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DESIGN OF A FUEL CELL POWERED BLENDED WING BODY UAV

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ABSTRACT

Small-scale electrically powered Unmanned Aerial Vehicles (UAVs) are currently in use for a variety of reconnaissance and remote sensing missions. For these missions, electrical propulsion is generally preferred over small internal combustion engines because of the low noise and IR signature, low vibration levels, ease of operational support, and physical robustness. A desire for longer endurance than is available from the current generation of batteries has motivated the development of fuel cell based hybrid electrical propulsion systems. These advanced powerplant designs often include implementation challenges that will require new development methods and tools. Fuel cells generally lead to very low fuel weight at a high specific energy (Wh/kg) but have low specific power (W/kg). A high specific power is required to improve aircraft performance and manoeuvrability. Aircraft concepts powered solely by fuel cells therefore require both extremely lightweight airframes with a large internal volume and low-power payloads, which remains a challenge for conventional airframe designs. A blended-wing-body (BWB) airframe has high aerodynamic and structural efficiencies, which therefore seem ideally suited for this new generation of powerplants.

This paper presents the development and testing of a novel BWB fuel-cell powered UAV. The paper first describes the initial design steps that led to the current airframe design. The Mark 1 platform has been developed, with a half-scale model built and currently being flight-tested. Based on the flight test results, the airframe will be scaled up and optimised to accommodate the fuel-cell and its associated systems. This aircraft will then be tested with a standard electrical propulsion system to determine the airworthiness with the restricted fuel cell power output as well as the design of the take-off boost system. This paper reports on the design, analyses, and preliminary testing of a fuel cell powered BWB UAV.

NOMENCLATURE

AVL Athena Vortex Lattice
BWB Blended-Wing-Body
c.g. Centre of Gravity
HWIL HardWare-In-the-Loop
KAIST Korea Advanced Institute of Science and Technology
Li-Po Lithium-Polymer
slpm Standard Liter Per Minute
PEM Proton Exchange Membrane
UAV Unmanned Aerial Vehicle

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INTRODUCTION

Small-scale, electrically powered unmanned aerial vehicles (UAVs) are currently in use for a variety of reconnaissance and remote-sensing missions. For these aircraft, electrical propulsion is generally preferred over small reciprocating engines or gas turbines because of the latter's low efficiencies at small sizes [1]. Electrical propulsion furthermore offers low noise and thermal signatures, low vibration levels, and physical robustness. The mission duration is limited, however, by the energy density of existing batteries. Current lithium-polymer (Li-Po) batteries possess an energy density of 150-200 W-hr/kg [2,3,4,5], which typically provides a UAV with an endurance of 60-90 mins. In contrast, a compressed-hydrogen tank with a 6% hydrogen-storage weight fraction, capable of providing fuel for a fuel cell or internal combustion engine, has an energy density in excess of 800-1000 W-hr/kg [2,3,4,5].

A desire for longer endurance than is available from the current generation of batteries has motivated the development of fuel-cell-based electrical propulsion systems for small, tactical UAVs [5,6,7]. Flight demonstrations of surveillance-type UAVs have been reported by university and governmental researchers with some fuel-cell-powered UAVs are now being commercially available [8,9]. The US Naval Research Laboratory developed and tested the *Spider Lion* [10] and *Ion Tiger* aircraft; and academic projects have resulted in the construction and trial of *Hy-Fish* at the University of Applied Sciences in Wiesbaden, Germany, *Pterosoar* at California State University in Los Angeles [11], and *Endurance*, powered by a solid-oxide fuel cell, at the University of Michigan [12]. Fuel-cell-powered UAVs have also been developed and demonstrated by researchers at the Korea Advanced Institute of Science and Technology (KAIST) and Chosun University [13], at the Georgia Tech Research Institute [14,15,16], and at Colorado State University [3].

Fuel-cell based powerplant designs however present implementation challenges that will require new development methods and tools. The majority of the reports on trialled aircraft and published design studies of various classes of UAS [17,18,19,20,21,22] provide only "high-level" conceptual aircraft designs. The necessary "low-level" compromises between aircraft requirements and the characteristics of the powerplant are not addressed, though some efforts have been made to develop design methodologies that encompass these considerations [23,24,25]. Detailed descriptions of the design and performance of the structure and subsystems used in fuel-cell-powered aircraft are scarce [3,11,14,17,26], as are comparisons of aircraft-design parameters and flight-trial results [13,27]; and ground testing through HWIL simulation has been reported in only a few instances [3,26,28].

Fuel cells generally have low specific power (W/kg), compared with internal combustion engines; whereas high specific power is required to improve aircraft (speed) performance and manoeuvrability. Aircraft concepts powered solely by fuel cells therefore require both extremely lightweight airframes and low-power payloads but will still result in designs that are highly constrained operationally [29]. In a hybrid-electrical propulsion chain, the fuel cell is combined with secondary power sources of higher specific power to provide momentary high-power capabilities. This could alleviate the performance restrictions of the low specific power of the fuel cell, leading to a platform with a better overall performance [17,30]. Batteries or ultra-capacitors could provide this short-term high power boost capability as shown on Figure 1. The figure shows the tradeoff between specific power and specific energy for different technologies. As diagonal lines indicate operating times for the different technologies. As shown batteries or ultra-capacitors provide significantly higher specific power than fuel-cells but their use is however limited to shorter duration as their energy density is much lower. Extended operations of batteries or ultra-capacitors would therefore involve an extremely high weight penalty. Hybrid systems therefore offer the best of both worlds.

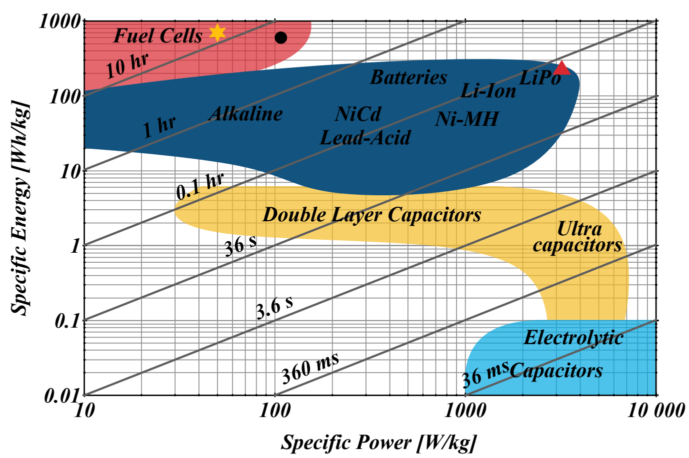

FIGURE 1. Ragone plot, adapted from [31]

Even with hybrid-electrical fuel-cell based propulsion systems, the aircraft performance will still be limited compared to conventional internal combustion powered platforms due to the limited available long duration power. This tends to drive existing fuel-cell powered platforms to very high aspect ratio designs to get high aerodynamic efficiencies [3,11,13,14,17,26,27,32]. A high aspect ratio however results in a higher wing weight as the wing root bending moment is increased. Novel airframe designs could however alleviate the performance restrictions. A blended-wing-body (BWB) airframe has high aerodynamic and structural efficiencies [33,34,35], which lends itself perfectly for this new generation of powerplants. After all, blending the wing and body leads to a reduction in airframe wetted area. This increases the overall wetted aspect ratio of the platform and leads to higher aerodynamic efficiencies without the need to go to very high aspect ratio wings [36].

The current article presents the design and development of a BWB fuel-cell powered UAV. The first section of the article describes the Aeropak hybrid electrical propulsion system around which the platform is designed. In a second section, the design and testing of the Mark 1 airframe is described. The development of the Mark 2 version is detailed next before conclusions are drawn and future work is outlined.

FUEL CELL BASED HYBRID ELECTRICAL PROPULSION SYSTEM

The propulsion system is built around the hybrid-electrical fuel-cell based Aeropak™ system from Horizon Energy Systems [37]. As shown in Figure 2, the system consists of a 35-cell Aeropak™ PEM fuel cell and a 6-cell 1350 mA-hr Li-Po battery pack. The fuel cell can deliver up to 10 A of current and has a nominal power output of 200 W. Its operating voltage ranges from 32 V (no load) to 21 V (full load). The fuel cell is self-humidified and air-cooled and only requires near-ambient cathode pressure. The hydrogen side (anode) is dead-ended, meaning all the hydrogen entering the anode compartment is either consumed by the fuel-cell reaction or wasted due to leakage.

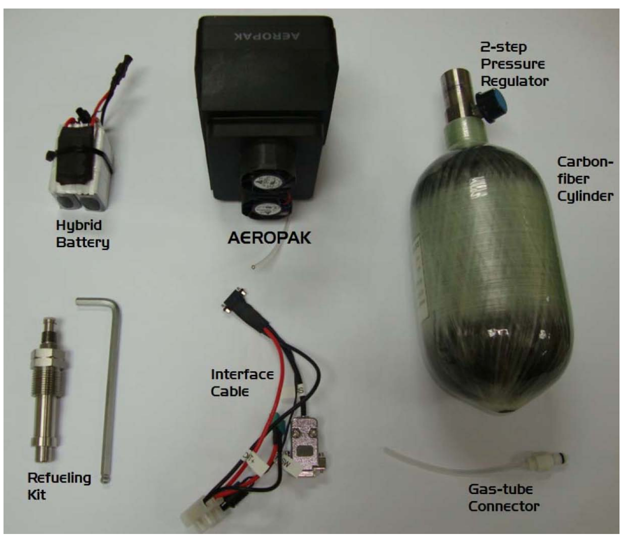

FIGURE 2. **Aeropak™ components**

The Li-Po battery is added to the system to provide a power boost capability of an additional 400 W for up to 2 min to meet the high-power requirements during UAVs take-off or climbing [37]. A power-management board combines the total power output from the fuel cell and battery before delivering it to the load and is limited to 800 W for ∼1 min to prevent its diode from overheating [37]. The board additionally recharges the battery when excess power is available from the fuel cell and provides power to the load during the short-circuiting of the fuel cell. The short-circuiting is built into the fuel-cell controller to increase the stack efficiency and forms part of the self-humidification process of the fuel cell [37]. During the short-circuit period, the controller disconnects the fuel cell from the load and the battery provides the total power required by the load.

As shown on Figure 2, the system includes an interface cable through which the fuel cell is started up and shut down. Through this cable several system parameters are reported. A carbon-fiber cylindrical tank with an integrated 2-step pressure regulator and a gas-tube connector to connect the fuel cell to the tank are included too. The Aeropak™ system can alternatively be purchased with either a bigger cylindrical tank, or with a hydride cartridge for operational convenience [37]. The hydride cartridges consists of a tank filled with $NaBH_4$ powder. When water is added to the tank hydrogen is generated and delivered to the fuel cell. Two different hydride cartridges are available providing 900Wh respectively 1750 Wh.

The fuel cell weighs 470 g and measures 8 by 12 by 10.6 cm. The battery and power management card weight 208 g. The 1.1-litre tank shown on Figure 2 weighs 1.12 kg, including the pressure reduction valve, has a diameter of 11 cm and a total length of 33 cm. The Aeropak™ system with the 1.1-litre tank has a power density of 125 W/kg, which is indicated by the black circle on Figure 1. The yellow star indicates the system energy and power density when the biggest of the two available hydride cartridges are used. The red triangle on Figure 1 denotes the 6 cell Li-Po battery of the system.

Due to the very small mass of fuel, fuel consumption is less critical in the flight stability of a platform powered by fuel cells as the aircraft is virtually flying at a constant weight. Fuel consumption data is nonetheless required for range or endurance estimates. A hardware-in-the-loop (HWIL) test bench has been constructed to obtain accurate fuel consumption data and to gain insight into the functioning of the power management card and fuel cell controller [28]. Fuel consumption was measured using this HWIL bench at several power settings; and the results are shown in Figure 3. The black symbols in the figure indicate "stationary" points where the power level was maintained for a sufficiently long period to ensure that transient effects were negligible. The blue symbols on the other hand indicate "transient" point, where the power was maintained for only a relatively short period.

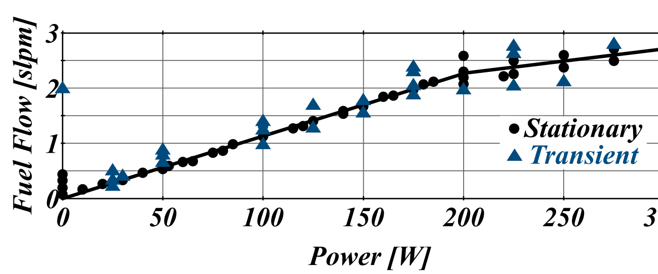

FIGURE 3. **Fuel-Cell Fuel Consumption [28]**

Figure 3 shows that the measured stationary fuel consumption is nearly linear up to 200 W, with a fuel consumption of approximately 2.25 standard liter per minute (slpm) at 200 W [28]. This corresponds to an efficiency close to 55% for the entire operating range between 40 and 200 W. Above 200 W, the slope of the fuel-consumption curve changes as the battery begins to contribute to the delivered power. At 300 W, the consumption is ∼2.69 slpm. At higher power settings, the fuel consumption levels off at ∼3 slpm [28]. At that setting, the fuel cell supplied around 270 W; and the remainder of the demanded power is supplied by the Li-Po battery [28].

During transient loads, the fuel consumption can vary significantly from the steady-state value as shown on Figure 3. Figure 4 indicates how the fuel cell can temporarily perform at voltages higher than the steady-state operating line (black line). The figure shows operating points measured during the simulation of a mission for a typical small tactical UAV. A previous paper [28] explained how this could be related to the hydration dynamics and temperature control of the fuel cell and depends on the design of the controller. More information on the mission performance can be found in that paper [28].

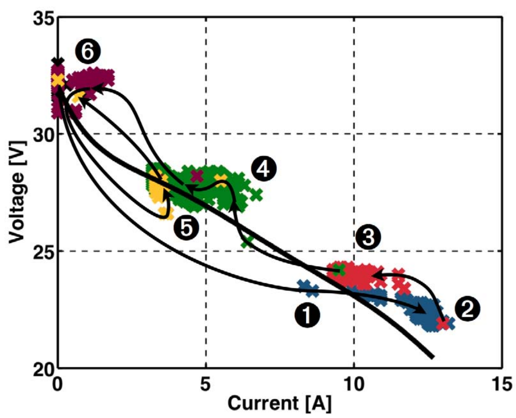

FIGURE 4. Transient performance during a mission simulation [28]

HYPERION/MILAN MARK 1 AIRFRAME DESIGN AND TESTING

As indicated previously, blended-wing-body airframes have high aerodynamic and structural efficiencies [33,34,35], which is well suited as fuel-cell powered platforms. The BWB configuration, as all tailless aircraft, however suffers from a reduced pitch stability [38,39]. The moment arm between the center of gravity (c.g.) and the elevator is short which means that the design is a compromise between static margin and elevator effectiveness. A practical c.g. placement leads to a reduced elevator moment arm which makes it difficult to trim the aircraft with reasonable elevator sizes and deflection angles. The reduced pitch stability furthermore prevents the use of flaps as the increased pitching moment can not be trimmed. Even without flaps, reflexed airfoils are required as they have low moment coefficients. For the airframe size under investigation airfoil selection is further complicated by the low Reynolds numbers at which the UAV has to operate. The low fuel weight when adopting a fuel cell however implies that the c.g. does not vary during flight, which reduces the aforementioned stability issues for the BWB platform. For the Milan, a platform wing sweep of 10° was adopted to provide the necessary roll stability without dihedral.

To investigate this complicated design space, a combination of panel methods was used in the preliminary design phase. AVL, a 2D panel method developed at MIT [40], was used for initial trade-off studies. Once a baseline was established, Panair, a full 3D panel method developed by Boeing and NASA [41,42], was used to fine-tune the design. After several initial configuration tradeoffs, a tractor configuration was selected to allow sufficient propeller clearance during takeoff. The tractor configuration additionally allows for a more forward c.g. placement, which allows a slightly reduced elevator size. A large single elevator with a chord of 20% of the main body was adopted to ensure that sufficient pitch control is available in the most critical flight conditions. Finally two vertical fins, one on each side of the body, were added to ensure weathercock stability. The fins were sized based on recommendations from [36]. Figure 5 shows the pressure distribution for the final Mark 1 configuration obtained with Panair.

The final wing area for the baseline configuration is 1.52 m^2 with a span of 3 m or an aspect ratio of 5.9. The takeoff weight is 16 kg for a stall speed of 15 m/s. The body length is 1.25 m. As only simplified panel methods were used to lay down the baseline configuration a half-scale model was built and tested in the 7 by 5 (7 ft by 5 ft test section) wind tunnel of the University of Sydney. These wind tunnel tests showed a very good agreement with the predictions obtained with Panair as shown on Figures 6 and 7.

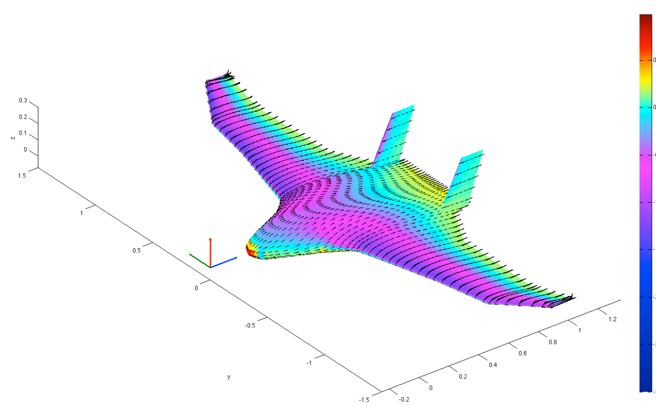

FIGURE 5. Pressure distribution from Panair for the Milan airframe

Figure 6 shows that the lift-to-drag ratio is accurately predicted by the Panair simulations except near stall, where the wind tunnel tests show a significantly higher lift-to-drag ratio.

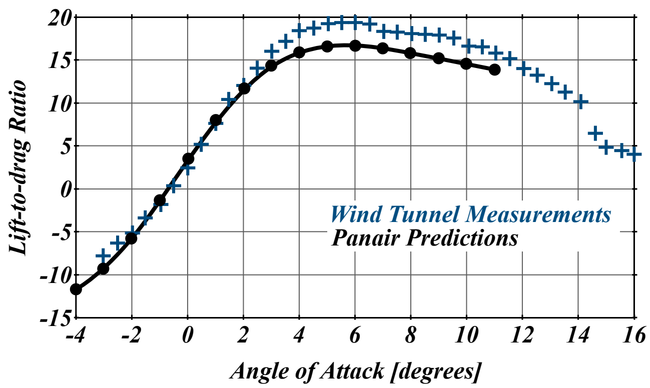

FIGURE 6. **Lift-to-drag ratio predictions and measurements at 20 m/s**

As shown on Figure 7, the overall drag polar is also predicted accurately. Only a small shift in minimum drag lift coefficient is observed which can be attributed to small differences in geometry between the wind tunnel and Panair models. The span efficiency obtained from wind tunnel data is slightly lower than the predicted span efficiency which can be attributed to low Reynolds number effects, which are not taken into account in the panel methods [43].

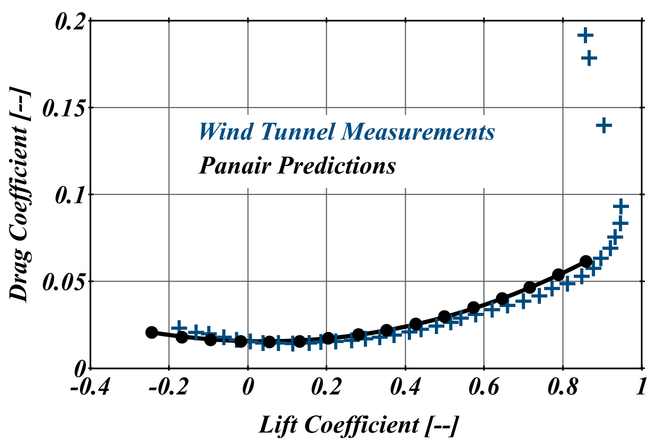

FIGURE 7. **Drag Polar at 20 m/s**

Flow visualisation in the wind tunnel revealed that the large change in chord in the wing-body transition area causes the aircraft to stall in this region and leads to an increase in lift-induced drag. Once the wind tunnel tests were completed, a full scale version was built and flown in Colorado [44]. These flight tests revealed that the aircraft has excellent handling qualities in flight. On takeoff, a reduced longitudinal stability was however observed, which can be attributed to propwash effects as explained in [43]. For the current BWB airframe, a significant portion of the airframe lift comes from the body, which is immersed in the propwash. As the neutral point of the body lies well forward of that of the wing, the propwash tends to shift the overall neutral point forward, which reduces the longitudinal stability on take-off. As this effect is caused by the interaction between the propeller induced flow field and the flow field over the body of the aircraft, it cannot easily be predicted using computational tools. By combining a propeller blade element momentum theory model with the Panair simulations a simplified and quick method that gave good agreement with powered wind tunnel tests was however devised, as detailed in [43]. Using this method, the c.g. of the aircraft was repositioned which resulted in excellent controllability on takeoff. Figure 8 shows the full-scale (Hyperion) Mark 1 UAV in flight at Colorado, USA.

FIGURE 8. **Hyperion UAV in flight at Colorado**

DESIGN OF THE MARK 2 MANTARAY AIRFRAME

After the successful flight tests of the Mark 1 airframe, the Mark 2 development was started based on the lessons learned during the Mark 1 development. In contrast to the initial version, the Mark 2 airframe was designed specifically to house the Aeropak™ fuel cell. As a consequence, the body volume had to increase considerably whilst simultaneously keeping the aircraft weight down. After all, the fuel cell only offers 200 W for cruise. Since takeoff from grass runways presented issues on several occasions, it was decided to design the Mark 2 airframe for launch and recovery without undercarriage. To allow a more detailed in-flight investigation into the longitudinal stability of the revised configuration a variable length inverted V-tail was also added. The tail is constructed so that the tail boom length can be varied in between successive flights to explore longitudinal stability and control. This allows flight testing at various tail volume coefficients and elevator arms. The wing aspect ratio was furthermore increased to 6.5 to reduce lift-induced drag and changes in chord-length were made more smoothly. To allow easy launching, the wing loading was limited to 4 kg/m^2.

To further enhance confidence in the design procedure and tools as obtained from Mark 1, it was decided to build a half-scale flying model of the new configuration before conducting further analysis and optimisation on the airframe design. Figure 9 shows the assembly of the half-scale model. As shown, laser-cut wooden ribs form the core of the structure. The body and wing are built from foam that is cut in shape using an in-house developed CNC hot wire cutter. The spar caps are built from carbon-fibre whereas the skin is make from fibreglass. The wings can be removed for ease of transportation and are held in place by shear clips in flight. The tail booms are carbon fibre rods.

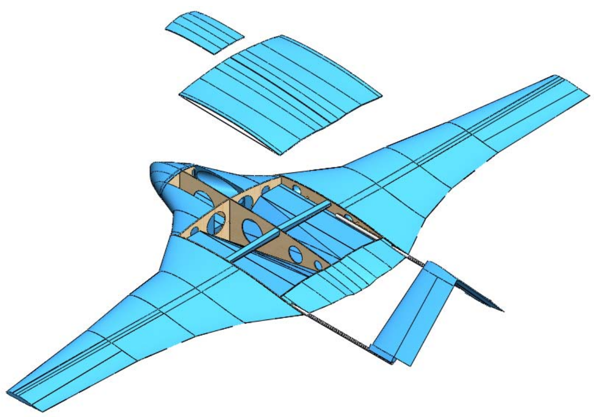

FIGURE 9. **Assembly of the half-scale Mantaray model**

Figure 10 shows the half-scale model in flight. The figure clearly shows how the belly of the body is shaped to provide grip for hand launching. The shape simultaneously serves as a landing skid. The figure also shows the alfa-beta vanes which form part of the flighttest data acquisition system that is currently under development. As shown the half-scale model is also equipped with a small digital videocamera positioned in the crest of the inverted V-tail.

FIGURE 10. **Flight of the Mantaray model**

This half-scale version weighs in at 2 kg for a wing area of 0.5 m^2. Flight tests show that the aircraft can easily be flown at 100-150 W, in contrast to a standard airframe of the same size (e.g. a Piper PA-28 model). The platform shows excellent handling qualities even at a much reduced tailboom length. Based on these flight tests, the Mark 2 airframe was redesigned slighlty. To limit the power requirement it was decided to keep the overall takeoff weight of the full scale version below 5 kg and to simultaneously increase the wing aspect ratio from 6.4 to 7.2. The maximum aspect ratio is limited by a wing span constraint of 3 m and the required wing planform area to keep the wing loading to 4 kg/m^2. This constraint was imposed to ensure that the wing weight remains sufficiently low to meet the takeoff weight restriction and to facilitate handling. Figure 11 shows the pressure distribution for the new airframe.

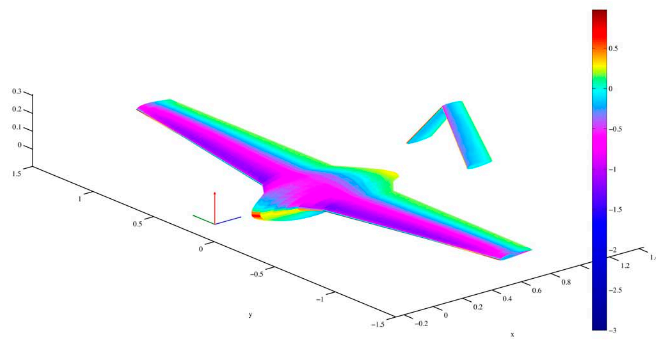

FIGURE 11. **Panair Pressure Distribution for the Mark 2.5 Airframe**

As shown on Figure 11 straight tapered wings are used for ease of manufacturing. A symmetrical airfoil was adopted for the body (in contrast to the reflexed airfoils used previously) so that the fuel cell/tank assembly, which is the heaviest component of the entire aircraft, can be placed on the c.g. Figures 12 and 13 show the predicted aerodynamic performance. The red triangles on Figure 12 indicate predictions from AVL, whereas the black circles and line indicate values derived from Panair. As shown on Figure 13 the stall speed of the Mark 2.5 airframe is approximately 8 m/s. This low stall speed is required for the hand launching and to minimise the impact on landing.

CONCLUSIONS

This work has highlighted an accelerated design-build-test UAV design life cycle, integrating the use of commonly available analysis tools with rapid-prototyping facilities. This approach shows promising outcomes towards the achievement of designing an airframe to very demanding power-weight requirements to capitalise on the benefits of fuel-cells. The rapid prototyping has

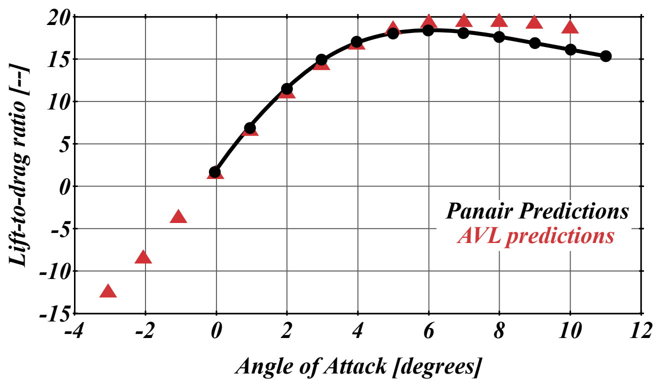

FIGURE 12. **Lift-to-drag ratio predictions**

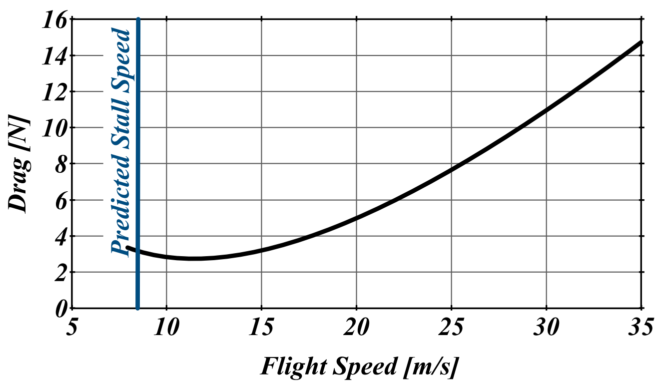

FIGURE 13. **Drag and Stall Speed Predictions**

enabled to establish confidence in the used panel method tools and design methodology.

The designed blended wing body platform has shown to provide good flight stability characteristics. The flight tests demonstrate that the platform operates well at low power as is required as a consequence of the restricted power output of fuel cells. The platform therefore allows to utilise the advantages of fuel cell technology while managing its shortcomings.

ACKNOWLEDGMENT

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