Slow flight in the lower Mars Atmosphere in support of NASA science missions

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Abstract— **Slow flight on the planet Mars is difficult due to the rarefied atmosphere (a low Reynolds Number regime), the lack of oxygen to support combustive propulsion, low temperature, and the low speed of sound. Flight in the anoxic, low pressure, cold lower atmosphere of Mars will be explored and viable solutions based on the Entomopter (an insect-like flapping wing, crawling vehicle) posed. The problem of efficient lift generation and controllable flight will be discussed along with proposed solutions.**

Keywords- Mars; Entomopter; slow flight; reciprocating chemical muscle; unmanned aerial vehicle; UAV; autonomous flight; low Reynolds number; leading edge vortex; LEV

I. Introduction

The first serious look at flying on Mars was done in the mid 1970s. Since then there have been numerous studies and designs for flying aircraft on Mars. Because of the very low atmospheric density on Mars all of these conventional aircraft designs have come across the same limitation, in order to generate sufficient lift the aircraft must fly fast. That fact and the rough rock strewn surface of Mars makes it almost impossible to produce a conventional aircraft that can safely land and take off again. Therefore all previously proposed aircraft missions have been limited in duration to the amount of fuel the aircraft could carry for one flight.

The Entomopter concept is a potential way around this problem of having to fly very fast within the atmosphere of Mars. The Entomopter doesn't generate lift in the same fashion as a conventional aircraft. The Entomopter concept uses the same lift generating means that insects do on Earth to generate lift within the Mars environment. Unlike aircraft or birds, insects generate lift by the continuous formation and shedding of vortices on their wings. This vortex formation and shedding produces very high wing lift coefficients on the order of 5 compared to maximum lift coefficients of 1 to 1.2 for conventional airfoils. This very high lift generating capability is what allows insects to fly, hover and maneuver as they do. It is believed that their ability to generate these large amounts of lift is a Reynolds number based phenomena. As Reynolds number increases the ability is diminished. This high lift generating capability under low Reynolds number flight conditions poses an interesting solution to flight on Mars. Because of the low atmospheric density on Mars, a vehicle with a wing-span on the order of 1m would be in the same flight Reynolds number regime as most insects encounter on Earth. Because of this, it is conceivable to construct a vehicle that can fly near the surface of Mars (up to 100s of meters in altitude) while generating sufficient lift to allow it to fly slow, maneuver easily, and land. This realization is the genesis for the Entomopter concept for Mars.

For the Entomopter to work within the Mars environment it will need to be as lightweight and efficient as possible. This means that systems and devices on the vehicle will need to perform more than one task if possible. This multiple use philosophy has been integral to the design effort. It begins with the propulsion system. The engine will decompose hydrazine to provide the power to move the wings. After a thorough evaluation of a number of potential fuels, hydrazine was chosen as the best candidate because of its high energy density and the fact that it is a monopropellant. hydrazine rapidly decomposes when passed over a catalyst, thereby allowing for a low risk combustion scheme. The gas produced during the decomposition of hydrazine will be used to produce the wing motion through a patented device called a Reciprocating Chemical Muscle actuator. Once the exhaust leaves the wing actuator, it is used for several other tribological and navigational functions before being blown out the trailing edge and tips of the wings. This gas entrainment into the flow field over the wings enables vortex stabilization and greatly enhances the lifting capacity of the wing. Wind tunnel experiments on fixed wings at the Georgia Tech Research Institute (GTRI) have shown that with the trailing edge blowing wing lift coefficients of 10 or greater are achievable [1][2]. CFD runs corroborate the lift enhancement of the blown wing in both fixed and flapping modes [3]. In addition to lift enhancement, the trailing edge blowing will be used as a means of stability control for the Entomopter. The gas flow to each of the individual wings will be controlled to enable differential lift to be generated between the wings. To steer the Entomopter, lift variation through control of the trailing edge blowing will be used to provide banking and pitching moments.

This paper describes the analytical, computational and empirical analyses that have been performed under National Aeronautics and Space Administration (NASA) Institute for Advanced Concepts (NIAC) program funding to extend the terrestrial Entomopter design foundations begun as Georgia Tech Research Institute (GTRI) internal research and development (IRAD), Defense Advance Research Projects Agency (DARPA) feasibility, and Air Force Research Laboratory (AFRL) propulsion developments, into a parallel development scaled and modified for flight in the lower Mars atmosphere.

II. Present Approaches to Survey Mars

A. Ground Vehicles

The 1997 Mars vehicle Pathfinder progressed only 52 meters in 30 days because it had to await instructions from Earth 190 million kilometers distant. Each command took 11 minutes to travel between the two planets. It couldn't move any faster without risking collision with obstacles. Even reprogrammed or autonomous ground-limited rovers cannot negotiate large obstacles nor can they venture out into canyons. Because of their slow progress, these ground-based rovers must pick their way through the Mars environment, to avoid even relatively small (meter-sized) obstacles. A poor choice as to whether to go to the right of the left of a large obstacle could cost days of survey time if subsequent unseen obstacles are encountered which force the rover to retrace its path to the decision point and replan.

B. Air Vehicles

The desire to survey Mars surface from above has obvious advantages. The earliest Mars missions conducted surveys from orbit with high resolution imaging equipment. This stand-off distance precluded certain in situ measurements such as atmospheric sampling, surface sampling, and close inspection of surface features. Unlike ground-based surveyors, orbital surveyors could investigate vast areas of the planet's surface, but were unable conduct the intimate inspections that a ground vehicle could. Ideally, NASA wanted a Mars surveyor that would be capable conducting flying in the lower Mars atmosphere to inspect large areas while avoiding surface obstacles.

The notion of flight on Mars has been a subject of NASA contemplation since Werner von Braun conceived a rocket plane as a means of Mars exploration in 1953. In the 1970s Mars flight was revisited more seriously, being spurred on by the successes of the Viking Program.

One of the most studied airborne platforms for Mars is the airplane, with initial concepts dating back to the late 1970's. Flying an airplane on Mars represents a significant challenge, mainly because of the constraints posed by the Mars environment. The lift on a wing is proportional to the atmospheric density, velocity, and wing area. The Mars atmospheric density is extremely low (0.020 kg/m3), approximately 0.000143% that at the Earth's surface. In order to compensate for this, the wing area and/or the velocity must be increased to generate sufficient lift. Wing area, however, is limited by spacecraft packing, volume, and deployment constraints. Therefore, in order for flight to be feasible on Mars, the plane must travel at higher velocities to compensate for the lack of density and the constrained wing area. Also, the speed of sound on Mars is approximately 20% less than on Earth. Both of these factors combine to put the plane in a low Reynolds number, high Mach number flight regime which is rarely encountered here on Earth.

The high velocities limit imaging camera stability and resolution. Also, given the rocky Mars terrain, it is virtually impossible for a plane to land and take-off again, thus limiting a mission to a single flight.

"The NASA Dryden Research Center, Developmental Sciences, Inc., and the Jet Propulsion Laboratory (JPL) proposed unmanned aircraft designs for Mars exploration in 1977 and 1978. Their concept was a propeller-driven fixed wing aircraft fueled by hydrazine. A decade later, JPL sponsored a Mars airplane study in which Aurora Flight Sciences proposed the electrically propelled "Jason" aircraft. About the same time, Ames Research Center and Sandia National Labs conceived a high speed aerospace plane named AEROLUS. Unlike the earlier attempts to make a slow speed aircraft that would be deployed from an aeroshell after touchdown on the Mars surface, AEROLUS would make a direct atmospheric entry and then fly through the Mars atmosphere at hypersonic speeds" [3]. Throughout the 1980s and early 1990s, a number of studies were conducted looking at various approaches to flight on Mars.

Successes with the Mars Pathfinder and Global Surveyor programs renewed interest in Mars flyers for exploration. In 1995 NASA Dryden and Ames Research Centers once again considered unmanned aerial vehicles to extend the reconnaissance range of Mars landers. The new concept was to launch a small unmanned aerial vehicle (UAV) from the lander after it had landed on Mars' surface. The expendable, one-flight UAV would be electrically powered with rocket assisted takeoff.

The following year in 1996, the Ames Research Center proposed an unmanned Mars aircraft in response to a NASA Announcement of Opportunity for Discovery Exploration Missions. Ames' approach was to use a propeller driven, sailplane configuration called "Airplane for Mars Exploration" (AME).

On the following NASA Announcement of Opportunity for Discovery Exploration Missions in 1998, JPL submitted a proposal for a multiple glider system named, "Kitty Hawk" (see Fig 1). Being gliders, the vehicles were obviously limited in endurance, but benefited from the lack of weight and complexity associated with a propulsion system.

This would allow greater numbers of vehicles to be deployed during a single mission. NASA Ames also submitted a proposal to the 1998 Announcement for a motorized UAV named "MAGE", This aircraft was based on a hydrazine propulsion system.

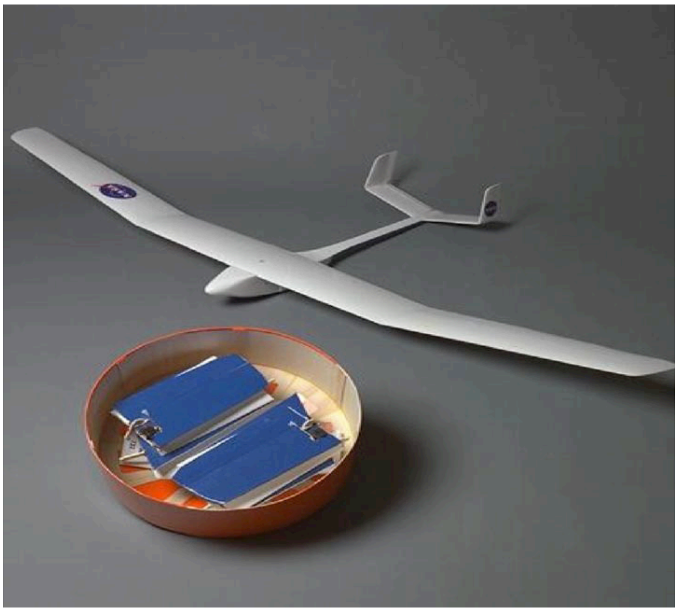

Figure 1. Kitty Hawk glider and folded version in aeroshell.

Figure 2. NASA Langley ARES full-scale and half-scale flight test vehicles.

Both concepts deployed from an aeroshell once it had become subsonic, approximately 12,000 meters above the Mars surface. As with all previous design concepts prior to 1999, neither concept was selected for implementation by NASA.

On February 1, 1999, NASA Director Daniel Goldin announced the "Mars Airplane Micromission," which would have been the first NASA micromission program to launch on an Ariane 5 rocket. The flight would have had the first Mars airplane arriving on Mars around December of 2003, coincidentally close to the hundredth anniversary of the Wright Brothers' first flight. Although conceptual designs of the plane were completed, the project was cancelled due to funding constraints.

Most recently, interest in a 2002 proposed NASA Langley proposal for a Mars flyer named "ARES" (Aerial Regional-scale Environmental Survey vehicle) has been rekindled (see Fig. 3)[4]. Companies such as Aurora Flight Sciences are proposing variants of this concept. ARES, upon entering the Mars atmosphere, would deploy from an aeroshell and complete its mission on the day of arrival. It would fly for about 500 km in one hour, making two U-turns along the way. This powered flight is necessarily fast (500 kph or 310 mph), because even as large as the proposed vehicle is, it will stall and crash if it flies slower. In fact, the destiny of ARES is to crash at the end of its maiden flight because surviving a 500 kph landing on the unprepared Mars surface will not be possible.

III. Slow Flight in Mars Atmosphere

Fixed wing vehicles must fly too fast in the thin Mars atmosphere to avoid stall (>350 kph for small vehicles) and besides passing over regions of scientific interest too quickly, they can not successfully land on the unprepared, boulder-strewn surface to refuel, harvest energy, or survive intact. "Lighter than CO_2 superpressure balloons have been proposed for flight on Mars, but these lack the ability to control their flight path because they are passive and at the mercy of the wind. Rotary wing vehicles have been proposed as a method for achieving slow controlled flight in the Mars atmosphere while allowing takeoff and landing. Unfortunately, the rarefied atmosphere brings with it a lower speed of sound. Rotor tips rapidly exceed the speed of sound at rotational speeds that are insufficient to lift the vehicle. This has forced those considering such an approach to use multiple smaller diameter articulated rotors or variable speed propellers. The redundancy of transmissions, motor casings, control mechanisms, and the structure to support the multiple rotor system are at the expense of performance (added weight). In addition, those techniques that rely on pitch changes in the rotor or the vehicle's fixed propeller's angle of attack, result in unwanted blade stall conditions due to the sensitivity of the low Reynolds number flow over these critical airfoils. This makes horizontal translation of the vehicle difficult [5]." Tests of a small unarticulated propeller in JPL's Mars atmosphere simulation chamber produced lift, but performance was disappointing compared to that which was originally predicted [6].

Another way to move air over a wing without fuselage translation is to move the wing relative to the fuselage and the surrounding air in a flapping motion rather than a rotary one. It could be argued that a flapping wing implementation is an inherently lower bandwidth system than one using a helicopter rotor or fixed pitch fans. 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. Because of the lower flapping frequencies required of a lower aspect ratio wider chord wing as opposed to a narrow high aspect ratio rotor, the tips do not approach supersonic speeds.

The lift of a flapping wing can be superior to that of a fixed or rotary wing, however it is still not optimal based on any conventional wing shape when operating in the atmosphere of Mars. Techniques such as active flow control of blown wing surfaces offer the potential to create significant added lift, thereby making a blown flapping wing plausible as a method for achieving relatively slow controlled flight in the lower Mars atmosphere. This can be done by "blowing" the surfaces of the wing to keep flow attached and 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).

Flapping wings are more survivable and robust in the presence of foreign object damage and grazing impacts than rotary wings. The flapping wing operates over a range of energies from zero at the top and bottom of the stroke, to maximum at mid-flap. Rotors and propellers on the other hand, concentrate all of their energy at their rotational frequency and tend to explode when coming in contact with objects. It is a well documented fact that birds and insects are able to sustain collisions with walls (or one another) without major damage when they become trapped indoors.

Further, the reciprocating nature of flapping wings lends itself to resonant operation with its accompanying energy efficiencies. Rotors can not be resonant in rotation and rotary wing designs tend to avoid resonance rather than capitalizing upon it. It should be noted that all insects store energy in a substance called "resilin" to recapture flapping energy in a resonant fashion. [7]

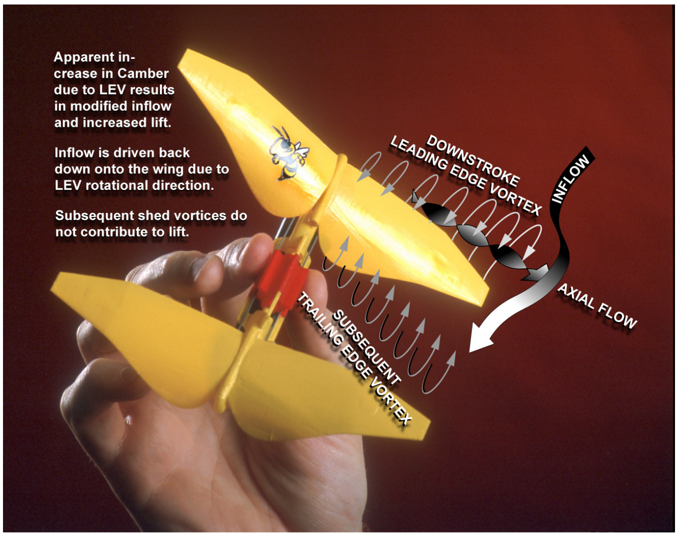

Figure 4. Flapping insect wing Leading Edge Vortex formation.

Another reason to consider flapping wing flight is benefits accruing from the leading edge vortex phenomenon. Flow visualization studies on the Hawk Moth Manduca sexta and a 10x scale mechanical model have identified dynamic stall as the high-lift mechanism used by most insects [8]. During the downstroke, air swirls around the leading edge of the airfoil and rolls up into an intense leading-edge vortex (LEV). The direction of circulation in the LEV augments the bound vortex and hence the lift. LEV grows until it becomes unstable at a distance of three to four chord lengths at which time it breaks away from the wing causing deep stall. Ellington and associates have shown that a strong axial (spanwise) flow in the LEV, when coupled with the swirling motion of the vortex, results in a spiral LEV with a pitch angle of 46 degrees across the surface of the flapping wing [8, 9, 10, 11]. The axial flow convects vorticity out toward the wing tip, where it joins with the tip vortex and prevents the LEV from growing so large that it breaks away (see Fig. 4). Thus stabilized, the LEV prolongs the benefits of dynamic stall for the entire downstroke. Helicopter rotors also experience spanwise pressure gradients, but these beneficial large-scale axial flows have not been observed [12], leading one to surmise that resonant flapping wing solutions in the rarefied Mars atmosphere will be more successful in producing required lift than nonresonant rotary wing attempts [5].

IV. The Mars Entomopter

A patented [13][14] micro air vehicle (MAV) has been developed for terrestrial applications (especially indoor flight) which uses biologically inspired design features that are married with circulation control techniques to create a flapping wing vehicle capable of abnormally high coefficients of lift at low Reynolds number. This is exactly what is needed for slow flight on Mars. This micro air vehicle known as the Entomopter (*entomo* as in entomology + *pteron* meaning wing, or a "winged insect machine") is designed to fly in the same Reynolds number regime on Earth as would be encountered in Mars lower atmosphere were the Entomopter to be scaled up from a 15cm wing span to a 1 meter wing span. NASA recognized that the Entomopter's ability to fly in low Reynolds number conditions without the need for air-breathing propulsion made it a natural candidate for flight in Mars' rarefied atmosphere, albeit in a larger incarnation. Unlike fixed wing flyers, an Entomopter-based Mars surveyor would be able to cover a wide area while still being able to fly slowly and return to a refueling rover to prolong the science missions.

The Entomopter began as a biologically inspired design, but rather than attempting to replicate biological kinematics and aerodynamics, improved systems have been devised to leverage what is observed in biological systems to produce a machine that is manufacturable, controllable, and able to generate the power necessary to fly from onboard energy sources.

The LEV produced by a pair of 180° out-of-phase flapping wings is modulated by circulation controlled airfoils that use waste gas from the Reciprocating Chemical Muscle motor that is able to operate anoxically in the 95.32% CO_2 Mars atmosphere.

Research [1][2] has indicated that active circulation flow control (blowing of wings) can tremendously increase the lift coefficient (C_L) for a fixed wing in steady flight by a magnitude of more than 5.

An assessment of the lift increase on Entomopter by computational fluid dynamics (CFD) [3]. The circulation control of a flapping wing will not only help keep the leading edge vortex attached for longer part of the flapping cycle, but will also avoid the flow separation thereby reducing the pressure drag. The circulation control will move the aft stagnation point from trailing edge to the lower surface and thus increasing lift tremendously. Figure 5 is a CFD case showing effects of the flapping Entomopter wing with (top) and without (bottom) circulation control.

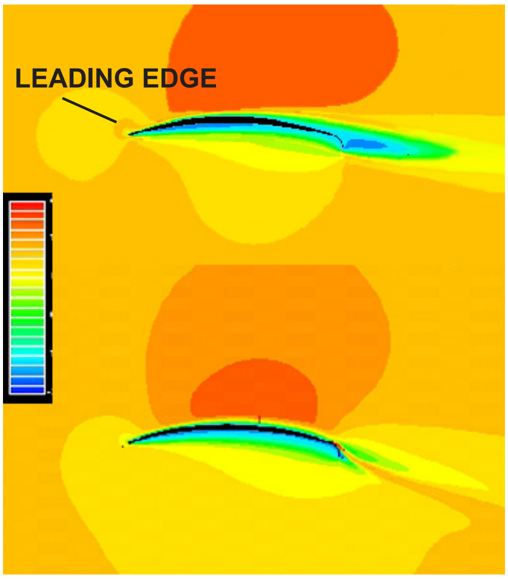

Figure 5. CFD run showing effect of circulation control to change pressure distribution.

Key to the use of active flow control in the flapping wing of the Mars Entomopter is the fact that the waste gas produced by the Reciprocating Chemical Muscle is used as a modulated gas source to effect this control scheme by intelligently venting the gas from the outer aft wing sections and the tips, thereby entraining the flow to induce it to stay attached longer.

Figure 6. Entomopter preparing to land on its refueling rover to extend mission endurance.

The energy cost of this approach is minimal since the waste gas product of the Reciprocating Chemical Muscle has already been used to flap the wings and would otherwise be jettisoned. In fact however, this waste gas is used seven times for different applications before it is finally jettisoned. By modulating the mass flow from the four winglets that comprise the two Entomopter wings (shown in Fig. 4), differential C_Ls can be generated to create moments that affect all degrees of Entomopter freedom (pitch, roll, yaw, heave, and even thrust) on a beat-to-beat basis.

The Hawk Moth (Manduca *sexta*) was chosen as a baseline model for the wing aerodynamics. The University of Cambridge in England was part of the initial Entomopter design team because it had studied Hawk Moth wing aerodynamics for more than a quarter of a century and had produced seminal works describing the Leading Edge Vortex and its effects on the flapping wing. The flapping mechanism for the Entomopter has been extended beyond that of the Hawk Moth to provide a resonant single-piece construction that takes advantage of torsional resonance in the Entomopter fuselage to recover flapping energy common to flying insects that temporarily store potential energy in either muscles or exoskeletal parts (resilin).

In the terrestrial version, and potentially the Mars version, the same structure that provides wing flapping also scans a frequency modulated continuous wave (FMCW) ultrasonic beam to provide front, side, and down-looking range measurements for obstacle avoidance and altimetry. It also has the potential to track and follow free-moving agents (other Entomopters or rovers) in a fashion similar to that employed by bats. This FMCW active sonar sensor derives its transmission energy from the waste gas evolved within the Reciprocating Chemical Muscle.

Stability and control in flight as well as navigation are achieved by actively modifying the lift of each wing on a beat-to-beat basis using pneumatic control of the atmospheric gases circulating over the beating wing. Also, as demonstrated in GTRI's wind tunnels, where pneumatically controlled wings have been shown to develop positive lift at negative angles of attack (α) as great as -70° [1][2], Entomopter wings (unlike those of the Hawk Moth) should be able to generate positive lift not only the downbeat but the upbeat as well. These wind tunnel tests have shown that coefficients of lift exceeding the theoretical maximum by 500% for the given wing shape can be achieved without the complexity of active angle-of-attack modulating mechanisms.[5]

A chemically fueled Reciprocating Chemical Muscle has been designed and is in its fourth generation of development. This actuator system has demonstrated 70 Hz reciprocation rates with throws and evolved power levels necessary to support flight of a fully autonomous Entomopter system [15]. The Reciprocating Chemical Muscle uses the energy locked in various monopropellants to produce reciprocating motion for propulsion as well as waste gas products for the operation of gas bearings, an ultrasonic obstacle avoidance ranging system, and full flight control of the vehicle. For the Mars Entomopter, hydrazine is the fuel of choice for missions lasting less than one year. For short and moderate mission duration, it is better to carry the fuel directly in a storage tank instead of trying to manufacture it on Mars. If a mission duration of a year or longer is proposed, then producing the fuel on Mars may have an advantage. If fuel is brought directly from Earth, additional, more energetic fuels too difficult to manufacture on Mars can be considered.

V. Conclusion

Slow flight is highly advantageous to the conduct of science missions on Mars where sensor dwell time and proximity are essential to many experiments. Slow flight on Mars by fixed wing vehicles is impractical due to the rarefied atmosphere. Slow fight is possible by means of superpressure balloons and rotorcraft, but these methods lack control and efficiency. Circulation controlled flapping winged vehicles promise to provide the high lift and controllability lacking in other aerial vehicle types.

The flapping wing Entomopter which was originally developed for terrestrial indoor MAV missions, incorporates the aerodynamics and fuel use economies necessary for use as a Mars surveyor. In addition, its Reciprocating Chemical Muscle power plant does not require oxygen to operate. Prototype Reciprocating Chemical Muscles have been demonstrated in the laboratories at the Georgia Tech Research Institute and exhibit adequate reciprocation speed, throw, and power to support efficient Entomopter flight both on Earth and Mars (when scaled up).

The Entomopter's abnormally high coefficient of lift resulting from its circulation controlled (blown) flapping airfoils, can provide the lift needed for sustained slow flight in the lower Mars atmosphere.

References

[1] Englar, Robert J., Smith, Marilyn J., Kelley, Sean M., and Rover III, Richard C., "Development of Circulation Control Technology for Application to Advanced Subsonic Transport Aircraft, Part I: Airfoil Development" AIAA Paper No. 93-0644, Log No. C-8057, published in AIAA Journal of Aircraft, Vol. 31, No. 5, pp. 1160-1168, Sept-Oct 1994.

[2] Englar, Robert J., Smith, Marilyn J., Kelley, Sean M., and Rover III, Richard C., "Development of Circulation Control Technology for Application to Advanced Subsonic Transport Aircraft, Part II: Transport Application" AIAA Paper No. 93-0644, Log No. C-8058, published in AIAA Journal of Aircraft, Vol. 31, No. 5, pp. 1169-1177, Sept-Oct 1994.

[3] Colozza, A., Michelson, R.C., et al., "Planetary Exploration Using Biomimetics - An Entomopter for Flight on Mars," Phase II Final Report, NASA Institute for Advanced Concepts Project NAS5-98051, October 2002

[4] http://marsairplane.larc.nasa.gov/index.html (retrieved 25 April 2009)

[5] Michelson, R.C., Naqvi, M., "Extraterrestrial Flight (Entomopter-based Mars Surveyor)," von Karman Institute for Fluid Dynamics RTO/AVT Lecture Series on Low Reynolds Number Aerodynamics on Aircraft Including Applications in Emerging UAV Technology, Brussels Belgium, 24-28 November 2003

[6] Kroo, I. and Kunz, P., "Mesoscale Flight and Miniature Rotorcraft Development," Fixed and Flapping Wing Aerodynamics for Micro Air Vehicle Applications, T. J. Mueller (Ed.), Prog. in Astronautics and Aeronautics, Vol., 195, 2001.

[7] Michelson, R.C., Reece, S., "Update on Flapping Wing Micro Air Vehicle Research - Ongoing work to develop a flapping wing, crawling Entomopter," 13th Bristol International RPV/UAV Systems Conference Proceedings, Bristol England, 30 March 1998 - 1 April 1998, pp. 30.1-30.1

[8] Wilmott, A.P., Ellington, C.P., and Thomas, A.L.R., "Flow Visualization and Unsteady Aerodynamics in the Flight of the Hawk Moth Manduca Sexta," Philosophical Transactions of the Royal Society B, Vol 352, 1997, pp. 303-316.

[9] Ellington, C.P., van den Berg, C., Willmott, A.P. and Thomas, A.L.R., "Leading-edge vortices in insect flight," Nature 38:D 1996, pp. 626-630.

[10] van den Berg, C. and Ellington, C.P., "The Vortex Wake of a 'Hovering' Model Hawk Moth," Phil. Trans. R. Soc. Lond. B, 352, 1997, pp. 317-328.

[11] van den Berg, C., and Ellington, C.P., "The Three-Dimensional Leading Edge Vortex of a 'Hovering' Model Hawk Moth," Philosophical Transactions of the Royal Society B, Vol 352, 1997, pp. 329-340.

[12] De Vries, O., "On the Theory of the Horizontal-Axis Wind Turbine." Annual Review of Fluid Mechanics, Vol. 15, 1983, pp. 77-96.

[13] "Entomopter and Method for Using Same", U.S. Patent No. 6,082,671, July 4, 2000

[14] "Reciprocating Chemical Muscle (RCM) and Method for Using Same", U.S. Patent No. 6,446,909, September 10, 2002

[15] Michelson, R.C., Amarena, C.S., "4th Generation Reciprocating Chemical Muscle: Reciprocating Chemical Muscle (RCM) for Specialized Micro UAVs and Other Nonelectric Anaerobic Aerospace Actuation Applications", Prepared under Grant No. F086300010007 to the U.S. Air Force Research Laboratories (AFRL/MNGN), October 15, 2001