An Interplanetary Mission Design of a Solar Sailing CubeSat to Mars

Andrew J Tang* and Xiaofeng Wu
School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW, 2006, Australia
*Email: andrew.tang@sydney.edu.au

Abstract. While solar sailing missions have been developed in the past, orbital solar sailing missions are limited in number. Increasing access to the solar system can be achieved by leveraging the potential of solar sailing spacecraft. A feasibility study is performed to analyse a controlled solar sailing mission to Mars using a CubeSat platform. The proposal to send a solar sailing CubeSat to Mars would be revolutionary in delivering small payloads to the red planet by harnessing the solar radiation pressure emitted from the Sun. By utilising solar sailing and aerocapture techniques in the mission design, the need for chemical propulsion for transfer and capture is greatly reduced, minimising launch mass and maximizing payload mass efficiency.

In this study, investigations were carried out as mission analyses in the area of trajectory architecture and subsystem overview for systems available today and in the future. The influence and evolution of trajectories under gravitational and environmental conditions on Mars and the interplanetary transfer were scrutinised individually as relevant restricted dynamic systems. For a chosen insertion orbit, several feasible trajectories to Mars based on different solar sail systems were investigated, including optimised ballistic trajectories and the Sundiver transfer for solar sails. For the interplanetary trajectories, the planetary capture manoeuvre of the spacecraft to a serviceable orbit using aerobraking capture is evaluated. The final trajectory design features minimum-time optimisation for the interplanetary transfer of a solar sailing spacecraft from Earth to Mars. As the selected spacecraft platform is limited to low-thrust solar sailing propulsion, severe performance limitations apply to this mission. This work aims to highlight possible interplanetary trajectories for present and future small satellite platforms despite these limitations by using dynamical orbital simulation models.

1. Introduction
The subject of solar sailing has long caught the imagination of man, with the promise of boundless exploration across the universe. Free from the limits of propellant, a solar sail can theoretically accelerate a satellite for as long as there is a Sun providing solar radiation pressure. This idea can be traced to Galileo in the early 17th century, verified as viable by Maxwell’s equations in the mid-19th century, but took until 1976 for Louis Friedman at JPL [1] to begin the first thorough mission design for solar sails. Since then, solar sailing has remained in its infancy in utilization, with only a handful of solar sailing missions to date. Most notably of these is JAXA’s IKAROS, and Planetary Society’s LightSail 1 & 2.

The studies performed in this paper investigate the shortcomings of solar sailing technology and the feasibility of methods used to overcome these. This includes the trajectory analysis for the interplanetary coast as well as orbital capture at the target destination, both of which have traditionally been dominated
by chemical propulsion. It is proposed that a solar sail can be used not only for propulsion to a Martian orbit, but also can be adaptable as a drag sail for aerobraking capture. The reduction or elimination of propellant requirements through the use solar sails is a key area in future space exploration, as the alternative propulsion option does not carry this limitation associated with most existing propulsion systems. Results in this study are reviewed for the practicality of solar sails in their use as the primary propulsion system for interplanetary missions.

1.1. Technology demonstrators

The Planetary Society (TPS) was established by members including Friedman who were keen on the future of solar sailing technology, and by 2001 had built a sail demonstrator for the COSMOS-1, an eight-sailed solar sailing satellite [2]. This had extended to a fully built COSMOS-1 mission to be launched by the Russian Volna rocket into orbit. The COSMOS-1 had a total sail area of 600m² which would have allowed it to be seen with the naked eye from Earth when launched to an altitude of 825km. By this point, NASA, ESA, JAXA and Roscosmos had already begun dedicated solar sailing research, but had only been used to test mechanisms, not active propulsion [3]. The COSMOS-1 would have been the first spacecraft to use solar sailing technology for active propulsion, but a launch failure on another Volna rocket restricted this feat.

The first solar sail demonstration would eventually occur in 2010 when JAXA launched the Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS). On the square shaped sail measuring 20m along the diagonal length, the unique addition of variable reflective devices allows the IKAROS to perform attitude adjustments with its solar sail [4]. At 310kg however, this satellite’s 196m² sail would be poor for actual solar sailing due to the very high areal density (mass to sail area ratio). Nevertheless, the demonstrator was able to confirm for the first time an actual solar sailing spacecraft in operation.

Following this, the planned SunJammer mission was the next major milestone for solar sailing demonstration, with a huge 1200m² sail for deep space application. This was paired with an overall weight of just 32kg, greatly improving the sailing ability of the SunJammer over the IKAROS satellite. Once again, however, this project was ended prior to completion [5].

Prominence for solar sailing returned with CubeSat-platform based solar sailing demonstrators LightSail-1 and LightSail-2. These are both 3U CubeSats designed to test the deployment and controlled orbital manipulation using solar sails. LightSail-1 did not launch to a suitable orbit for testing orbital maintenance but was successful in demonstrating the deployment mechanism of its 32m² aluminised Mylar sail [2]. This sail measures at 4.6 microns thick and is attached to a retractable boom mechanism each measuring 4m long, deploying from a spindle to its fully extended position [6]. Whilst the first LightSail launched back in mid-2015 into a highly elliptical orbit thus unable to operate as a function solar sailing satellite, LightSail-2 was launched in July 2019 to a 709x725km orbit. Since then, LightSail-2 has demonstrated the ability to perform apogee raising using its on-off switching technique, a forward step in solar sailing demonstration using the CubeSat platform [7].

Despite all these efforts to forward the technology, there is still yet to be an integrated, fully solar sailing mission.

1.2. CubeSat platform

The CubeSat platform is known for its adaptability and relatively low-cost operations in the nanosatellite category. Dedicated commercial-off-the-shelf (COTS) components available allow satellites developed using the CubeSat platform to be rapidly prototyped, leaving only specialist payload components to be developed rather than the entire system bus. With the base unit of 1U being a standard 10x10x1cm frame, larger CubeSat missions are being planned with 3U, 6U and even 12U bases, expanding the capability of these satellites yet retaining the benefits of COTS componentry [8].

The LightSail program is a key milestone to creating affordable demonstrations for the solar sailing technology, allowing such technologies to mature with a wider community at a lower cost. Other CubeSats including the MarCO spacecraft demonstrate the ability of CubeSats to be tasked with interplanetary operations to Mars, communicating through NASA’s Deep Space Network (DSN) [9]. Such demonstration missions have shown the ability for smaller spacecraft to perform similar duties.
once relegated only to large, expensive spacecraft. If considerations are made for the effects of deep space travel, including but not limited to communication distances and effects of radiation, CubeSats can theoretically achieve low-cost Solar System exploration missions with capabilities beyond existing small satellites [10]. Thus, it becomes financially sensible to develop the smaller CubeSats for more ambitious missions and as technology demonstrators.

1.3. The lightness ratio

The fundamental measure of performance for a solar sail is known as its characteristic acceleration and can be used as a comparative value between different solar sailing spacecraft. This acceleration value is usually described in \( mm/s^2 \) to illustrate the general scale of acceleration of solar sailing spacecraft. At the mean distance between Sun and Earth, 1 AU, the solar radiation pressure, \( P \), is \( 4.56 \times 10^{-6} N/m^2 \). For a reflecting surface (reflected photons double the pressure force) with some efficiency factor, \( \eta \), the characteristic acceleration is [11]:

\[
a_{SRP} = \frac{2\eta P}{\sigma}
\]

where \( \sigma \) is the areal density \( (g/m^2) \), or the total mass to sail area ratio and efficiency is generally around 0.85 to 0.9 for a real solar sail [12].

The characteristic acceleration is the performance measure at 1 AU, whereas another parameter of lightness ratio, \( \beta \), is a measure of the ratio of solar sail power relative to the solar gravitational attraction. This means that, at \( \beta = 1 \), a perpendicularly oriented sail will exert the same force as the gravitational attraction of the Sun. This value is irrespective of the distance to the Sun, and hence is a good measure when considering interplanetary exploration. Calculation for this is achieved by non-dimensionalising the characteristic acceleration:

\[
\beta = a_{SRP} \times \frac{AU^2}{\mu}
\]

where \( \mu \) is the Solar gravitational constant and is equal to 1.3271244004193938 \( \times 10^{20} m^3/s^2 \). Thus, when combining equations (1) and (2), and assuming a perfectly reflecting surface we get:

\[
\beta = \frac{\sigma^*}{\sigma}
\]

where \( \sigma^* = 1.53 g/m^2 \) is the critical sail loading value [13]. The lightness ratio is thus a simple but useful index which can be used to compare the performance of interplanetary solar sailing spacecraft only requiring the total mass and sail area to compute.

| Satellite/Sail Project | Sail Area \( (m^2) \) | Areal Density \( (g/m^2) \) | \( a_{SRP} \) \( (mm/s^2) \) | \( \beta \) |
|------------------------|------------------------|------------------------|------------------------|------------------------|
| IKAROS                 | 196                    | 1582                   | 0.005                  | 0.001                  |
| NanoSail-D2            | 10                     | 420                    | 0.018                  | 0.004                  |
| COSMOS-1               | 600                    | 167                    | 0.047                  | 0.009                  |
| LightSail Project      | 32                     | 154                    | 0.050                  | 0.010                  |
| NEA Scout              | 86                     | 140                    | 0.056                  | 0.011                  |
| SunJammer              | 1200                   | 26.7                   | 0.29                   | 0.057                  |
| Halley’s Comet Sail    | 576000                 | 7.6                    | 1.01                   | 0.207                  |

1.4. Example solar sails.

With a fair number of solar demonstrators, and many more proposed solar sailing spacecraft, a comparison between their sailing performances can be made. These results are displayed in table 1, ordered by their characteristic acceleration.
The solar sail for Halley’s rendezvous mission was first conceived by Friedman’s team at JPL in 1976 and included a massive 800x800m solar sail with an areal density of 7-8g/m². Additional technical challenges included the necessity of 2.5μm Kapton, which for the 576000m² sail would weigh a total of 2540kg including the aluminium and back emissive coatings. This was necessary to generate the required 70km ΔV for the rendezvous with the comet, but this design never came to fruition due to the significant technical challenges associated with building the sail [14].

The final assembled COSMOS-1 solar sail was planned for a March 2005 launch and included 8 triangular sails with 15m length booms. The 5μm Mylar sails would deploy in two stages giving the COSMOS-1 a characteristic acceleration of roughly 0.05mm/s² [3].

The NanoSail-D and subsequent NanoSail-D2 were the primary and backup demonstrators to test the deployment and deorbiting functionality of a solar sail, the latter launching in 2010. The sail membrane was manufactured using an aluminised CP1 polymide to provide reflectivity yet remaining as lightweight as possible. Triangular Rollable And Collapsible (TRAC) booms made from Elgiloy material were used as the main support – a similar design to that used on the LightSail missions [15].

JAXA’s IKAROS mission launched in 2010, but unlike most of the other sailing missions listed here, did not have a favourable areal density. However, the unique properties of the IKAROS solar sail included LCD panels which could switch on and off to induce a torque, and hence rotation of the spacecraft. Additionally, solar panels were placed on the solar sail to provide for the electrical requirements of the spacecraft. The 196m² sail was constructed with 7.5μm aluminised polymide and weighed only 2kg itself, giving it a sail areal density of 10g/m² [4].

The SunJammer mission envisioned a huge 1200m² sail used to fly beyond Earth orbits. The 38x38m sail would weigh just 8.5kg and pack into a volume of 0.5m³, with an overall satellite mass of around 32kg. This design called for the development of 5μm Kapton film to be utilised as the sail membrane, a product previously unavailable. An inflatable, rigidisable technology developed by L’Garde would promise to provide an innovative boom extension method that would be scalable to greater sail sizes. However, the SunJammer project was cancelled by NASA citing inability to execute the requirements [5].

The LightSail projects followed a similar 3U CubeSat design as the NanoSail demonstrators, but executed with a larger 32m² sail and a 4.6μm Mylar film. A similar TRAC boom system was utilised, extending 4m for each diagonal for a length of 5.6m for the sail edge. The technology utilised on the LightSail-2 features the latest sail material which has been tested in space to date [2].

The Near Earth Asteroid (NEA) Scout is the successor to LightSail and NanoSail projects, developed as a 6U CubeSat mission to visit an asteroid. With a thinner 2.5μm CP1 aluminised sail, the larger satellite is expected to perform a 3-year demonstration mission of asteroid reconnaissance [16].

The above missions indicate the current and theorised state of technology with regards to sail booms and membranes. With sail designs, larger sail areas tend towards lower areal densities, although there is a trade-off with regards to rigidity of boom structures and other mechanisms to reinforce the sail’s shape. Current sail areal densities reach 10g/m² and below, but further developments to reduce boom weight must be realised as they add another 15g/m² to the areal density depending on the size of the entire setup, excluding payload and satellite bus [17].

2. Mission overview

To promote the adoption of solar sailing technology, a solar sailing interplanetary mission to Mars utilising the CubeSat architecture is envisaged. As interest continues to grow on the colonisation of Mars, the investigation of low-cost missions to the red planet are crucial to the expansion of human exploration. It could be envisioned in the future that solar sails provide a critical cargo service to interplanetary destinations including Mars (Fig.1).

This mission will involve two stages, considering trajectory optimisation of various sail architecture launched from Earth. The aerobraking capture performance of solar sailing spacecraft will also be analysed, as this currently presents a significant challenge for such satellites to perform interplanetary travels without chemical propulsion for orbital insertion. The ability for the solar sail to perform a dual
function as a drag sail is theorised to allow for a controlled orbital capture of a satellite with minimal or no propellant usage, vastly improving its merit as a complete propulsion package. Values of analysis determined using a solar sail include the transfer time and aerobraking capture performance of various solar sailing satellite architectures. These solar sailing architectures significantly reduce the need for interplanetary orbit injection velocities that are typically supplied by a launch vehicle, reducing the size of launch vehicle and overall cost required for a similar mission.

2.1. CubeSat design
The overall mission targets the 12U volume to maximize sail size whilst managing requirements for an interplanetary mission such as radiation hardening, with a maximum weight of 24kg. 8U of this will be reserved for the solar sailing mechanism with all communications handled by NASA’s IRIS V2.1 Deep Space Transponder taking up 0.5U to provide 1-4 kbps data link at 2AU distance. Another 0.5U will be reserved for command and data handling, with 0.5U reserved for the power subsystem. This gives 1.5U for an attitude determination and control subsystem, consisting of a miniature star tracker, reaction wheel system and cold gas thrusters. This allocation gives 1U volume for payload, which should be sufficient given the low data transmission rate from Mars and can be modified for a specific mission use. 0.48$m^2$ of solar panels give a max power of 112$W$ at Earth and 48$W$ at Mars, assuming 80% efficiency, although this value is likely much lower due to the angle relative to the Sun [8].

2.2. Solar sail designs
The studied solar sail designs utilised in this study will be square sails (Fig.2), like many past and existing designs. Four evolutions of a square sail design will be investigated, involving technology that extends from today into the distant future. These test designs, as populated in table 2, assume the same CubeSat bus layout as described in subsection 2.1, with progressively thinner and lighter sail membrane and stiffer boom structures. These square designs assume diagonal boom lengths of 12.8$m$, 18.4$m$, 30$m$ and 45$m$ boom, which would likely result from developments in carbon nanotube technology and robust sail membranes. Also given in the table are lightness ratios and examples of required technologies to reach these stages.
**Table 2.** Solar sail designs for comparison.

| Solar Sail Timeline | Sail Area (m²) | β | Technology                          |
|---------------------|----------------|---|-------------------------------------|
| Present-Day         | 298            | 0.019 | Present Day                        |
| Near-Future         | 614            | 0.039 | Thinner Kapton, Stiffer TRAC       |
| Mid-Future          | 1620           | 0.103 | Thinner Kapton, Early Nanotubes    |
| Far-Future          | 3645           | 0.232 | Thinner Kapton, Carbon Nanotube    |

**Figure 2.** 12U solar sailing CubeSat without solar sail deployed.

3. **Spacecraft dynamics**

The spacecraft dynamics for this study are broken down into two separate regions using a patched conics assumption for interplanetary trajectories. These involve the aerocapture of the solar sailing spacecraft into Martian orbit, and the interplanetary travel from Earth to the red planet. For these analyses, it is assumed that the solar sail is modelled as a perfect flat plate, void of deficiencies such as wrinkles and thermal or structural deformation.

3.1. **Forces on a solar sail**

Solar radiation pressure (SRP) occurs when photons impinge on a surface, and can be described as either being absorbed, \( \rho_a \), specularly reflected, \( \rho_s \), or diffusely reflected, \( \rho_d \), such that:

\[
\rho_a + \rho_s + \rho_d = 1
\]

The SRP forces acting on a flat plate at 1AU distance can thus be modelled as [18]:

\[
F_{SRP} = PA_e \left\{ (\rho_a + \rho_d) s + \left( \frac{2}{3} \rho_d + 2 \rho_s \cos(\alpha) \right) n \right\}
\]

where \( A_e \) is the effective area, \( s \) is the sun vector, \( n \) is the sail normal vector, and \( \alpha \) is the solar clock angle between the vectors \( s \) and \( n \). When assuming a perfectly specularly reflecting plate as in figure 3, this can otherwise be written as:

\[
F_n = PA_e \{ \cos(\alpha n) - \sin(\alpha t) \}
\]

\[
F_t = PA_e \{ \cos(\alpha n) + \sin(\alpha t) \}
\]
\[ F_{SRP} = F_n + F_t = 2PA \cos^2(\alpha)n = 2PA(s \cdot n)^2n \]

where \( t \) is the sail transverse vector. Finally, normalising with respect to AU using equation (2) and reintroducing the lightness parameter, \( \beta \), we get:

\[ a_{SRP} = \beta \frac{\mu}{r^2} \cos^2(\alpha)n = \beta \frac{\mu}{r^2} (s \cdot n)^2n \]

This equation allows us to use a single parameter to define the performance of a solar sail anywhere within our Solar System under the relevant assumptions.

![Solar radiation pressure model for an ideal flat solar sail.](image)

**Figure 3.** Solar radiation pressure model for an ideal flat solar sail.

### 3.2. Potential theory

Considering a method with patched conics, a potential function represents the gravity field of a body, namely the Sun during the interplanetary cruise phase between Earth and Mars:

\[ \Phi = \frac{\mu}{r} \]

When seeking the acceleration between two bodies, we can find the partial derivative in that direction, or as a complete vector as:

\[ \ddot{r} = \frac{d\Phi}{dr} \Rightarrow \ddot{r} = -\frac{\mu r}{r^3} \]

This function represents the basic unperturbed motion of the satellite in interplanetary transfer and can also be used between any two bodies by selecting the relevant gravitational constant.

### 3.3. Kinematic equations for aerobraking

When considering the drag effects of the solar sail only, the cartesian equations of motion can be represented as:

\[ \dot{r} = v \]

\[ \dot{v} = -\frac{\mu}{r^3} + a_d \]

where in cartesian coordinates, the states \( r = [x, y, z]^T \), \( v = [v_x, v_y, v_z]^T \) are the position and velocity vectors, and \( a_d \) is the acceleration due to aerodynamic drag, given by:

\[ a_d = -\frac{1}{2m} c_d \rho v S \cdot v \]

where \( m \) is the satellite mass, \( \rho \) is the density, \( S \) is the sail area and the drag coefficient, \( c_d \), is 2.2 from past CubeSat literature [19].

The density for Martian atmosphere was generated using the marsGRAM 2010 model up to an altitude of 1000km [20] and can be seen in figure 4 below.
3.4. Kinematic equations for solar sailing

When considering the perturbation effects of the solar sail only, the cartesian equations of motion can be represented as:

\[ \dot{r} = v \]  \hspace{1cm} (15)
\[ \dot{v} = -\frac{\mu}{r^3} + a_{SRP} \]  \hspace{1cm} (16)

However, additional assumptions include the interplanetary trajectories based on circular, co-planar orbits of Earth (1AU) and Mars; this can also be written excluding the z axis, or the cone angle, in polar coordinates:

\[ \dot{r} = v_r \]  \hspace{1cm} (17)
\[ \dot{\theta} = \frac{v_\theta}{r} \]  \hspace{1cm} (18)
\[ \dot{v}_r = \frac{v_r^2}{r} - \frac{\mu}{r^3} + \beta \frac{\mu}{r^2} \cos^3 \alpha \]  \hspace{1cm} (19)
\[ \dot{v}_\theta = -\frac{v_r v_\theta}{r} + \beta \frac{\mu}{r^2} \cos^2 \alpha \sin \alpha \]  \hspace{1cm} (20)

where \( x = [r, \theta, v_r, v_\theta]^T \) is the state vector and \( \alpha \) is the controlled sun clock angle of the solar sail.

For the solver, several conditions were imposed for the interplanetary trajectory problem. Namely, the initial conditions for the solver were:

\[ r(t_0) = r_0 \]  \hspace{1cm} (21)
\[ v_r(t_0) = 0 \]  \hspace{1cm} (22)
\[ \theta(t_0) = 0 \]  \hspace{1cm} (23)
\[ v_\theta(t_0) = v_0 \]  \hspace{1cm} (24)

The final conditions would set the bounds within the assumed circular and coplanar orbit of Mars, deemed to be 1.524 AU, and are given as:

\[ r(t_f) = r_f \]  \hspace{1cm} (25)
\[ v_r(t_0) = HEV^* \]  \hspace{1cm} (26)
\[ v_\theta(t_f) = v_f + HEV^* \]  \hspace{1cm} (27)

where HEV* is the split components of the total allowed HEV (hyperbolic excess velocity). The final polar angle, \( \theta \), is unbounded.

For a time-optimal problem, the objective function is simply defined as:
\[ J = \int_{t_0}^{t_f} 1 \, dt = t_f - t_0 \]  

(28)

The control variable, \( \alpha \), was bounded as:

\[ \frac{\pi}{2} \leq \alpha \leq \pi \]  

(29)

All values for the interplanetary analysis were normalised to AU/day.

4. Aerobraking capture using drag sails

The capacity for solar sailing CubeSats to perform as drag sails for aerobraking capture in a Martian orbit was required to establish feasible hyperbolic escape velocities with which an interplanetary CubeSat could enter within the sphere of influence of Mars. Establishing this capacity with minimal or no chemical propulsion will expand the potential for solar sailing missions of the future by removing the need for a dedicated thruster for orbit insertion. The Mars Reconnaissance Orbiter (MRO) utilised a similar aerobraking technique to establish a polar Martian orbit, dipping to altitudes as low as 93 km [20] during progressive orbital aerobraking. Thus, as a reference guideline, the minimum allowed altitude for aerobraking was 100 km above the Martian surface. Finally, two separate hyperbolic excess velocities were tested, 100 m/s and 2000 m/s to simulate near-zero and low HEV.

4.1. Near-zero velocity hyperbolic excess speed aerobraking

Several effective areas were tested, ranging from 0.06 m² to 200 m² to simulate minimum to almost maximum area of the present-day test satellite. Using the model established from equation (13), and the Martian density in figure 4, it was noted that aerobraking performance scaled exponentially with proximity to the red planet, and proportionally with the drag area. This denotes the necessity of high accuracy insertion when considering aerobraking capture with any satellite. Thus, the inclusion of onboard cold gas thruster in this design would be utilised to correct for the orbital insertion, in addition to raising the satellite out of the Martian lower atmosphere to prevent further orbital decay. Alternatively, it is theorised that solar radiation pressure forces be controlled to manoeuvre the solar sailing spacecraft to a suitable orbital altitude, eliminating the necessity for any propulsion system.

Figure 5. Aerobraking capture of various small drag sails at HEV of 100 m/s.
Figure 6. Aerobraking capture of various sized drag sails at HEV of 100\(m/s\).

The results for various sized drag sails with a 100\(m/s\) HEV of a 24kg CubeSat can be seen in figures 5 and 6. From these results, we can see that aerobraking capture into an orbit of Mars is possible for solar sailing CubeSats with smaller solar sail areas, assuming non-deformation of the solar sail and a near-zero hyperbolic excess velocity. For spacecraft with a reasonable surface area, such as with large solar panels, it is noted that aerobraking capture is still possible. However, the initial orbital periods for spacecraft with low drag area is in the order of days or weeks, indicating a poor suitability to aerobraking capture techniques.

Spacecraft with drag areas of 50\(m^2\) or greater begin to represent suitable candidates for aerobraking capture, as seen in figure 6. These spacecrafts have initial orbital periods of hours, which with continued aerobraking can quickly become injected into the desired Martian orbit. It should be reiterated that spacecraft with greater surface areas can approach the planet at an angle to reduce the degree of aerobraking, whereas the opposite cannot occur. Thus, for our solar sailing designs, aerobraking capture is entirely possible, where solar radiation pressure forces at Mars can then be utilised to manoeuvre the spacecraft around to reconfigure its orbit.

4.2. Low velocity hyperbolic excess speed aerobraking

Figure 7 illustrates the capture performance of the same reference areas given a greater HEV of 2000\(m/s\), closer simulating the insertion performance of classical interplanetary travel systems. The results here reflect a change to the minimum required area for effective aerobraking capture to be performed on Mars. Where previously captured with an initial orbit period of less than a day, the 50\(m^2\) reference drag sail is unable to be captured by the gravity of Mars, continuing outside the planet’s sphere of influence. The performance of the larger drag sail areas indicate that they are able to be captured, although there seems to be some minimum requirement of insertion accuracy to maintain the desired 100\(km\) approach altitude. It is extrapolated that sails with greater drag area have the ability to be captured when given greater excess velocities.
Figure 7. Aerobraking capture of various sized drag sails at HEV of 2000 m/s.

4.3. Aerobraking performance summary

Table 3 summarises the performance characteristics of the present-day solar sailing satellite given a minimum approach altitude of 100 km. From these results, a HEV of 2000 m/s can reasonably be assumed for the specifications outlined for the present-day satellite, with greater HEV’s permissible for future solar sailing spacecraft. These early studies performed indicate the capability of aerobraking capture techniques as an alternative for chemical propulsion for orbital insertion.

Table 3. Performance of drag sail with different hyperbolic excess velocities.

| Drag Sail Area (m²) | Excess Velocity - 100 m/s | Initial Orbit Period (hr) | Excess Velocity - 2000 m/s | Initial Orbit Period (hr) |
|---------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| 0.06                | No Capture                | No Capture                |                           |                           |
| 10                  |                           | 187 hr                    | No Capture                |                           |
| 30                  |                           | 43 hr                     | No Capture                |                           |
| 50                  |                           | 20.7 hr                   | No Capture                |                           |
| 100                 |                           | 7.5 hr                    | 16.25 hr                  |                           |
| 200                 |                           | 2.6 hr                    | 2.5 hr                    |                           |

5. Ideal interplanetary trajectory

A previously conducted study by Percy et al. examined solar sailing spacecraft with initial excess velocities of 3 km/s, and HEV values between 5 km/s and 12 km/s [21]. However, such high HEV values assume some greater degree of chemical propulsion for planetary capture, and so lower values of 2000 m/s was assumed for the present-day solar sail. The allowable HEV value used was suitable for present-day solar sailing spacecraft, but was scaled to 2500, 4000 and 7000 m/s for near, mid and distant future solar sailing spacecraft respectively to accommodate their greater aerobraking capture
performance. Initial excess velocity was set at 0\(m/s\) to allow for possible solar sailing escape from Earth, which is assumed but not computed in this study. The selection of greater initial excess velocities greatly impacts the travel time and feasibility of solar sailing missions but have been selected as a worst-case scenario such as departure from an uninhabited orbit to best investigate the capability of solar sails when used for interplanetary travel.

For solar exploration for outer planets missions and beyond, the Sundiver manoeuvre, involving ‘diving’ to a close approach to the Sun to generate massive forces from SRP, is popular amongst the solar sailing community. However, for a mission to Mars, it was studied that the Sundiver manoeuvre would take over twice as long to reach the destination in comparison to a direct transfer orbit [21]. Furthermore, a large degree of initial excess velocity is required to perform the ‘diving’ manoeuvre, which was not available in the scopes of this study. As such, the focus of this study would concentrate on direct transfer trajectories to Mars.

5.1. Optimisation methodology
Various methods of interplanetary trajectory optimisation were utilised, including Runge Kutta 4\(^{th}\) order multiple shooting, trapezoidal direct collocation, Chebyshev-Lobatto orthogonal collocation and Hermite-Simpson direct collocation [22]. The Runge-Kutta multiple shooting method was utilised to generate the initial approximations to the results, which were then refined and utilised again to initialise all four optimisation methods. For a present-day solar sailing satellite configuration, these methods were utilised to generate the results in figure 8. These preliminary results indicate a roughly similar performance in trajectory generation, and that interplanetary solar sailing is achievable.

![Figure 8](image.png)

**Figure 8.** Present day satellite configuration using different optimisation methods
5.2. Trajectory optimisation comparison

These optimisation methods were again tested now against the four test satellite configurations, with the results visible in figure 9. The results indicate that there is very little difference in the solutions between each of the optimisation methods used, including the ‘near-future’ solution where there is slightly more disparity between the optimised trajectories. The biggest trend which is apparent within figure 9 is the significant improvement in performance, or transfer time, with an increase in the lightness ratio. Recalling from equation (3) that the lightness ratio is strictly a function of the areal density, or the total mass divided by sail area, this correlation is evident as the test configurations assumed stiffer boom structures and more massive sails for the same satellite system.

Comparing the results here with figure 8, we can see that the arrival polar angle difference in the solutions are not prioritised in time-optimization trajectories, with each simulation spread between a time of just 7 days, despite the seemingly large differences in the arrival position of the solar sailing spacecraft. Although the arrival times may be similar, this would indicate a significant difference in departure and arrival time as the position of Earth and Mars have not been included in this study. Furthermore, it should be noted however that the explicit solution of the Runge-Kutta method took significantly longer to generate a result. As a relatively fast and accurate optimisation method, the Hermite-Simpson optimiser was used to model the comparisons of the test satellite configurations.

![Figure 9. Transfer time to Mars vs lightness ratio using various optimisation methods.](image)

5.3. Hermite-Simpson optimisation of present and future solar sail designs

Using Hermite-Simpson direct collocation, the solar sail design configurations for the present and future and their projected trajectories can be seen in figure 10. The trajectories generated in this figure are reflective of the trend illustrated in figure 9, illustrate the significant difference in the required arrival times for present fairing solar sail designs, in comparison to solar sailing spacecraft of the future. In particular, the generated solutions for the mid-future solar sail configuration appear like that of a Hohmann transfer orbit, and the far-future solar sail configuration result appears like a one-tangent burn. However, these results have been generated with zero initial excess velocity when departing from the Earth orbit, illustrating the effectiveness of solar sails as a primary interplanetary propulsion method, especially for solar sails with the expected improved technologies of the future.

For the purposes of comparison, further results using the Hermite-Simpson direct collocation were generated for the same solar sailing satellite configurations, but with an added initial excess velocity of 2000 m/s. The allowable hyperbolic excess velocities for orbital insertion were increased by the same amount, and the results for these are shown in figures 11.
Figure 10. Present and future solar sail designs and their trajectories.

Figure 11. Transfer time vs lightness ratio with zero vs 2000 m/s initial velocity.
The results shown in figure 11 indicate that there is an appreciable difference in the transfer time of almost half a year for present-day solar sailing spacecraft with a given initial velocity of 2000m/s, which can be provided by the launch vehicle. This influence is decreased as the lightness ratio increases, with distant-future spacecraft benefitting very little from any increased initial velocity.

6. Conclusion

In conclusion the results of the aerobraking capture study with the trajectories generated using optimisation methods in solar sailing generates a complete trajectory simulation from Earth to orbit around Mars. The results show that, for a present-day configured solar sailing CubeSat, it can utilise the techniques of solar radiation pressure and aerobraking to transit to and capture within a Martian orbit, taking less than 2 and a half years. Whilst present day solar sailing spacecraft designs are capable, improving technologies should show great promise to the interplanetary sailing missions of the future by cutting the transit to Mars to less than half a year. Thus, it would become practical to utilise solar sails as the primary propulsion system for satellites, and possibly a necessity for interplanetary missions of the future.

Requiring little to no fuel beyond the gravitational bounds of Earth, there is high potential to produce spacecraft capable of sustained interplanetary travel at low cost by reducing the size of the required launch vehicle. In addition, solar sailing spacecraft of the future can attain transfer times shorter than traditional Hohmann and one tangent burn transfers trajectories possible with existing chemical propulsion.

The capture technique at Mars of utilising aerobraking was evaluated and found to be an effective consequence of developing technology for solar sailing missions. Although highly precise insertions are required, aerobraking can reduce excess velocities of solar sailing spacecraft sufficiently to be captured within the Martian atmosphere, providing a solution to a challenge previously resolved with chemical propulsion systems. This shows promise of similar techniques being applied to various other destinations, expanding the potential of solar sails to a wider catalogue of mission applications.

7. Future works

Extension of this study would include the trajectory planning from a Low Earth Orbit (LEO) to the extremities of the sphere of influence of the Earth, to demonstrate the full capabilities of solar sailing spacecraft. The achievement of this, if possible, would significantly increase the appeal of solar sailing technology due to the extremely large costs associated with current interplanetary launch vehicles. In addition, this would allow a solar sailing satellite to rideshare on any suitable LEO rocket and progress forward with the mission on its own. With flexibility on launch opportunities and a low cost, solar sails would quickly become the primary, albeit initially slow, method of propulsion.

Further work would be carried out on the refinement of the models used here. Numerous assumptions were made for the models to present a generalised solution of solar sailing spacecraft, but the reality is that solar sails are non-ideal reflective surfaces, can deform and degrade over time. Works discussed in this study, including the ‘present-day’ technologies presented are an extension of currently existing systems, but are not existing spacecraft. Construction of and flight testing of solar sailing spacecraft would be necessary to validate the premises proposed in this study, and those of more refined models.

References

[1] Friedman L 1986 Starsailing: Solar Sails and Interstellar Travel (Hoboken: Wiley)
[2] Ridenoure R, Munakata R, Diaz A, Wong S, Plante B, Stetson D, Spencer D, and Foley J 2016 Testing The LightSail Program: Demonstrating Solar Sailing Technology Using a CubeSat Platform Journal of Small Satellites 5 p531-50
[3] Alexander A and Friedman L D (2004 November) COSMOS 1: The Journey Begins The Planetary Report (Pasadena: The Planetary Society) 24 p6-11
[4] Mori O, et al 2010 First solar power sail demonstration by IKAROS Trans. JSASS, Aerospace Technology Japan 8 (ists27) To 4 25-31
[5] Barnes N C, Derbes W C, Player C J and Diedrich B L 2013 Sunjammer: A solar sail
demonstration 3rd Int. Symp. on Solar Sailing (June 2013, Glasgow, Scotland, United Kingdom)

[6] Ridenoure R, Munakata R, Diaz A, Wong S, Plante B, Stetson D, Spencer D, and Foley J 2015
LightSail program status: One down, one to go 29th AIAA/USU Conf. on Small Satellites
(August 2015 Logan, Utah, USA)

[7] Davis J 2019 LightSail 2 spacecraft successfully demonstrates flight by light [Internet] (Pasadena: The Planetary Society) July 31st 2019 [cited August 5th 2019] Available from:
http://www.planetary.org/blogs/jason-davis/lightsail-2-successful-flight-by-light.html

[8] Tang A, Sun X, Long X, Huang Y, Mu Z, Wu S and Wu X 2019 LONIM: A 6U lunar ice mapping
cubeSat with intelligent on-board processing 32nd Int. Symp. on Space Technology and
Science (June 2019, Fukui, Japan)

[9] Klesh A et al 2018 MarCO: Early operations of the first CubeSats to Mars 32nd AIAA/USU Conf.
on Small Satellites (August 2018, Logan, Utah USA)

[10] Staehle R et al 2013 Interplanetary CubeSats: Opening the Solar System to a broad community at
lower cost Journal of Small Satellites 2, p161-186

[11] McInnes C 2003 Solar sailing: mission applications and engineering challenges Philosophical
Transactions A: Mathematical, Physical and Engineering Sciences 361, p2989-3008

[12] Wawrzyniak G G 2011 The dynamics and control of solar-sail spacecraft in displaced lunar
orbits (ProQuest Dissertations Publishing, Purdue University, West Lafayette, Indiana)

[13] Ma Y and Pan B 2017 Solar sail time-optimal trajectory optimization using Kustaanheimo–Stiefel
transformation 4th Int. Symp. on Solar Sailing (January 2017, Kyoto, Japan)

[14] Sauer C G 1977 A comparison of solar sail and ion drive trajectories for a Helley’s Comet
rendezvous mission Astrodynamics Specialist Conf. (September 1977, Jackson Hole,
Wyoming USA)

[15] Johnson L, Whorton M, Heaton A, Pinson R, Laue G and Adams C 2009 NanoSail-D: A solar
sail demonstration mission 6th IAA Symp. on Realistic Near-Term Advanced Scientific Space
Missions (July 2009, Aosta, Italy)

[16] Sobey A R and Lockett T R 2016 Design and development of NEA Scout solar sail deployer
mechanism 43rd Aerospace Mechanisms Symp. (May 2016, Santa Clara, California USA)

[17] Herbeck L, Sickinger C, Eiden M and Leipold M 2003 Solar sail hardware developments 54th Int.
Astronautical Congress (September 2003, Bremen, Germany)

[18] Wie B 2004 Solar sail attitude control and dynamics, part 1 Journal of Guidance, Control, and
Dynamics 27, p526-35

[19] Tang, A and Wu, X 2019 LEO satellite formation flying via differential atmospheric drag
IJSACESE accepted

[20] Long S M et al 2007 Mars Reconnaissance Orbiter aerobraking daily operations and collision
avoidance 20th Int. Symp. on Space Flight Dynamics (September 2007, Annapolis, Maryland
USA)

[21] Percy T, Taylor T and Powell T 2014 A study of possible solar sailing applications for Mars
missions 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conf. and Exhibit (July 2014, Fort
Lauderdale, Florida USA)

[22] Kelly M 2017 An Introduction to Trajectory Optimization: How to Do Your Own Direct
Collocation Society for Industrial and Applied Mathematics 59, p849-904