FLIGHT TEST OF A FUEL-CELL/BATTERY/SUPERCAPACITOR TRIPLE HYBRID UAV PROPULSION SYSTEM

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Abstract

This paper presents the world's first flight test results of a hydrogen fuel-cell/battery/supercapacitor triple hybrid power system for UAV propulsion. An introduction to the flight test vehicle is provided, followed by details of the fuel-cell, battery and supercapacitor and integration to form a cohesive triple hybrid power system in the UAV. Flight test results are analysed for two flights, demonstrating the impact of the supercapacitor to provide load smoothing to the fuel cell during dynamic flight conditions. The supercapacitor is found to provide a maximum boost power of 310 W and absorb up to 100 W, and cycles more than 1.4 Wh of energy during the second test flight.

1 Introduction

Hydrogen fuel-cell based hybrid power systems are under consideration as a technology to improve the range and endurance of small electrically-powered unmannned aerial vehicles (UAVs) [1–4]. Hydrogen fuel-cells have a considerably greater specific energy than competing electric power sources, whilst maintaining the benefits of zero CO_2 emissions, reduced noise, and low thermal signatures [5, 6]. However, despite significant progress in the past few years, fuel-cells still possess relatively low specific power and comparatively slow response to transient loads.

Hybrid power systems, where multiple power sources are combined, allow the benefits of fuel cells to be leveraged whilst minimising the potential downsides. Batteries and supercapacitors are fast acting power sources with high specific power, and can act as a buffer during periods of high power demand and rapid load transients [7]. This provides a short reserve of boost power for take-off, climb and other manoeuvres, as well as smoothing the load on the fuel cell for enhanced fuel cell life.

This article will outline the world's first flight testing of a hydrogen fuel-cell/battery/supercapacitor triple hybrid in a UAV. A description of the flight test vehicle is given, along with details of the fuel-cell, battery, supercapacitor, and other components that make up the triple hybrid system. Next, the integration of the power system will be presented along with flight test results showing the overall performance of the propulsion system.

2 Airframe

A 1:6 scale Aeronaut model Grob 109 is used as the airframe for flight testing of the triple hybrid power system (Figure 1). This aircraft has a wingspan of 2.8 m, a wing area of 0.577 m^2, and nominal take-off weight of 4.8 kg (Table 1).

The addition of the fuel-cell hybrid system and instrumentation increases the weight to 6.5 kg.

Fig. 1 : UAV undergoing flight testing

Table 1: Grob G109 UAV Specifications

Specification	Value
Nominal take-off weight	6.5 kg
Wingspan	2.77 m
Length	1.4 m
Aspect ratio	13.9
Wing area	0.577 m^2

The Grob features a lightweight fibreglass fuselage with cut-outs for the transparent polycarbonate canopy. The wings consist of a foam core surrounded by fibreglass reinforcement, and is surface finished with a layer of Obeche hardwood. A layer of coloured plastic film is further added to provide a consistent appearance and low drag finish. An 8mm solid carbon fibre spar is used to support the wings with the carry-through reinforced into the centre fuselage. The rudder and elevator control surfaces are built up from plywood ribs and balsa spars finished with plastic film for the skin. A 10 mm plywood firewall is fibreglassed into the fuselage to provide a sturdy mount for the motor, motor controller, and hydrogen storage system.

3 Triple Hybrid Power System

3.1 Hybrid Architecture

The triple hybrid architecture takes advantage of the performance characteristics of each power source. The hydrogen fuel cell performs best when used for low power and long endurance, whilst the supercapacitor provides short bursts of high power and can be rapidly recharged. Because of the limited energy stored in the supercapacitor, a battery is still required to satisfy the medium duration high power requirements. This battery provides the excess power needed in flight stages such as take-off and climb, and is sized to provide the required duration of boost power. The fuel cell, battery, and supercapacitor are all placed in parallel, enabling load sharing between each of the three power sources (Figure 2).

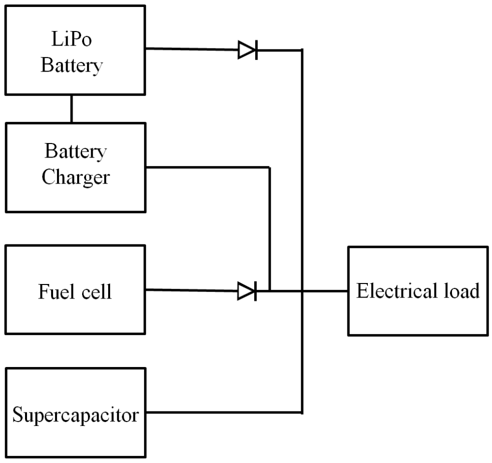

Fig. 2 : Hybrid Configuration

The supercapacitor acts constantly in unison with the fuel cell to provide load smoothing and reduce the rate of change of current seen by the fuel cell. The battery system does not act until the electrical load demand is great enough to bring the fuel cell steady state voltage below the voltage of the battery (16.8 V for a fully charged 4S battery). Once the fuel cell voltage is at the same level as the battery voltage, all three power sources work together with power management achieved through voltage matching of the three components. To ensure safe operation, power is not allowed to flow back to the fuel cell and power to recharge the battery is limited by the maximum charge current. This leaves the supercapacitor to absorb the bulk of any excess power from the fuel cell during rapid decreases in throttle. The voltage matching ensures that when the fuel cell is at full power there is always capacity to store excess energy in the supercapacitor.

3.2 Fuel Cell

The fuel cell stack that forms the core of the hybrid propulsion system is the FLY-150 polymer electrolyte membrane (PEM) fuel cell manufactured by Spectronik (Figure 3). This is a lightweight 150 W rated fuel cell stack with 25 cells in series giving an operating voltage range of 15 V–23 V. A plastic casing is used to keep mass to a minimum. A single fan is used to manage both reactant flow and cooling, and the fuel cell is self-humidifying eliminating the requirement for external reactant humidification. However, self-humidification has implications such as slower response to transient loads compared to humidified fuel cells [8]. Specifications can be found in Table 2, and detailed performance characteristics in Ref [9].

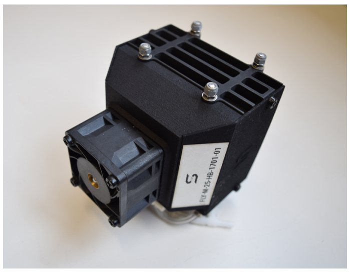

Fig. 3 : Spectronik Fuel Cell

Table 2: Spectronik FLY-150 PEMFC Specifications

Specification	Value
Number of cells	25
Rated power	150 W (10 A @ 15V)
Weight	320 g
Max H_2 flow rate	1.75 slpm @ 150 W
H_2 pressure	0.4-0.7 bar
Peak Efficiency	48%
Humidification	Self-humidified

3.3 Battery

The fuel cell hybrid system requires an auxiliary power source during high power and rapid transient loads. This auxiliary power source is most commonly provided by a battery. For UAV applications, lightweight high performance lithium polymer (LiPo) batteries are the preferred battery chemistry with high specific energy and power levels [10–12].

For these tests, high discharge rate LiPo batteries are used to provide maximum additional power for a given weight. Turnigy 65 C rated 1500 mAh batteries are used as the nominal battery, with the 4S (four cells in series) battery chosen to best match the output voltage characteristics of the Spectronik fuel cell. A 4S battery will begin to provide power at 15–16.8 V, depending on the state of charge of the battery. This enables the battery to provide power while the fuel cell is running close to its maximum power. Charging control is provided by a Spectronik supplied PCB which operates at a fixed charge rate. The PCB can be reconfigured via a resistor to operate at a charge current from 1–10 A. For these tests, a nominal charge current of 1 A (0.67 C) is used. Specifications of the battery can be found in Table 3.

Table 3: Turnigy 4S 1500 mAh 65C LiPo battery

Specification	Value
Number of cells	4
Nominal voltage	14.8 V
Weight	343 g
Max current	97.5 A

3.4 Supercapacitor

An alternative auxiliary power source for use in fuel cell based hybrid power systems is the supercapacitor, also known as an ultracapacitor. Supercapacitors have a high current capability, enabling both rapid charge and discharge capabilities [13]. This is particularly advantageous when a quick recharge is required to regain the boost ability from the auxiliary power source. Furthermore, supercapacitors can deliver power over the full voltage range from 0 V to the maximum nominal voltage, compared to batteries which must operate within the range of minimum and maximum voltage. Cycle lifetimes in excess of

10 million cycles have been reported, making them highly suited to load transient smoothing and load levelling [14]. The main drawback is that supercapacitors have a lower specific energy than batteries, leading to a reduced energy capacity for a given mass.

A Yunasko supercapacitor is selected to provide a high power supercapacitor in a compact format. The Yunasko supercapacitor consists of small pouches assembled together in a compact rectangular shape. A maximum voltage of 25 V was selected to provide a well matched system for the Specktronik fuel cell, with an overall capacity of 7 F. Two assembled Yunasko supercapacitor modules are shown in Figure 4, with the specifications of the modules given in Table 4.

Fig. 4 : Yunasko Supercapacitor Bank

Table 4: Yunasko Supercapacitor Specifications

Specification	Value
Part Number	YEDLM-0007E25R
Capacity	7 F (0.6 Wh at 25 V)
Max current	10 A, continuous
	50 A, burst
Max nominal voltage	25 V
Weight	279 g
Specific energy	2.2 Wh/kg
Specific power	2.7 kW/kg
	5.6 kW/kg burst

3.5 Hydrogen Storage

Hydrogen storage is provided using metal hydride canisters mounted to the motor firewall. Eight HydroStik Pro canisters and pressure regulators manufactured by Horizon Fuel Cell Technologies are used to supply hydrogen to the fuel cell system. Details of the hydrogen storage system can be found in reference [9].

3.6 Airframe System Integration

All propulsion system components including the fuel cell hybrid system and data acquisition system are integrated into the fuselage of the Grob G109 model airframe. A summary of the components used in the Grob G109 flight test vehicle is provided in Table 5, with a weight breakdown of the aircraft given in Figure 5. This includes both the power generating components (fuel cell, battery and supercapacitor) as well as the power sinking components (electronic speed controller, motor and propeller).

Table 5: Baseline Flight Test Components Used

Component	Model
Propeller	APC 17x12 thin electric
Motor	Rimfire .55 480 kV
ESC	Castle Creations Phoenix Edge HV 120
Fuel cell	Spectronik FLY-150
Battery	Turnigy Graphene 4S 1500 mAh
Supercapacitor	Yunasko 25 V 7 F
Receiver	Spektrum AR9020
Flight logging	PIXHAWK + Raspberry Pi
Comms radio	433 MHz serial

3.7 Power System Integration

The Spectronik fuel cell and controller are mounted on a laser cut plywood tray, which is then attached to mounting points in the aircraft fuselage (Figure 6). The battery charge controller is also fastened to this tray, to enable easy removal of the complete fuel cell and associated electronics. The LiPo battery itself is located in the space between the plywood tray and the fuselage bottom, allowing for repositioning of the

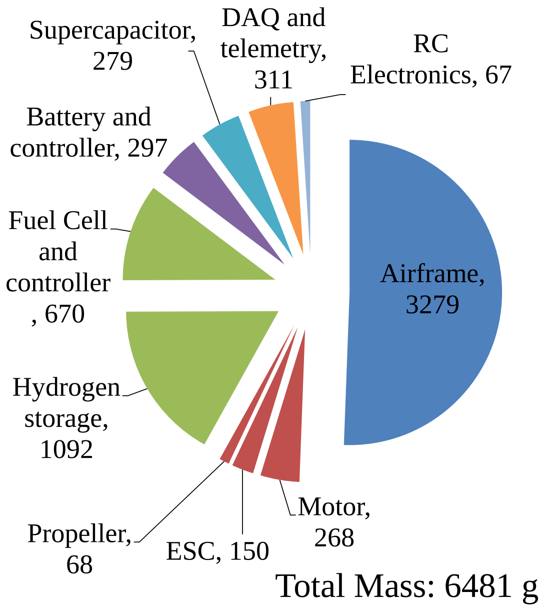

Fig. 5 : Mass Breakdown (in grams)

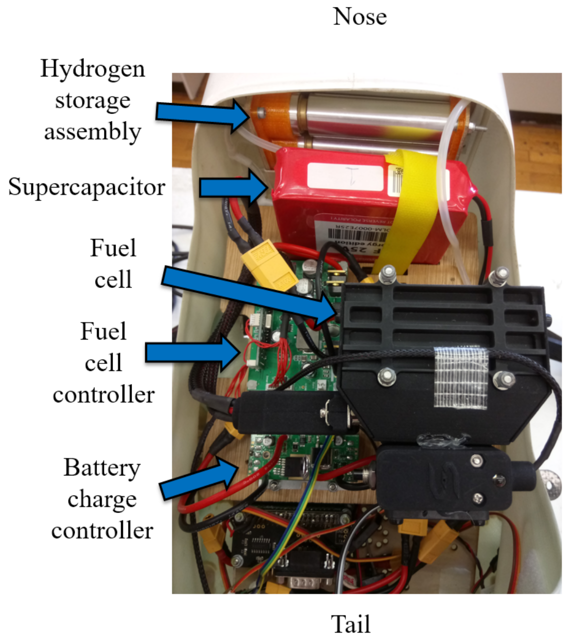

Fig. 6 : Hybrid Power System Integration into Airframe

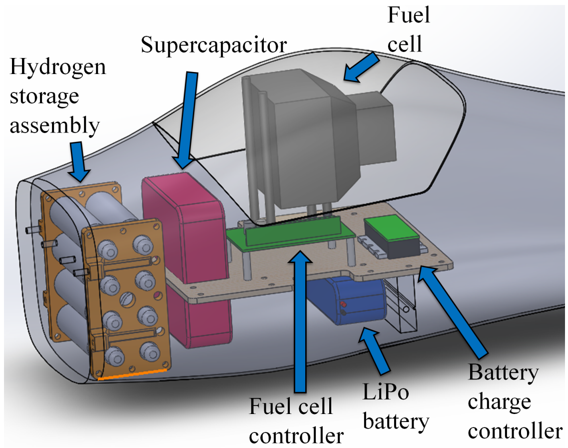

Fig. 7 : Complete Fuel Cell Triple Hybrid Vehicle Integration

centre-of-mass to fine-tune the aircraft centre of gravity (Figure 7). The Hydrostik metal hydride hydrogen storage assembly has substantial mass (>1 kg), and is fastened to the rear of the firewall inside the main section of the fuselage. Four bolts hold the assembly securely in place. The supercapacitor module is secured into a slot between the hydrogen storage assembly and the fuel cell. The complete fuel cell hybrid power system is shown in Figure 7. Wiring and hydrogen gas piping is not shown for clarity.

3.8 Propulsion Unit

The electric propulsion system consists of a motor, speed controller and propeller commonly used in hobby RC aircraft. A Rimfire .55 480 kV motor is used to drive an APC 17x12 thin electric propeller. Motor control is provided by a Castle Creations Phoenix Edge 120 HV controller rated up to 120 A and 50 V. Further details can be found in ref. [15]

4 Flight Test Results

The flight testing aims to validate the performance of the supercapacitor in the triple hybrid system, with results of two flight tests using this power system presented here. The supercapacitor is used to provide load smoothing to the fuel cell by either releasing or absorbing power during electrical load changes. These two flights represent two different profiles, with the first operating for extended periods of time at constant throttle to represent performance under cruise type conditions. The second test flight has multiple climb and descent phases with increases and decreases in throttle setting to demonstrate performance under a more dynamic flight profile.

4.1 Flight 1

The first triple hybrid flight test is approximately 10 minutes in duration. This flight consists of take-off, climb to 50 m followed by cruise at approximately constant power for a period of time. The aircraft altitude and airspeed during the flight are seen in Figure 8.

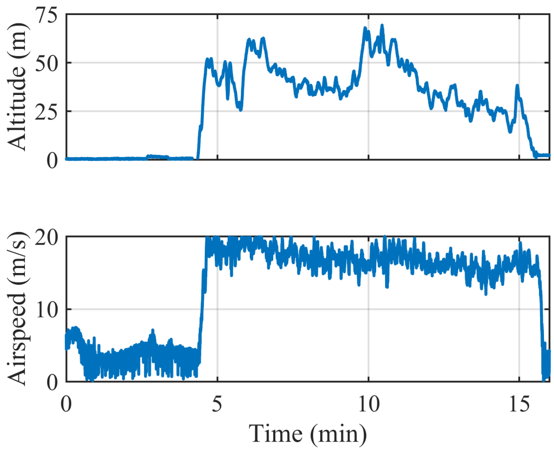

Fig. 8 : Triple Hybrid Flight 1 Altitude and Airspeed

The voltage, current, and power delivered by each of the power system components can be seen in Figures 9, 10, and 11. The fuel cell idles at a voltage of 20–21 V, before dropping to 14.5 V under the high power demand of the take-off roll. There is some fluctuation in voltage due to throttle changes from 4–7 minutes, before the aircraft settles into a constant power cruise between 7–9 and 11-14 minutes. During this flight, it can be seen that there is reduced voltage fluctuation of the fuel cell, battery, or supercapacitor, particularly during cruise from 7–14 mins. This is primarily due to the constant throttle setting being maintained for long periods during cruise. However the supercapacitor also has a stabilising effect on the fuel cell and overall system voltage. Airspeed is maintained at 16–18 m/s with power demand of ≈ 100 W for cruise.

The power source currents are displayed in Figure 10, with negative current signifying recharging of that component. During the initial

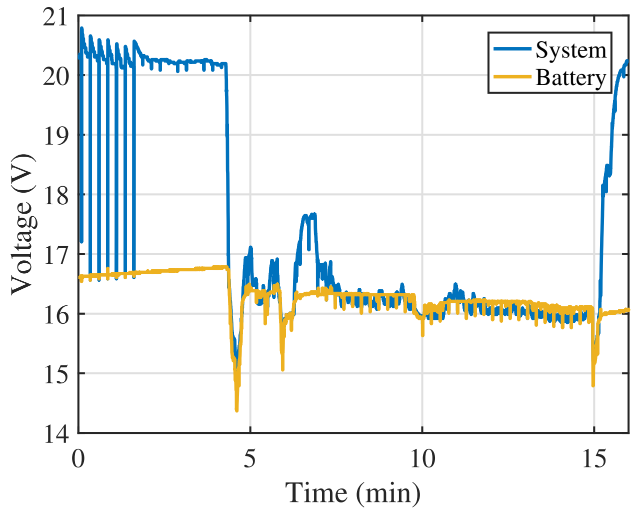

Fig. 9 : Triple Hybrid Flight 1 System Voltage

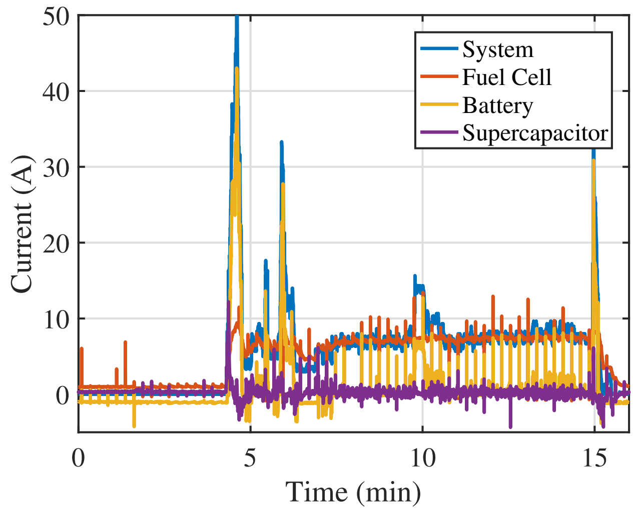

Fig. 10 : Triple Hybrid Flight 1 System Current

throttle up on take-off, all three components (fuel cell, battery, and supercapacitor) provide current for a total of 50 A. The fuel cell and supercapacitor current can be seen more clearly in Figure 12, which shows a zoomed in display of the current and power output of these components. Note the gradual ramp up in fuel cell current to 10 A starting at 4.25 mins as the supercapacitor provides a peak of 12 A during the initial throttle up. Power output shows a similar trend, with the supercapacitor providing a peak power of 200 W in response to the large increase in power demand allowing the fuel cell power to gradually ramp up. However, once the current demand has decreased (and the voltage increasingly slightly),

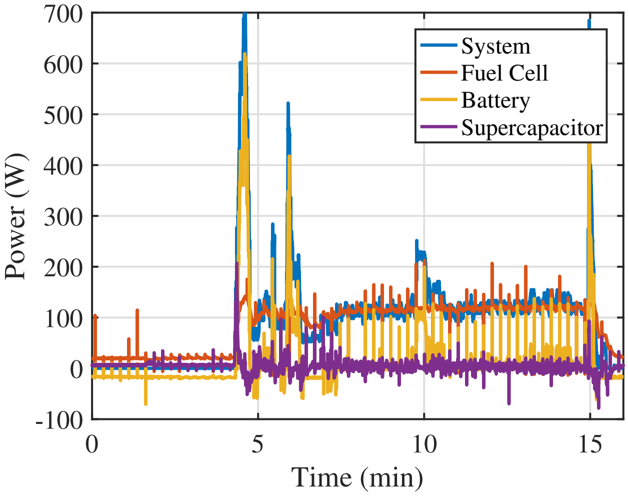

Fig. 11 : Triple Hybrid Flight 1 System Power

the fuel cell and battery supply current while the supercapacitor absorbs current to recharge. Except for the brief burst of power required from 9.5–10 mins, the battery and supercapacitor provide minimal contribution to the system current and power. The battery provides a higher power boost up to 100 W at 9.5 mins in response to a short period of climb. The supercapacitor provides smoothing by providing up to ±20 W of power in cruise in response to load fluctuations. However as the load is relatively constant the voltage does not fluctuate much and the supercapacitor is not highly active in absorbing or releasing energy.

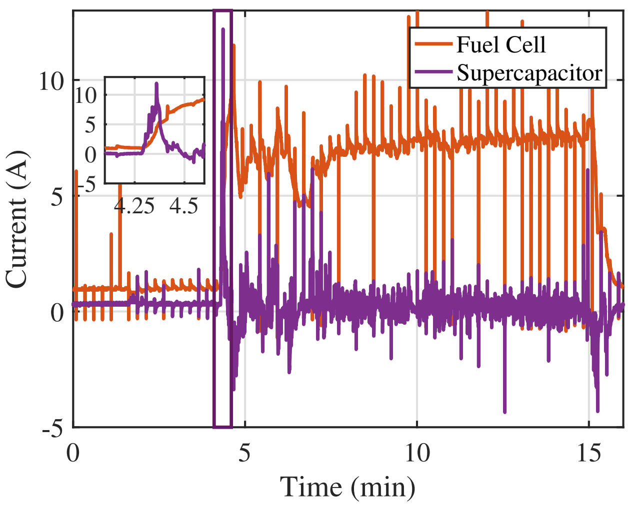

Fig. 12 : Flight 1 Fuel Cell and Supercapacitor Current

To quantify the impact of the supercapacitor on electrical load smoothing, the total energy absorbed and released by the supercapacitor over the flight is shown in Figure 13. The supercapacitor module absorbs 0.92 Wh of energy and releases 0.82 Wh of energy. This compares to the fuel cell which released 23 Wh and the battery which released 5 Wh but absorbed only 2 Wh of energy. Thus, the supercapacitor with a total energy storage capacity of 0.47 Wh has cycled more than double its capacity over the course of a 10 minute flight.

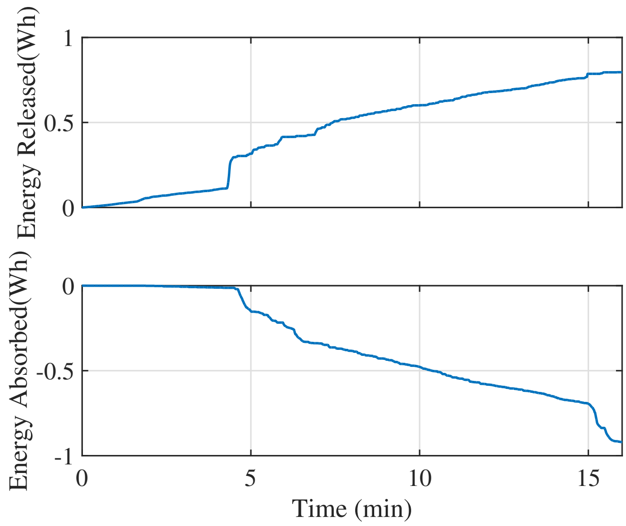

Fig. 13 : Flight 1 Supercapacitor Energy Released and Absorbed

Hydrogen pressure and fuel cell temperature are shown in Figure 14. The hydrogen pressure decreases from 0.5 bar to 0.25 bar as the hydrogen in the metal hydride cartridges is depleted. Fuel cell temperature rises quickly to 53 °C before remaining steady at 48 °C for most of the flight.

The fuel cell power, estimated fuel flow, and estimated hydrogen consumption are given in Figure 15. Steady state cruise fuel consumption is approximately 1.3 slpm, and a total of 17 L of hydrogen was used over the duration of the flight.

4.2 Flight 2

This flight demonstrates the operation of the fuel-cell/battery/supercapacitor triple hybrid in a more

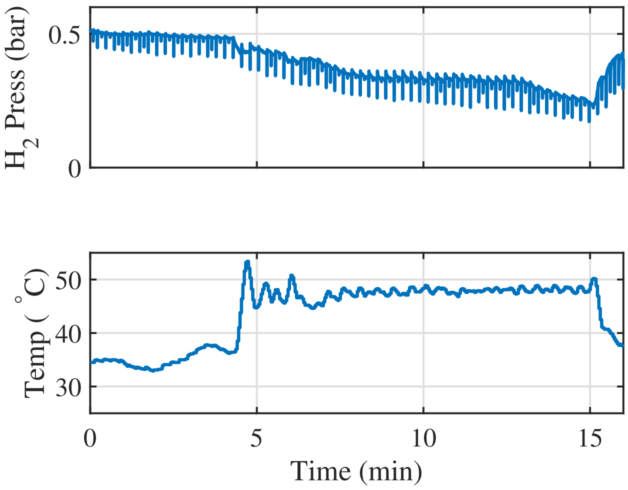

Fig. 14 : Hydrogen Pressure and Fuel Cell Temperature

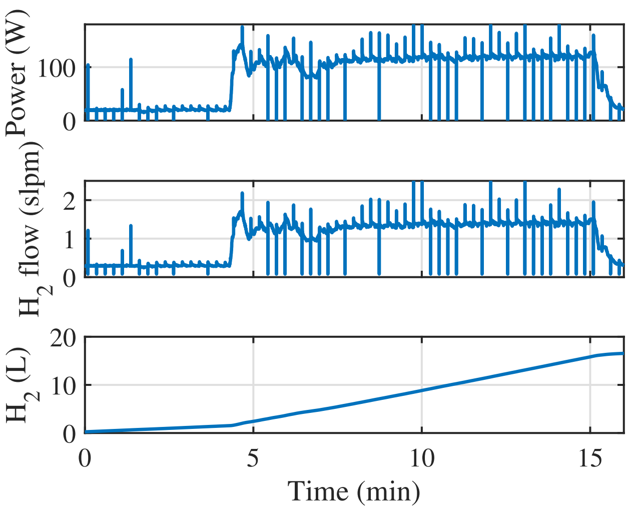

Fig. 15 : Fuel Flow

dynamic flight profile. The supercapacitor is most active during rapid changes to throttle (and power), providing load smoothing to the fuel cell and boost power for short bursts. It is anticipated in this flight test that the supercapacitor will provide much greater quantity of load smoothing to the fuel cell system.

The ground track of this second triple hybrid flight test can be seen in Figure 16. A series of circuits were performed over a duration of approximately 10 minutes, with a number of throttle changes ranging from high to zero throttle. The altitude and airspeed over the duration of the flight can be seen in Figure 17.

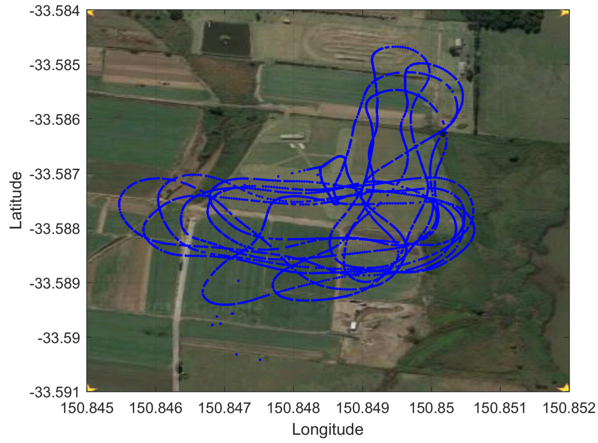

Fig. 16 : Flight 2 Ground Track

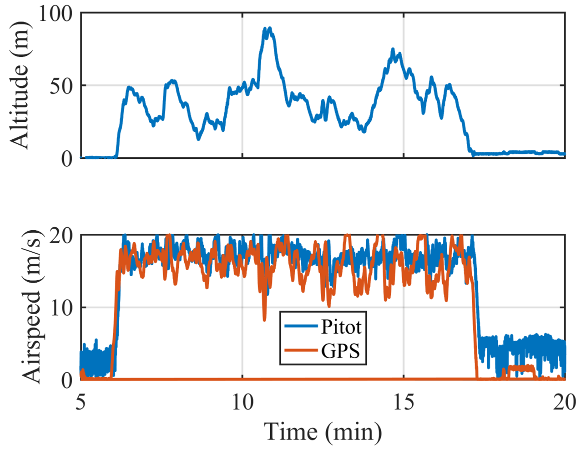

Fig. 17 : Flight 2 Flight Profile

The voltage, current, and power evolution of each power system component is presented in Figures 18 and 19. The fuel cell and supercapacitor voltage fluctuate between 14 and 20 V, while the battery voltage remains more constant at between 14–16.8 V.

The system current and power outputs show the large throttle changes commanded, with numerous current spikes above 25 A with corresponding power requirements above 300 W, and two short bursts exceeding 500 W. These large throttle commands require much more power from the hybrid system compared to the previous flight, with both the battery and the supercapacitor providing significant extra power and load smoothing respectively. A zoomed in view of the fuel cell and supercapacitor power is given in

Figure 20. The supercapacitor module provides a maximum boost of 310 W during this flight, with a maximum of 100 W absorbed during rapid throttle decreases. Peak current for the supercapacitor exceeds 15 A when supplying power and 5 A when absorbing power. The battery provides a peak power of 450 W and peak current of 32 A.

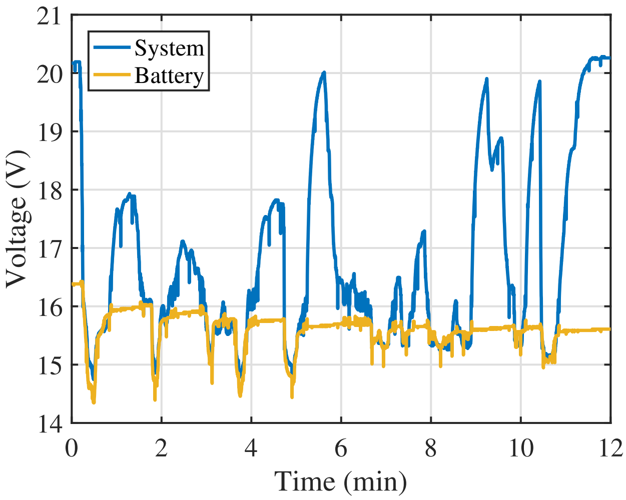

Fig. 18 : Flight 2 System Voltage

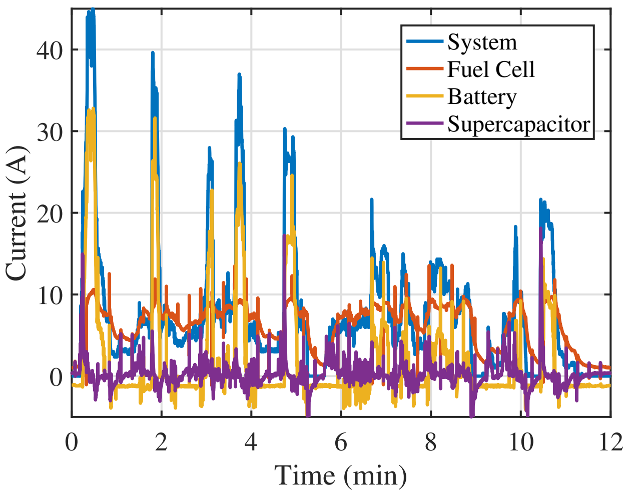

Fig. 19 : Flight 2 System Current

Quantifying the supercapacitor load smoothing for this more dynamic flight, the supercapacitor releases 1.4 Wh of energy and absorbs 1.7 Wh. This is 70% more buffering provided by the supercapacitor on the system compared to the previous flight. During this flight, the fuel cell released 21 Wh of energy, whilst the battery provided 7 Wh of energy and used 3.5 Wh of energy to recharge.

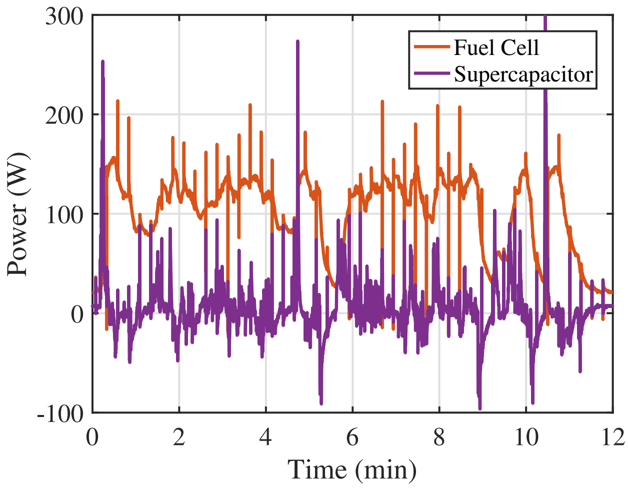

Fig. 20 : Flight 2 Fuel Cell and Supercapacitor Power

5 Conclusion

This paper has presented the world's first flight test results of a hydrogen fuel-cell/battery/supercapacitor triple hybrid power system for UAV propulsion. A description of the flight test vehicle has been provided, and details of the integration of the fuel-cell, battery, and supercapacitor into a triple hybrid system within the aircraft presented. Next, the flight test results for two test flights using this system are evaluated, demonstrating the benefit of the supercapacitor to provide load smoothing to the fuel cell during dynamic flight conditions. During the test flights the supercapacitor provided a maximum boost power of 310 W, and absorbed a maximum power of 100 W during rapid throttle changes.

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