Solid State Aircraft

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The aircraft concept is to integrate three unique types of materials (thin film solar arrays, thin film lithium batteries and an ionic polymer metal composite) to produce an aircraft that has no moving parts, can fly at high altitudes, is easily deployable and has applications on Earth, Venus and Mars.
Aircraft Operation

The aircraft operates by collecting and converting sunlight to electricity through a thin film photovoltaic array. This electricity is then stored in a battery.

At specified intervals, the energy is discharged to the anode and cathode grids to set up an electric field about the IPMC (synthetic muscles) material. This electric field causes the IPMC to move thereby causing a flapping motion of the wing.

This flapping motion produces lift and thrust for the aircraft.

The electric field generated by the grids is controllable, therefore the shape and motion of the wing is controllable on each flap.
Thin Film Photovoltaic Array

Light Weight: Active material is on the order of 1 to 2 microns thick

Highly Flexible: Ideal for the flexing and motion of a flapping wing

Substrate: Can be made of most materials, presently the best candidate is Kapton (or other polymers). Potentially the Battery or IPMC can be utilized as the substrate

Specific Power: 1 kW/kg near term, 2 kW/kg projected
Thin Film Battery/Capacitor Characteristics

- Rechargeable, Lightweight and Flexible
- Configurable in any series/parallel combination
- Rapid charging/discharging capability
- Can be charged/discharged 1000s of times with little loss in capacity
  – Enables long duration flight times

ITNES sample battery

- Long shelf life with little self discharge
  – Ideal for stowage during interplanetary transit
- Operate over a wide temperature range
  – Enables the batteries to operate under various environmental conditions
- The batteries have the capability to provide high pulse currents
  – Ideal for short duration power loading such as flapping the wings
Ionic Polymer-Metal Composite (IPMC)

- This is the core material of the aircraft. It provides the propulsion and control for the vehicle.
- The IPMC material has the unique capability to deform when an electric field is present across it. The amount and force of the deformation is directly related to the strength of the electric field.
- The deformation is not permanent and returns to its original shape once the electric field is eliminated.
- The material can be manufactured in any size and initial or base shape.
IPMC Material

Constructed of an Ion Exchange Membrane that is surface coated with a conductive medium such as Platinum

Placement of the electrodes can be used to tailor the bending of the material to any shape

The material will bend toward the anode side of the electrodes
IPMC Motion

Under an electric field the ion exchange membrane enables the migration of ions which allows water molecules and hydrated cations to migrate toward the negative pole.

This internal movement of water molecules is responsible for creating internal strains within the material which enable it to move.

For the IPMC material to operate it must be sufficiently hydrated.

Leakage and operation in dry environments may require sealing or redesign of the material for efficient long term use.
Potential Operational Environments

The analysis is set up so that the environments of either Venus, Earth or Mars can be easily selected.

- All the relevant environmental conditions are expressed in equation format for easy use in the analysis.
- A single variable is used to select the planet of operation. All subsequent environmental information is changed to the selected planets environment.
Environmental Properties

**Constants**

- Mean Solar Intensity
- Orbital Eccentricity
- Day Length
- Maximum Declination
- Mean Orbital Radius
- Days in the Year
- Perihelion Day Number
- Mean Planet Radius
- Gravitational Force

**Variables as Function of Altitude**

- Solar Attenuation
- Atmospheric Density
- Atmospheric Temperature
- Atmospheric Viscosity
- Wind Velocity

**Variable as Function of Time of Year and Location**

- Solar Elevation Angle
Earth Surface

Rotation Period (Day) of Venus is Longer than Revolution Period (Year) Potentially Enabling Continuous Flight

Atmosphere is mainly Carbon Dioxide (96.5%) Also contains trace amounts of corrosive Compounds (Hydrochloric, hydrofluoric & Sulfuric Acids)
Atmospheric Density Equals Earth Surface Density at ~50 km
Incident Solar Intensity is ~2600 W/m²
Very high wind speeds above the cloud tops ~100 m/s
Clouds On Venus Extend Upwards to ~64 km
Venus Atmospheric Structure

80 km  Ice Crystal Haze  -93°C

70 km  Sulfuric Acid Cloud Deck  Thin Smog  -43°C

60 km  Slow Convection Circulation  -23°C

50 km  Thick Opaque Clouds, High Sulfuric Acid  67°C

10 to 50 km Atmosphere

40 km  Convectively Stable, Global Circulation Patterns Horizontal With Rising Currents at the Equator Descending at the Poles  Haze layer - Thin Likely Sulfuric Acid Particles  142°C  210°C

30 km  Atmosphere is Clear Below 30 km  390°C

20 km  Gloomy Red Murk

10 km  Slow Convection Cells, Low Winds  410°C

0 km  Surface  455°C
Earth Environment

- Gravitational Force 9.81 m/s²
- Solar Intensity 1352 W/m²
- Atmospheric composition is approximately 80% Nitrogen, 20% Oxygen

Wind speeds generally increase from the surface up to a maximum around the top of the Troposphere (Jet Stream)

The majority of Earth’s weather occurs within the Troposphere which extends to approximately 12 km
Mars Environment

• The atmosphere on Mars is very thin. At the Surface the density is similar to 30 km on Earth
• The atmosphere is composed mostly of Carbon Dioxide

• The temperature on Mars is on average much colder then on Earth. Although at certain times of the year and locations the temperature will rise above freezing, most of the time temperatures are well below the freezing point of water.
• The gravitational force on Mars (3.57 m/s²) is about 1/3 what it is on Earth.
• Solar intensity at Mars is ~590 W/m²
• There are few clouds but dust storms are fairly common
Environmental Considerations on the Structure

• The SSA must be capable of withstanding the environmental conditions at the various proposed operational locations.
• Resistance to corrosive atmospheric compounds (ex, sulfuric acid on Venus).
• Resistance to water evaporation from IPOC within arid environments.
• Low temperature operation.
• Erosive effects of dust (especially for Mars operation).

The selection and evaluation of coatings to resist these environmental effects is under way.
Nature Inspired Configuration

- Initial Chord distribution is based on the Pteranodon wing shape.
- Chord distribution will be optimized through CFD analysis for the design flight conditions of the SSA.

Nature Has A Way Of Finding The Optimum

- The Pteranodon is the largest animal that ever flew.
- It is the closest in size, weight and wing span to the SSA.
- As an initial starting point for a more detailed wing design the Pteranodon wing shape will be used as the model.
Baseline Aircraft Configuration

Like all flapping wing flyers in nature (birds, bats) the solid state aircraft will have a low wing loading and operate within a low Reynolds number flight regime.

Wing geometry and motion are all variable that can be adjusted to provide optimum array output and flight performance.
Material Integration: Near Term

Goal: To produce a method for combining the solar array, battery and IPMC materials into a single flexible structure for lab testing.

• Off-the-Shelf components will be used as much as possible.
• The array & IPMC will be assembled using adhesives, lamination or other readily available means.
• The control grid will be constructed integral with the IPMC material.
• Potential adhesion methods will be tested on coupon samples of the thin film array, IPMC, wiring and electrodes.

• Due to the development stage of thin film batteries, these initial integration tests will only include the array and IPMC materials.
• External batteries or capacitors will be used during this initial testing.
• The various integration methods will be tested for adhesion and bending capability.
Electrode Placement & Operation

This is one of the more critical & challenging tasks to be undertaken

• For efficient flight the wing must be capable of flapping, twisting & changing the camber of the airfoil along the wing length

• This is accomplished by the placement and operation of the electrodes that control the IPMC material motion

Analysis of the electric field generation for various electrode placements

Devise a means of controlling electrode voltage from a single processor & power source

Devise an electrode layout & associated voltage strength / polarity to achieve a given wing shape

Produce a wing test section to validate the electric field analysis & control scheme
IPMC Material Properties & Construction

Two of the largest pieces of IPMC (~45 cm X 23 cm) ever made have been constructed to serve as test wing sections.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's Modulus E</td>
<td>Up to 2 GPa</td>
</tr>
<tr>
<td>Shear Modulus G</td>
<td>Up to 1 GPa</td>
</tr>
<tr>
<td>Poisson's ratio, v</td>
<td>Typical: 0.3-0.4</td>
</tr>
<tr>
<td>Power density (W/mass)</td>
<td>Up to 100 J/kg</td>
</tr>
<tr>
<td>Max force density (Cantilever Mode)</td>
<td>Up to 40 Kgf/Kg</td>
</tr>
<tr>
<td>Max displacement/strain</td>
<td>Up to 4% linear strain</td>
</tr>
<tr>
<td>Bandwidth (speed)</td>
<td>Up to 1 kHz in cantilever vibratory mode for actuations</td>
</tr>
<tr>
<td></td>
<td>Up to 1 MHz for sensing</td>
</tr>
<tr>
<td>Resolution (force and displacement control)</td>
<td>Displacement accuracy down to 1 micron</td>
</tr>
<tr>
<td></td>
<td>Force resolution down to 1 mg</td>
</tr>
<tr>
<td>Efficiency (electromechanical)</td>
<td>Up to 6% (frequency dependent) for actuation</td>
</tr>
<tr>
<td></td>
<td>Up to 90% for sensing</td>
</tr>
<tr>
<td>Density</td>
<td>Down to 0.8 g/cm³</td>
</tr>
</tbody>
</table>

Material Efficiency

![Graph showing efficiency vs. frequency with different markers for PVP treated and untreated samples.](image)
Long Term Integration Strategy

Goal: To provide a scheme to producing a fully integrated composite structure from the three main materials and subsequent components.

• The potential of constructing the SSA by depositing each component material layer onto the subsequent layer is being investigated.
• This method would use the IPMC material as the main substrate.
• The battery layer and solar cell layer as well as the electrodes and wiring would be build directly onto the IPMC through a combination of deposition and lithography techniques.

• Some of the main issues that are to be examined are the material compatibilities, adhesion characteristics, material thickness and deposition and lithography techniques, their capabilities and requirements.
Feasibility analysis is an iterative process between the power available and the power required to fly. The flight environment and aircraft geometry and properties factor into determining these quantities.
Power Production

The amount of power available to the aircraft is based on the Environmental conditions it is flying within

Output power will vary based on the
Latitude of flight ($\phi$)
Time of year ($\delta$)
Time of day ($\theta$)

Available power also depends on the
Atmosphere attenuation ($\tau$)
Solar cell efficiency ($\eta$)
The output power of the array is calculated by determining the power of a small segment of the array and integrating this over the length of the wing. This is performed throughout the flap motion.

Approximately 50,000 spreadsheet cells are used to calculate the array output.
The analysis allows the SSA attitude to be varied. The SSA can be pointed in any direction (360°) within the plane of flight. This will eventually enable the analysis to simulate a mission flight. The examples shown are for Earth. It should be noted however, that the attitude of the aircraft did not have a significant effect on the output power for summertime month operation.
• The wing was curved in a parabolic shape.
• The wing curvature is also a variable in the analysis and effects both power output and lift generation.
Power Output Along the Wing

- Power output along the wing is shown for different wing angles, times of the day, latitudes and aircraft attitude.
- This calculation of instantaneous output power is integrated and summed to provide the energy available throughout a flap cycle.

Variation in output power along the wing is not significantly effected when that aircraft is at an attitude of 0°
Power Output Along the Wing

More significant effects on the output power along the wing are seen at attitudes of 90°.
Power Production Throughout A Flap Cycle

• Total energy available is the integrated area under the flap cycle power curve
• This energy is compared to the energy required to determine feasibility under the given flight conditions and aircraft geometry.

The shorter the flap duration the greater the energy produced & however, the greater the power required.

<table>
<thead>
<tr>
<th></th>
<th>Maximum Glide</th>
<th>Minimum Glide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Available</td>
<td>12,658 J</td>
<td>11,961 J</td>
</tr>
<tr>
<td>Energy Required</td>
<td>12,658 J</td>
<td>2,439 J</td>
</tr>
<tr>
<td>Flap Duration</td>
<td>3.3 s</td>
<td>13.9 s</td>
</tr>
<tr>
<td>Glide Duration</td>
<td>10.6 s</td>
<td>0 s</td>
</tr>
</tbody>
</table>
Power Consumption

Motion of the Wing

Bending

Twisting

Communications

Induced Drag

Parasite Drag

Power required by internal systems & their inefficiencies

Drag due to lift generation & movement through the air

- Payload
- Control Grid
- Avionics
- Computer System
Power Consumption due to Motion

Motion of the wing consists of a flapping rate and maximum angle traversed during the flap.

The forces generated by the wing motion are due to the acceleration and deceleration of the wing mass. These forces vary along the wing length.

- The force and therefore energy required to move a small segment of the wing is calculated.
- These are summed and multiplied by the efficiency of the IPMC in generating the required force.
- This integrated force calculation is performed over the flap cycle.
Wing Force Due to Motion

The power required to move the wing is the area under the force vs distance traveled curve.

The distance traveled varies along the wing length to a maximum at the tip.

The tapered planform minimizes the mass at the wing tip and therefore minimizes the force required to move the wing.
The required lift needed for the aircraft to fly will depend on the total mass of the aircraft.

The wing mass is dependent on its shape (area) and the specific masses of the components that make it up.

- Payload mass (0.25 kg)
- Solar array specific mass (~0.12 kg/m²)
- IPMC material specific mass (~1.5 kg/m²)
- Thin film battery specific mass (~ 0.25 kg/m²)
- Operational systems (communications, flight computer, etc.) mass (0.5 kg)
Producing Enough Lift to Fly

For a given airfoil & chord distribution, the lift produced by the wing is calculated throughout a flap cycle. This lift generation will be dependent on the various wing motion parameters

- The angle the wing traverses
- The rate at which the wing is moving
- The twist or change in angle of attack of the specific segment of the wing

The lift produced by each segment of the wing throughout the flap motion is calculated and summed to get the total wing lift generated.
Determination of Lift & Thrust Generation

The propulsion force and lift generation of the aircraft are accomplished by the flapping of the wings.

By altering the shape and angle of attack of the wing the amount of lift and the direction of this lift force can be controlled.

This is the same method birds use to generate lift and thrust.

The lift and lift vector generated can vary between each wing as well as along the wing span itself.

This provides a significant amount of control and provides a means for maneuvering.
Airfoil Selection: Thin Airfoil with 1% thickness & 5% Camber
Attributes: Good low Reynolds number characteristics
Thin cross section minimizes mass
Performance data is being generated at low Reynolds numbers (~100,000)

Ongoing Aerodynamic Analysis & Design

• 2-D performance estimates will be generated under specific flight conditions using airfoil analysis tools (FLUENT, XFOIL, JavaFoil)
• SSA Analysis tool will be used to evaluate the performance of the SSA with various types of airfoils based on their 2D performance characteristics
• Using the 2D results an airfoil and wing distribution will be selected. Full 3D steady-state modeling of the wing will be done at fixed points throughout the flapping motion.
• An evaluation of the tools and approach necessary to perform a full 3D analysis of the moving wing are being determined
CFD Airfoil Analysis

• CFD analysis is ongoing to provide lift coefficient and drag coefficient data for a thin curved airfoil at Angles of attack and Reynolds numbers representative of the estimated SSA flight regime and wing motion.
• Various Flat Plate Airfoils, Eppler 378 & Selig 1091 are being evaluated.
Aerodynamic & CFD Analysis Goals

• The aerodynamic analysis is to provide a performance estimate (lift & drag) of the SSA under various operational conditions.
• Through an iterative process this analysis will be used to determine the optimum wing geometry, motion and SSA performance capabilities.
• Ultimately the CFD analysis is to provide a full steady-state 3D flow field over the SSA using the optimized wing geometry and motion for discrete points throughout the flapping motion.
• Requirements and a plan for achieving a full transient 3D analysis are being assembled.
Total drag is the summation of the parasite & induced drag or each of the individual segments along the wing.

\[
D_f = \sum_{i=0}^{i} \frac{1}{2} \rho V_i^2 (c_f 2S + c_d S)
\]

\[P_i = D_i V_i\]

The power needed for each individual wing segment to overcome this drag is equal to the drag on that segment and the segments instantaneous velocity.

\[
V_{fi} = \sqrt{V^2 + \frac{4\theta r_i}{t_f}}
\]
Overall Energy Balance

• The energy balance is performed over a complete flap cycle.
• The energy collected by the solar array must be equal to or greater than that needed by the vehicle to fly and power all its systems.
• Sufficient lift must be generated during the flapping portion of the cycle so that the aircraft can climb.

For a given wing geometry, motion and flight location, the flap duration / glide duration are iterated upon to produce a combination that enables the aircraft to fly.
• Or to produce a combination that minimizes energy consumption.
Analysis Method

The energy consumed during the flap has to equal the energy collected during the total flap and glide cycle.

- The analysis was an iterative process
- For a given set of inputs the flight speed and flap to glide ratio would be calculated.
- If no solution existed then certain inputs would be varied until a solution was found.

Inputs
- Flapping Frequency
- Flap Angle
- Aircraft Size
- Altitude

Power Available

Lift Generated

Power Consumed (Motion & Drag)

Flight Speed
Flap to Glide Ratio
Analysis Progress and Objectives

• Using the analysis described results on the flight capabilities under Earth environmental conditions were produced.
• These results were generated to validate the analysis method as well as investigate the aircraft performance sensitivity and flight envelope to variations in operational conditions and size.
  - Effect of Latitude
  - Effect of Altitude
  - Effect of Flight Time of Year
  - Effect of Aircraft Size

• Updated aerodynamic data will be incorporated into the analysis to provide more accurate results.
• The analysis tool will be utilized to optimize the aircraft geometry and wing motion.
• Results will be generated for Venus and Mars flight environments.
Effect of Latitude
For Flight on Earth at 15 km Altitude on March 21st with a 10m wingspan

• As latitude increases the available energy decreases.

• The energy required decreased with increasing flap duration, until the glide duration equals zero.

• Energy available increases as the cycle time (flap duration + glide duration) increases.

• The minimum power required occurs when the glide duration goes to zero. This is because the required flap duration time increases at a faster rate then the decrease in glide duration.
Effect of Altitude
For Flight on Earth at 45°N Latitude on March 21st with a 10m wingspan

- Energy required varies slightly with increasing altitude.
- As altitude increases the maximum flap duration decreases. Shorter more frequent flaps are needed to compensate for the lower density air.
- Energy available is reduced as altitude increases due to the shorter flap cycles.
Effect of Time of the Year
For Flight on Earth at 45°N Latitude at 15 km Altitude with a 10m wingspan

• The available energy decreases in the winter months and increased during the summer due to seasonal effects.
Effect of Aircraft Size
For Flight on Earth at 45°N Latitude, Altitude of 15 km on March 21st

• The aircraft scales with size by increasing the flap duration.
• Larger aircraft require more energy per flap but also produce much more energy.
• At a given altitude the larger the aircraft the larger the flap durations can be and therefore the more efficient the aircraft is.
Maximum Achievable Altitude
For Flight on Earth at 45°N Latitude,

- Curves show flight at the maximum efficiency when the glide duration is zero.
- As the aircraft size increases the maximum altitude increases but this is a diminishing
Mission Analysis

• Utilizing the SSA capabilities established from the performance & communications analysis & vehicle design work, an evaluation of the potential mission the SSA may be capable of carrying out will be made.
  • Critical factors will be flight duration, flight altitude, payload capacity, payload power availability & data transfer capability.
  • From these various types of science data gathering & observing equipment will be assessed.
• The mission assessments will be performed for all three potential planets of operation.
• Both individual & multiple aircraft operations will be considered.
• For multiple aircraft missions, a fleet of SSAs can be considered which could either perform a unique task or provide an infrastructure such as a communications network.
• Specific aspects of the missions are also being considered these include:
  • Stowage while in space transit (for Venus and Mars missions)
  • Deployment
  • Navigation
  • Altitude Control
  • Landing
Science & Payload

Science & other equipment will be evaluated for use on the SSA. This evaluation will take into consideration the instruments mass, volume, power requirements and operational concerns such as vibration as well as the potential for miniaturization.

Potential science & data gathering includes:
• Camera, high resolution and context
• Atmospheric measurements: temperature, pressure etc.
• Magnetic field measurements.
• Communications relay transmitter / receiver
• Atmospheric sounding with various frequencies (dependent on the capabilities of the communications system)
• Beacon

In addition to specific payloads, the systems on board the SSA will be evaluated to determine if any dual use potential exists. For example the communications antenna may be used to send receive signals at various frequencies in order to collect data in a sounding fashion.
Science: High Resolution Imagery

- Detailed images can be taken on a regional scale at high resolution
- Vertical structures (canyon, mountain) can be imaged at various angles
- Imagery can be used for surveillance, mapping or geological characterization of the planet.
Science: Atmospheric Sampling & Analysis

- **Examine the Atmosphere Both Vertically & Horizontally (Temperature & Pressure)**
- **Sample Atmospheric Trace Gases**
  - Determine Concentrations of Trace Gases and Reactive Oxidizing Species
  - Examine the Correlation with the Presence of Active Oxidizing Agents and Absence of Organics in Martina Soil
- **Investigation of Dust within the Atmosphere and Dust Storms**
  - Sample Long Lived Airborne Dust in the Atmosphere (Size, Distribution, Electrostatic Charging etc.)
Science: Magnetic Field Mapping

Mapping of the Magnetic Fields can Give Insight into the Tectonic History of the Planet & Investigate the Geology and Geophysics of Venus
Communications System

Communications or data collection through sounding to surface with thin film antenna

- Getting data & information to and from the SSA is a critical function.
- The unique configuration of the SSA & its thin light flexible structure pose a unique challenge for the communications system.
Quickly Deployable Observation / Communications Network

Inter-aircraft Communication

Satellite Communication

Surface Communication
Solid State Aircraft Mission Animation