York University
Faculty of Science and Engineering

Specifications and Milestones Report
Solar Sail Interplanetary Propulsion System (SSIPS)

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ENG 4000
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1.0 - Team Members and Their Roles

Shreyas Bidadi (bshreyas@yorku.ca) - Project Manager. Will be responsible for deciding upon the best sail material and analyze the performance of the sail through calculations. Will also be responsible for assembly of all reports.
Ryan Orszulik (orszulik@yorku.ca) – Will be responsible for webpage design, editing of reports, and for modeling and developing control and steering algorithms as well as analyzing theoretical background and models..
Alexander Dolgansky (alexd221@yorku.ca) – Will be responsible for modeling and analyzing structural loads, forces produced on the sail in its operation, and material variation.

The role of secretary will be rotated between the team members according to what section of the sail is of current interest. We also have a joint e-mail account, solarsail06@gmail.com where all of us can be reached at one time. The website is http://www.students.yorku.ca/~orszulik/Home.html

2.0 - Introduction

The solar sail is a relatively simple and elegant propulsion method, as it does not require a complex engine or the ability to carry fuel onboard the spacecraft. The solar sail moves due to solar radiation pressure, which is basically photons of light striking the solar sail being reflected, and as a result exchanging their momentum with the highly reflective sail.

Since the acceleration is directly related to the solar radiation pressure, and the solar radiation pressure falls with the square of the distance from the sun, the sails must be very large and made from a very thin and light material, with a high reflectivity. Solar sails typically have very small accelerations, but what is important to remember is that the acceleration is almost constantly applied. Even a small acceleration of 1 mm s^{-2} will build up into large velocities as the seconds turn into minutes, the minutes to hours, and the hours to days.

2.1 – Historical Background

After observing comets and the appearance of what looked to be tails, Johannes Kepler proposed that comet tails were particles that were swept out by sunlight pressure on the comet. The presence of light pressure was proved in theory by Maxwell in 1873 and verified by Lebedew a quarter century later in Russia. Konstantin Tsiolkovsky and Fridrickh Tsander proposed the concept of using large mirrors of very thin sheets as a means of accelerating spacecraft in the 1920's but the concept remained pretty much dormant until the 1950's. In 1951, Carl Wiley published an article in a fiction magazine while writing under a pseudonym so as not to lose credibility in his field, for a feasible solar sail design. Seven years later, Richard Garwin published the first western technical paper on solar sailing (and coined the term in the process). In the 1970's NASA's Jet Propulsion Laboratory began an in depth study of the solar sail for a Halley's Comet rendezvous mission. The solar sail eventually lost out to solar electric propulsion due to time constraints and political considerations, but the mission was later scrapped, and neither option was flown.

2.2 – Theoretical Background

The theoretical background presented here is strongly based upon the work presented in [1] and theories learned in the course Physics of the Space Environment.

2.2.1 – Solar Radiation Pressure

The physics of radiation pressure can be derived through either the quantum or electromagnetic description of light, and the results have proven to be the same regardless of the method used. A brief analysis of radiation pressure through the quantum description of light is presented here.

The solar energy flux crossing unit area in unit time is given as

$$W = W_{Earth} \left(\frac{R_{Earth}}{d}\right)^2 \quad (2.1)$$

where d is the distance from the Sun, R_{earth} is the radius from the sun to the Earth (1 AU), and W_{Earth} is the flux at the Earth must commonly given by

$$W_{Earth} = \frac{L_s}{4\pi R_{Earth}^2} \quad (2.2)$$

where L_s is the solar luminosity.

In a discrete interval of time, the total energy passing through a surface of area A normal to the incident flux is given as

$$\Delta E = W A \Delta t \quad (2.3)$$

Using the mass-energy equivalence of special relativity, for a photon assumed to have a rest mass of zero, the photon's energy can be written as

$$E = pc \quad (2.4)$$

Combining the two previous equations, it can be seen that

$$\frac{\Delta p}{c} = W A \Delta t \quad (2.5)$$

Pressure is defined most simply as force per area

$$P = \frac{F}{A} \quad (2.6)$$

where force is the derivative of momentum with respect to time, pressure becomes

$$P = \frac{1}{A} \frac{\Delta p}{\Delta t} \quad (2.7)$$

Combining equations (2.5) and (2.7) gives the radiation pressure as

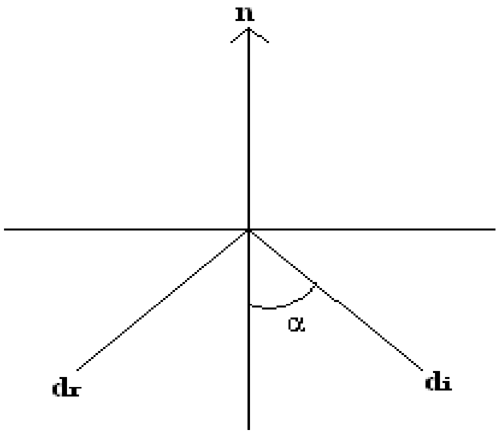
$$P = \frac{W}{c} = \frac{W_{Earth}}{c} \left(\frac{R_{Earth}}{d}\right)^2 \qquad (2.8)$$

where W_{Earth} is simply the mean solar constant of 1368 J s^{-1} m^{-2}.

However, to get exact results of the radiation pressure, the inverse square law has been shown to be inadequate, and corrections for the appearance of a finite size solar disc and limb-darkening of the sun must be made. These corrections typically show a maximum -30% deviation from the idealized case presented above, and will be accounted for in stages which require advanced model generation.

2.2.2 – Ideal Solar Sail Force Model

This argument assumes the idealized solar radiation pressure presented above and a perfectly reflecting solar sail.



From the diagram shown above, it can be seen that

$$\vec{F}_i = P\,A(\vec{d}_i\cdot\vec{n})\vec{d}_i \quad \text{and} \quad \vec{F}_r = -P\,A(\vec{d}_r\cdot\vec{n})\vec{d}_r \quad (2.9)$$

where the subscripts i, and r denote whether the photons are incident or reflected, F is the force on the sail, P is the radiation pressure, A is the sail area, and n is the sail normal.

The total force is found as

$$\vec{F}_T = \vec{F}_i + \vec{F}_r = P\,A(\vec{d}_i\cdot\vec{n})\vec{d}_i - P\,A(\vec{d}_r\cdot\vec{n})\vec{d}_r \quad (2.10)$$

from here the vector identity

$$\vec{d}_i - \vec{d}_r = 2(\vec{d}_i\cdot\vec{n})^2\vec{n} \quad (2.11)$$

which gives

$$\vec{F}_T = 2\,P\,A(\vec{d}_i\cdot\vec{n})^2\vec{n} \quad (2.12)$$

Substituting 2.8 for P gives

$$\vec{F}_T = \frac{2\,A\,W_{Earth}R_{Earth}^2}{d^2\,c}(\vec{d}_i\cdot\vec{n})^2\vec{n} \quad (2.13)$$

However, r and n are both unit vectors, and α is the angle between r and n, therefore

$$(\vec{d}_i\cdot\vec{n})^2\vec{n} = \cos^2(\alpha)\hat{n} \quad (2.14)$$

Therefore the force on a perfectly reflecting solar sail is

$$\vec{F}_T = \frac{2\,A\,W_{Earth}R_{Earth}^2}{d^2\,c}\cos^2(\alpha)\hat{n} \quad (2.15)$$

2.2.3 – Solar Sail Force Model

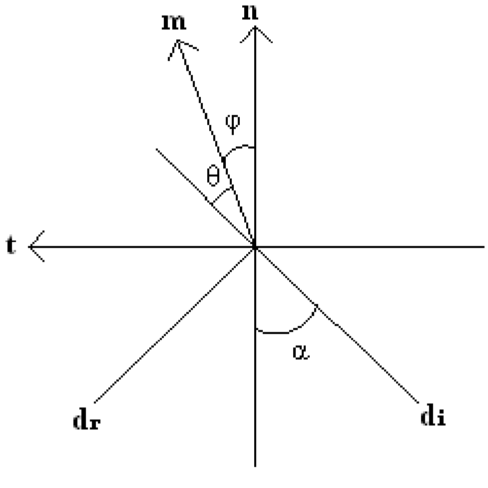
This model considers the effects on the solar sail force when the solar sail is not coated with a perfectly reflecting layer, which more accurately reflects a real solar sail. This model is also known as the optical force model. The total force will depend upon the optical properties of the sail film where r is the reflection coefficient (fraction of photons reflected), τ is the transmission coefficient (fraction of photons transmitted) and a is the absorption coefficient (fraction of photons absorbed). It is of note that in many applications the absorption coefficient is α, but since this has already been termed the sail pitch angle, 'a' will be used here. Since the transmission coefficient of the front of the sail will be zero, it can be seen that the absorption and reflection coefficients are related as:

$$r + a = 1 \quad (2.16)$$

The force on the sail can be broken up into components as

$$\vec{F} = \vec{F}_r + \vec{F}_a + \vec{F}_\epsilon \quad (2.17)$$

where F_r, F_a, F_ε are the forces due to reflection, absorption, and emission by the sail.



As can be seen from the diagram, the total force can also be broken into those components acting normal to the sail, and those acting transverse to the sail.

$$\vec{F}=\vec{F}_n+\vec{F}_t \quad (2.18)$$

From geometry, and following a lengthy derivation, the following results are obtained:

The force on the sail due to reflection is

$$\vec{F}_r=PA(rs\cos^2(\alpha)+B_f(1-s)r\cos(\alpha))\hat{n}-PArs\cos(\alpha)\sin(\alpha)\hat{t} \quad (2.19)$$

where s is the fraction of photons specularly reflected in direction d_r, and B_f is the non-Lambertian coefficient of the front of the sail.

The force on the sail due to absorption is

$$\vec{F}_a=PA(\cos^2(\alpha)\hat{n}+\cos(\alpha)\sin(\alpha)\hat{t}) \quad (2.20)$$

The force on the sail due to emissivity is

$$\vec{F}_\epsilon=aPA\frac{\epsilon_f B_f-\epsilon_b B_b}{\epsilon_f+\epsilon_b}\cos(\alpha)\hat{n} \quad (2.21)$$

where a is the absorption coefficient, ε_f is the front emissivity of the sail, ε_b is the back emissivity of the sail, and B_f and B_b are the front and back non-Lambertian coefficients. The Lambertian terms can be roughly approximated as 0.8 and 0.55 respectively, although they must be determined numerically with respect to the sail design.

Breaking the force into axial components, the force acting along the normal is

$$\vec{F}_n=[(1+rs)\cos^2(\alpha)+B_f(1-s)r\cos(\alpha)+a\frac{\epsilon_f B_f-\epsilon_b B_b}{\epsilon_f+\epsilon_b}\cos(\alpha)]PA\hat{n} \quad (2.22)$$

and the force acting along the perpendicular direction is

$$\vec{F}_t=PA(1-rs)\cos(\alpha)\sin(\alpha)\hat{t} \quad (2.23)$$

Thus the total force can be seen to be

$$\vec{F}=f\,\hat{m} \quad (2.24)$$

where

$$f=\sqrt{(f_n^2+f_t^2)} \quad (2.25)$$

It is interesting to note that the force exerted on a non-ideal solar sail no longer acts perpendicular to the sail, but at an angle determined by the reflective coefficient of the sail material. This is due to the fact that more photons will be incident on the sail than will be reflected due to a small absorption, and the effect of the small force due to re-radiating the absorbed photons out the back of the sail. The sails equilibrium temperature was determined to verify these results and is found as

$$T=[\frac{acP\cos(\alpha)}{\sigma(\epsilon_f+\epsilon_b)}]^{\frac{1}{4}} \quad (2.26)$$

where σ is the Stefan-Boltzmann constant, and changes to the sails equilibrium temperature can be viewed as instantaneous due to the sails small thickness.

2.3 – Recent Work in the Field

Before the current era of solar sailing, the last time the solar sail was considered as a viable alternative for a mission was with NASA in the 1970's when the government was receiving proposals for the Halley's Comet Rendezvous Mission (which was later scrapped). The last few years have seen a larger amount of funding for solar sailing technologies with the Planetary Society leading the way. However, the Planetary Society's solar sails have failed to reach orbit as their launch craft failed on both occasions. JAXA (the Japanese Space Agency) also successfully launched two solar sail prototypes into low earth orbit in 2004, however their full scale solar sail opened incompletely earlier this year. Despite these setbacks, small steps such as the Russian deployment of a spinning reflector in 1993, and the 1996 NASA deployment of an inflatable antenna, provide optimism that solar sailing is becoming a more realistic possibility.

2.4 – Literature Review
The most useful book by far on the theory of solar sailing is *Solar Sailing: Technology, Dynamics and Mission Applications* by Colin R. McInnes. As it was written by a physicist, it provides lots of information on the physics governing the solar sail, but is somewhat lacking in terms of design work. The book *Star Sailing: Solar Sails and Interstellar Travel* written by former JPL engineer Louis Friedman is very informative however it is only a qualitative study of the solar sail, and is lacking in specific information as it has been written for the general public.

Two other books that look very interesting are *Space Sailing* by Jerome L. Wright and *Space Flight Using a Solar Sail – The Problems and the Prospects* by E. Polyakhova, however, both are rare and out of print books and neither the Toronto Public Library, the York Library, or internet bookstores seem to carry them right now. Besides these references, there are many articles on solar sailing on IEEE, some of more use than others.

2.5 – Plans, Obstacles, and Innovative Features
For this project, a 1 meter by 1 meter, three-axis stabilized solar sail will be constructed. The sail will be made from Kapton with a thin aluminum coating on the front side. Ripstops and grounding straps must also be laid to prevent rip propagation and electric discharge due to billowing of the sail. The sail will also include a steering and control algorithm based on control vanes at the tips of the sail axes.

The largest obstacle that must be overcome in this project is finding a way to actually test the solar sail. The first main requirement, is that a light bright enough to generate a flux large enough to move the solar sail be used. The other main problems with testing is that the solar sail is designed to be used in the microgravity of space, but it will be tested in the gravity environment of the Earth. Thus a test setup, that supports the weight of the solar sail must be constructed. However, the test setup must be mounted on rollers with very small static and kinetic friction coefficients so that the small acceleration exerted on the sail will allow it to move. If this cannot be done, the sail will be mounted horizontally with pressure sensors below it to monitor the pressure exerted on it by the radiation pressure, and to test the control vanes to see what torques are generated.

The most innovative feature of this solar sail is its small size. While this is meant to be a small scale prototype that could be extended to much larger sizes, with the recent developments in MEMS, it has been shown that small solar sails with areas on the order of meters could be used for specialized missions with payloads less than a ¼ kilogram.

3.0 - Equipment and Budget
The following is a list of materials and equipment that will be required for constructing the solar sail.

3.1 - Vacuum Chamber
The thermal vacuum chamber is required to test the response of the sail structure in vacuum. The new CRESS Space Instrumentation Laboratory (CSIL) in PSE building contains a new thermal-vacuum chamber that is capable of replicating the environment of space. It allows us to test objects with sizes of up to 1 and a half by 2 meters. Our prototype with dimensions of 1m by 1m should easily fit into the chamber.

Cost: $0

3.2 - Booms/Spars
To prevent the sail from collapsing in the plane of the sail and in the third dimension requires support structures called booms. The outer edges of the sail will be attached to stiff booms to prevent the

collapse. Our prototype will have 4 booms fixed at the center to support the 4 triangular sail sections to support bending and compression as sunlight pushes on the sail as shown in the figure below:

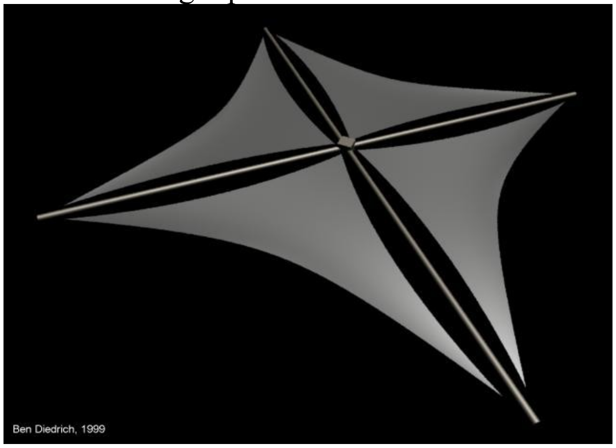


Fig. Booms for 3 axis stabilization

The material we are planning to use for the booms is CFRP (Carbon Fiber Reinforced Plastics). CFRP is a strong, light, and very expensive composite material or fiber reinforced plastic. It has a specific mass of 100g/m. These booms consist of two laminated flexible Ώ-shaped sheets which are bonded at the edges to form a tubular shape. Due to this advanced design the deployable CFRP booms combine high strength and stiffness with extremely low density.

Cost: $300

If we are unable to find or purchase the material, we will go in for a cheaper next best alternative.

3.3 - Solar Sail Film

While a variety of solar sail films have been considered, for now, a Kapton VN film of 1 to 5 um in thickness appears to be the most appropriate choice for reasons detailed in section 4.1. The Kapton film will be vacuum deposited with aluminum between 0.1 um and 1 um thick on the front side, and back side deposited with chromium at 0.5 um to 0.1 um in thickness. Three square meters of this material will be required at a cost of around $100 and it will be obtained from DuPont.

Cost: Approx. $100

3.4 – Instruments

Instruments in the CRESS lab can be used to:

1. To handle the delicate sail structure.
2. To modify and measure the thickness of the sail material.

Cost: Approx. $50

3.5 – Electronics and Microactuators

This area is subject to the highest cost fluctuations as the electronics and microactuators required for control of the tip vanes are still being determined. This is due to the fact that the control torques required and stresses upon the actuators and sail structure have still to be modeled which will determine exactly how much mass can be allocated to the actuators. Despite this, using an FPGA programmed in VHDL for a predetermined control test algorithm is looking desirable as the FPGA costs roughly $20 and the microactuators around $15 each.

3.6 – Sun Simulator

A single light or array of lights that have been vacuum-tested will be required to simulate the solar flux. Therefore an optical device capable of emitting a flux of 1000 W/m^2 as a minimum is required.
CRESS has a few instruments capable of generating light intensities at smaller values, however there is

a possibility that we will be able to either assemble or rent a simulator. This has been budgeted to cost about $300 as an upper limit.

3.7 – Maximum Cost Allocation per Section

These are rough estimates of what the cost per section may be, thus there may be extra money in some sections, and an overrun in another.

Section	**Cost**
Materials and Construction	$400
Testing	$300
Electronics and Actuators	$50
Poster	$250
Total Cost	**$1000**

4.0 – Technical Specifications

The technical specifications presented below are where the group currently stands, but are subject to change as the design process proceeds.

4.1 – Analysis and Design

4.1.1 – Materials and Mass

The sail requires a substrate to allow packing and handling of the sail film. The solar sail substrate will be made from 5 um thick Kapton VN, although it will be thinner if a supplier of thinner Kapton can be found. Kapton was chosen over other materials for its low density of 1.42 g cm^{-3}, its reasonably high tensile strength and modulus, and its ability to withstand UV radiation. Type VN Kapton was chosen since it was designed for high temperature applications with a coefficient of thermal shrinkage of less than 0.03, a small thermal expansion coefficient, and with a well defined material parameters up to 520 K as a lower safety limit.

The front side of the Kapton substrate will be coated with a 0.5 um thick layer of aluminum (at thickest) through vacuum deposition. Aluminum has been chosen for its high melting point of 933 K, its high reflectivity of 0.85 and low bulk density of 2.70 g cm^{-3}. Oxidized aluminum has an emissivity of 0.1, and while unoxidized aluminum has a lower emissivity, work will be done in an oxygen rich environment thus we won't be able to

The back side of the Kapton substrate will be coated with a 0.1 um thick layer of chromium (at thickest) through vacuum deposition. The reason for the back side coating of chromium is that it has an emissivity of 0.64, and thus will allow a lower sail equilibrium temperature. Chromium has a density of 7.14 g cm^{-3}.

This gives a total sail mass of

$$M = V_{aluminum} d_{aluminum} + V_{Kapton} d_{Kapton} + V_{chromium} d_{chromium} \quad (4.1)$$

$$M = (100)(100)(5 x 10^{-4})(2.70) + (100)(100)(0.5 x 10^{-4})(1.42) + (100)(100)(0.1 x 10^{-4})(7.14)$$

$$M = 9.164\, grams$$

4.1.2 – Equilibrium Temperature

Using the values supplied above, the maximum equilibrium temperature of the sail in orbit around Earth can be calculated from a simplified form of 2.26 with 1 – r substituted for a:

$$T=\left[\frac{(1-r)W_{Earth}R_{Earth}^{2}\cos(\alpha)}{\sigma(\epsilon_f+\epsilon_b)d^2}\right]^{\frac{1}{4}} \quad (4.2)$$

where r = 0.85, W_{Earth} = 1368 W m^{-2}, R_{Earth} = 6.378 x 10^6 m, alpha = 0, d = 150 x 10^9 m. This gives an equilibrium temperature of T = 1.72439 K. This is suitable for the sail itself, however, the payload may require its own heat source, or a different set of coatings.

4.1.3 – Characteristic Acceleration

For an ideal solar sail, the square sails' characteristic acceleration would be calculated as

$$a_0=\frac{9.12\,\eta\,A}{m_p+m_s} \quad (4.3)$$

with a conservative sail efficiency parameter η = 0.85, gives a_0 = 0.4045 mm s^{-1}, which is well above our targeted minimum value of 0.1 mm s^{-1}.

4.1.4 – Spar Design

Since the solar sail has small dimensions, four spars will be extended from a hub at the center of mass of the solar sail. Due to the sails size, stays will not be required to reinforce the spars. The spars can be modeled as a first approximation as simple cantilever beams with a distributed load that conform to the following equations.

The displacement of any point along the beam can be calculated as

$$D(x)=\frac{-F\,x^2(6L^2-4xL+x^2)}{24\,E\,I} \quad (4.4)$$

where F is the force applied by the solar radiation pressure distributed along the beam, x is the linear position along the beam, L is the length of the beam, E is Young's modulus of the beam material, and I is the moment of inertia of the beam given by

$$I=\frac{wt^3}{12} \quad (4.5)$$

The maximum deflection is calculated as

$$D_{max}=D(x=L)=\frac{-F\,L^4}{8\,E\,I} \quad (4.6)$$

The spars will either be made from a thin rods of CFRP (carbon fibre reinforced plastics) or very thin rods of titanium. Both these choices are due to the fact that the materials have high Young's Modulus' and small coefficients of thermal expansion.

4.1.5 – Ripstops and Preventing Electrical Discharges

Ripstops will be built in since Kapton comes on a roll, and thus consecutive strips will need to be bonded together with adhesive to create the entire sail. Additional ripstops will be constructed by depositing an extra strip of Kapton over top, and these placements will be determined by finite element modeling. The structural stability of the sail will also be improved through this process of modelling.

Electrical discharges due to the different potentials at the front and back of the sail can be prevented by using grounding straps between the front and back of the sail, as well as between consecutive strips of Kapton to prevent charge buildup. The sail will also be grounded to the structure.

4.1.6 – Steering and Control

For steering and control of the sail, control vanes will be used. Control vanes are like miniature solar sails mounted on the tips of the actual sail, and give precise control actuation, however they add mass to the tips of the sail, requiring a structure that is able to support larger loads. However, center of mass displacement methods for the solar sail are coarse and for small payloads, with small sails, even pointing an antenna could lead to a center of mass offset causing the solar sail to steer. For testing a FPGA will be programmed using VHDL to control the two tip actuators and run them through a finite number of movements. The moments about each axis are determined as

$$M_x = 0$$

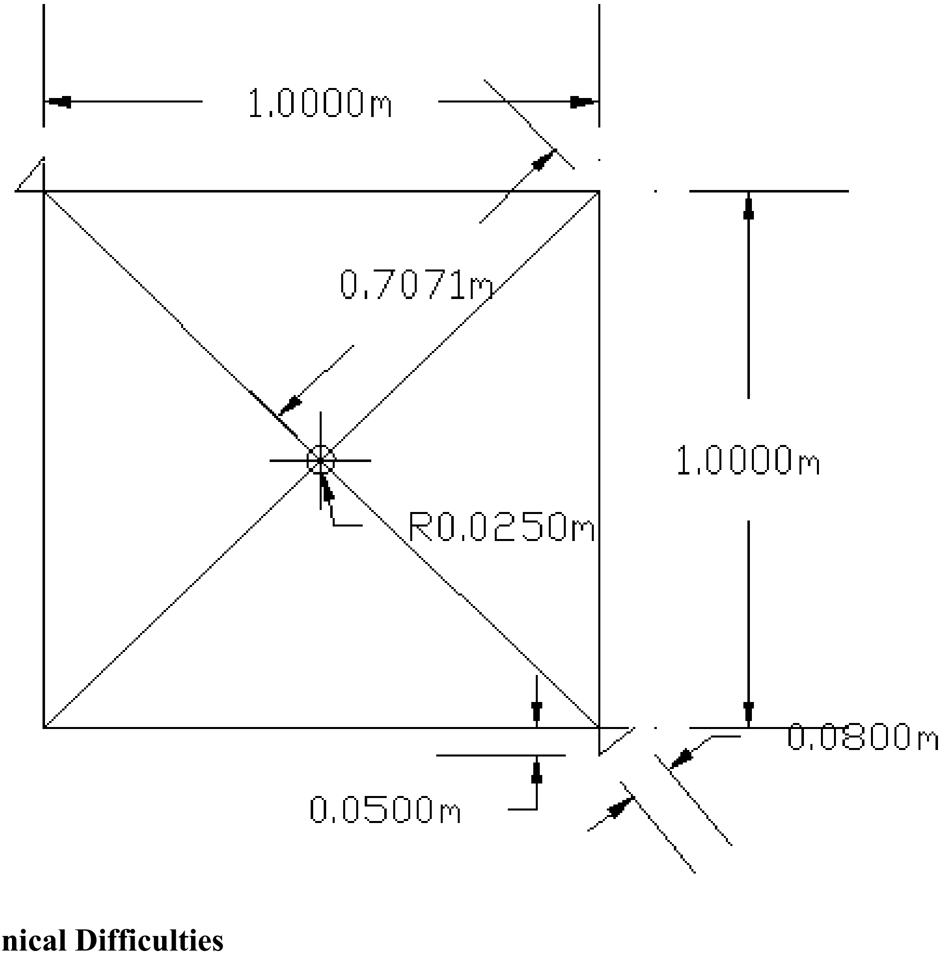
$$M_y = F_v d \cos^2\alpha(\cos^3\delta_1 - \cos^3\delta_2)$$

$$M_z = F_v d \cos^2\alpha(\cos^2\delta_1 \sin\delta_1 + \cos^2\delta_2 \sin\delta_2)$$

Where x, y, and z are the body fixed axes of the sail. While it shows that no yaw control is possible due to absence of moment in x, it can be achieved through combinations of rotations through pitch and roll.

4.2 – Design Structure

Below is a simple schematic of what the solar sail will look like. The vane size is the parameter most likely to vary throughout the development of the steering and control algorithm. A scale drawing of the side is not possible, but its parameters have been listed above.



4.3 - Technical Difficulties

In order to obtain good performance from the solar sail while maintaining its stability and rigidity, it is important to select appropriate materials. As a result, the main issues encountered in the project at this stage are related to determination of appropriate material for the solar sail. The material must be inert to large temperature swings and very low pressures of the space environment. At the same time, the material must be of very low density in order to maximize the the performance of the sail. Currently, Kapton appears to be the best choice, however, due to budget constraints, its effectiveness can only be determined once sail is built and tested (which can put the project at jeopardy if Kapton fails to satisfy the required criterion).

Since no practical solar sail design exists as of today, there are no real models or data sets available that can be used with this project as a reference. Thus, all of the models must be created from ground up and are experimental in nature. Models of the solar sail will be created using a CAD software for maximum accuracy. Currently, a good candidate for such a CAD software is Pro-Engineer Wildfire 3© by PTC. This software is available to York University and can be used to design and graphically test (using numerical solvers) the physical response of a system due to a given set of loads (this software is also capable of performing thermal simulations). Since the group is not familiar with this particular software, part of the time budget will be spent on learning this software. Current models describing the performance of the solar sail for the given sail configuration and material type will be implemented, however, it will not be possible to verify the results of these models until thorough testing of the final design is done.

Aside from current issues, the possible future issues will also be discussed. One possible issue that could arise in the future is the inability to secure a time slot with the required test facilities (either at York or elsewhere) for the testing purposes. As it can be seen in the "Testing Plans" section, various equipment and test facilities are required to complete the testing phase of the project. If access to these facilities will not be secured, the project success will be impossible to verify. Another issue that may arise in the future, can be related to storage of the constructed sail. Although the sail must be rigid, it will still be a fragile structure. As a result, a safe storage facility for the sail will have to be located prior to its construction and final presentation. The final issues that may arise in the future are related to possible errors in final design that can only be deduced after the sail is fully constructed. This particular issue can only be resolved by testing the frame of the sail before the final sail is constructed and selecting the very best material for the sail surface.

4.4 - Testing Plans

The solar sail design will be put through rigorous testing to verify its performance. Since the main focus of this project is on structural stability and integrity of the solar sail, structural components will be tested in detail. Because of the requirements of solar sail to be very light and thin, force distribution in the sail as result of various maneuvers is an important testing subject.

To conserve the given budget, only the final design will undergo physical testing. All prior designs will be tested using Pro-Engineer Wildfire 3© CAD software by PTC. Using this software, the sail design can be both drawn and analyzed. The model will include all of the features of the final design which are: steering module of the sail, folding capability of the sail and thickness and mass of the sail.
Once the design of the sail is finalized and results from the Wildfire are satisfactory, the construction of the sail will commence. Once the sail is constructed, series of physical tests will be conducted. First set of tests will determine the structural rigidity of the sail structure only and compare the results with that of a model created with Wildfire. The first set of tests will include:

1. Measure of force distribution in the sail structure during slow steering maneuvers
2. Measure of flapping of the sail structure during fast steering maneuvers

To measure the force distribution in the sail structure during the first test, strain gauges will be used. Expected forces will be defined with use of a sail structure model simulation obtained from Wildfire. The measured forces will be compared to the expected ones to see if there are any discrepancies. Depending on the degree of discrepancies found, structure of the sail will be reinforced or rebuilt entirely. During the second test, the flapping of the structure as result of fast steering will be analyzed. The degree of flapping will be measured using the following technique. The final configuration of the sail after a maneuver will be captured on camera. The image of the sails final configuration after a fast steering maneuver will be compared to expected configuration which will be superimposed on the image. In order to conserve time and budget, the sail material will be chosen based on the properties that provide best performance as predicted by the sail performance models. These properties will be obtained from the manufacture. As result, no physical testing will be performed on the sail material itself.

The second set of physical testing will be conducted with the complete solar sail. The following set of tests will be conducted:
1. Measure of sail flapping during fast steering maneuvers
2. Analysis of tears in the solar sail as result of prolonged steering cycle.
3. Vibrational test
4. Vacuum chamber test.
5. Disassembly and reassembly test.

The first test of the second set will be conducted in a similar fashion as for the first test in the first set. Strain gauges will be used to measure force distribution in the sail. This test will allow determination of stability of the whole sail. The second test will be used to determine the rigidity of the sail. Visual inspection of the sail will be conducted to make sure there are no rips in the sail.

In order to determine how the sail structure will react to launch vibrations, the Vibration Test System will be used. Various forms of vibrations such as sinusoidal, shock etc. will be used. The fourth test in the second set will deal with performance of the sail in the space environment. The space environment will be simulated using a vacuum chamber. With this test, it will be possible to determine if the solar sail can survive the space environment. Final test in the second set will be used to determine the ease of assembly of the sail. This particular test will be conducted prior to the “measure of sail flapping during fast steering maneuvers” test and after “Vacuum chamber” test.

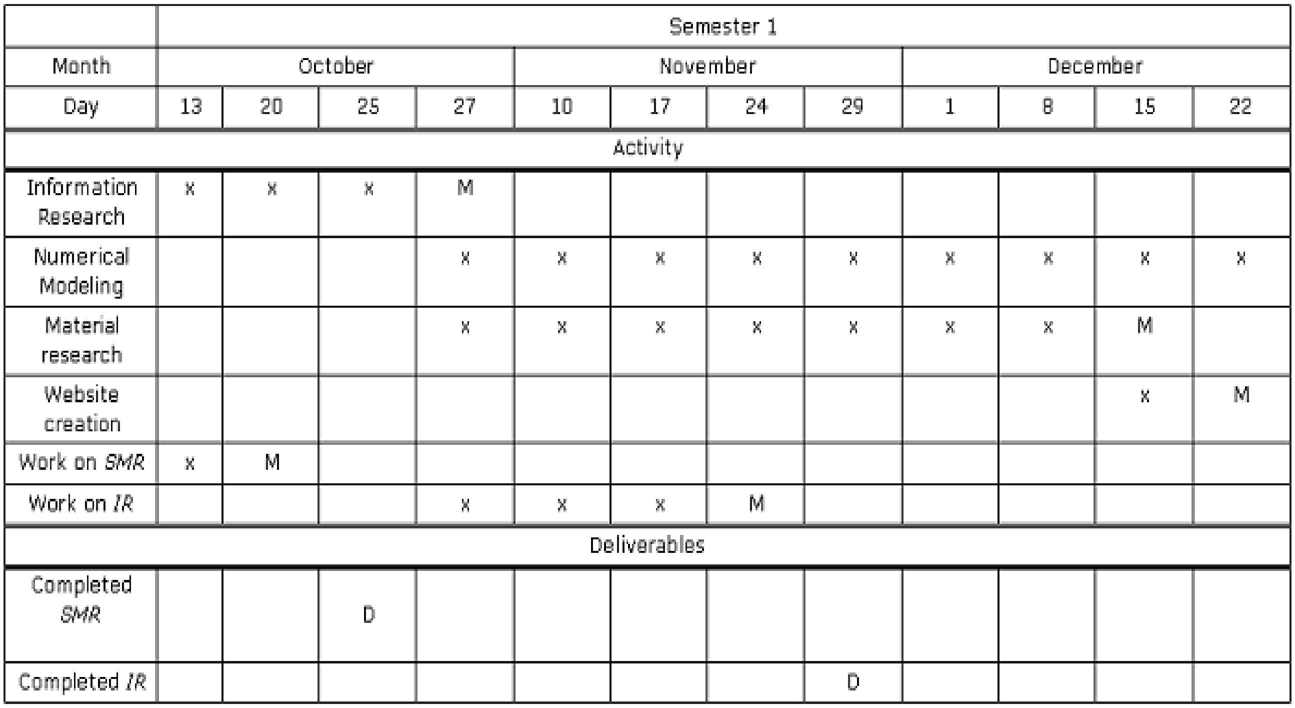
The final set of tests will determine solar sail performance. The following tests are included in the final set:
1. Determination of sail acceleration in static state.
2. Determination of sail acceleration during steering maneuvers.

Sun's rays will be simulated using a powerful light source and acceleration of the sail will be measured. These tests will be conducted in 1G environment in order to conserve the cost of testing. The first test will determine the maximum performance of the sail in the 1G environment while the second test will determine how the sail will perform during steering maneuvers. Finally, above set will be repeated (if possible) in the vacuum chamber to determine sail performance in the zero G environment.

5.0 – Milestones

The purpose of milestones is to set self-imposed deadlines by which significant portions of the project must be completed.

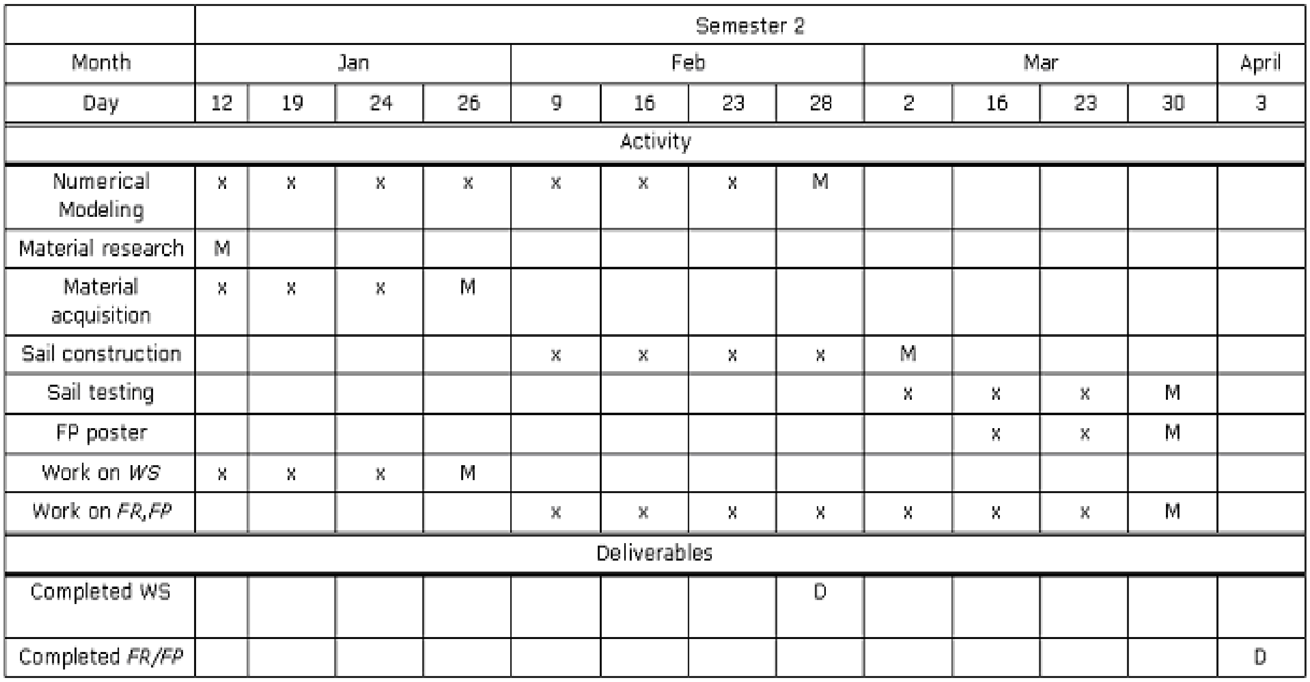
5.1 – Milestones for Semester 1



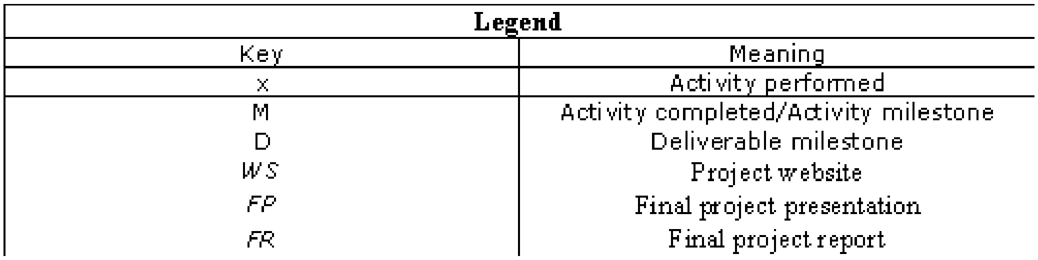
	Semester 1											
Month	October				November				December			
Day	13	20	25	27	10	17	24	29	1	8	15	22
Activity												
Information Research	x	x	x	M								
Numerical Modeling				x	x	x	x	x	x	x	x	x
Material research				x	x	x	x	x	x	x	M	
Website creation											x	M
Work on *SMR*	x	M										
Work on *IR*				x	x	x	M					
Deliverables												
Completed *SMR*			D									
Completed *IR*								D				

Legend	
Key	Meaning
x	Activity performed
M	Activity completed/Activity milestone
D	Deliverable milestone
SMR	Specification and Milestones Report
IR	Interim report

5.2 – Milestones for Semester 2



	Semester 2												
Month	Jan				Feb				Mar				April
Day	12	19	24	26	9	16	23	28	2	16	23	30	3
Activity													
Numerical Modeling	x	x	x	x	x	x	x	M					
Material research	M												
Material acquisition	x	x	x	M									
Sail construction					x	x	x	x	M				
Sail testing									x	x	x	M	
FP poster										x	x	M	
Work on *WS*	x	x	x	M									
Work on *FR,FP*					x	x	x	x	x	x	x	M	
Deliverables													
Completed WS								D					
Completed *FR/FP*													D



Legend

Key	Meaning
x	Activity performed
M	Activity completed/Activity milestone
D	Deliverable milestone
WS	Project website
FP	Final project presentation
FR	Final project report

6.0 – Deliverables

The deliverables include an interim report on our progress, a web page dedicated to the project, the final report and the presentation on the work done in the duration of the project. The main deliverable, however, is a working prototype of a 1 meter by 1 meter three-axis stabilized square solar sail with a characteristic acceleration value of at least 0.1 mm/s^2. The sail substrate will be no more than 5 um thick, with a reflective coating of 1 um that is structurally stable, and not susceptible to displacements from small dynamic loads. The sail will also include an algorithm for steering and control based on a control vane routine.

7.0 – Future Work and Conclusions

The most pressing concerns with this project right now are those of testing, and correctly modeling the solar sail behaviour in the space environment. As a result, these areas will need to be addressed first. Also, finding the cheapest suppliers of quality components will be important due to the limited budget of this project. Despite this, the solar sail is an exciting project and we are looking forward to the future challenges facing us.

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