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# Development of a Fuel Cell Hybrid-Powered Unmanned Aerial Vehicle

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***Abstract*—This paper describes the design and development of a hybrid fuel cell/battery propulsion system for a long endurance small UAV. The high level system architecture is presented, followed by the hardware-in-the-loop testing and performance analysis. A high fidelity 6-DoF simulation model of the complete system was developed and used to test the system under different battery state-of-charge. The simulation model included the power manager for the hybrid propulsion system configuration, which is based on rule-based control. The simulation results are compared with the experimental results obtained from the Hardware-in-the-Loop testing.**

***Keywords—UAV; PEMFC; Hybrid Propulsion System; Power Management; Ruled-Based Control; Hardware-in-the-Loop Test.***

## I. Introduction

Today the majority of large Unmanned Aerial Vehicles (UAVs) are powered by an internal combustion engine (ICE) due to its high power and energy density [1]. On the other hand, small UAVs, which have lower power requirement, are usually powered by electrical motors due to their high efficiency and reliability. However, over the last couple of decades, the number of experimental fuel cell powered UAVs have significantly increased. They offer greater advantages over other conventional power sources such as batteries and Internal Combustion Engines (ICEs); in terms of power density, emissions and noise.

In the US, unmanned aircraft systems developer AeroVironment has managed to fly its small Puma unmanned aerial vehicle (UAV) for more than 9-hours, powered by an on-board fuel cell/battery hybrid energy storage system. The Puma UAV was powered by Protonex Technology's Pulse UAV fuel cell system. The system couples fuel cell technology with an advanced chemical hydride fuelling technology to increase energy density [2]. In 2006, Georgia Tech University built a UAV powered by a 500 W fuel cell [3]. It was one of the first projects undertaken by a University to study the benefits and suitability of fuel cells for UAVs. The first flight of a fuel cell powered rotorcraft was made by United Technologies Research Centre [4]. It was a milestone because rotorcrafts need higher power density requirement compared with fixed wing UAV. In 2013, the Office of Naval Research achieved a world record endurance flight with its fuel cell powered UAV—the Ion Tiger, with a flight duration of 48 hours [5]. The UAV was equipped with a liquid hydrogen tank and a fuel cell rated at 550 W. More recently, EnergyOR Technologies Inc. built a fuel cell powered multi-rotor [6]. It was equipped with a 310 W fuel cell and achieved a flying record time of 3 hours and 43 minutes.

The fuel cell system can achieve greater efficiencies (potentially>50%) than an ICE. Moreover, it also provides increased efficiency and endurance over the use of conventional battery alone. However, one limitation of fuel cells system is their slow dynamic response. This is due to the complex dynamics associated with mass and heat balances of the stack [7]. The dynamic behaviour plays an important role in evaluation of the whole system performance and obtains stable performance under various operating conditions. Not only the external power source is needed for the start-up of the systems (reaction), combining the fuel cell with a battery in a hybrid system allows for much higher peak power while preserving the high energy density to meet the requirements of these applications. The battery could now supply the transient power and enable the fuel cell to more slowly adjust to the new power levels or operate under nearly steady state conditions. Otherwise the rapid increase in load demand could not be handled by the fuel cell or would result in a significant drop in its output voltage, which may cause shutdown of the system.

Most of the experimental UAV platforms that have been built are based on PEM fuel cells. Due to their high efficiency, ease of start-up and shut-down, low operating temperature and weight make them an ideal solution for aerospace applications in general. Other types of fuel cells such as Alkaline Fuel Cell, because of the high purity level for the hydrogen and oxygen that is needed, contamination issues are important. In addition, they are expensive and their commercialisation is moving at a slower pace. Direct methanol fuel cell would be another option however; methanol toxicity in larger quantities of catalyst and the lower efficiency than Proton Exchange Membrane Fuel Cell (PEMFC) would make the use of PEMFC option more attractive for small UAVs. Although some research work looking at exploiting high temperature Solid Oxide Fuel Cell (SOFC), due to their high output power. SOFC has been suggested as a concept for use in high altitude UAV applications [8]. They remain very expensive and the technology is not as mature and cost effective as PEMFC.

A partial-hybrid architecture combining the fuel cell and the battery was first proposed by the Hawaii Natural Energy

Institute [9]. During their collaboration with the Naval Research Laboratory of the U.S Navy, the institute verified the potential benefits of fuel cell/battery + converter hybrid types. Two past projects carried out at Cranfield University, designed and tested a hybrid propulsion system by connecting the fuel cell in parallel with the battery and DC/DC converter. The work showed promising results both in dealing with rapid power demands and in extending the UAV endurance [10, 11]. However, due to the weight and size of the fuel cell system and power converters, the system was only tested in Hardware-in-the-loop (HIL), since it was too heavy and big to fit on the UAV.

The purpose of this study is to design and build a flight-ready hybrid fuel cell powered UAV. Firstly, a hybrid propulsion system architecture, in which no high power DC/DC converters are required, is proposed for the prototype UAV in question. Secondly, platform design and modelling are performed under the present hybrid frame. Following this, a power management strategy, using a rule-based control approach is developed in order to manage the switch between different operating modes. Finally, system performance is analysed and validated for different battery State-of-Charge (SoC).

## II. SYSTEM DEVELOPMENT

In this section, system developments are divided into two parts; namely, the hardware and software development. For the hardware part, the structure of the hybrid configuration, the UAV platform components and integration are presented. Whereas, the software part includes the simulation model and power manager development.

### A. *System Developemnt*

#### 1) *Hybrid Propulsion System Configuration*

The hybrid system configuration is consists of a fuel cell, a battery connected in parallel and a DC/DC converter as is shown in Fig. 1. In this configuration, the DC/DC converter acts as a voltage regulator for the fuel cell. Specifically, a low power converter is adopted to reduce power losses caused by the high power converter.

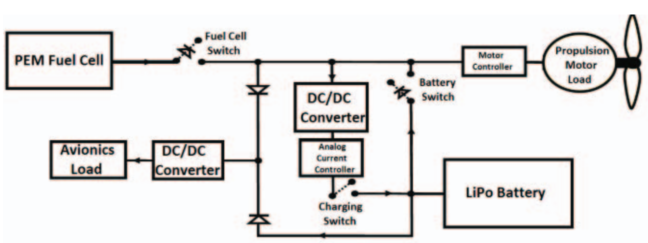


Fig. 1. The proposed partial hybrid system architecture [9]

The presented architecture allows three different modes of operation. The first mode, denoted as 'Parallel Mode', allows both the fuel cell and the battery to connect to the drivetrain, thereby combining two power sources. The second one, called as 'Charging Mode', is a mode in which the battery can be charged. Finally, in a third mode, the 'Load Following Mode', only the fuel cell provides power to the system.

#### 2) *Components Selection and Modelling*

*Fuel Cell:* As shown in Table I, the UAV is around 13 kg maximum take-off weight. It would require no more than 500W of nominal power during cruise. Meanwhile, a propulsion system generally accounts for 40–60% of gross take-off weight. Therefore, the HES A-500 fuel cell from Horizon Energy Systems, was selected due to its light weight and ability to provide the required power for cruise. The main features of the hybrid system are listed in TABLE. 1, below.

TABLE. 1 Components Weight

| **Components** | | **Weight (kg)** |
|---|---|---|
| Hybrid Propulsion system | Fuel Cell | 1.38 |
| | Battery | 0.915 |
| | DC/DC Converter | 0.01 |
| | Hydrogen Tank | 1.169 |
| | Electric Motor | 0.27 |
| | Electric Speed Controller | 0.108 |
| | Propeller | 0.03 |
| Main Processor Board (with sensors) | | 0.3 |
| Accessories | | 1.0 |
| Airframe | | 4.891 |
| **Total Weight** | | **13.041** |

*Battery:* The lithium polymer (Li-Po) battery has been widely adopted for small-scaled UAVs due to its lightweight, high current draw property and high efficiency. The HES A-500 fuel cell requires a minimum of 28V external power supply during the start-up phase. Thus, the eight cells TP3300-8SP battery was selected, providing a nominal voltage of up to 29.6 V.

*DC/DC Converter:* The output of DC/DC voltage converters were selected to meet the battery voltage range required to complete charging operation. Moreover, the current controller should be integrated into converters, on the account of limit of the maximum charge rate. To charge the TP3300-8SP battery, a low power DC/DC converter able to handle 100 W was sufficient.

*Electric Motor:* A brushless direct current motor (BLDC) is used in this electrical propulsion configuration because it is the most suitable option for the aircraft of this size. The BLDC motors do not have brushes and therefore they have less maintenance cost, higher efficiency and increased reliability.

*Main Processor Board:* The main processor board (MPB) of the UAV considered in this study is both the flight controller of the vehicle, and the power management controller of the propulsion system. The Panda II Autopilot System was selected because it is light weight and includes all the required sensors. Moreover, it contains a separated power module for the power management of the propulsion system.

#### 3) *Integrated UAV Platform*

A series of CATIA V5 models were developed to better understand the aerodynamic, geometry and mass properties of the UAV and to analyse the best layout when integrating the propulsion system inside the UAV airframe. The complete propulsion system was modelled as shown in Fig. 2. It is worth noting that the fuel tank base and the tube, for the connection of the stack and the tank were included in the 3D model.

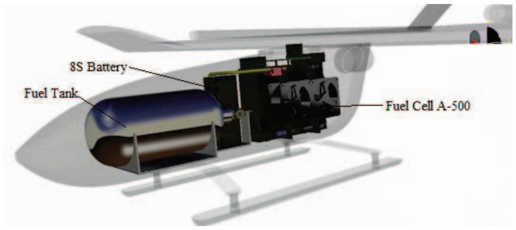


Fig. 2. A 3D CAD model of the integrated UAV fuel cell power system.

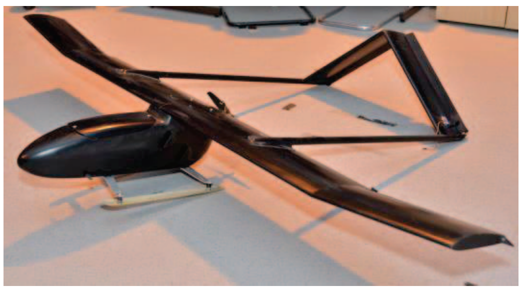

Fig. 3. Prototype UAV platform.

By completing the UAV platform integration, the fraction weight and total weight can be estimated. The weight of main components and the aircraft are listed in the Table 1.

### B. *Simulation Model*

A complete high fidelity simulation model of the UAV and the hybrid system was developed using Matlab/Simulink. The model was used to simulate and predict the response and behaviour of each component of the UAV and calculate the load for different phases of flight.

#### 1) *Fuel Cell Model*

A PEMFC model was built based on the generic fuel cell model embedded in MATLAB/SIMULINK. The following assumptions are made:

(1) The nominal stack efficiency is 47%;
(2) The nominal air flow rate is 20 slpm;
(3) The operating fuel cell stack temperature is set at 55°C

To verify the fuel cell model, simulations were carried-out and their results were compared with experimental data obtained from the manufacturer. Fig. 4 shows comparison of voltage-current characteristics and power-current curves, respectively. The developed model gave acceptable results with the difference in values provided by the manufacturer and those obtained from the simulation model were always less than 4%.

It is worth noting that although the system is rated at 500W, it is possible for short intervals to push the system to deliver around 10% more than the rated power e.g. in case of an emergency.

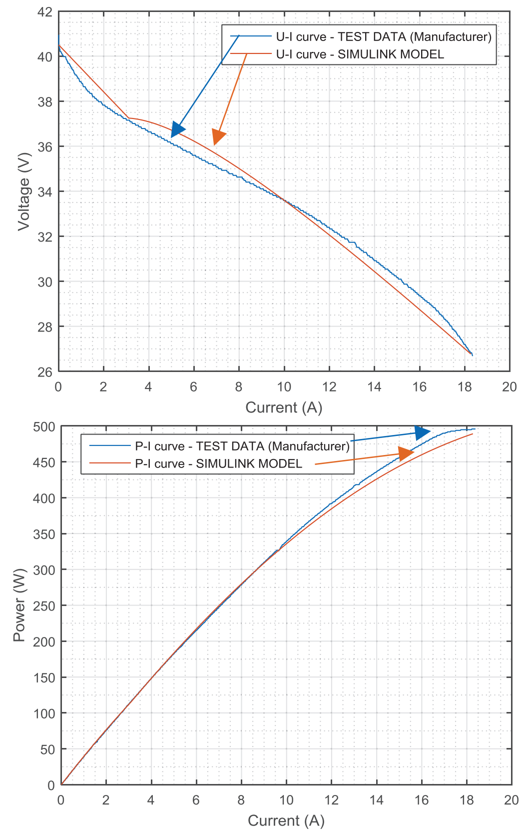


Fig. 4. Comparison between simulation data and experimental data of HES A-500

#### 2) *Electrical Motor Model*

Prior to modelling the BLDC motor load, physical tests were undertaken on a motor test bench in order to obtain its main parameters. A resistive load generator was then used to approximate the motor load. However, the variable resistive load is generally modelled to follow the current load demand, so Ohm's law is applied to modify the model to accept the power demand as an input.

Furthermore, the model designed in this paper is suitable for approximating the actual behaviour of other loads in the electrical system, like motor loads, ancillary loads and avionics loads, etc.

#### 3) *Battery Model*

The battery model also is adapted from the generic battery model in MATLAB/SIMULINK. Similarly, a model with the battery and a variable load was built in order to verify the battery performance characteristics.

To quantify the performance of the TP3300-8SP battery, its discharge characteristics were analysed at different values of current drawn. As shown in Fig. 5, all discharge curves have an initial exponential area, where the peak voltage is reached. In nominal area of operation, the voltage remarks approximately constant. A rapid drop in the voltage is presented before the discharge of the battery (deep discharge zone).

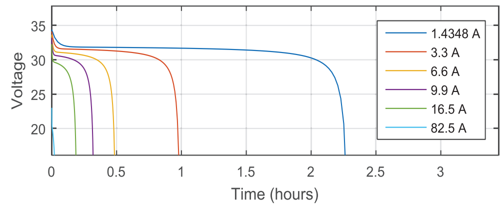


Fig. 5. Current discharge characteristics of TP3300-8SP

#### 4) *UAV model*

A full six-degrees-of-freedom (6DoF) model of the UAV was developed in Matlab/Simulink. The model was then linked to FlightGear to visualize the response of the aerial vehicle. The dynamic model of the aircraft is based on the linearised equations of motion. The aerodynamic derivatives of these formulae are estimated from lookup-tables as a function of altitude and airspeed. An Autopilot Stability Augmentation System (SAS) was developed. This part of the model is based on classical PID control and hold autopilots. In order to be able to extrapolate the power requirements with respect to the generated RPM, the experimental test results obtained for the motor were derived and integrated into the nonlinear model.

### C. *Power Management*

The power management strategy implemented in this study is based on rule-based control. Instead of using current as a control variable, it is more intuitive to design a rule-based control approach based on power demands. Hence, the present controller has the following inputs: total power demand, the battery and fuel cell output power, the battery SOC, the fuel cell and battery voltage. While its outputs are the fuel cell power demand, the battery power demand and the fuel cell voltage demand.

The architecture allows different modes of operation. By using control switches, it is possible to alternate between the three modes. The first mode, denoted as 'Parallel Mode', both fuel cell and battery are connected to the bus, and then, the load is shared by both power sources. The second mode, called now as 'Charging Mode', will set charging switch on and hence, the battery can be charged. Finally, a third mode is presented, the 'Load Following Mode', where the fuel cell is the only that are supplying all the power to the system including the battery charging power.

The Parallel Mode of operation will be the main mode of operation. It will run just after the start-up phase and until the SOC of the battery is below 20%. The key point in the control of this mode is the battery voltage because it will determine the maximum output that the fuel cell can provide. Secondly, the battery Charging Mode operates at the condition that the power demand is lower than the power generated by the fuel cell. Thus, the extra power can be utilized to charge the battery. In this mode, the fuel cell will supply all the power including the part to charge the battery. If the battery SOC is below 20%, a Load Following Mode will be activate, which is formed of Parallel and Charging Modes alternating over time. This is an emergency mode that is activated when the battery is almost depleted. The aim of this mode is to keep the battery SOC between some limits until all the hydrogen fuel is consumed. After that the battery will supply the rest until it is completely depleted. In an emergency situation this will provide the maximum endurance time.

The corresponding schematic is illustrated in Fig. 6, where $P_D$ is the total power demanded, $P_{FC}$ is power supplied by the fuel cell, $P_B$ is power supplied by the battery, $P_{FCmax}$ is maximum output power of the fuel cell, $P_{Bc}$ is power supplied to the battery for charging, $U_{FC}$, is fuel cell voltage and $U_B$ is battery voltage.

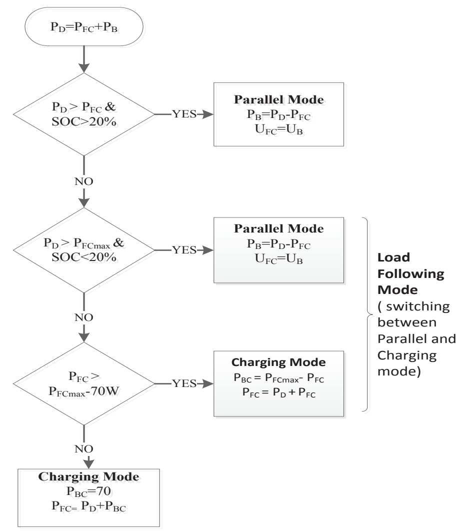


Fig. 6. Power management logic.

## III. Simulation and Discussion

### A. *Power Requirement*

Before analysing the different case studies, a mission load demand profile should be proposed. The power demand profile was generated using the developed simulation model; the mission included different manoeuvres to emulate different power demand requirements throughout the flight.

As shown in Fig. 7, the take-off and climb phase continues until 200 seconds and then the cruise phase starts. At around 300 and 500 seconds a descent (altitude change) is simulated to test the dynamic response of the system. This profile will be used as a baseline for the case studies that are analyzed in the following subsections. Please note that this initial study is focused on testing the fuel cell and the controller logic and therefore, no disturbances were included in these tests.

### B. *SOC 100%*

The first case analysed here is when the initial SOC of the battery is at 100%. Fig. 7 illustrates the performance of fuel cell and battery power. As shown in the Fig. 8, the fuel cell can meet the majority of the power demand while the rapid power demand is supplied by the battery. For example, at around 100 and 180 seconds, the fuel cell cannot cover the power demand when the demand exceeds the maximum output power of the fuel cell. This rapid increase is covered by the battery. The controller also works as expected: it allows the fuel cell to operate at ideal condition considering the power profile; the negative battery power implies that the Charging Mode is activated and the fuel cell will supply all system loads and charge the battery.

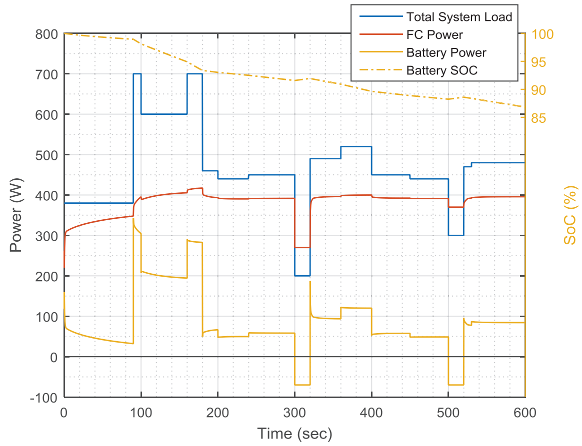


Fig. 7. Fuel cell and battery power at SOC 100%

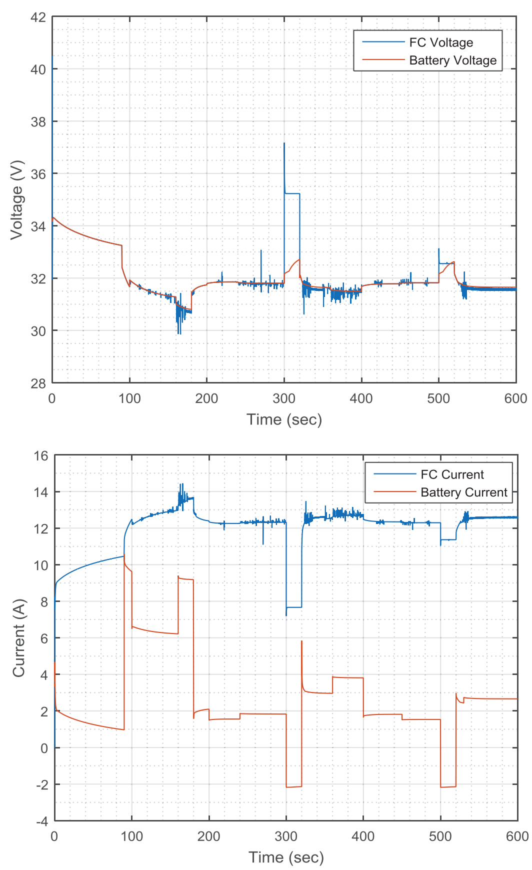


Fig. 8. Comparison of voltage and current of fuel cell and battery at SOC 100%

Fig. 8, shows the variations of fuel cell and battery voltage and current, respectively. It can be seen that the voltage of the fuel cell and battery can be matched quite well, and it is possible to share the load in the Parallel Mode with small discrepancy. Note that in the Charging Mode, the fuel cell voltage must be higher than the battery voltage. From the current graph, the charging power is fixed to a maximum of 70W, which will be equivalent to a charging current of approximately 2 Amps.

### *C. SOC 60%*

Fig. 9 shows the power supplied by the fuel cell and battery, when the SOC of the battery is almost half depleted (at 60%). Compared with the fully charged case, the fuel cell is operated at a higher output power range, resulting in higher hydrogen consumption and lower stack efficiency. At the beginning of the simulation, the fuel cell also charges the battery because the power demand is lower than the fuel cell maximum output power. The maximum charging power again is set to 70W, at which the fuel cell stack is operating close to its maximum output power. It is worth noting that as the battery voltage progressively drops (this is the result of its decreasing power), the output power from the fuel cell increases to compensate for this performance.

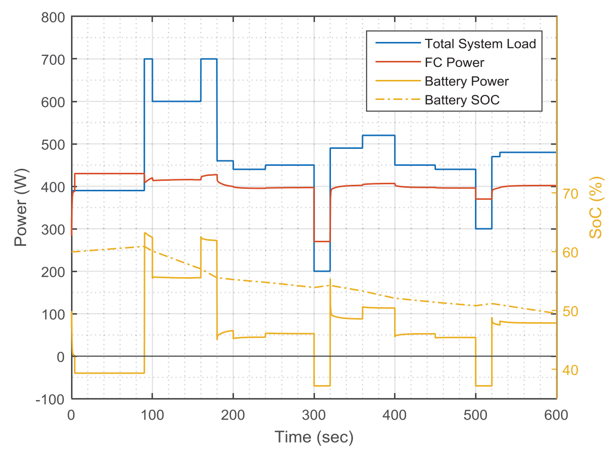


Fig. 9. Simulation results at SOC 60%

## IV. HARDWARE-IN-THE-LOOP TESTING

### *A. Hardware Configuration and Description*

Two independent computer systems were used in the hardware-in-the-loop (HIL) simulation. The first ran the 6-DOF simulator, the flight visualization and the electronic load control. While the second computer had the fuel cell data logging and monitoring software installed. The performance of the closed loop control can be verified using virtual experiments; whereas when flying in manual mode (open loop) a joystick is connected to the 6-DOF simulator for external pilot command input. Fig.10 shows the four main blocks of the HIL setup.

#### *1) Workstations-Visualisation Systems*

The workstation was connected through a Serial RS232 to USB cable, with the fuel cell for receiving, logging and displaying in real-time the fuel cell parameters such as, the temperature, pressure, current, and voltage. The laptop was used to run the 6-DoF Simulink model of the UAV, in which the power demands for the electronic load were generated according to the autopilot or the 'manual' pilot control input (open loop). Furthermore, in same Simulink model, another block was running in parallel for visualising the 3D UAV model in a virtual environment in real-time using FlightGear.

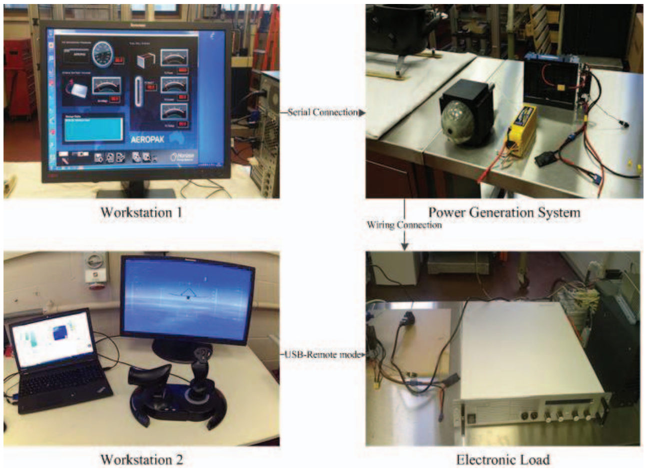


Fig. 10. Hardware-in-the-loop setup.

*2) Power Generation System*

The power generation system is composed of three main components, namely the fuel cell, the battery, and the hydrogen fuel tank. The fuel cell was supplied with compressed hydrogen, which was stored in light weight composite 1.1 litre fuel tank, as shown Fig. 10.

*3) Electronic Load*

During the experiments operating the UAV engine during the ground test trials at full power was not a safe option. Therefore, an electronic load bank was used to simulate the power demand of the electric propulsion system. The device was connected to the laptop and controlled remotely.

### *B. Experimental Process and Test Results*

In this experiment, the UAV started from an initial altitude of 1200 meters and testes were carried-out for different phases of flight such as ascent, cruise and descent. The mission lasted for approximately 6 minutes. The power demand was varying from 0 to 280W and is shown in Fig. 11. During the test, the fuel cell was operating using compressed hydrogen and the flight was conducted in manual mode (open loop). The external pilot command inputs through the joystick were fed to the 6-DOF simulation model and translated in real-time to power demands and sent to the electronic load.

The experimental results were quite encouraging and the fuel cell hybrid system behaved very closely to what was conducted in simulation, validating and verifying the Matlab/Simulink model results.

## V. Conclusions

This paper presented the development and testing both in simulation and hardware-in-the-loop of a flight ready fuel cell powered UAV. The system is based on Horizon A500 PEM fuel cell. The hybrid propulsion system used a rule-based control strategy and the system has three different modes of operation. The present hybrid propulsion system has been validated first in simulations with a series of case studies and later in hardware-in-the-loop.

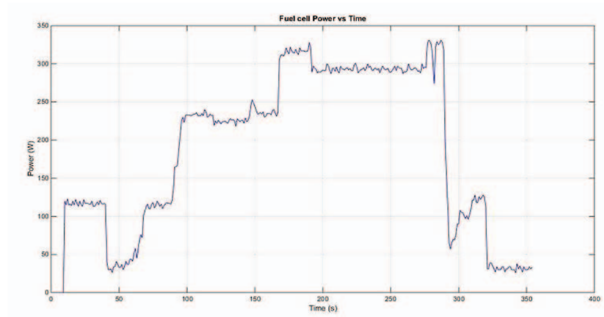


Fig. 11. Power output of fuel cell in watts, measured using the Aeropak interface.

Based on the results obtained and load profiles, it can be concluded that the developed hybrid system using a 500W fuel cell and a 8S battery is capable of powering UAV during different phases of flight. Moreover, this configuration allows the fuel cell to operate in a partial load range and at constant output power, thus maximising stack efficiency and improved power quality of the system.

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