The T-Wing: A VTOL UAV for Defense and Civilian Applications

R.H. Stone[†], G. Clarke[‡‡],

Abstract

This paper describes progress made on the T-Wing tail-sitter UAV programme currently being undertaken via a collaborative research agreement between Sonacom Pty Ltd and the University of Sydney. This vehicle is being developed in response to a perceived requirement for a more flexible surveillance and remote sensing platform than is currently available. Missions for such a platform include coastal surveillance, defence intelligence gathering and environmental monitoring. The use of an unmanned air-vehicle (UAV) with a vertical take-off and landing (VTOL) capability that can still enjoy efficient horizontal flight promises significant advantages over other vehicles for such missions. One immediate advantage is the potential to operate from small patrol craft and frigates equipped with helipads. In this role such a vehicle could be used for maritime surveillance; sonobuoy or other store deployment; communication relay; convoy protection; and support for ground and helicopter operations. The programme currently being undertaken involves building a 50-lb fully autonomous VTOL tail-sitter UAV to demonstrate successful operation near the ground in windy conditions and to perform the transition maneuvers between vertical and horizontal flight. This will then allow the development of a full-size prototype vehicle, (The "Mirli") to be undertaken as a prelude to commercial production.

The Need for a Tail-Sitter UAV

Defence Applications

Although conflicts over the last 20 years have demonstrated the importance of UAV systems in facilitating real-time intelligence gathering, it is clear that most current systems still do not possess the operational flexibility that is desired by force commanders. One of the reasons for this is that most UAVs have adopted relatively conventional aircraft configurations. This leads directly to operational limitations because it either necessitates take-off and landing from large fixed runways; or the use of specialized launch and recovery methods such catapults, rockets, nets, parachutes and airbags.

One potential solution to these operational difficulties is a tail-sitter VTOL UAV. Such a vehicle has few operational requirements other than a small clear area for take-off and landing. While other VTOL concepts share this operational advantage over conventional vehicles the tail-sitter has some other unique benefits. In comparison to helicopters, a tail-sitter vehicle does not suffer the same performance penalties in terms of dash-speed, range and endurance because it spends the majority of its mission in a more efficient airplane flight mode. The only other VTOL concepts that combine vertical and horizontal flight are the tilt-rotor and tilt-wing, however, both involve significant extra mechanical complexity in comparison to the tail-sitter vehicle, which has fixed wings and nacelles. A further simplification can be made in comparison to other VTOL designs by the use of prop-wash over wing and fin mounted control surfaces to effect control during vertical flight, thus obviating the need for cyclic rotor control.

For naval forces, a tail-sitter VTOL UAV has enormous potential as an aircraft that can be deployed from small ships and used for long-range reconnaissance and surveillance; over-

[†] Department of Aeronautical Engineering, University of Sydney

[‡] Sonacom Pty Ltd

the-horizon detection of low-flying missiles and aircraft; deployment of remote acoustic sensors; and as a platform for aerial support and communications. The vehicle could also be used in anti-submarine activities and anti-surface operations and is ideal for battlefield monitoring over both sea and land. The obvious benefit in comparison to a conventional UAV is the operational flexibility provided by the vertical launch and recovery of the vehicle. The US Navy and Marine Corps who anticipate spending approximately US$350m on their VTUAV program have clearly recognized this fact.

Figure 1: A Typical Naval UAV Mission: Monitoring Acoustic Sensors

For ground based forces a tail-sitter vehicle is also attractive because it allows UAV systems to be quickly deployed from small cleared areas with a minimum of support equipment. This makes the UAVs less vulnerable to attacks on fixed bases without the need to set-up catapult launchers or recovery nets. It is envisaged that ground forces would mainly use small VTOL UAVs as reconnaissance and communication relay platforms.

Civilian Applications

Besides the defence requirements, there are also many civilian applications for which a VTOL UAV is admirably suited. Coastal surveillance to protect national borders from illegal immigrants and illicit drugs is clearly an area where such vehicles could be used. The VTOL characteristics in this role are an advantage, as they allow such vehicles to be based in remote areas without the fixed infrastructure of airstrips, or to be operated from small coastal patrol vessels.

Further applications are also to be found in mineral exploration and environmental monitoring in remote locations. While conventional vehicles could of course accomplish such tasks their effectiveness may be limited if forced to operate from bases a long way from the area of interest.

Tail-Sitters: A Historical Perspective

Although tail-sitter vehicles have been investigated over the last 50 years as a means to combine the operational advantages of vertical flight enjoyed by helicopters with the better horizontal flight attributes of conventional airplanes, no successful tail-sitter vehicles have ever been produced. One of the primary reasons for this is that tail-sitters such as the Convair XF-Y1 and Lockheed XF-V1 (Figure 2) experimental vehicles of the 1950s proved to be very difficult to pilot during vertical flight and the transition maneuvers.

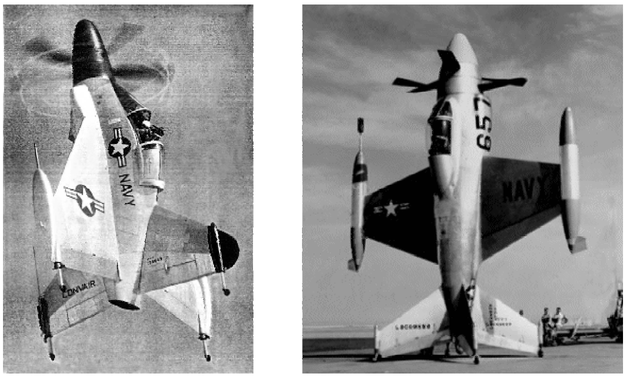

Figure 2: Convair XF-Y1 and Lockheed XF-V1 Tail-Sitter Aircraft.[1 2]

With the advent of modern computing technology and improvements in sensor reliability, capability and cost it is now possible to overcome these piloting disadvantages by transitioning the concept to that of an unmanned vehicle. With the pilot replaced by modern control systems it should be possible to realise the original promise of the tail-sitter configuration.

The tail-sitter aircraft considered in this paper differs substantially from its earlier counterparts and is most similar in configuration to the Boeing Heliwing vehicle of the early 1990s. This vehicle had a 1450-lb maximum takeoff weight (MTOW) with a 200-lb payload, 5-hour endurance and 180 kts maximum speed and used twin rotors powered by a single 240 SHP turbine engine[3]. A picture of the Heliwing is shown in Figure 3.

Figure 3: Boeing Heliwing Vehicle

The Current Vehicle

The proposed *T-Wing* vehicle also has twin wing-mounted propellers but differs from the Heliwing in a number of important respects.

- In keeping with the basic simplicity of the tail-sitter configuration, control is effected via prop-wash over the wing and fin control surfaces, rather than using traditional helicopter cyclic control. Collective blade pitch control is still required to achieve efficient horizontal flight performance and produce adequate thrust on take-off.

- The current vehicle uses a canard to allow a more advantageous placement of the vehicle centre of gravity (CG).
- Two separate engines are used in the current design though the possibility of using a single engine with appropriate drive trains could also be accommodated.

A diagram of a typical vehicle showing some of the important gross geometric properties is given in Figure 4.

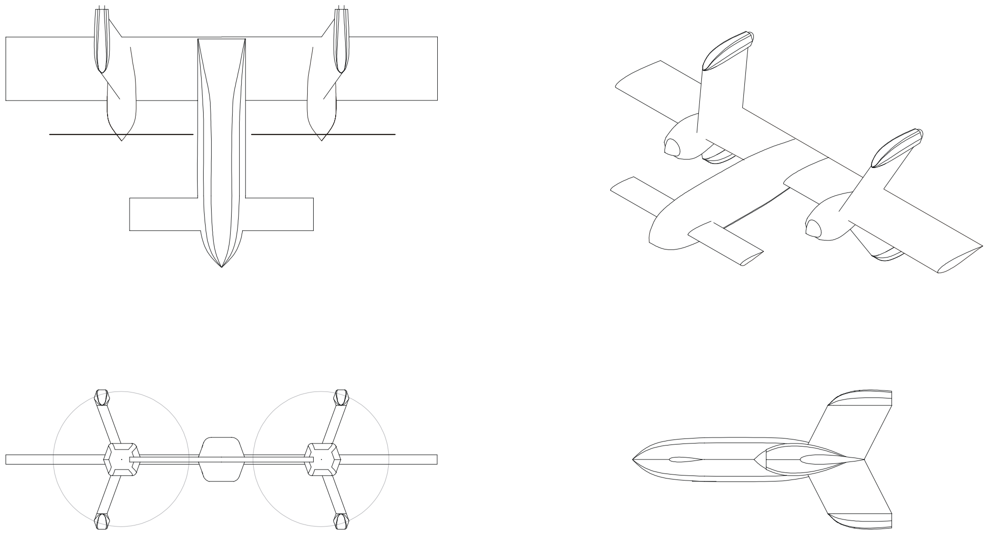

Figure 4: T-Wing Vehicle Configuration

Although a tentative MTOW of approximately 300-kg (660-lb) is envisaged for the full size *Mirli* vehicle, the design methodology has been kept as generic as possible to allow rapid vehicle resizing as mission specifications are changed. This also allows for the design of a family of vehicles to meet a variety of separate tasks. To date successful T-Wing type vehicle designs have been produced ranging from 22.7-kg (50-lb) to 454 kg (1000-lb) to meet a variety of mission requirements.

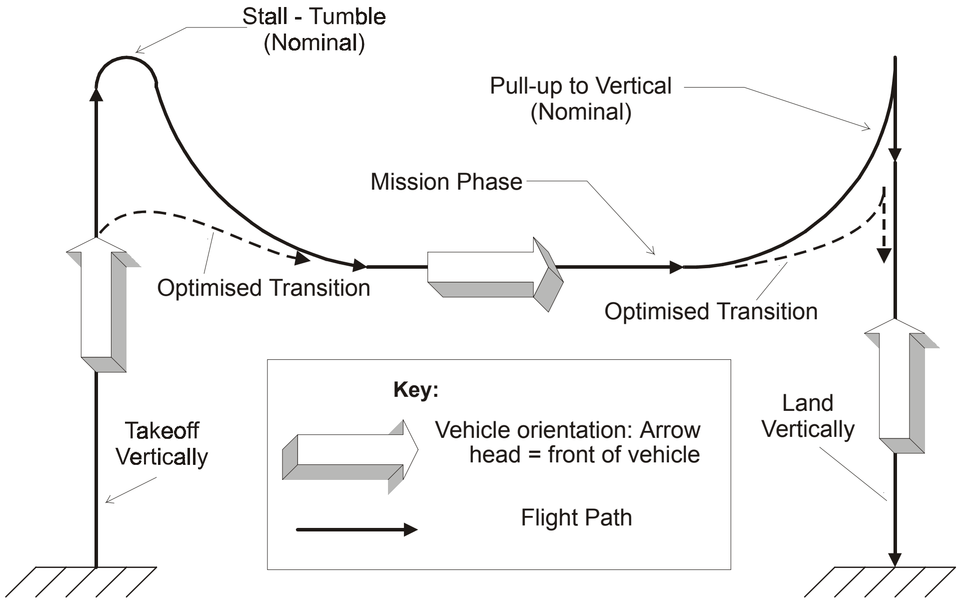

Figure 5: T-Wing Vehicle Flight Path

The flight profile of the T-Wing vehicle also involves some novel characteristics associated with the transition maneuvers between horizontal and vertical flight. Essentially the vehicle takes off in a vertical attitude, climbs to a prescribed height above ground and then performs a "stall-tumble" maneuver[§] after which it recovers to horizontal flight during which it accomplishes the mission phase of its flight profile. Finally, when it returns to land the vehicle regains a vertical attitude via a pull-up maneuver and then descends slowly to land. This flight regime is shown in Figure 5.

The purpose of the remainder of this paper is to provide an overview of the T-Wing programme currently being undertaken by the University of Sydney in collaboration with Sonacom Pty Ltd. This paper will not attempt to deal with the technical aspects of the work in any great depth but will rather give a broad picture of the most salient features together with a report on current progress and provide a look to the future capabilities of such vehicles.

Overview of T-Wing Technology Demonstrator

It is important to realise at the outset that the T-Wing vehicle programme that has been under way since July 1999 is a *technology demonstrator program* and not a prototype production one. The aims of this programme are to prove the critical technologies required of a tail-sitter vehicle before committing funds to full-scale development. The most important aspects of the T-Wing design that have to be demonstrated are reliable autonomous hover control and the ability to perform the transition maneuvers between horizontal and vertical flight.

Description of Demonstrator Vehicle

The T-Wing technology demonstrator vehicle has a nominal a 50-lb (22.7-kg) Maximum Takeoff Weight (MTOW) with a 7 ft (2.13 m) wing span and a total length (from nose to fin tip) of 5 ft (1.52 m). The vehicle was originally designed to be powered by two geared 4.5 HP electric brushless DC motors driving 30 inch fixed pitch counter-rotating propellers and supplied by up to 20 lb (9.1 kg) of Ni-Cd batteries. This was designed to give the vehicle a maximum endurance of 5 - 6 minutes, which was long enough to accomplish the critical flight control objectives of demonstrating stable autonomous hover along with the two transition maneuvers. The reason for initially selecting electric rather than petrol propulsion was because electric motors promised easier set-up and operation in comparison to petrol engines. Unfortunately problems with the particular electric motor speed controllers selected caused excessive delays and doubts about system reliability. For these reasons, it was decided in August 2000 to convert the vehicle to run on petrol engines.

The petrol engined version uses two 6 HP 2-stroke motors and has the same nominal weight as the electric vehicle. The petrol engines drive two counter-rotating 23-inch fixed pitch propellers directly. For the sake of system simplicity there is no cross shafting between the two engines. Due to the higher installed power of the petrol engines this vehicle has considerably more excess thrust than the electric vehicle and it is anticipated that the MTOW can be pushed to at least 65-lb, (29.5-kg). Although the petrol vehicle is still very much a concept demonstration platform, this increased take-off weight should allow an endurance of up to several hours carrying a 5-lb payload.

The vehicle is built primarily of carbon-fibre and glass-fibre composite materials with local panel stiffness provided by the use of Nomex honeycomb core material. The airframe has been statically tested to a normal load factor in excess of 8 G's[4]. A picture of the completed T-Wing vehicle is shown in Figure 6.

[§] The actual amount of post-stall flight and loss of altitude will be dependent on the vehicle power and wing loading characteristics.

Figure 6: Completed T-Wing Technology Demonstrator Vehicle, (Electric Powered Configuration).

Completed Milestones

- Construction of electric powered test vehicle (completed January 2000).
- Tethered vehicle hover testing (completed March 2000).
- Conversion of vehicle from electric to petrol power, (completed November 2000).[**]
- Completion of backup airframe, (October 2000).
- Airframe Static Test to 8 g Loading, (October 2000)
- Demonstration of manual hover flight, (first flight December 2000 and ongoing).
- Development of full non-linear real-time simulation of vehicle, (completed December 2000).

[**] This was NOT a part of the initial vehicle program.

Figure 7: First Free Flight of T-Wing Technology Demonstrator Vehicle under Manual Control. (Note "training" undercarriage").

Outstanding Milestones

- Demonstration of stability augmentation system (SAS) for hover flight, (April 2001 projected).
- Demonstration of autonomous hover flight capability, (June 2001 projected).
- Demonstration of vertical to horizontal flight transition, (August 2001 projected – possibly earlier if performed manually).
- Demonstration of the reverse horizontal to vertical transition (August 2001 projected – possibly earlier if performed manually).
- Full autonomous flight from take-off to landing, (December 2001 projected).
- Further system testing and refinement, (until June 2002).

Comments on Programme

Of all the milestones the most critical for the success of the programme will be the development of effective hover controllers for the vehicle. These will be required to function effectively in conditions of strong steady winds (> 25 kts)[††] augmented with significant gust components. The ability of the vehicle to function in windy conditions is especially critical for a naval UAV landing on a ship deck as the speed of the ship is combined with prevailing wind conditions to give the total relative wind that the vehicle must operate in during landing. As well as this steady-wind speed problem, ship superstructures often cause significant air-wakes to impinge on rear-deck landing areas, which in turn increase the turbulence of the landing environment of the vehicle. Thus the ability of the vehicle to maintain a stable hover in adverse wind conditions is vital for its overall effectiveness.

[††] Hover in a 25 kt wind is the minimum requirement for the US VTUAV program; 40 kts is the desired capability.

The demonstration of the two transition maneuvers will also be critical to the success of the project. While there is little doubt that these maneuvers can be completed, the usefulness of the vehicle will be enhanced if they can be made to occur at as low an altitude as possible. This is suggested in Figure 5, by the "optimized transition" paths shown.

Although the programme description given so far has focussed on the achievement of physical milestones it is also important to realise that the T-Wing concept is supported by a many years of engineering analysis conducted at the University of Sydney. This analysis underpins the whole program, from the initial vehicle design studies through to the design of flight control software for the T-Wing. While it is not the object of this paper to give in-depth discussions of this underlying analysis, a brief overview will be presented in the following sections to demonstrate the solid theoretical framework that the T-Wing vehicle rests on.

Design Issues for Tail-Sitter Vehicles

A tail-sitter vehicle controlled via prop-wash over control surfaces has a number of unique design requirements in comparison to a conventional aircraft. Some of these are given below.

- Total thrust must exceed vehicle weight by a reasonable margin. Although some researchers have suggested fixed values for the amount of excess thrust, (for instance Stoney[5] suggests 15%), the actual amount will almost certainly depend on particular mission specifications. This is especially true for naval systems were the UAV is operated from the deck off a ship. Operation from smaller ships or in higher sea-states requires greater excess thrust to allow the vehicle adequate ability to maneuver close to a pitching and heaving deck. As well, prescribed "overload" requirements may be desired of the vehicle in benign conditions which would also have a bearing on the total excess thrust required.
- The vehicle must be able to control itself during hover. This is affected by the slipstream velocity distribution, the sizing of the control surfaces and their position in the slipstream and the positioning of the wing and fins relative to the vehicle CG. This issue relates both to the transient gust response of the vehicle (in terms of its maximum sideways displacement) as well as to its steady crosswind limit during hover. The latter effect is particularly important for shipboard operations, where a steady wind component may be augmented by the relative wind due to the ship motion.
- The ground footprint, (determined by the fin size and position on the wings) must provide a reasonable minimum tip-over angle (~25°) to allow for skewed landings and the like.

These particular requirements for tail-sitters must also be balanced alongside many conventional design issues such as prescribed stability margins for horizontal flight; structural integrity and vehicle performance in terms of range, endurance and maximum speed.

Generic Design Optimisation

Many of the above design requirements impose conflicting directives on the design. For instance, the propellers are required to operate efficiently at both high and low forward speeds; they are required to provide the flow over the elevons for low-speed controllability and they are required to provide thrust in excess of the vehicle's weight for take-off and landing. Altering propeller size and shape will affect all these parameters as well as others including the engine power required and the overall vehicle weight. In a similar manner, altering wing-shape and disposition relative to the canard and centre of gravity will affect low-speed controllability, horizontal flight stability, cruise lift to drag ratio as well as wing loading and structural efficiency. High aspect ratio wings will tend to give improved cruise performance, but at the cost of smaller control moments during hover and increased skin gauges, when compared to lower aspect ratio ones. They may also pose problems for wing-tip clearance during landing.

It should also be stated that unlike more conventional air-vehicles there is little information available regarding the design of tail-sitter aircraft. Thus although conventional aircraft design involves choosing a variety of parameters that affect competing disciplines, there is at least a large database of previous designs to draw on to guide the designer in fashioning a good solution for a given mission requirement. No such database of 1000's of previous solutions exists for tail-sitter aircraft.

To overcome these problems generic design optimisation software was developed at the University of Sydney by one of the authors (Stone)[6] to allow vehicle sizing to be automated based on desired performance specifications. This has proven to be a key technology because it allows rapid investigation of vehicles for different mission specifications to be undertaken. This allows the suitability of the T-Wing concept to be quickly judged in different scenarios and also easily allows the sensitivity of the design to particular mission specifications to be gauged.

The optimisation software is parametric in nature and allows vehicle preliminary design to be performed in a structured manner to achieve minimum weight designs for a given mission specification. Some of the secrets to achieving successful, realistic designs using formal optimisation techniques are as follows.

- The optimisation should cover a variety of flight conditions, (three are used in the current work), to mitigate against a "point-design" solution with poor off-design characteristics.
- All significant disciplines should be included in the analysis to ensure that their effects and interactions are fully captured. For the tail-sitter vehicle this requires consideration of the vehicle aerodynamics, its propulsion sub-system, its structural design, the vehicle flight mechanics and rudimentary control system design.
- The analysis methods employed should be sufficiently robust to handle wide variations in the vehicle definition, as this is likely to occur during the course of an optimisation run. While statistical methods can be used for designs that do not vary far from established vehicles, good *physical models* are preferred as they allow the design to vary outside the boundaries of current solutions. In the case of tail-sitter vehicles, the small number of previous designs also precludes the significant use of statistical methods.

The major ingredients of the analysis used in the optimisation are given below. These are described more fully elsewhere.[7 8].

Analysis Models

Aerodynamic and Propulsion Model

A fixed wake panel method model is used to capture the aerodynamic characteristics of the vehicle[9]. This is coupled with a blade element solution for the propellers to allow the prediction of the slipstream characteristics, which are critical in hover flight, where vehicle control is effected via prop-wash over wing and fin mounted control surfaces. The blade-element solution also gives the propeller forces for any flight condition. Both the blade element and the panel method calculations use judicious 2D viscous corrections to achieve more realistic results in the presence of non-linear effects such as wing, canard and blade stall.

A typical aerodynamic model of a T-Wing vehicle is shown in Figure 8 indicating the pressure field over the vehicle for a cruise flight condition.

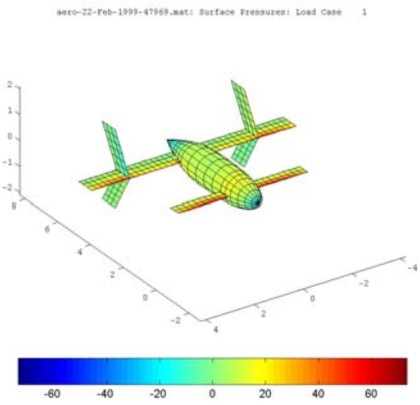

Figure 8: Aerodynamic Model of Vehicle, (Dimensions in ft; Pressure in psf)

Structural Model

The vehicle structure is modeled as a series of simple beam elements able to resist shear, bending moment and torsion loads. Flight loads are obtained from the aerodynamic model by integrating the pressure distribution over the vehicle for particular loadcases and applying an appropriate normal load factor. Inertial relief of the basic airloads is also included. Ground loads are based on a consideration of the energy absorption of a sprung landing gear in the presence of both symmetric and skewed drop conditions.

Hover Control Model

The hover control of the vehicle in the presence of wind gusts and the maximum control authority in the presence of steady winds are critical features of the tail-sitter design. The vertical flight controllability and control authority analysis is based on the aerodynamic coefficients (control and damping derivatives) obtained from the panel method analysis coupled with a mass model of the vehicle. By linearising and partitioning the vehicle hover dynamics it is possible to automate the design of simple LQR controllers to stabilize the vehicle in the presence of prescribed wind gusts and incorporate this directly into the optimization problem. Graphs of a vehicle response to a lateral (side) 10 knot gust are shown in Figure 9.

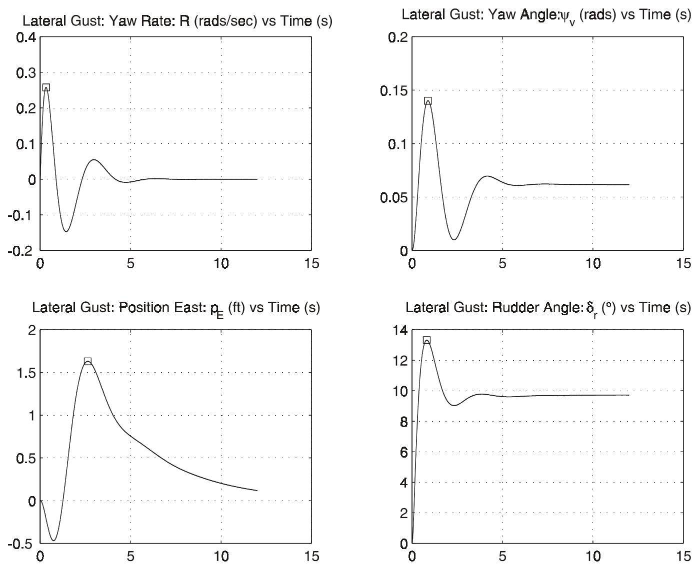

Figure 9: Typical Lateral Step Response: 10 knot Side (East) Wind Gust.

Optimisation

The formal design optimisation is based on a gradient-based technique applied to a parametric vehicle model with a total of 37 physical optimisation variables. The optimisation was cast in a classical fashion as a single objective problem to minimise vehicle weight while meeting a variety of performance and other constraints. A large number of numerical tests confirm that the optimisation process has relatively reliable convergence properties over a wide range of different design specifications. Typical before and after optimisation profiles are shown in Figure 10 for a 50-lb payload, 600 mile range specification.

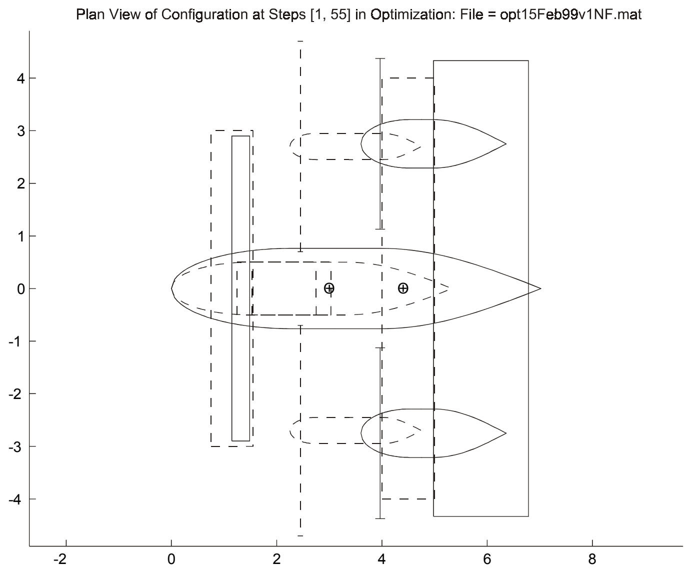

Figure 10: Before and After Vehicle Profiles for a 50-lb Payload 600-Mile Range Vehicle, (dimensions in ft).

Real Time Flight Simulation

Using the aerodynamic model previously described a full non-linear 6-degree of freedom (DOF) flight model of the actual technology demonstrator vehicle has been constructed. This enables the prediction of the dynamics of the vehicle to be calculated in all phases of flight from hover, through the "stall-tumble" transition maneuver to full-speed horizontal flight and includes real-world effects such as wind gusts and sensor errors. This model is currently implemented in the SIMULINK[10] environment and has now been refined to run in real time via use of an add-on product, The Real Time Workshop[11]. This is a significant advance on the previous simulation work, which ran at approximately 1/30th of actual speed.

One of the primary results of this is the development of a visual pilot training simulator, which allows a ground based remote pilot to practice *manual* flight of the vehicle without risking an airframe. This is required because the technology demonstrator vehicle is initially being test flown without any automatic controls in place. It will also be of great use in the future as stability augmentation systems (SAS) and then full automatic controls of the vehicle are implemented. By coupling models of these control systems with the basic flight dynamic SIMULINK model and then re-compiling the real-time executive it will be possible to test new controller designs quickly and easily. This is particularly true for SAS controllers: new designs can be incorporated and "flown" in real-time on the simulation by a pilot to gauge how well they perform. In fact, all the real-time coding for the actual vehicle control system will also be done via the use of the Real Time Workshop. It is expected that this will substantially compress the control system design cycle.

The improved vehicle simulation will also be important in future work to optimise the transition maneuvers for the vehicle. As mentioned previously, one of the goals of the current programme is to make these maneuvers as efficient as possible. In practical terms this means minimising the altitude loss in the vertical to horizontal transition, while minimising the altitude gain for the reverse maneuver. In performing these optimizations a fast simulation is expected to be of great benefit.

A figure showing snap-shots of a typical vehicle undergoing a vertical to horizontal transition maneuver under rudimentary automatic control is given in Figure 11. The simulation and its underlying aerodynamic modeling will form the basis of the control system design and sensor suite selection work over the next 1 1/2 years.

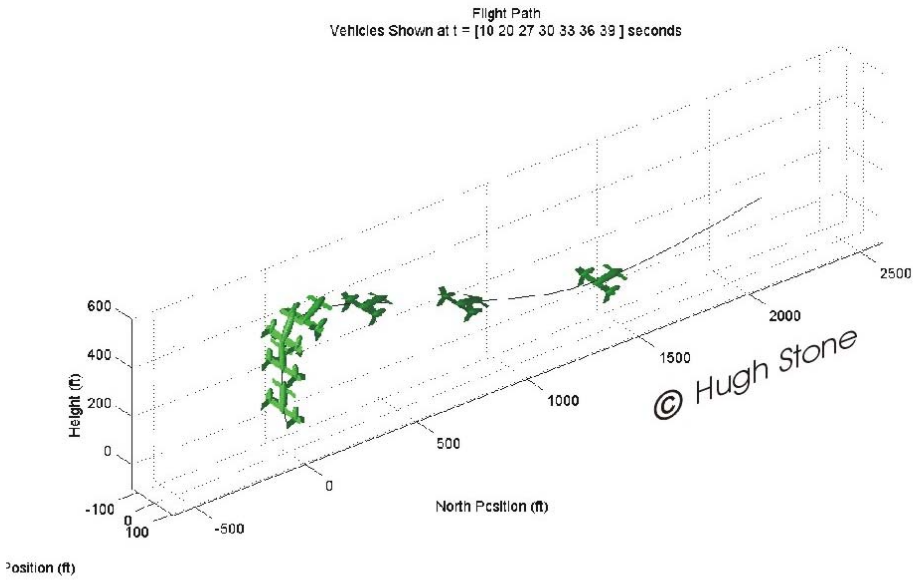

Figure 11: Typical Simulation of Vertical to Horizontal Transition Under Automatic Control: (unequal time increments).

Operational Capabilities for Full Sized Vehicles

Once the vehicle concept has been proven, development of the full-sized aircraft, the *Mirli*, will begin. The proposed Sonacom / Sydney University aircraft will have a comprehensive surveillance capability, carry a payload of 100-kgs and have an operating range of at least 1,000 kilometres. This versatile and novel design concept will provide a fully recoverable, low-cost tactical UAV option that is currently not available. Important features of the aircraft are given below.

- Vertical Take-off and Landing capability. This means that runways, rockets, catapults, nets and parachutes can be dispensed with. This gives the vehicle the operational flexibility to take-off and land from almost any geographical location ranging from a jungle clearings to the back of a small Navy ship with minimal fixed infrastructure.
- The ability to hover as well as fly conventionally.
- Modular construction will allow aircraft to be adapted to specific mission requirements and will also facilitate easy storage.
- The vehicle will be able to be used by all three services for joint operations as well as in civilian roles.
- One of the vehicle's primary missions will be area surveillance over difficult terrain including remote areas of land and sea in most weather conditions.

- Low cost of development and a low unit cost.
- The ability to carry significant radar and optical sensor packages.
- The use of heavy fuel engines (diesel/kerosene) for safety and compatibility with defence force fuel policies.
- A robust and modular design will ensure that easy repairs can be made in the field.
- Synergy with current defence force assets to increase total force effectiveness.
- Fully autonomous operation without the need for skilled ground controllers.

Conclusion

In conclusion it can be seen that the tail-sitter UAV concept being developed by Sydney University and Sonacom exhibits great promise both for defence and civilian applications in the future. Progress from purely theoretical analyses to physical hardware has now occurred. The programme is currently entering a significant period of flight during which the level of vehicle autonomy will steadily be increased culminating in a full autonomous flight from takeoff to landing. It is the authors' belief that this UAV implementation will finally allow the tail-sitter concept to realise its full potential: something that was never possible for manned tail-sitter vehicles.

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