EXTRATERRESTRIAL FLIGHT
(*Entomopter-Based Mars Surveyor*)

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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 mission endurance and navigation apart from artificial cues such as GPS will be discussed along with proposed solutions.

1.0 WHY FLY ON MARS?

The 1997 Mars vehicle Pathfinder progressed only 52 meters in 30 days because it had to await instructions from Earth 190 million km away. Each command took 11 minutes to travel between the two planets. It couldn't move any faster without risking collision with obstacles. A flying surveyor would serve to expand the area of regard for a ground-limited rover which cannot negotiate large obstacles nor can it venture out into canyons.

During the mid 1990s the Defense Advanced Research Projects Agency began considering the feasibility and uses for tiny terrestrial flying vehicles on the scale of small birds and insects. In response to this interest, the notion of the 'Entomopter' (*entomo* as in entomology + *pteron* meaning wing, or a "winged insect machine") was borne as an internal research and development (IRAD) program within the Georgia Tech Research Institute (GTRI). The Entomopter will extend a rover's eyes and will allow the rover to choose its path ahead more intelligently. The rover will be able to move more rapidly with less risk. The result will be a greater science return per unit time. With Entomopter augmentation, the field of regard for the rover will be swaths of hundreds of meters for close inspection/sampling, and to the horizon for high perspective line-of-sight remote inspections. In addition, the Entomopters will be able to perform scientific investigations that otherwise could not be attempted by a rover (e.g., cliff side inspections or magnetic profiling), or which would be too time consuming (e.g., wide area geologic characterization such as the mapping fault lines or strata). [1]

The environment on Mars makes the ability to fly conventional aircraft much more difficult than on Earth. The main obstacle is the very low atmospheric density. This low density requires an aircraft to fly within a very low Reynolds number/high Mach number regime unlike any experienced by present day aircraft. This low-density atmosphere translates into flight Reynolds numbers for the

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wing of around 50,000 and for a propeller of around 15,000. The Reynolds number is a ratio of the inertia forces to the viscous forces for a fluid flow. As a practical matter, if the Reynolds number of two vehicles is similar then the aerodynamics of the vehicles should be similar.

Reynolds Number = (Density)•(Characteristic Length)•(Velocity) ÷ (Viscosity)

With a low flight Reynolds number, a conventional aircraft has a number of aerodynamic issues that severely limit its performance. The main issue is laminar separation of the boundary layer. This separation can cause loss of lift resulting in a catastrophic loss of the aircraft. To avoid this flow separation, the boundary layer must be transitioned from laminar to turbulent. Within low Reynolds number flow it is very difficult (if possible at all) to transition to a turbulent boundary layer. This flow restriction is a major factor that severely limits the flight envelope and capabilities of a conventional aircraft. [1]

2.0 CHALLENGES TO MARS FLIGHT

Besides the alien physical environment of Mars (reference atmospheric conditions on the Mars surface are: density = 0.0000279 slugs/ft3, atmospheric pressure = 0.11475 psia, temperature = 243°K (-30°C), only 37% of Earth's gravity, and an almost non existent magnetic field), the composition of the atmosphere is almost entirely Carbon Dioxide (CO_2) 95.32%. The next greater constituents are Nitrogen (N_2) at 2.7%, Argon (Ar) at 1.6%, and Oxygen (O_2) at 0.13%. With only one tenth of one percent atmospheric O_2, conventional combustion is not feasible even with multiple stages of super-charging, so traditional high energy internal combustion propulsion systems are useless. With a weak and anomalous magnetic field and no man-made global positioning reference, navigation is also problematic. In summary, not only is it difficult to fly on Mars, but it is difficult to power a flying vehicle and it is difficult to find one's way once airborne.

Although conventional flight may be difficult under such low Reynolds numbers, insects have succeeded in efficiently exploiting the low Reynolds number flight regime. The mechanisms in insect flight are significantly different of conventional aircraft and are not completely understood. First investigated in 1994 by Charles Ellington at the University of Cambridge, the main mechanism for lift generation on an insect wing was determined to be vortex interaction caused by the flapping motion. This interaction is dependent on the Reynolds number. As the Reynolds number increases, this lift-producing mechanism diminishes. Experiments have shown that flow on an insect wing at Reynolds numbers greater than 10^6 there is a crisis of flow over the wing caused by early boundary layer separation. As the Reynolds number decreases around 10^4 this crisis is greatly reduced and the flow displays a smoother shape. At Reynolds numbers of 10 to 10^3 flow separation is absent. As the Reynolds number decreases, other lift-producing mechanisms such as differential velocity and drag, and other boundary layer effects may come into play. These Reynolds number effects are a main reason for the difference in the flight characteristics between birds and insects. A diagram of this vortex generation is shown in Figure 1. This vortex generation is not completely explained by present theory. However, it is believed that it is caused by the separation of flow over the leading edge of the insect wing. [2, 3]

Flapping alone is not sufficient to generate the maximum vortex circulation possible for achieving maximum lift. This limit on reaching the maximum circulation levels is due to the flapping rate of the wings and the time delay required for the growth of the vortex circulation. It is believed that some insects overcome this issue by the interaction of the insect wing with the vortex as it is shed.

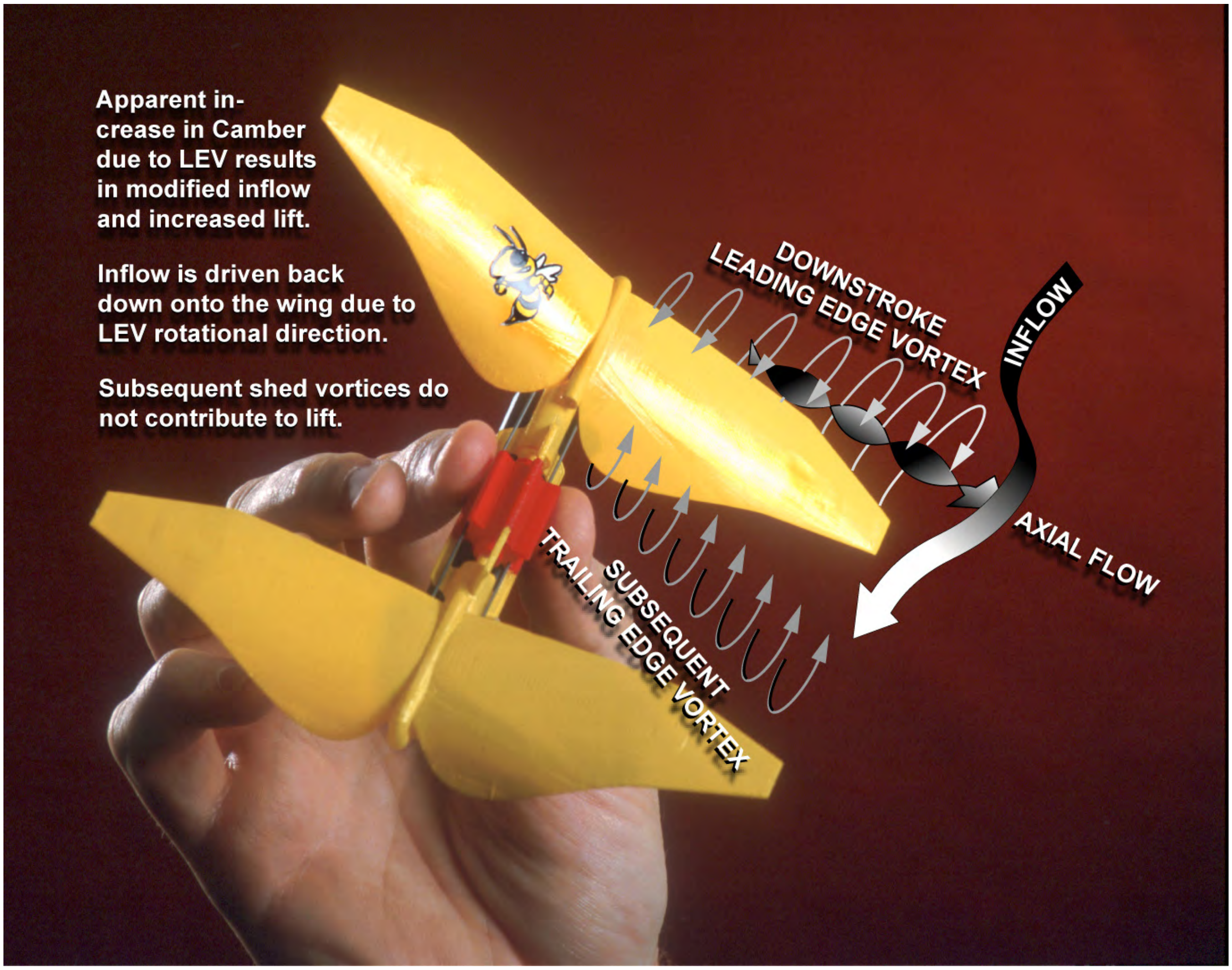


Figure 1. Flapping Insect Wing Leading Edge Vortex Formation.

Unlike conventional airfoils, there is no dramatic reduction in lift after the wing achieves super critical angles of attack. This suggests that flow separation prior to the vortex formation does not occur. It is believed that this resistance to flow separation during vortex formation is due to the low flight Reynolds number and the high wing flap rate of 10^{-1} to 10^{-2} seconds. [1]

An additional lift producing mechanism for which an insect avail itself is the Magnus force. This is the force generated due to the rotational motion of the wing during each flap. This force is responsible for a curved “hook shot” in golf. Insect flight control is achieved by modifying these lift-producing mechanisms from wing to wing. Based on these mechanisms insects are capable of achieving lift coefficients on the order of 5. This high lift coefficient and the forces that are used to generate it are what allows them to fly in a manner that is different from conventional aircraft or birds. It also gives them the ability to hover, rise vertically and change direction instantly. [2, 3]

An Entomopter on Mars, with an approximate 1-meter wingspan, would be operating with a Reynolds number similar to that of terrestrial insects. Flight within the Mars environment can take advantage of the lift-producing mechanisms of insects with a vehicle of significant size and operating close to the surface. This combination of physics and environmental conditions may lead to an elegant way of producing an aircraft to fly on Mars. Mars has an additional advantage in that the gravitational force is 37% of that on Earth. This reduced gravity enables thinner, lighter structures to be used, which can be an important factor in the feasibility of this concept.

Biologically inspired flapping wings may have advantages in the rarefied lower Mars atmosphere, but a high energy density power source will be required to flap these wings. A Reciprocating Chemical Muscle (RCM) has been developed which requires no atmospheric oxygen to operate. This device has been demonstrated in the laboratory to have the power-to-weight ratio and energy density to propel a flapping wing Entomopter.

The RCM is an anaerobic, ignitionless, catalytic device that can operate from a number of chemical fuel sources. It 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.

The implementation of an RCM is motivated chiefly by the basic necessity for very high rate of energy release from compact energy sources. Electrically-driven systems suffer from the poor energy density of batteries, while electrical actuators are typically dense (heavy), or suffer from insufficient force and motion as in the case of electrostatic or piezoelectric propulsors. To increase motion, piezoelectric ceramics can be stacked, but this leads to greater weight, stiffness, and often higher required voltages. Rheological fluids can be slow to respond and will therefore be difficult to use with flapping wing implementations requiring beat frequencies of 20 to 50 Hz. Faster acting polymeric muscles have been demonstrated, but require high actuation voltages, dictating the need for power conversion circuits which add weight and loss to the already heavy onboard battery pack. Actuators of NITINOL wire are totally out of the question due to the significant current requirements and variable performance under environmental extremes. Although small amounts of solar power could be harvested to support the electrically-driven actuators and motors mentioned, the solar flux usable on Mars is quite limited due to the distance of the planet from the Sun, the present state-of-the-art in solar cell conversion efficiency (approximately 28% for the best space-qualified cells at the time of this writing). At least one of the fuels with which the RCM operates can be synthesized from constituents of the Mars environment, thereby opening the door to energy harvesting for Entomopter sustainment. Studies [1] have shown that this is practical for missions exceeding 300 days.

The challenges to slow flight on Mars with respect to aerodynamics and navigation are yet to be solved to the degree that the propulsion system has been investigated. The following sections will address these two areas in more detail.

3.0 HOW BEST TO FLY IN THE MARS ENVIRONMENT

Why Flapping Wing Flight? 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. 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. [4]

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 (FOD) 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. [5]

There is another reason to consider flapping wing flight, and that is due to 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. [6] During the downstroke, air swirls around the leading edge of the airfoil and rolls up into an intense leading-edge vortex. 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 [7, 8, 9, 6]. 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. 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 [10], 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.

AERODYNAMIC DESIGN OF A MARS ENTOMOPTER

Fixed wing aircraft don't have the capability to hover, except in very few cases, where a propulsive device can support the weight of the vehicle. In order to maintain steady level flight, fixed wing aircraft have to fly at a certain speed with a certain angle of attack. The airfoil and wing characteristics are determined by the values of a lift curve slope and value of C_{Lmax}. At every flight condition, the basic weight and lift balance while drag and thrust balance. In propeller driven aircraft, thrust is normally not a criterion, hence, the power required must be balanced by power available. The normal relation which must hold in vertical direction is as follows:

$$\text{Lift} = L = \text{Weight} = W$$

Where

$L = 1/2 \cdot \rho \cdot V^2 \cdot S \cdot C_L$
$\rho =$ Air Density
$V =$ Free Stream Velocity
$S =$ Wing Area
$C_L =$ Non Dimensional Lift Coefficient

Here, air density represents the atmosphere and altitude where aircraft is operating, wing area is a size representation (just like a scaling parameter), and Lift Coefficient represents the Geometric characteristics of the wing including the airfoil shape, sweep, camber, angle of attack, taper, etc. Basically lift coefficient is defined as

$$C_L = C_{L\alpha} \cdot \alpha$$

Where

$C_{L\alpha} =$ Lift Curve Slope
$\alpha =$ Angle of Attack

Lift Curve Slope is dependant on Reynolds Number, and Mach Number. The Reynolds number takes into account the viscosity and friction effects, while Mach Number takes accounts for compressibility. There is a minimum value of airspeed which must be maintained in order to achieve flight such that weight and lift are balanced, and that is dictated by the value of C_{Lmax}. Based on particular airfoil and wing characteristics, this is determined by the maximum angle of attack at which the flow no longer remain attached to the surface, and the ensuing flow separation causes adverse pressure gradients which reduces lift and dramatically increases drag. The minimum speed is defined as the "stall speed",

$$\text{Stall speed} = V_{stall} = (2W \div (\rho \cdot S \cdot C_{Lmax}))^{1/2}$$

The mission dictates the desired maneuverability of an aircraft and its operating velocities. Since velocity and C_L are interrelated by weight, lift, and balance, if velocity is known, we can determine the value of C_L required for that specific flight condition. Furthermore, based on the Reynolds Number and Mach Number, we can translate the C_L value into the desired angle of attack.

Micro air vehicles (MAV) operate best indoors where conditions are benign however this mission space requires a high degree of maneuverability and low speed operation. The C_{Lmax} acts as the maximum achievable C_L. But it must be kept in mind that an increase in angle of attack causes C_L to increase, which is also accompanied by a dramatic increase in drag. Fixed wing aircraft employ high lift devices at take off and landing to reduce their stall speeds, so that take off and landing velocities remain low. In order to achieve a low airspeed mission, the wing must operate at high values of C_L, and that is a basic reason for preferring flapping wing designs over fixed wing designs for indoor micro air vehicle operations.

Flapping wing can achieve much higher values of C_L due to the formation of a leading edge vortex creating a dynamic stall phenomenon. Some also have the unique capability of hovering, which can not be achieved in conventional fixed wing airplanes. In addition to operation at much lower speeds due to high C_L values, flapping wing machined also possess much higher maneuverability than their fixed wing counterparts. Generally the excellent values of C_{Lmax} for fixed wing aircraft (without the use of high lift devices) range from 1.2 to 1.4, and operation at these high C_L values require very high aspect ratio wings to minimize the effects of induced drag, as in the case of U-2 aircraft. U-2 has a aspect ratio of 14 to 15, as it was designed to operate at velocities close to stall, where induced drag effects were very prominent. The flapping wing vehicle however generates much higher values of C_L. A mechanical model dynamically scaled to the Reynolds Numbers appropriate for small insects such as Drosophila was investigated by Dickinson [11]. The values of C_L produced are shown in Figure 2, which show a maximum C_L value achieved close to 3.0. The reason for such higher angle of attacks in Figure 2 is the presence of the leading edge vortex.

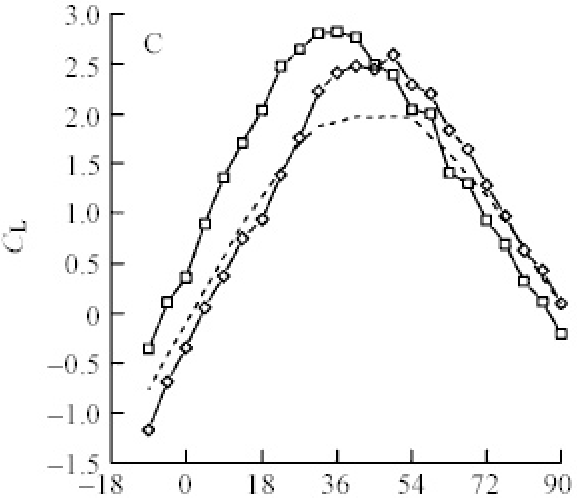


Figure 2. Lift Coefficient Vs Angle of Attack curve for Flapping wing Flight [11]

Although tremendous effort and research is being made to design a flapping wing micro air vehicle for terrestrial use, no realistic numerical tool or simulation environment for design of such vehicles has yet to be formulated. Most of the data has been obtained either by Computational Fluid Dynamics (Navier Stokes solution), or empirical data (e.g., [11]). The basic hindrance has been the replication of the complex kinematics involved in insect and bird flight.

Now, in case of Entomopter design, feasibility is further constricted by the lift constraints and high values of lift coefficients required in the thin atmosphere of Mars. Although, the gravity is also reduced on Mars, reduced values of atmospheric density require much higher coefficients of lift than at the same altitude on Earth. For a fixed wing airplane, very high values of dynamic pressure (higher velocities) are required to lift a mass on Mars, which would seem to contradict the basic premise of Entomopter use as a Mars surveying platform.

The specifications of baseline design for the Mars Entomopter and atmospheric values are:

Wing Span = 1m
Aspect Ratio = 5.874
Wing Area = S = 0.546 sq m
Wing Planform is approximated by the following polynomial
$c(r) = (6.9105r^5 - 19.883r^4 + 21.551r^3 - 11.177r^2 + 2.3791r + 0.3395) \bullet span/6.56$
Mars Density = ρ = 0.0000279 Slugs/ft^3
Atmospheric Pressure = P_{atm}= 0.00807 kg/sq cm (0.11475 psia)
Temperature = T = 244° K

Now operating velocity can be plotted against required values of C_L to support different payload weights. The Figure 3 depicts the trends for vehicle weight of 2, 3, 4, and 5 Mars lb weight. Since the gravity at Mars is approximately 37% of earth's value, 1 kg of weight at Mars can be considered equal to 2.7 kg on Earth.

It can be seen that for a nominal weight of 3 to 4 lbs (1.36 - 1.81 kg) and operating speed of 100 ft/sec (30.48 m/s), one would need lift coefficients in excess of 8.0. Such values are not attainable by conventional flapping wing aircraft, so lift augmentation will be required. Before going into the details of how lift coefficient values are augmented in the Entomopter, it is pertinent to mention the characteristics of baseline design chosen for the Entomopter.

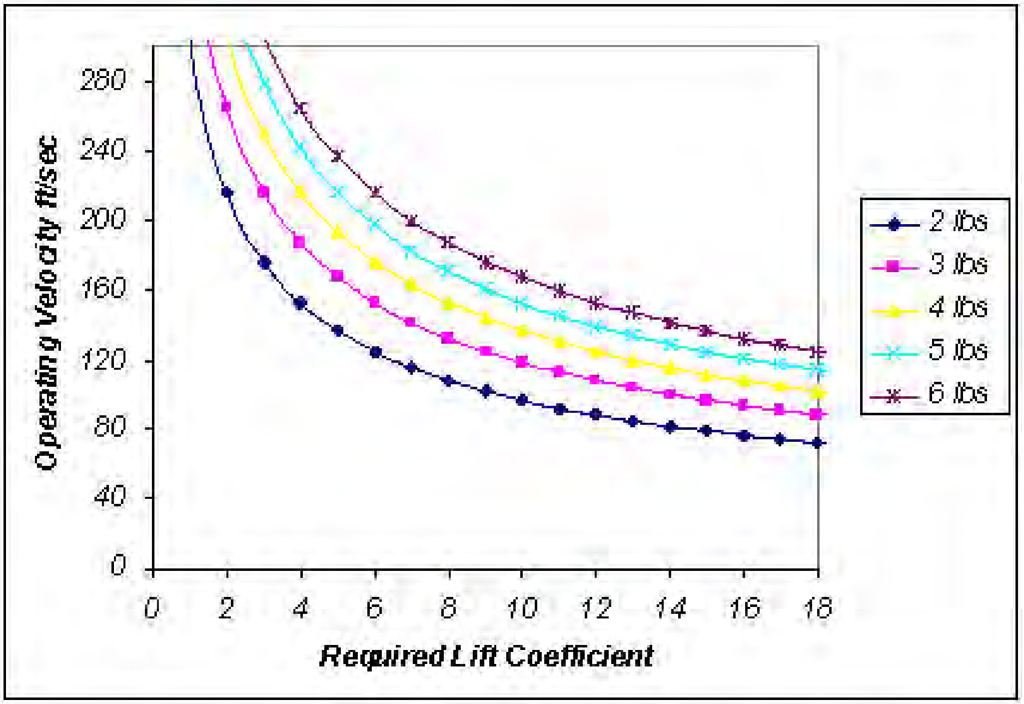


Figure 3. Entomopter flight speed vs C_L required curves for different vehicle weights.

Entomopter uses an X wing design configuration with two sets of wings. The traditional flapping found in nature has both sides of wing flapping in the same direction, however, in x-wing configuration, once one side flaps up, the other side flaps down, and vice versa. This configuration is not only easier to model and fabricate, but also can be easily incorporated with the Reciprocating chemical Muscle (chosen propulsive mechanism for Entomopter). The X-wing configuration uses two wings, and the flapping of each wing is equal and opposite in direction to the other, hence alleviating the rolling moment generated. In addition to these benefits and simplifications, the aerodynamic of X-wing would have some peculiarities which must be addressed for realistic modeling:

(a) The vortex shed by front wing, will interact with the aft wing, which might reduce its thrust and lift generation capabilities in addition to increasing the harmonic content and vibrations.

(b) Since the efficiency of aft wing may be affected by the vortex wake interaction of front wing, it will not be able to nullify the rolling moment generated by front wing, so this might require different configurations for the front and rear wings (twist, span, α, etc.), or different degrees of C_L augmentation.

(c) Placement of wings on fuselage and their axes of rotation will be key variables affecting the amount of lift generated, so the number of variables is increased for parametric analysis.

As pointed out by Figure 3, C_L values in excess of 8.0 are required for Entomopter's operation on Mars. Research [12, 13] has indicated that active circulation flow control (blowing of wings) can tremendously increase the lift coefficient for a fixed wing in steady flight by a magnitude of more than 5.

Since, no numerical formulation exists for employment of active flow control on a flapping wing, an effort was made to assess the lift increase on Entomopter by computational fluid dynamics (CFD). [1] The circulation control on 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 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 4 is a CFD case showing effects of the flapping Entomopter wing with (top) and without (bottom) circulation control.

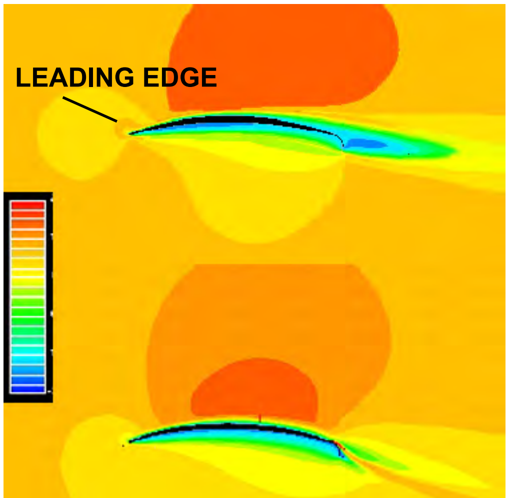


Figure 4. CFD run showing effect of circulation control to change pressure distribution.

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.

The 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, 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 formulation given by [14] was utilized in [1] for flapping wing aerodynamics and are given as follows:
(*details of this formulation are beyond the scope of this paper– see* [1] *for a discussion and derivation of these equations*):

$$\begin{aligned}\mathrm{Cl}(\phi,t) = {} & \mathrm{Cl\theta 0}(\phi)\cdot\alpha 0(t) + \left(\mathrm{Cl\theta c}(\phi)\cdot\cos\left(\omega\cdot t+\phi\alpha(t)\right) + \mathrm{Cl\theta s}(\phi)\cdot\sin\left(\omega\cdot t+\phi\alpha(t)\right)\right)\cdot\alpha 1(t) \ldots \\ & + \left(\mathrm{Clhc}(\phi)\cdot\cos\left(\omega\cdot t+\phi h(t)\right) + \mathrm{Clhs}(\phi)\cdot\sin\left(\omega\cdot t+\phi h(t)\right)\right)\cdot\frac{k(\phi)}{2\cdot b(\phi)}\cdot h1(t)\end{aligned}$$

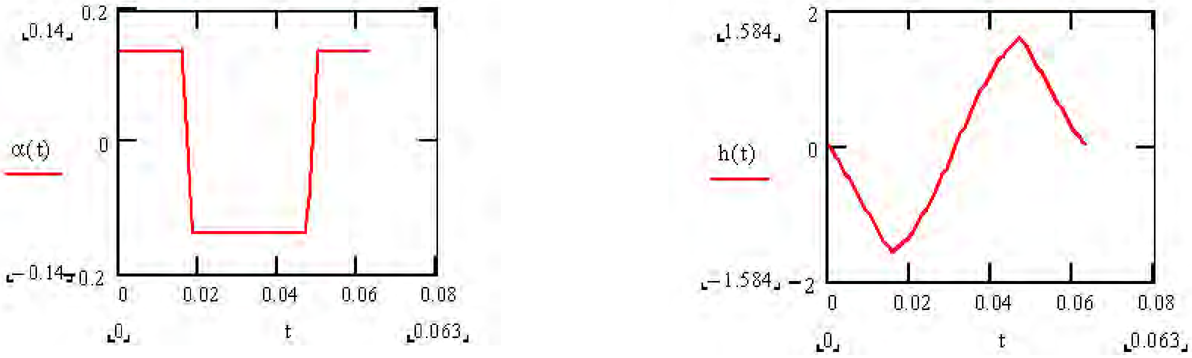
$$\begin{aligned}\mathrm{Cm}(\phi,t) := {} & \left(\mathrm{Cm\theta c}(\phi)\cdot\cos\left(\omega\cdot t+\phi\alpha(t)\right) + \mathrm{Cm\theta s}(\phi)\cdot\sin\left(\omega\cdot t+\phi\alpha(t)\right)\right)\cdot k(\phi)\cdot\alpha 1(t) \ldots \\ & + \mathrm{Cmh}(\phi)\cdot\cos\left(\omega\cdot t+\phi h(t)\right)\cdot k(\phi)\cdot\frac{h1(t)}{2\cdot b(\phi)}\end{aligned}$$

$$\begin{aligned}\mathrm{Ct}(\phi,t) := {} & \left(\mathrm{Ct\theta\theta 0}(\phi) + \mathrm{Ct\theta\theta c}(\phi)\cdot\cos\left(2\cdot\omega\cdot t+2\cdot\phi\alpha(t)\right) + \mathrm{Ct\theta\theta s}(\phi)\cdot\sin\left(2\cdot\omega\cdot t+2\cdot\phi\alpha(t)\right)\right)\cdot\alpha 1(t)^2 \ldots \\ & + \left(\begin{array}{l}\mathrm{Ct\theta h0}(\phi)\cdot\cos\left(\phi h(t)-\phi\alpha(t)-\phi h\theta(\phi)\right) \ldots \\ + \mathrm{Ct\theta hc}(\phi)\cdot\cos\left(2\cdot\omega\cdot t+\phi\alpha(t)+\phi h(t)\right) \ldots \\ + \mathrm{Ct\theta hs}(\phi)\cdot\sin\left(2\cdot\omega\cdot t+\phi\alpha(t)+\phi h(t)\right)\end{array}\right)\cdot\alpha 0(t)\cdot\left(\frac{k(\phi)\cdot h1(t)}{2\cdot b(\phi)}\right)^2 \ldots \\ & + \left(\mathrm{Cthh0}(\phi) + \mathrm{Cthhc}(\phi)\cdot\cos\left(2\cdot\omega\cdot t+\phi\alpha(t)\right) + \mathrm{Cthhs}(\phi)\cdot\sin\left(\omega\cdot t+\phi\alpha(t)\right)\right)\cdot\alpha 0(t)\cdot\alpha 1(t) \ldots \\ & + \left(\mathrm{Ct\theta 0hc}(\phi)\cdot\cos\left(\omega\cdot t+\phi h(t)\right) + \mathrm{Ct\theta 0hs}(\phi)\cdot\sin\left(\omega\cdot t+\phi h(t)\right)\right)\cdot\alpha 0(t)\cdot k(\phi)\cdot\frac{h1(t)}{2\cdot b(\phi)}\end{aligned}$$

$$\begin{aligned}\mathrm{Cp}(\phi,t) = {} & \left[\begin{array}{l}\mathrm{Cp\theta\theta 0}(\phi) + \mathrm{Cp\theta\theta c}(\phi)\cdot\cos\left[(2)\cdot\omega\cdot t+2\cdot\phi\alpha(t)\right] \ldots \\ + \mathrm{Cp\theta\theta s}(\phi)\cdot\sin\left(2\cdot\omega\cdot t+2\cdot\phi\alpha(t)\right)\end{array}\right]\cdot\alpha 1(t)^2 \ldots \\ & + \left[\begin{array}{l}\mathrm{Cp\theta h0}(\phi)\cdot\cos\left(\phi h(t)-\phi\alpha(t)-\psi\theta h(\phi)\right) \ldots \\ + \left(\mathrm{Cp\theta hc}(\phi)\cdot\cos\left(2\cdot\omega\cdot t+\phi h(t)+\phi\alpha(t)\right)\right) \ldots \\ + \mathrm{Cp\theta hs}(\phi)\cdot\sin\left(2\cdot\omega\cdot t+\phi h(t)+\phi\alpha(t)\right)\end{array}\right]\cdot\alpha 1(t)\cdot k(\phi)\cdot\frac{h1(t)}{2\cdot b(\phi)} \ldots \\ & + \left[\begin{array}{l}\mathrm{Cphh0}(\phi) + \mathrm{Cphhc}(\phi)\cdot\cos\left(2\cdot\omega\cdot t+\phi h(t)\right) \ldots \\ + \left(\mathrm{Cphhs}(\phi)\cdot\sin\left(2\cdot\omega\cdot t+\phi h(t)\right)\right)\end{array}\right]\cdot\left(k(\phi)\cdot\frac{h1(t)}{2\cdot b(\phi)}\right)^2 \ldots \\ & + \alpha 0(t)\cdot k(\phi)\cdot\frac{h1(t)}{2\cdot b(\phi)}\cdot\mathrm{Cp\theta hs}(\phi)\cdot\sin\left(\omega\cdot t+\phi h(t)+\phi\alpha(t)\right)\end{aligned}$$

where:
C_L means 2-d lift coefficient
C_m means pitching moment coefficient 2d
C_t means Thrust Coefficient 2d
C_p means Power Coefficient 2d

The flapping and pitching cycle was used similar to a humming bird in that all the wing rotation (pitch changes) takes place in last 10% of the strokes which is shown in Figure 5. The result for Lift coefficient for baseline configuration is shown in Figure 6.



Flapping Motion

Pitching Motion

Figure 5. Flapping and pitching cycle.

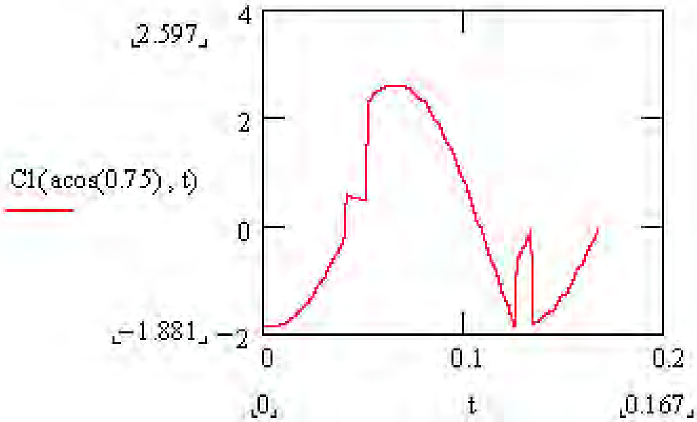
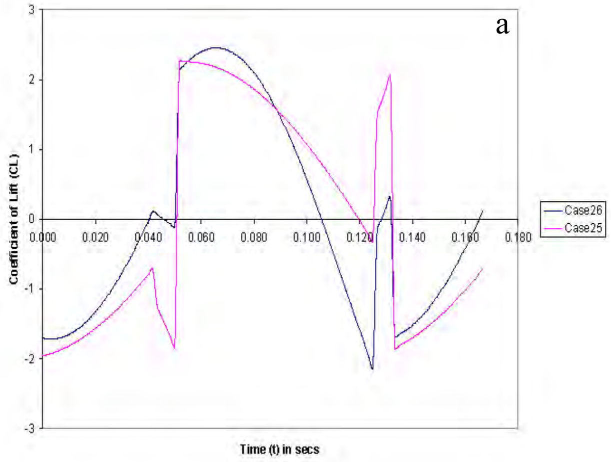


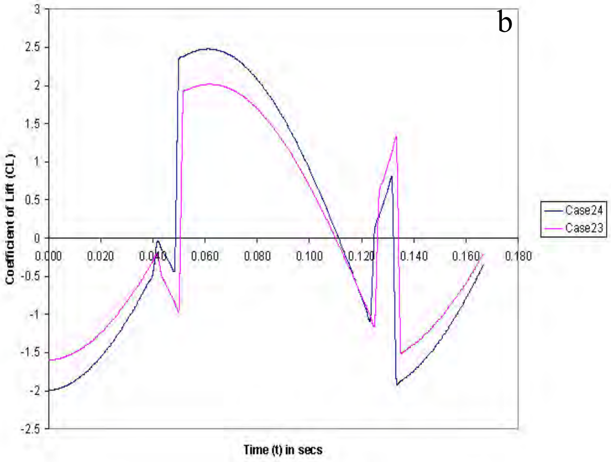
Figure 6. Lift Coefficient over the flapping cycle.

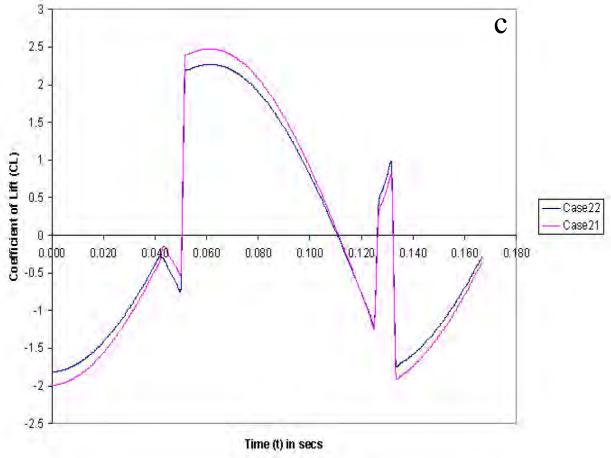
The formulation of [14] was coded, and since it could only encompass 2-dimensional effects, a correction factor for 3-dimensional planform effects [15] was also coded to analytically evaluate the aerodynamics of Entomopter without active flow control. Then this model was used to assess the variability of lift, thrust and power coefficients with different control variables, which are as follows:

(a) Since the model described above [1] could not encompass the airfoil characteristics, and had the results based on thin flat plate, span represents the scaling factor of scaling the vehicle up or down in size.
(b) Free Stream Velocity.
(c) Flapping Frequency
(d) Pitch Amplitude
(e) Flapping Amplitude

Adequate working ranges were then selected for these variables and based on a composite "design of experiments" array, 28 runs for different variable settings were performed and the range of lift using these variables being given in Figures 7a through 7e.







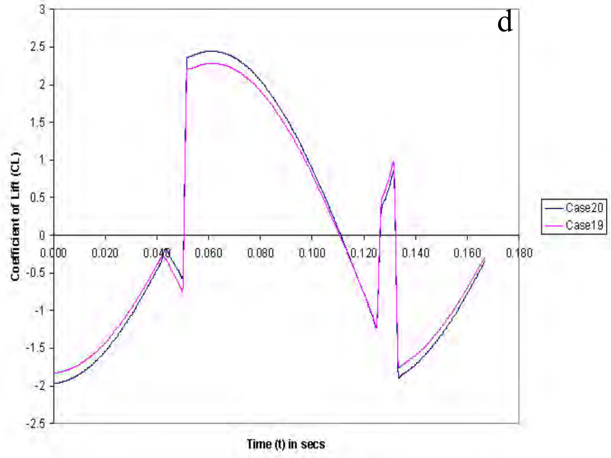
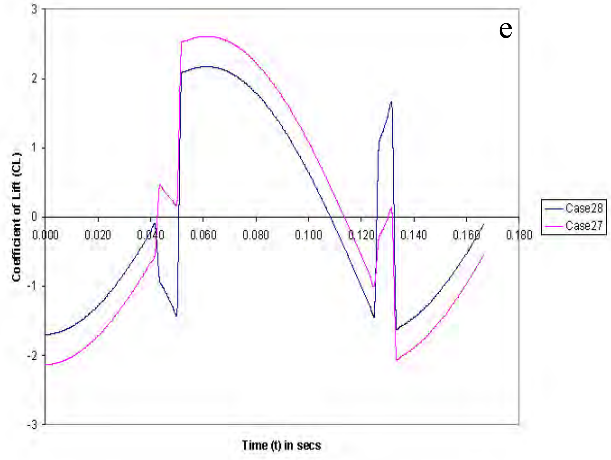


Figure 7a. Variation of lift coefficient with span.
Figure 7b. Variation of lift coefficient with forward velocity.
Figure 7c. Variation of lift coefficient with flapping frequency.
Figure 7d. Variation of lift coefficient with flapping amplitude.
Figure 7e. Variation of lift coefficient with pitch amplitude.



METHODOLOGY FOR SIZING A MARS ENTOMOPTER

An effort is being made [16] to create an analytical model for Entomopter aerodynamic design, with and without the active flow control. Rather than using the formulation provided by past research, an analytical model on the lines described in the companion paper [17] is being formulated. The previous analytical model [1] was not comprehensive, including few design variables, but the model under construction [16] will account for the following list of variables:

- (a) Planform variables (maintaining the same baseline shape)
    - a. Span
    - b. Wing Area
    - c. Location of kink in the wing
- (b) Airfoil lift curve slope (airfoil type)
- (c) Flapping frequency
- (d) Pitch amplitude
- (e) Rotation axis for pitch changes
- (f) Horizontal placement of wings
- (g) Built in incidence angle of attack
- (h) Phase angle between flapping and pitch
- (i) Free stream velocity
- (j) Noise variables
    - a. Density on Mars, while operating at different places on Mars
    - b. Kinematic viscosity on Mars

A three level "design of experiments" orthogonal array will be used to determine the different variable settings and all these settings will then be analyzed by the formulated model, and results of the simulations will be used to create "response surface equations". These response surfaces equations will not only provide the sensitivity analysis of variability of responses to variables but will also serve as a meta model which is not computationally intense and can be instantly queried to perform the probabilistic evaluation of feasible design space.

Then, based on the response surface equations metamodel, optimization will be performed and an optimum design will be taken as a baseline model for active flow control application. CFD will be used to assess the effects of active flow control. The following blowing variables will be used:

- (a) Blowing slot length
- (b) Radius of the slot-adjacent trailing edge
- (c) Gas velocity/mass flow
- (d) Gas temperature

Based on the "design of experiments" array for these variables, results will be obtained by CFD for different settings and then based on the results a separate set of response surface equations for active flow control variables will be created. Optimum settings for circulation control blowing variables will be ascertained by optimization of these response surface equations, and based on these optimum settings, the initial design of experiments of basic variables will be executed with the baseline values already accounting for blowing value increments.

Upon completion of this analysis, one or two optimum designs will be fabricated and validated in the wind tunnel under similar or scalable Mars conditions. The results of wind tunnel testing, and corroborating CFD results will help validate the analytical model and thus the optimum design configuration for Entomopter. Procedures such as this are necessary because in situ testing of a Mars vehicle is otherwise not practical.

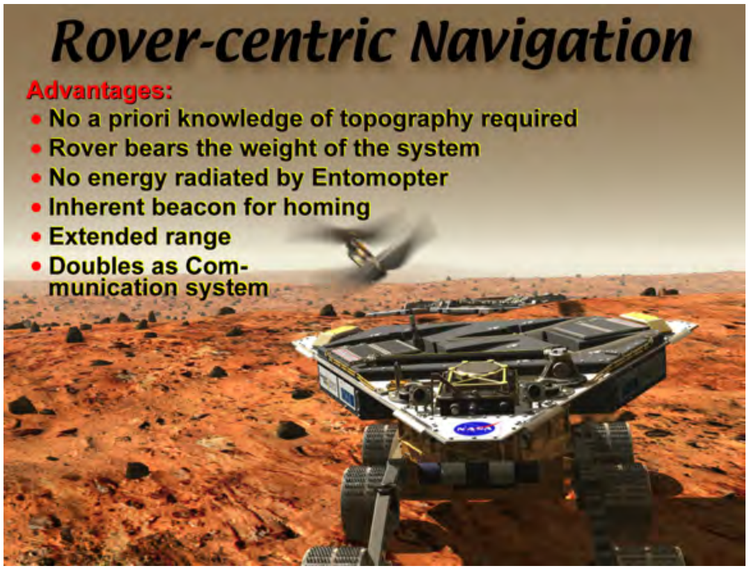
4.0 FLIGHT ENDURANCE

Because the Entomopter is operating under adverse conditions near the surface of Mars, it will necessarily be weight limited. The majority of the weight to be carried by the Entomopter will be fuel. While this is advantageous in that the vehicle becomes lighter as the mission progresses due to fuel consumption (something that can not be said for battery powered approaches), the amount of fuel that can be carried will still be small. A baseline mission will have the Entomopter working in tandem with its refueling rover which itself is moving across the Mars landscape performing science experiments. Entomopters would be launched from the refueling rover to scout the vicinity and return with data, potentially samples, and to refuel. The Entomopters will be launched and recovered from the refueling rover. Entomopter flights will therefore be brief (5 to 10 minutes), but numerous due to the ability to refuel. As envisioned, the Entomopters will not be long range reconnaissance or independent planetary surveyors. Figure 8 shows an Entomopter returning to its refueling rover for a "carrier deck" landing. A robotic arm on the refueling rover repositions the Entomopter for refueling, data and sample download, as well as relaunch via catapult. Mission flight endurance is therefore determine not by how much fuel can be carried by the Entomopter, but how long it can reliably operate and how much fuel can be carried (or manufactured) by the refueling rover.

Figure 8. Mars Entomopter landing on the deck of a refueling rover.

5.0 NAVIGATION

Another issue to be addressed by a Mars Entomopter system is the fact that the one-way communication delay between Earth and Mars is about 8.5 minutes, giving a man-in-the-loop control system latency of at least 17 minutes. So, flight control, navigation, and collision avoidance must be accomplished autonomously by the Entomopter system. A rover-centric scheme has been devised in which a refueling rover-borne range-gated Doppler radar tells each Entomopter its relative position to the rover, other Entomopters, and detected obstacles. Range, azimuth, elevation, and velocity information is sent to each Entomopter as well as a map of nearby obstacles. The radar provides not only an inherent homing beacon, but bidirectional communication through direct transmission from the refueling rover and electronic signature modulation of the return by the Entomopter. The Doppler signature of the Entomopter is unique in the Mars environment, thereby facilitating tracking. Therefore the Entomopter can act as an extended sensor platform for the rover without the aid of external GPS-like navigation aids. This also reduces the weight carried by the Entomopters and eliminates the need for the Entomopters to have onboard emitters. Figures 9 and 10 shows schematically what information is known by each component of the Entomopter-based Mars surveying system.



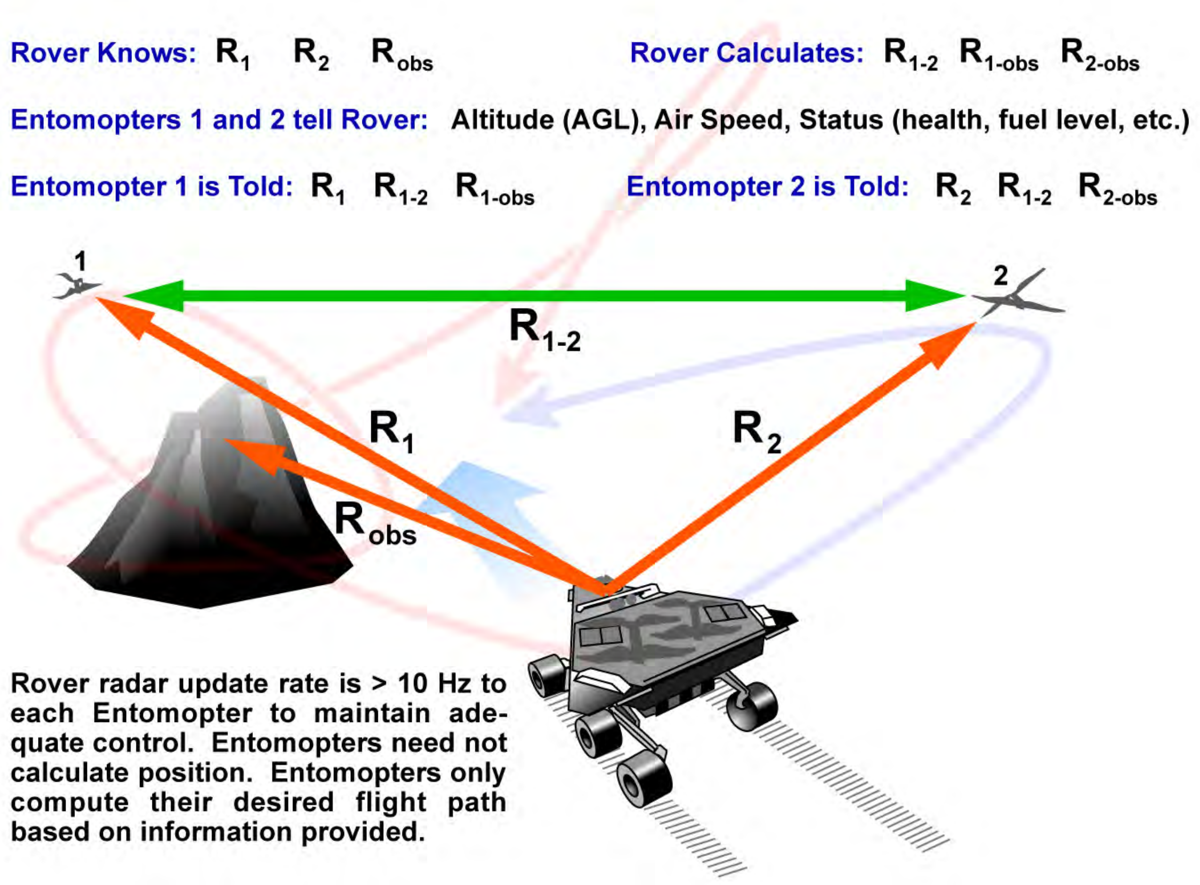
Rover-centric Navigation

Advantages:

- No a priori knowledge of topography required
- Rover bears the weight of the system
- No energy radiated by Entomopter
- Inherent beacon for homing
- Extended range
- Doubles as Communication system

Figure 9. Advantages of rover-centric navigation (right).

Figure 10. Information paths emanating from a rover-centric navigation and communication approach (below).



Rover Knows: R_1 R_2 R_{obs}

Rover Calculates: $R_{1\text{-}2}$ $R_{1\text{-}obs}$ $R_{2\text{-}obs}$

Entomopters 1 and 2 tell Rover: Altitude (AGL), Air Speed, Status (health, fuel level, etc.)

Entomopter 1 is Told: R_1 $R_{1\text{-}2}$ $R_{1\text{-}obs}$

Entomopter 2 is Told: R_2 $R_{1\text{-}2}$ $R_{2\text{-}obs}$

Rover radar update rate is > 10 Hz to each Entomopter to maintain adequate control. Entomopters need not calculate position. Entomopters only compute their desired flight path based on information provided.

6.0 SUMMARY

Slow flight on the planet Mars is beneficial for many science missions but it 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. Of the various air vehicle configurations that could be used as a Mars surveyor, the best appears to be a flapping wing approach augmented with circulation control blowing to increase C_L beyond the already high values derived from flap-induced dynamic stall and the leading edge vortex phenomenon. Sizing of the vehicle is problematic in the Earth environment, however analytical modeling validated through CFD and empirical wind tunnel testing can lead to a "design of experiments" methodology that results in a parametric exploration of the design space to reveal optimum configurations. The basic Entomopter design is a good starting point because of its slow fight efficiency, anaerobic ignitionless propulsion system, and controllability at slow speed. The problem of mission endurance can be solved by limiting flight duration coupled with the ability to refuel in concert with a refueling rover. Navigation is also possible apart from artificial cues such as GPS by allowing the refueling rover to act as an absolute reference in the environment. The energy replete rover carries the burden of interrogating its surroundings and reporting to the airborne Entomopters, thereby alleviating the need for energy-expensive Entomopter radiation emissions.

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