EXTENDED FLIGHT DURATION SMALL-SCALE QUADROTORS POWERED BY HIGH-ENERGY-DENSITY, HIGH-POWER-DENSITY MICRO ALUMINUM-AIR BATTERIES

Yanghang Huang, Haoxuan Lyu, Mark G. Allen and Sue Ann Bidstrup Allen
University of Pennsylvania, USA

ABSTRACT

As the application of small-scale, centimeter-sized aerial quadrotors expands in the fields of IoT sensor monitoring and product visual assessment, the demand for energy sources that enhance small-scale quadrotor operation becomes critical. Aerial quadrotors have minimum requirements on both gravimetric power density (to achieve liftoff and maneuverability) as well as gravimetric energy density (to achieve necessary flight duration). Micro lithium-ion batteries (mLIBs), while meeting power density requirements, suffer from low energy density that limits flight duration, primarily due to the increased packaging overhead of these batteries as scales shrink. To address this challenge, this work investigates the use of micro aluminum-air batteries (mAABs) as an alternative energy source for the small-scale quadrotor. Due to their high theoretical energy density and favorable scaling properties, mAABs present significant potential advantages over mLIBs. In this work, we have engineered a 2-gram mAAB that delivers the power density and energy density to meet the demands of small-scale quadrotor operation. Additionally, a customized 3D-printed small-scale quadrotor platform is developed to evaluate the flight duration. In this testbed, the mAAB delivers a total flight duration of 8.75 minutes, substantially surpassing the 4.5-minute flight time achieved with mLIBs. To our knowledge, this marks the first successful attempt at untethered powering of a small-scale quadrotor using air batteries. We have also explored additional approaches to cathode fabrication for mAAB, utilizing an Ag-based cathode developed through microfabrication techniques to maximize the electrochemically active surface area. This cathode can support the required power density for the small-scale quadrotor while offering a cost reduction of 1/1500th of that of conventional cathodes. This work highlights the potential of mAABs to serve as efficient, cost-effective, and long-lasting power sources for small-scale quadrotors.

KEYWORDS

Micro-batteries, Small-scale quadrotor, Catalysts, Micro-fabrication, Air batteries

INTRODUCTION

Small (cm-scale) aerial quadrotors are finding increasing application in IoT sensor monitoring and visual assessment of goods and products [1] [2]. Two of the most important design metrics for power sources used in quadrotors are specific power (i.e., power per unit weight or gravimetric power density) and specific energy (i.e., energy per unit weight or gravimetric energy density. The liftoff and maneuverability capabilities of the quadrotor necessitate an onboard power source with adequate specific power to meet these dynamic requirements, while the specific energy is a determinant factor in quadrotor flight duration.

The predominant energy storage system for small-scale quadrotors has been the micro lithium-ion battery (mLIB) due to its availability and high-power capability. The mLIB can easily meet the power requirement of small-scale quadrotors; however, the limited energy density of mLIBs constrains their flight duration. This limitation arises partially from unfavorable scaling. LIBs require hermetic packaging due to the inherent instability of the electrodes and electrolytes in LIBs when exposed to ambient atmospheric conditions [3]. Consequently, as the size of the LIB decreases, more mass is allocated to packaging materials due to the hermetic packaging requirement. These battery packaging materials do not contribute to electrochemical reactions, thereby reducing the overall energy density.

Metal-air batteries are a promising candidate in this application due to their exceptionally theoretical energy density. Among these, aqueous metal-air batteries are particularly compelling, as they forego the use of organic solvents. The use of aqueous electrolyte is also more environmentally benign compared to the organic electrolyte. This is a significant advantage for agricultural applications where ecological impact is a concern [4]. Among the aqueous electrolyte metal-air batteries, aluminum-air batteries (AAB) can deliver a remarkable theoretical specific energy of 8100 Wh/kg, which is orders of magnitude higher than the current LIBs [5]. The advantage of AABs is further augmented by the stability of AAB cell components when exposed to the air, as well as the cathode's reliance on the oxygen from the air for its electrochemical reaction. Therefore, the hermetic packaging that is often required for other battery types to mitigate rapid atmospheric degradation, is not necessary for AABs. As a result, AABs can be housed in simpler packages that serve only to contain the electrolyte, markedly reducing the packaging weight. A potential disadvantage of the aqueous electrolyte AAB in some applications is that it is typically a primary (non-rechargeable) energy source.

A typical mAAB is comprised of an aluminum anode, an alkaline electrolyte, and an air cathode. The overall reaction of the mAAB is given in Reaction 1. Under discharge, the aluminum anode is oxidized to aluminum hydroxide, as shown in Reaction 2. Oxygen diffuses through the cathode and is reduced at the electrolyte-cathode interface, as shown in Reaction 3.

$$4Al + 3O_2 + 6H_2O \rightarrow 4Al(OH)_3 \quad (1)$$

$$Al + 3OH^- \rightarrow Al(OH)_3 + 3e^- \quad (2)$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (3)$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (4)$$

Despite all the advantages abovementioned, AABs have been long criticized for rapid anode corrosion in the alkaline electrolyte. In parallel with the oxidation of aluminum, there is a parasitic reaction involving the reduction of water resulting in hydrogen gas generation, as shown in Reaction (4). Reaction (3) and reaction (4) are competing reactions on the surface of aluminum exposed to the alkaline electrolyte. This undesirable parasitic reaction leads to aluminum anode consumption without contributing to the external circuit's electron flow, which in turn, reduces the anode utilization efficiency. Such rapid corrosion has been a barrier to the adoption of AAB technology in devices where long-term operation is required, such as electronics, electric vehicles, and off-grid power supplies. Interestingly, the typical corrosion issues that limit the use of AABs in intermittent, long duration applications are less of a concern in the small-scale quadrotor application, where the battery is typically under continuous use over a short period of time. In addition, the use of an expensive Pt-based cathode is another potential shortcoming of the mAAB technology. Recent advancements in this area have identified promising low-cost cathodes, suggesting potential ways to substantially reduce the cost of mAABs [6] [7].

In this study, we fabricate a 2-gram mAAB with only 13% packaging overhead. We assess the electrochemical performance of this mAAB in comparison to that of conventional mLIBs. Our results demonstrate that mAABs can achieve the requisite power and energy densities for the small-scale quadrotor. We also conduct comparative flight tests between mAABs and commercial mLIBs using a commercial small-scale quadrotor, HS190, which is one of the smallest quadrotors in the market (weight ~25g) [8]. Additionally, we present a microfabrication approach that yields a high-surface area Ag-based cathode, delivering the needed power performance for quadrotor operations while drastically reducing the cost of the cathode component.

RESULTS AND DISCUSSION

A lightweight packaging method for mAABs has been developed to maximize the energy and power density of aluminum-air batteries at the cell level. In the context of aqueous electrolyte AABs, the primary function of the battery package is to retain the aqueous electrolyte within the cell. The typical cathode of AABs consists of two layers: a gas diffusion layer and a catalyst layer. The function of the catalyst layer is to bear catalysts that can facilitate the oxygen reduction reaction, while the gas diffusion layer provides an oxygen diffusion pathway and mechanical support for the catalyst layer. A commercial Pt-based cathode (FuelCell Store) is used in this application that incorporates a polytetrafluoroethylene (PTFE)-treated carbon cloth as the gas diffusion layer. After the PTFE treatment, the hydrophobic cathode can serve not only as an electrode for the battery cell but also as an integral component of the cell packaging. The hydrophobic carbon cloth cathode shows the capability to effectively retain the aqueous electrolyte.

To enhance the mechanical integrity of mAAB pouch cells, 3D-printed polypropylene (PP) is utilized as the body frame of the mAAB, providing a robust and lightweight structure. PP is

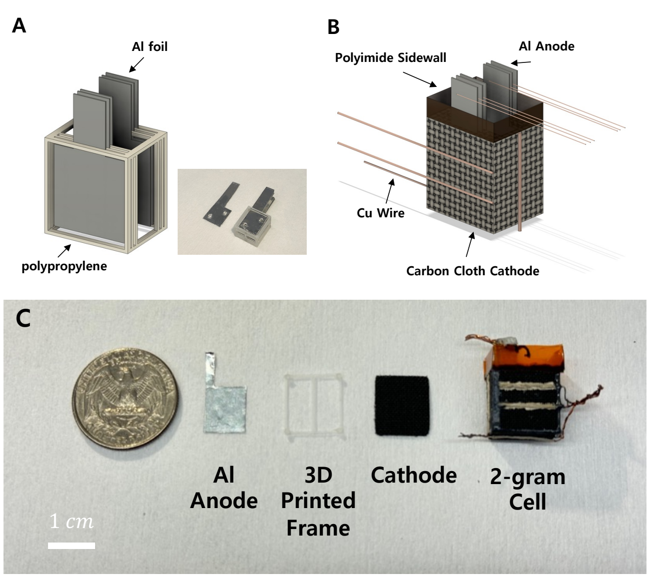

Figure 1: (A) Schematic of the mAAB anode structure; B) Schematic of the mAAB; C) cell components and assembled 2-gram mAAB cell.

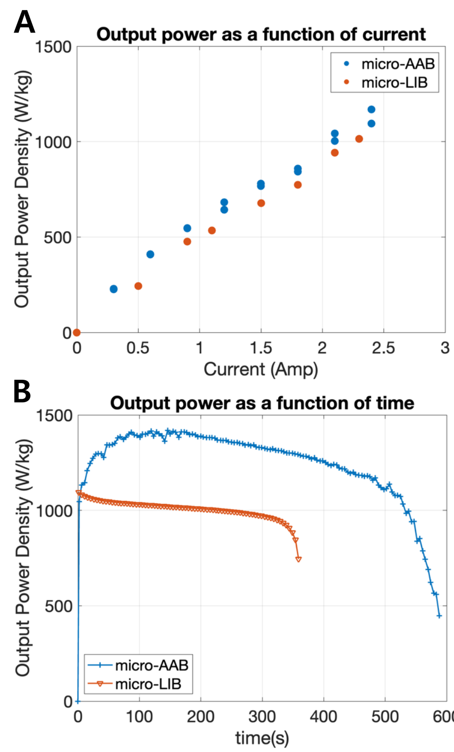

Figure 2. (A) Power performance comparison between mAAB and mLIB; B) 2-Amp discharge performance comparison between mAAB and mLIB.

selected because its melting point is higher than the operational temperature of the battery cell, as well as its stability when in contact with the alkaline electrolyte of the mAAB.

The conventional cell design for AAB presumes an anode/cathode area ratio (A/C ratio) greater than unity. In this design space for the conventional AAB, the power performance is typically limited by the cathode area. The pouch cell design of the mAAB significantly increases the cathode area for enhanced power performance. As a result, the A/C ratio can be considerably less than unity. This packaging approach, however, introduces the potential for reduced power performance due to the lack of anode surface area. To counter this, the structure of the anode has been re-engineered to enhance its power capabilities. A multi-layered anode structure, supported by a 3D-printed polypropylene scaffold, has been developed for the mAAB pouch cells. A schematic and photo of a 3D-printed polypropylene-supported multi-layer anode structure are shown in Figure 1(A). This design effectively increases the A/C ratio and enables rapid ion and electron transport within the multi-layer anode.

Figure 1(B) and Figure 1(C) show a schematic and photo of the fabricated 2-gram mAAB, respectively. Polyimide sidewalls are integrated to mitigate electrolyte spillage during the small-quadrotor operation. Remarkably, the electrochemically inactive packaging materials comprise less than 13% of the total cell weight, achieving the goal of minimizing packaging material to enhance battery performance. As a comparison, the packaging material of gram-scale mLIBs can contribute to over 30% of total cell weight.

The electrochemical performance of assembled mAAB pouch cells is evaluated to assess their suitability for small-scale quadrotors. The Holystone HS190 quadrotor is chosen as a testbed for the developed batteries. A crucial benchmark is the power density requirement of the HS190 quadrotor, which is approximately 800 $W/kg_{battery}$ at a discharge current of 2 Amps.

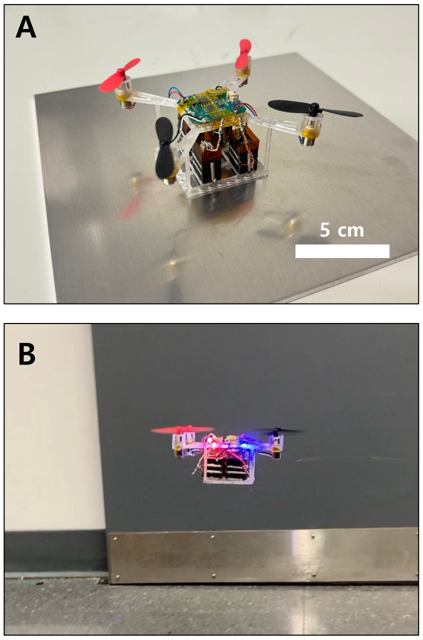

Figure 3: A) Integrated quadrotor with 3D printed frame using mAAB as the onboard power source; B) mAAB-powered small-scale quadrotor in untethered flight.

Figure 2A provides comparison of power densities between mAABs and commercial small-scale quadrotor mLIBs. Notably, mAABs exhibit a peak power density exceeding 1000 $Wh/kg_{battery}$ at 2 Amp, outperforming the power density provided by the commercial mLIBs. This is particularly significant as the weight of the battery includes all components: anode, cathode, electrolyte, and battery packaging materials.

Figure 2B compares the 2-Amp discharge performance of a commercial mLIB and the mAAB. At the beginning of the discharge, both the mLIB and the mAAB deliver a similar power density of about 1100 $W/kg_{battery}$. However, the mAAB demonstrates an upward trend, climbing to a peak power density close to 1400 $W/kg_{battery}$ within the first 200 seconds. This notable rise in power density early in the discharge is likely due to improved electrode wetting and a gradual increase in cell temperature during the discharge process. In contrast, no increase in the discharge power density is observed for the mLIB over the discharge. The mAAB has a discharge duration of 9.4 minutes that is above the 800 $W/kg_{battery}$ power density threshold for the HS190 quadrotor, exceeding that of the mLIB by 65%. Furthermore, the anode utilization rate, which is a critical indicator of the aluminum anode's efficiency and is calculated from dividing discharge capacity by the total available capacity of the Al anode, reaches over 70% for the mAAB. This high utilization rate suggests that anode corrosion is not a significant issue during the typical operation time of a small-scale quadrotor. Such efficient anode performance aligns with the design objectives of the mAAB, aiming for both high power and high power, making it a promising candidate for small-scale quadrotor energy sources.

Following the successful demonstration of the superior electrochemical performance of mAABs, the next phase involves integrating these power cells with the HS190 quadrotor to evaluate their actual flight duration. Initially, the larger dimensions of the mAAB pack present a challenge, as the standard HS190 quadrotor frame cannot house the large mAAB pack. The mAAB power pack, composed of four 2-gram cells connected in series, is necessary to meet the voltage requirement of the HS190.

To overcome the size discrepancy, a customized small-scale quadrotor frame is developed to properly house the mAAB pack. Utilizing 3D printing technology, a customized quadrotor body is created, allowing the integration of the HS190's operational components and the mAAB pack. The off-the-shelf HS190 propulsion system and control circuitry are transplanted to the 3D-printed body frame. Subsequent tests confirm that the 3D-printed small-scale quadrotor platform, equipped with the standard HS190 mLIB, can maintain a stable flight. Figure 3A shows a photo of the integrated platform with the HS190 onboard control system and propulsion system, together with the mAAB pack. Figure 3B shows a successful flight of the HS190 powered by the mAAB. When powered by the 8-gram mAAB pack, this small-scale quadrotor achieves a flight duration of 8.75 minutes, nearly double that of the 4.5-minute flight powered by the 6.8-gram mLIB. To the best of our knowledge, this is the first successful attempt at untethered powering of a small-scale quadrotor using air batteries.

Economic considerations are important for the adoption of mAABs. In assessing the economy of AABs, particular attention is given to the cost considerations associated with their cathodes. Currently, platinum-based catalysts serve as the benchmark catalysts in the cathode of high-power metal-air batteries, making the cathode the most expensive component. A high Pt loading air cathode can contribute to over 99% of the AAB cost. To address this cost challenge, lower-cost Ag-based cathodes have been investigated as potential replacements for the expensive Pt-based cathodes. The cost of silver is only 2% of that of platinum. This significant cost reduction, however, comes with a trade-off: silver has a lower intrinsic catalytic activity compared to platinum. The power performance of catalysts depends on two key factors: electrochemically active surface area (ECSA) and intrinsic catalytic activity. Therefore, to maximize the power performance of the Ag-based cathode, we exploit a microfabrication technique to maximize the ECSA. The microfabrication technique involves co-sputtering Cu and Ag on a porous carbon substrate, subsequently followed by a selective etching process that removes Cu, leaving behind a high-porosity, high-surface-area, and silver-rich catalyst layer.

An $Ag_{28}Cu_{72}$ (atomic percentage) catalyst with 0.3 mg/cm^2 Ag loading is fabricated using Lesker PVD75 DC Sputterer using the following sputtering conditions: 10 mTorr of sputtering pressure, 2500 seconds of sputtering duration, 100 W sputtering power for Ag, and 220 W sputtering power for Cu. The subsequent dealloying stage, crucial for refining the catalyst's structure, is conducted by applying voltages determined by the oxidation potentials of Cu and Ag. Based on the oxidation voltage of Cu (-0.06Vvs. Ag/AgCl) and the oxidation voltage of Ag (0.58V vs. Ag/AgCl), the dealloying first applies a constant voltage of 0 V vs. Ag/AgCl until the dealloying current falling to 0 Amp, followed with a constant voltage of 0.1 V vs. Ag/AgCl until the dealloying current falling to 0 Amp. Upon the finish of the Cu dealloying, the alloy atomic percentage is calculated to assess the efficiency of the

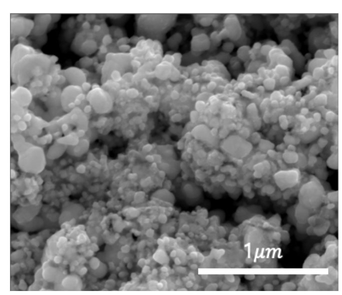

Figure 4: SEM detail of the microfabricated 0.3 mg-Ag/cm² cathode.

dealloying process. The calculation is based on the assumption that the weight loss from the dealloying process is attributed to Cu dissolution alone. The calculation shows the silver-rich cathode with an atomic composition approaching 80% Ag, which may signify the approach to the thermodynamic dealloying limits of the AgCu alloy. Figure 4 shows the resultant catalyst layer microstructure through an SEM image of the AgCu alloy after the Cu etching, highlighting nanoscale particle sizes. These nanostructured particles are key to the enhancement of the (ECSA) of the cathode, significantly enhancing the mAAB's power performance.

Figure 5 compares the 2-Amp discharge performance between the 0.3 mg-Ag/cm^2 Ag-based cathode and a commercial 4 mg-Pt/cm^2 cathode. The Ag-based mAAB achieves a discharge peak power density of 1000 W/$kg_{battery}$, 70% of the Pt-based cathode. Notably, when discharging above the 800 W/$kg_{battery}$ threshold, the Ag-based mAAB achieves a discharge duration of 9.3 minutes, comparable to the Pt-based mAAB. The cost analysis reveals a significant economic advantage, that the material costs of 0.3 mg-Ag/cm² cathode are 1500 times less than those of the 4 mg-Pt/cm² cathode. This significant cost reduction, combined with the comparative discharge performance, highlights the promise of Ag-based cathodes in delivering extended operational periods at a fraction of the cost associated with Pt-based cathodes.

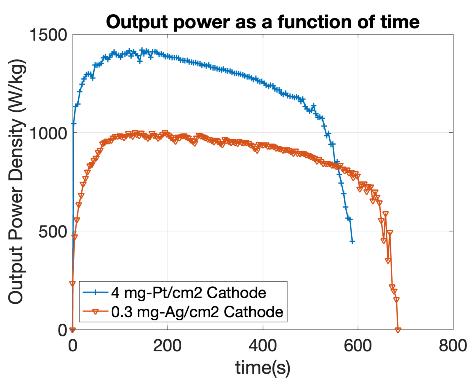

Figure 5: Discharge performance comparison under a 2-Amp discharge for the 4mg-Pt/cm² cathode and the microfabricated 0.3 mg-Ag/cm² cathode.

CONCLUSION

In this work, mAABs are developed and successfully demonstrated as a power source for small-scale quadrotors when compared to mLIBs. The weight-efficient packaging approach for the mAAB leads to only 13% of package overhead for a 2-gram mAAB. The mAABs have also demonstrated a notable increase in flight duration, with an 8.75-minute flight time compared to the 4.5-minute flight duration of conventional mLIBs. This marks an approximately 94% improvement in flight endurance. A pathway toward significant reduction in the cost of cathode materials is also achieved, with microfabrication-based Ag cathodes costing 1/1500th that of conventional Pt-based cathodes on a materials basis. These results underscore the potential of mAABs to enhance the flight duration and operational efficiency of small-scale quadrotors.

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CONTACT

*Y. Huang, tel: +1-520-599-4196; yanghang@seas.upenn.edu