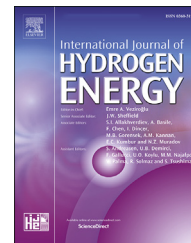


Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ijhydene

Experimental evaluation of a passive fuel cell/battery hybrid power system for an unmanned ground vehicle

Eduardo López González ^{a,*}, Jaime Sáenz Cuesta ^a,
Francisco J. Vivas Fernandez ^a, Fernando Isorna Llerena ^a,
Miguel A. Ridao Carlini ^b, Carlos Bordons ^b, Emili Hernandez ^c,
Alberto Elfes ^c

^a Instituto Nacional de Técnica Aeroespacial (INTA), Ctra. S. Juan-Matalascañas, km. 34, 21130, Mazagón (Huelva), Spain

^b Universidad de Sevilla, Escuela Técnica Superior de Ingeniería, Departamento de Ingeniería de Sistemas y Automática, Camino de los Descubrimientos, s/n, 41092, Sevilla, Spain

^c Commonwealth Scientific and Industrial Research Organization (CSIRO), Data61, Robotics and Autonomous Systems, QCAT, 1 Technology Court, Pullenvale, QLD 4069, Australia

ARTICLE INFO

Article history:

Received 13 July 2018

Received in revised form

20 September 2018

Accepted 12 October 2018

Available online 22 November 2018

Keywords:

Electrical energy storage

Unmanned vehicles

Fuel cells

Hybrid power systems

Electric propulsion

ABSTRACT

Unmanned vehicles are increasing the performance of monitoring and surveillance in several applications. Endurance is a key issue in these systems, in particular in electric vehicles, powered at present mainly by batteries. Hybrid power systems based on batteries and fuel cells have the potential to achieve high energy density and specific energy, increasing also the life time and safe operating conditions of the power system. The objective of this research is to analyze the performance of a passive hybrid power system, designed and developed to be integrated into an existing Unmanned Ground Vehicle (UGV). The proposed solution is based on six LiPo cells, connected in series, and a 200 W PEM fuel cell stack, directly connected in parallel to the battery without any limitation to its charge. The paper presents the characterization of the system behavior, and shows the main results in terms of performance and energy management.

© 2018 Hydrogen Energy Publications LLC. Published by Elsevier Ltd. All rights reserved.

Introduction to passive hybrid power systems in unmanned vehicles

Unmanned vehicles offer multiple possibilities in industrial, scientific and security applications, due to their ability to provide high quality data in real-time, at a lower cost than other techniques. On-board energy storage is one of the most

relevant issues in the design, development and operation of unmanned platforms due to its influence on the performance and capabilities of the vehicle [1,2]. A majority of current unmanned vehicles are powered with internal combustion engines, mainly UAVs and UGVs, but in other applications (e.g. UUVs and microUAVs) electric propulsion is the only available option, which requires suitable energy storage systems to

* Corresponding author.

E-mail address: lopezge@inta.es (E. López González).

<https://doi.org/10.1016/j.ijhydene.2018.10.107>

0360-3199/© 2018 Hydrogen Energy Publications LLC. Published by Elsevier Ltd. All rights reserved.

Nomenclature	
BMS	Battery Management System
CSIRO	Commonwealth Scientific and Industrial Research Organization
DC	Direct Current
EMS	Energy Management System
INTA	Spanish National Institute for Aerospace Research
IUFCV	“Improving efficiency and operational range in low-power unmanned vehicles through the use of hybrid fuel-cell power systems” Project
LHV	Lower Heating Value
OCV	Open Circuit Voltage
PEM	Proton Exchange Membrane
SOC	State of Charge
UGV	Unmanned Ground Vehicle
UAV	Unmanned Aerial Vehicle
UUV	Unmanned Underwater Vehicle
USV	Unmanned Surface Vehicle
Abbreviations	
E	Energy
I	Current
m	Mass
P	Power
t	Time
V	Voltage
List of indices	
batt	Battery
FC	Fuel cell
H ₂	Hydrogen
load	Load
diode	Diode

provide high specific energy and power density, to increase life time (number of charging and discharging cycles) and to ensure safe operating conditions, among other requirements. In a similar way to other electric vehicles, most electric unmanned vehicles use lead-acid or Li-ion batteries at present. Despite the rapid progress of these technologies [3] issues remain, and the use of hybrid configurations, combining different energy storage technologies is seen as a promising option to overcome the existing gaps for power systems in electric vehicles [4]. The main advantages of hybrid power systems with respect to battery-based ones are the possibility

of achieving higher specific energy while providing redundancy in power supply, which reduces the probability of energy failure, and improves system performance. In the case of power systems based on fuel cells and batteries, several research works have tested and evaluated systems based on both configurations in mobile and stationary applications [5–16].

In general, hybrid power systems are classified in two architectures: active, with control elements (typically using DC/DC converters); and passive, with a direct coupling among the system components. The choice of the most adequate configuration for a given application depends on the vehicles power and energy requirements, weight and volume constraints as well as the characteristics of the fuel cell system and batteries. The active configuration allows a decoupling of sizing and operating conditions on batteries and fuel cell using DC/DC converters, allowing a more precise control of the power system thanks to the control and management of such converters. Their main disadvantages are the more complex system topology, reduced efficiency due to voltage loss, system cost, and higher weight and volume. Passive configurations with direct connections to the DC bus offer the advantages of lower losses, reduced cost and simpler architecture. However, active power control is not possible in this configuration, due to the absence of converters. This could be managed by an external control system, allowing modifications in the operating conditions of the batteries and/or the fuel cell. In consequence, careful design and integration of fuel cells and batteries is required to ensure a similar voltage range operation and proper charging conditions of the batteries from the fuel cell [6,17,18]. Table 1 shows a comparison of active and passive hybrid power systems, with batteries and a fuel cell, summarizing the main advantages and disadvantages for each configuration.

There are also several possible architectures in passive configuration systems, depending on whether the fuel cell is able to charge the batteries without any restriction (Fig. 1a), if there are charging regulation requirements during this process (Fig. 1b), or even if it is not possible to charge the batteries from the fuel cells (Fig. 1c).

Using the configuration depicted in Fig. 1a (direct coupling of fuel cell and batteries) the batteries are the main source to supply power to the load, while the fuel cell supplements the power supplied by the batteries, operating as a “range extender” system. In this operation mode, the fuel cell generates energy when the state of charge (SOC) and the battery voltage reach a predefined minimum value. Once this minimum voltage is reached, the energy generated by the fuel cell is injected into the DC bus that connects the power system to

Table 1 – Comparison between active and passive fuel cell/battery hybrid power system.

	Advantages	Disadvantages
Active configuration	<ul style="list-style-type: none"> • Decoupling of sizing and operating conditions on batteries and fuel cell • More precise control of the power system 	<ul style="list-style-type: none"> • More complex system topology • Losses in the DC/DC converters • Higher system cost • Higher weight and volume
Passive configuration	<ul style="list-style-type: none"> • Lower losses • Reduced cost • Simpler architecture, lower risk of failure • Lower weight and volume 	<ul style="list-style-type: none"> • Active power control is not possible. Fuel cell operates at the voltage set by batteries. • Careful design and integration of fuel cell system and batteries to fit the requirements of the load is needed

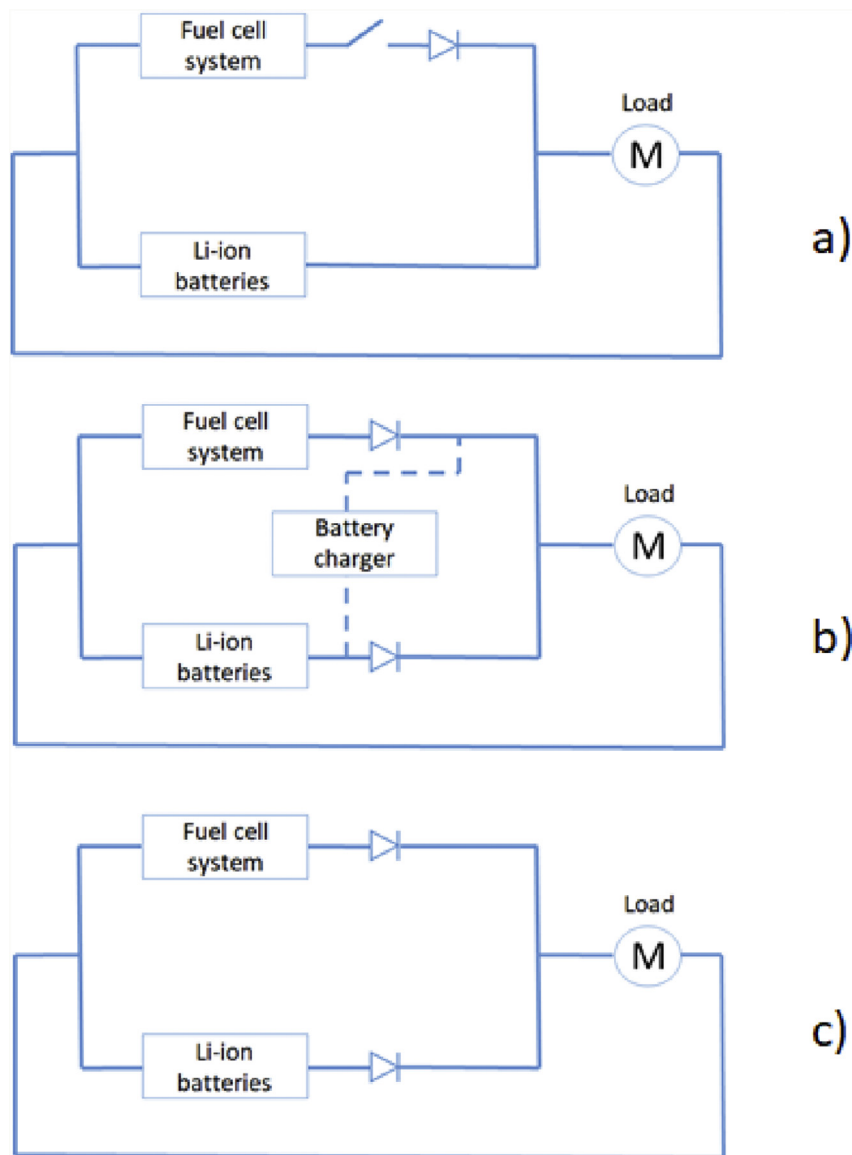


Fig. 1 – Passive hybrid fuel cell/batteries power system configurations.

the electric load. Depending on the energy balance, part of the energy is used to supply the demand while the rest is used to charge the batteries.

In this operation mode, the demanded power load profile largely determines the design of the fuel cell and its nominal power when operating in the battery voltage range. The voltage of the battery sets the fuel cell current, according to its polarization curve. Maximum battery current values, as well as suitable charging/discharging criteria from the safety, performance and durability points of view, have to be taken into account in the design and selection of the right batteries for the system. The passive configuration offers a relatively simple architecture, providing power self-regulation of fuel cells and batteries through appropriate design and selection of both components, at the expense of careful monitoring and supervision of the system in operation.

Taking into account these general characteristics, hybrid power systems based on batteries and fuel cells are

considered a suitable option to power unmanned vehicles, mainly to increase the operational range of these platforms. Active and passive hybrid power systems have been already evaluated for unmanned vehicles in several demonstration projects [18–30]. Most of fuel cell/battery power systems demonstrated in small unmanned aerial vehicles correspond to passive configurations, usually according to the scheme depicted in Fig. 1b, with the fuel cell as main power source, and the battery supporting the operation of the fuel cell when the power load is higher than the power supplied by the fuel cell [18,20–24,31–35]. Nevertheless, its application in UGVs has received less attention [36–39].

This paper addresses the use of a passive hybrid power system in a UGV, based on the direct coupling of a fuel cell and Li-ion batteries, without restrictions to the charging of the battery from the fuel cell, with the goal to improve the capabilities and performance of these platforms in real applications. A demonstration of this configuration in an existing

UGV is proposed, and preliminary results, regarding the experimental evaluation of the system on a test bench, are presented and discussed. The main contributions of this research are related to the understanding of the joint performance of fuel cell and batteries in a direct coupling, without charging regulation of the battery, operating under demanding load profiles taken from real data. In this topology, the battery plays a fundamental role as the main power source, acting at the same time as a buffer that minimizes the effect of load variations on the fuel cell, which acts as a “range extender”. This configuration and operation mode present an alternative approach to passive hybrid systems for unmanned vehicles, reported in previous experimental works, mainly in small UAVs, where the fuel cell covers the main power demand of the vehicle, being supplemented by batteries at high load [23,24,40].

The first part of the paper offers information about hybrid power systems, introducing the architecture of passive systems based on fuel cells and batteries, and their use in unmanned vehicles. The next section details the development of a passive hybrid fuel cell/battery power system, specifically designed to fulfill the load and endurance requirements of an existing unmanned ground vehicle (UGV), as well as the test and experimental evaluation of the system. The last section exposes the conclusions and future work.

Testing and characterization of passive hybrid systems for unmanned ground vehicles

This research work is developed in the framework of the project “Improving efficiency and operational range in low-power unmanned vehicles through the use of hybrid fuel-cell power systems (IUFCV)” [41,42]. The objective of this project is the increase of the operational range of three existing unmanned vehicles, two UGVs and one UUV, using hybrid power systems based on batteries and fuel cells. These platforms and hybrid power systems will be evaluated in real applications.

Power load profile for the unmanned ground vehicle

The UGVs used in the project are an all-terrain Husky UGV from Clearpath Robotics [43] provided by the Robotics and Autonomous Systems Group at CSIRO, and a Summit XL UGV from Robotnik [44], owned by the Energy Area of INTA. The goal of this project is to increase the endurance on both platforms up to seven hours of continuous usage on field missions, maintaining its core payload, speed capabilities thought the mission execution.

Both platforms will integrate hybrid power systems based on batteries and fuel cell to accomplish these technical targets. The development and testing works presented in the article correspond to the Summit platform. Similar methodology will be applied to the other UGV in the short term. The Summit XL UGV (Fig. 2) is used at INTA for testing multiple power systems configurations and technologies, as well as for integrating sensors and simulate missions defined by different end-users. The main characteristics of this platform, according to the manufacturer, are as follows:



Fig. 2 – Summit XL platform (INTA).

- Weight: 45 kg
- Maximum payload: 20 kg
- Speed: 3 m/s
- Drive system: 4 wheel, 4 brushless motors
- Batteries: 8 × 3.2 V, 15 Ah LiFePO₄
- Endurance (nominal/idle): 5/20 hours

Taking into account the limitations of the UGV in terms of available weight and volume, the proposed systems should be as simple as possible in terms of components, trying to achieve the maximum specific energy and energy density with these restrictions, but offering at same time enough warranties to provide the necessary energy and power to fulfill the required missions. Passive hybrid power systems, without DC/DC converters, seem in this case a suitable solution, if designed and sized according to the technical specification of the vehicle. This passive hybrid system is based on open cathode - air cooled Polymer Electrolyte Membrane (PEM) fuel cells, and Li-ion batteries. Compressed hydrogen and metal hydrides will be the hydrogen storage technologies used in the platform. In the first phase, the battery and fuel cell of the hybrid power system designed for the Summit XL UGV were integrated and tested in a test station.

In order to evaluate the performance of the passive hybrid power system under power demand profiles similar to those used by the platforms in real scenarios and missions, the vehicle performed intensive tests under different driving conditions and types of terrain. The power consumption profiles were obtained by measuring the voltage and current in the 8 LiFePO₄ batteries connected in series provided by the platform. These driving tests considered the vehicle in: standby mode (idle), smooth driving on flat terrain (with low accelerations and few turns), and more aggressive driving trials on flat terrain with frequent turns and strong accelerations. From the power perspective, the smooth driving is commonly used in autonomous surveillance missions while the aggressive maneuvers are typically required in off-road navigation tasks. The measured load profiles show that the vehicle maximum power peak is around 600 W. Most of the

missions combine different terrain and driving modes. The average power varies from a minimum of around 38 W when the vehicle is in stand-by (idle, with the only consumption of the on-board electronic equipment), to a maximum of 200 W when driving aggressively on flat terrain. During these tests in the real conditions required by INTA, combining different driving modes, the real autonomy of the vehicle was around 2 hours, lower than the autonomy specified by the manufacturer in its nominal conditions. Fig. 3 depicts the power curves for smooth and aggressive driving of the vehicle in a flat terrain.

Based on these real profiles, a standard basic mission profile was created, combining the power at stand-by (corresponding to the minimum power consumption of the vehicle), power peaks and several power up and down ramps, representatives of the variations in the vehicle's load profiles analyzed above. This basic profile, covering all these cases and measured variations of the load, has a duration around 300 s. In order to estimate the performance of the system during the

targeted operating period (more than 7 hours on the Summit XL), this basic profile was repeated throughout the seven-hours period to create a long-term test profile for the test bench. Fig. 4 illustrates this basic profile.

From this basic load profile, repeated during seven hours, the total energy consumed in this period was calculated, giving a value of around 1 kWh. This is the minimum electrical energy that the power system has to store, in the battery and the hydrogen storage system, and supply to the vehicle.

Development of passive hybrid power system

The passive hybrid power system, designed, developed and evaluated for the Summit XL UGV, integrates an open cathode, metal bipolar plates PEM fuel cell stack, with fan, from the manufacturer BCH, model TH-200. This stack has 30 cells, is air-cooled and able to supply 200 W at 24 V [45] and six 6 KOKAM Ultra High Energy NMC LiPo cells (27 Ah nominal capacity (C), max. charge 27 A (1C), max. discharge 54 A (2C),

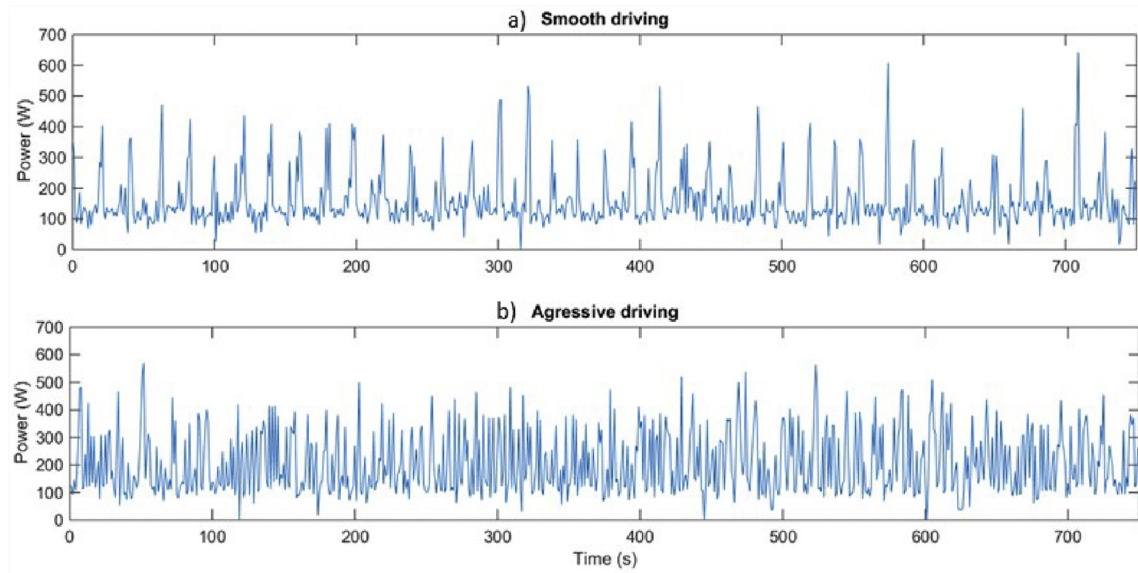


Fig. 3 – Summit XL UGV load profile - Smooth (a) and aggressive driving (b) in flat terrain.

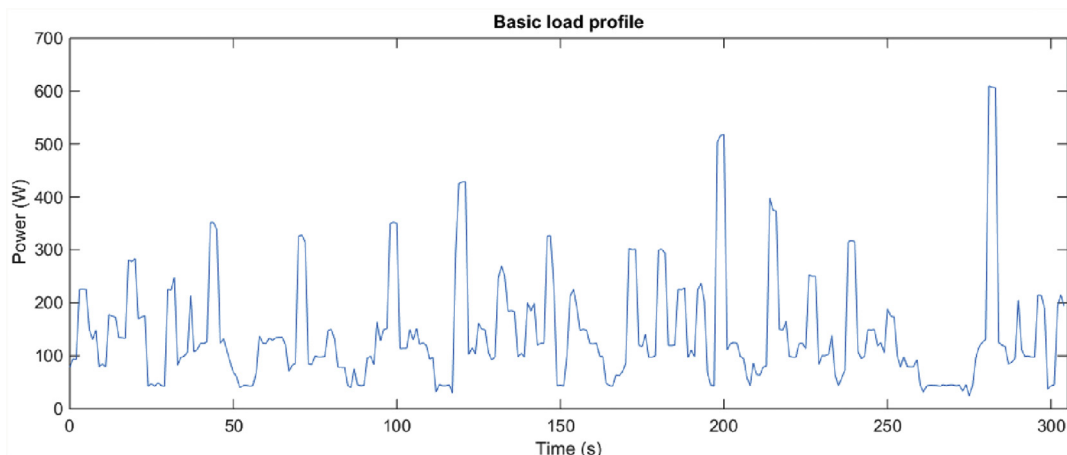


Fig. 4 – Summit XL UGV Basic load profile.

peak discharge 108 A (4C) connected in series (22.2 V nominal voltage, 25.2 V max. voltage, 16.2 V min. voltage at pack level) [46]. The stack and the batteries, jointly with the hydrogen storage system and a custom developed Energy Management System (EMS), which integrates the functions of a typical Battery Management System (BMS) and the monitoring and control of the fuel cell system, are the main components of the proposed passive power system, which will replace the existing LiFePO_4 battery pack in the vehicle. The battery, the fuel cell and the hydrogen storage system were selected and developed to achieve a specific energy higher than 180 Wh/kg and to store at least 1 kWh of electrical energy, equivalent to seven hours of autonomy in the vehicle operating under the basic load profile.

The fuel cell and the batteries were previously tested and characterized in a test bench, in order to obtain the polarization curves (voltage and power vs. current) and the charging-discharging curve respectively (Figs. 5 and 6).

According to Fig. 5, the OCV of the fuel cell is 37.5 V, and the maximum power achieved, at 15.3 A, is 324 W. In these conditions, the fuel cell generates 12.25 A at 24 V, supplying 294 W

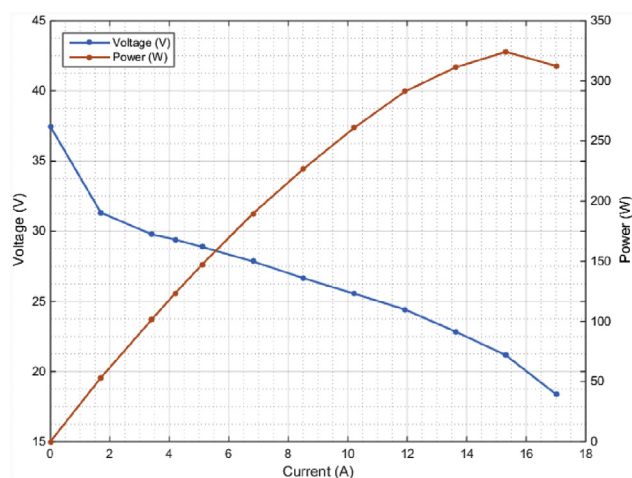


Fig. 5 – Polarization curves of the BCH-T200 fuel cell stack.

of power. This value is higher than the nominal values specified by the manufacturer (200 W at 24 V).

Fig. 6 shows the characterization curve of one battery cell, corresponding to a charging step at 5.5 A, up to a maximum voltage of 4.2 V, a discharging step at 2.7 A (0.1 C) until a minimum voltage of 2.7 V, and finally a charging step until the maximum voltage. The measured capacity (C) from this cell and test was 26.91 Ah.

The hybrid system was connected in a direct coupling configuration between the fuel cell stack and the batteries, without limitation to the charge of the batteries from the fuel cell (thanks to the characteristics of the battery in terms of maximum charging/discharging current and capacity) according to the scheme depicted in Fig. 1a. Fig. 7 shows the electric circuit of this passive hybrid power system.

This architecture allows the simplest passive system, avoiding the use of battery charger or similar device. In this configuration, power sharing between battery and fuel cell depends only on the battery voltage (and SOC). The tests were performed in an ARBIN BT-ML 60 V-100 A battery test station [47], programmed to repeat the basic load profile shown in Fig. 4 in a cyclic mode, at least during seven hours. In a first phase, the fuel cell (fan and purges) was managed with a control board supplied by the manufacturer jointly with the stack. Other data from batteries and fuel cell were measured and acquired in a suitable SCADA included in the experimental set-up, as well as in the battery test station, which were also programmed to ensure the operation of the batteries in the voltage range specified by the manufacturer. Fig. 8 depicts this experimental set-up.

Testing of passive hybrid power system for summit XL

Fig. 9 shows voltage and current of the fuel cell/battery power system during the +7 h test.

Fig. 9 illustrates the operation associated to Fig. 1a in section Introduction to passive hybrid power systems in unmanned vehicles. Three clearly-defined steps are observed in the figure:

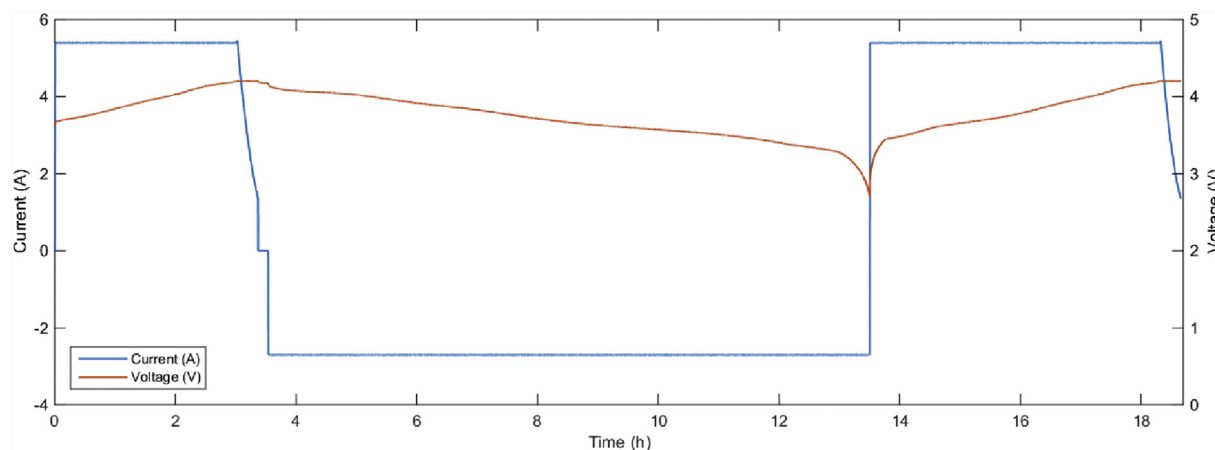


Fig. 6 – Characterization curve of a KOKAM Ultra High Energy NMC cell.

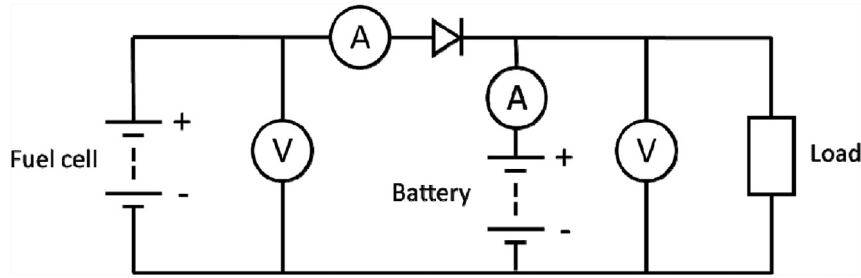


Fig. 7 – Electric circuit of the passive hybrid power system.

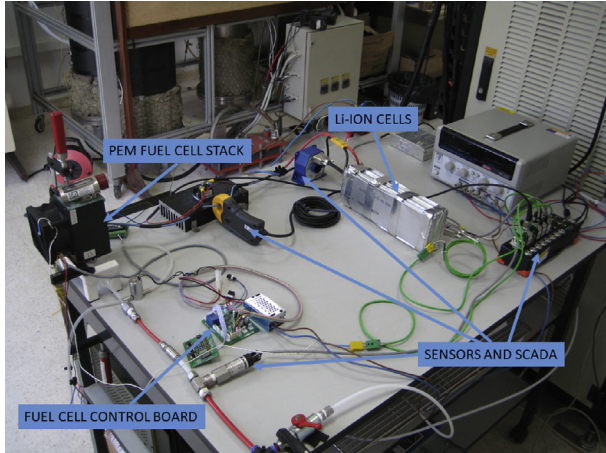


Fig. 8 – Experimental set-up of the passive hybrid fuel cell/battery power system.

a) Step 1

At the beginning of the operation, the load is initially powered only from the battery. In these conditions:

$$\begin{aligned}
 V_{load} &= V_{batt} \\
 I_{load} &= I_{batt} \\
 P_{load} &= P_{batt} \\
 E_{batt,1} &= \int_{t_0}^{t_1} P_{batt} \cdot dt = E_{load,1}
 \end{aligned}
 \tag{1}$$

This step had a duration of 2.45 hours, from t_0 to t_1 , and it finished when the battery achieved a predefined minimum voltage of 21.5 V.

b) Step 2

The fuel cell operated jointly with the battery, powering the load and charging the battery. This step started at t_1 , when the battery achieved the minimum voltage threshold mentioned above, set to ensure a safe operation of the fuel cell, according to the manufacturer's specifications. In these conditions:

$$\begin{aligned}
 V_{load} &= V_{batt} = V_{FC} - V_{diode} \\
 \text{If } P_{load} < P_{FC}, I_{load} &= I_{FC} - I_{batt}, P_{load} = P_{FC} - P_{batt}
 \end{aligned}
 \tag{2}$$

$$\begin{aligned}
 \text{If } P_{load} > P_{FC}, I_{load} &= I_{FC} + I_{batt}, P_{load} = P_{FC} + P_{batt} \\
 \text{In general, } E_{FC,2} &= E_{load,2} \pm E_{batt,2}
 \end{aligned}$$

where:

$$\begin{aligned}
 E_{FC,2} &= \int_{t_1}^{t_2} P_{FC} \cdot dt \\
 E_{batt,2} &= \int_{t_1}^{t_2} P_{batt} \cdot dt
 \end{aligned}$$

From t_1 , the fuel cell voltage was the sum of the battery voltage plus the diode voltage (approximately a constant value of 0.82 V in this range of operation). The fuel cell operated until the battery voltage achieved a predefined value, 24.5 V in this test, which assured a high SOC of the battery. This voltage

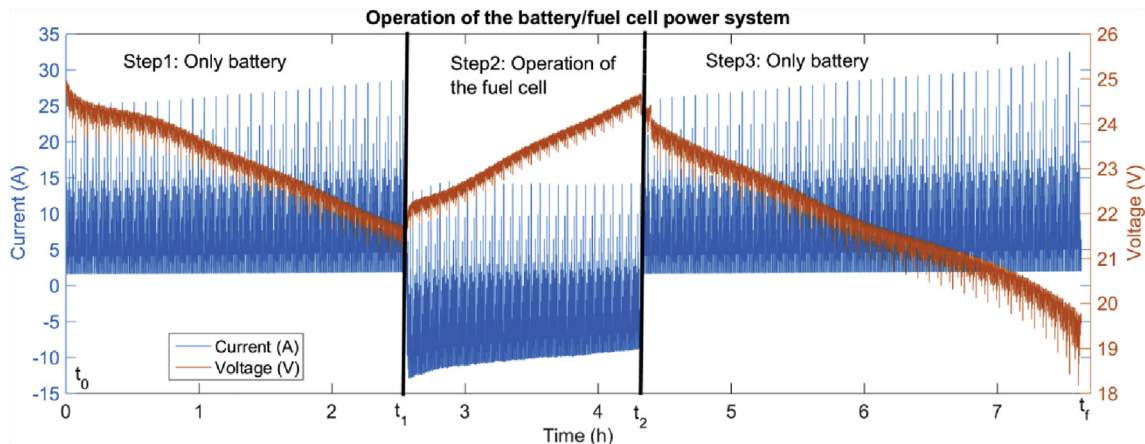


Fig. 9 – Operation of the battery/fuel cell power system for Summit XL UGV.

value was also set considering the hydrogen available in the storage system and the energy provided by the fuel cell, taking into account the minimum energy needed for seven hours of operation of the vehicle under the basic load profile. This step lasted 2.08 hours, from t_1 to t_2 .

c) Step 3

Once the battery is recharged to the voltage achieved at t_2 it assumes all the vehicle power load until the voltage drops around 18 V, at t_f . This value was still far from the minimum voltage of the battery pack (16.2 V), but was considered a conservative limit to avoid the total discharge of battery in these first tests, as well as to operate in the voltage range of the on-board DC/DC converters of the Summit platform, used to power its internal electronic systems. As such, not all the available energy in the battery was consumed in the experiment. The operating conditions of the power system are the same as detailed in Eq. (1), with:

$$E_{\text{batt},3} = \int_{t_2}^{t_f} P_{\text{batt}} \cdot dt = E_{\text{load},3} \quad (3)$$

The duration of this step, from t_2 to t_f , was 3.1 hours.

The total duration of the test was 7.6 hours, corresponding to 2.08 hours of the joint operation of the fuel cell and the battery, and 5.55 hours to the operation only with the battery. Fig. 10 depicts in detail the evolution of voltages and currents in the operation period of the fuel cell.

Battery and fuel cell voltage curves have a similar shape, being the difference the voltage drop at the diode, with a constant increase as the LiPo cells are recharged and their voltage increases. In this voltage range, the average power of the fuel cell (291.8 W) was greater than the average power load (153.2 W). Consequently, the energy generated in the fuel cell was enough to power the UGV and recharge the battery simultaneously when the fuel cell power was higher than the load. Because of this, the battery current curves show positive values when it is charged and negative when is discharged. The current of the fuel cell remained always positive, while the current from/to the battery changed rapidly, from negative (charging) to positive (discharging) values, depending on the demand profile of the vehicle. The fuel cell current decreased smoothly as the battery voltage increased and the battery was charged. The battery buffered all the demand

variations, supplying energy when the requested power exceeded the power generated by the fuel cell, or when being charged because of an energy excess generated by the fuel cell respect to the demanded power. The maximum battery current reached in this charging process was 12.7 A. The charging rate for the 27Ah battery was less than 0.5 C, according to the manufacturer's requirements for safe battery charging. Similarly, the maximum battery discharging current during this period was 14.7 A, which is slightly higher than 0.5 C, and much lower than the maximum discharge current specifications (54 A for continuous discharge and 108 A for peak discharge). The fuel cell current variation was almost linear, from a maximum value of 14.7 A at the beginning of its operation to a minimum value of 10.4 A at its end. The fuel cell voltage values agree with the expected ones, according to the polarization curve (Fig. 5).

In terms of power, Fig. 11 shows the power provided by the battery and the fuel cell, as well as the total power demanded by the vehicle. The total power corresponds to the pattern load profile previously explained. The basic load profile is highlighted in the total power curve, and corresponds to the profile depicted in Fig. 4. Most of the battery power corresponds to the charging process, with a maximum of 282 W. The battery power also presents discharge peaks around 300 W, with a maximum of 341 W. These peaks were generated by the vehicle power demand, and its maximum reaches 610 W. Since the fuel cell power varied almost linearly from 336 W at the beginning of the operation to 264 W at the end, all the additional power, around 50% during these discharge peaks, was supplied by the battery. The contribution of the battery to the total power allowed to the hybrid fuel cell/battery system to provide higher power density than power systems based exclusively on fuel cells [40].

In terms of energy, taking into account the three steps previously defined, the total energy supplied to the system would be:

$$E_{\text{load}} = E_{\text{load},1} + E_{\text{load},2} + E_{\text{load},3} \quad (4)$$

Total energy consumption in the 7.6 hours test (E_{load}) was 1065 Wh. During the fuel cell and battery joint operation period, the total energy produced in the fuel cell (E_{FC}) was 608.4 Wh, with a measured hydrogen consumption of 47.1 g. 51% of this energy (308.03 Wh) was used to charge the batteries, and the remaining 49% (300.35 Wh) was used in the energy demand of the vehicle. During this period, the battery

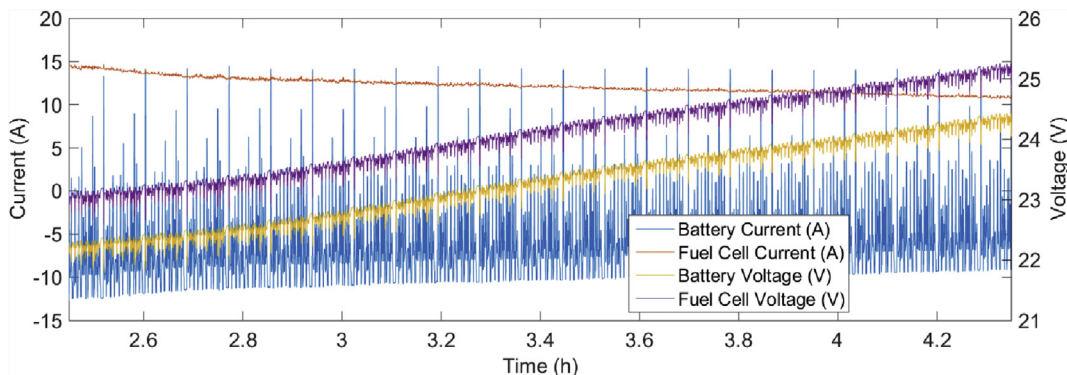


Fig. 10 – Voltage and current evolution.

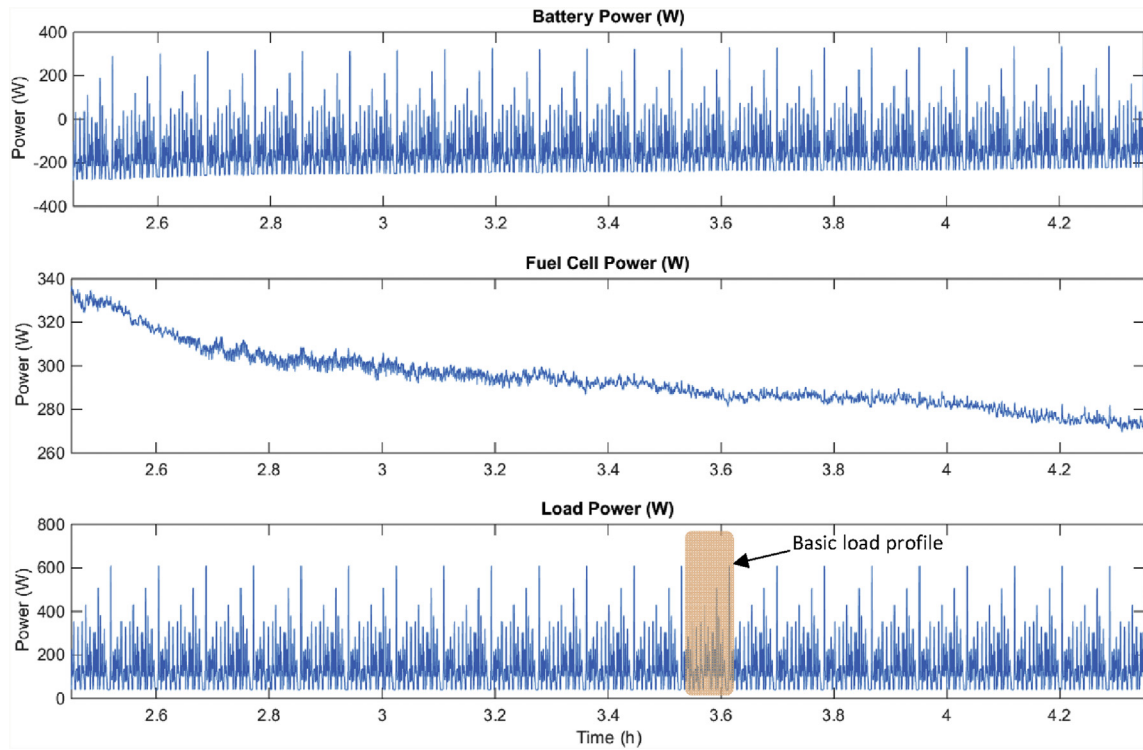


Fig. 11 – Battery, fuel cell and load power.

had an energy output of 18.84 Wh when discharging, mainly due to the peaks in the vehicle load.

The energy supplied by the fuel cell to the battery was in the same order of the energy provided by the battery to the vehicle prior to the operation of the fuel cell (around 327 Wh). Consequently, the battery SOC at the end of fuel cell's operation was almost the same as the SOC at the beginning of the long term test (t_0), when the battery was fully charged. The average fuel cell efficiency over the operating period was calculated as shown in Eq. (5):

$$\eta = \frac{E_{FC}}{E_{H_2}} \quad (5)$$

E_{H_2} is the energy content of the hydrogen consumption, and it is calculated as shown in Eq. (6):

$$E_{H_2} = m_{H_2} \cdot LHV_{H_2} \quad (6)$$

E_{FC} was the energy generated by the fuel cell (608.4 Wh), m_{H_2} the mass of hydrogen consumed during the test (47.1 g) and LHV_{H_2} the lower heating value of hydrogen (120.1 MJ/kg or 33.3 Wh/g). With these values, the average fuel cell efficiency was 39%. A more adequate selection of the operating voltage range in fuel cell and battery could achieve higher efficiency when adjusting the fuel cell voltage range around the maximum efficiency point.

Conclusions and future work

This paper has analyzed the main characteristics of hybrid power systems based on batteries and fuel cells using a passive architecture. After considering different passive

configurations, a direct coupling between fuel cell and batteries showed to be most suitable for the considered application because of its simplicity, in terms of components, and flexibility, in terms of operation.

The proposed solution is based on six LiPo cells, connected in series, and a 200 W PEM fuel cell stack, directly connected in parallel to the battery without any limitation to its charge. In a first version, the system was monitored and managed with a control board of the fuel cell stack and a suitable SCADA developed for the tests. A specific Energy Monitoring and management System (EMS) is being developed, and it will be integrated in further versions of the systems. The hybrid power system was tested under a pattern load profile obtained from power consumption data in different real missions of one of these UGVs. The duration of the whole test (7.6 hours) was greater than the minimum period targeted in the project to operate the vehicle (7 hours), and notably greater than the autonomy provided by the original batteries of the vehicle in missions with similar load profile (around 2 hours). The results showed good performance of the fuel cell and the battery during the tests of the hybrid system, which operated the fuel cell when the battery reached a low voltage threshold, around the two hour mark of continuous operation. During the operation, around 49% of the energy produced by the fuel cell was used by the vehicle, and the remaining 51% recharged the battery. The design of the system allowed to the battery to cover the peaks when the required power was higher than that generated in the fuel cell. Battery charging and discharging currents were around 13–14 A (i.e., around 0.5 C), fulfilling the specifications of the manufacturer. In these conditions, the voltage of the fuel cell was set by the voltage at the DC bus; the fuel cell current, voltage and power presented

a smooth variation from the maximum values at the beginning of its operation to the end, which resulted in greater durability of the power system. The average fuel cell efficiency achieved in the tests was 39%.

It is important to highlight that, to guarantee a suitable joint operation of the fuel cell and the battery, careful design, selection and development of both components is required. Based on the experimental data, the next step will be focused on voltage range optimization, which will increase the efficiency and durability of the whole system, as well as minimize fuel cell degradation. Further steps will include integration in the hybrid power system of the hydrogen storage system and the energy management system (EMS). In a first estimation, considering a 3 l compressed hydrogen type III cylinder, operating at 200 bar, as hydrogen storage, the specific energy in the hybrid power system would be around 200 Wh/kg, achieving the technical target of the project (180 Wh/kg). The definitive power systems installed in the UGV will be evaluated in field test under real operating conditions, in order to assess its advantages/disadvantages, in terms of cost, risk of failure, specific energy and energy density, with other possible technical solutions.

Acknowledgments

The authors would like to acknowledge the NATO Science for Peace and Security Program for partially funding this work through the project “Improving efficiency and operational range in low-power unmanned vehicles through the use of hybrid fuel-cell power systems” (IUFCV), Ref. 985079.

REFERENCES

- [1] euRobotic aisbl. European Robotics technology platform, strategic research agenda for robotics in Europe 2014–2020. 2014.
- [2] U.S. department of defense unmanned systems roadmap 2007–2032. 2007.
- [3] Hannan MA, Hoque MM, Mohamed A, Ayob A. Review of energy storage systems for electric vehicle applications: issues and challenges. *Renew Sustain Energy Rev* 2017;69:771–89.
- [4] Keil P, Hofmann M, Horsche MF, Pichlmaier S, Jossen A, Zimmermann T. Review of system topologies for hybrid electrical energy storage systems. *J Energy Storage* 2016;8:78–90.
- [5] Andreasen SJ, Ashworth L, Menjón Remón IN, Kær SK. Directly connected series coupled HTPEM fuel cell stacks to a Li-ion battery DC bus for a fuel cell electrical vehicle. *Int J Hydrogen Energy* 2008;33:1737–45.
- [6] Bernard J, Hofer M, Hannesen U, Toth A, Tsukada A, Büchi FN, et al. Fuel cell/battery passive hybrid power source for electric powertrains. *J Power Sources* 2011;196:5867–72.
- [7] Serincan MF. Validation of hybridization methodologies of fuel cell backup power systems in real-world telecom applications. *Int J Hydrogen Energy* 2016;42:19129–40.
- [8] Zhang X, Liu L, Dai Y, Lu T. Experimental investigation on the online fuzzy energy management of hybrid fuel cell/battery power system for UAVs. *Int J Hydrogen Energy* 2018;43(21):10094–103.
- [9] Fathabadi H. Combining a proton exchange membrane fuel cell (PEMFC) stack with a Li-ion battery to supply the power needs of a hybrid electric vehicle. *Renew Energy* 2019;130:714–24.
- [10] Wang Y-X, Ou K, Kim Y-B. Modeling and experimental validation of hybrid proton exchange membrane fuel cell/battery system for power management control. *Int J Hydrogen Energy* 2015;40(35):11713–21.
- [11] Wang Y-X, Ou K, Kim Y-B. Power source protection method for hybrid polymer electrolyte membrane fuel cell/lithium-ion battery system. *Renew Energy* 2017;111:381–91.
- [12] Roda V, Carroquino J, Valiño L, Lozano A. Remodeling of a commercial plug-in battery electric vehicle to a hybrid configuration with a PEM fuel cell. *Int J Hydrogen Energy* 2018;43(35):16959–70.
- [13] Hwang JJ, Chang WR. Characteristic study on fuel cell/battery hybrid power system on a light electric vehicle. *J Power Sources* 2012;207:111–9.
- [14] Das HS, Tan CW, Yatim AHM. Fuel cell hybrid electric vehicles: a review on power conditioning units and topologies. *Renew Sustain Energy Rev* 2017;76:268–91.
- [15] Belmonte N, Luetto C, Stauro S, Rizzi P, Baricco M. Case studies of energy storage with fuel cells and batteries for stationary and mobile applications. *Challenges* 2017;8:9. <https://doi.org/10.3390/challe8010009>.
- [16] Chen Y-S, Lin S-M, Hong B-S. Experimental study on a passive fuel cell/battery hybrid power system. *Energies* 2013;6:6413–22. <https://doi.org/10.3390/en6126413>.
- [17] Samsun RC, Krupp C, Baltzer S, Gnörich B, Peters R, Stolten D. A battery-fuel cell hybrid auxiliary power unit for trucks: analysis of direct and indirect hybrid configurations. *Energy Convers Manag* 2016;127:312–23.
- [18] Nishizawa A, Kallo J, Garrot O, Weiss-Ungethüm J. Fuel cell Li-ion battery and direct hybridization system for aircraft applications. *J Power Sources* 2013;222:294–300.
- [19] Gross T, Poche A, Ennis K. Beyond demonstration: the role of fuel cells in DoD's energy strategy. LMI; 2011.
- [20] Dudek M, Raźniak A, Lis B, Kawalec M, Krauz M, Wójcik T. Power sources involving ~ 300W PEMFC fuel cell stacks cooled by different media. *Energy Fuels* 2016. E3S Web of Conferences 14, 01042 (2017).
- [21] Gong A, Palmer JL, Brian G, Harvey JR, Verstraete D. Performance of a hybrid, fuel-cell-based power system during simulated small unmanned aircraft missions. *Int J Hydrogen Energy* 2016;41:1141–11426.
- [22] Renau J, Sanchez F, Lozano A, Barroso J, Barreras F. Analysis of the performance of a passive hybrid powerplant to power a lightweight unmanned aerial vehicle for a high altitude mission. *J Power Sources* 2017;356:124–32.
- [23] Dudek M, Tomczyk P, Wygonik P, Korkosz M, Bogusz P, Lis B. Hybrid fuel cell-battery system as a main power unit for small unmanned aerial vehicles (UAV). *Int J Electrochem Sci* June 2013;8(6):8442–63.
- [24] Verstraete D, Gong A, Lu DD-C, Palmer JL. Experimental investigation of the role of the battery in the AeroStack hybrid, fuel-cell-based propulsion system for small unmanned aircraft systems. *Int J Hydrogen Energy* 2015;40(3):1598–606.
- [25] Mendez A, Leo TJ, Herreros MA. Current state of technology of fuel cell power systems for autonomous underwater vehicles. *Energies* 2014;7:4676–93.
- [26] González-Espasandín O, Leo TJ, Navarro-Arévalo E. Fuel cells: a real option for unmanned aerial vehicles propulsion. *Hindawi Publish Corp Sci World J* 2014;2014. Article ID 497642.

- [27] Sohn S-I, Oh J-H, Lee Y-S, Park D-H, Oh I-K. Design of a fuel-cell-powered catamaran-type unmanned Surface vehicle. *IEEE J Ocean Eng* APRIL 2015;40(2):388–96.
- [28] Savvaris A, Xie Y, Malandrakis K, Lopez M, Tsourdos A. Development of a fuel cell hybrid-powered unmanned aerial vehicle. In: 24th mediterranean conference on control and automation. MED; 2016.
- [29] Swider-Lyons KE, Stroman RO, Gould BD, Rodgers JA, MacKrell J, Schuette M, et al. Hydrogen fuel cells for small unmanned air vehicles. *ECS Transac* 2014;64(3):963–72.
- [30] Gong A, Verstraete D. Fuel cell propulsion in small fixed-wing unmanned aerial vehicles: current status and research needs. *Int J Hydrogen Energy* 2017;42:21311–33.
- [31] Lee B, Park P, Kim C, Yang S, Ahn S. Power managements of a hybrid electric propulsion system for UAVs. *J Mech Sci Technol* 2012;26(8):2291–9.
- [32] Donato T, Ficarella A, Spedicato L. Fuel cell based-on powertrain to hybridize small unmanned aerial vehicles. In: European Fuel Cell Technology & Applications Conference; 2017.
- [33] Lapeña-Rey N, Blanco JA, Ferreyra E, Lemus JL, Pereira S, Serrot E. A fuel cell powered unmanned aerial vehicle for low altitude surveillance missions. *Int J Hydrogen Energy* 2017;42:6926–40.
- [34] Verstraete D, Lehmkuehler K, Gong A, Harvey JR, Brian G, Palmer JL. Characterisation of a hybrid, fuel-cell-based propulsion system for small unmanned aircraft. *J Power Sources* 2014;250:204–11.
- [35] Kim T, Kwon S. Design and development of a fuel cell-powered small unmanned aircraft. *Int J Hydrogen Energy* 2012;37:615–22.
- [36] Protonex powers UGV for record mission duration. *Fuel Cell Bull* June 2009;2009(6):3.
- [37] Baldic J, Osenar P, Lauder N, Launie P. Fuel cell systems for long duration electric UAVs and UGVs, Proceedings SPIE Defense, Security, and Sensing. 2010. Orlando, Florida, United States.
- [38] Broderick JA, Tilbury DM, Atkins EM. Control of a lead-acid battery/fuel cell hybrid power system for a UGV: experimental report, Automotive Research Center. University of Michigan, Tech. Rep.; 2014.
- [39] Bugár M, Ferencey V. Control management system of the hybrid - electric power sources simulation for unmanned ground vehicle, 2016. Levoca: Cybernetics & Informatics (K&I); 2016. p. 1–6. <https://doi.org/10.1109/CYBERI.2016.7438631>.
- [40] Gong A, Verstraete D. Role of battery in a hybrid electrical fuel cell UAV propulsion system. In: 52nd Aerospace Sciences Meeting. AIAA SciTech; 2014.
- [41] <http://iufcv.com/objectives/>. [Accessed in November, 2018].
- [42] López E, Isorna F, Ridaó MA, Bordons C, Elfes A, Hernández E. Proyecto IUFCV: incremento de la autonomía en vehículos no tripulados mediante el uso de sistemas híbridos de potencia con pila de combustible. *Boletín de Observación Tecnológica en Defensa* n° 2017;53. 1.er trimestre.
- [43] <https://www.clearpathrobotics.com/husky-unmanned-ground-vehicle-robot/>. [Accessed in November, 2018].
- [44] <https://www.robotnik.eu/mobile-robots/summit-xl/>. [Accessed in November, 2018].
- [45] http://www.bchpower.com/en/QingNengDianDui_v109.html#. [Accessed in November, 2018].
- [46] <http://kokam.com/cell/>. [Accessed in November, 2018].
- [47] <https://www.arbin.com/products/battery-testing/module-testing/>. [Accessed in November, 2018].