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Covert Air Vehicle
2003 LDRD Final Report

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Abstract

This report describes the technical work carried out under a 2003 Laboratory Directed Research and Development project to develop a covert air vehicle. A mesoscale air vehicle that mimics a bird offers exceptional mobility and the possibility of remaining undetected during flight. Although some such vehicles exist, they are lacking in key areas: unassisted landing and launching, true mimicry of bird flight to remain covert, and a flapping flight time of any real duration. Current mainstream technology does not have the energy or power density necessary to achieve bird like flight for any meaningful length of time; however, Sandia has unique combustion powered linear actuators with the unprecedented high energy and power density needed for bird like flight. The small-scale, high-pressure valves and small-scale ignition to make this work have been developed at Sandia. We will study the feasibility of using this to achieve vehicle takeoff and wing flapping for sustained flight. This type of vehicle has broad applications for reconnaissance and communications networks, and could prove invaluable for military and intelligence operations throughout the world. Initial tests were conducted on scaled versions of the combustion-powered linear actuator. The tests results showed that heat transfer and friction effects dominate the combustion process at "bird-like" sizes. The problems associated with micro-combustion must be solved before a true bird-like ornithopter can be developed.

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1 Introduction

While mesoscale air vehicles offer exceptional mobility, the many current attempts are lacking in key areas of time on station, unassisted launching, and covert flight. Previous mesoscale air vehicle results concentrating primarily on producing small-scale airplanes have been disappointing. The usefulness of a mesoscale air vehicle that mimics a bird is readily apparent, as it is inherently covert due to quiet flight and the ubiquitous presence of natural birds. If able to perform unassisted takeoffs, the vehicle utility is even more greatly increased. The greater efficiency of moveable wing flight in small scale makes it more achievable than fixed wing flight.

1.1 Current State of Ornithopter Development

Machines that fly by means of flapping wings (ornithopters) are not new. The first ornithopter flew in 1870 powered by gunpowder. Most ornithopters from 1871 to the present have used rubber bands for power. The rubber band produces a large amount of power for its weight; however while its power density is very high, its energy density is very low. Thus, rubber band power offers insufficient duration for practical flight. Internal combustion engines, compressed air, and battery-powered electric motors offer improved performance over the rubber band.

There are a wide variety of methods for achieving flapping flight. As with birds and insects, there are an incredible number of ornithopter designs and states of development. These will be summarized here.

One of the most advanced ornithopters is the Aerovironment MicroBat shown in Figure 1. It is electric powered, weighs 12 grams, and has 3-channel radio control [6]. The longest flight is 6 minutes at 24 km/hr. This is a significant and notable achievement but still falls short of practical use due to the very short flight time.

Figure 1: Aerovirnonment's MicroBat Ornithopter

Another recent ornithopter development of interest is the series of small electric radio-controlled ornithopters by Vincent and Jin-Wook Lee of Seoul, Korea [8]. A photo of the RC-ornithopter is shown in Figure 2. This particular design weighs a total of 28 grams and has a wingspan of 39 cm.

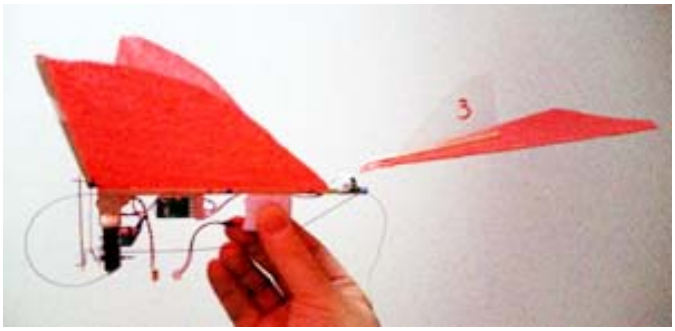

Figure 2 - Lee's RC electric ornithopter.

The smallest RC ornithopter that has been mass-produced is the Cybird RC ornithopter developed by Neuros Co., Ltd., of South Korea. Cybird is a three channel RC ornithopter powered by an electric motor. It can perform loops, power dives, and other maneuvers. The Cybird weighs 280 grams and has a wingspan of 39 inches. It uses a lithium polymer battery and can fly up to 18 minutes on a single charge. A photo is shown in Figure 3 [8].

Figure 3: Cybird RC ornithopter.

The world's first reconnaissance video was taken from a radio-controlled ornithopter in April 2003. The camera was mounted on a Skybird ornithopter designed by Sean Kinkade and Nathan Chronister. This particular ornithopter has a 7-foot wingspan and ½-hp internal combustion engine. For this first flight, video was recorded onboard using a digital video recorder. A second flight occurred in June 2003 using a smaller Kinkade Park Hawk ornithopter. In this system, live video was transmitted to a portable LCD display unit [8].

Although ornithopter research and development continues to be conducted around the world, it is apparent that a truly covert bird-like ornithopter has yet to be developed. Thus, the thrust of this LDRD project.

2 Initial Feasibility Calculations

A bird-like ornithopter will, of course, flap its wings during flight. An initial estimate for the specific power requirements of the ornithopter can be taken from the metabolic rate of birds in flapping flight. Specific metabolic rate for flapping flight ranges from a minimum of approximately 60 W/kg to a maximum of 120 W/kg [7]. Flapping flight requires 7 to 15 times the basal or resting metabolic rate; therefore, it can be assumed that the basal metabolic rate ranges from 4.0 W/kg to 17.1 W/kg. Short hops consisting of rapid take-offs and landings require 30 times more energy that the basal metabolic rate of the bird. This results in a maximum power requirement of 514 W/kg for short time periods. From these values, it can be estimated that an ornithopter will require specific power of approximately 120 W/kg during basic flapping flight with a maximum specific power requirement of 514 W/kg for short durations if "hopping" flight is necessary. Assuming a flapping flight time of 1 hour, the specific energy required by the ornithopter is estimated to be 120 W·hr/kg (4×10^5 J/kg) for sustained flapping flight.

3 Potential Power Systems

Internal combustion, electric motors, compressed air, carbon dioxide, steam, and rubber bands have all been used to power ornithopter vehicles on their short flights. With the exception of internal combustion, the primary difficulty in producing a practical ornithopter is obtaining sufficient specific power and energy from the propulsion system. Internal combustion systems do have a significant power advantage but suffer due to significant efficiency losses in small-scale and the difficulty in converting rotary to flapping motion.

The feasibility calculations above can provide guidelines for concepts and potential power systems. Assuming sustained flapping flight one hour in length, the ornithopter power system will require an energy density of 120 W·hr/kg and a power density of 120 W/kg. Assuming that take-off and landing flight is similar to "hopping" flight, a maximum power requirement of 500 W/kg is needed for short durations. Table 1 lists some classes of power supplies including the energy source, prime mover, and expected efficiencies.

An explanation is in order concerning the relatively low value of conversion efficiency listed for the fuel cell. This is because current fuel cells use compressed hydrogen or metal hydride for fuel storage. Unlike the other power systems listed, the mass of the storage tank is about three times the mass of the fuel. This means that, even for a 100% efficient conversion of fuel to mechanical energy, the total weight of the fuel and tank reduces the effective efficiency to 25%. This is analogous to battery ratings where the energy density includes the entire battery weight rather than the weight of the reacting chemicals only. The 20% value reflects additional inefficiencies in the fuel cell, power required to run the fuel cell, and final conversion efficiency of the electricity generated to mechanical motion using an electric motor. This same weight penalty does not apply to the compressed gas power supply because a gas can be chosen with a high enough critical temperature so that it liquefies under pressure. One example is carbon dioxide. At room

temperature and 73 atmospheres pressure, it has a specific gravity of 0.69. If it behaved as an ideal gas at these conditions (like hydrogen) the specific gravity would be 0.14. Here the liquefaction increases the energy stored at a given pressure by factor of five.

One further issue regarding fuel cells is the need for and mass of the intermediate conversion device in addition to the prime mover. All other types of power supplies use the prime mover to convert energy from the power source into mechanical motion. The fuel cell converts compressed hydrogen to electric power. An electric motor is required to convert the electric power into mechanical motion.

Table 1: Comparison of various potential power sources for the ornithopter.

Type	Energy Source	Prime Mover	Conversion Efficiency (%)	Fuel Energy Density (watt-hr/kg)	Prime Mover Power Density (watt/kg)
Electric	Lithium battery	Electric motor	80%	200	1000
Internal combustion	hydrocarbon fuel	Internal combustion engine	30%	3900	1000
Compressed gas	Compressed liquefied gas	Pneumatic or hydraulic motor	80%	55	2000
Solid elastic material	Compressed spring	Spring	100%	40	NA
Fuel cell	Compressed hydrogen	Electric motor	20%	8900	15

The table shows that only battery-electric and internal combustion systems are capable of providing power for the ornithopter for a reasonable amount of time (1 hour). Other power systems simply do not provide the necessary energy or power density for any type of sustained flight.

When selecting a potential power source, two factors must be considered: specific energy and specific power. For example, for battery systems the specific energy is determined by the voltage of the cell and the amount of charge that can be stored. Specific power is related to the energy density at a given discharge rate, and indicates how rapidly the cell can be discharged and how much power generated. A cell with high energy density may exhibit a significant voltage and capacity drop at higher discharge rates and therefore have a low power density [9]. This same information is shown in a Ragone plot in Figure 4.

As shown in the Ragone plot, a battery system is just capable of providing the estimated power and energy densities required for flapping flight. A battery system simply would

not be capable of providing the power density estimated for hopping flight, take-offs, and landings.

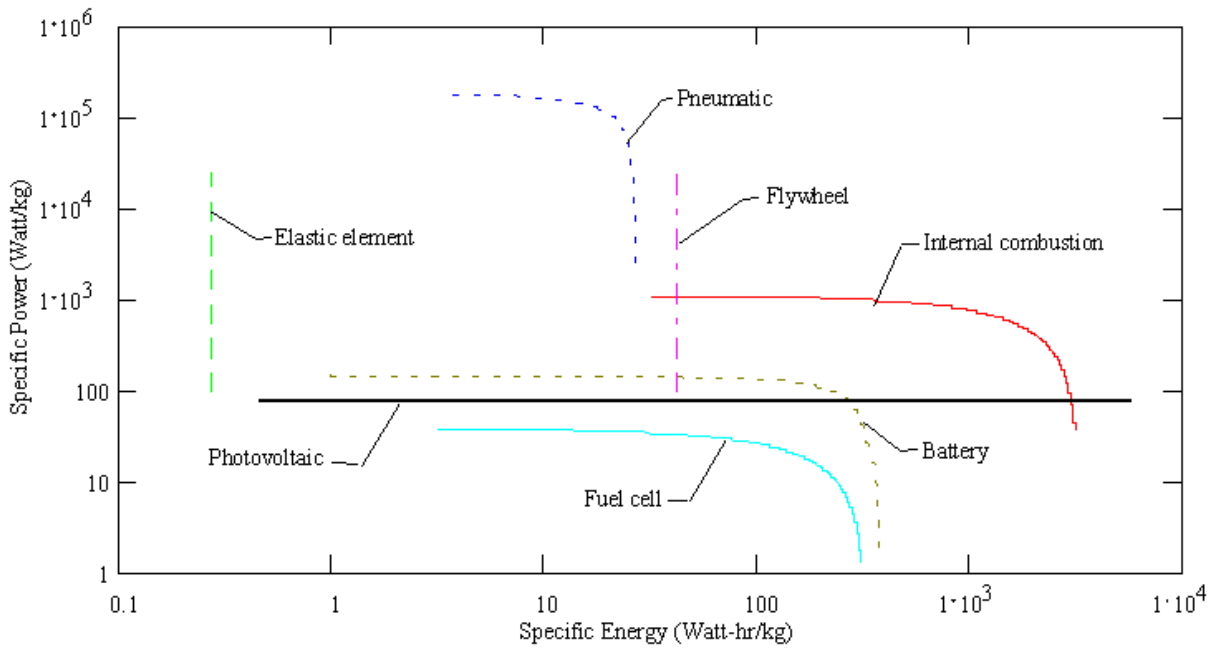

Figure 4: Ragone plot showing energy and power densities for various power systems.

Using the values for fuel energy density and prime mover power density shown in Table 1, estimates can be made for the power system weight in relation to the overall ornithopter weight. For a battery powered, electric-motor driven "bird", the percentage of the total system weight required for the battery/motor is approximately 72%. This is an estimate required for sustained flapping flight. Analyses have shown that a battery system will simply not be capable of autonomous take-off and landing. For an internal combustion powered ornithopter, the fuel and engine weight would be approximately 15% of the overall system weight utilizing a fuel/air mixture (as opposed to a fuel/oxidizer mixture). Because the use of battery power requires the use of such a significant amount of the overall weight for the power system and does not provide the power density necessary for take-off and landing, an internal combustion system was pursued.

4 Pertinent Sandia National Laboratories Technologies

As stated above, the development of a bird-scale ornithopter should be based on an internal combustion system. Basing the design on a combustion powered linear actuator originally developed to drive the SNL hopping robots solves many of the problems

inherent with internal combustion engines and provides exceptional power and energy. The soundness of this approach can be realized by comparing the characteristics of our linear actuator to an internal combustion engine. Small-scale engines must operate at very high speeds (on the order of 20,000 rpm) to produce significant power. Problems of incomplete combustion and purging due to short cycle time cause these small engines to operate at very low efficiencies. Recent tests show thermal efficiency is on the order of 6%. Because of the relatively short stroke and high-speed, complex mechanical systems would be needed to amplify the stroke and reduce the frequency to drive flapping wings.

The SNL actuator is a combustion-driven, single-acting linear piston. A photo is shown in Figure 5. A fuel charge is introduced into the chamber and ignited. The resulting pressure causes the piston to move. A simplified sectional view of the actuator is shown in Figure 6. On the current hoppers, the fuel is methyl acetylene and the oxidizer is nitrous oxide. Both components are gaseous at atmospheric conditions and liquefy under pressure. This provides a self-pressurizing fuel system. The fuel and oxidizer are controlled by high-pressure miniature motor operated valves, which were also invented as part of the hopper program. A complete three-valve gallery and manifold is shown in Figure 7.

Figure 5: Hopper Combustion Powered Linear Actuator

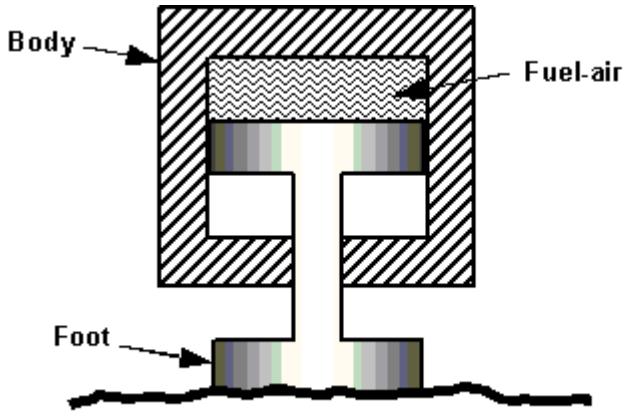

Figure 6: A simplified sectional view of the combustion-powered linear actuator

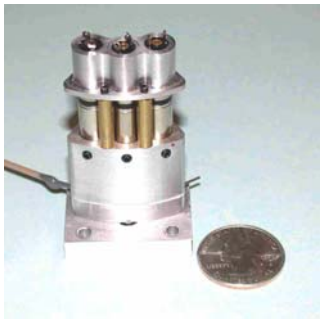

Figure 7: Sandia Developed High Pressure Miniature Valve Gallery

Tests have shown a thermodynamic efficiency in excess of 30% and a power density of 10 horsepower per cubic inch of displacement volume. These actuators operate well at long aspect ratios with the stroke being up to ten times the cylinder bore. These actuators can be well matched to a flapping wing in required force, stroke, and frequency. Here, high speed is not necessary to achieve sufficient power and the actuator could be fired once for each wing beat.

The fuel-oxidizer version of our actuator was developed to provide self-starting ability to the Hopper. The system can fire reliably from a cold start with no additional power or specific starting cycle requirement. In the case of an ornithopter powered by this actuator, the cold start capability is important but, once flapping begins, the return stroke of the actuator can be used to compress ambient air allowing fuel-air operation rather than fuel-oxidizer. This would result in a significant savings of onboard consumables and extension of range since about eight times as much oxidizer is needed as fuel for fuel-oxidizer operation.

The use of combustion rather than batteries for propulsion provides tremendous advance in time aloft. Assuming a thermodynamic efficiency of 15%, one gram of fuel (less than the battery weight in the MicroBat) could provide propulsion for six hours rather than 6 minutes. Even using fuel-oxidizer operation, the run-time would be around 45 minutes. There is no doubt that combustion systems provide much higher power and energy than electric systems. Our linear actuator provides the means to harness the exceptional energy stored in hydrocarbon fuels for use with a small-scale ornithopter.

One other significant advantage our actuator has over previous designs is that it can provide power for autonomous takeoff. The actuator was originally designed for the hopping robot. It has been shown that, using actuators that are no more than 10% of the vehicle mass, hop heights of 50 feet can be achieved. Using a similar approach, an ornithopter could land and launch itself autonomously since the hopping actuator provides enough altitude to achieve sustained flight. Autonomous takeoff has not yet been achieved by any small-scale flying vehicle. For reconnaissance and surveillance it is a very important attribute since it can extend the time on station indefinitely.

For this feasibility study, limited testing was performed to verify the potential for achieving vehicle takeoff and wing flapping for sustained, long duration flights of at least 1 hour. The challenges of incorporating this approach into an autonomous, bird-like vehicle are great. However, the payoff for developing this type of vehicle is even greater and the crucial technologies to make it work exist nowhere else.

5 Small Scale Combustion

From the sections above, it is obvious that a practical ornithopter capable of more than a few minutes worth of flight must be based on a combustion power source. Use of the SNL-developed combustion powered linear actuator lends itself to potential autonomous take-off as well as sustained flight. However, the current size of the linear actuator is too large for a practical bird-size ornithopter. Therefore, development and testing of smaller scale combustion driven linear actuators was necessary.

5.1 Background

Obviously, there is a clear advantage to utilizing a combustion-driven actuator over a battery-powered actuator for the development of a bird-like vehicle. However, the efficiency of internal combustion engines tends to drop with cylinder diameter for a number of reasons. First, the surface-to-volume ratio increases with reduced scale thus increasing the ratio of heat loss to heat generation for the flame. This means that it is more difficult to initiate and sustain combustion in smaller scale. This leads directly to the fact that the ignition system for an internal combustion engine does not scale. The same amount of energy, or even more, is required to initiate combustion in small scale as in large scale. Further since machining tolerances do not scale, valve and piston leakage scales linearly with size while cylinder volume scales as the cube of size. Leakage through the valves and around the piston becomes a significant factor at very small scale.

Development of miniature internal combustion engines is currently of great interest to the technical community. Obviously, a combustion driven generator could easily out perform and therefore replace batteries in many systems. The development of a miniature engine has even more difficulties than the development of a linear actuator. For example, to achieve acceptable performance, small-scale engines must operate at very high speeds. The stress-limited speed of an engine is inversely proportional to scale and power is proportional to speed. This means that the ignition timing, valve timing, and fuel injection timing become more crucial as scale is reduced. These timing and mechanical complexity issues push engine manufacturers to produce simple two-stroke designs with ported cylinders. These designs significantly reduce the efficiency of the engine since adequate purging of the combustion volume cannot be attained at high speeds.

5.2 Test Results

Several tests were conducted to measure the change in thermal efficiency of the combustion-driven linear actuator as the diameter of the combustion chamber is

reduced. Combustion chamber/piston diameters of 0.625 to 0.75 inch are used in the current hopper design with a measured thermal efficiency of approximately 30%. A known volume of fuel/oxidizer is introduced into the combustion chamber of an actuator. Upon combustion, the actuator piston is "shot" up into the air. The time of flight for the piston is measured to determine the mechanical energy output. A photo of the pistons and cylinders used in the tests is shown in Figure 8.

Figure 8: Photo of the pistons and cylinders used in the combustion tests.

Results of the tests are shown in Figure 9. For a combustion chamber size of 0.625 inch and greater, the thermal efficiency of the actuator is approximately 30%. However, as the combustion chamber size is decreased below 0.625 inch, the efficiency drops rapidly, dropping essentially to zero for a ¼-inch diameter combustion chamber. This is the largest size considered practical for a bird-size ornithopter.

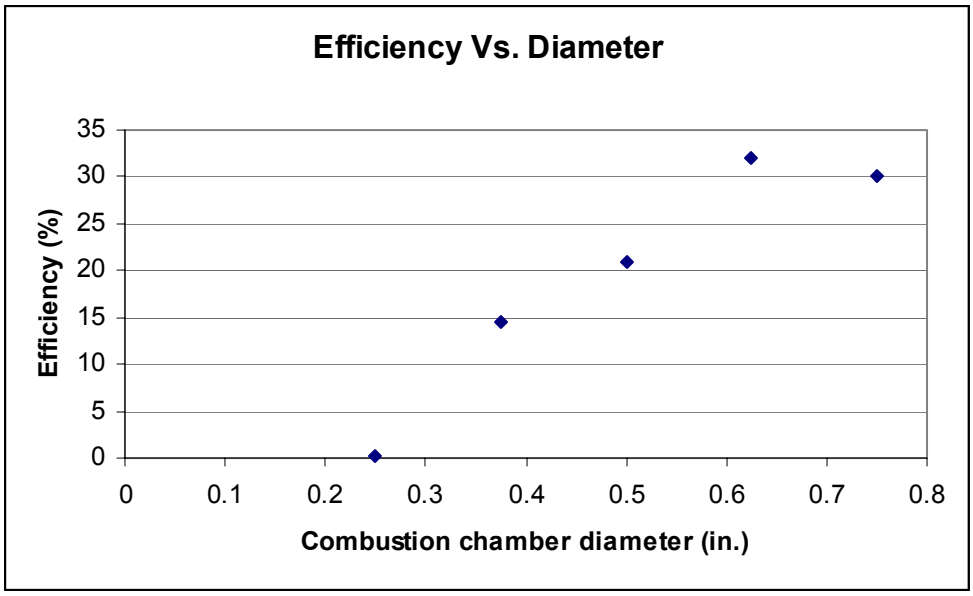

Figure 9: Efficiency vs. combustion chamber diameter

5.3 Discussion

As shown in the efficiency graph above, something is obviously affecting the combustion process as the combustion chamber is made smaller. Several factors could be at play [3]:

- Wall heat transfer effects begin to dominate the combustion process. Heat loss to the walls of the chamber depends on the surface area of the combustion chamber while the combustion energy depends on the volume. As the diameter decreases, the surface to volume ration increases inversely. A small diameter means a large heat transfer surface area in relation to the volume, heat transfer losses to the walls begin to dominate the process.
- Wall quenching not only affects the combustion process, but also the ignition phenomena. A flame is quenched in a tube when the two mechanisms that prevent flame propagation, diffusion of species and heat, are affected. Tube walls extract heat and the smaller the tube, the greater the number of collisions with the wall and destruction of the active radical species. Quenching diameter depends on a number of factors, but lies in the range of 1 to 4 mm for many combustion processes. A chamber diameter of 0.25 in (6 mm) is certainly approaching the quenching diameter where a flame simply will not propagate. Wall quenching is certainly of importance in this range.
- Since the surface area of the combustor becomes large compared to the combustion volume, piston friction begins to play a more important role in energy output of the linear actuator. The energy of combustion of the small volume may not be enough to overcome wall friction in small diameters.

- Along the same lines, leakage between the piston and the cylinder becomes more dominant as the cylinder diameter decreases. Leakage will reduce the energy delivered to the piston.

Research in the area of micro-combustion is currently being conducted at many universities and institutions [1, 2, 5, 10] and was considered beyond the scope of this project.

6 Conclusion

Preliminary analysis of potential power systems showed that internal combustion engine power was the only system capable of the power densities necessary for any type of sustained flight lasting more than a few minutes. It was thought that the SNL combustion driven linear actuator developed for the Hopper robot could be modified and scaled to provide the perfect actuator for a flapping air vehicle. Initial tests of the actuator in sizes scaled to the size of interest show that the thermal efficiency of the actuator drops off rapidly at piston diameters less than 0.625". Without significant research into micro-combustion, the Hopper linear actuator could not be used to develop a bird-size ornithopter.

Future research and development tests must be conducted in order to gain a better understanding of the processes in these scales. Further work include expanding the testing that was already completed as well as additional testing such as decreasing piston diameter while maintaining a constant combustion volume. In addition, the possibility of utilizing external combustion should be investigated in detail.

Several development efforts have been initiated to create a flapping wing aircraft. These efforts have met with varied success, the main shortcoming being the lack of an appropriate power source. Therefore, the immediate problem to be solved becomes one of micro-combustion rather than development of a flapping air vehicle. Once the power source has been appropriately addressed, the next challenge will be to integrate it into a practical vehicle design capable of autonomous take off, free flight, and landing. Development was continued no further than the research and tests reported here.

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