Power Sources for Micro-Autonomous Vehicles- Challenges and Prospects

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1.0 Power Requirements of Micro-Autonomous Vehicles

Micro-autonomous vehicle systems are expected to have expanded role in military missions by providing full spectrum intelligence, surveillance and reconnaissance support on the battlefield, suppression of enemy defenses, and enabling co-operative (swarm-like) configurations [1]. Of the numerous demanding requirements of autonomy, sensing, navigation, mobility, etc., meeting the requirement of mission duration or endurance is a very challenging one. This requirement is demanding because of the constraints of mass and volume that limit the quantity of energy that can be stored on-board. Energy is required for mobility, payload operation, information processing, and communication.

Mobility requirements typically place an extraordinary demand on the specific energy (Wh/kg) and specific power (W/kg) of the power source; the actual distribution of the energy between mobility and other system functions could vary substantially with the mission type. The power requirements for continuous mobility can vary from 100-1000 W/kg depending on the terrain, ground speed and flight speed. Even with the power source accounting for 30% of the mass of the vehicle, the best of rechargeable batteries can provide only up to 1-2 hours of run-time for a continuous power demand at 100W/kg. In the case of micro-aerial vehicles with flight speed requirements in the range of 5-15 m s^{-1}, the mission times rarely exceed 20 minutes [2]. Further, the power required during take-off and hover can be twice or thrice that needed for steady level flight, and thus the number and sequence of such events is also limited by the mass and size of the power source. For operations such as “perch and stare” or “silent watch” the power demand is often only a tenth of that required during continuous flight. Thus, variation in power demand during various phases of the mission importantly affects the power source selection.

2.0 Overview of Power Source Options

The design and selection of a power source to maximize run-time within the mass, size and operational constraints of the system design presents varied opportunities and challenges. The specific energy and specific power of various types of power sources are usually represented in a Ragone Plot shown in Figure 1. This plot has been specially constructed for a packaged power source in that the specific energy calculation for fuel cells and engines includes the mass of fuel and the generator.

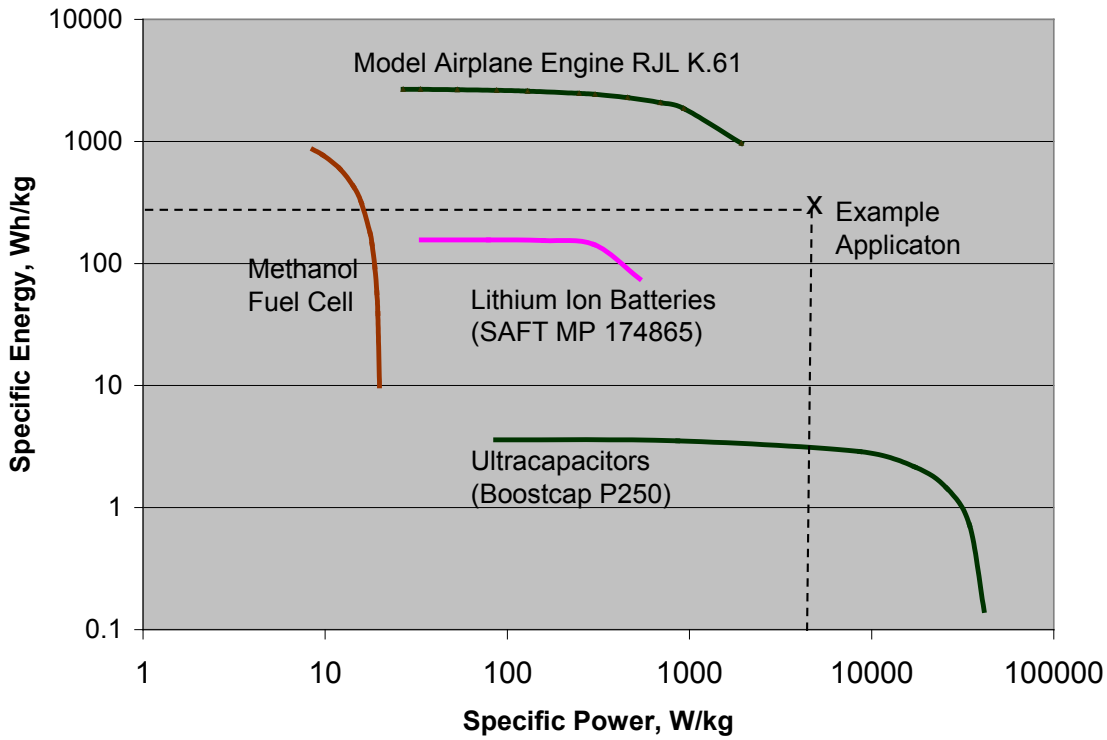

Figure 1. Ragone Plot for package power sources that include fuel and

From Fig. 1 it is clear that combustion engines operating on liquid fuels have some of the best energy and power characteristics for achieving the long run times. However, combustion engines produce strong noise and heat signatures that compromise stealth. Thus, quiet electric power sources such as fuel cells, batteries and ultracapacitors that can work in conjunction with motor drives are favored. Fuel cells operating on liquid fuels such as methanol can provide high specific energy but at low values of specific power. However, lithium-ion batteries can offer specific power levels comparable to combustion engines, but their energy content is about a tenth of that of combustion engines for the same power level. Similarly, ultracapacitors can provide at least ten times the specific power of combustion engines, but ultracapacitors are really poor in energy content. Fuel cells can continue to operate if the fuel is replenished and such re-fueling operation can usually be arranged to occur in less than five minutes. However, rechargeable batteries and ultracapacitors require to be recharged electrically, and the recharge time for batteries is typically longer than the time required for just re-fueling. These power sources are always used in conjunction with a power management and distribution system that converts and conditions the output of the power source to the appropriate voltage suitable for use at the electric motor. The maximum efficiencies of power conversion for d.c. to d.c. conversion are in the range of 90% and the modules usually perform at about 1000 W/kg in a packaged configuration.

Methanol Fuel Cells

Fuel cells operating on liquid fuel such as methanol are particularly attractive because of the compact nature of the liquid fuel. Direct methanol fuel cells (DMFC) are based on the ability to achieve the complete electro-oxidation of methanol to carbon dioxide in a liquid-fed polymer-electrolyte membrane fuel cell. This technology was pioneered by JPL in the early 1990s and has now been commercialized. In a DMFC, methanol is diluted into an aqueous solution and fed to the anode of the fuel cell. Air or oxygen is supplied to the cathode of the fuel cell. DMFC systems are configured to allow for the continuous supply of fuel solution at the appropriate concentration to the stack, removal of by-product water and carbon dioxide, recovery water needed for the anode reaction, and rejection of the heat generated. The internal temperatures in a methanol fuel cell do not usually exceed 65°C. Small methanol fuel cells operating in the range of 15-25 Watts have been developed by Smart Fuel Cell Corporation. For long operating times, specific energy values as high as 600-700 Wh/kg can be realized.

Hydrogen Fuel Cells

Although hydrogen is a more energetic fuel than methanol, hydrogen fuel cells have lower specific power and specific energy values compared to the methanol fuel cell because of the inability to store hydrogen efficiently. Jadoo Systems now offers a 100-Watt system. N-Gen ^{TM}, that uses hydrogen supplied a metal hydride canister (N-Stor^{TM}). This system serves as a good benchmark of a hydrogen-powered system. This system offers about 3.6 hours of operation on a single cartridge, which calculates to 78 Wh/kg at the system level. Such specific energy values are lower than that attainable with lithium-ion batteries. Hence there is no advantage of using such a fuel cell based on metal hydrides for micro-autonomous vehicle applications. However, to overcome the limitations of conventional methods of hydrogen storage Protonex Inc. and Millenium Cell Inc. have demonstrated fueling by hydrogen generated from sodium borohydride solutions. These fuel cells also have an internal operating temperature that does not exceed 60°C. Specific energy values as high as 375 Wh/kg have been demonstrated for systems that operate for 7 hours on a single charge[3]. This type of chemical hydride based portable fuel cell has been shown to be very promising in increasing the run-time of unmanned aerial and ground vehicles used by the US Air Force and Army.

Solid Oxide Fuel Cells

The solid oxide fuel cell has the advantage of operating on liquefied hydrocarbon gases such as propane and butane and can thus offer very high energy densities and power densities comparable to the direct methanol fuel cell. For example, the Amie 25 and Amie 150 fuel cells developed by Adaptive Materials Inc. are constructed with a unique lightweight micro-tubular cell design and employ propane as the fuel. Specific energy values as high as 1200 Wh/kg have been reported with a propane-fueled system [4]. These fuel cell systems are particularly attractive since they utilize logistic military fuels. However, solid oxide fuel cells operate at internal temperatures as high as 1000°C and thus have to contend with the thermal signature issues faced by combustion engines.

The mass of a fuel cell system scales with the power output and the amount of fuel carried on board. Thus, operating the fuel cell at low specific power is the best way to maximize the energy content of the system for a given total mass. For specific power levels in the range of 5 W/kg, specific energy values as high as 900 Wh/kg can be achieved with direct methanol and solid oxide fuel cells.

Rechargeable Batteries and Ultracapacitors
Lithium-ion batteries based on metal oxide cathodes, carbon anodes, and organic liquid electrolyte have advanced considerably in the last five years to achieve specific energy values as high as 175 Wh/kg at 200 W/kg. Cylindrical cells manufactured by Panasonic Corporation are a good example of metal oxide based lithium-ion batteries that combine high specific energy and specific power; "Li-Poly"cells use the same chemistry except that they use a polymer-gel electrolyte instead of a liquid electrolyte. The use of a polymer gel electrolyte allows the Li-Poly cells to be packaged in plastic pouches resulting in a lighter cell for a given energy content. Lithium ion batteries based on iron phosphate cathodes can provide specific energy values of 90 Wh/kg but at a specific power level of 1000 W/kg. Batteries manufactured by A123 Systems Inc. are examples of such batteries with very high specific power capability. The high specific power levels provided by lithium-ion batteries form the basis of the current designs of power sources for micro-autonomous vehicles. However, the specific energy values still present a substantial limitation to achieving the long run times. Ultracapacitors are particularly attractive when extraordinarily rates of energy delivery are required for a few seconds. For example, communication systems and certain payloads aboard a micro-autonomous vehicle could require repeated short bursts of large amounts of power depending on the mission type. A rechargeable battery may not be able to support this type of short power burst without being oversized.

3.0 Integrated Power Solutions

When the mission duration requirements cannot be met by one of the power sources described above, then the following strategies may be adopted to increase the energy on-board the vehicle.

a. A hybrid design that combines various types of power sources to match the load profile in terms of specific power and efficiency.
b. Adopt integration approaches that will allow more of the power source mass to be put on the system.
c. Designs that eliminate ancillary components and render the actual power source lighter.
d. Adopt operational strategies that will allow for replenishment of energy or using alternate sources of power for specific phases.

Hybrid Power Source
The properties of methanol fuel cells, lithium-ion batteries and ultracapacitors are compared with the requirement of an example application in Figure 1. If the example application required this capability on a continuous basis it is clear that none of the power sources shown have the ability separately to meet the specific power and specific energy

requirement. However, if the power requirements are intermittent, a hybrid power source that a combination of fuel cells, batteries and/or ultracapacitors may be able to meet the requirements. We shall illustrate this in the following section.

An arbitrary load profile for a vehicle is shown in Figure 2. A power source supporting this load profile must be capable of providing 250 Watts for just about 2% of the run time. The time averaged power requirement over a single cycle (that includes the rest period) is about 85 Watts. Thus, the peak load is about three times the averaged load. Let us also assume that this load profile is repeated over the mission duration of 100 hours.

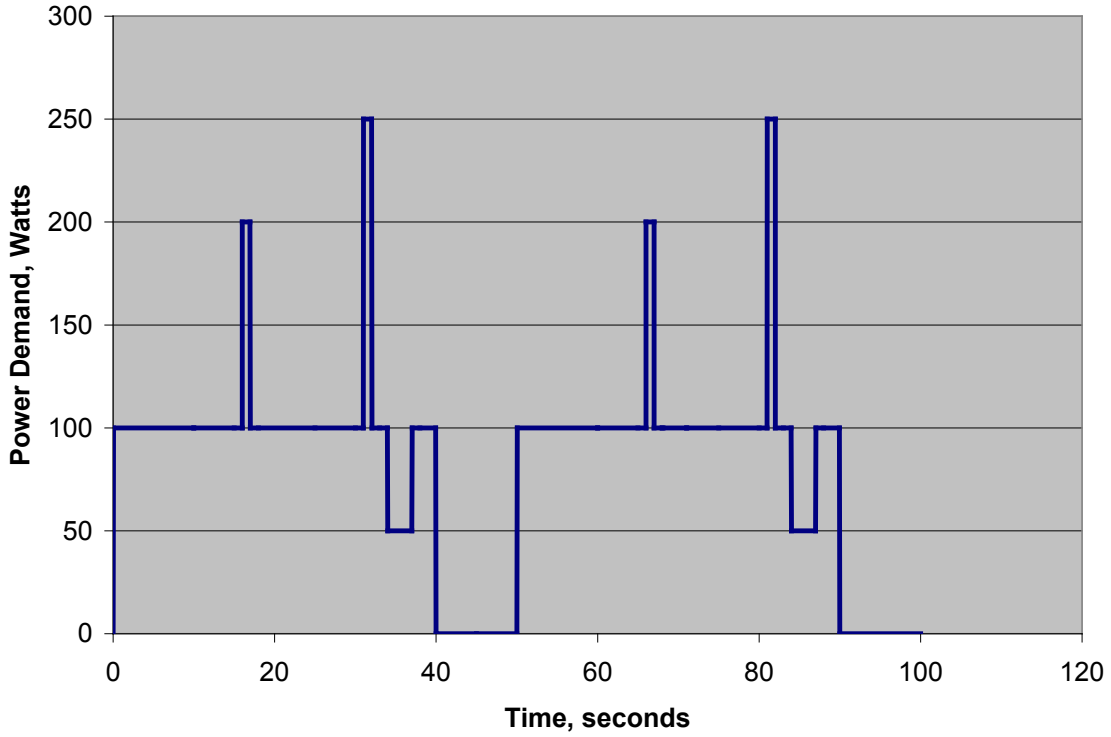

Figure 2. An arbitrary load profile that can benefit from a hybrid power source design.

This mission will require 8500 Wh of electrical energy to be stored on board if recharge or refueling is not permitted. Achieving 8500 Wh in a lithium rechargeable battery will require about 49 kg of power source. If this mass value does not fall within the constraints of the requirements, a hybrid power solution could be sought. A hybrid system is then designed as follows. We need a high energy power source to meet the long-duration mission requirement. This high energy source must then be hybridized with a device with high specific power output to meet the peak loads. In a hybrid solution, a lithium-ion battery could provide the high power demand for only about 2% of the time. Therefore, the battery will have to be sized up to support at least 250 Watts and carry at least 2% of the energy required in each cycle. At the end of each cycle the battery would be recharged by a methanol fuel cell. The methanol fuel cell will have to be sized to

deliver enough power to support the base load and also support the charging of the battery. The power level for such a fuel cell would be in the range of the average power requirement of 85 Watts. The 8500 Wh of energy required for the mission must be contained on board as methanol fuel. Such a hybrid design is estimated to weigh only 20 kg inclusive of fuel (4 kg of fuel cell, 8 kg of fuel and 1.5 kg of batteries and 0.5 kg of power management electronics). This mass is 40% of the mass of a battery-only design of 49 kg. Thus, tremendous reductions in overall mass of the power source can be achieved by hybridization. The actual configuration of such a hybrid power source is determined by the load profile, the characteristics of the various power sources, and the mass/volume requirements.

JPL has recently designed, fabricated and tested hybrid systems based on direct methanol fuel cells and lithium ion batteries for military applications. The hybridization enabled the integration of fuel cells as true load-following power sources, for, otherwise fuel cells prefer to operate under a steady load. Figure 3 shows a direct methanol fuel cell, originally designed to operate at constant power of 50 Watts hybridized with a 24 Wh lithium iron phosphate battery to become a true power source capable of instant start up and following load variations from 0-100 Watts.

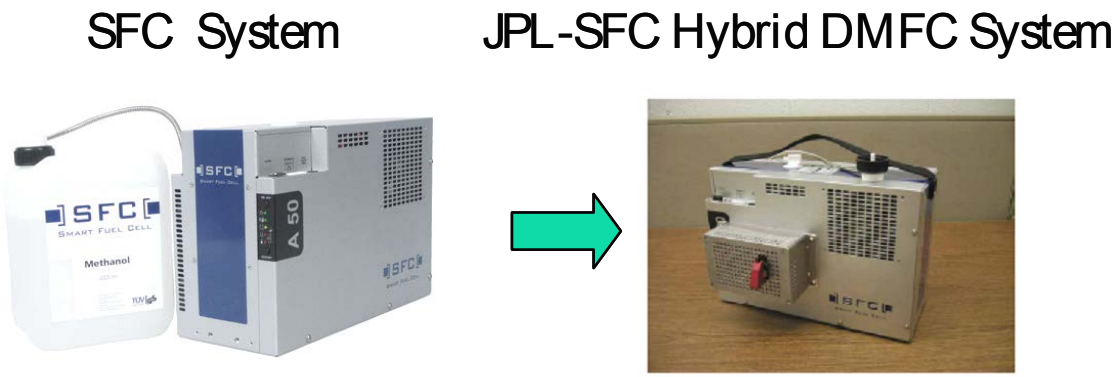

Figure 3. Hybridized DMFC system capable of load following, 0-100 Watts incorporating lithium-iron phosphate batteries and power management unit

Integration Approaches

Increasing the mass fraction of the total system attributed to the power source would also be highly desirable. This could be done if other functions of the system are not impacted. One example of such a replacement is using the structural components constituting the power source as also the structural parts of the vehicle. For example, the fuselage of an aerial vehicle could be constructed with batteries or fuel cells; legs of robots can house fuel cell systems, batteries and fuel. To enable such multi-functionality of energy storage and structural properties, the shapes of fuel cells and batteries will have to be reconfigured. For example, batteries can be made in tubular configurations. Also, fuel cells can be configured in tubular form and arranged such that they can conform to

relevant shapes and structures. Examples of tubular energy storage structures that can serve multi-functionally are shown in Figure 4.

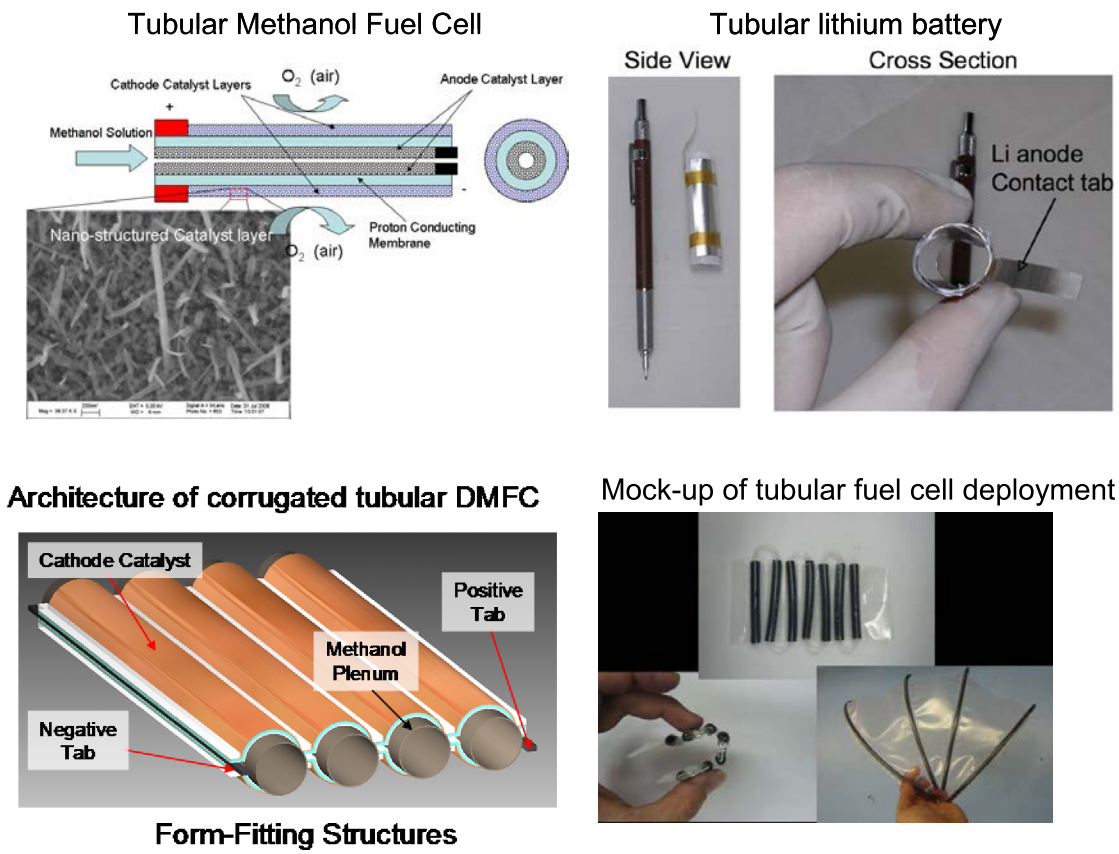

Figure 4. Tubular architectures for batteries and fuel cells that can be used to achieve multi-functionality.

Elimination of Ancillary Components

The monopolar stack configuration for fuel cells and fuel feed concepts that use system resources can have a significant impact on improving the specific power. Figure 5 shows various lightweight stack designs developed at JPL for portable power source applications. A monopolar back-to-back cell without any bipolar plates achieves thrice the specific power of conventional stacks. A flat-plate fuel cell stack with multiple cells on a single sheet allows for achieving high stack voltage without the use of heavy interconnecting bipolar plates.

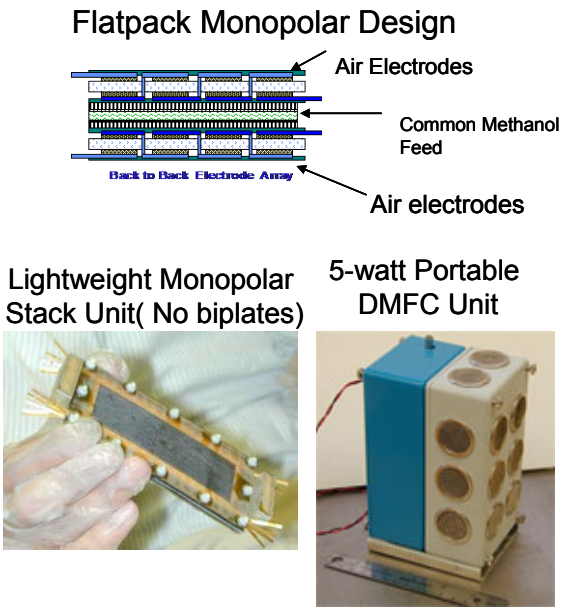

Figure 5. Lightweight stack configurations that allow high specific power values to be attained.

Further reduction in mass and efficiency can be achieved by using functions of the vehicle such as flight to aid in the uptake of air and removal of products, eliminating the need for pumps and blowers. Also, the energy regenerated during motion of the vehicle can be harnessed for pumping the fluids around the fuel cell system. Further, much like animals where energy is produced in cells throughout the body, the energy generation elements can be distributed throughout the body of the vehicle. This will ensure maximum utilization of the resources for thermal management and product rejection.

Operational Strategies

It is possible to mimic the concept of feeding of insects in flight for restoring energy to the vehicle and increasing mission duration. The hummingbird needs to feed every 15 minutes in order to maintain flight. Micro-autonomous vehicles can harvest the energy from the sun when in light, or acquire fuel supplies from another vehicle. To accomplish such refueling, certain vehicles carrying fuel cargo may have to be deployed strategically. Then the vehicle with active payload that faces imminent depletion of fuel can come to this cargo vehicle and get re-fueled and extend its mission. Both electrical and fuel recharging can be accomplished by this method. To avoid supporting energy intensive steps such as take-off or launching using the on-board power source, micro-autonomous vehicles can be hand-launched or propelled from another dedicated vehicle. This will reduce the specific power requirements on the power source.

Future Directions

Since the need for keeping missions powered for long periods is a growing reality, it is clear that many of the approaches described above will see considerable development in the near future. The hybridization concept is the most straightforward to implement and is likely to see the widest use. Advances in rechargeable batteries for consumer applications will continue to benefit the micro-autonomous vehicle application especially for short run time applications. Lithium alloys based anode materials have the potential to provide the much-needed improvements in specific energy. Developments in fuel cells for soldier applications where high specific power is required will have a significant impact on the power source design for micro-autonomous vehicles because the similarity of the requirements. This requires new focus on the basic issues of electro-catalysis of the oxidation of organic molecules. Other approaches involving modified mass-saving architectures require technical development in materials and configurations that are quite likely to be pursued under the US Army's effort under the Collaborative Technical Alliance for Micro-Autonomous Systems Technology.

Acknowledgement

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