A feasibility assessment of annular winged VTOL flight vehicles

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ABSTRACT

This paper presents a feasibility study to integrate a developed lift system (an annular wing wrapped around a centrifugal flow generator) into a Vertical/Short Take-Off and Landing V/STOL aircraft. Different physical scales, from micro aerial vehicle to a Harrier Jump Jet scale, for a variety of propulsion systems are explored. The system has shown to be viable for several classes of aircraft but with better performance offered by a micro-aerial-vehicle (~40g) and a large vehicle (~10,000kg) with a turbofan engine, albeit in both cases with apparently worse performance than is offered by current technologies. The wingform does not appear to be feasible in the light aircraft scale whilst using internal combustion engines.

1.0 INTRODUCTION

A new lift-system was proposed in Ref. 1 to achieve Vertical/Short Take-Off and Landing V/STOL; the approach being to generate lift from a static blown-annular-wing, see Fig. 1. Theoretical and experimental investigations[2] showed that the system is capable of generating lift. An attempt at optimisation of the annular-wing suggested using pure upper surface blowing with Coanda-effect as shown in Fig. 2 whereas initially a fully wetted wing (symmetrical blowing across lower and upper surfaces) was considered. The modified configuration offers an aerodynamic efficiency, defined as lift to thrust ratio, of at least 61% that could be enhanced to ~80% with the aid of passive-lift-devices for example a Gurney flap and a guided vane.

The next stage however was to investigate whether such a wing could really be used in a practical vehicle? This paper describes a study into the potential of the wing to work, at a range of scales from a 'palmtop' size, to a larger and more powerful aircraft in the Harrier scale.

Previous work[2] has shown that the compressor (or the radial flow generator) is the component against which everything else must be scaled. Selecting the radial fan will start estimation of annular size, power requirement, and thus powerplant size and mass. This will subsequently allow initial estimation of the primary vehicle mass from which it will be inferred whether the vehicle can vertically take-off. The next task will be to quantify the achievable performance of the vehicle. The road map to vehicle integration is summarised in Fig. 3.

2.0 STRUCTURAL WEIGHT ESTIMATION AND MATERIAL SELECTION

To initially estimate structural mass we will assume that the largest dimension of the vehicle will be the outer diameter of annular wing. The major components are located within the wing, mounted, or (more likely) hung from it, at or close to the circle of maximum lift, which will be around the 25% mean chord. The resultant forces and moments are transmitted to the wing with uniform distribution around the annulus as shown in Fig. 4.

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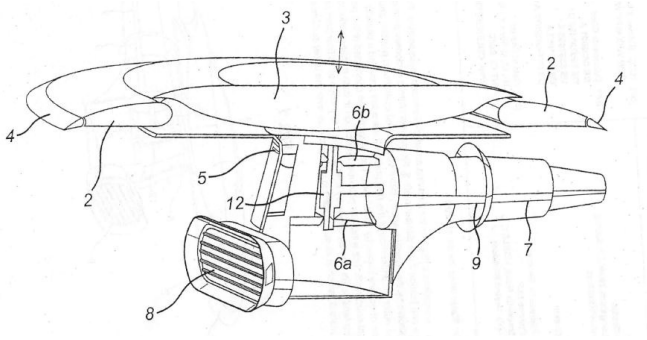


Figure 1. Proposed powered-lift system.

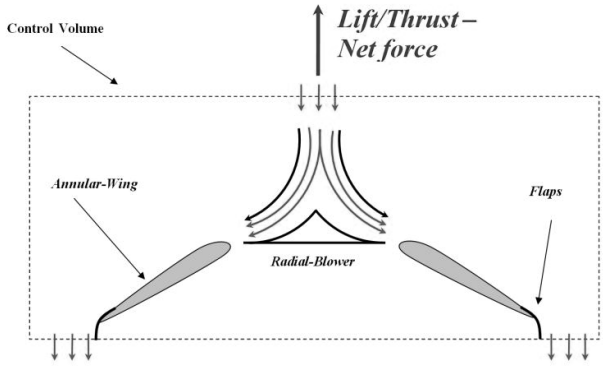


Figure 2. Developed lift-system configuration.

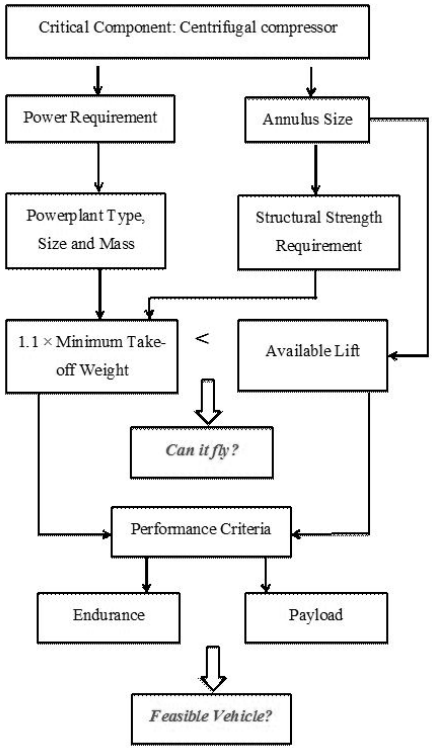


Figure 3. Conceptual design process to integrate the annular wing into a vehicle.

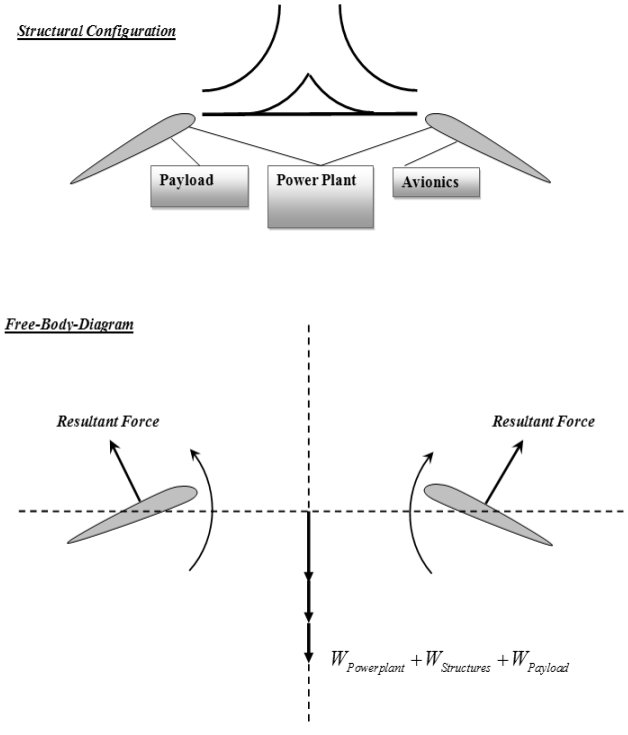


Figure 4. Simplified structural configuration and free-body-diagram (strictly schematic).

The structural mass, m_a, of annular wing was evaluated in Ref. 2 and expressed by;

$$\Rightarrow m_a \propto t_{\max} 2\pi \left(r_0 + \frac{R_0 - r_0}{4} \right) c \qquad \ldots (1)$$

where t_{max} is the maximum aerofoil thickness, r_0 annulus inner radius, R_0 annulus outer radius and c the aerofoil chord length

This is most valid for micro-scale vehicles where low and relatively constant density materials such as foams, are usable. For larger vehicles, typically, most of the volume covered by wing surface area is left hollow and the structural weight will be dominated by a spar and ribs. However, the shape and lift distribution, combined with an assumption of payload primarily being distributed around the main spar, mean that the peak structural loads on both the main spar and ribs, will be low: of the order of skin loads – in effect we have near 100% structural alleviation, such as typically permits ~2/3 of wing mass to be disregarded in conventional aeroplane structural approvals[3]. So, with a lightweight spar and ribs, the latter being evenly distributed around the annulus, even at a much larger scale the wing may for conceptual design purposes continue to be treated as if it is manufactured from a foam-like material of constant density; values for this density will be discussed later, but can initially be based upon wing structural density of existing aircraft of a similar scale.

3.0 EXAMPLE VEHICLE 1: MINIATURE/MICRO UAV

The smallest current class of aircraft are micro-aerial vehicles (MAV): typically with a maximum dimension of about 150mm and maximum operating speeds of 11ms^{-1} [4]. Current MAV development is concentrating upon surveillance roles where larger vehicles are inappropriate (for example inside buildings).

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Most MAVs will operate in the Reynolds number range between 10^3 and 10^5 (Fig. 5); within this range, viscous forces dominate, and as discussed in Section 2.2 this can cause sudden increases in drag and hence losses of efficiency. However, it is observed in Ref. 5 that VTOL capable birds with such low Reynolds numbers fly stably due to their exceptional low wing-loadings. This is similarly the case for many current MAVs, such as those shown in Fig. 6 below, with large wing area and ultra-low body masses (~50g).

For existing MAVs, the propulsion system typically constitutes 50-80% of the vehicle mass. Sensitivity analysis of CTOL MAVs has shown that an additional 0·01N of drag will typically decrease the endurance by 180 seconds and additional 1 gram of mass can typically decrease the endurance by 20 seconds[9]. These numbers have a significant impact on the overall performance of MAVs as the typical endurance values lie in the range of 15 to 30 minutes. This indicates that the propulsion system's thrust to weight ratio is a key parameter in maximising endurance of a MAV. A MAV propulsion system will typically have the following characteristics[10]:

- A direct drive propulsion system (which is more efficient than a geared propulsion system at the MAV scale, since mass is saved, propeller tip Mach numbers still tend to be small)
- Propeller efficiencies of 80% or greater (primarily believed to be due to low Reynolds numbers which lend themselves to high L/D values at propeller or rotor blades)
- Electrical propulsion (avoiding the mass penalties of fuel storage and transmission systems)
- Motor efficiencies of 70% or greater (possible on very small electric motors)

Figure 7 displays some common motors used in miniature aircraft, with one small 2-stroke internal combustion engine shown for comparison. The smallest available electric motor, the Firefly coreless planetary motor will be chosen for this conceptual design. Figure 8 shows a compatible battery and a signal receiver. Table 1 provides specifications of some commercially available propellers for small micro-scale aircraft, with an indication of efficiency following in Fig. 10. In propeller selection at any scale, the relationship between thrust, power and size is nonlinear[11] and available design data is limited, so at this stage propeller selection will be nominal: this will be the GWS4540 with 114mm diameter giving annular size of 187mm.

The motor will require a compatible power source for which a lithium-ion battery with lowest possible mass is selected (as indicated by Fig. 9). The battery life, and thus vehicle endurance, will subsequently be estimated as:

$$Battery_life(seconds) \approx \frac{Battery_Capacity(Joules)}{Power_Consumption(Watts)}$$

Table 1
Data collected for different propellers used with coreless planetary motor[14]

	Diameter (mm)	Current (Amps)	Power (Watts)	Speed (rpm)	Thrust (grams)	Lift/Thrust by Coanda Effect
GWS4350	109	0.26	2.5	6300	26	18.2
GWS4540	114	0.47	3.3	6100	30	21
GWS4530	114	0.69	7.1	9000	56	39.2
GWS4540	114	0.85	9	8600	64	44.8
GWS5030	127	0.42	3	6200	36	25.2
GWS5030	127	0.79	8.3	8800	74	51.8
GWS6030	152	0.64	3.7	6000	44	30.8
GWS7035	178	0.82	5.8	5400	60	42

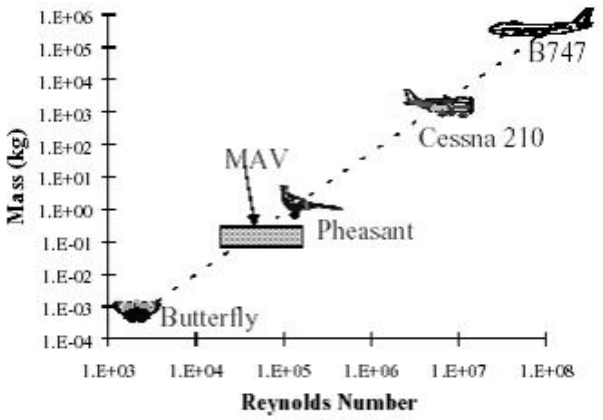
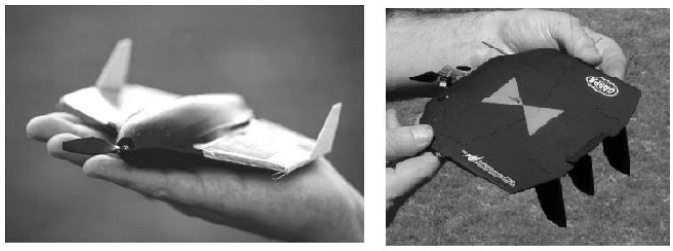


Figure 5. The Micro Air Vehicle flight regime compared to birds and flight vehicles[6].



Lockheed Martin MicroSTRAR — Black Widow MAV

Figure 6. Current micro-aerial vehicles[7,8].



Figure 7. Common torque generator systems for micro/miniature vehicles[12].

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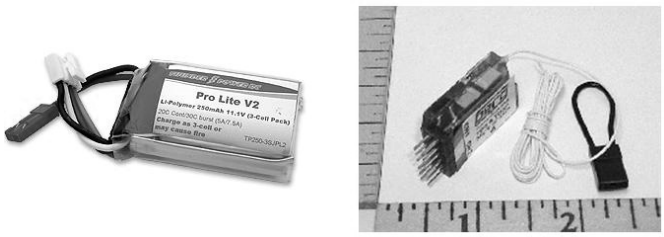


Figure 8. 250mah/900J Lithium Battery (Mass: 24 grammes, Volume: 16 × 21 × 40mm) and Ch Receiver MICROSTAMP 4[13].

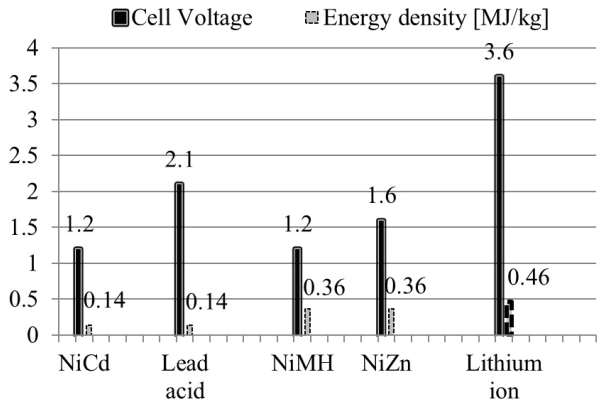


Figure 9. Energy density and voltage for different closed batteries[10].

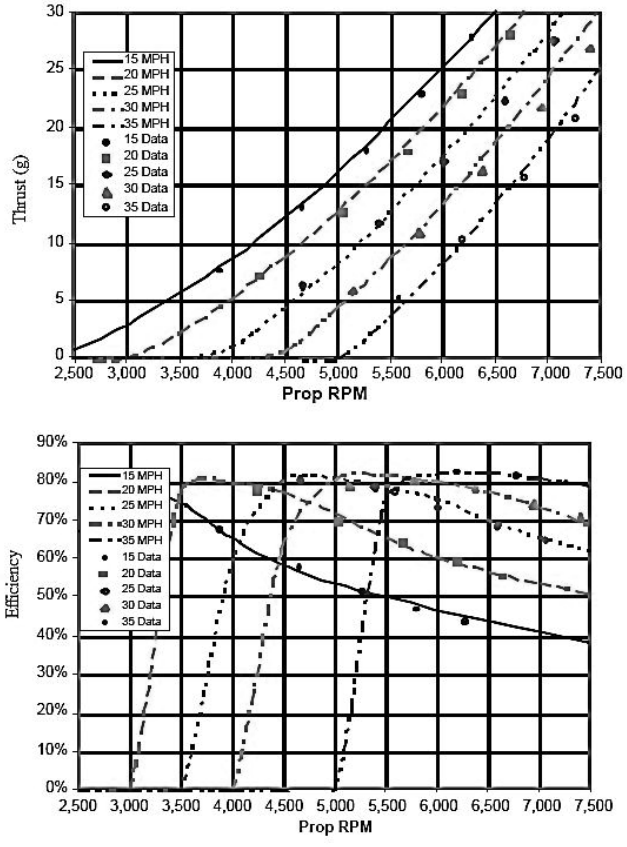


Figure 10. Performance characteristics of a 97mm diameter propeller[8].

Noting that the motor may well be operating below capacity to match the propeller or performance requirements, and thus that power consumption should be factored accordingly (e.g. if a 10W motor is running at 7W to match a 7W propeller, then the power consumption is 7W, not the 10W motor capacity).

Table 2 indicates now the mass of each of the major components. The minimum take-off mass (excluding any payload) is approximately 37·2 grammes, indicating that for VTOL, at-least 0·40N thrust (= 37·2g × 1·1 = 40·9g at 1g) will be required. Now, referring to Table 1 for thrust available the previously selected GWS4540 is unsuitable, but the slightly larger GWS4530, generating 0·55 N of thrust (= 56g at 1g) and with a mass of 1·25g[16] appears more suitable.

Payload and endurance calculations below show that a larger power setting achieves better payloads and a lower will achieve better endurance – which is intuitively correct and consistent with all other scales of aircraft. Therefore, a trade-off may occur depending on the exact function of this vehicle.

Table 2
Mass allocation for the primary flight system of MAV

Component	Specification	Mass (grammes)
Propeller	GWS4530 (114mm)	1.2
Batteries	250mah Lithium Battery	24
Electric Motor	Firefly Coreless Planetary Motor	14
Structure	Foam (1500g/m^3)	8
Avionics	4 Ch Receiver MICROSTAMP 4	4
Minimum Take-off Mass		37.2

Table 3
power and time budget for sample annular MAV on surveillance mission

Phase	*Thrust (N)*	*Time (s)*	*Power (W)*	Energy Usage (J)
Take-off and initial climb, full power	0.549	20	7.1	142
Cruise, power set to give thrust = weight, power scaling with thrust (first approximation only)	0.463	119	6.0	713
Descent and landing, assuming thrust = 75% weight (likely all that is available at end of battery life)	0.347	10	4.5	45
	Total:	149	-	900

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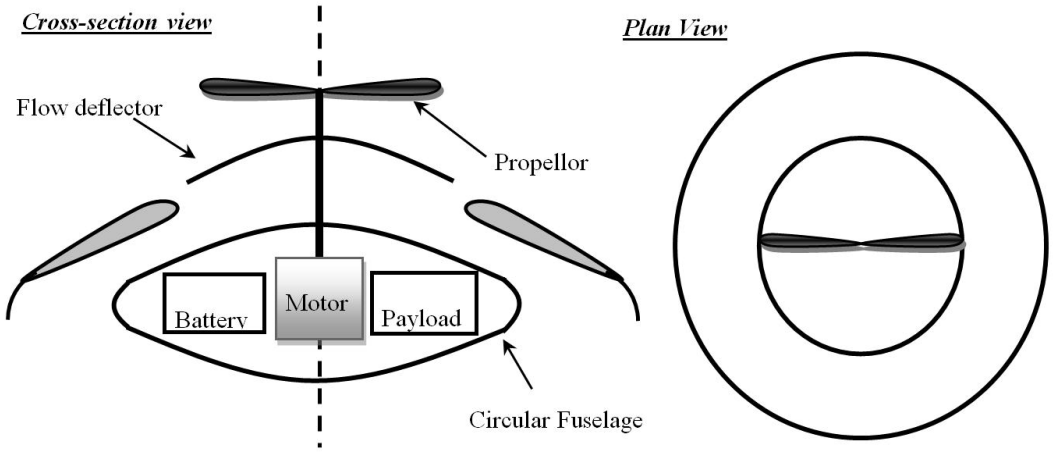


Figure 11. Conjected form of Annular UAV with electric propulsion.

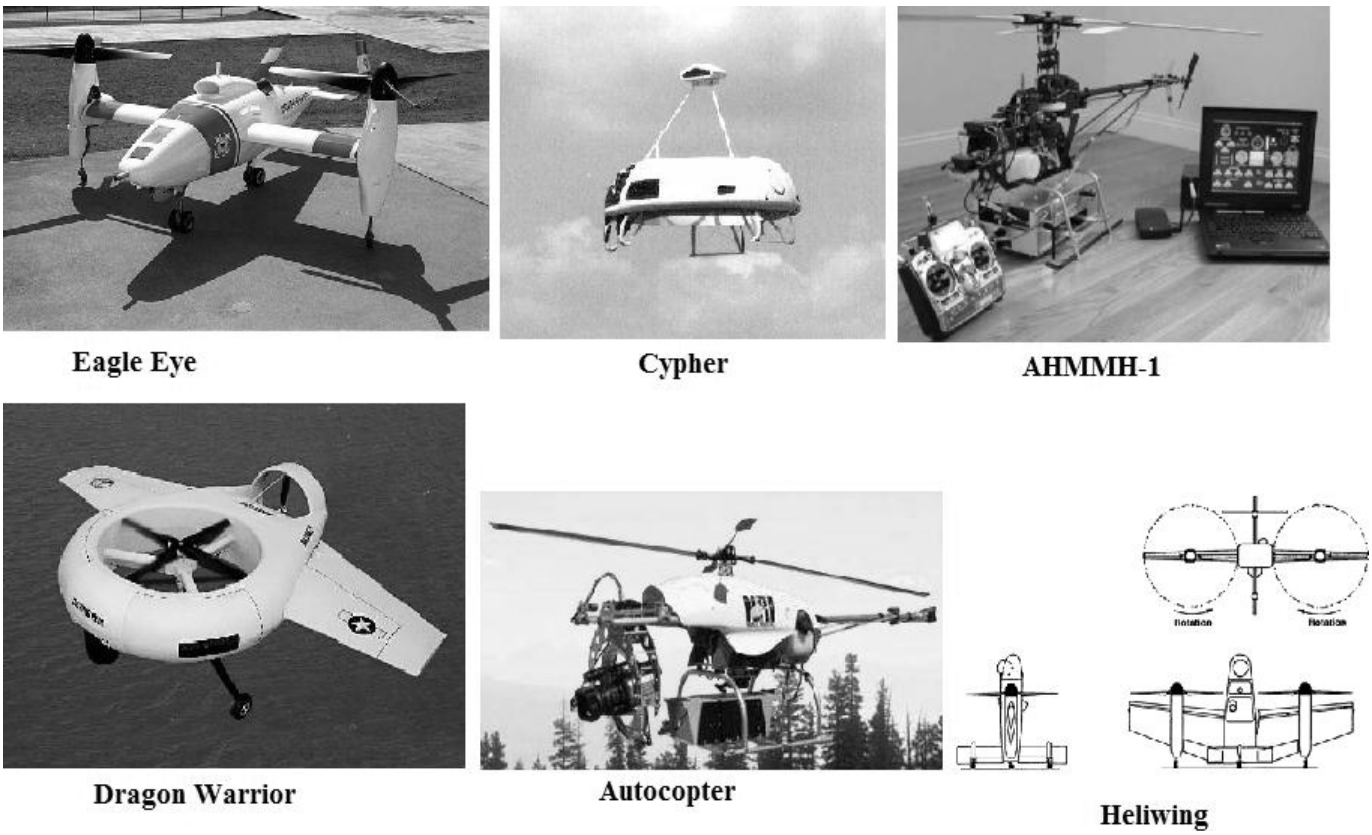


Figure 12. Illustrations of small VTOL UAVs[18].

So, let us consider briefly the performance and potential mission of this vehicle, then the form of it. Let us assume a mass of 37·2g for the empty vehicle, and a 10g payload, giving a gross mass of 47·2g, or weight of 0·463N. Available thrust at the propeller's optimised condition of 7·1W is 0·549N (56g) – an excess of 18·6% thrust over weight; this is satisfactory for both VTOL and for sustained flight. Constructing a power budget for a flight, Table 3 indicates that a mission endurance of around 149s: 2½ minutes is potentially achievable; this is short but may fit the vehicle for a short term emergency services surveillance mission inside a building carrying a micro-scale camera/transmitter package. Nevertheless, its hover capability will provide a further benefit with clearer image capturing compared to a forward moving vehicle.

For comparison Table 4 shows a selection of current MAVs in use; it will be seen that at a similar size to this study, the Black Widow is a successful 150mm span electric MAV capable of downlinking live colour video from a range of 1·8km, and provides a good benchmark; it is of a similar size and mass, but has a substantially (order of magnitude) better endurance and thus range. This clearly shows that the annular-Coanda wingform MAV must find advantages over conventional forward flight forms to hold any advantage – it is likely that this advantage, if it exists, will depend upon the ability to hover.

It is then interesting to conject the form of this vehicle. Figure 11 indicates the form of such an MAV – with the propeller mounted over the annulus driven by a thin shaft and bevel gear from a small electrical motor protruding from the wing surface, whilst the battery, any control circuitry and mission payload are contained within the wing annulus. If required, fine structural wires, similar to external bracing and undercarriage on a conventional microlight or vintage

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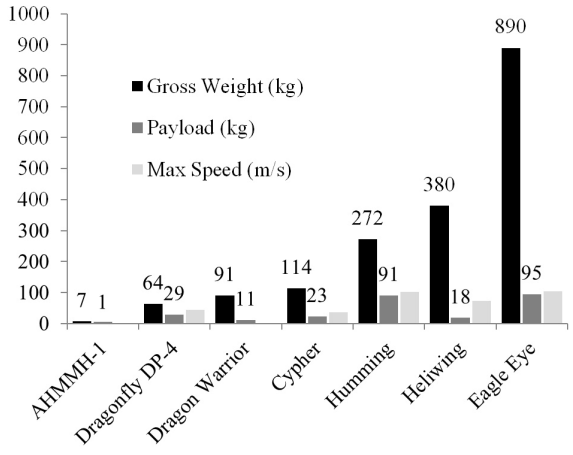


Figure 13. VTOL UAV data[13].

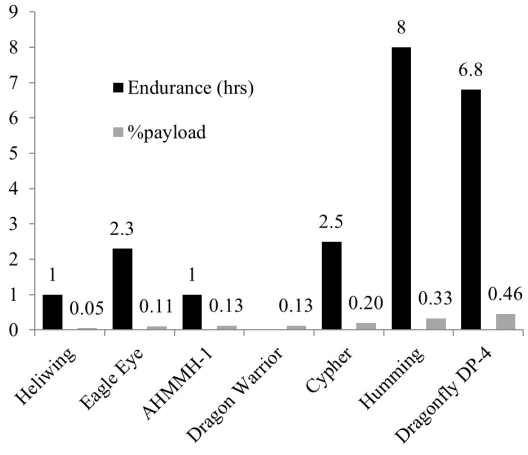
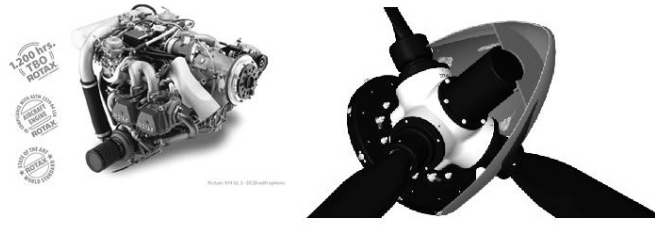


Figure 14. VTOL UAV performance chart.



Rotax 914 UL

Power: 75.5kW (100hp) @ 55,00rpm
Fuel Consumption: 33l/h @55,00rpm
Weight: 68kg

Airmaster AP332

Weight: 12.1kg
Diameter: 1.83m

Figure 15. Engine and propeller specifications[20].

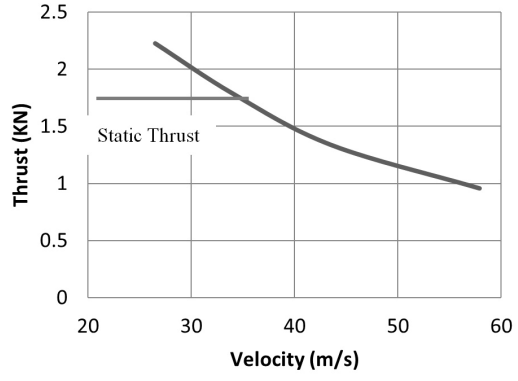


Figure 16. Thrust generated by propellers at different flowvelocities[22].

Table 4
Trend study of MAVs[17]

		Black Widow	WASP	HoverFly C	Carolo 40	Carolo 50	Dragon Slayer
Wingspan	*b [mm]*	152	330	~200	400	490	330
Length	*l [mm]*	152	-	-	-	-	-
Wing area	*S [m²]*	0.0195	-	-	-	-	-
Weight	*W [g]*	80	170	180	350	550	300
Endurance	*t [min]*	30	107	13.2	45	-	35
Airspeed	*V [m/s]*	13.4	-	15-20	20	15-20	18-40
configuration		flying wing	flying wing	flying wing	canard	classical	flying wing
planform		modified rectangular	tapered	rectangular	semi-elliptical	rectangular , T-tail	delta

aeroplane, may be used to support the structure. A circular tapered fuselage is chosen to have a minimum possible profile drag which for preliminary calculation purpose is taken to be equal to of a semi sphere (C_{DP} ~0·42).

4.0 EXAMPLE VEHICLE 2: MID-SCALE UNMANNED AERIAL VEHICLE

Currently UAVs are used primarily for military purposes; however, there has been considerable discussion about other potential roles including urban area surveillance, research flying in hostile environments, or 3D imaging for everyday improving mapping. This variety of roles precludes easy classification in terms of weight, size or endurance, as illustrated by Figs 12, 13 and 14. Typically smaller vehicles will achieve better endurance and payload fraction values.

So, for the time being, this scale will not be considered further since it offers no new lessons not found above for the MAV or in the following sections for larger vehicles.

5.0 EXAMPLE VEHICLE 3: FLYING CAR SCALE WITH INTERNAL COMBUSTION ENGINE

In the light aircraft design community, it has become common practice to design aircraft around common and preferred powerplant combinations; this approach will also be taken here in selecting the Rotax 914 liquid cooled four-stroke light aircraft engine, and an Airmaster AP332 propeller, shown in Fig. 15, this is a constant speed propeller specifically developed for Rotax 900 series engines (note: constant speed propellers are not most commonly used with these engines, but a variable pitch/constant speed propeller such as this, despite being heavier, offers certain efficiency advantages). Selecting this propulsion system enables us to again size primary vehicle components; this is shown in Table 5 below, which also assumes a standard pilot of 86kg (as in accordance with Ref. 3).

Figure 16 shows thrust characteristics of the fixed pitch propeller, indicating the static/fine pitch condition which has been estimated as equivalent to an air velocity through the propeller of about 33ms^{-1}. This indicates that the static thrust generated by the fan at about 1·8KN (175kgf) is approximately half of the 298kg minimum take-off mass. So, with currently available technology, an internal

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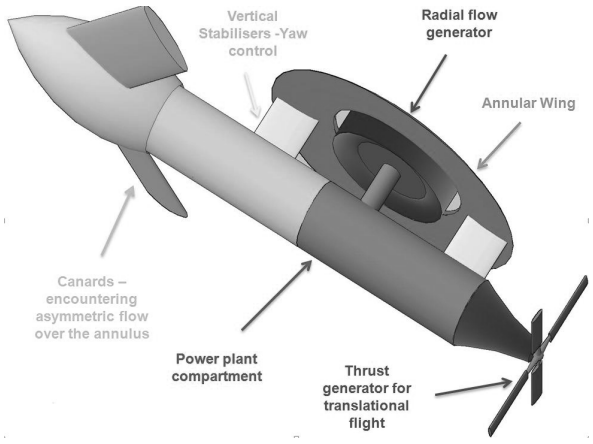


Figure 17. A conceptual sketch of single seat turboshaft powered flying car.

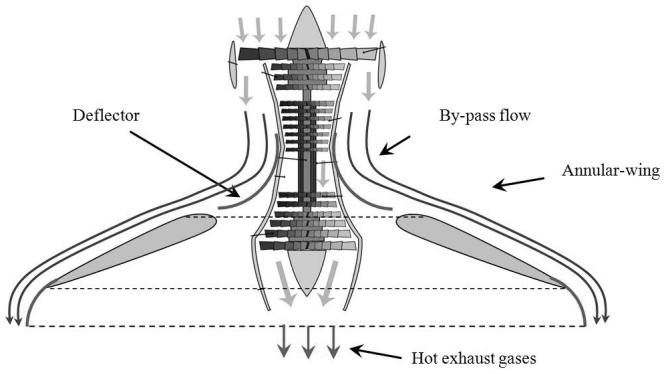


Figure 18. Possible configuration to integrate the annular-wing around a turbofan engine.

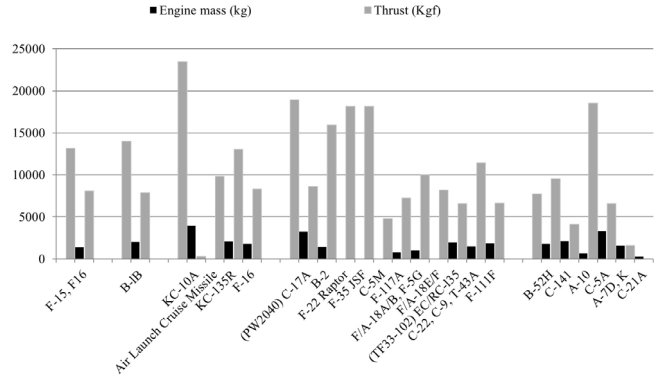


Figure 19. Military aircraft engine data[27].

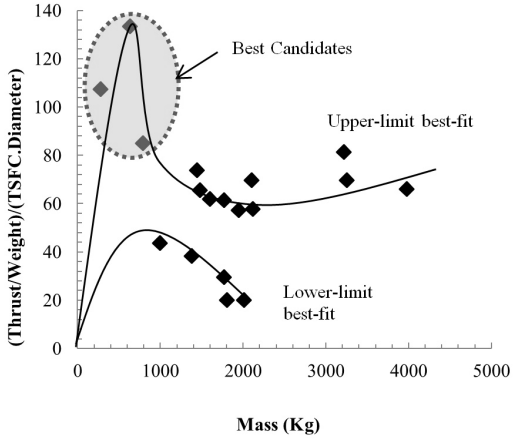


Figure 20. Thrust to weight ratio versus outer diameter of military aircraft engines.

combustion engine powered 'flying car' at the single seat scale would not be feasible.

However, lightweight turbo-shaft engines are readily available, for example the Pratt and Whitney Canada PT6 family. Taking for example the P&W PT6a-6 at its most basic low power free turbine model, this has a minimum available power output of 550hp which offers potential thrust of ~9kN (920kgf) whilst only requiring a slightly larger installed mass of 129kg[23]. This apparently permits a feasible 'flying car' scale vehicle, as shown in Table 6:

Table 5
Mass allocation for the primary flight system (flying car with Rotax 914 engine and constant speed propeller)

Component	Specification	Mass (kg)
Propeller	Airmaster AP332 (1.83m)	12
Fuel	50 litres (90mins) + 5kg lightweight tank and hosing	40
Engine	Rotax 914 UL (100hp)	68
Structure including wing	Represented by mass of the Alatus AL12 Ultralight Sailplane [1]	90
Avionics	AC200 SmartPitch	2
Pilot	Standard pilot as per CS.VLA	86
Minimum Take-off Mass		298

Table 6
Mass allocation for the primary flight system (flying car with P&WC PT6a-6 engine)

Component	*Specification*	*Mass (kg)*
Propeller	Estimated propeller mass	20
Fuel	200 litres (90mins at 60% available power) + 15kg lightweight tank and hosing	195
Engine	P&WC PT6a-6	129
Structure including wing	50% greater than that for 914 engined vehicle at **Error! Reference source not found.**	135
Avionics	AC200 Smart Pitch	2
Pilot	Standard pilot as per CS.VLA	86
Minimum Take-off Mass		567

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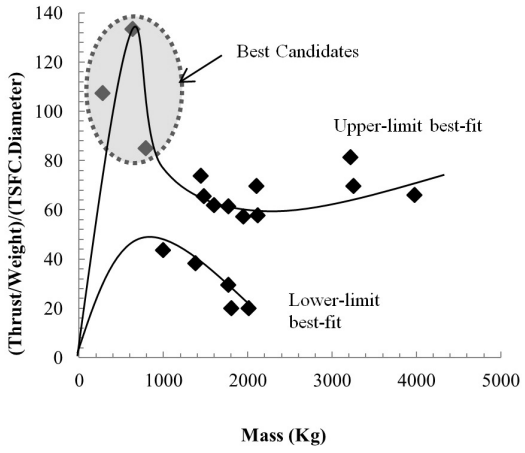


Figure 21. Performance parameter versus mass of engine.

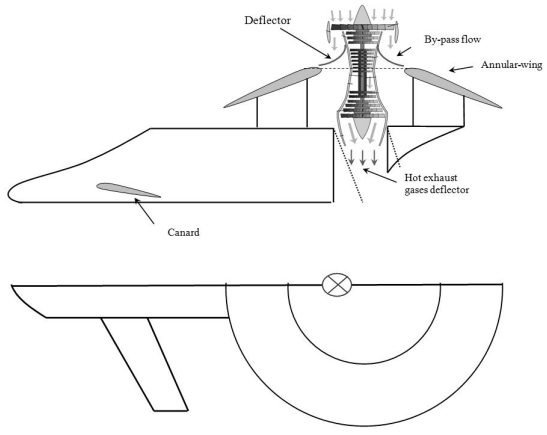


Figure 22. Sketch and basic configuration of a Harrier-like scale aircraft.

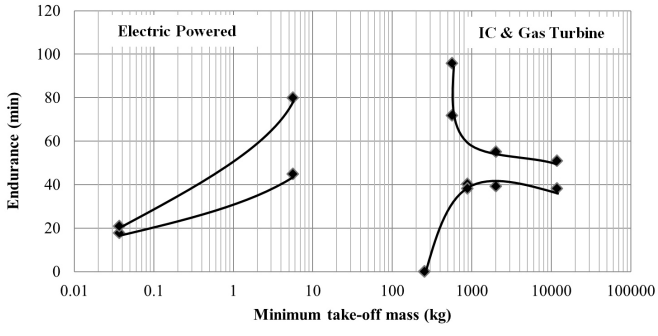


Figure 23. Endurance profile for different sized aircraft.

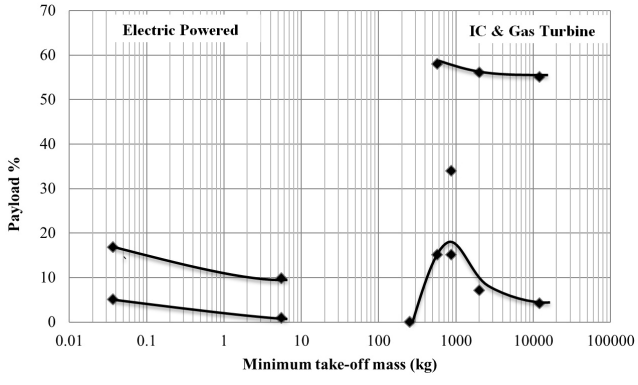


Figure 24. Payload performance for different sized aircraft.

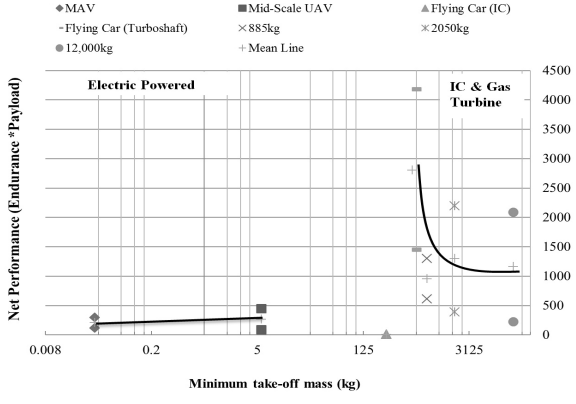


Figure 25. Performance summary.

This offers the potential of a turboshaft operated flying car with significant payload (~300kg), which may be feasible although will clearly be an expensive way of generating low performance single seat flight compared to most currently available options – an aircraft role would have to be found which justified this cost compared to the well-established helicopter option, given the low payload and low endurance. Nonetheless, such a role may potentially be found – most likely a reconnaissance or low-payload role in an environment where FOD (Foreign Object Damage) is a major concern – such as for example into confined space in jungle or urban areas.

A conceptual approach to such vehicle is displayed in Fig. 17. The proposal is to integrate the annular wing onto a radial flow generator driven by a turboshaft engine, also, driving a propeller to generate thrust in translational flight mode. The fuselage may be split into two compartments; one housing the powerplant, fuel/engine, and the other payload. Canards may be integrated to encounter pitching moment resulting from reverse flow, as discussed in Section 4.6, and hence may also offer better pitch stability.

6.0 EXAMPLE VEHICLE 4: LARGE VEHICLE WITH GAS TURBINE ENGINE

The next and obvious scale here would be a larger vehicle making fuller use of the capabilities of gas turbine engine technology. There are three major kinds of gas turbine engines: turbojet, turbofan and turboshaft/turbopropeller. This section proposes the integration of a high-bypass turbofan engine into an annular wing vehicle, a possible configuration for which is shown in Fig. 19. The arrangement is such that the by-pass flow, or the cold air from the fan, is extracted and blown over the annular wing which further deflects the flow vertically downwards. Typically, for a turbofan engine, around 70% of the thrust is generated by the fan and 30% from the hot exhaust gases[24]. This derives a new relationship of net lift/thrust generated by the annular-turbofan configuration.

$$Lift_{net} = \underbrace{0{\cdot}3Thrust_{engine}}_{\text{Thrust from hot-gas impulse}} + \underbrace{0{\cdot}65}_{\text{Annular Reduction Factor}} \times \underbrace{\left(0{\cdot}7 \times Thrust_{engine}\right)}_{\text{Thrust from by-pass flow}} \quad \ldots (2)$$

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$$\Rightarrow L_{net} \approx 0 \cdot 76 T_{engine} \quad \ldots (3)$$

The above expression shows that this arrangement, with partial axial flow, achieves significantly higher net lift/thrust compared to pure Coanda lift, although from operating experience there will be substantial operational concerns – particularly those associated with damage to the surface below the aircraft during take-off[25].

As shown in Refs 5 and 25 the thrust to weight ratio for a typical combat aircraft is necessarily above unity, hence, making their propulsion system a suitable design starting point for V/STOL applications, although some such aeroplanes with low bypass ratios will not suit this application whilst large commercial engines may well do. Figure 19 displays specifications of a range of engines used on large or combat aircraft; these engines have a range of bypass ratio from 0·4 to 6·42. The thrust to weight ratio of these engines is plotted versus the fan diameter in Fig. 20; the relationship is nonlinear, with installed thrust to weight values ranging from four to ten with a mean of six.

Generally, an engine's performance is evaluated from its thrust to weight ratio and thrust specific fuel consumption TSFC. However, for this particular configuration another crucial parameter, the diameter of the fan, needs to be considered. The specific performance parameter may be defined as $(T/W)(1/TSFC \times \text{diameter})$, which must then be maximised to ensure maximum endurance and payload, while keeping the diameter at a minimum to reduce the overall vehicle size and thus mass. The derived performance parameter is plotted in Fig. 21 for the range of turbofan engines presented in Fig. 19. The relationship between engine mass and the performance parameter is nonlinear forming two curves with lower and upper limits. There are clear maxima and hence maximum performance may be achieved by the General Electric T34 engine used on the A-10 Thunderbolt II and S-3 Viking aircraft. An interesting point to be noted here is that the winning engine has the highest bypass ratio (6.42) from the range considered: generally, engines with higher bypass ratio may offer better performance for the annular wing application. Selecting the best engine allows mass of the whole vehicle to be deduced in the table below. The flight endurance is given by;

$$Endurance = \frac{Weight_{fuel}}{Thrust_{req.} \times TSFC} \quad \ldots (4)$$

where the required thrust is defined as;

$$T_{req} = \underbrace{1 \cdot 1 \times 1 \cdot 32}_{\text{Reduction Factor}} \times \left(W_e + W_f\right) \quad \ldots (5)$$

This might potentially now be extended to a conceptual vehicle in the class of the Hawker Harrier, such as shown in Fig. 22. In this configuration the exhaust flow momentum would need to be deflected to generate forward thrust in cruise flight: in effect the core flow provides forward propulsion whilst the bypass flow provides lift, unlike a Harrier in semi-jetborne flight.

Table 7
Specification of an AV-8B Harrier II[28]

For comparison the specifications of the Harrier are presented in Table 7.

Length	14·12m
Wingspan	9·25m
Height	3·55m
Wing area	22·61m²
Empty weight	6,340kg
Loaded weight	10,410kg
Maximum speed	297ms^{-1} at sea level
Range	2,200km
Combat radius	556km
Ferry range	3,300km
Rate of climb	75ms^{-1}

Table 8
Component mass breakdown for proposed Harrier-like annular-Coanda vehicle

The predicted mass budget for this aircraft is given in Table 8 below.

Component	Specification	Mass (kg)
Engine	F108-CF-100 (1·83m diameter)	2,093
Fuel	1,000 litres	3,000
Payload		-
Structure	CFRP (1,600kg/m^3)	1,200
Avionics		250
Minimum Take-off Mass		6,543
	Payload Fraction %	**Endurance (mins)**
@T = 1·1W	7	56
@Tmax	36	50

Whilst this aircraft may have an equivalent weapons carriage role to that of the Harrier, it appears unlikely that it will at the current state of technology compare to it in terms of manoeuvrability or high speed flight.

7.0 PERFORMANCE SUMMARY

The achievable Endurance and Payload performance is evaluated in Figs 23 and 24 respectively for a range of take-off mass; each mass corresponds to a minimum and an absolute performance value. The maximum values on the endurance chart correspond to minimum values on a payload chart. The performance charts display two regions, with regard to powerplant, split by a region where the flight is not possible at that scale: that corresponding to a flying car with an internal combustion engine, of a similar scale to current light aeroplanes and helicopters. So, internal combustion engines are not feasible for medium scale annular wing configuration.

Figure 25 summarises the achievable performance range of different sized vehicles that may fall into certain class of aircraft. The net performance is taken as a product of endurance and payload fraction for two different thrust settings: firstly the thrust required for minimum take-off weight and secondly the maximum engine thrust available. Several crucial finding are derived from the above feasibility study and these are highlighted below.

- For a given class of propulsion, performance must be evaluated with regard to the size/diameter of fan/compressor, particularly because this influences vehicle size and thus empty mass.
- A turbofan engine with a high bypass ratio achieves relatively better performance range for the Coanda-annular wing configuration
- Maximum performance is achieved by selecting the engine with maximum specified performance parameter, defined above, that includes the fan diameter
- A larger vehicle (>600kg) with turbofan engine achieves significantly higher net performance compared with electric powered miniature aircraft.

8.0 CONCLUSIONS

It has been shown that the proposed annular wing lift-system is feasible at MAV scale, at a single-seat flying car scale if a

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turboshaft/turboprop (but not internal combustion) engine is used, and perhaps most effectively, at a large Harrier-like scale by integrating a large high bypass turbofan engine into the annular wing into a new type of combined lift/propulsion system. In none of these cases does the annular-Coanda wing offer performance (range, endurance or payload fraction) advantages over existing technology. The advantages then, if they exist, will concern then the specific characteristics of this wing – that is the combination of VTOL capability, and lack of external moving parts of lower/forward surface air intakes.

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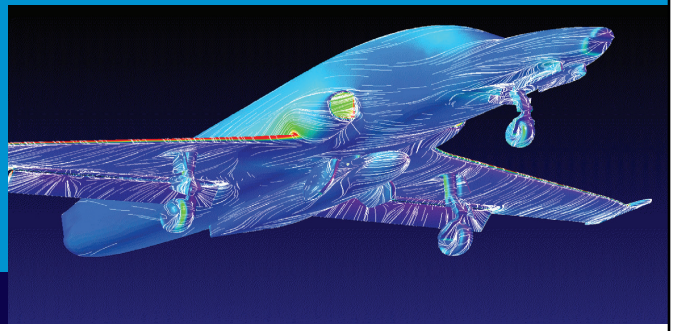
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