UPDATE ON FLAPPING WING MICRO AIR VEHICLE RESEARCH

Ongoing work to Develop a Flapping Wing, Crawling "Entomopter"

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ABSTRACT: An electromechanical multimode (flying/crawling) insect is being developed by Robert Michelson and his design team at the Georgia Tech Research Institute. The project has received initial IRAD funding from the Georgia Institute of Technology. The mechanical insect, known as an "Entomopter" is based around a new development called a Reciprocating Chemical Muscle (RCM) which is capable of generating autonomic wing beating from a chemical energy source. Through direct conversion, the RCM also provides small amounts of electricity for onboard systems and further provides differential lift enhancement on the wings to achieve roll and hence, steered flight. A testbed for the RCM technique has been constructed and demonstrated. Trimmed stable short range flight in a micro version of the entomopter is expected during 1998. In contrast to the testbed, entirely different mechanisms will be used to implement the RCM in the flying version. This paper details progress to date on the Entomopter development.

AUTHOR BIOGRAPHICAL SKETCH

Robert Michelson is the Technical Area Manager, Battlefield Robotics & Unmanned Systems at the Georgia Tech Research Institute. He is currently Director of the Department of Transportation's Traffic Surveillance Drone project as well as Director and Principal Investigator for the top-rated IRAD program at the Institute for FY97 involving the development of a multimode mechanical insect-based micro air vehicle.

He has worked on and directed a number of remote sensing projects related to RF and radar applications. In addition he has performed verification and validation analyses of man-in-the-loop virtual reality flight simulators for STRICOM. He directed a project to develop the avionics suite for an Air Force Robotic Air-to-Air Combat vehicle. He directed a project to specify dual-mode IR/MMW seeker parameters for a lethal unmanned aerial vehicle (UAV) system. He was responsible for generating remote flight control system specifications for Soviet "HAVOC" and "HOKUM" gunship drone simulators for the U.S. Army, and directed a task to develop a rotary winged UAV digital stability augmentation system for MICOM.

As adjunct Associate Professor to the School of Aerospace Engineering, he teaches classes in avionics for UAVs. He is also the creator and organizer of the annual International Aerial Robotics Competitions. Prior to joining the GTRI staff, he participated in design and endo-atmospheric flight testing of computer-controlled space-based radar ocean surveillance systems while employed by the Naval Research Laboratory in Washington, DC. He is author/coauthor of more than 60 major technical publications.

Steven Reece has been instrumental in implementing the milli-scaled reciprocating chemical muscle testbed, testing it, and compiling the performance data contained in this paper.

Nothing in creation exhibits fixed wing flight behavior or propeller-driven thrust. Everything that maintains sustained flight, uses flapping wings. Even though there has been considerable analysis in the literature of mechanisms for bird flight (Ellington[1], 1984) and insect flight (e.g., Azuma[2], 1992, and Brodsky[3], 1994), and ornithopter-based (bird flight) machines have been demonstrated– nothing at the size level of an 'Entomopter' (*entomo* as in entomology + *pteron* meaning wing, or a "winged insect machine") has been tried.

An mechanical entomopter, or robotic insect, capable of short distance trimmed flight and ground locomotion using a "reciprocating chemical muscle" technique is currently under development by the authors. In addition, autonomous navigation schemes (homing) based on Georgia Tech's integrated-optic interferometric waveguide sensor will be developed as a means of directing controlled flights and crawling in the future

Major Hurdles

Beyond the challenges of low Reynolds number aerodynamics (*inertial force of body ÷ viscous force of air*), three major system-specific technological areas must be addressed before a any practical MAV can be fielded. These are:

- NONSCALING ITEMS
- STORED ENERGY
- PROPULSION

NONSCALING ITEMS may be functions of external factors such as established GPS frequencies over which there is little control. For example antennas may be of suboptimal gain or directivity in order to fit the form factor of a MAV, while ground station frequencies may of necessity, preclude anything but line-of-sight operation. A reconnaissance MAV operating line-of-sight at a distance of several kilometers may require an operational altitude of several thousand feet in order to clear tree lines, hills, and cultural items. The cost of being small becomes of questionable benefit when the mission envelope begins to overlap that of existing assets which can perform the same reconnaissance mission.

STORED ENERGY becomes a significant impediment as MAV mission duration increases. The present state-of-the-art in battery technology does not allow for long endurance MAV missions, though it is hoped that someday improved electrical storage media (carbon-air, fuel cells, etc.) will result in the energy densities required for useful long endurance (> 1 hour) missions in MAV-sized vehicles. Near term solutions to onboard energy storage will come from chemical or fossil fuels because of their superior energy density. As a point of comparison, consider the amount of releasable energy stored in a drop of gasoline compared to that which can be stored in a battery the size of a drop of gasoline.

Given that a high energy fuel source is used, the third system-specific technological area which must be addressed is PROPULSION, that is, how one converts the fuel's stored energy into useful, controllable work. This involves some sort of engine, and a propulsor system. The approach described in this paper is to use a chemical fuel source driving a specialized scalable engine known as the "reciprocating chemical muscle" (RCM), coupled to flapping wing propulsors. This combination is deemed to be optimal for indoor MAV missions where the MAV is more than a simple flying machine, but a robot capable of demonstrating various insect-like behaviors including the ability to land, crawl, and take off again.

Form Follows Function

Beyond the fact that every living thing capable of sentient navigation employs flapping wings for sustained aerial locomotion, certain features of flapping wing flight make it attractive for those missions in which micro air vehicles are believed to have the greatest potential.

Many missions for micro air vehicles (MAV) have been proffered, but all basically fall into the categories of "outdoor", "urban", and "indoor". The domain for MAVs will be as key elements of indoor missions. Major, and perhaps insurmountable obstacles confront MAVs that fall prey to the forces of the environment. Wind and rain can prevent outdoor MAV flight from taking place as the tiny air vehicle could expend its entire energy store getting nowhere in an attempt to fly at 20 kph in a 20 kph head wind. Similarly, rain will not only attenuate signals from the necessarily high frequency command links but may even push the tiny craft to the ground. Besides, assets exist for most outdoor reconnaissance missions– why use a MAV?

Proponents would argue that MAVs put the reconnaissance potential in the hands of the users that need specific information in a timely manner. Perhaps a better solution would be to invest in networked communications systems that can get the same information to the foot soldier in a timely manner from existing unmanned aerial vehicle (UAV) assets such as Predator or the Global Hawk. Global Hawk will look over *all* hills in the theater of war, providing continuous 0.09 square meter (1 square ft) resolution views of the ground from an altitude of 20 km (65,000 ft) for periods of up to 36 hours! Multiplexing the Global Hawk sensors to take snap shots of specific regions of the battlefield and to deliver them to individual users on the ground in near real time is probably an easier and better integrated approach to C^3I than the anarchy of hundreds of tiny personal eyes in the sky careening at the mercy of the wind.

Urban settings, where the next generation of conflicts are predicted to occur, present difficulty for existing UAV assets. This is because most UAVs are fixed wing vehicles and are too fast to negotiate the urban canyons. Flying high over a city is of use, but if one could gather reconnaissance down in these urban canyons– between buildings, then a greater situational awareness could be had. MAVs are a reasonable candidate for this mission since they are smaller and potentially slower than conventional UAVs. Even fixed wing MAVs could conceivably negotiate city streets, but MAVs capable of slow flight and even hover would afford the ability to stop, look into windows, or even land in tight spaces to place sensors. On the other hand, wind and rain will still plague these tiny air vehicles, and the occlusion of signals by buildings will exacerbate communication and navigation.

The real mission niche for MAVs will be indoors where the environment is controlled, and there are *no* existing airborne reconnaissance craft that can negotiate hallways, crawl under doors, or navigate ventilation systems in an attempt to complete a reconnaissance mission. It is the indoor mission that will ultimately justify the development expense. The very nature of an indoor mission will necessitate (1) multimode vehicles (flying/crawling/rolling), and (2) autonomous navigation. These two features of an indoor MAV are not absolutely necessary for outdoor missions, but outdoor MAV missions are themselves not absolutely necessary. Therefore, investment in the design of autonomous multimode MAVs which incorporate these features from the inception of their design is paramount.

Why Flapping Wing Flight?

If the most justifiable missions for MAVs are indoors, then a vehicle must be optimized to negotiate constricted spaces that are bounded on all sides, land and take off with minimal ground roll, and circumvent obstacles (e.g., doors). Fixed wing solutions are immediately discounted because they require either high forward speed, large wings, or a method for creating circulation over the wings in the absence of fuselage translation.

High speed is not conducive to indoor operations because it results in reduced reaction time, especially when autonomously navigating through unbriefed corridors or amid obstacles. When indoors, slower is better.

If, on the other hand, the wings are enlarged to decrease wing loading to accommodate slower flight, the vehicle soon loses its distinction as a "micro" air vehicle. Current wisdom defines a micro air vehicle as having no dimension greater than 15 cm. Even at this scale, the forward speed required for a fixed wing vehicle to efficiently stay aloft violates the criteria for negotiating constricted spaces..

Finally, there are methods for creating circulation over the wings in the absence of fuselage translation. This can be done by "blowing" the surfaces of the wing to increase lift in an intelligent manner by using an internally-generated pressure source. This has been demonstrated in manned aircraft and certain experimental unmanned vehicles, but is typically inefficient unless there is a source of gas pressure already available (such as bleed air from a gas turbine engine).

Another way to move air over a wing without fuselage translation is to move the wing relative to the fuselage and the surrounding air. This can be a circular motion as in a helicopter rotor, or it can be a reciprocating motion as in a flapping wing. Both serve to create a relative wind over an airfoil thereby creating lift.

A rotor is mechanically simple to spin, but does not use all parts of the wing (rotor) with the same efficiency since the inner section near the rotor hub moves more slowly than the tip. The same thing can be said for a flapping wing where the greatest relative wind is created at the wing tip, and none at the root.

A significant advantage of a flapping wing over a rotor is the rigidity of the wider chord wing relative to the high aspect ratio of a narrow rotor blade, and the fact that it can be fixed relative to the fuselage (e.g., nonflapping glide) to reclaim potential energy more efficiently than an autorotating rotor.

It could also be argued that a flapping wing implementation is an inherently lower bandwidth system than one using a helicopter rotor. Both systems require cyclic (once-per-flap or once-per-revolution) control inputs to maintain vertical lift and stability, but the frequencies at which these inputs must be generated can be much lower for comparably sized flapping implementations.

There is also a stealth advantage of a flapping implementation over a comparably sized rotor design in that the acoustic signature will be less because the average audible energy imparted to the surrounding air by the beating wing is much less than that of a rotor. The amplitude of vortices shed from the tips of the beating wing grows, and then diminishes to zero as the wing goes through its cyclical beat, whereas the rotor tip vortices (which are the primary high frequency sound generator) are constant and of higher local energy. The sound spectrum of a flapping wing will be distributed over a wider frequency band with less energy occurring at any particular frequency, thereby making it less noticeable to the human ear. All the energy of the rotor spectrum will be concentrated in a narrow band that is proportional to the constant rotor tip velocity.

As the diameter of a rotor system decreases with the size of the air vehicle design, it will become less efficient since the velocity at the tips will decrease while the useless center portion becomes a larger percentage of the entire rotor disk. To compensate for this, the designer will tend to increase the rotation frequency of the rotor to maintain lift for a given fuselage mass and power source. The increased rotation frequency will increase the frequency and energy content of the sound produced.

On the other hand, as the wing span of a flapping wing system is decreased, wing beat frequency must similarly be increased to maintain lift for a given fuselage mass, but the spectrum of the sound produced will simply broaden with more energy occurring at higher frequencies. Though the work produced to lift the fuselage mass may be the same as that for the rotorcraft, the energy will be expended over a wider acoustic bandwidth, but unlike the rotorcraft, it will be nonuniformly distributed in the horizontal plane. The net result is that a any flapping wing approach will be less noticeable than a rotary wing approach because the sound spectrum produced will approximate wide band white noise rather than a discrete tone.

The flapping wing is conducive to slow flight and even hover. It allows for short take off and landing, and may have advantages over other techniques in terms of its acoustic signature. All of these features are desirable for indoor operations, but what about circumvention of obstacles such as doors? None of the techniques mentioned so far has any particular advantage when it comes to movement through small openings such as partially-opened doors or under closed doors. Similar problems exist for small openings like windows, air vents, and pipes.

The solution is to have a multimode vehicle that is capable of not only flight, but ground locomotion. Crawling is not a particularly efficient form of locomotion if large distances must be traversed, but a machine capable of only flight is effectively neutralized were it to encounter a closed door. If a flying machine could drop to the floor and crawl the small distance necessary to go under the door, then the mission could continue.

The notion of a hovering "humming birdlike" sensor platform that darts about a room inspecting different items of interest, is constricted in the near term by the energy density of its power source. Until greater power densities can be achieved, the likely mode of operation will entail a covert quick entry to a distant area using flight, followed by a precise positioning of a sensor using ground locomotion. This may represent one percent of the overall mission. The remaining ninety nine percent will revolve around the operation of the emplaced sensor from its remote vantage point.

Flight Concept Under Development

Various wing beating concepts have been analyzed by the authors and modeled kinematically using the computer aided design (CAD) tool, IDEAS. The obvious flapping mechanism of two opposing wings used by most natural fliers was ultimately discarded in favor of an X-wing design incorporating two sets of wings.

The advantage of the our X-wing concept is that it can be conveniently scaled to micro sizes because it is mechanically simpler than the birdlike flapping mechanism. The use of four wings is necessary to resolve moments about the fuselage, but also adds longitudinal (pitch) stability to the vehicle. A built-in dihedral in each wing pair provides a degree of lateral (roll) stability.

An X-wing glider has been built and has demonstrated stable roll and pitch qualities at the "milli scale" where the initial internal research is focused. Our milli scaled testbeds are being constructed with wing spans on the order of 30 to 46 cm (12 to 18 inches). This rationale comports with the reasoning of Ellington who states that sizing constraints for near term flying robotic insects"… *suggest that larger machines would be the best starting point. Maximum speeds would be low, but because of their larger size, fabrication would be easier and they would offer a more convenient testbed for the development of control systems*." (Ellington[4], 1997). All designs are being done with scalability in mind. Many concepts that were workable at the milli scale have been abandoned because they would not scale to the micro level as easily as others.

A kinematically-correct X-wing flapper was constructed for evaluation (see Figure 1) and now resides on display at the Museum of Victoria, Australia. This vehicle was designed to move with opposing wing motions in which the forward wing pivots in one direction while the aft wing pivots in the opposite direction. The net result is a balancing of forces, with two wings always in an up-stroke, and two wings always in a down-stroke. The wings and mechanism in Figure 1 are not what will be used in a flying version, but only demonstrate the X-wing kinematics.

Flapping Dynamics in the Insect Kingdom

Four degrees of freedom in each wing are used to achieve flight in nature: flapping, lagging, feathering, and spanning. This requires a universal joint similar the shoulder in a human. Flapping is an angular movement about an axis in the direction of flight. Lagging is an angular movement about a vertical axis which effectively moves the wing forward and backward parallel to the vehicle body. Feathering is an angular movement about an axis in the center of the wing which tilts the wing to change its angle of attack. Spanning is an expanding and contracting of the wingspan.

Figure 1. X-wing entomopter kinematic model.

Not all flying animals implement all of these motions. Unlike birds, most insects do not use the spanning technique. Insects with low wing beat frequencies (17-25 Hz) generally have very restricted lagging capabilities (Brodsky[3], 1994). Insects such as alderflies and mayflies, have fixed stroke planes with respect to their bodies, and the only way these insects can alter the stroke plan with respect to gravity is to change their body angle (Brodsky[3], 1994). Thus, flapping flight is possible with only two degrees of freedom: flapping and feathering.

Using only these two degrees of freedom, there are 3 important variables with respect to wing kinematics: wing beat frequency, wing beat amplitude, and wing feathering as a function of wing position. When coordinated, these motions can provide lift not only on the down stroke, but also on the up stroke. The ability to generate lift on both strokes results from a change in the angle of attack of the wing whose tip inscribes an ellipse when considered relative to a body-referenced point. The ability to generate lift on both the up- and down-stroke leads to the potential for hovering flight in entomopters and ornithopters.

Wing beat amplitudes vary in nature from approximately 25° to 175°. In general, as wing beat frequency increases, wing beat amplitude decreases. The feathering of the wing as a function of wing position is crucial to the flight dynamics. Each line represents the wing section at some arbitrary position across the span of the wing (Ward-Smith[5],1984). Generally insects with a constant, vertical stroke plane must use a large angle of attack on the descending part of their wing trajectory.

Other techniques such as optimizing wing shape, using elastic wing deformation, and employing the Weis-Fogh clapping mechanism (Lighthill[6], 1975) can be used to enhance the wing kinematics, and thus produce more efficient flapping flight.

Entomopter X-Wing Flapping

Like the alderflies and mayflies, the entomopter will have a fixed stroke plane for each of its four wings. Coupled to the RCM, each wing pair will be part of resonant mechanical structure that will provide a self-regulating wing beat frequency. The amplitude of the wing beat is a function of the stiffness and spring constant of this structure. The third important variable, feathering, is accomplished through the use of "smart materials" that exhibit a different compliance under varying loads.

This latter feature will be controlled by not only by the wing rib structure, but also the interstitial wing material itself. Stereolithography and Fused Deposition Modeling techniques have allowed the design team to create intricate wing structures directly from computer models. Careful attention is being paid to material selection. Resilience, stiffness in opposite planes, chemical compatibility, and ease of bonding are but a few of the points being considered in the choice of wing materials. Figures 2 through 4 show wings being grown in our stereolithography machines as well as ABS wing stiffening structures with, and without interstitial materials.

These wing structures are designed with hollow micro passages to allow intelligent venting of waste gas from the RCM over the wing surface for directional control of the entomopter. The circulation controlled airfoils of the entomopter allow differential modulation of the lift while maintaining a constant autonomic wing beat. This simplifies the mechanics of the wing and is scalable to the micro level by using valves constructed with microelectromechanical systems (MEMS) techniques.

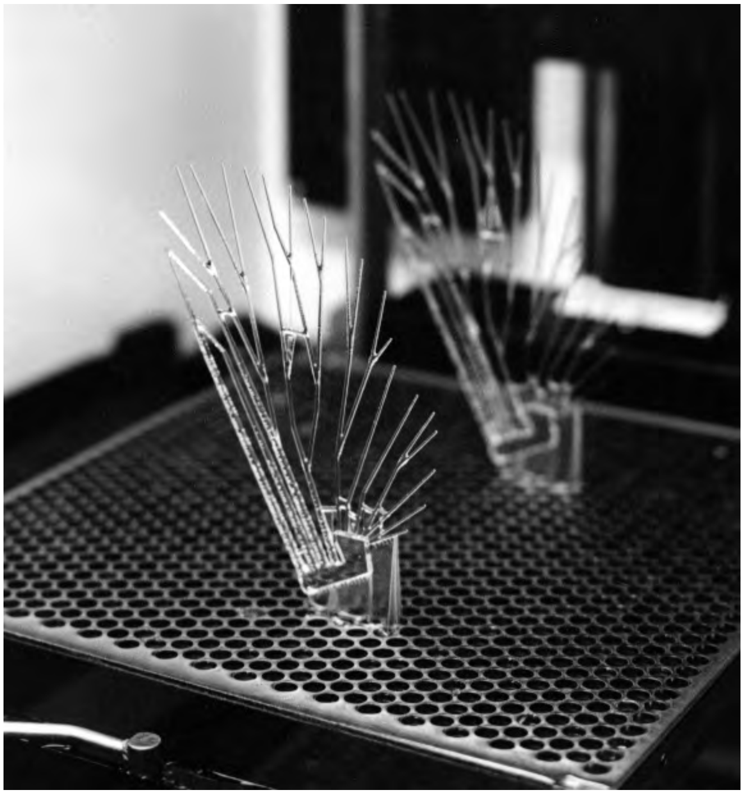

Figure 2. Wings grown using Stereolithography.

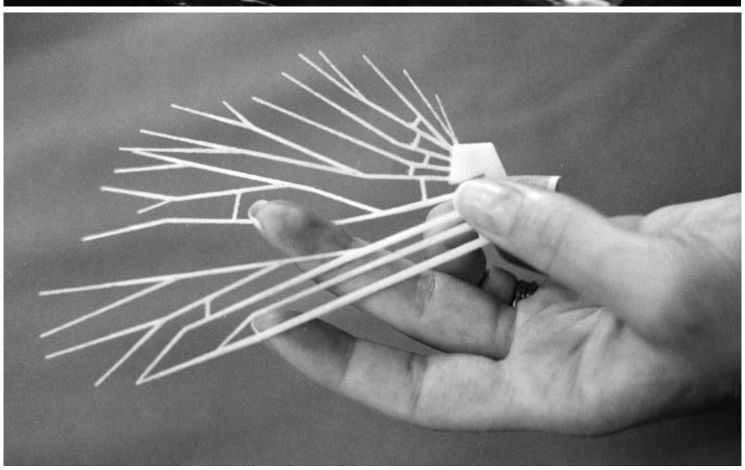

Figure 3. Wing rib structure produced

through Fused Deposi-

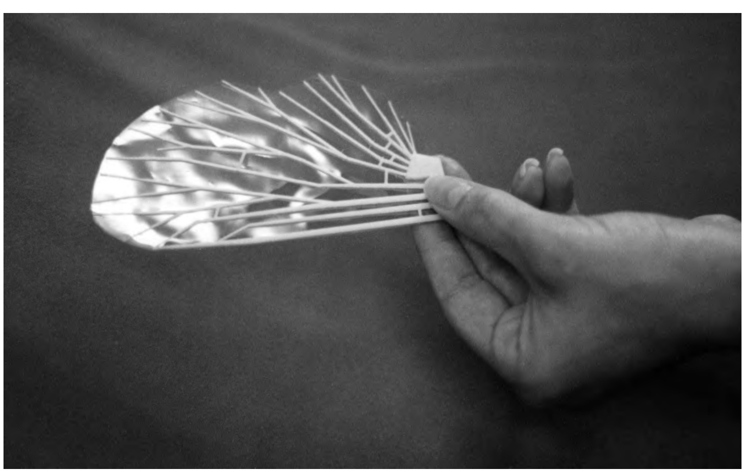

Figure 4. Fused Deposition Modeled

wings with interstitial

Power to Fly

The power necessary to achieve flapping flight can be calculated by using formulas derived by Azuma[2], 1992. This power is mainly a function of the following variables: vehicle mass, flapping frequency, forward speed, wing chord, wing span, and wing beat amplitude. Example calculations for a vehicle weighing 50g and having an ideal 100% efficient RCM have been estimated (Michelson[7], 1997). Based on this analysis, just over a watt of power would be necessary to propel such an entomopter. Weight reduction is the most critical factor in creating a successful entomopter. The equations of flight contain terms in which weight contributes to the fourth power. Note that a doubling the entomopter mass from 50g to 100g results in almost eight times the required power. For this reason it is critical that entomopter structures serve multiple purposes. As an example, wings could also be antennas, legs could be inertial stabilizers in flight— perhaps someday the fuselage might even be itself a consumable fuel source!

Reciprocating Chemical Muscle

The Reciprocating Chemical Muscle is a mechanism that takes advantage of the superior energy density of chemical reactions as opposed to that of electrical energy storage which is the approach currently being taken by most other MAV researchers. For example, the energy potential in one drop of gasoline is enormous compared to that which can be stored in a battery of the same volume and weight.

The RCM is a regenerative device that converts chemical energy into motion through a direct noncombustive chemical reaction. Hence, the concept of a "muscle" as opposed to an engine. There is no combustion taking place nor is there an ignition system required. The RCM is not only capable of producing autonomic wing flapping as well as small amounts of electricity for control of MEMS devices and the "nervous system" of the entomopter, but it creates enough gas to energize circulation-controlled airfoils. This means that simple autonomic (involuntary, uncontrolled) wing flapping of constant frequency and equal amplitude can result in directional control of the entomopter by varying the coefficient of lift (C_L) on each of the wings, thereby inducing a roll moment about the body of the entomopter while in flight.

Of particular interest to the RCM design team was the correspondence between the amount of force that can be generated by a reciprocating muscle and the maximum frequency with which this force can be applied. Also, as the frequency is increased, how much linear motion can be achieved in a reciprocating device.

Initial tests using a nonflying RCM testbed to which simple wing spars were attached (see Figure 5), demonstrated that the reciprocating chemical muscle concept is valid. This test bed was mechanically inefficient, but was still able to produce wing beat frequencies of up to 10 Hz in the rather massive testbed structure.

The amount of power necessary for flapping wing vehicle flight has been the subject of many articles, and has been estimated for insect-based flying machines by both Ellington[4] and Michelson[7]. Calculations based on empirical data taken from the RCM testbed indicate that the power available for flight is greater than the power necessary for flight (Michelson[7], 1977). From this, the force required to move a wing can be estimated, as can the required wing beat frequency for a given wing design. If the force available is sufficient, then the amount of linear motion achieved by the muscle will become less important as any motion can be amplified through something as simple as a lever arm, but with the attendant loss of force deriving from the ratio of the mechanical disadvantage presented by the motion amplifying mechanism used.

The frequency of operation is much more critical. Some polymer, rheological, or shaped memory alloy muscles are able to create motion, but not at the high repetition rates needed for flight. As shall be discussed below, resonance is critical to the energy balance of the flight system. It is conceivable that slower acting muscles could pump energy into a resonant system which is operating at a harmonic of the fundamental muscle actuation frequency, but this will require more force from the muscle each time it imparts energy into the more rapidly flapping system.

The RCM is intended to operate at the same fundamental frequency as the resonant wing structure. Some authors have questioned whether energy is stored in the muscle of an insect, or in portions of its exoskeleton (Alexander[8], 1995). The RCM stores small amounts of energy in its structure, but this is releasable at a higher frequency than flapping will occur in the milli-scaled entomopter. The predominant energy storage medium in the milli-scaled entomopter is clearly the fuselage/wing structure, and the resonance of this structure is what will determine the fundamental resonant frequency of the entire system. The RCM is self regenerative but its speed of reciprocation is governed directly by the resonance of the flapping structures and not the muscle itself. So long as the muscle response is faster than the resonant wing beat, then energy will be imparted to the system at the right time, including that energy stored temporarily within the muscle itself.

Ellington has tabulated estimates of the wing beat frequencies necessary to support various masses in a hovering entomopter. He has made certain assumptions about the physical properties of the entomopter such as a peak-to-peak wing beat amplitude of 120 degrees (without Weis-Fogh clapping), wing aspect ratios on the order of 7, and a mean coefficient of lift (C_L) in hover of 2. From this

Figure 5. Reciprocating Chemical Muscle Test Bed.

analysis (Ellington[4,] 1977) one can extrapolate that a milli-scaled entomopter weighing approximately 50g could fly with a wing span of approximately 25 cm (10 inches) and a wing beat frequency of 20 Hz. In reality, the wing beat frequency might only be between 10 and 20 Hz when the double X-wing design of the entomopter is considered.

One question remaining to be answered is how much motion should a muscle typically produce in order to efficiently move a flapping wing? Fortunately, the literature reports at least one benchmark test in which the wing muscles of wasps were observed through an opening cut in the cuticle of the thorax during flight. This experiment revealed that contraction and expansion of the muscle fibers only accounted for two percent of the overall muscle length during each full beat of the wing (Gilmour[9], 1993).

Another benchmark measurement has been reported in the literature in which the muscle efficiency and level of resonant energy storage has been estimated for the fruit fly *Drosophila hydei*. In this study, the mechanical efficiency of the flight muscle was determined to be only ten percent, while the energy stored elastically for resonant release was estimated to be somewhere between 35 and 85 percent (Dickson[10], 1995).

Bench Test Performance Comparisons for the Milli-Scale RCM

The next step in the development of the RCM was to reduce it to a size that would be compatible with the milli-scaled entomopter. The 7.62 cm (3 inch) milli-scale muscle shown in Figure 6 was constructed as both a test article and for incorporation into the milli-scaled entomopter.

Both frequency sweeps at fixed operating pressures and variable pressure tests were conducted. Figures 7 and 8 show some of the results obtained.

Figure 7 is a graph comparing the force available to do work versus linear travel in inches for different operating pressures at a frequency of 10 Hz. The maximum pressure that the RCM can accommodate is merely a strength of materials question. For convenience, the milli-scaled entomopter is being designed to operate in the 40 psi pressure range. Increasing the pressure has several effects. First, higher operating pressures are less fuel efficient. Second, the pneumatic stiffness of the muscle is greater and hysteresis is minimized. Third, the range of travel increases for higher operating pressures.

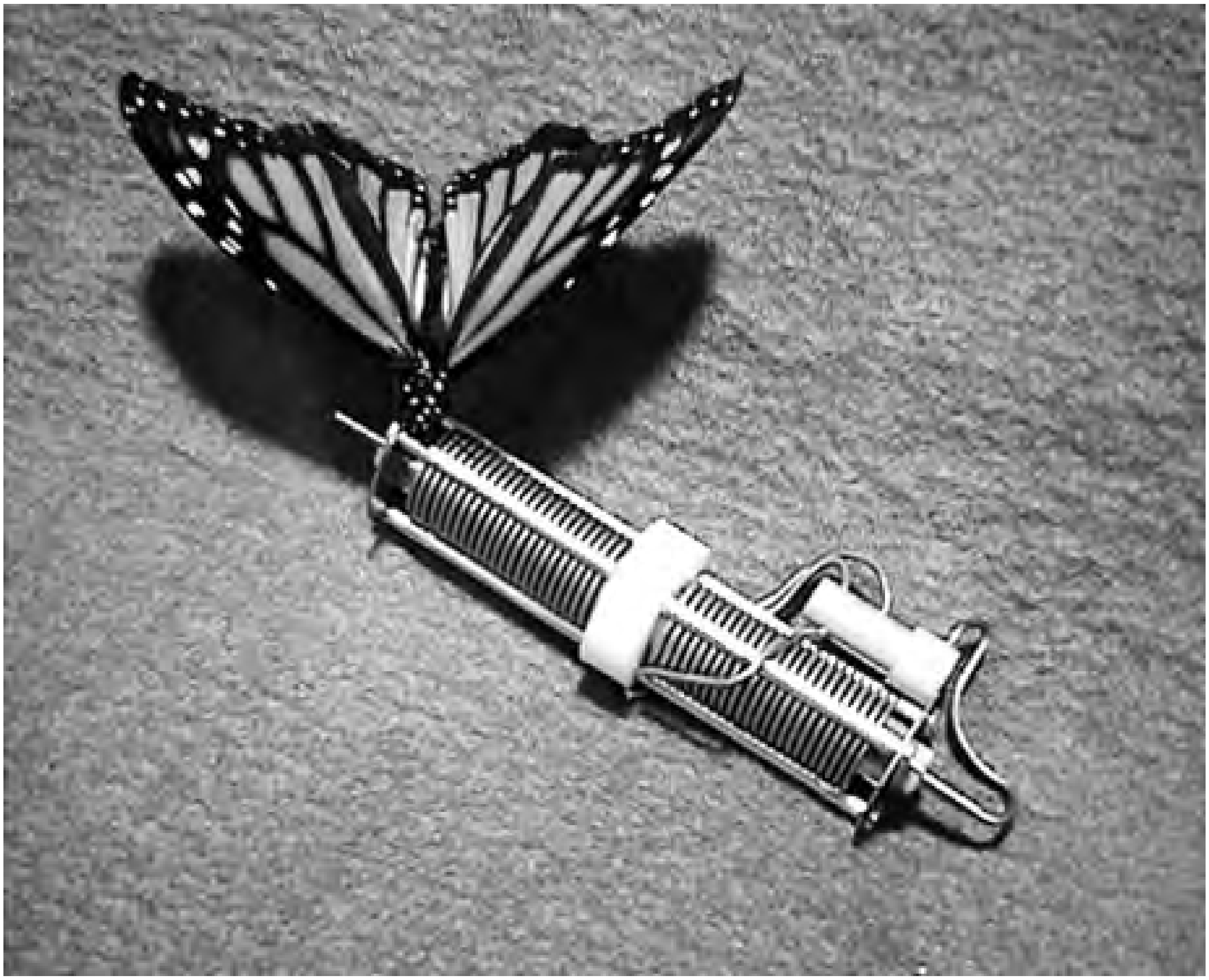

Figure 6. Milli-scaled Reciprocating Chemical Muscle.

Of primary interest is the relationship between fuel use (endurance) and the benefits derived from operating a higher pressures. Figure 7 shows that doubling the pressure provides four times the force available to do work while approximately doubling the linear travel of the muscle. For this discussion, the minor hysteresis differences between 30 psi and 60 psi will be ignored.

As mentioned earlier, certain wasp muscles only move on the order of two percent of the overall muscle length during each full beat of the wing. The empirical data shown in Figure 7 indicates that the 7.62 cm (3-inch) RCM is able to provide travel ranging from three to six percent of its length for pressures between 30 and 60 psi. This relatively large range of motion is accompanied by significant forces of approximately 2 to 6 pounds available to both the up beat and the down beat.

With this excess in available force to do work and a reasonable range of motion, the benefits of higher operating pressures become less attractive since twice the fuel will be consumed when operating the RCM at 60 psi than when it is operating at 30 psi. The RCM structures can also be less massive when designed for lower maximum pressures. So greater endurance and less weight direct the design toward lower operating pressures.

An important design consideration is the frequency of operation. As pointed out above, high flapping frequencies will result in more aerodynamic lift for a given wing size. Since the RCM is a reciprocating mechanical device, it has inertial limits to its maximum useful frequency of operation at a given size and mass. The inertia of the RCM moving masses necessarily limits the linear travel of the muscle due to the time required to accelerate those masses at mid stroke and decelerate them at the maximum stroke excursions. This, of course will be true for any reciprocating muscle. As the frequency of reciprocating motion increases, the travel distance will decrease while maintaining an average position at the center of its range of motion. This center will also correspond to the point of greatest linear velocity.

For a reciprocating muscle of given mass and force potential, increasing frequency will result in decreasing linear travel. Figure 8 shows the operational envelope for the milli-scaled RCM based on empirical data collected at an operating pressure of 40 psi. Note that the force to do work in flapping the wings remains essentially constant over the entire cycle, but as the frequency increases, the linear travel of the muscle decreases almost exponentially.

For a reciprocation frequency of 20 Hz, the maximum peak-to-peak excursion drops to about 0.05 inches (0.13 cm) which is only about 1.7 percent of the muscle length. This is just under the value reported for certain wasps as reported by Gilmour and Ellington (Gilmour[9], 1993), but it should be noted that the corresponding power available to do work is between 2.5 and 3 lbs! Because of the high power available, a mechanical transmission (fulcrum) of poor mechanical advantage can be used to convert this small range of motion into a large one while maintaining sufficient wing force in both up and down stroke. To the degree that the milli-scaled entomopter can be made to operate at lower beat frequencies with larger chord wings, the frequency of operation can be reduced, but the average power available to do work drops as the linear travel of the muscle is increased.

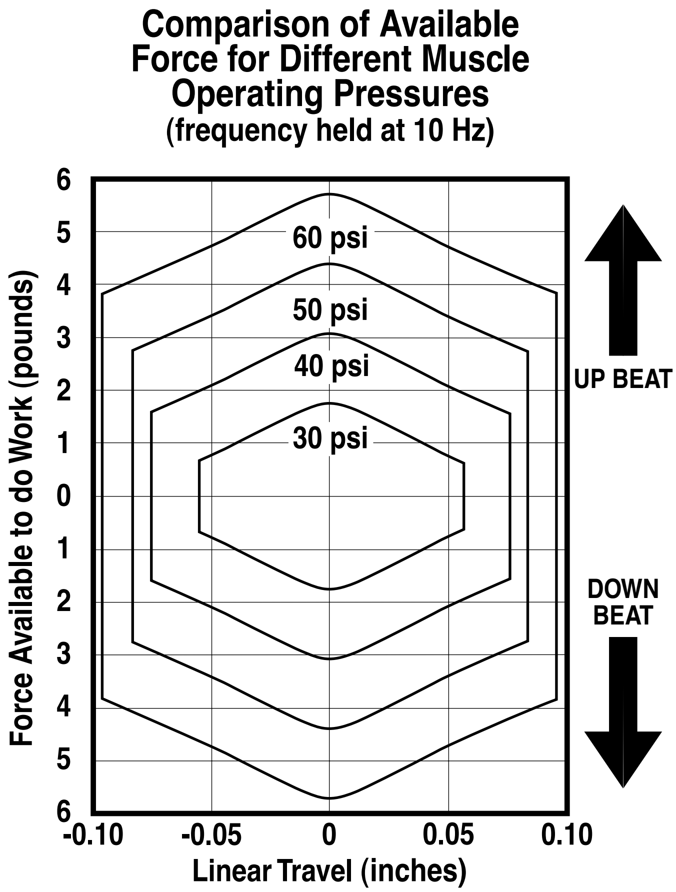

Figure 7. Comparison of Available Force for different muscle operating pressures.

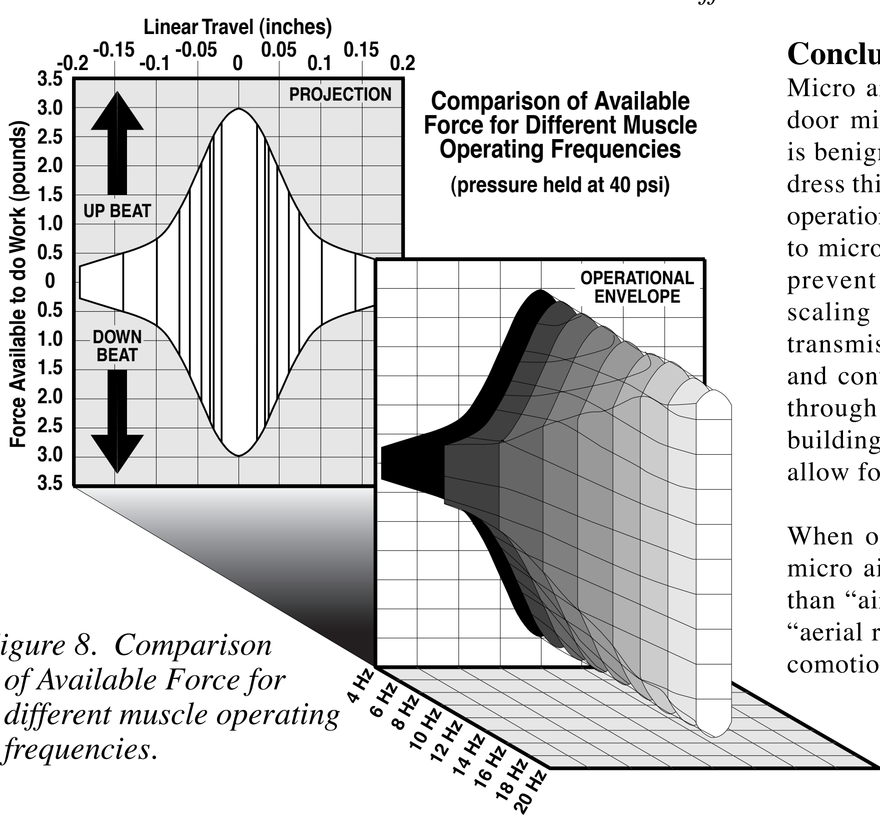

Figure 8. Comparison of Available Force for different muscle operating frequencies.

Conclusions

Micro air vehicles are best suited to indoor missions because the environment is benign and no other assets exist to address this area of reconnaissance. Indoor operations will have to be autonomous due to micro air vehicle size constraints that prevent it from carrying various non-scaling items such as lower frequency transmission systems. Also, command and control information can not be sent through most steel-reinforced concrete buildings with the required bandwidth to allow for teleoperation of the vehicle.

When operating autonomously indoors, micro air vehicles will have to be more than “air vehicles”, they will have to be “aerial robots” capable of multimode locomotion that will include not only flight but crawling. When in flight, they will have to be able to move slow enough to negotiate winding corridors, stairwells, and narrow openings. Slow flight for unobtrusive reconnaissance missions is best done with flapping-wing propulsors.

Near term propulsion for tiny multimode robotic vehicles will be fueled from chemical or fossil fuel sources. Electrical storage density is insufficient to support missions of reasonable endurance at this time. A reciprocating chemical muscle (RCM) has been developed and tested at a macro- and milli-scale for use in a mechanical insect called an "entomopter". The Entomopter uses a novel X-wing pair design that is resonantly driven by the RCM.

Empirical tests on the milli-scaled RCM show that it develops sufficient force and motion to drive the wings of an entomopter at frequencies necessary for flight. The characteristics of the RCM comport with those of insects, though currently at a larger "milli scale". In particular, a muscle extension/contraction range of 1.7 percent of the overall muscle length has been demonstrated at a reciprocating frequency of 20 Hz and a force available of between 2.5 and 3 lbs over the entire range of motion.

The design of the entomopter and its RCM have been tailored with size reduction in mind, such that MEMS implementations will be possible to further reduce size and final production cost.

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