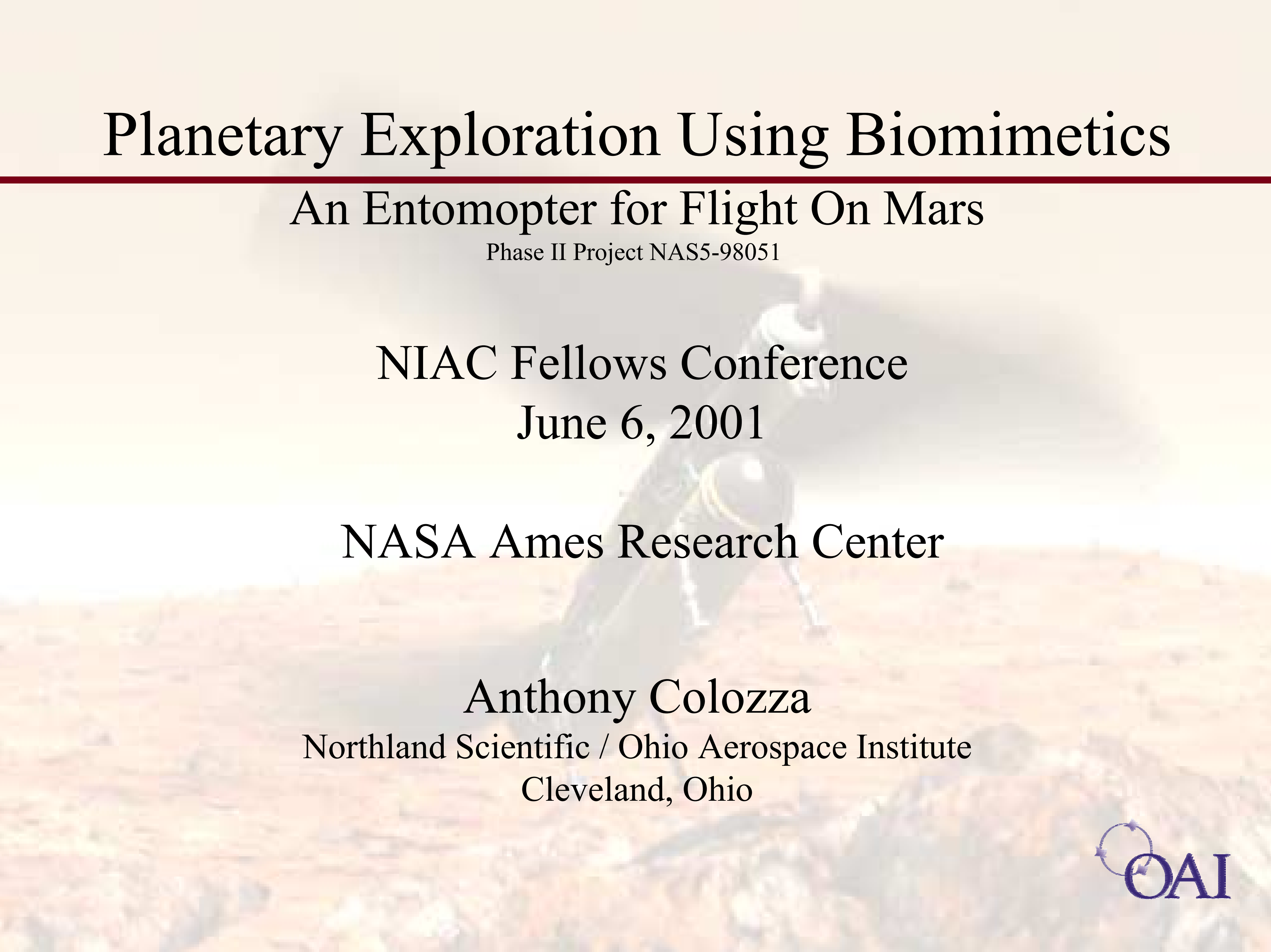

# Planetary Exploration Using Biomimetics

## An Entomopter for Flight On Mars

Phase II Project NAS5-98051

NIAC Fellows Conference
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NASA Ames Research Center

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# Planetary Exploration Using Biomimetics

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# Mars Exploration

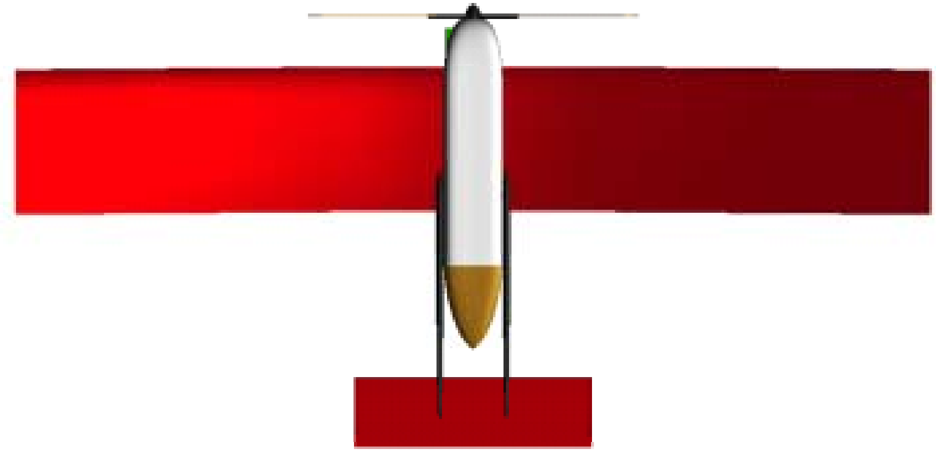
***A Flight vehicle can be used to revolutionize Mars exploration.***

- Mars has been a primary objective of planetary exploration for the past 20 years.
- To date, all exploration vehicles have been landers, orbiters, fly-bys and, most recently, a rover (Sojourner).
- The ability to fly on Mars has the potential to expand the range covered with greater resolution and can provide a means for atmospheric sampling.
- Present day aerospace technology (aerodynamics, materials, propulsion, power, communications) have advanced to the point to enable this type of vehicle.

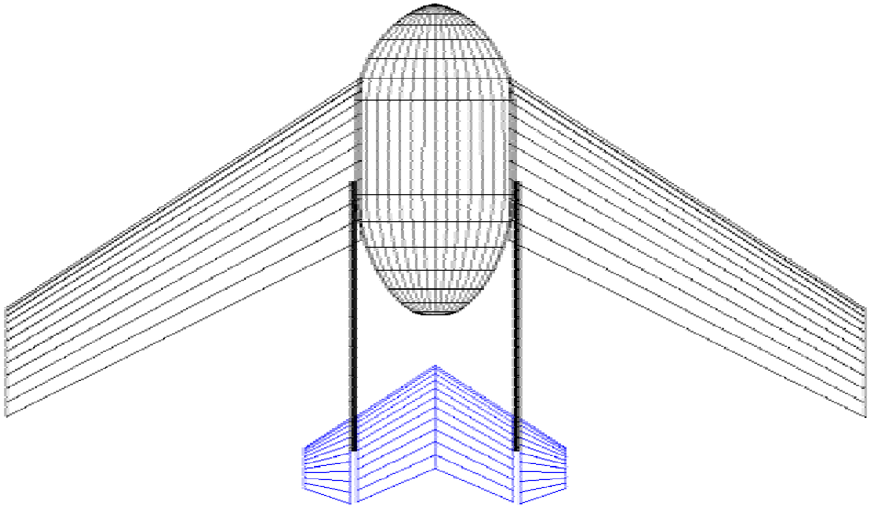
# History of Mars Aircraft

# Candidate Mars Micromission Aircraft

Battery Powered Electric Aircraft



Rocket Powered Aircraft



# Flight on Mars – General Issues

- Deployment is required on entry, since there is no ability to take off with a conventional aircraft from the ground.
- No place to land aircraft after flight is complete.
- Aircraft must fly at 0.5 to 0.8 Mach. This limits imaging and data gathering capability.
- For the micromission, aircraft endurance is limited to 20 minutes due to the available communication window during flight.

# Flight on Mars – Environmental Issues

- Extremely low atmospheric density - 1/70th that at Earth surface
- Lower speed of sound than on Earth - 22% less
- Conventional aircraft must fly in a low Reynolds number, high Mach number flight regime (difficult aerodynamics)
- Gravity 1/3 that of the Earth
- Atmosphere is 95% Carbon Dioxide
- Surface temperature extremes -143°C to 27° C

# Flight on Mars – Aerodynamics Issues

- No conventional aircraft has previously flown in aerodynamic flight regime in which flyer will operate:
  - Wing: Re < 50,000, M > 0.5
  - Propeller: Re = ~15,000, M = ~0.8
- Aerodynamic performance of airfoils in this regime not well understood.
- Main issue is laminar separation of boundary layer.
- Ability to transition flow to turbulent and re-attach boundary layer is main challenge.
- Need to investigate physics of this boundary layer.
- New airfoil and boundary layer trip mechanisms will need to be designed.

# Project Goal

The Goal of this Project is to Use the Present State of Knowledge on Entomopter Development and Apply this to Developing an Entomopter for the Mars Environment.

# An Entomopter is an Innovative Approach to Small Aircraft Flight on Mars

## *What is an Entomopter?*

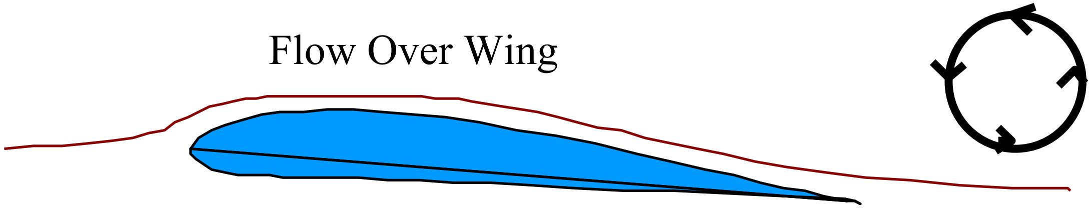
- An Entomopter is a flying vehicle that generates lift in a fashion similar to that of an insect.
- It is based on a present DARPA program to develop micro-aircraft (on Earth) with flight characteristics like those of insects (flapping wings).
- Mars flight would be in the same flight Reynolds number regime experienced by large insects on Earth.
- Extremely high potential lift generation capability ($C_L \simeq 5.0$)

# Theory of Insect Flight

- The aerodynamic force generated via conventional mechanisms is insufficient to explain the nature of insect flight.
- The probable mechanism for lift generation is an interaction of the wings with a starting vortex.
- This interaction is dependent on the low Reynolds number of insect flight.

# The Main Difference Between Flapping Flight and Airfoil Flight is the Continual Formation and Shedding of the Wing Vortex in Flapping Flight.

## Air Moves Over Wing Surface with no Separation.

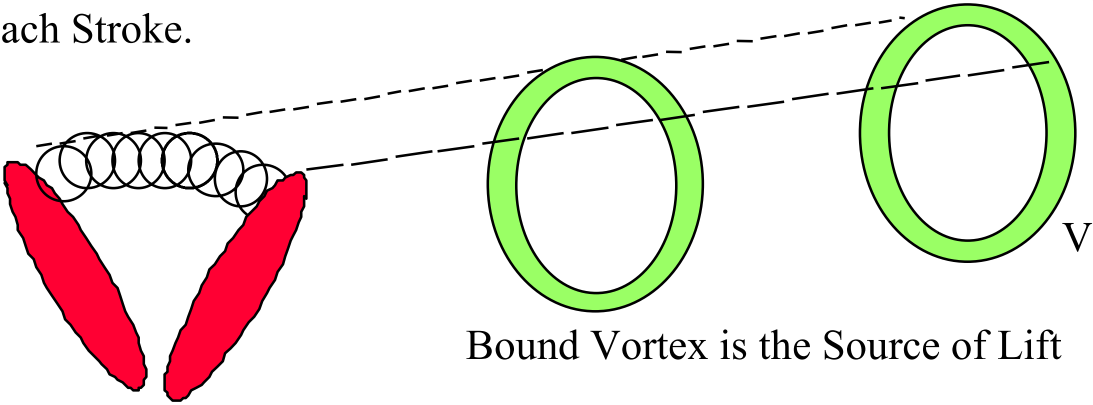


Flow Over Wing

Trailing Vortex

Vortex Does Not Effect Lift Generation by the Wing.

Conventional Airfoil Produces a Steady State Standing Vortex.



Bound Vortex is Formed After Each Stroke.

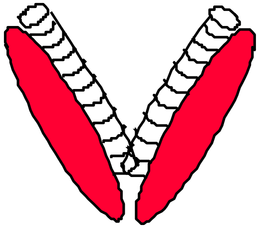
Vortex is Shed After each Stroke

3 Dimensional Wake Structure

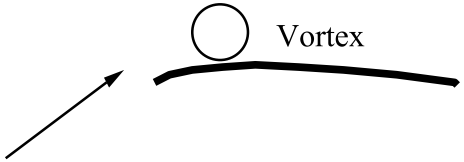
Vortex Tube

Bound Vortex is the Source of Lift

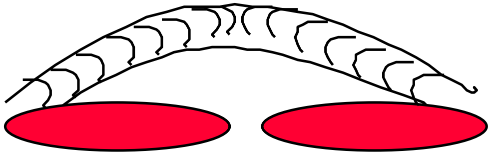
# Vortex Wake is not Completely Understood. It is Believed that the Vortex is Caused by Flow Separation Over the Leading Edge of the Wing



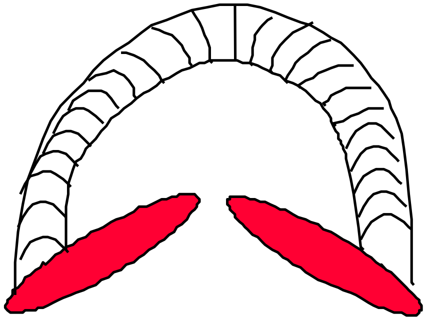
Stroke cycle starts with downward motion.



Start of the vortex tube occurs over the entire edge of the wing.



During the stroke, the tubes merge and form a vortex.



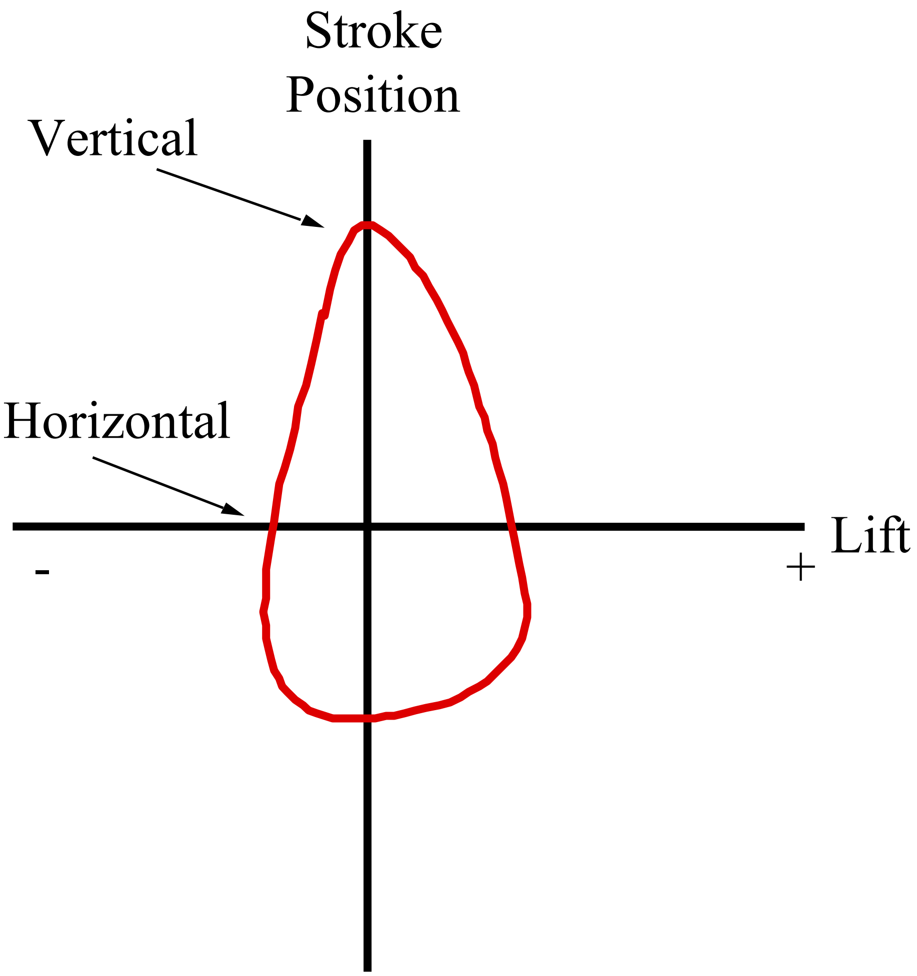
Vortex tube unites at the end of the down stroke and is then shed.

Due to rotation of the wing, there is no vortex ring formed on the upstroke.

# Vortex Interaction

- Flapping wings are not capable of generating the maximum circulation possible.
- This is due to the rate of flapping and the time delay required for the growth of this circulation.
- It is believed insects overcome this by interacting with their own vortex wake.

# Wing Lift Distribution
# Throughout the Stroke Cycle



Lift is 0 at the beginning of the stroke.

Increases and achieves its extreme value in the second half of the downstroke.

Begins to lessen at the end of the downstroke.

Becomes negative throughout the upstroke.

# Lift Generation

- 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 vortex formation) does not occur.
- It is believed that this is due to low Reynolds number flight and the high wing flap rate ($10^{-1}$ to $10^{-2}$ seconds).
- Additional lift producing mechanisms include:
  - Rotational motion of the wing (Magnus force)
  - Wake interaction
- Control is achieved by lift variations through these mechanisms.
- $C_L = 5.3$ has been demonstrated on terrestrial Entomopter wind tunnel tests.

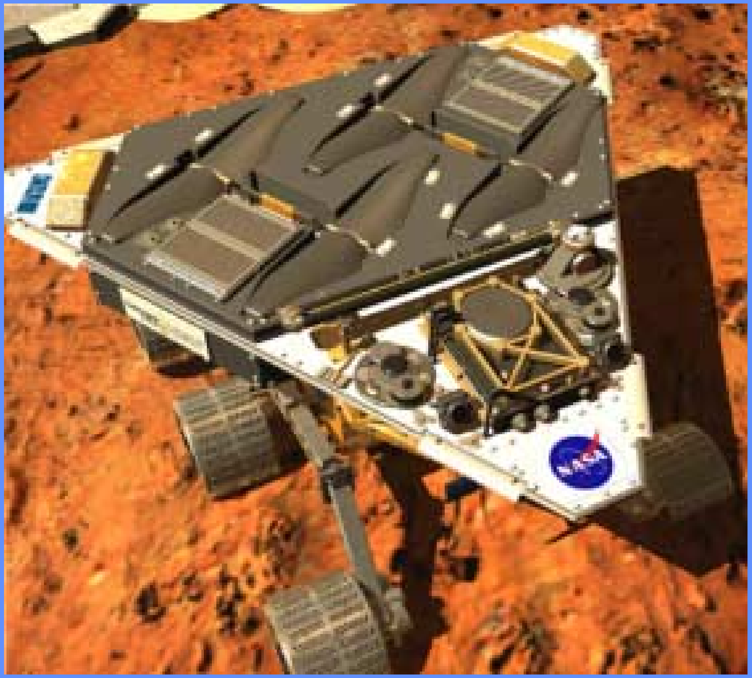
# Reynolds Number Effect

- Reynolds Number $\geq 10^6$ polar curves indicate an evident crisis of flow, caused by early separation around a still wing.
- Reynolds Number $\geq 10^4$ this flow crisis is greatly reduced and the flow displays a smooth shape.
- $10 <$ Reynolds Number $> 10^3$ flow separation is absent.
- As Reynolds Number decreases, other lift producing mechanisms may come into play (differential drag & velocity and boundary layer effects).

# An Entomopter on Mars

- The Mars environment may be ideal for Entomopter flight:
  - Low atmospheric density means a larger vehicle (≈ 1 m wingspan) which reduces the need for miniaturization, increases lifting capacity
  - Low gravitational force (1/3 that of Earth) increases the potential flapping frequency and reduces the required wing loading
- An Entomopter would have the ability to take off, fly, land and possibly hover.
- An Entomopter would be capable of slow flight and precision flight control.

# Entomopter Flight System for Mars



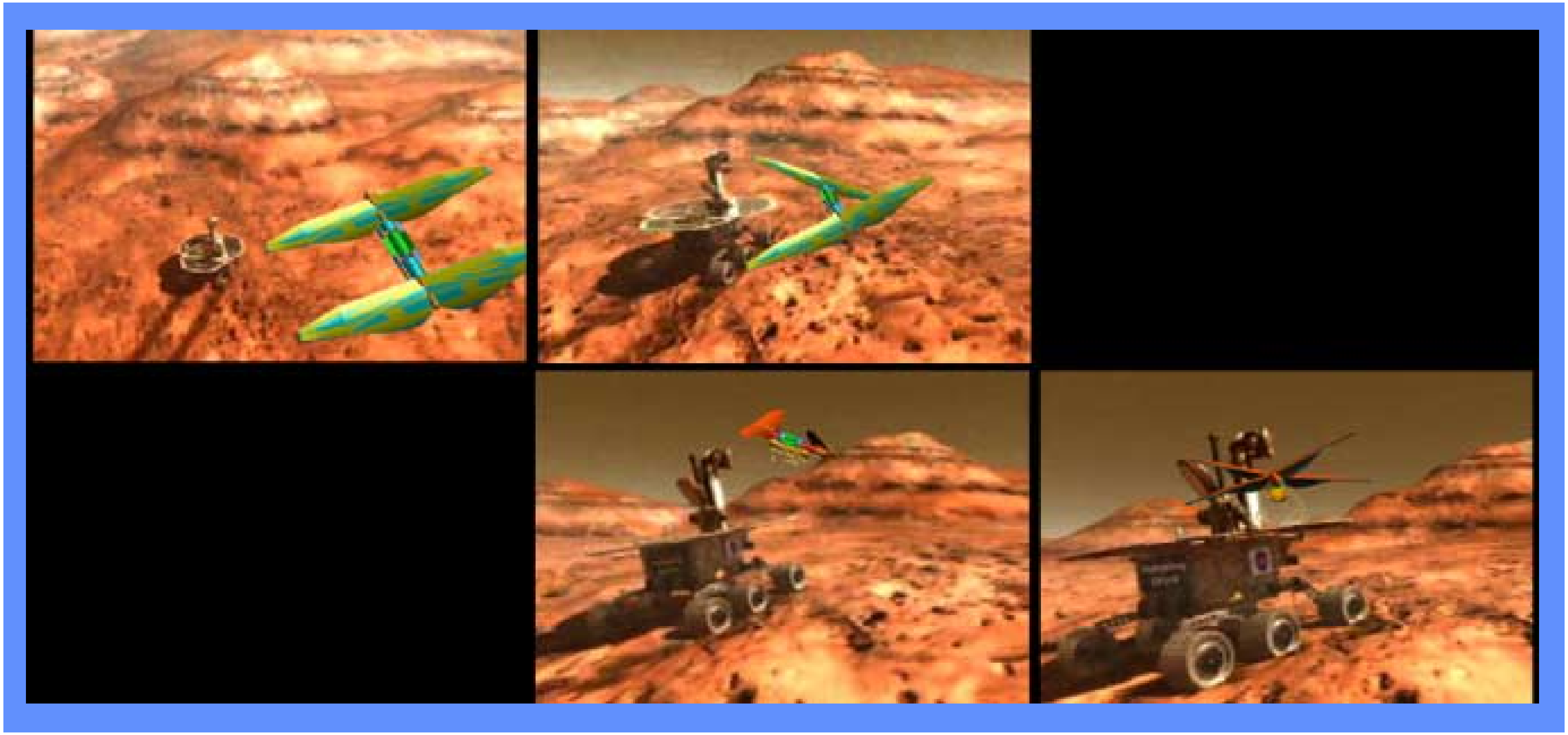
Rover Mobile Base Refueling Station

Entomopter

# Mission Profiles

- Independent exploration using an Entomopter
  - Pro: Entomopter is not restricted to the area around a central vehicle
  - Con: Short mission duration since fuel supply is limited to carrying capacity
- Exploration in conjunction with a fixed lander
  - Pro: Can provide the ability to refuel (possibly using "In-Situ" fuel production) with multiple flight capability and bring back samples for analysis on the lander
  - Con: Limited to the area around the lander
- Exploration in conjunction with a rover vehicle
  - Pro: Extended terrain coverage as the rover moves across the surface, enhancing navagation of the rover, potential to refuel with multiple flight capability, capability to bring back samples to the rover for analysis
  - Con: Increased logistical complexity

# Rover/Entomopter Operation



- Multiple Entomopters would be flown on each mission.
- Each Entomopter would carry one or more science instruments which could be different for each vehicle.

# Mission  Profile Diagram

Flight Profile

Four Entomopter Vehicles Operating
From a Base Ground Vehicle

12 Minute Round Trip Flight Time

Flight Profile 1 Minute
Flight or Hover Intervals

Base Vehicle

15 Minute Period on Surface,
Relay Data, Receive Navigation Commands
Take Surface Data, Collect Samples

3 Hour Period on the
Surface for Detailed
Sample Collection
& Analysis

0 2 4 6

Time (Hours)

# Science Objectives

- Surface Mineralogy and Sampling
  - Collect and return samples to the base vehicle
  - Perform composition analysis with an alpha proton X-ray spectrometer
- High resolution Surface Imaging
  - Image terrain, atmosphere and horizon. Also provide close up views of surface material
- Atmospheric Condition and Sampling
  - Collect atmosphere samples at various altitudes, record temperature, pressure, wind speed/direction and dust content
- Payload Delivery
  - Deliver payloads (micro science stations) to the surface
- Magnetic Field Mapping
- Infrared and Radar Mapping
  - IR imaging of the surface
  - Radar transmitter to provide a radar map while in flight

# Planetary Exploration Using Biomimetics

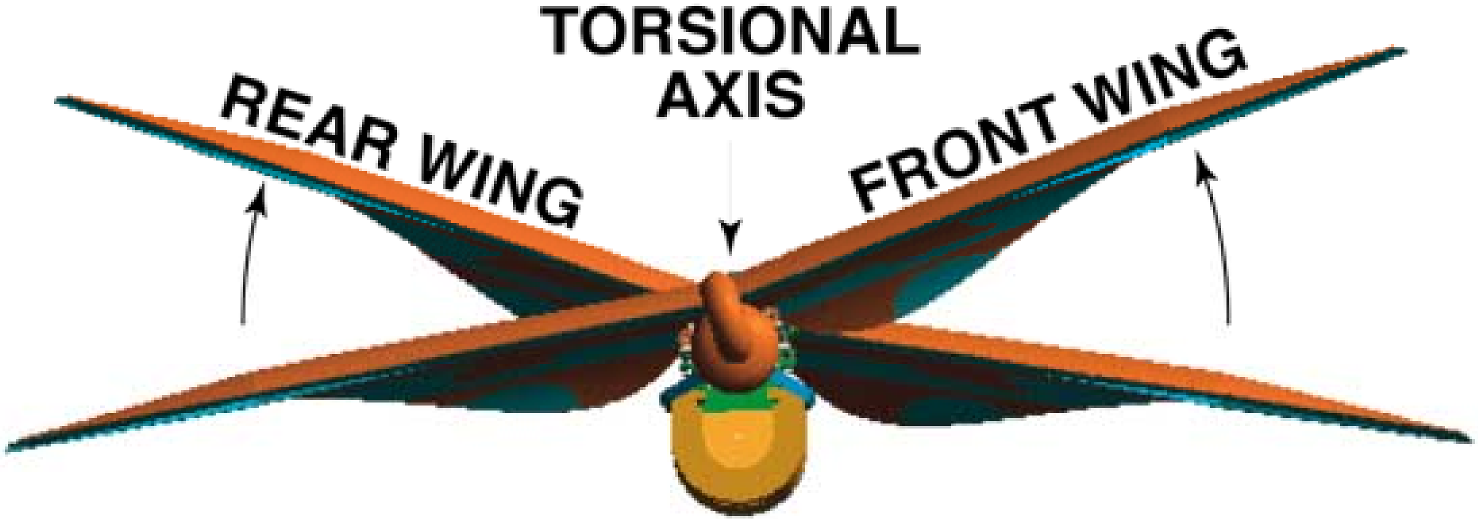
# Entomopter Development

- Entomopters for terrestrial applications have been under development for a number of years.
- Mainly supported by DARPA and performed by universities and some private companies, i.e. Georgia Tech Research Institute (GTRI), Stanford University, etc.
- GTRI design is the baseline for the Mars Entomopter development.
- Mars Entomopter will be a larger version of the terrestrial design to maintain the correct flight Reynolds number.
- The wing loading for both the Mars and Earth versions will be the same, but due to the increased size and lower gravity on Mars, the Mars version will carry significantly more mass.

# GTRI Entomopter Design

- Flapping wing vehicle with tandem “see-saw” wings phased at 180° about a central torsional fuselage
- Integrated lift, control, and propulsion systems
- Simplicity & weight reduction from non-moving lift & control surfaces
- Instantaneous response characteristics from pneumatics
- High $C_L$ at Low $\alpha$ = No need to fly near $C_{lmax}$
- Positive lift at negative $\alpha$ on upstroke due to pneumatic flow control
- Leading-edge pneumatic lift augmentation induces flow structure over the wing to remain attached longer, increasing $C_L$

# Entomopter Wing Motion

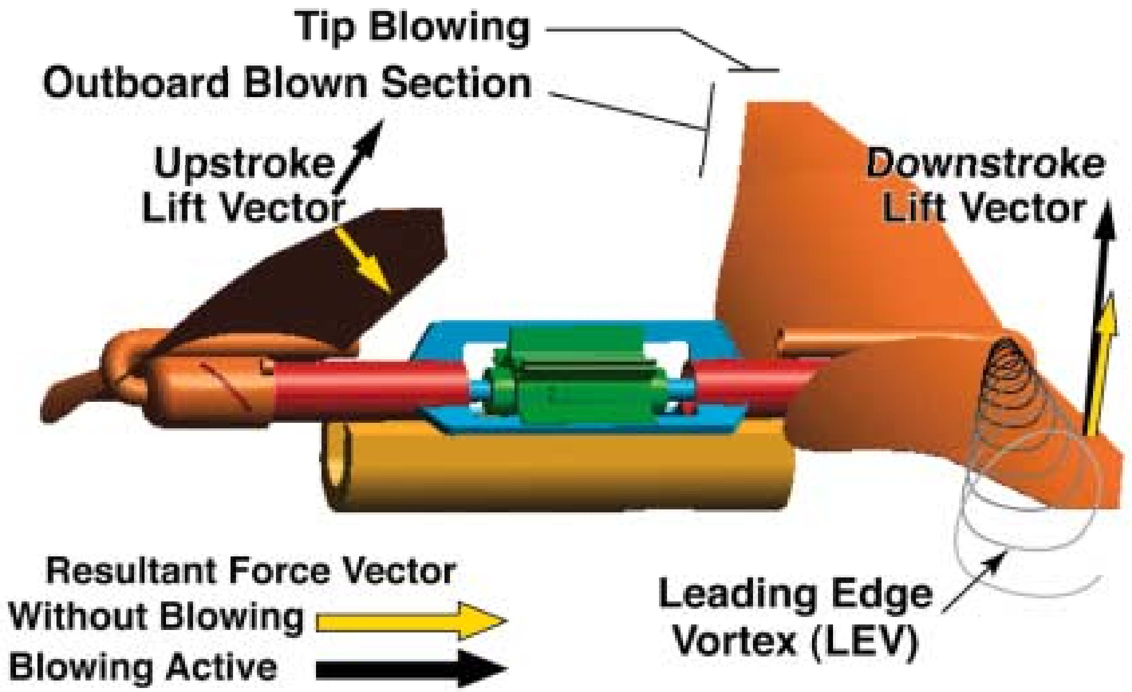


- Wings oscillate at a constant rate. (On the Earth-based Entomopter, it is between 25Hz and 30 Hz.)
- Because of the constant rate motion the structure can be designed to act as a spring tuned to this frequency to store energy from the wing motion.

# Aerodynamic Approach

- The aerodynamics of the terrestrial Entomopter is applicable to Mars flight if the vehicle is properly scaled (i.e. Wing span increases from 15 cm to 92 cm).
- Wing airfoil is thin with moderate camber and a sharp leading edge to enhance vortex formation.
- The vortex separation point is controllable through the venting of exhaust gasses onto the wing surface, enabling lift control on each wing while maintaining a constant beat frequency.
- The design of the flexible ribs within the wing in conjunction with circulation control allows for lift to be produced on both the up and downstrokes.

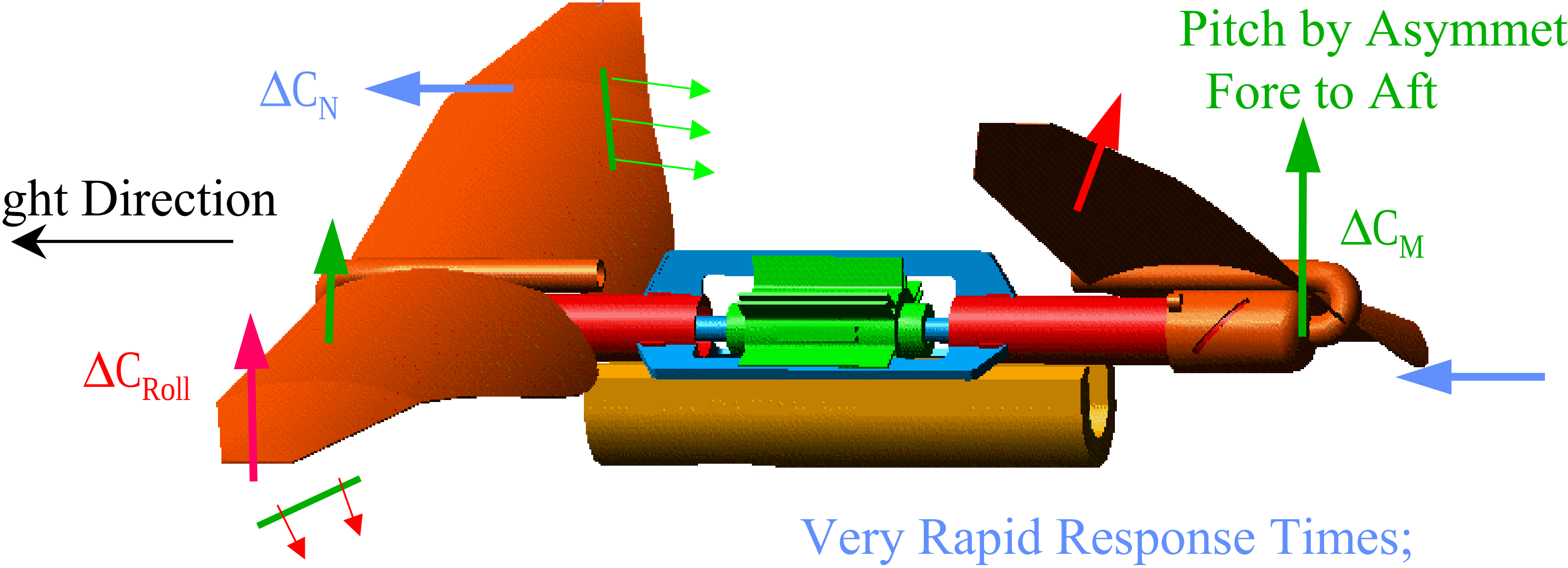
# Lift Generation



- It is estimated that the combination of boundary layer blowing in combination with the wing flapping will produce lift coefficients between 7.95 and 10.6.
- Based on this, a 1 m wingspan Entomopter on Mars should be capable of lifting between 5 and 7 kg total mass.

# GTRI Entomopter Flight Control

$C_L$ can be modulated independently on each wing to change lift on each beat by recycling waste gas and blowing it out the edges of the wing.



Yaw by Asymmetric Thrust by Reduced Jet Deflection, Port to Starboard

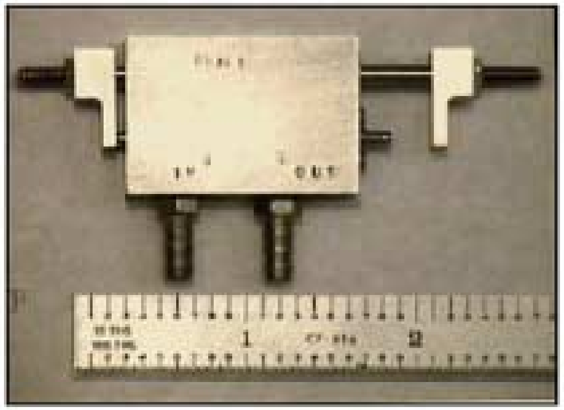
Pitch by Asymmetric Lift, Fore to Aft

Roll by Asymmetric Lift, Port to Starboard

Very Rapid Response Times; Unsteady blowing augments forces

# Propulsion System

- The wing motion is supplied by a "Reciprocating Chemical Muscle (RCM)" that presently uses Hydrogen Peroxide as its energy source.
- The RCM has gone through 3 stages of development to reduce mass and size and is presently capable of 70 Hz operation - 4th development stage is presently under way.
- The RCM utilizes gas expansion based on the fuel decomposition. The fuel can either be a mono-propellant or a bi-propellant.
- A process control system meters the fuel into the reaction chamber.



# Additional Uses for the Exhaust Gases

- For gas bearings to reduce friction without wetted parts
- To produce an ultrasonic sonar signal (frequency modulated continuous wave FMCW) for obstacle avoidance and altimetry
- For flow augmentation over the wings enabling lift control over the wings on a beat-to-beat basis
- For directional thrust
- To entrain atmospheric gasses through an ejector as a means of cooling the exhaust gases and increasing mass flow

# Operational Design Considerations

- Fuel to power the Entomopter
  - Must be compatible with the extremes of the Mars environment.
  - Is desirable to be able to manufacture the propellant (at least partially) for indigenous materials.
- Autonomous control and self-stabilized behavior
  - Ability to navigate, takeoff, land, refuel, adjust attitude and situational/environment awareness.

# Propellant Selection

- To be utilized, the propellant must be in liquid form during storage and operation, ideally with minimal thermal control.
- The ability to refuel the Entomopter is a vital component of the proposed mission scenario and greatly enhances the science data collection ability.
- Extra fuel for the Entomopter would need to be either brought from the Earth or manufactured on Mars using “In-Situ” resources or some combination of these.
- The components to make up most propellants (Nitrogen, Carbon, Oxygen and Hydrogen) with the exception of Hydrogen, can be found within the atmosphere or soil of Mars.

# Candidate Propellants

| Fuel / Oxidizer | Chemical Makeup | Percent $H_2$ by Weight | Boiling / Freezing Point |
|---|---|---|---|
| Monomethyl Hydrazine & Nitrogen Tetroxide | $(N_2H_6C)+2(N_2O_4)$ | 2.61% | 89.2°C / -52.5° C (MMH)<br>21.2°C / -11.2°C (NTO) |
| UDMH & Nitrogen Tetroxide | $(N_2H_6C)+2.7(N_2O_4)$ | 1.96% | 63.8°C / -52.2° C (MMH)<br>21.2°C / -11.2°C (NTO) |
| Hydrogen Peroxide | $(0.9H_2O_20.1H_2O)$ | 5.38% | 141.1°C / -11.5°C |
| NitroMethane | $(CH_3NO_2)$ | 4.92% | 10.6°C / -112.8°C |

# Propellant Production

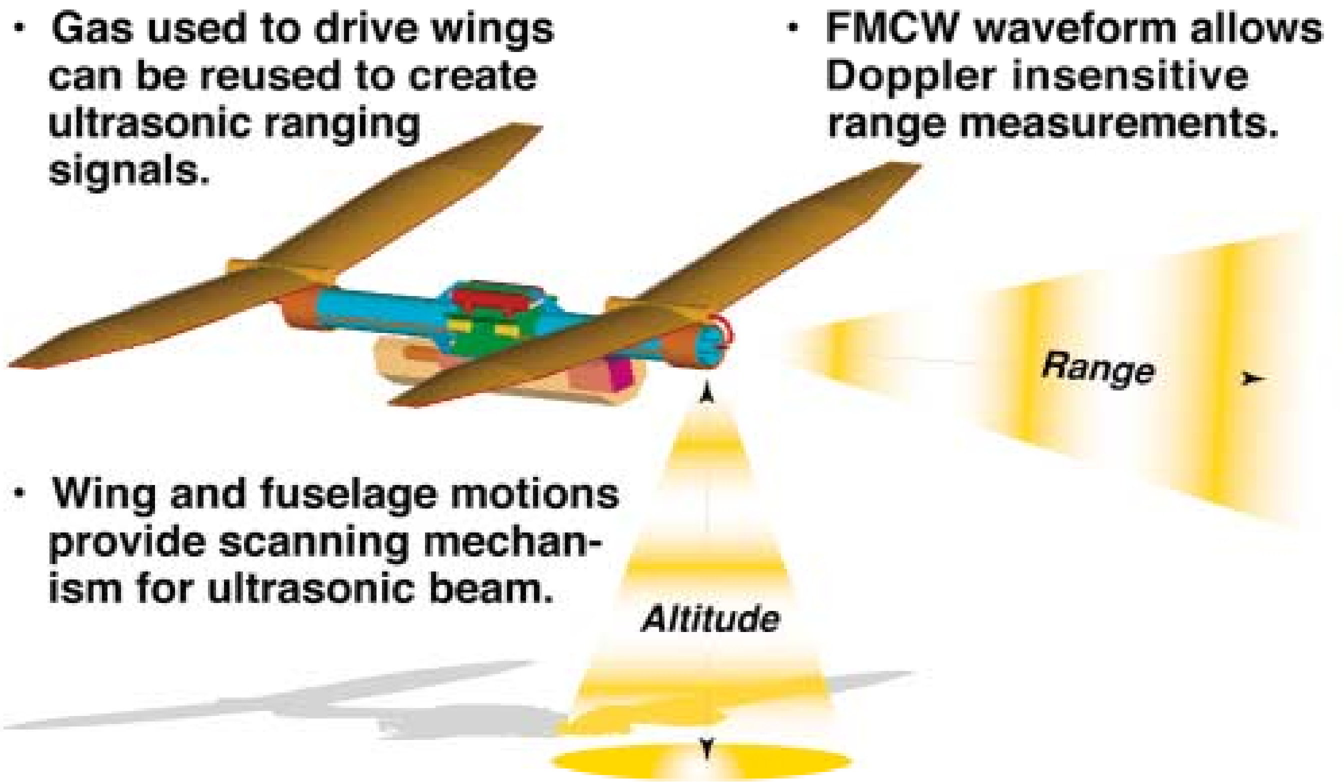
- The basic components of these propellants (Nitrogen, Carbon & Oxygen) can be obtained from the atmosphere.
- The $CO_2$ can supply the Carbon & Oxygen, and Nitrogen can be obtained directly from the atmosphere.
- The $CO_2$ & N can be separated from the atmosphere using a sorption compressor.
- Once separated, the $CO_2$ can be broken apart using a Zirconia solid-oxide generator

# Direct Oxidation with $CO_2$

- An additional non-conventional propellant concept was considered: the direct combustion of $CO_2$ with a metal.
- Main issues are: High $CO_2$ pressure required, producing correct distribution and density of metal particles & $CO_2$ and metal oxides that are formed are difficult to remove.

| **Metal** | **Reaction** | **Ignition Temperature** |
|---|---|---|
| **Magnesium** | **$Mg + CO_2 = MgO + CO$** | **340°C** |
| **Lithium** | **$2Li + CO_2 = Li_2O + CO$** | **851°C** |
| **Aluminum** | **$2AL + 3CO_2 = AL2O_3 + CO$** | **> 2000°C** |

# Range and Altitude Determination

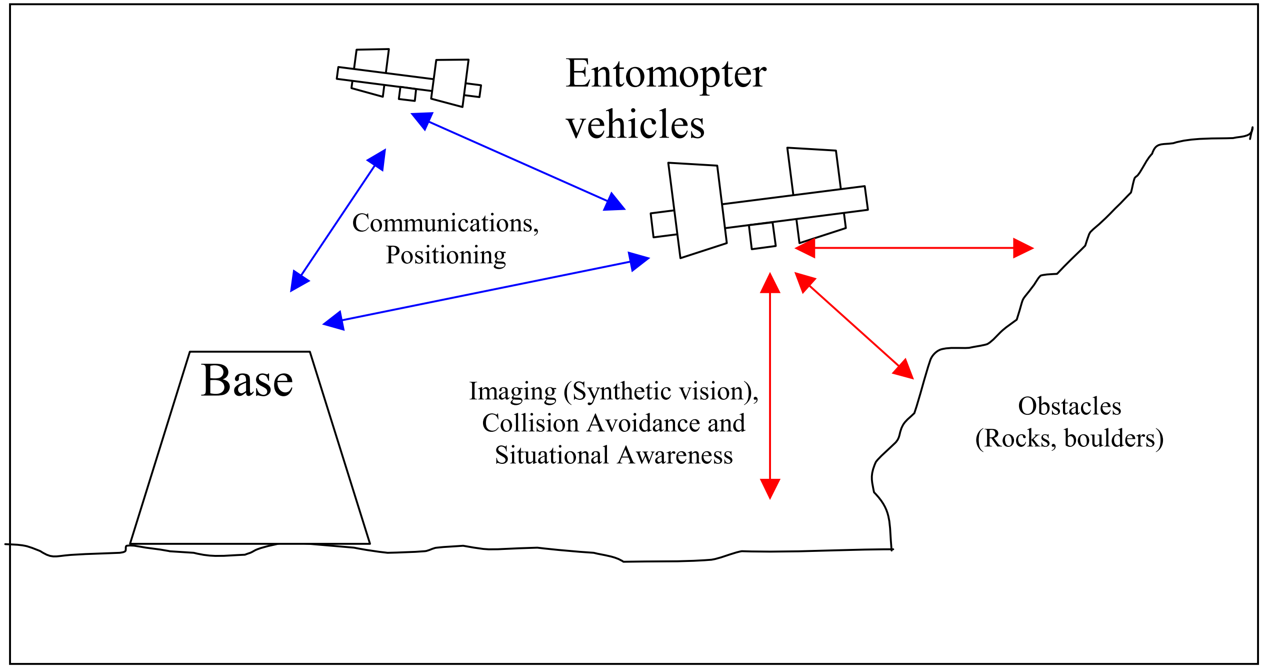


- Gas used to drive wings can be reused to create ultrasonic ranging signals.
- FMCW waveform allows Doppler insensitive range measurements.
- Wing and fuselage motions provide scanning mechanism for ultrasonic beam.

# Communications Scheme

- The communications scheme is based on ultra-wideband (UWB) technology.
  - UWB emits rapid sequencing of extremely short (< 1ns) wideband (> 1 GHz) low power bursts of radio frequency energy.
- UWB system will reduce power, mass and volume over conventional communications systems.
  - Analysis has predicted that data can be transferred over a 10 mile range at a T1 rate on 56 mW of average power.
- UWB  system is software controlled and reconfigurable in real time to perform different functions as needed.

# Direct Oxidation with $CO_2$

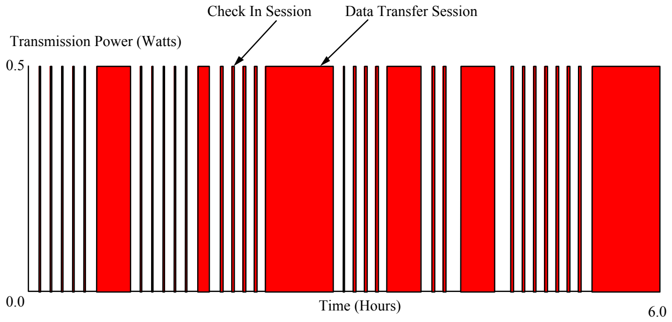


UWB can be simultaneously used for a number of tasks:

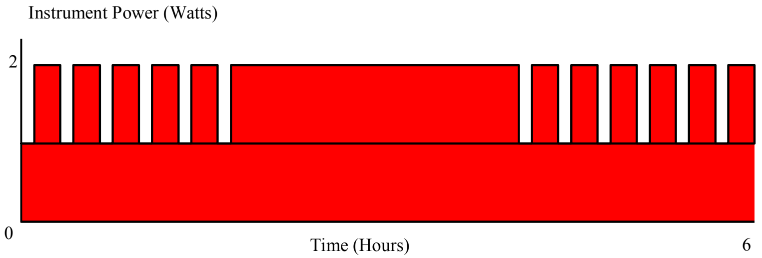
- High rate digital communications between one or more of the Entomopters and the lander or rover.
- Precise position control between the Entomopters and surface or obstacles.
- In-flight collision avoidance radar imaging.
- Timing synchronization between Entomopters.

# Power Production Requirements

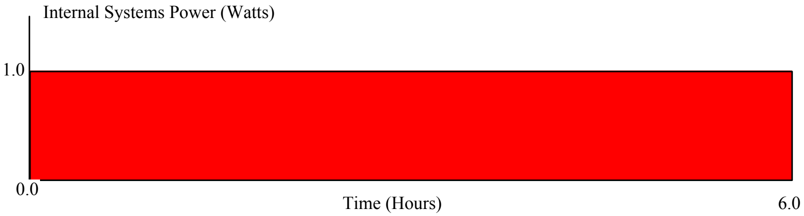
- Communications
  - 0.5 Watt peak
  - 3 W-hr total energy



- Science Instruments
  - 2 Watts peak
  - 10.7 W-hr total

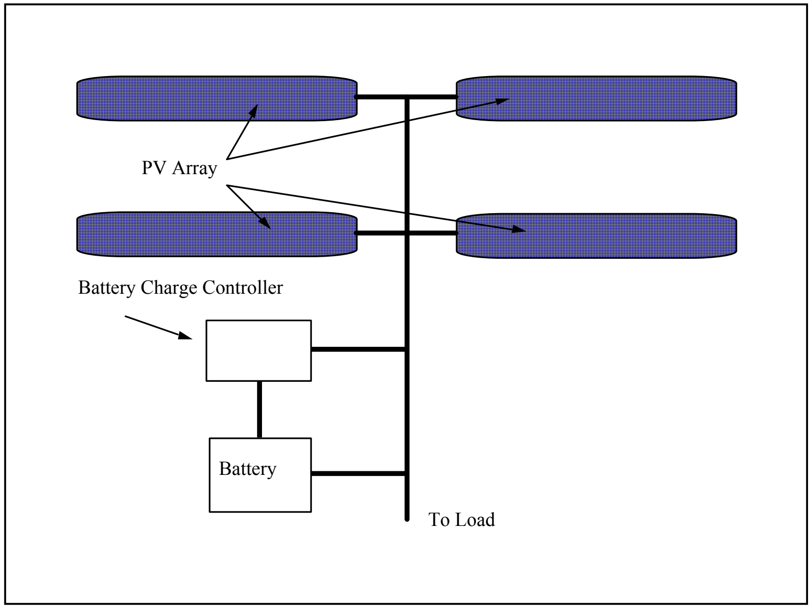


- Internal Computer Systems
  - 1 Watt continuous
  - 6 W-hr total



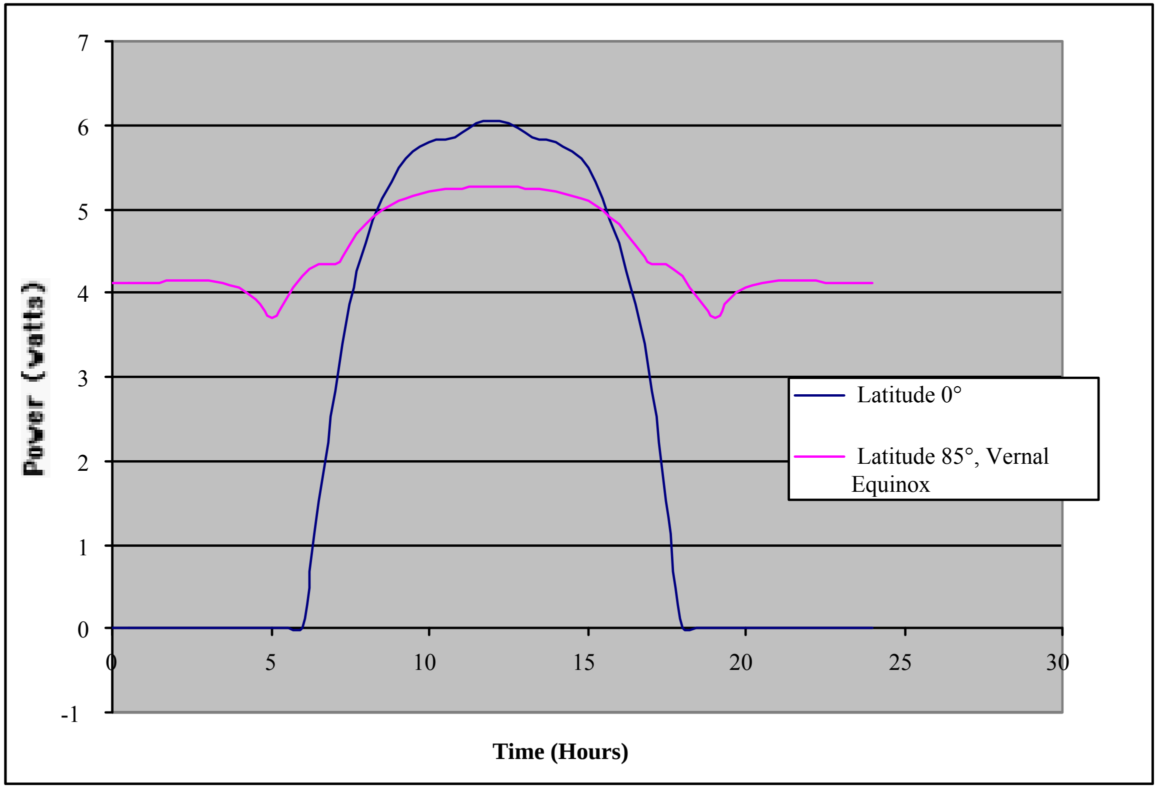
# Photovoltaic/Battery Power System

- This system was the most attractive based on performance and weight.
- Consists of $CuInSe^2$ thin film array on the wings with a Lithium Polymer battery for storage.
- Array Performance
  - 10% efficient
  - 0.20 $m^2$ area
  - Array Mass 0.014 kg
- Battery Performance
  - 6.5 W-hr capacity
  - Battery Mass 0.048 kg
- Estimated system mass 0.068 kg



# Array Performance

- Equator
  - – 55.71 W-hr
- 85° N Latitude
  - – 107.67 W-hr



# Alternate Power System Concepts

- Thermoelectric powered by exhaust gases
- Linear Alternator on the RCM
  - For these concepts to produce power, the vehicle must be running. During down time (on the surface) a battery backup would be needed to supply power. The weight of this battery was greater than the PV system.
- Thermoelectric powered by radioisotope heater unit (RHU)
  - Can produce power during the complete mission. However, the mass of the required RHU alone is greater then the PV/ battery system mass.

# Phase II Goals: Aerodynamic Analysis

- Aerodynamic analysis will be the main focus of the Phase II work:
  - Analysis of unsteady low Reynolds number flow over the wing.
  - Analysis of boundary layer blowing scheme.
  - Production of a 3-D flow field visualization over the wings.
  - Investigation of shed vortices interaction with wings and fuselage.
  - Wind tunnel flow visualization tests.
- The analysis work will be used to validate the Entomopter concept:
  - Validate aerodynamic performance projections.
  - Validate scaling of the Entomopter to size required on Mars.

# Additional Phase II Goals

- Vehicle Design
  - Scale-up from the terrestrial version will be investigated, also component placement, instrumentation, payload, and operations
- Structural Analysis
  - Analysis of the structural loading and design of the fuselage for maximum momentum storage of the wing energy.
- Communications System Analysis
  - Proposed ultra-wide-band (UWB) communications system will be further evaluated.
- Propulsion System and Propellant
  - Additional work is planned for scaling the propulsion system to operate within the Mars environment. This includes weight reduction, performance, and types of fuels.

# Additional Phase II Goals

- Flight Control System
  - Evaluation and lay out of an autonomous flight control system based on the UWB capabilities and or exhaust ultrasonic emissions
- Power System
  - Component lay out of power system based on Phase I results
- Mission Analysis
  - Operational issues, science capabilities, lander / rover interaction, exploration capabilities will be examined
- Development Plan / Cost Estimate
  - Establishment of a development plan for identified technologies. A preliminary cost estimate for the development and operation of an Entomopter system