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Extending Endurance of Multicopters: The Current State-of-the-Art

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This paper presents a detailed analysis on the viability of using alternate power methods for small multicopter Unmanned Air Vehicles (UAVs). Recently, fuel and solar cells have been successfully used to power autonomous winged UAVs for a wide range of applications, but alternate power supplies in multicopters have been much less explored due to increased power requirements compared with their winged counterparts. In this paper we discuss the theory and barriers to this technology along with ways multicopter UAV endurance can be theoretically increased by more than 50% using solar and fuel cells and how future advancements will quickly improve upon these numbers by more than 60% in the coming years.

I. Nomenclature

M	=	Mass of multicopter
M_B	=	Mass of battery
M_S	=	Mass of supplementary power source
m	=	Mass of air
d	=	Energy density in battery
v	=	Velocity of air
E	=	Energy
E_A	=	Actual energy needed
E_T	=	Theoretical energy needed
E_B	=	Energy in the battery
T	=	Torque
ρ	=	Density of air
A, r	=	Area and radius of the propellers
b	=	Number of propellers
P	=	Power
P_B	=	Power from the battery
P_S	=	Power from the supplementary source
η	=	Efficiency
t	=	Time of flight
B	=	Battery life

II. Introduction

The diversity of desired missions and associated requirements for multicopter Unmanned Air Vehicles (UAVs) is expanding rapidly. Their utility primarily lies in their agile flight and hovering capabilities, which makes them adept at inspection [1, 2], delivery [3], retrieval, and interacting closely with their environment [4]. The energy and power requirements needed to enable this, however, are also a major weakness. These limitations greatly restrict multicopter UAV mission types. The restrictions impact the distance the vehicle can travel, flight speed, and flight time – the consequences of which means multicopters are primarily good for short, nearby, slow missions, preferably with minimal payload and unaggressive maneuvers. To address this weakness lithium polymer, or LiPo, batteries capable of producing

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large amounts of power have been developed and continue to be the primary source of energy for propulsion. However, their energy density is low compared to other sources such as hydrogen or gas and it is difficult to quickly recharge them in the field.

Both solar cells and hydrogen fuel cells are potential solutions for these problems either by replacing or supplementing LiPo batteries. Solar cells can be used to indefinitely extend mission life by supplementing a battery in cases where landing and charging during daytime hours is an option. Currently, however, they cannot provide nearly enough power for continuous operation of a multicopter. As a result a vehicle must stop, possibly in an undesirable location or time, and recharge. Hydrogen fuel cells are compelling because of their large energy density compared to current battery technology. Hydrogen based fuel cells can contain more than 1000 $\frac{\text{W h}}{\text{kg}}$ compared to ~200 $\frac{\text{W h}}{\text{kg}}$ for typical LiPo batteries used in most multicopters [5]. This presents an opportunity to significantly extend the range of capabilities if the technology can be made to work with a multicopter UAV. In this paper, we introduce theory to analyze these alternative fuel sources and their ability to power multicopters. We explore the state-of-the-art for these alternative fuel sources and present case studies of several popular classes of multicopters. Through this, we quantify current capabilities with solar and hydrogen powered multicopters showing the ability to increase flight times by up to 25% with solar and over 50% with hydrogen in certain cases. These contributions to the field should clarify the situations in which solar and hydrogen power can be of use to the industry. Our final contribution is a look forward – we quantify the required advances in this technology that would allow a breakthrough in this area.

A. Related Work

This section focuses on four related areas that informed our work. The common uses of fuel cells in industry and research, the use of fuel and solar cells in fixed winged UAVs, the types of fuel cells available and their advantages, and the use of solar cells in flight. We use these to build the case that alternate energy is a critical advancement in multicopter UAVs, and indicate which current capabilities could translate to these advancements.

Using hydrogen and solar energy to power vehicles has been most prominently done in automobiles. Their lack of green house gas emissions and ability to run quietly have helped fuel their development as we push forward into a greener world. Tollefson explored the prospects of hydrogen cars on behalf of Nature in [6]. Hydrogen fueled automobile research seemed to pass its peak after initial investment in the early 2000's but has made a comeback as fuel cell technology has rapidly improved in the last decade. Fuel cells are getting smaller and more efficient addressing previous concerns.

There are still many obstacles for hydrogen fuel cells to overcome before they become a commercially viable option for cars but they are already a great alternative in other sectors, especially the military. A recently declassified review of potential military uses for fuel cells by the Australian government confirmed that Departments of Defense across the world are intrigued by fuel cell potential [7]. In this review Campbell, Crase and Sims discuss the advantages of replacing typical fuel and batteries with a number of different fuel cells. The positives are shown specifically in missions that require silent power. Fuel cells and batteries are excellent options for these cases as both run quietly while gasoline and other combustible fuels do not. Fuel cells though, have a much higher energy density and do not require a long charging time, instead just the filling or changing of the tank. This is important for vehicles where space and weight come at a premium or vehicles that cannot afford a long down time.

Kim and Kwon's recent paper [8] shows the potential for using fuel cells as alternates to battery power to increase flight times on unmanned winged aircrafts. They showed that hydrogen fuel cells can be quite effective at this goal especially when a hybrid system is used to overcome the pitfalls of the cells. This technique combined with the replacement of some materials with lighter acrylic will be useful in adapting fuel cells for multicopter UAVs. Such work isn't uncommon as fuel cells on winged aircrafts have been explored for over a decade. The different generations of fuel cells that have been used on winged flight can be seen in [9], [10], and [11].

Other work into exploring the effectiveness of fuel cells for flight have shown promising results. Krawczyk, Mazur, Sasin, Stoklosa present a detailed analysis of the benefits and pitfalls of different fuel sources for UAVs in their paper [5]. They compared $LiCoO_2$, $LiFePO_4$, LiPo, and Li-ion before determining that LiPo and Li-ion are typically the best battery types for flight applications due their high energy density, stability, and ability to maintain their effectiveness over many charging cycles. When compared to a fuel cell the primary advantage of LiPo batteries is its ability to supply very high power at low weights (power density) and its efficiency at discharging usable energy. However, energy density in the fuel cell was shown to be much better and the weight needed to achieve a specific flight time much lower. In [5] battery and fuel cell weights are compared for different flight time requirements. For 1 hour flight time the LiPo battery required enabled a slightly lighter craft than the fuel cell. However, after that point the weight of the LiPo battery required grew much quicker to 10 kg for a 10 h flight as opposed to 4 kg for the fuel cell.

Similar research has looked into using different sources of hydrogen with fuel cell flight in mind. In [12], K. Kim, T. Kim, Lee and Kwon create and test a hydrogen fuel cell system to help increase the performance of a winged UAV. They surmise that the potential in fuel cells for military applications comes from their low noise and heat signature being ideal for covert ops alongside the high energy density compared with batteries. In their experiment [12], the authors use a hydrogen based solution and explore how to best maximize the fuel. Such methods will be useful to future research and applications as this technology grows. The authors also discuss their use of a hybrid system allowing the fuel cell to stay constantly at peak performance, sharing the load with the battery when necessary, and charging the battery when supplying excess power. Such a system would likely significantly increase flight times even in multicopter applications.

There are also other fuel cell types that could possibly be used. In their paper [13], Dudek, Tomczyk, Wygonik, Korkosz, Bogusz, and Lis explore a number of different types of fuel cells for the purpose of extending the flight of UAVs. Electrolyte Membrane Fuel Cell or Proton Exchange Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC) were all considered. PEMFC were determined to be likely the best for this application due to its temperature range (between 30 °C and 100 °C) and its potential for large power outputs. They found that using a continuous power for the fuel cells is the most efficient use. Increasing the load too quickly causes a sharp fall off in productivity and can cause a quick drop in power produced. This reaffirms the usefulness of a hybrid system which allows a battery to account for fluctuations in the load.

Gong and Verstraete also explore the historical uses of hydrogen fuel cells and compare different fuel cell tanks and fuel sources [14]. They show that PEM fuel cells are the most popular because they have the best operating power, energy density and power density when compared to other fuel cell types. When considering brands, their comparison shows Horizon Aerostack A-1000 and Protonex ProCore VI as the two best in terms of specific power having 571 $\mathrm{W\,kg^{-1}}$ and 1961 $\mathrm{W\,kg^{-1}}$ respectively. The ProCore VI is the fuel cell used on the Aerovironment Puma UAV, a UAV that was able to fly 9 h non-stop. When considering fuel types Gong and Verstraete explored pressurized hydrogen, chemical hydrogen and liquid hydrogen. Pressurized hydrogen is the most commonly used and is quite efficient but has the issue of requiring a large bulky tank which negatively affects its specific power and energy. Chemical hydrogen has the advantage that you can safely store high density hydrogen at a low pressure. This removes the need for a pressurized tank but requires a chemical reaction to separate the hydrogen for use. Liquid hydrogen, however, may not make sense because of the extremely low temperatures in which it must be stored.

For winged aircraft there is now a fleet of hydrogen powered UAVs being deployed by some militaries. In her article [15], McConnell discusses the shift of military research to creating drones powered by fuel cells. Military projects have ranged from small UAVs such as the Swedish HyFish to larger High Altitude, Long Endurance (HALE) UAVs. This shows the range that fuel cells can be useful. The power requirements from some of these projects are as small as 50 W while other can be in excess of 10 kW. McConnell illustrates that these fuel cells have become a huge area of interest to the military because of increased flight time and ease of adding more fuel thus limiting down time. The ability to use different fuels such as different hydrides, which are stable compounds or just pure hydrogen also gives a tactical advantage as it can be adjusted for the situation. In a spot where having soldiers carry pure compressed hydrogen may be too dangerous, safer alternatives can be found.

Solar power, unlike hydrogen, will not likely be the sole power source for commercial vehicles any time soon, but has become prevalent in military research of UAVs. The potential to fly continuously without refueling during the day gives solar power a unique advantage over other forms of fuel. In fact a number of papers present analysis and experiment for exploring the viability of using solar cells on winged UAVs [16–18]. Some results show the ability to create an aircraft that can continuously fly for 6 hours on a day with solar radiation conditions that are about the world average. In fact winged UAVs aren't the only UAVs that can be powered by solar energy. Shaheed, Abidali, J. Ahmed, S. Ahmed, Irmantas, and Pourshid demonstrated that purely solar powered flight was possible for a multicopter by creating a quadcopter to run purely on solar energy [19]. They explain the selection of solar panels and how to properly protect them from in flight vibrations. For the purposes of this paper, knowing that sustained solar-powered flight is possible, gives us an experimental example of increasing the flight time of a multicopter using solar cells.

Multicopter UAV efficiency is another important area to consider. Strong efficiency will help overcome some of the limitations of alternate fuel sources. The fuel source, the motors, the propellers all add to the overall efficiency of the aircraft. The efficiency of different propellers on different multicopters was done by S. Z. Sverdlov in [20]. Zulkipli, Raj, Hashim, and Huddin describe their experiments to pick the most efficient motor [21] where they show the efficiency of different motors at different power levels. Other research has been done demonstrating creative ways to increase efficiency. Holda, Ghalamchi, and Mueller showed how the yaw tilt of a multicopter UAV can change the efficiency of flight [22].

In this paper we combine information from these related areas to build a theory to demonstrate the limitations of the current technology and suggest the quantity and type of improvements needed to create multicopter UAVs powered by alternative sources.

III. Theory

Here we develop the equations and theory that determine hover endurance of a multicopter. We consider the power required to hover, the multicopter's efficiency, and discuss how to determine the energy contribution from each source. Using this we derive equations for the life of the battery in hybrid systems, which is generally a necessity as current fuel cells struggle to provide the necessary peak power and adjust to changing conditions without a battery.

A. Power to Hover

In this section we derive the equations which describe the power necessary to hover, similar to the work done in [23] and [24]. To start, we consider the lift generated by the air moving through the rotors of our multicopter, which in a hover will equal the weight of the craft. Rearranging this with M being the mass of the craft, m being the mass of air being moved and using v as the velocity of the air we get

$$\frac{Mg}{v}\,dt = dm, \tag{1}$$

Considering the infinitesimal changes of the kinetic energy formula we get

$$dE = \frac{1}{2} dm\, v^2. \tag{2}$$

To solve for air velocity, consider the equation for torque from a propeller rearranged for velocity

$$v = \sqrt{\frac{T}{\rho A}}. \tag{3}$$

Where ρ is the density of air and A is the area of the propeller. Note that this is the force of thrust for each single propeller. The thrust from all the propellers will equal the gravitational force for hovering. Therefore $bT = Mg$ Where b is the number of propellers on the multicopter. Knowing the area of a circle and that power is energy per second we derive

$$P = \frac{M^{\frac{3}{2}}}{r}\sqrt{\frac{g^3}{4\pi b\rho}}, \tag{4}$$

where the constant $\sqrt{\frac{g^3}{4\pi b\rho}}$ will be often denoted as k.

B. Efficiency

Using Equation 4 the theoretical power that is necessary for the multicopter UAV to hover is calculated. To find the theoretical energy used in a battery this theoretical power is multiplied by the time the multicopter can hover in seconds, $E_T = Pt$. The hover time is taken from each multicopter's specifications provided by the manufacturers. The actual energy that the multicopter uses is equal to the amount of energy the batteries can provide, also taken from the manufacturers specification, leaving us with the actual energy used or E_A, and the theoretically required energy, E_T. Efficiency is then

$$\eta = \frac{E_T}{E_A}. \tag{5}$$

This calculated efficiency will be assumed to stay constant for all the energy sources we use for the remainder of this paper.

C. Time of Flight

Since alternate fuel sources can struggle to deliver sufficient peak power or adjust to quickly changing conditions fast enough the multicopter will only fly as long as its battery can provide the power. Therefore the flight time is calculated by dividing the energy in the battery, E_B, by the power required from the battery, P_B. Therefore,

$$t = \frac{E_B}{P_B}. \tag{6}$$

Using the assumption that the supplementary fuel source's power, P_S, will be directly applied to the multicopter and that the efficiency in which the power is used is the same as the battery we get

$$P = \eta(P_B + P_S) \tag{7}$$

This equation though, is only valid for $t < t_S$ where t_S is the lifetime of the supplementary power source, after that $P_S = 0$. In all cases explored in this paper the lifetime of the supplementary power source is much larger than that of the battery.

D. Solar Cells

Recent improvements in solar panels make them a viable option for supplementing power for a multicopter. Solar cells have become so light weight, flexible and efficient that their addition can often add much more power to the system than is required to carry them. To calculate the added flight time we make the following assumptions. First, since taking load off the battery is a common goal of solar-supplemented flight, power from the solar cells can directly be applied to the multicopter, therefore skipping the loss in efficiency that charging the battery would face. Second, we assume that the multicopter uses the power from the solar cell with the same efficiency that it uses power from the battery. It is believed that the low efficiency is primarily due to the multicopter's dynamics so the source that is delivering power should not have a huge impact. Finally, we assume that the solar cells are working as efficiently as claimed by their manufacturer. This assumes they are constantly in direct sunlight during flight which may not always be the case.

Two specifications are necessary when trying to determine the added flight time; power per area, p_d, and mass per area, m_s. Using these we can determine the total power added

$$P_s = p_d A_s, \tag{8}$$

and the total mass added

$$M_s = m_s A_s. \tag{9}$$

Where A_s is the area of the solar cell.

Adding solar cells also creates a distinct advantage to other power sources; near unlimited energy. Every other option has a limited fuel supply limiting their potential. With the solar cells there is the option to park and charge as many times as necessary. This allows for missions outside of the typical range by using multi-flight planners [25].

E. Hydrogen Fuel Cells

The hydrogen fuel cells present another option for increasing the flight times. They are lightweight, can be scaled up to provide a lot of power to take the load off a battery and have a much higher energy density than the batteries used on current multicopter, providing up to 4 times as much energy per kg in some cases[5]. There are limitations though, as mentioned in Section II.A. Fuel cells are not as good at quickly adjusting to changing loads as batteries are and can and often struggle to deliver enough peak power to keep a multicopter running by itself. To complete the calculations, the fuel cells will be assumed to be running at full power at all times, a reasonable assumption considering the power they provide is generally less than the power required by the multicopter to hover. Energy the fuel cell can provide will be its nominal power multiplied by the number of seconds it can operate, t_s giving us

$$E_H = P_H t_S. \tag{10}$$

We use P_H as the supplementary power source in Equation 10 which will then hold valid as long as $t < t_S$. After that point though the multicopter goes back to being operated purely on battery power or battery and solar if a solar cell is attached.

Table 1 Multicopter Specifications

Make/Model	Airframe mass	Total standard mass	Standard flight time	Max Takeoff Weight
DJI Matrice 600	5.96 kg	9.5 kg	32 min	15.1 kg
DJI M200	2.76 kg	3.80 kg	27 min	6.1 kg
Kitty Hawk	4.08 kg	9.15 kg	30 min	18.6 kg

Table 2 HES Aerostak Fuel Cell Specifications

Power	Mass	L/min	Operating pressure	Equivalent volume at STP	Time at max power
200 W	2.06 kg	2.8	0.5 bar	1200 L	25714 s
500 W	2.90 kg	6.5	0.5 bar	1200 L	11077 s
1000 W	3.75 kg	14	0.55 bar	1091 L	4675 s

F. Ideal Battery Size

The battery is the limiting factor of multicopter flight time due to its ability to deliver peak power and quickly adjust to changing conditions. It may be beneficial to increase the size of the battery even though the batteries comparatively inefficient source of energy. To find the ideal battery size for each alternate power source we derive equations for the total battery life, B, which will also be the total hover time

$$B = \frac{E_B}{\frac{P}{\eta} - P_S}. \tag{11}$$

where $E_B = M_B d$. Since the goal is to get battery life as a function of the battery's mass we split up the mass of the battery from the mass of the system. This gives $M = M_B + M_S$. These equations are substituted into Equation 4 to get

$$B = \frac{M_B d}{(M_B + M_S)^{\frac{3}{2}} \frac{k}{\eta r} - P_S}. \tag{12}$$

We then use this equation to graphically demonstrate results for specific cases below.

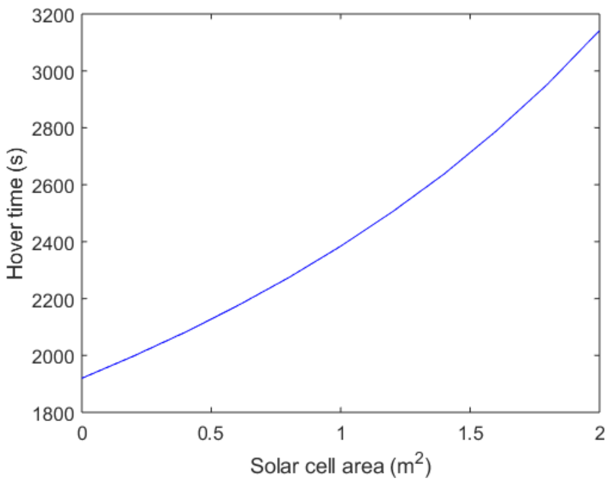
IV. Case Study

Our case study consists of three parts: initial investigation, current advancements, and future advancements. The initial investigation contains our simulations and analysis on the systems available at the beginning of 2018. For the current advancements we consider the newest available technology as of November 2018 in our simulations. Finally in future advancements we explore what the future landscape of hydrogen powered multicopters could look like with some small improvements to technology.

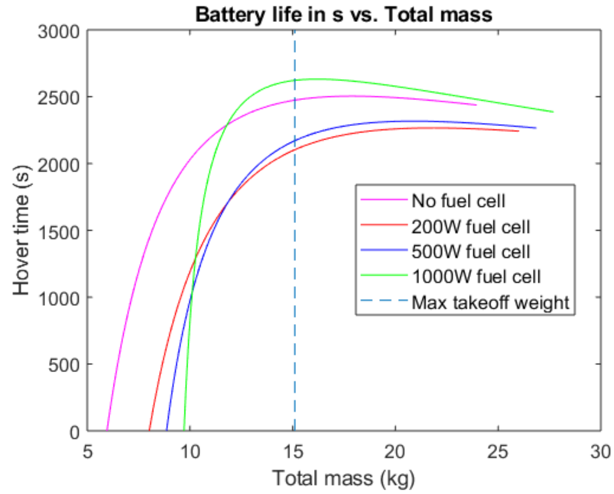
A. Initial Investigation

We apply our theory to three different multicopters, a DJI Matrice 600, DJI M200, and a KittyHawk HDX4. Each of these multicopters are different sizes and allow three distinct cases to support our theory. For auxiliary power supplies, only commercially available products are explored to show current viability. Alta Devices technology solar panels are considered to model the equations and theory. The solar panels that they supply are highly efficient compared to the industry standard, about 28.8-31.6% giving a power output of about 250 $\frac{\text{W}}{\text{m}^2}$ while weighing 0.174 $\frac{\text{kg}}{\text{m}^2}$[*]. The fuel cells used are HES Aerostaks and have a Ultra-Light Composite Storage Cylinder (E-Series) tank[†]. The 200 W, 500 W and

[*]https://www.altadevices.com/ accessed on 12/01/2018
[†]https://www.hes.sg/aerostak accessed on 12/01/2018



(a) Flight time with solar cell



(b) Flight time with fuel cell and increasing battery size

Fig. 1 Matrice 600

1000 W cells equipped with a tank that can hold 2 L at a pressure of 300 bar (Model # 3271522) are considered for this case study. Larger tanks could be useful in future research or if the plan is to park to charge but will not be included in this analysis.

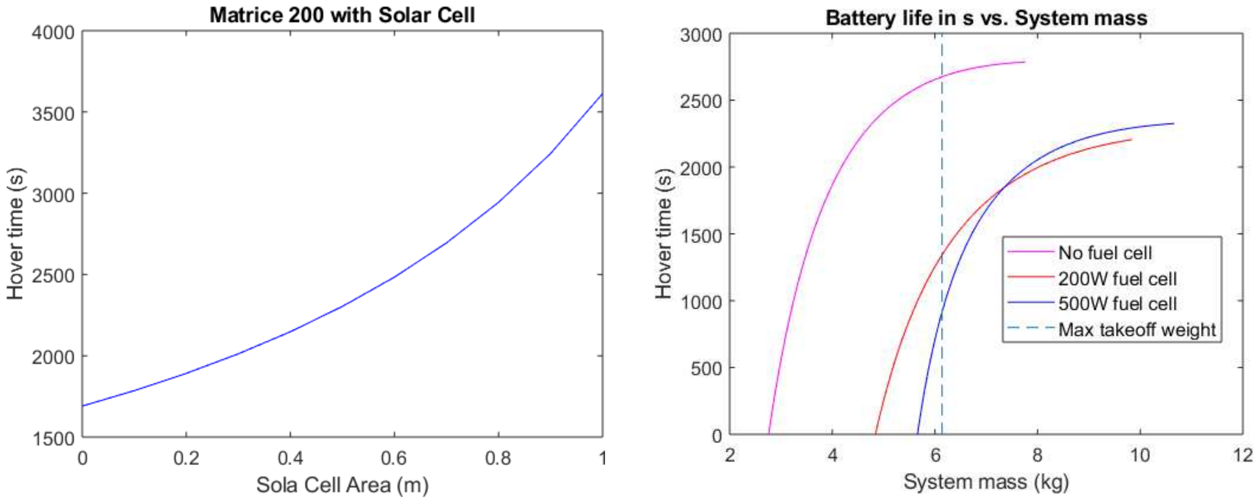
Table 2 shows the specifications of the fuel cells that will be used. All calculations for fuel cells are made based on these specifications. The time at max power is the operating time each of these fuel cells can achieve. This is much greater than the overall flight time of the multicopter and therefore will not be considered in analysis.

The Matrice 600 specifications can be seen in Table 1. Plugging in these numbers, along with the added power and mass of the solar cell into Equation 12 a curve describing the relationship between solar cell area and flight time is shown in Figure 1a. We note that the quadratic shape will not hold if the size of the solar cell continues to increase, this is due to the $M^{\frac{3}{2}}$ relationship as seen in Equation 4. That though, is not of concern due to the relatively small amounts of area available on the multicopter. Figure 1a shows the flight time was increased by 64% when a 2 m^2 solar cell was added and about 24% when there is 1 m^2. The requirements of needing direct sunlight still exists but in good conditions one can expect a significant boost to the flight time. With such little weight added also there is very little fall off from standard performance if those conditions are not met. Knowing the potential to increase flight time also lends itself to the idea of multi-flight planning missions where there are scheduled charge times as mentioned earlier. In practice integrating enough area of solar cells to effectively harvest energy could be challenging on a multicopter.

For the fuel cells to add value a larger battery becomes useful. In Figure 1b, the graph of total mass including the fuel cell, the multicopter and the increasing battery size is plotted vs total time of hover in seconds. The multicopter's default battery specifications, particularly its energy density, is used as the standard in this case study. Figure 1b shows the 200 W and 500 W fuel cells are less effective than just increasing the size of the battery. This is a product of the battery life. The smaller fuel cells only take a small load off of the battery but leave unused excess energy when the battery dies. For the fuel cell to be effective it needs to take the majority of the load off of the battery. The 1000 W fuel cell shows good potential for increasing the flight time topping out at 2601 s with a total mass of 16 kg. This 16 kg is comprised of 3.75 kg for the fuel cell, 5.96 kg for the multicopter and the remaining 6.29 kg for the battery. This configuration increases the flight time by about 11.33 min, or by 35.5%. Although 16 kg is above what DJI suggests as the maximum take off weight, tests we conducted with this vehicle anecdotally show it can take off and is stable at that weight. Worth discussing is the case where the size of the battery is increased. At under 11.8 kg the increased battery size, 5.84 kg of battery, outperforms any of the other options besides the 1000W fuel cell, and improves flight time by 19.5% from 1920 s to 2294 s.

Though the area available to fit a solar cell on the M200 is small, improved flight time could still be realized. In Figure 2b a 19% increase in hover time is shown for as small as 0.3 m^2 of solar cell area. Anything larger will be a challenge to fit on the limited area but the added extra 6 min could prove to be useful in certain situations.

In contrast to the M600, the M200 is not suitable for the fuel cell. Being a much smaller craft, as seen in Table 1, it requires less power to hover but cannot carry nearly as much. Considering the load restrictions of this vehicle, a 1000 W



(a) Flight time with solar cell

(b) Flight time with fuel cell

Fig. 2 Matrice 200

fuel cell is unreasonable to carry. For this reason analysis will be kept to the 200 W and 500 W fuel cell. As seen in Figure 2b the M200 does not seem like a viable option to run on hydrogen. The weight added by either fuel cell actually adds less power than is required to carry it. This is a problem small multicopters will face as the base weight of a fuel cell large enough to help is much higher than what they can carry.

The KittyHawk is a prime candidate for solar cells. In the right conditions a theoretical increase in the KittyHawk's flight time occur with every reasonable denomination of solar cell area.

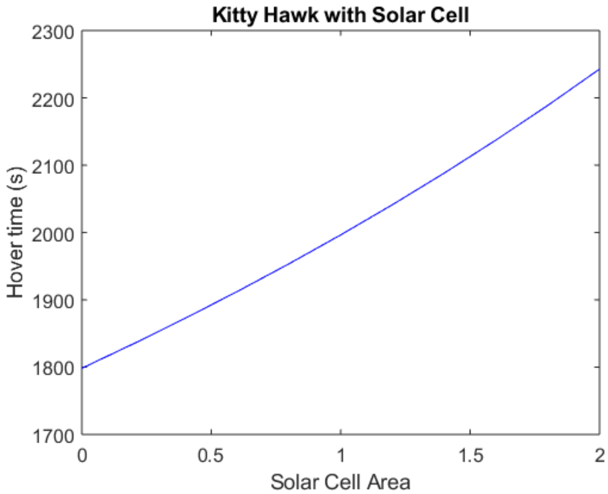
From Figure 3a, with 2 m^2 of solar cell, up to 2243 s of theoretical flight time can be achieved. This is about a 25% increase from the original 1800 s that the specifications show. This gives some confidence that solar cells, as light as they have become, will add extra flight time to a system of this size. However, the lack of efficiency from the aircraft creates serious obstacles for applying a fuel cell. The KitttyHawk had a calculated efficiency of about 25%, compared to about 31% for the Matrice aircrafts. This difference causes the fuel cell effectiveness to be severely limited because of the inability to use most of its power. The results, shown in Figure 3b, demonstrate that the fuel cells require more power to carry than can be used from them.

Increasing the size of the battery for this multicopter is the most effective way to increase the flight times. When the system weight, including increased battery, is at 12 kg a max flight time of 2343 s can be realized. This includes a base weight for the aircraft of 4.08 kg and 7.92 kg of battery. For the 1000 W fuel cell we max out at a flight time of 2149 s at 14.13 kg showing the fuel cell's inability, in this case, to outperform the battery even with its superior energy density. This, like in previous cases, is due to limitations of the battery as the fuel cell has an excess of energy when the battery dies.

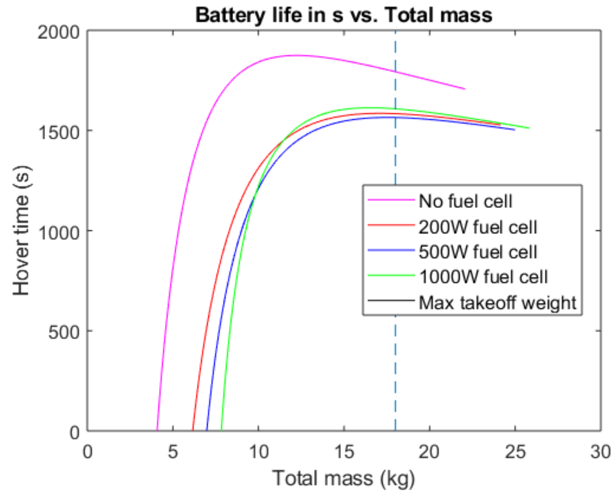
B. Current Advancements

As of November 2018, HES Energy Systems has reduced the weight of their new line of fuel cells. Their Aerostak 200 W system has been increased to 250 W at 0.13 kg less than the previous iteration. The Aerostak 500 W system weighs 0.4 kg less than the previous iteration and the Aerostak 1000 W system weight went down 0.78 kg. For this analysis we assume these fuel cells have a F2 F-series tank also from HES fuel systems.

Since less weight requires less power, a smaller, lighter battery is sufficient to hover, and the vehicle can take advantage of the high energy density of the fuel cells. In Figure 4 there is a significant difference the lighter 1000 W fuel cell makes on the Matrice 600. Hover time peaks at 3148 s, or 52.5 min, as compared to 43.4 min for the last generation of fuel cell. Additionally, the peak flight time in the newest iteration occurs when the system weighs 11.23 kg which is a significant decrease from the 16 kg that was previously necessary. This improvement comes not only from the 0.78 kg savings from the fuel cell but the fact that only 2.3 kg of battery is necessary to power the system instead of the 6.29 kg. This weight difference can have a large impact on mission logistics. A take off weight of 16 kg is above the DJI's suggested maximum while the new system can easily carry the fuel cell and a small payload. Even with the weight



(a) Flight time with solar cell



(b) Flight time with fuel cell

Fig. 3 Kitty Hawk

savings the smaller fuel cells still will not increase the flight time on the Matrice 600 and are not useful for the same reasons previously outlined.

The new fuel cell is not quite viable to be used as a source of energy for the M200. As can be seen in Figure 5a, though there is an increase in viability from the previous iteration of fuel cell it is still not enough to be useful for the M200. Small UAV multicopters such as this are still likely far from being able to use hydrogen cells.

The Kitty Hawk also did not show the same potential with the improvements to the fuel cells in large part due to less efficiency as previously outlined. As seen in Figure 5b, the battery still outperforms the new advancements. The amount of power needed to power the vehicle, even at the lower weight, is too much for the fuel cell to overcome. This illustrates that higher efficiency multicopters will likely be the first to make use of on board fuel cells, further increasing their capabilities.

1. Hydrogen Multicopters

Since our first analysis in Spring 2018, a number of hydrogen powered multicopters have been advertised. HES fuel systems has released its HyCopter, a lightweight hydrogen powered multicopter UAV with a 1500 W fuel cell attached[‡]. Based on advertised specifications, this multicopter can sustain flight for 1.5 h to 3.5 h depending on the tank attached[§]. At the smaller tank the weight is about 11.5 kg and an additional 2.5 kg of payload can be added. MMC has also released a hydrogen powered multicopter called the HyDrone 1550. Based on specifications this multicopter can fly for about 2.5 h at a standard weight of 17 kg with the ability to carry an extra 1.5 kg of weight. This multicopter is equipped with a spare battery though it is not clear whether it is needed for sustained flight or difficult maneuvers.

These new releases show how the effects of new generation of fuel cell technology can have on the multicopter industry. New high efficiency fuel cells have allowed for specially made, high efficiency multicopters to be created that can effectively take advantage of the high energy density in hydrogen fuel. These new multicopters are also consistent with the analysis provided in this paper. A small advancement in fuel cell technology has increased the power density allowing it to completely take the load off of a battery. This allows the limiting factor for flight time to be the amount of fuel that can be carried rather than the battery's energy. As a result they can fly much longer, fully taking advantage of the high energy density of hydrogen. These technologies, though still in their infancy, are exciting and we look forward to seeing how these vehicles will perform in practice.

C. Future Advancements

Current technology is just now breaking through the barriers previously preventing growth in multicopter flight time using hydrogen fuel cells or solar cells. Presumably minor advancements in fuel cell and multicopter weights and

[‡]https://www.hes.sg/hycopter accessed on 12/01/2018

[§]http://www.mmcuav.com/drones/hydrone1550/ accessed on 12/01/2018

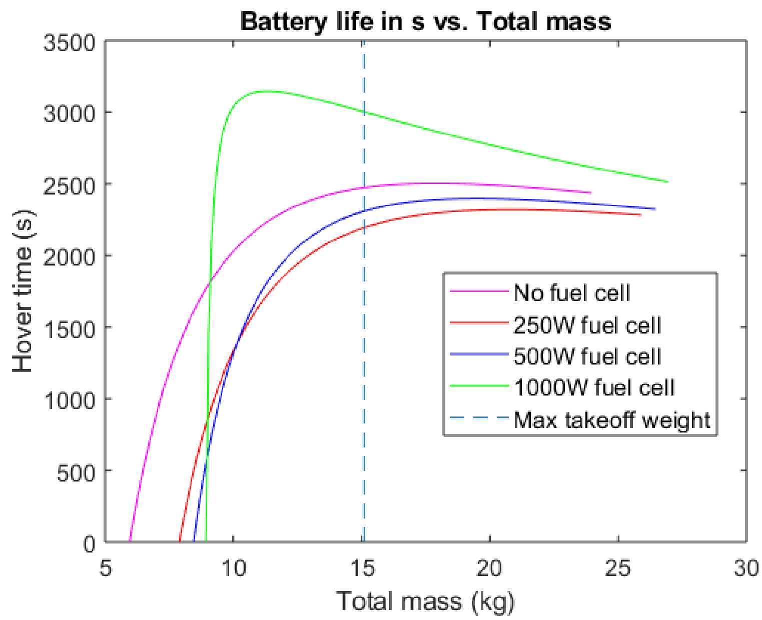


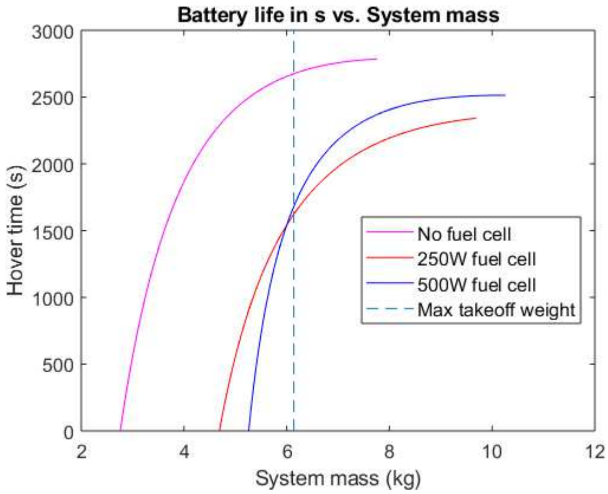
Fig. 4 Matrice 600 flight time with current fuel cell

efficiencies are all that is needed for more fuel-cell-powered multicopters. There were two areas we have identified for potential advancement: fuel cell efficiency and aircraft efficiency. Fuel cells need to take the majority, if not all of the load off of the battery to unlock the potential of fuel cells. With either of these advancements the load on the battery quickly approaches zero making the limiting factor of flight time the fuel carried on the multicopter. To illustrate this, two theoretical graphs, Figure 6a and Figure 6b show how the flight time of the Matrice 600 would be extended if the power output from a fuel cell could be increased while maintaining the 1000 W weight or if increases to how efficiently the Matrice 600 uses energy could be made.

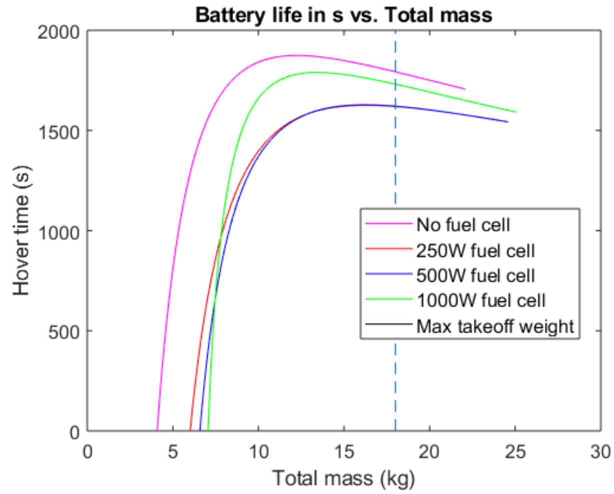
There are two important takeaways from Figure 6a. First, a modest increase in power output of just 30%, from 1000 W to 1300 W, increases the flight time by more than 63% compared to the current fuel cell. An advancement allowing this fuel cell to nominally produce its current max power corresponds to a large increase in flight time. Second, as fuel cell technology advances, our ability to traverse long distances with them will rapidly grow, only being limited by fuel storage. Figure 6b shows a different, but interesting effect of increasing the efficiency of the system; a hybrid fuel cell system benefits much more than a battery-only system. This happens because the improvement overcomes the issue with power density in the fuel cell. As efficiency increases, more usable power becomes available removing the load on the battery. The relationship seen will hold until the limiting factor becomes the energy in the form of hydrogen the drone is carrying. Once we reach this point, flight time will become linearly proportional to total energy just as it is with the battery. This goes to show that the multicopter efficiency increase has a similar effect as in Figure 6a, there is more power available to the multicopter therefore decreasing the load on the battery and extending the life.

V. Discussion

Here we discuss key takeaways we have found during our research that can impact how researchers design, build, and use multicopters. First, using current, commercially available solar cells is a viable path to increase flight time for both single flights and multi-flight missions. 1 m^2 of solar cell can increase the flight time of the multicopters analyzed by around 25%, and can be considered for applications where solar charging is an option. Second, in specific cases, using a 1000W fuel cell on currently available vehicles can increase the flight time. This has the potential to be useful in a number of different applications, but is limited to little or no payload, even on large multicopters. In cases where landing and battery charging is an option, an excess of hydrogen can be carried to supplement the batteries and increase average flight time. Lastly, we are on the cusp of exponentially increasing the flight times and distances of multicopters using fuel cells, and this technology is advancing rapidly as can be seen by the jump from our initial investigation to our analysis of current technology. The industry is starting to break through the barriers to sustained hydrogen-powered multicopter flight, and some companies are releasing their own hydrogen-powered multicopters.

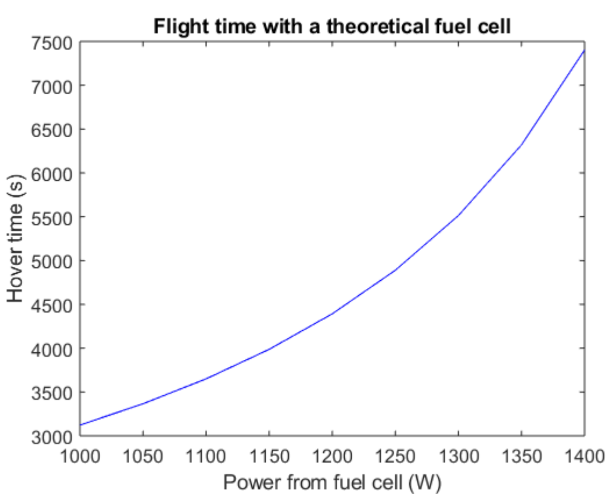


(a) Matrice 200 flight time with new fuel cell

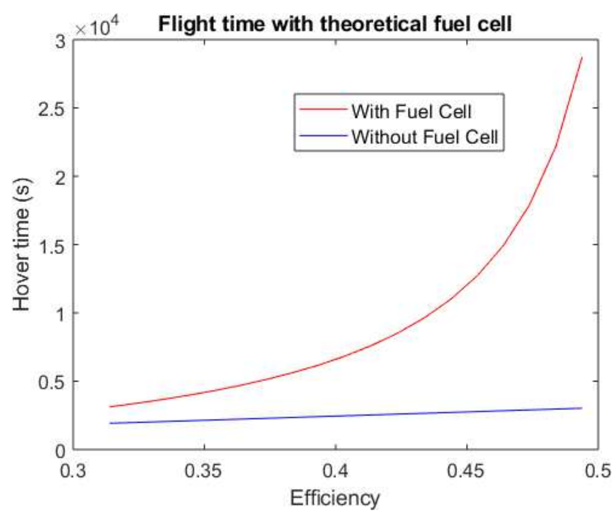


(b) Kitty Hawk flight time with new fuel cell

Fig. 5 New fuel cells



(a) Theoretical fuel cell



(b) Theoretical efficiency

Fig. 6 Matrice 600 with theoretical improvements

VI. Acknowledgements

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