Evaluation of a Hybrid Copter Drone Using Hydrogen fuel cell and Batteries

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Abstract

Copter drone use has been a steady increase over the last couple of decades. The main obstacle that has slowed down the widespread use of these systems has been their limited flight time. This research paper will focus on implementing a hybrid system that includes a hydrogen fuel cell (HFC) along with a battery in a hex-copter configuration to determine its effectiveness and if possible, increase its flight time. The reason for the use of hydrogen relies on the fact that it has a higher energy density (120 kJ/g) than commercial lithium-ion polymer batteries (LiPo), the type of batteries most civilian drones currently use, which only have an energy density of 1 kJ/g. This project was divided into several smaller tasks for its completion: Assembling the drone, preparing a testing flight with only LiPo batteries, testing the HFC and batteries with a parallel circuit composed of lightbulbs, and finally testing both the HFC and LiPo batteries on the drone to spin the motors without propellers. The data used for the analysis of the performance of the drone was the power drawn over the duration of each test. The results show a delay of less than 1 second between the transition from the fuel cell power to battery power. Additionally, it was found that both fuel cell and battery supplied battery at the same time, but the latter was almost negligible. However, the battery effectively supplied the drone with almost the same amount of power as the fuel cell when hydrogen was exhausted. Finally, it was found that the battery system plays an important role when the fuel cell is being turned on or off.

Keywords

Fuel Cell, Student Paper, Polymer Electrolyte Membrane, Light Detection and Ranging, and Lithium-Polymer Batteries.

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Introduction

During the past two decades, there has been an increase in the use of unmanned aerial vehicles for communication, delivery of products, and transportation. Aerial entertainment for the movie industry, photography, precision agriculture, and law enforcement are some of the many industries drones are currently used in [1]. Drones are being used for military purposes in extensive missions [2]. Drones can also be employed to survey roads, inspect infrastructure projects, and scan bridges for failure points in conditions where remote access is crucial. Container and tower cranes could be easily accessible by drones to be inspected, reducing the probability of accidents and injuries. The agricultural industry can also employ the drone for precision farming by outfitting a spraying system for autonomous pesticide spraying, mounting a camera to track livestock, configuring Light Detection and Ranging (LIDAR) to map the terrain for crop fields, and structure planning [3].

As a general overview, most drones are designed with batteries because of their easy accessibility and lower price. The low energy density found in batteries drastically reduces the drone's flying time [1,4]. Furthermore, due to its limited power output, batteries may limit drones when having to perform fast response maneuvers [1]. For longer duration flights hydrogen fuel cells (HFC) can be employed, due to their higher power density, excellent output power, and high efficiencies (around 50%). Due to these facts fuel cell flight times can range between 5 to 25 hours, depending on drone configuration [2,5]. One of the reasons for their high efficiency is the fact that they can operate at high or low temperatures without any notable change in their performance [6]. Despite the many advantages HFC drones provide, they also possess disadvantages. Firstly, hydrogen fuel cells have expensive and extensive hardware [2,5]. Secondly, hydrogen also poses a problem in terms of storage. The use of hydrogen as fuel for drones also brings some risk factors since hydrogen is considered volatile under certain circumstances. Both batteries and HFC have their merits and drawbacks, thus if a hybrid system were to be utilized combining both types of energy sources could achieve higher efficiencies. Having batteries to support HFCs when they cannot provide enough power for drones, or the hydrogen is exhausted, would create an insurance that would also allow for longer and safer flights.

The objective of the present study is to determine the power-time behavior of the HES Aerostak A-1000 (HV) Polymer Electrolyte Membrane (PEM) fuel cell coupled with 2 x Max Amps 5s 3250mAh Lithium-Polymer (LiPo) batteries. Two different ground tests were employed, one using lightbulbs and another coupling the power system to the drone to test its motors. The reason for this is to determine whether the hexacopter drone can use a hybrid system involving HFC and batteries and investigate the possibility of increasing the range and flight time by analyzing the drone power consumption and the HFC performance. The design of the drone leaned towards a larger size of approximately 1.5 m in diameter and a height of 0.4 m. The reason behind this focus is due to the lack of extensive literature regarding larger drones employing hybrid systems. The applications for the drone will be centered toward infrastructure inspection; therefore, it must be capable of flying for extensive hours. Furthermore, the drone must be easy to control, maneuver, and environmentally/user safe. Once the fuel is exhausted, it must be capable of working with a backup battery or if the drone requires more power than the HFC can produce then the batteries must be able to supply that demand. Thus, lag and other power supply delays must be diligently studied.

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System Components

The drone is constructed in a hexagonal X structure capable of maximizing flight times while keeping high stability. The drone is equipped with 6 U8II Lite KV100 brushless DC motors and 6x60 amp 12s electronic speed controllers. The power supply comes from a 1.1kW PEM fuel cell and two 3250mAh LiPo batteries as an emergency power backup. A carbon fiber chassis was chosen to maximize the weight-to-strength ratio and improve aerodynamics. ABS mounts created with an FDM 3D printer are used for additional components such as mounting for the flight stack, Hydrogen fuel tank, and the fuel cell itself. A picture of the drone can be seen in Figure 1. Table 1 shows a more in-detail description of the components used, their manufacturers, and weights.

Figure 1: Hexacopter Drone.

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Table 1: List of Drone Components.

Part	Manufacturer	Model	Weight	Notes:
Motors	T-Motor	T-Motor U8II Lite KV100	256g x 6	Smooth control, low noise, high efficiency.
Propellers	T-Motor	T-Motor G28 x 9.2 propeller	85g x 6	28” carbon fiber propellers.
Electronic Speed Controller	T-Motor	T-Motor Flame 60A ESC	73.5g x 6	Efficient, reliable, high amperage.
Frame	Gryphon Dynamics	Gryphon Hexa 1600VX Frame	2,020g	Carbon Fiber 1600mm wheelbase, hex copter design.
Batteries	Max Amps	Max Amps 5s 3250mAh LiPo	405g x 2`	Two 5 cell 3250mAh LiPo batteries wired in series.
PEM Fuel Cell	H3 Dynamics	HES Aerostak A-1000 (HV)	2,131g	1kW proton exchange membrane hydrogen fuel cell in parallel with a 10 cell LiPo battery.
Hydrogen Tank	H3 Dynamics	HES F3 3L 300bar Hydrogen Tank	1,360g	3L carbon fiber construction tank.
Flight Controller	Cube Pilot	Cube Orange	73g	Fast highly powerful H7 processor with build in redundancies.
Carrier Board	Cube Pilot	Kore Carrier Board	250g	Lightweight carrier board that gives easy access to all pins of the cube orange.
Ground Station	Ardupilot	Mission Planner	N/A	Used to setup and control flight controller.

Experimental Setup

Several experimental tests have been conducted to assess the compatibility and effectiveness of the hydrogen fuel cell (HFC) system as well as the integrated system combining the hexacopter and the fuel cell system. In order to evaluate the capability of the HFC to deliver power for varied power loads, three tests were carried out using lightbulbs (200W each). The maximum number of lightbulbs used were 3 (Figure 2), 10 (Figure 3) and 18 (Figure 4) respectively.

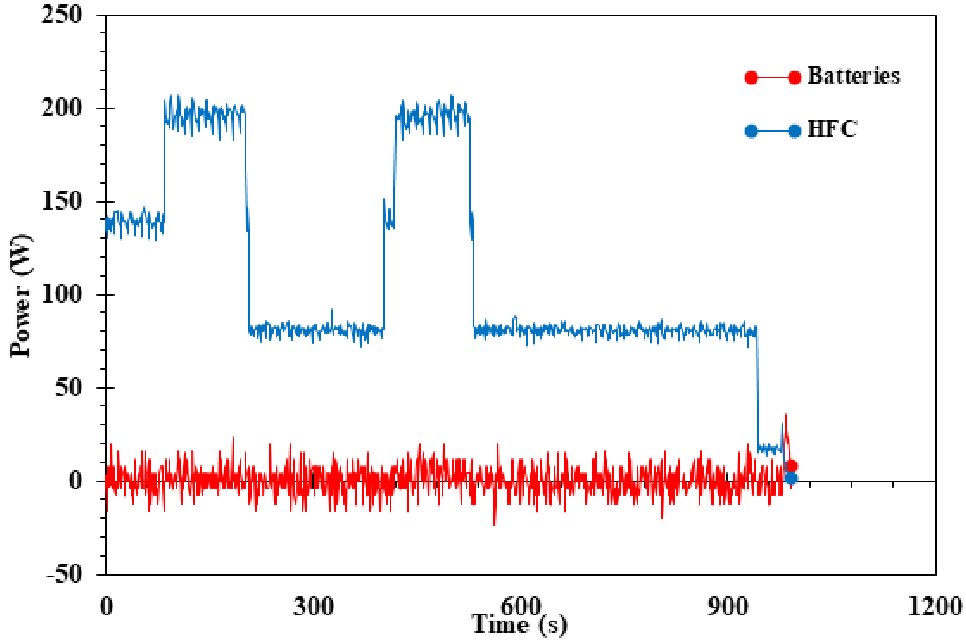

Figure 2: Power Supply from HFC and Batteries During Lightbulb Test 1.

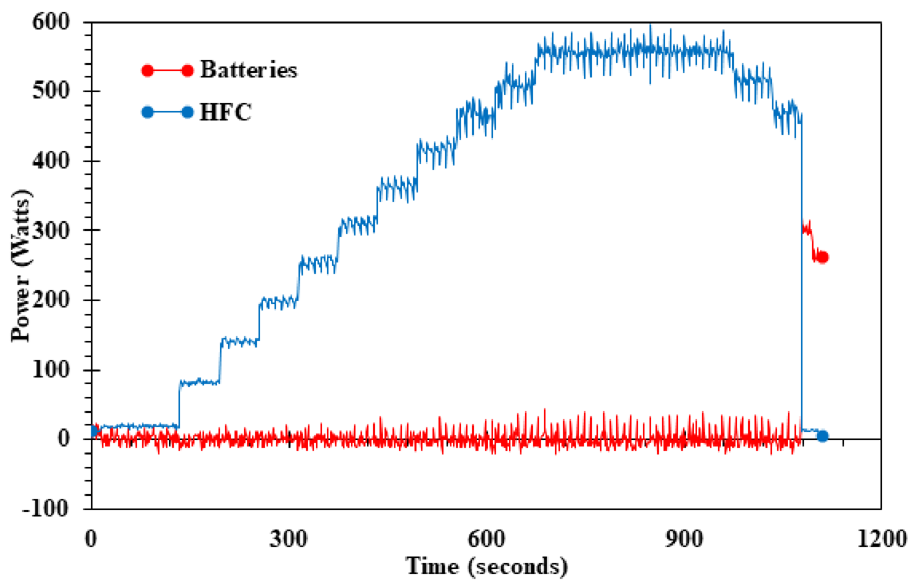

Figure 3: Power Supply from HFC and Batteries During Lightbulb Test 2.

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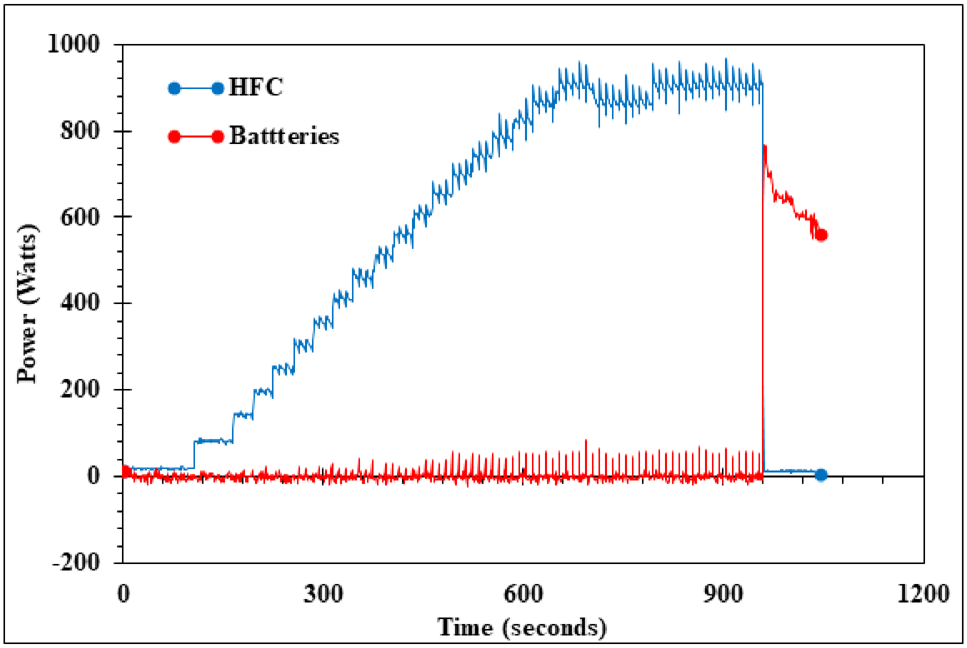

Figure 4: Power Supply from HFC and Batteries During Lightbulb test 3.

The lightbulbs in every test carried were arranged in a parallel circuit as seen in Figure 5 and Figure 6, meaning that all lightbulbs would have the same voltage across them. This arrangement was chosen to maximize the power consumption in the circuit. If a series configuration had been chosen, the overall power consumption would have decreased since this type of circuit would result in a much larger resistance when compared to a parallel configuration. The greater the resistance of the circuit, the lower the power consumption since their relation is inversely proportional according to Equation 1 derived from Ohm's law:

$$P = \frac{V^2}{R} \quad \text{(Eq.1)}$$

The reason behind maximizing the power consumption was to create a high-demand environment for the hydrogen fuel cell, thus testing its capabilities before proceeding to flight tests. During each test, the number of active lightbulbs was gradually changed. For example, in the last test involving 18 lightbulbs, they were turned on one by one from 0 to 18 over the course of the test and maintained for certain time periods to note the corresponding power levels and fluctuations. The sudden spikes in the power levels in the aforementioned figures occurred when additional lightbulbs (increased load) were gradually turned on. During the tests, the power drawn from the batteries was mostly negligible compared to that from the HFC. However, they were significant during the initiation of the HFC system as well as during the safe shutdown of the system when it ran out of hydrogen gas.

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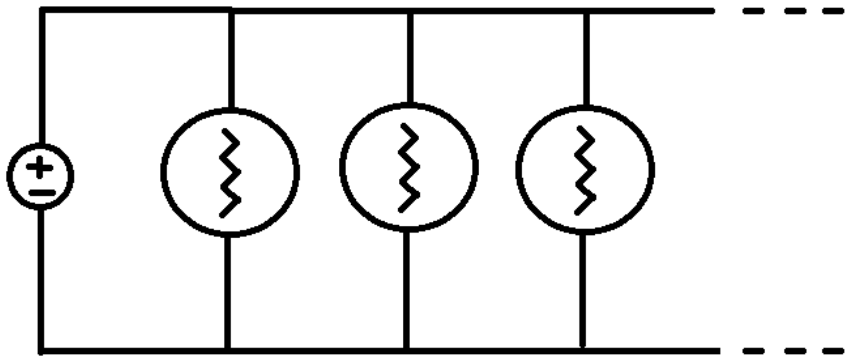

Figure 5: General Schematic of Parallel Circuit Design for Lightbulb Test Stand.

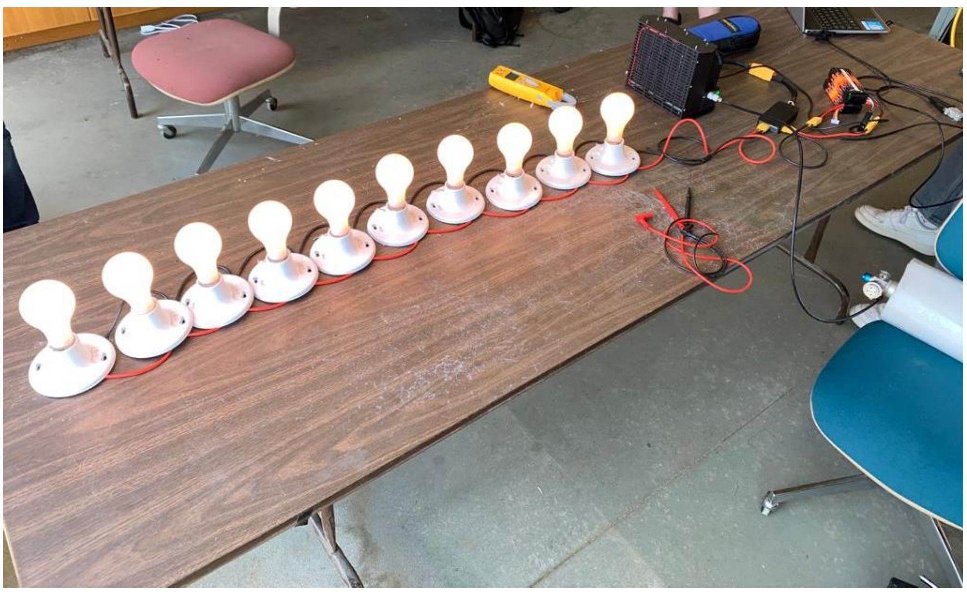

Figure 6: Lightbulb Test 2 Setup.

After the lightbulb tests, the HFC system was integrated with the hexacopter to carry out a motor spinning test to evaluate its operational consistency and power delivery to the drone. During the test, all 6 motors of the drone were spun with varying intensities. The motors did not have the propellers set up because this test was carried inside the laboratory. The activity of the power consumed by the motors can be seen in Figure 7 as a function of time.

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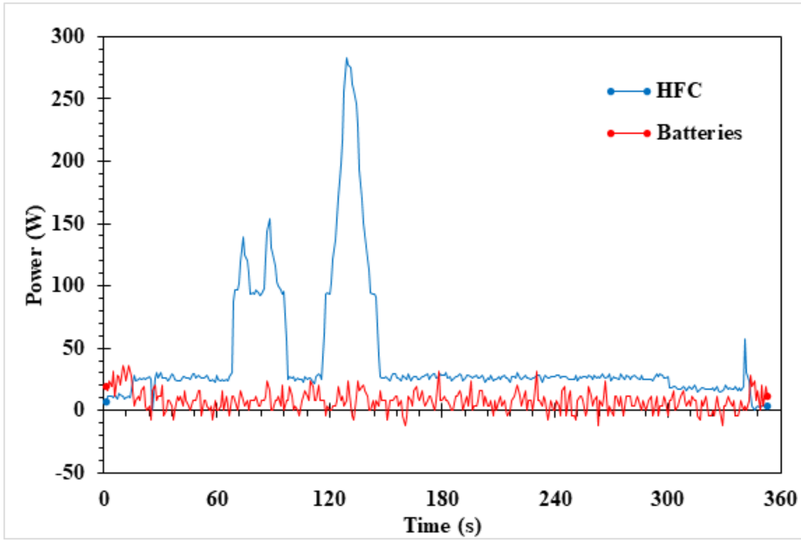

Figure 7: Power Delivered to Hexacopter by HFC & Batteries in Motor Spinning Test.

Results and Discussion

The obtained data from the lightbulb tests showed a mild fluctuation in power supply for a fixed number of lightbulbs, but the variations increased in magnitude as the number of lightbulbs increased. Figure 8 shows the average power level and the amount of time at that level for each different number of lightbulbs for tests 1,2, and 3 combined. By taking the area under the curve from Figure 8 the total power used in tests 1,2, and 3 can be obtained, which amounts to 1080 kJ of energy. When divided by the 12 grams of hydrogen present in the tank, the energy density comes out to be ~90 kJ/g. The deviation from the theoretical value presented in the literature (120 kJ) may be due to the uncertainty found in the pressure gauge which contributed to the error when the Ideal Gas Equation was used to obtain the mass of hydrogen.

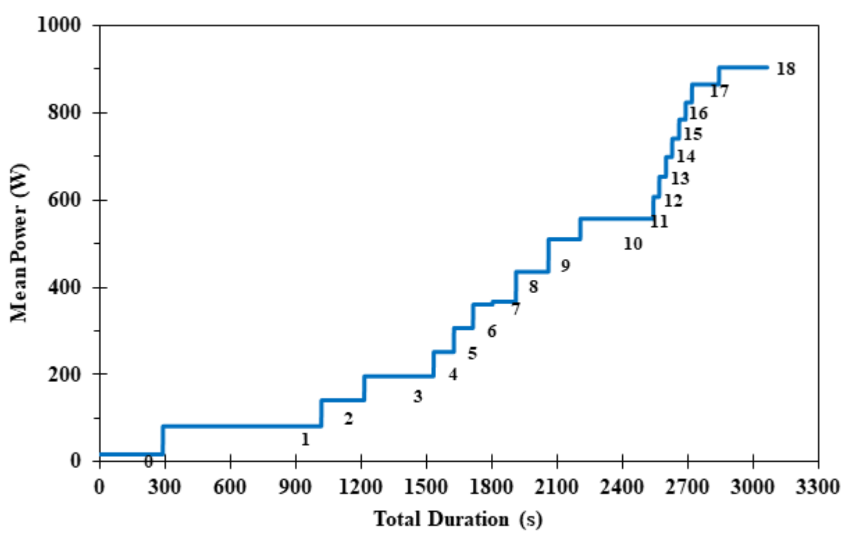

Figure 8: Mean Power Supply by HFC for Different Total Lightbulb Counts.

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Despite the increased range of variability at higher power levels, the general trend of total power delivered by both HFC, and batteries closely followed a linear trend, as depicted in Figure 9. The standard deviation of the total and HFC-only power delivered was calculated as a function of the number of lightbulbs as shown in Figure 10. This figure also illustrates that the standard deviation for both cases increase with the load, explaining the steeper peaks and valleys shown in Figures 1,2, and 3 for higher amounts of lightbulbs. Furthermore, when compared to its HFC counterpart, the smaller slope for the "Total Power Delivered line" in Figure 10 would explain how the batteries help to reduce this variability. Therefore, it can be concluded that the load draws energy from both sources and that when there is an energy surplus the batteries get recharged (negative power values in Figures 1-4).

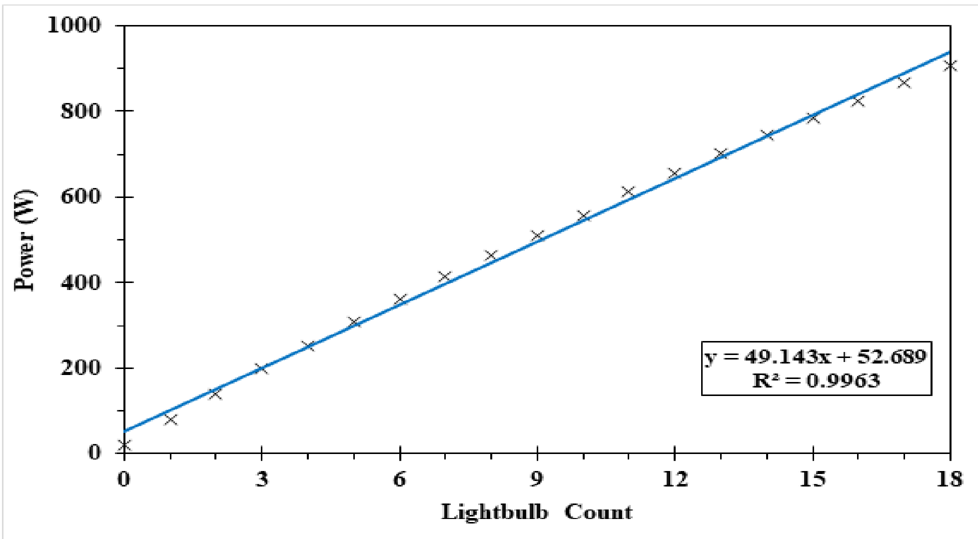

Figure 9: Combined Average Power Supply to Drone from HFC & Batteries.

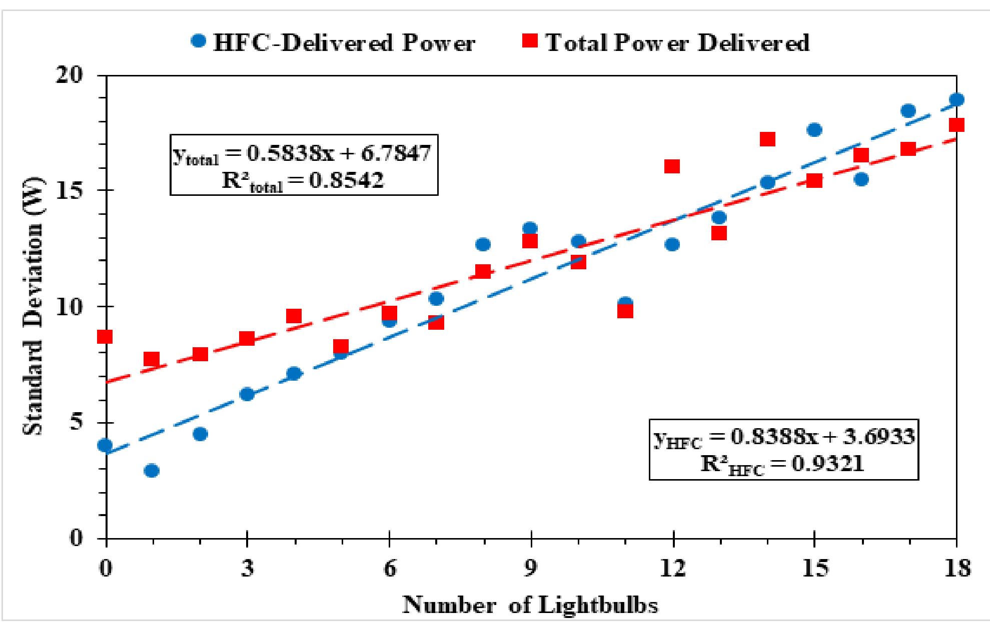

Figure 10: Standard Deviation of Mean Power Supply.

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The relatively wide gap between the lines in Figure 10 shows that the batteries compensated for the power supply during the beginning period and when the power demand was on the higher end. It is likely that there exists an optimal power load for which the integrated system will be dependent on the HFC for the entirety of the test. Although, more rigorous testing is required to precisely obtain that information.

Regarding the results from the spinning test of the motors utilizing the HFC, Figure 7 demonstrates the power supplied to the drone by the HFC and the batteries with respect to time. Similar to the lightbulb tests, the power contributions from the batteries in the beginning and towards the end were not negligible, which is most likely due to the battery providing energy to the fuel cell during its startup and shut-down sequences, as seen from the surges in seconds 12 and 350 from Figure 7. Although during the test the HFC was the dominant energy source to the drone, there were few momentary power spikes from the batteries. While the exact interaction between the HFC and the batteries are not completely understood at this time, the system seems capable of seamless delivery of power without any discernible lag. This can also be seen in Figure 3 and Figure 4 at 1125 and 975 seconds respectively, where the fuel cell ran out of hydrogen and the batteries started in less than a second of delay.

Conclusion

In conclusion, from figures 3 and 4 the battery delay response is almost negligible. Additionally, an increase in the variation of the power supplied is directly proportional to the load in the system. This fact proves how both sources supply energy into the system. It was also found that the battery reduces this variation for higher loads. Furthermore, the percentage of power supplied by the batteries plays an important role when turning the fuel cell on or off. The hydrogen energy density was determined to be ~90 kJ/g. It is suspected that the deviation from true value may be due to the uncertainty present in the pressure value when applying the Ideal Gas Equation.

The current work and testing mentioned above have shown great promise in terms of utilizing hydrogen and hybrid systems for drone flights. That said, this research is still a work-in-progress and several facets of it, such as maximum achievable flight duration and comparison with battery-operated drones, its autonomous capability, payload capacity, economic feasibility, diversification of its applications, etc. are to be gradually explored through more laboratory and field testing.

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Gerardo Urdaneta

Gerardo Urdaneta is from Maracaibo, Venezuela. He is pursuing a Bachelor of Science in Mechanical Engineering at Arkansas Tech University. From June 2019 to October 2021, he worked as a tutor helping students with such as Calculus, Differential Equations, and Thermodynamics. Since January 2021, he has been working as a research assistant in different groundbreaking projects such as the creation of a drone powered by hydrogen and the development of a deep learning algorithm capable of detecting checkboxes in scanned documents. His interests about space and engineering have led him publish two articles about drones' potential benefits for human life as well as the feasibility of space power satellites.

Jacob Crawford

Jacob Crawford is a Junior Electrical Engineering student at Arkansas Tech University. He has been actively working on hydrogen fuel cell projects since January 2021 and has been to state-level events for the project. Jacob has won state competitions in both engineering and computer science in FBLA and Senior Beta. Jacob has worked on many engineering projects involving drone technology over the past 5 years and is a certified sUAS pilot. His other research interests include power systems, astronomy, and low emission aviation.

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Andres Dewendt

Andres Dewendt is from Maracaibo, Venezuela. He is majoring in Electrical Engineering (Biomedical track) at Arkansas Tech University. He has worked as tutor for the university since August 2019, helping students in classes such as Calculus, General Chemistry, and Principles of Biology. Since September 2020, he has worked in different research projects including the development of Machine learning algorithm to detect COVID-19, the development of a deep learning algorithm that is capable of detecting checkboxes from scanned surveys and the creation of drone that is powered by hydrogen and batteries in a hybrid system.

Zuhanee Khan

Zuhanee Khan is currently pursuing his master's in mechanical engineering degree and also working as a graduate assistant at Arkansas Tech University. Prior to this, he received his B.Sc. degree in the same major from Bangladesh University of Engineering & Technology. Apart from his current works on HFC drones, he has been involved in thesis and/or projects related to natural fiber-reinforced composites, RC plane, control design of robotic manipulator, and functionally graded additive manufacturing. His other research interests include fluid and nanotechnology, sustainable energy systems etc.

Kyle McMillan

Kyle McMillan is from Texarkana, Arkansas. He is currently working towards a Bachelor of Science in Mechanical Engineering at Arkansas Tech University. He was awarded an Arkansas Space Grant Consortium Workforce Development Award for 2022 enabling him to work on a hydrogen powered drone project. His interest in space travel and exploration drives his desire to further his knowledge in the areas of robotics and advanced materials. Other interests include 3D printing and carbon fiber composites. He hopes to one day work as a part of the modern space era with the goal of taking mankind beyond the Moon.

Christopher Meyers

Christopher Meyers is from Hot Springs, Arkansas and is currently studying Mechanical Engineering at Arkansas Tech University. In addition to his engineering major, he will be receiving minors in Physics and Mathematics upon his graduation in December of this year. He has served on the research and development team at XpressBoats for the last two years as an engineering intern, where he designs and tests components for aluminum hull boats, and prototypes new boat designs. He has project experience on the ATU Shell Eco Marathon Car, and Hydrogen Fuel Cell drone teams. His previous research experience includes solar power satellites and the applications of drones.

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