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MASS AND FLIGHT ENDURANCE OPTIMIZATON OF A HYDROGEN POWERED SEARCH AND RESCUE QUADCOPTER

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ABSTRACT

Increased flight time of search and rescue quadcopters is essential for critical missions that endanger public safety. An inhouse mathematical model was built to analyse the drone's performance using both batteries and hydrogen fuel cells. The aim of this study is to determine the viability of utilizing hydrogen fuel cells in drones to extend their flight time. The analysis was done by modelling power equations to find the drone's flight time as it was the most important performance parameter. A Li-Po battery with a specific energy density of 200Wh/kg was compared with hydrogen fuel cells to obtain the drone's endurance. The results of this study determined that fuel cells are desirable above a critical mass point of 1.32 kg of the energy system while batteries are more suitable below this point. A mass sensitivity analysis was conducted to investigate the importance of mass savings on the endurance of the quadcopter. Peak endurance is achieved when the mass of the energy system is precisely two-thirds of the total quadcopter's mass.

Keywords: Search and Rescue (SAR), Hydrogen Fuel Cell, Quadcopter, Endurance.

INTRODUCTION

In this modern age, Unmanned Aerial Vehicles (UAVs) have revolutionized the aerospace industry by integrating into various applications in sectors such as agriculture, search and rescue, transportation, surveillance, and many others. Experts predict that the market for these UAVs, better known as drones, will grow up to $6.3 billion by 2026 [1]. Drones are extensively used in search and rescue missions as they can explore inaccessible terrains. SAR operations are unpredictable as missions include objectives such as locating a missing person, scanning the surrounding area for any threats, and helping injured individuals. SAR drones are fitted with advanced camera and tracking systems so that they can search rapidly compared to ground search teams. Quick deployment is crucial as time is of the essence in these types of missions. 96% of drones sold worldwide are battery powered and thus have limitations on flight times and range [2]. Current standard SAR drones only have a flight time of less than an hour which may not be sufficient for extended missions that require a larger search area [3]. This is due to the limited capacity of the battery installed. In many drone applications the Lithium Polymer (Li-Po) battery is used more often than the Lithium Ion (Li-ion) battery as it provides an improved energy density of 200Wh/kg compared to 150Wh/kg of the Li-ion battery [4]. SAR drones come in different configurations such as fixed wing and rotary wing. Fixed wing drones can fly at a higher altitude and for longer durations compared to rotary wing drones, however fixed wing drones need a runway or a mechanism that is able to launch the drone into the air, hence slowing the deployment of the fixed wing drone. Moreover, fixed wing drones cannot hover at a specific area which reduces its versatility [5]. Rotary wing UAVs are preferred in SAR missions and thus will be considered in this study.

Alternative power sources such as using hydrogen fuel, solar power or micro gas turbines are being tested to replace batteries. Hydrogen propulsion has been suggested as the way forward as it does not emit any carbon dioxide as highlighted by Cecere [6]. Moreover, hydrogen fuel has been gaining popularity due to its high energy density (Wh/kg) thus making it an attractive option for researchers and industries. With the growing demand for SAR drones to increase public safety, optimizing the power sources to achieve longer endurance remains a priority. Hydrogen fuel is the best alternative to a Li-Po battery as it boasts a higher energy per mass ratio [7]. Kang et al. determined the energy density of liquid hydrogen to be within the range of 2000-2500Wh/kg while Apeland has shown that hydrogen fuel cell systems exhibit an energy density of 250-540Wh/kg [8-9]. Fuel cell systems have lower energy per mass because the mass of the additional equipment was accounted for rather than just the mass of hydrogen as shown by Kang et al. Fitting a hydrogen fuel tank on a SAR drone can increase the flight time however storage of hydrogen is a complication especially on a drone where weight is critical. Zhao et al. proposed an optimization algorithm for mass and power of a hydrogen powered quadcopter. This study has shown that the optimal design has a mass reduction of 25% while maintaining the same high-level performance [10]. Similarly, Wang et al. showed, using a mathematical model, a mass reduction of 30% can be achieved [11]. Hydrogen can be stored either as a liquid cryogenically at -252.8°C or as a gas, in insulated high pressurized containers with pressures ranging from 350-700 bar due to its low volumetric density. Brewer concluded his study by showing that an aircraft fueled with liquid hydrogen instead of kerosene is beneficial in terms of weight reduction [12]. Lee et al. have investigated weight optimization for hydrogen storage vessels using genetic algorithm. The limitation of their study is that they did not consider the total mass of the drone [13]. Storing hydrogen requires additional apparatus that may hinder the endurance and the maneuverability of the drone due to the increase in overall mass. Another alternative is to explore hydrogen fuel cells for mass optimization. In Huang’s study a hybrid power system of a quadcopter, consisting of a hydrogen fuel cell and a Li-ion battery, improved endurance and reduced the total mass [14]. A particle swarm optimization algorithm has been proposed by Boston et al. to show that a mass reduction of 15% of a hydrogen powered quadcopter is possible [15]. In this study, a basic quadcopter concept was created, shown in Figure 1, will be used to find the optimized performance of the quadcopter with an installed hydrogen storage. The aim of this project is to show how small can a hydrogen powered SAR quadcopter be without compromising the flight time.

Figure 1: CAD design of a basic quadcopter concept.

Basics of Hydrogen Fuel Cells

Figure 2 shows how a basic hydrogen fuel cell work. The stored hydrogen fuel is compressed and fed into the fuel cell and combined with oxygen obtained from the air at the cathode. In this example, a Proton Exchange Membrane (PEM) fuel cell is shown, and it uses a proton conducting polymer membrane as the electrolyte. A catalyst breaks down the hydrogen atoms into protons and electrons. The electrons flow at the external circuit towards the cathode to generate and electric current while the protons move across the selectively permeable membrane. This membrane blocks the electrons and prevents mixing of the hydrogen and oxygen gas by having separate cathode and anode compartments.

The protons and electrons are combined again at the cathode with the introduction of oxygen to produce water and heat as by-products.

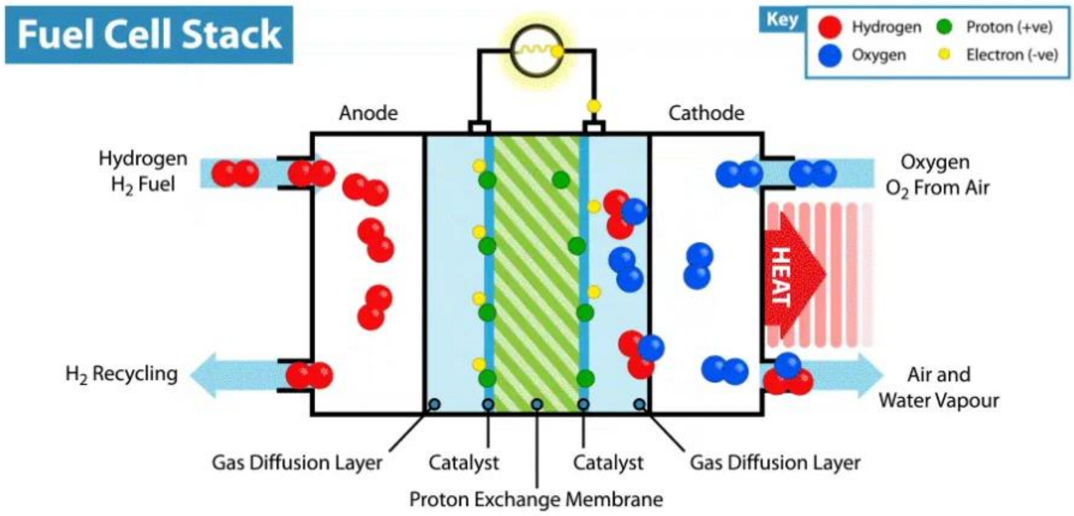

Figure 2: PEM fuel cell process reproduced by Unmanned® Systems Technology [16].

Fuel cells are devices that convert chemical energy into electrical energy through an electrochemical reaction. They are most viable for drones as fuel cells have a higher energy density and a longer operating time compared to batteries. Moreover, fuel cells are lightweight which is critical for drone applications as it results in an increase in payload capacity and an extended flight range.

METHODOLOGY

Analytical methods were used to optimize the mass of the hydrogen powered quadcopter by comparing with a battery powered counterpart. A mathematical model was created based on simple model equations and was validated with data from reliable literature sources published from manufacturers and experimental results. This resulted in correlations between different design parameters. The initial analysis was based on the battery powered Mavic 3 to validate the model which is then used to analyze the hydrogen powered quadcopter and make performance comparisons.

Parameters Initial Sizing

The Mavic 3 drone was used as the baseline concept as it boasts a flight time of 45 minutes and has a battery capacity of 5000 mAh. The total mass of the quadcopter (m_{total}) is decomposed into the fixed mass of the SAR equipment (m_{SAR}), the fixed mass of the drone's frame and avionic subsystem (m_{EW}) and the mass of the onboard energy system (m_{ES}) which is essentially the propulsion system. The dimensions and the mass distribution of the Mavic 3 drone will be shown in Table 1 [17].

$$m_{total} = m_{SAR} + m_{EW} + m_{ES} \tag{1}$$

Drones used for SAR missions are equipped with a 4K camera, a thermal imaging camera, a GPS system (RTK module), a radio transceiver, and other essential rescue gear which include first aid kits and harnessing equipment. The m_{SAR} is fixed as there is no priority to reduce weight on SAR essential equipment as it is vital for rescue missions. m_{EW} is fixed in this study although it could be altered by choosing different materials. The airframe and its components can be manufactured with lighter