

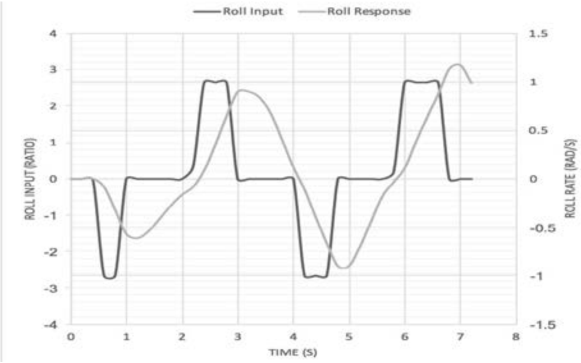


Figure 8. Hovering Roll Response Graph

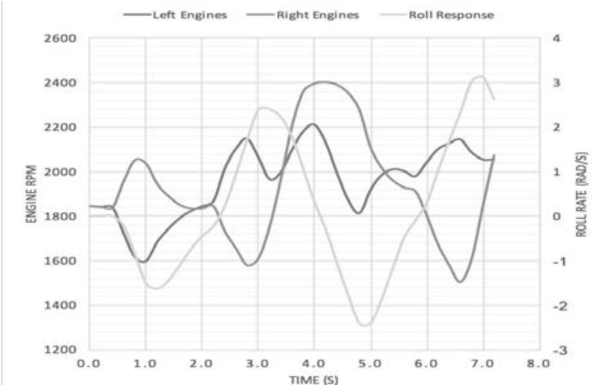


Figure 9. Engine RPM versus Roll Response Graph

5.2 Transition from Vertical to Horizontal Flight

This transition phase involves the vehicle's wings rotating from a vertical position to a horizontal position to move from vertical/hovering flight, to horizontal/ wing-borne flight. Both wings rotate simultaneously, and move at 15 degrees per second, completing the rotation in 6 seconds. These rates were derived from the X-Plane knowledge base for VTOL rotations.

It is important that the vehicle was not unstable, and that the pilot does not lose control during the transition phase. For this test, the simulation vehicle was placed in a hover, and the transition phase was initiated. As the vehicle's wings rotated, the vehicle accelerated, and the wings gradually began to generate lift. However, the vehicle may have pitched upwards or downwards as its various surfaces accelerated in the airflow. Pilot elevator input was required to keep the aircraft straight and level.

This test observed the natural stability of the vehicle during this transition phase, meaning it assessed the degree of pilot input needed to maintain straight and level flight. It can be seen from all the graphs (which were obtained from the same test) that a moderate elevator input was required to compensate for varying aircraft pitch and wing lift during the transition. Very little corrective input was needed until the wings reached a 60 degree change from the vertical, where large downward pitch is needed to correct the vehicle's tendency to pitch upwards. However, this pitching effect was not significant enough that vehicle control became difficult or challenging.

5.3 Straight and Level Flight

From straight and level flight at 30 m above ground level and 180 km/h airspeed, the vehicle was rolled, pitched, and yawed with maximum control inputs in each direction. The control responses in the three axes were observed and recorded.

Roll response is extremely fast and accurate, with minimal overshoot. The vehicle is very agile in this axis. The pitch response is slightly more sluggish, and the response gradually tapers as opposed to rapidly changing (see Figure 10). The reason for this is differing mass moments of inertia between the axes. The yaw response, however, was very interesting (see Figure 11). Once a control input is given, the vehicle responded almost immediately but it snapped back in the other direction in an oscillatory manner. This situation was a case of positive dynamic stability. This occurred because the vertical tail entered the airflow at an angle relative to the airflow, which caused it to generate a lifting force that torqued the aircraft in the direction opposite to the yaw, producing a damped oscillation. This characteristic requires further tuning to ensure it becomes sufficiently stable.

Aerodynamic stability of the UAV was explored using two methods. Firstly, it was banked up to 30º left and right, and the sideslip characteristics were observed and recorded. Secondly, from straight and level flight, the UAV was pitched upwards and downwards with full elevator control input.

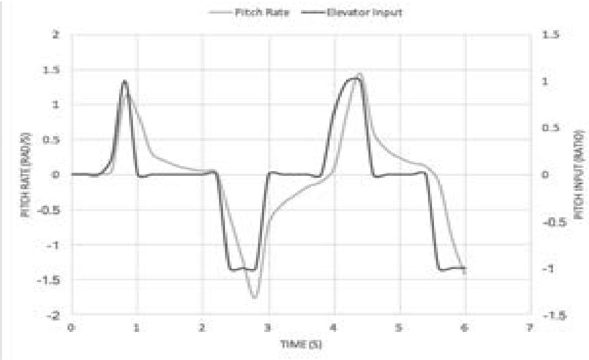


Figure 10. Horizontal Pitch Response

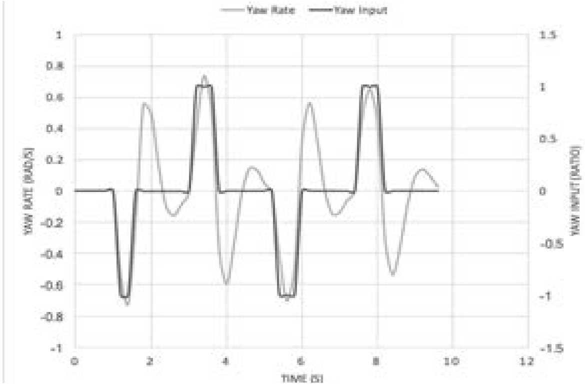


Figure 11. Horizontal Yaw Response

Slip is a phenomenon whereby the axis of an aircraft is misaligned with its trajectory. High slip during indicates aerodynamically inefficiency and reduces lift-to-drag ratio, adding drag without increasing lift. An aircraft flying with a slip is in uncoordinated flight. The vehicle was tested in banking turns: as the vehicle banks up to ±30º, the slip reaches a maximum of 3º (see Figure 12). Slip above 10º is considered excessive, but this slip angle is acceptable.

Angle of Attack (AOA) refers to the angle between the aircraft's pitch and its actual flight path. A low AOA during manoeuvring indicates efficient flight, as the lift-to-drag ratio remains low, and good manoeuvrability as the aircraft is capable of changing trajectory at the desired rate, as opposed to drifting and lagging behind. As vehicle pitch rate increased, AOA also increased in an almost 1:1 fashion (see Figure 13).

The UAV did drift initially, but rapidly recovered. When the vehicle was initially pitched upwards, AOA spiked, but it rapidly settled to near zero within 2-3 seconds. This response shows minimal amounts of drifting and thus very efficient pitch manoeuvrability. This pitch efficiency is due to the vehicle's tandem wing arrangement. As the vehicle pitched and AOA changes, both wings experienced a change in lift. This is a characteristic of all airfoils, where higher AOA generates greater lift up to an angle of about 10º. The rear wing thus either increases or decreases in lift asymmetrically to the fore wing due to its larger size and produces a torqueing effect to point the vehicle into the airflow.

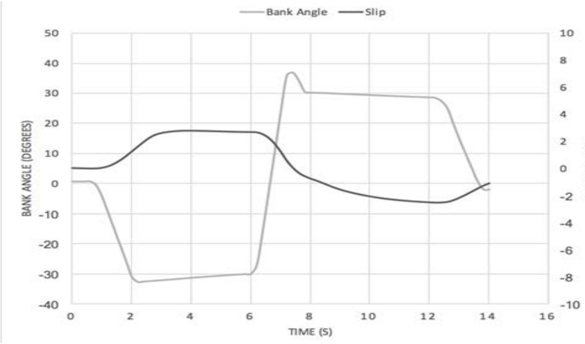


Figure 12. Slip During Banking Turn

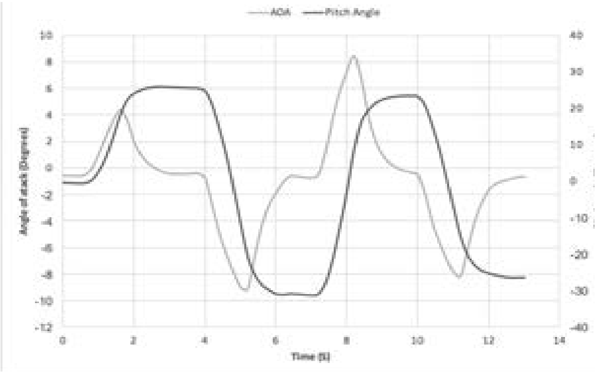


Figure 13. AOA vs Pitch Angle

5.4 From Horizontal to Vertical Flight

This transition was the inverse of the previous transition analysed and involved the vehicle's wings rotating from a horizontal position to a vertical position to shift from horizontal flight, to hovering flight. As before, both wings rotated simultaneously at 15º per second.

As before, to assess stability, the simulation vehicle started from stable horizontal flight, and the transition was initiated. As the vehicle's wings rotated, it began to decelerate, and the wing lift decreased as the engines took over. It is immediately noticeable that this transition (in Figure 14 through Figure 17) is less stable than the Vertical to Horizontal transition. The UAV oscillates and adept pilot input was needed to keep it level. This instability was due to the wing interacting with the bulk airflow.

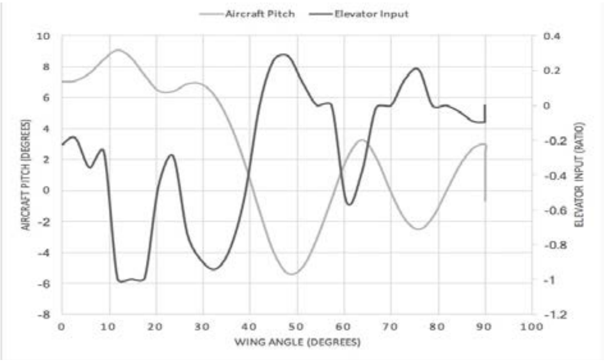


Figure 14. 2nd Transition Natural Stability wrt Wing Angle

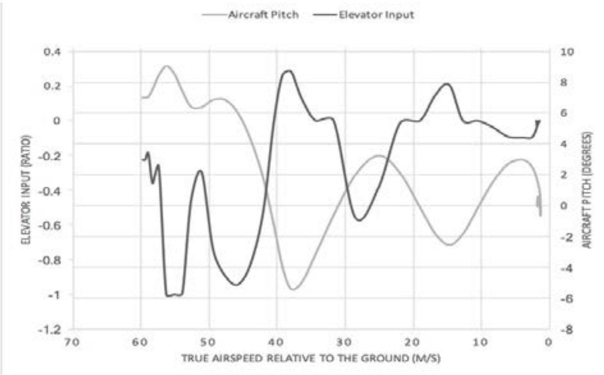


Figure 15. 2nd Transition Natural Stability wrt Airspeed

Figure 16. 2nd Transition Lift Forces wrt Wing Angle

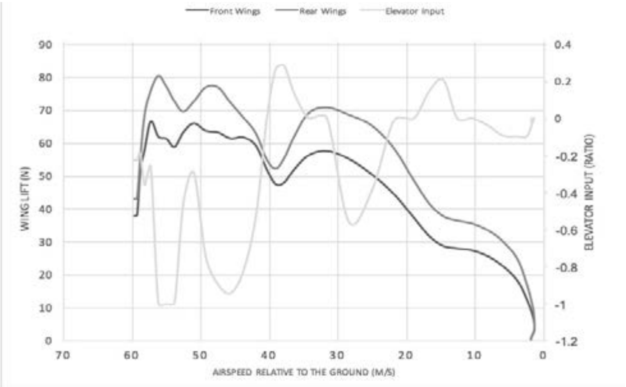


Figure 17. 2nd Transition Lift Forces wrt Airspeed

As the wing rotated vertically and began to stall, it essentially became a flat plate moving perpendicularly through air. This caused the vehicle to slow down rapidly to a hover, but it generated turbulent vortices which cause pitch instability. Analysing the wing in a virtual wind tunnel, the below images help to illustrate these phenomenon (see Figure 18).

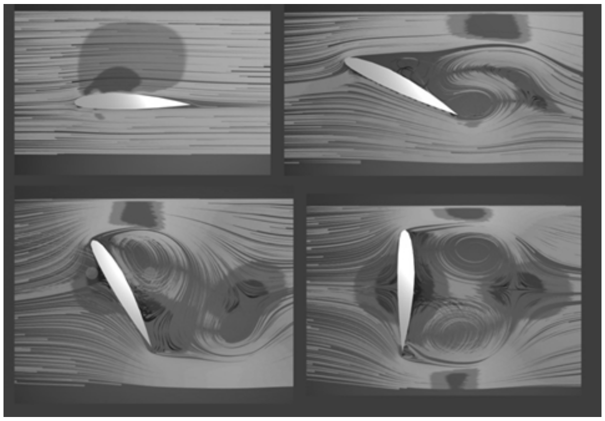


Figure 18. Turbulence Generated During 2nd Transition Phase

The Horizontal to Vertical Flight transition phase could be improved by modifying the wing design so that only a segment of it rotates, or reducing the overall wing area, thereby reducing the area forming turbulent air; rotating the wing more slowly, or in steps to dilute the effects of instability; or rotating the wings at different rates to modify the effects of the vortices along the vehicle. With more time, these options could be investigated in the simulation environment.

5.4 Summary of Analysis

With all four phases of flight being analysed, we can come to the following conclusions:

For Hovering Flight, the UAV control responses are slightly delayed, but acceptable. The asymmetrical mass moment of inertias between the pitch and roll axis result in both having differing responses, different to a typical quadcopter.

For the Vertical to Horizontal Flight Transition, the UAV requires some control input, but it is not so much that the transition becomes difficult or challenging. Low required control input means less work for a pilot or an automated transitioning system.

For Straight and Level Flight, the UAV demonstrates excellent pitch and roll response characteristics. When yawed sharply the UAV enters a damped dynamic oscillation. Slip and AOA are within acceptable rates for aircraft, and the vehicle is aerodynamically efficient in flight.

For the Horizontal to Vertical Flight Transition, the UAV requires some complex control inputs to counteract the tendency to naturally pitch around on its own. This pitching is due to the wing rotating vertically in the airflow and producing an unstable mass of vortices which cause unstable wing airflow. Design modifications could be explored to correct this.

6. Conclusion

This paper has reported on the use of simulation tools to accelerate the design and virtual testing of a novel UAV concept as an undergraduate student project. It demonstrates the usefulness of knowledge-based tools to accelerate the concept design process, and to produce a much more optimised final product. Further detailed design and developments are required, including validation of simulation results, but a relatively robust and well-tested design of a complex system has already been developed with minimal financial cost and without physical testing. That this was done by an undergraduate engineer as his final year project is a showcase for the potential democratisation of design processes by using software-based tools to greatly speed up the prototyping and design process.

The UAV developed and analysed in this paper performs satisfactorily in all phases of flight in still air, and the overall performance accomplishes the goals set out initially. The vehicle is stable and easy to control in three of the four flight phases, with the fourth phase being of a more moderate stability. Future work includes testing in non-stable air; validation of the simulation results using a physical prototype in a wind tunnel; and further refinement of the design solution, particularly the Horizontal to Vertical flight transition.

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