

Current and Next-Generation Energy Storage Devices for Micro Vehicle Applications

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ABSTRACT

The range and duration of micro vehicles, and in particular, micro aerial vehicles, is significantly restricted due to the limitations of available on-board energy storage devices. The number and type of energy storage units that can be housed in the vehicle structures is significantly limited by the demanding voltage and power requirements and stringent size and weight constraints of the vehicle. While most commercial and developmental vehicle platforms currently utilize commercial-off-the-shelf lithium polymer batteries for their energy storage needs, endurance times are limited to minutes and high discharge rates and dynamic electrical loads limit battery life.

Recently, researchers have demonstrated the ability to produce lightweight, flexible energy storage devices based on nanomaterials such as carbon nanotubes and graphene. Due to their low mass, small size, and high energy storage potential, carbon nanomaterial-based energy storage devices are excellent candidates for use in micro vehicle applications. Because the performance of these prototypical devices is still limited, a significant amount of research must first be conducted before these energy storage devices can be incorporated into a micro vehicle platform. This work will examine existing energy storage devices in the context of micro vehicle applications, review recent advances in energy storage technologies, and discuss how these technologies may affect future micro vehicle design and performance.

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INTRODUCTION

Over the last decade, researchers have made great strides in the development of small, lightweight unmanned aerial vehicles, or micro aerial vehicles (MAVs). While early prototypes were large and had limited functionality [1, 2], many MAVs now weigh less than twenty grams and can hover [3], stream live video [4], and even avoid obstacles [5]. Although a number of MAV designs (e.g. fixed wing, flapping wing, and rotorcraft) are currently being researched, a reoccurring issue for all vehicle platforms is the on-board power supply. Like all unmanned aerial systems (UASs), MAVs require a significant amount of power to generate lift and a substantial amount of energy to sustain flight. Unlike their larger brethren, however, MAVs are severely limited in the number, size, and type of energy harvesting and/or storage units that can be integrated into the vehicle platform. For instance, although it has both high specific power and energy, the four cylinder gas engine utilized in the General Atomics Predator UAS is too complex to be simply scaled to a size that would be appropriate for MAV insertion [6]. Similarly, the solar panel array that has been successfully integrated into the QinetiQ Zephyr UAS to enable sustained,

continuous flights of over two weeks, would not achieve the same level of overall efficiency for a vehicle with a wingspan that is 1/100th of its size and operating primarily at low altitudes or indoors [7].

Due to the scaling difficulties outlined above, the options for MAV energy storage are currently limited to commercial-off-the-shelf (COTS) batteries and capacitors. Although they do not have the specific power and energy of combustion engines and gas turbines, batteries and capacitors are ideal for MAV insertion because the energy storage systems are reliable, do not require consumable fuel, have a low auditory signal, and can be made in small form factors. While batteries are currently the best energy storage option for MAV developers, these electrochemical energy storage devices have a number of disadvantages. For instance, the high discharge rates and dynamic electrical loads that typify MAV flight are the primary cause of reductions in battery capacity, cycle stability, and usage life.

This work will examine the mass breakdown and endurance of state-of-the-art MAV platforms with a gross takeoff mass of less than 20 g. Based on the information gathered from this review, contemporary energy storage options will be examined within the context of MAV

demands and their feasibility for MAV insertion will be determined. Finally, this work will review recent advances in energy storage technologies and discuss how these technologies could potentially impact future MAV design and performance.

MICRO AERIAL VEHICLES

Propelled by micro flyer feasibility assessments [1, 8], in 1997 the Defense Advanced Research Projects Agency (DARPA) created a research initiative to develop low-altitude, highly maneuverable aircrafts that have a maximum dimension of 15 cm [9]. The program, entitled “Micro Air Vehicles”, was intended to leverage technological advances in micro-devices for covert reconnaissance-based defense applications [1]. At the time of the program's inception, the smallest UAS platform was the Naval Research Laboratory's (NRL) SENDER (Self-Navigating Drone, Expendable/Recoverable), a multipurpose platform with a wingspan of 1.2 m and a gross weight of 10 pounds [1]. Although the NRL SENDER and its UAS contemporaries had a proven track record of success, the size limitation imposed by the DARPA program prevented developers from simply miniaturizing larger platforms. Larger platforms could not be miniaturized because the new platforms would be required to generate lift and sustain flight at low Reynolds numbers. As a result, old aircraft designs (e.g. flapping wing [4, 10], quadrotors [11, 12], and samaras [13]) were revisited and new vehicle designs were explored as a means to achieve flight at low Reynolds number regimes. Although this initial DARPA program ended over a decade ago, research in this area is as active as ever, with hundreds of researchers in Government, academia, and industry working on reducing vehicle size and weight [14, 15], improving flight performance [16, 17], adding platform functionality [4, 5], and increasing vehicle autonomy [18].

Although there is a significant amount research in the area of MAV development, researchers still face a number of formidable engineering challenges. One of the most common issues found in the literature, however, is energy storage. The stringent size and weight constraints of MAV platforms significantly limit the number and type of energy storage units that can be housed in the vehicle structure. While most commercial and developmental vehicle platforms currently utilize COTS lithium polymer (LiPo) batteries for their energy storage needs, the actual capacity and operational voltage of LiPo batteries are often reduced (with respect to nominal capacity) due to high discharge rates. As a result, the vehicle functionality, control authority, and flight time is severely limited. Battery life, or more appropriately the lack thereof, is such a significant issue that researchers working on three-dimensional aerial mapping have had to resort to walking their MAV platforms through a building to collect sufficient data [19]. Although the mapping process was designed for a small quad-rotor platform, the maximum flight time of these aerial vehicles was not long enough to complete

the data collection and mapping process. Regardless of the MAV application or mission, COTS batteries are not keeping up with the demands of the robotics community.

The energy storage problem is present in all MAVs, regardless of the vehicle size, weight, or actuation modality. In order to demonstrate the gravity and scope of the situation, a list of MAV platforms weighing under 20 g was compiled (Table 1). Regardless of the actuation technique employed, all of the MAV platforms utilized batteries for their primary energy storage needs. Of those platforms that had detailed system specifications, the battery weight accounted for 13-61% of the overall system mass, more if one included the weight of battery peripheral electronics such as an undercharge indicator or a voltage regulator. Although there were a few outliers in the data, the battery weight percentage was typically higher for smaller vehicles, as the percentage of inert material (*i.e.* packaging) in batteries increases with decreasing battery weight. The DARPA Bug [14] had the heaviest battery of the group, a 130 mAh Atomic Workshop LiPo battery weighing 3.6 g, while the Newell Sharks [20] and the Prox Ornithopter [21] had the lightest battery, an 8.5 mAh Atomic Workshop LiPo battery weighing 0.34 g. For those systems that contained endurance statistics, the average flight time was just over 7 minutes, with the shortest times listed as being less than 1 minute. Clearly, if MAV platforms are ever to be successfully utilized in commercial, civilian, or military applications, advances must be made in the area of lightweight energy storage devices. In order to understand the energy problem, it is necessary to first understand the basic requirements of a MAV-compatible energy storage unit. Once the basic requirements are met, platform specific energy storage conditions can be discussed.

From a physical standpoint, MAV energy storage devices must be lightweight and ‘small’. For MAVs on the scale as those listed in Table 1, lightweight can be defined as weighing less than 4 g. “Small” in this context can be defined as any device that can be fully integrated into the vehicle structure. Possible configurations can include two-dimensional (*i.e.* thin film) energy storage materials (to be incorporated onto the wing or propeller structure) or the more conventional three-dimensional energy storage device (to be housed within the vehicle body/chassis). Secondly, the on-board energy storage device must have both high specific power and high specific energy. In the field of energy storage, specific power is used to describe the power to weight ratio of a device, where power is the rate at which electric energy is discharged from the device. Specific energy, on the other hand, is used to describe the amount of energy that can be stored in the device per unit weight. Within the context of a MAV, high specific power is needed to generate lift while high specific energy is needed to sustain flight. MAV energy storage devices must also be capable of withstanding dynamic electrical loads. During the course of a realistic flight path or mission, an MAV will likely encounter air currents or wind gusts that will necessitate the use of flight stabilization countermeasures to avoid large course

Table 1. Battery and flight time survey of non-tethered MAVs weighing less than 20 g. N/A = Not available.

Vehicle	Actuation Method	Energy Storage Type	Vehicle Weight (g)	Battery Weight %	Estimated Flight Time (min)
Newell Sharks [20]	Fixed Wing Propeller	LiPo 8.5 mAh	0.485	61	1.7
Prox Ornithopter [21]	Flapping Wing	LiPo 8.5 mAh	1.1	N/A	< 1
Proxflyer Nanoflyer [21]	Rotorcraft	LiPo 20 mAh	2.7	N/A	< 1
MicroGlider [22]	Passive	LiPo 20 mAh	2.22	32	10
Micro DelFly [14]	Flapping Wing	LiPo 30 mAh	3.07	33	3
Proxflyer Picoflyer [21]	Rotorcraft	LiPo 30 mAh	3.0	26	2-3
Interactive Toy's DaVinci [23]	Flapping Wing	N/A	3.5	N/A	5
Jumbo [14]	Flapping Wing	LiPo 50 mAh	7	N/A	N/A
Interactive Toy's MAV Mosquito [23]	Rotorcraft	LiPo 20 mAh	7.6	N/A	3
DARPA Bug [14]	Flapping Wing	LiPo 130 mAh	9.3	39	N/A
MC1 [24]	Fixed Wing Propeller	LiPo 65 mAh	10.3	19	10
Modified SilverLit WingMaster I-Bird [25]	Flapping Wing	LiPo 60 mAh	12.4	13	N/A
Modified Interactive Toy's VAMP [26]	Flapping Wing	LiPo 90 mAh	13.6	19	N/A
PD-100 Black Hornet [21]	Rotorcraft	N/A	15	N/A	25
DelFly [4]	Flapping Wing	LiPo 140 mAh	17	N/A	15
DelFly II [4]	Flapping Wing	LiPo 130 mAh	17	N/A	8
Nano Hummingbird [27]	Flapping Wing	N/A	19	N/A	11

deviations, platform damage, or vehicle destruction. Because the vehicle must compensate for the additional loads on the structure, the actuator current-draw during flight stabilization periods will likely increase. Current-draw is also likely to vary during different flight maneuvers (*e.g.* forward motion, turning, and hovering). The on-board energy storage device must be able to withstand fluctuating power conditions. Lastly, it is desirable that the energy storage unit be

rechargeable or reusable to increase the sustainability of the platform. Ideally, the unit should be able to be refueled or recharged with minimal changes to the vehicle platform.

ENERGY STORAGE OPTIONS FOR MAV PLATFORMS

Like all aircraft systems, MAVs require energy to power actuation systems and/or electronic devices (*e.g.* processors,



sensors, and communication devices). If energy cannot be collected or generated, an on-board energy storage device is needed to sustain MAV flight. Energy can be stored in a variety of different mediums, however, only a few are of practical importance for MAV platforms. Figure 1 contains a simplified Ragone plot of the energy storage domains that are currently being explored for MAV insertion: capacitors, supercapacitors, batteries, fuel cells, combustion engines, and gas turbines. Although mechanical energy storage mechanisms such as rubber bands and springs have been successfully utilized as primary energy sources in model airplanes and as energy recovery systems in the DARPA Bug [14], these energy storage devices are not currently equipped to convert the stored energy into electrical energy. Because mechanical energy storage systems cannot supply the electrical energy needed for on-board electronic systems and sensing payloads, these energy storage systems will not be discussed in any further detail. In the following sections, each of the energy storage options outlined above will be reviewed and examined within the context of a MAV platform.

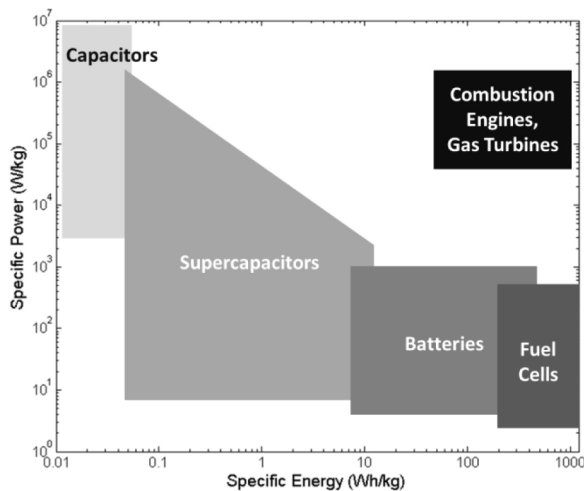


Figure 1. Simplified Ragone plot of energy storage domains that can be used in a MAV. Adapted from [28].

CAPACITORS

Capacitors are direct electrical energy storage devices in that charge is stored in an electrostatic manner via charge accumulation on two opposing conductive plates. Because their discharge is not dependent on a chemical reaction or diffusion of ions, capacitors can release stored energy very quickly. As a result, capacitors have extremely high specific power (Figure 1), an ideal property for certain high power MAV operations (e.g. gust alleviation and takeoff). Unfortunately for MAV designers, capacitors also have very low specific energy, a property which translates to extremely short powered flight times. Another potential issue for MAV designers is the voltage profile of a capacitor on discharge (Figure 2). Unlike an ideal battery, which has a stable operational voltage on discharge, the voltage of an ideal

capacitor decreases linearly as the capacitor is discharged. This is problematic for researchers because most MAV actuation systems and electronic devices require a constant operational voltage for continuous operation.

Therefore, because capacitors cannot efficiently power electronic devices nor can they provide sufficient energy to sustain flight, capacitors cannot be used as stand-alone energy storage devices on MAV platforms. If, however, the capacitor is light and small enough, developers could potentially use the device as a supplementary energy storage device for rapidly supplying energy in high-power situations.

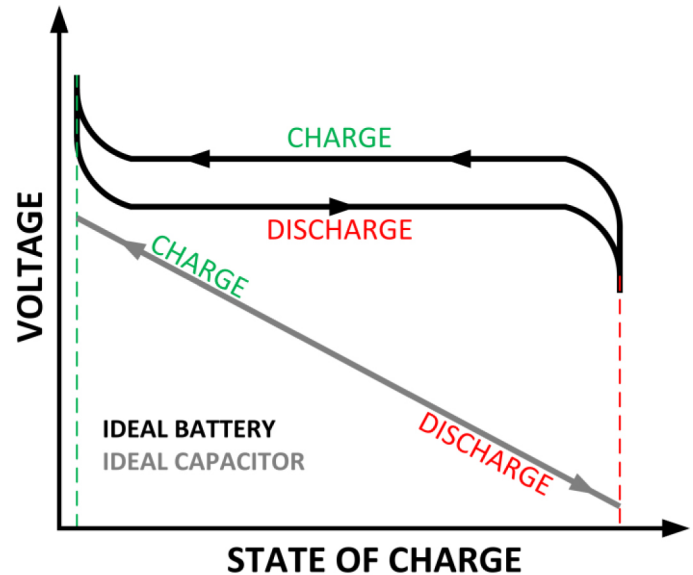


Figure 2. Charge-discharge behavior of ideal batteries and capacitors. Adapted from [29].

SUPERCAPACITOR

In terms of specific energy and specific power, supercapacitors, also known as ultracapacitors or electric double layer capacitors, lie in between capacitors and batteries. As with all capacitors, energy in supercapacitors is stored via charge separation, however instead of charging plates, a supercapacitor stores energy in the electric double-layers that are formed at the interface between the electrodes and the electrolyte (Figure 3). Supercapacitors can store more energy than traditional electrostatic capacitors because the surface area of the porous electrode material is typically much larger than that of a solid, flat plate. The high surface area increases the amount of interaction between the electrolyte ions and the electrode material and as a result, the amount of charge that can be accumulated is much larger. The power density of a supercapacitor, on the other hand, is less than that of electrostatic capacitors because the process depends on the diffusion of ions in the electrolyte and not on the simple accumulation of charges on a metal plate. Although the charge-discharge process of an electric double layer capacitor is diffusion limited, it does not rely on a chemical reaction at the electrode-electrolyte interface. As a