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DESIGN OF A SOLAR SAIL MISSION TO MARS

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AUBURN UNIVERSITY

INTRODUCTION

A new area of interest in space vehicles is the solar sail. Various applications for which it has been considered are attitude control of satellites, focusing light on the jungles of Vietnam, and a Halley's comet rendezvous. Although for various reasons these projects were never completed, new interest in solar sails has arisen. The solar sail is an alternative to the rocket-propelled space vehicle as an interplanetary cargo vehicle, and manufacture of solar sails on the space station is a possibility. Solar sails have several advantages over rockets, including an unlimited power supply and low maintenance.

The purpose of this project is to design a solar sail mission to Mars. The spacecraft will efficiently journey to Mars powered only by a solar sail. The vehicle weighs 487.16 kg and will be launchable on an expendable launch vehicle.

The project includes an investigation of options to minimize cost, weight, and flight duration. The design of the sail and its deployment system are a major part of the project, as is the actual mission planning. Various topics researched include solar power, materials, space environment, thermal control, trajectories, and orbit transfers. Various configurations are considered in order to determine the optimal structure. Another design consideration is the control system of the vehicle. This system includes the attitude control and the communication system of the sail.

This project will aid in determining the feasibility of a solar sail and will raise public interest in space research.

STRUCTURES

There are many aspects of the solar sail vehicle to consider in the design of the actual structure of the vehicle, including sail configuration, stability, method of stiffening, and housing for the various systems.

Designing the sail of the solar sail vehicle included consideration of several configurations such as various separated panels as used in the helio-gyro vehicle considered for a Halley's Comet rendezvous, and uniform panels such as the square sail chosen for this project. The square sail, as seen in Fig. 1, was chosen for several reasons. The simplicity of deployment of the square configuration is a major advantage, as is its high area-to-mass ratio(1). This design consists of four booms, 114 m in length, connected tangentially to a cylindrical bus measuring 1.4 m in diameter and 1 m in length. The sail has four triangular sections contained between the booms and has a total area of 25,992 m$^{2(2)}$. The weight limitation determined the final measurements of the sail and the total force, 210,040.00 N/m^2, on the bus determined the thickness of the bus at 1 cm. This thickness includes a large increase from the necessary thickness calculated to insure reliability.

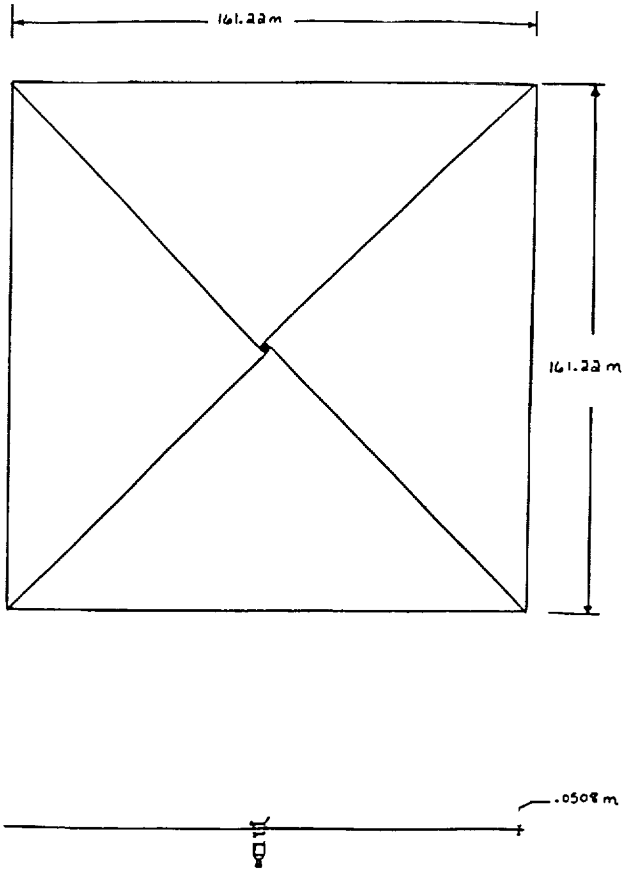

Fig. 1. Two-View Drawing of the Solar Sail

The method of stiffening the structure is also an important design consideration. Spinning the sail after deployment was not feasible because of complications in attitude control. Extendable booms were ruled out because of complexity and weight. A free sail without booms was considered but lacked sturdiness for such a long trip. Uncured booms were chosen for their flexibility and compactness in the uncured state; curing takes place after deployment(1).

DEPLOYMENT

One of the major design considerations for the solar sail vehicle is the method of deploying the sail. Minimizing weight and complexity of the deployment system are primary concerns in designing the method of deployment.

The sail folds accordion-style into a wedge shape between the booms. Both the sail and the booms will coil around the bus before deployment and be encased in an open-ended cylinder. The enclosed solar sail vehicle will be set into orbit spinning. The casing will slide off with the small rocket used to initially escape Earth orbit. The sail will then deploy due to the force of the spinning motion and the strain energy in the sail and boom material(2). The attitude control system will stop the spin.

SPACE ENVIRONMENTAL EFFECTS

Several aspects of the space environment influence the solar sail, such as electromagnetic radiation, solar particle radiation, electrostatic charging, and micrometeors.

The most significant of these environmental phenomena is electromagnetic radiation, which consists of optical and ultraviolet radiation. Optical radiation is the sail's means of propulsion. As photons of light impact and reflect from the sail, they impart a momentum, causing an increase in pressure on one side of the sail resulting in acceleration. The main effect of ultraviolet radiation is to cure the sail booms after deployment.

A means of measuring solar radiation is the solar constant, the amount of energy from all wavelengths produced by the sun per second per square meter(3). At Earth the constant is 1370 W/m^2 and decreases to 590 W/m^2 at Mars(4).

The force on the sail is obtained from this solar constant by multiplying the pressure increase on the sunside of the sail by the area of the sail. The force decreases from Earth to Mars and also as the sail is angled away from the sun. Acceleration and velocity are calculated to range from 0.0005650 m/sec^2 and 32.73 m/sec at Earth, to a velocity of 238.14 m/sec halfway between Earth and Mars, to an acceleration of 0.0002437 m/sec^2 at Mars(5). The duration of flight, calculated assuming that the effective sail area is equal to the sail area, is 5.2 years; however, the sail will have to change its orientation to maintain its trajectory.

The rate of temperature increase is used to determine materials and thermal control requirements. The maximum temperature increase is 0.4466°$C/sec\text{-}m^2$ and is based upon the solar constant and the distance from the sun.

Solar particle radiation originates from the solar wind and consists of high-energy free electrons, positive ions, and neutral particles. Its density is dependent on the sun's 11-year emission cycle. At the peak of its cycle, known as the solar maximum, the sun is emitting several tons of particles per second. The next solar maximum will occur in 1992, which coincides with the start of the mission and makes particle radiation a potential hazard. There are not many materials that are effective against particle radiation, so the sail will use redundant electrical systems.

Electrostatic charging is the buildup of a potential difference between the sail and the plasma in which it is immersed in the space environment. The most feasible solution to this potential problem is to use as many conductive surfaces as possible and to cover nonconducting surfaces with a conductor.

The large surface area of the sail and its thin material make the problem of micrometeor collisions a concern. These particles, ranging from micrometer to millimeter proportions, present problems in the space environment due to the extremely high velocities of particles in space.

MATERIALS

The solar sail materials are classified into two parts: the actual sail materials, and all structures reinforcing the sail and bus. The sail itself consists of several thin layers, a film base with a sunside coating to increase both reflectance and emittance and a backside coating to increase emittance.

The film chosen for the solar sail is a 2.0 μm thickness of Kapton, a polyamide film made by Dupont. It can withstand temperatures up to 350°C, has a low thermal expansion, and a high resistance to tearing from micrometeors. Kapton is easy to metallize to resist radiation. Furthermore, Kapton will fold and crease well, making it easy to pack(6).

A metallic coating of the sunside is necessary for the effective transfer of momentum from the photons and for thermal control. A 1000 Å thickness of aluminum is chosen because it exhibits these qualities as well as being electrically conductive and able to give the sail protection from UV radiation. Aluminum will provide a high reflectance to reduce thermal absorption and a high reflectance component to help maximize the thrust while not adding significant weight to the sail. Furthermore, a 100 Å layer of chromium is chosen to coat the sail's backside for thermal control(7). The solar sail film will also have a polyamide composite tape with unidirectional graphite fibers bonded to the sail's rearside to avoid "billowing" and therefore loss of force, and to help control rips from micrometeors.

Composite beams are chosen for the sail's reinforcing structure because of their strength, light weight, and versatility for packing. The booms will consist of the F263 Epoxy Resin, a high-temperature resin for aerospace applications produced by HEXCEL, combined with a UV activator and woven with carbon fibers into a fabric. The uncured boom is joined with the sail material with a polyester adhesive and wrapped around the bus for storage. Normally this resin system is cured by heat, but the addition of the activator will cause the curing by UV radiation after deployment(8).

The material for the bus, based on the density and minimum strength required, is a magnesium alloy sheet AZ313-H24. The rear side of the bus is coated with silvered Teflon for thermal control of the bus(9).

POWER SYSTEM

Various components of the power system to be chosen for the sail mission include an energy source, energy conversion, energy storage, and a power conditioning and control system. The energy source will be direct solar radiation, converted into power by a 0.75 m × 0.75 m flat solar sail array located on the bus (Fig. 2). The array is comprised of silicon cells that are well tested and reliable(7). For energy storage, rechargeable nickel-cadmium cell batteries are used. They are charged by

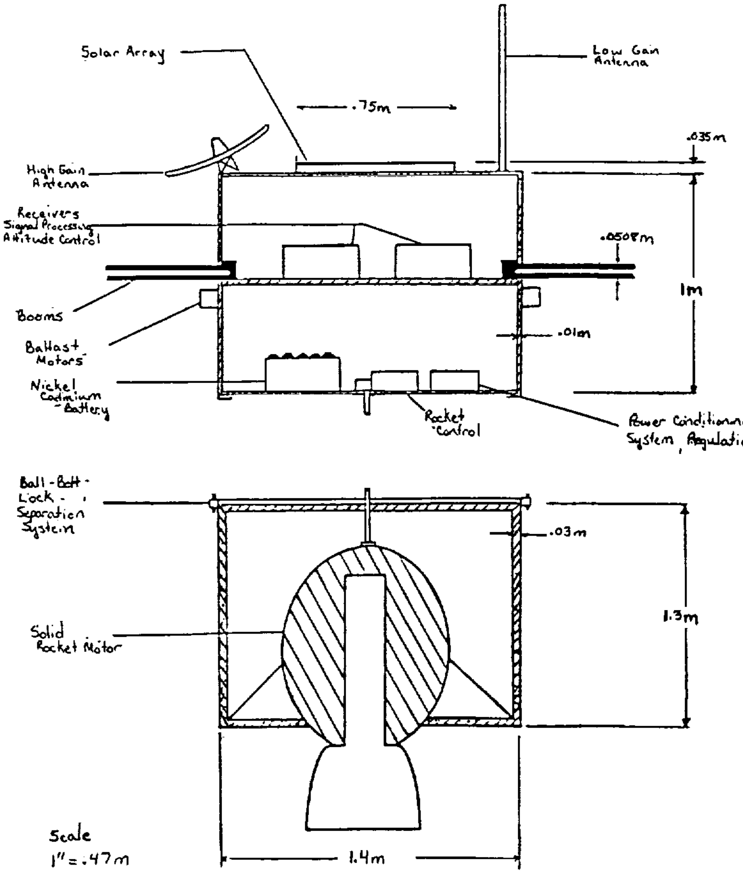

Fig. 2. Cross-Sectional View of the Sail Bus

the solar panels and used for energy storage and as a back-up.

The power conditioning and control system uses regulators, AC/DC converters, and control circuits to match the power produced by the solar cells with that required by the sail subsystems such as telemetry, control, and communciations. It will also control and regulate the charging of the battery.

ATTITUDE CONTROL

The attitude control system can be broken down into three different categories, the attitude sensors, computer system, and the motors used to move ballast masses. The attitude sensor system will consist of two star trackers. They will define the pitch axis and the yaw axis; the spin axis will be fixed at an angle of 35° with respect to the sun. A star tracker is locked onto a target star by focusing the image of the star on a photosensitive surface with an optical telescope(10). When the target star is not focused properly, an error signal is sent to the computer system, which will counter the improper rotation. The computer system will send a signal to the ballast motors, which will move the ballast masses to their necessary position.

The resultant force from the solar radiation is assumed to act through the center of the solar sail. When the ballast masses are moved from their equilibrium positions, the center-of-mass for the solar sail is changed, producing a moment-arm between the resultant force and the center-of-mass that causes the moment required to stop the unwanted angular velocity. The moment needed to produce critical yaw or pitch is much larger than that needed to produce spin. Therefore, the unwanted yaw and pitch due to inconsistencies in the sail material can be easily handled by the attitude control system. The spin due to these inconsistencies is not as troublesome since the orientation with the sun will not be affected.

COMMUNICATIONS

The main components in the communications system will consist of a low and high gain antenna, a transmitter, and a receiver. The main purpose of the communication system is to periodically transmit the coordinates of the solar sail to the Earth, about once a week. The power required by the communication system will peak at about 20 W over a short period of time.

THERMAL CONTROL

The solar sail will experience a wide range of temperatures along the trajectory from Earth to Mars. These temperature variations will affect not only the solar sail itself, but also the electronic equipment and the supporting structure of the sail. Excess heat due to heat dissipation of the solar arrays must be directed away from the electronic equipment since the electronics temperature range is -5°C to 65°C, the batteries 0°C to 20°C, and transmitter 10°C to 60°C(9). Heat pipes will transport excess heat of internal components to an external radiator surface. Reducing the amount of heat radiated from the surface will protect the vehicle from very cold temperatures. The batteries and the bus except for the two ends will be wrapped in a thermal blanket to minimize temperature fluctuations(9).

TRAJECTORY

The solar sail is mounted on a launch vehicle (possibly the Titan IV) that will place it directly into a geosynchronous transfer orbit(11). In order to overcome the gravity of Earth, a solid rocket motor will be fired. The correct phase angle for interception is 107.56°(9). The heliocentric longitude of Mars is found in the *American Ephemeris and Nautical Almanac* and the possible launch times can be determined.

The logarithmic spiral trajectory was chosen for several reasons. From a mathematical point of view, it is the simplest to model and the necessary initial conditions can be met by the mission profile. These conditions include a hyperbolic excess velocity to establish the proper velocity direction required for insertion into the spiral trajectory(12). Finally, the spiral trajectory is very effective when compared to more complicated optimal strategies(9). The spiral trajectory is achieved by maintaining the velocity vector at a constant spiral angle and the sail's orientation with respect to the incoming radiation at a fixed value of 35°. The point of closest approach is 6087 km.

AUXILIARY PROPULSION

A solid rocket motor was chosen because it is easier to separate from the bus. A system capable of sustaining large loads, high reliability, minimum weight, good survival of temperature and radiation, minimum impulse, and no debris or contamination was essential to ensure that the sail is not damaged before deployment. For these reasons, the ball-lock-bolt separation system was chosen(12).

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