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# Solid State Aircraft Concept Overview


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*Abstract*

*Due to recent advances in polymers, photovoltaics, and batteries a unique type of aircraft may be feasible. This is a "solid-state" aircraft, with no conventional mechanical moving parts. Airfoil, propulsion, energy production, energy storage and control are combined in an integrated structure.*

*The key material of this concept is an ionic polymeric-metal composite (IPMC) that provides source of control and propulsion. This material has the unique capability of deforming in an electric field and returning to its original shape when the field is removed. Combining the IPMC with thin-film batteries and thin-film photovoltaics provides both energy source and storage in the same structure.*

*The characteristics of the materials enables flapping motion of the wing to be utilized to generate the main propulsive force. Analysis shows that a number of design configurations can be produced to enable flight over a range of latitudes on Earth, Venus and possibly Mars.*


## 1. Introduction

Due to the recent advancements in photovoltaics, batteries, and polymer materials, a unique type of unmanned aircraft may be feasible. This is a “solid state” aircraft (SSA) with no moving parts. An artist rendering of the concept is shown in Figure 1. The unique structure combines aerodynamic lift, propulsion, energy collection, energy storage and control. Thin-film solar arrays are used to collect sunlight and produce power that is stored in a thin-film lithium battery. This power is used to fly the aircraft by setting up an electromagnetic field (EMF) along the wing of the vehicle. The wing, made with ionic polymeric-metal composite (IPMC) synthetic muscles, bends in the presence of this EM field producing the desired flapping motion.

**Figure 1. Artist's drawing of the Solid State Aircraft concept**

This layering of the various component materials is shown in Figure 2. This aircraft would fly in a similar fashion to a hawk or an eagle. It would glide for long distances and flap infrequently to regain altitude. The solid state nature of the aircraft allows it to be very robust, extremely lightweight and capable of flight unlike any other present day air vehicle.

This type of air vehicle has a number of potential applications as a research platform on both Earth and other planetary bodies. Because of its projected relatively small mass and flexibility, the aircraft is ideal for planetary exploration. These characteristics allow the aircraft to be easily stowed and launched at a


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minimal cost. Potentially, a fleet of these aircraft could be deployed within a planet's atmosphere and used for comprehensive scientific data gathering/observation or as communications platforms. A whole planetary science gathering or communications/navigation architecture can be built around these lightweight, easily deployable, robust aircraft.

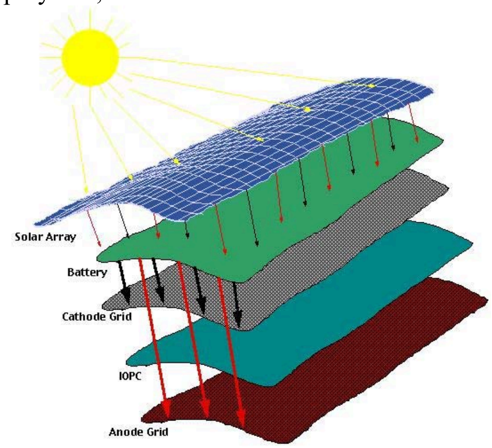


**Figure 2. Component layout of the SSA**

The technology to produce this type of aircraft is presently available. There have been great advances in recent years in each of the three main components areas that make up the aircraft (thin-film photovoltaic arrays, thin-film batteries, and polymer composites). Because of these advances this type of aircraft may now be possible.

## 2. Component Materials

The power source for the aircraft is a thin film photovoltaic array, an example of which is shown in Figure 3. This type of array is ideal for the

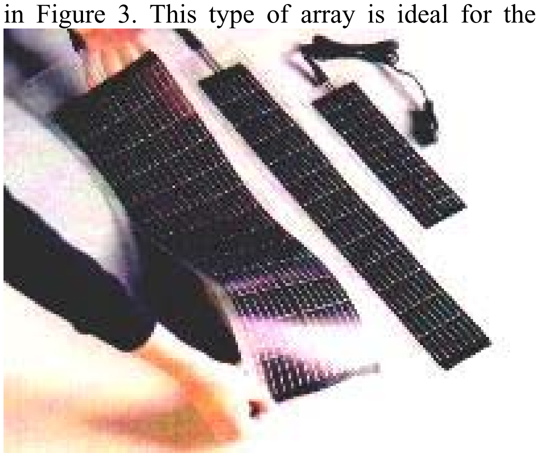

**Figure 3. Thin film array**

SSA. It is flexible, light weight and can potentially be manufactured on a variety of substrate materials. The active material in thin film arrays is on the order of 1 to 2 microns thick and present day production efficiencies are on the order of 8% depending on the type of conversion material used. The SSA can easily take advantage of the current development efforts for space thin film PV arrays. Thin film solar cells of sufficient efficiency and specific power already exist that will enable prototype development of the SSA. The most mature thin film technology is the triple junction amorphous silicon cells produced on a 1.27E-4 mm stainless steel substrate. Cells of similar design have also been produced on 2.54E-4 mm thick Kapton film.

Utilizing Kapton as the substrate provides specific power values greater than 1 kW/kg. In the future, 10 to 20 years, new materials such as CuInGaSe and CdTe could provide thin film arrays approaching efficiencies of 20%. This type of light weight high efficiency solar array will have a significant effect on the capabilities of the SSA. The next main component is the thin film battery or capacitor. Lightweight energy storage is critical for the operation of the SSA. Due to the movement of the wings the output power will vary significantly during each flap cycle. Therefore energy storage must be utilized to level off the variation and provide continuous power to the wings. Also by having energy storage available the power produced by the solar array while the SSA is gliding can be stored and utilized during the next flap cycle. Supercapacitors can provide the low capacity, high impulse power required to manage the loads associated with alternately gliding and flapping the wings. These devices have a very high peak-power capability and can withstand the millions of charge discharge cycles needed for a flapping wing.

Supercapacitors with energy densities of nearly 10 kW/kg are commercially available. A potential candidate for this type of supercapacitor is a newly developed thin film capacitor based on a dielectric polymer film, Ployvinylidenefluoride.

Another option is to utilize the emerging technology of thin film lithium ion or lithium polymer batteries. These types of batteries, an example of which is shown in Figure 4, are rechargeable, lightweight and flexible. They can be rapidly charged and discharged, have a log shelf life, operate over a wide temperature range and can be utilized over 10,000s of charge / discharge cycles with little loss in capacity. The thin film battery is produced by depositing the various material layers, cathode, electrolyte, anode and current collector, onto a substrate.

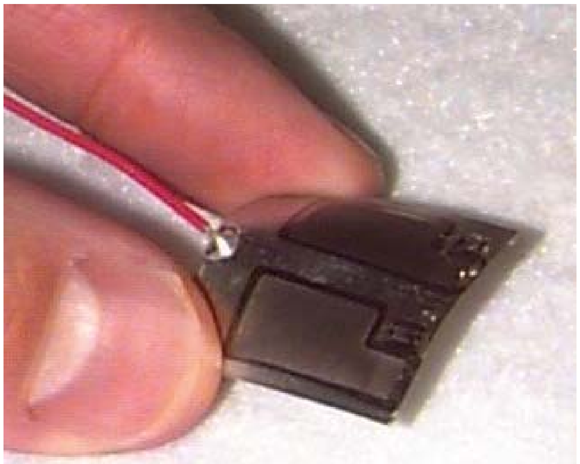

**Figure 4. Thin film li-ion battery**

Variations in the cathode material (magnesium oxides, cobalt oxides or yttrium oxides) are the main difference in different types of Lithium-Ion batteries. These types of batteries are presently not commercially available.

The main component of the SSA is the ionic polymer metal composite (IPMC). An IPMC will exhibit a large dynamic deformation if placed within a time-varying electric field. An example of this is shown in Figure 5 for a 1 cm wide, 4 cm long and 0.2 mm thick strip of the material. This sequence demonstrates the very large deformation capability (up to 4 cm) of the material in the presence of an electric field. For this example the time of motion was 0.5 seconds and 2 volts were applied. This motion is illustrated in Figure 5.

Conversely if the IPMC material is deformed by an external force, it will produce a dynamic electric field across the electrodes that are connected to it. This is a key factor that comes into play in the control scheme for the SSA.

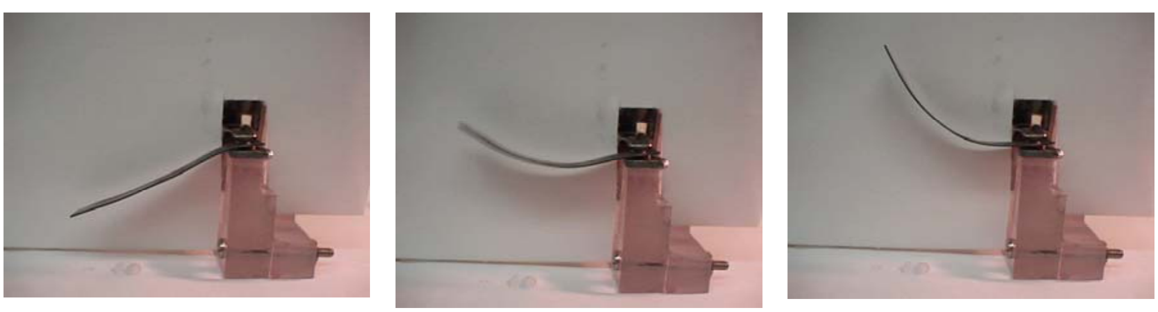

**Figure 5. Successive photographs of an IPMC strip in a time varying electric field**

IPMC material is constructed using an ion exchange membrane. This refers to a material, usually a polymer, designed to selectively pass ions of a particular charge (cations or anions). The two main classes of polymer ion exchange membranes are perfluorinate alkenes which interact with water to enable the passage of the appropriate ions and styrene/divinylbenzene based polymers that are more rigid and analogous to gels. The IPMC is constructed by layering a conductive coating onto the ion exchange membrane and then placing electrodes at various locations on the conductive coating. The conductive coating is designed such that it extends into the polymer. This enables the generation of localized EMF fields of very high strength which provides the source for ionization. A diagram of the layered structure of the IPMC is shown in figure 6.

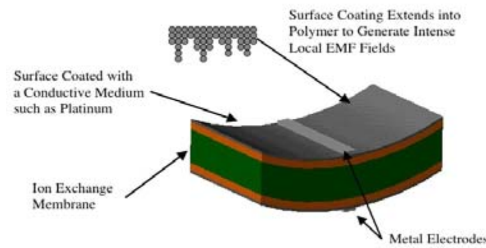


**Figure 6. Internal structure of IPMC material**

The IPMC will bend toward the anode when a field is applied. This motion is set up by the migration of ions within the material. One side of the material will expand and the other will contract due to the ion movement within the material thereby producing the bending motion. Water within the material is critical for ion formation and setting up the internal strains within the material the produce its motion. The absence of water will greatly degrade its performance. Therefore water leakage from the material is a critical issue in the SSA development, especially for its use in dry environments. To reduce or eliminate the loss of water the material can initially hydrated and then sealed with a water impermeable coating.

Another option is to utilize a different type of ionic liquid instead of water, one that would not as easily be lost or evaporate away. Some general specification of the IPMC material are given in Table 1.

**Table 1. Basic properties of the IPMC material**

| Property | Value |
|---|---|
| Young's Modulus, E | Up to 2 Gpa |
| Shear Modulus, G | Up to 1 Gpa |
| Poisson's Ratio, ν | Typical 0.3-0.4 |
| Power Density (W/kg) | Up to 100 J/kg |
| Maximum force density (Cantilever Mode) | Up to 40 Kgf/kg |
| Maximum displacement / strain | Up to 4% linear strain |
| Bandwidth (speed) | Up to 1 kHz in cantilever vibratory mode for actuations, Up to 1 Mhz for sensing |
| Resolution (force and displacement control) | Displacement accuracy down to 1 micron, Force Resolution down to 1 mg |
| Efficiency (electromechanical) | Up to 6% (frequency dependent) for actuation, Up to 90% for sensing |
| Density | Down to 1.8 g/cm$^3$ |

A key aspect to the feasibility of the SSA concept is the successful integration of these three component materials into a single composite. The integration must be performed in a manner that enables each component to operate as designed and provide control of the IPMC. Initially the integration of the component materials will be performed to demonstrate the ability for the materials to operate together and provide a means for determining a control scheme for the IPMC. The initial integration setup will consist of an Amorphous Silicon thin film array, an external battery a controller and a section of the IPMC material. This setup is shown in Figure 7. Ultimately the potential exists for constructing the SSA by depositing the layers of each component material onto the subsequent material with the IPMC as the base substrate. This would minimize mass and enable a truly integrated structure.

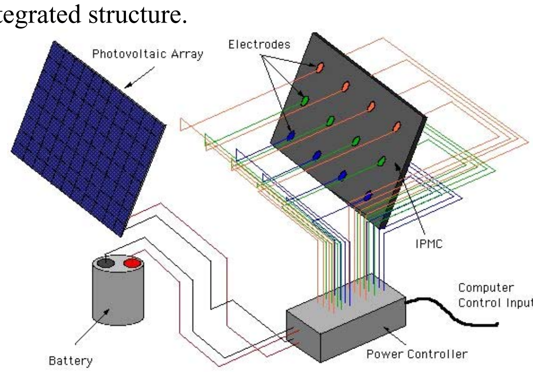


**Figure 7. Initial integration and control test setup**

## 3. Vehicle Operation

The unique material composition of the aircraft enables flapping motion of the wing to be utilized as the main means of propulsion, thereby eliminating the need for a more conventional propulsion system. The aircraft flight motion will consist of an intermittent flapping and periods of gliding. During the flapping portion of the flight the aircraft will gain altitude. Then, during the gliding portion, will glide back down to the starting altitude. This cycle is shown in Figure 8.

Due to the estimated low wing loading of the aircraft, it will be able to soar for periods of time and utilize the wing flapping to regain lost altitude. The ratio of the flap time to the gliding time will depend on the available power, power consumption rate and flight conditions. The flap to glide ratio is a critical aspect of the vehicle optimization. Various combinations of glide times to flap times can be utilized. During gliding, the wing shape can be altered to enable steering and control of the aircraft. This control mechanism is similar to that of gliding birds, changing the angle of attack and/or wing shape to produce directional lift on a given wing. This variation in shape can be achieved by a grid of electrodes that are computer controlled. The voltage potential can be varied over the grid thereby tailoring the electric field generated to produce a non-uniform bending in the wing. The variation in lift between the wings can be used to steer and control the aircraft. The force vectors generated by the wing are shown in Figure 9 for the upstroke and downstroke.

Like all flapping wing flyers in nature the SSA will operate within a low Reynolds number flight regime. This is due mainly to its low wing loading and the potential for high altitude

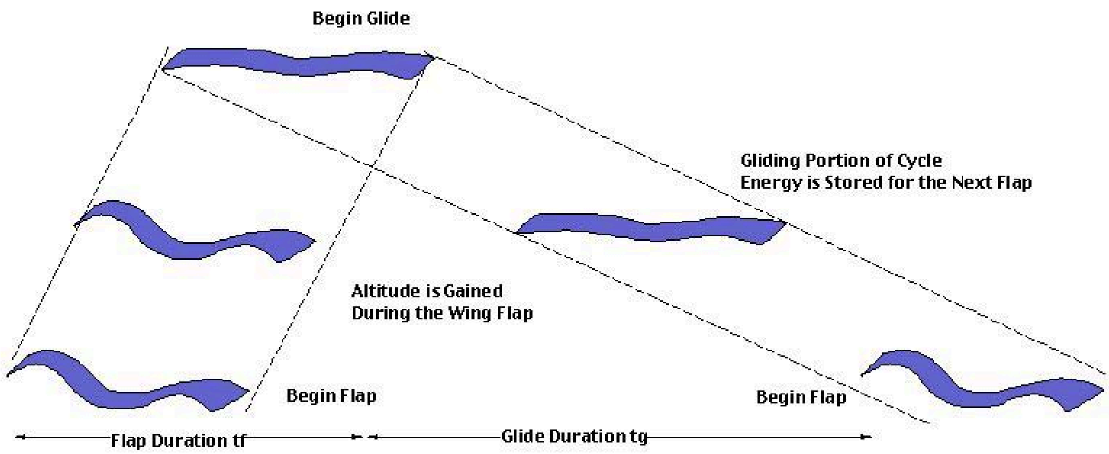


**Figure 8. Flap--glide cycle flight profile**

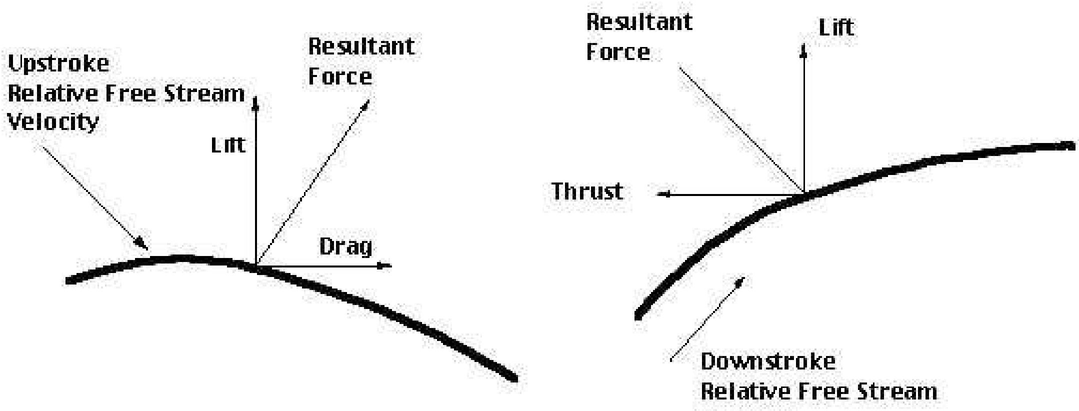


**Figure 9. Wing forces on upstroke and downstroke**

operation where the air density is low. Selecting the correct wing geometry and airfoil properties will be a key aspect in providing good aerodynamic performance and minimizing power consumption. To minimize mass as well as be compatible with the IPMC material properties the wing will have a thin cross-section. The overall shape of the wing will be optimized to the flapping motion of the wing. The initial wing design point is based on that of a Pteradon. The Pteradon, shown in figure 10, was the largest flying creature that ever lived on Earth. Its thin membrane wing and its estimated wing loading are similar to that of the SSA. Because of this and the realization that nature has a way of finding the optimal design configuration, the Pteradon is a good starting point for the SSA wing design.

Because the sun is the main power source it needs to operate at locations that have sufficient available solar radiation. However, this also means that oxygen is not required for the operation of this aircraft. This is a large benefit, compared to conventional powered aircraft, in applying this concept to atmospheres outside of Earth. Potentially the inner planets of the solar system, which have atmospheres (Venus, Earth and Mars), would be places where this type of aircraft could be utilized. An evaluation was performed to determine where this concept would be applicable and what the altitude flight range would be. Initial results were generated for various sized SSA. These results were based on an energy optimization between the flapping rate and duration and the gliding duration performed over a range of altitudes at the planets of interest. This energy balance analysis showed that there is a large range of operation on both Venus and Earth. The operational range on Mars was small and the SSA required size was very large. A summary of these results are shown in figure 11.

There are a number of potential applications for the SSA from planetary exploration to a quickly deployable Earth observation and communication system. By integrating a thin film

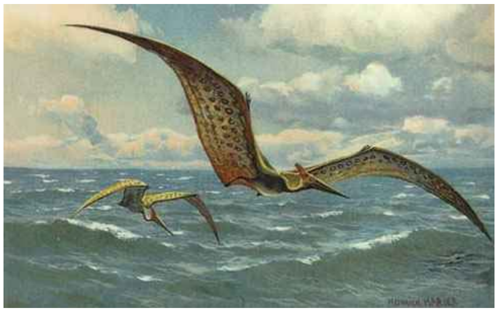

**Figure 10. Artist's drawing of a pteradon**

antenna to the underside of the SSA, communications between the aircraft and the surface can be achieved. Also transparent metallic antenna technology would allow for the installation of an antenna on the upper surface of the aircraft on top of the solar array. This would enable the SSA to communicate to a satellite. An illustration of this capability is shown in figure 12. These antennas can also be used for science data gathering by providing a means of sounding the atmosphere. Other potential science and data gathering capabilities include, high resolution and context camera imagery, atmospheric measurements, magnetic field measurements, communications relay transmitter/receiver, atmospheric sounding, beacon.

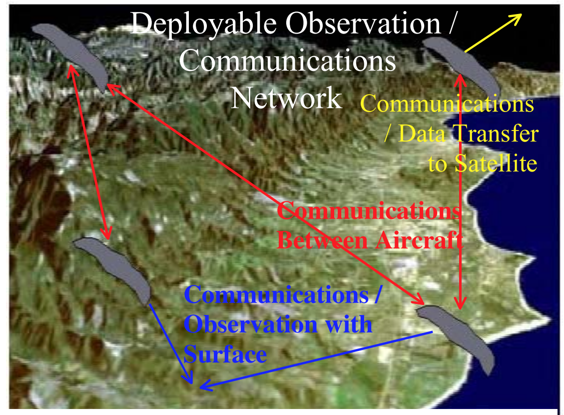


**Figure 12. SSA Communication/data transfer**

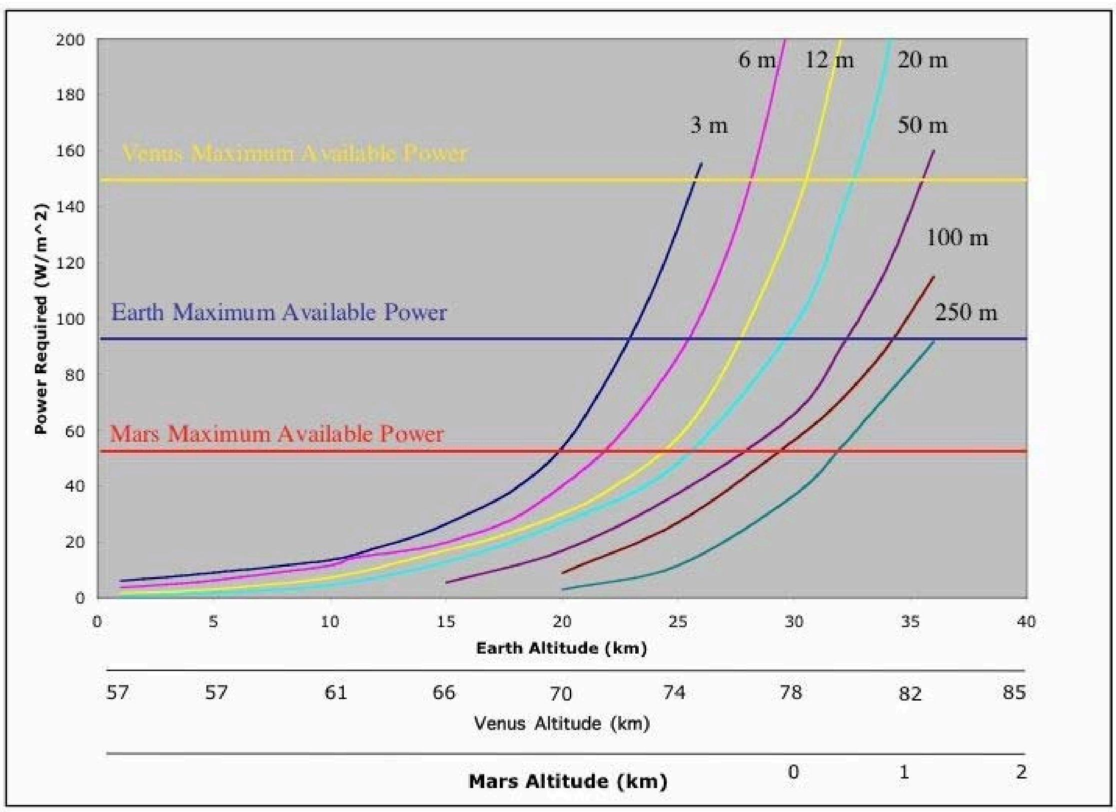


**Figure 11. Flight altitude range for SSA of various sizes on Venus, Earth and Mars**

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