Imperial College London

16/06/2022

Preliminary design of a solar sail propelled spacecraft for extrasolar trajectories

Final Thesis Presentation

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Structure of presentation

1. Introduction
    1. Background information
    2. Objectives
2. Sailcraft design
3. Attitude sensitivity study
4. Conclusions

Context and Motivation

- Prior extrasolar missions:
  - Voyager I and II
  - Pioneer 10 and 11
  - New Horizons

- Notable prior solar sailcraft:
  - IKAROS
  - LightSail 1 and 2 (3U CubeSat)

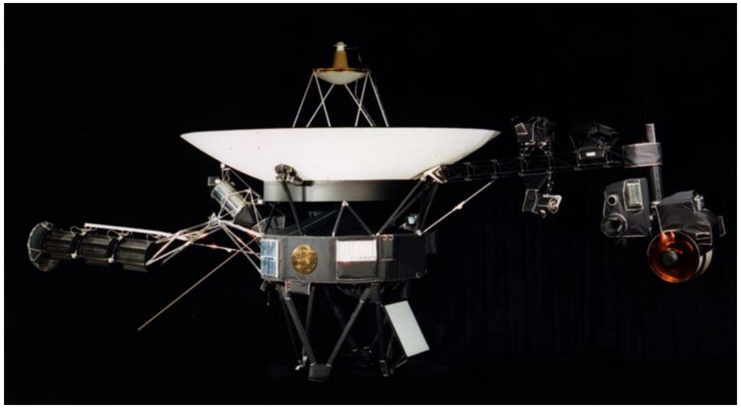


Fig 1: Photo taken of Voyager assembled [1]

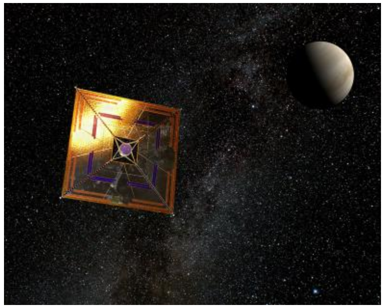


Fig 2: Artist depiction of IKAROS [2]

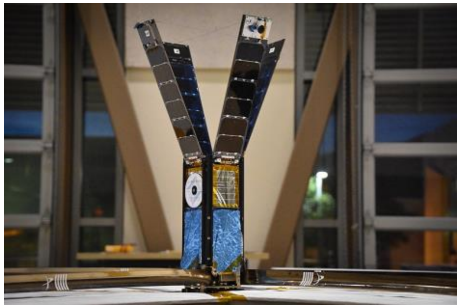


Fig 3: LightSail 2 after boom deployment test [3]

[1] https://voyager.jpl.nasa.gov/assets/images/galleries/images-of-voyager/spacecraft_profile.jpg [2] https://commons.wikimedia.org/wiki/File:IKAROS_solar_sail.jpg
[3] http://www.planetary.org/multimedia/space-images/spacecraft/lightsail-2-ground-finale.html

Project Objectives

Primary Objectives:

- To launch a **solar sailcraft** to exit the Solar System **within 100 years** to maximise its scientific utility
- To carry out **measurements of the sailcraft's trajectory** and produce a method of designing larger-scale extrasolar missions

Secondary Objectives:

- To produce a high-TRL solar sailcraft
- To **advance CubeSat capabilities**
- To attract funding for CubeSat development in subsequent years
- To establish Imperial College London as leader for CubeSats within UK and an innovator in space technologies worldwide

Previous works

- Feasibility study by Moore [4]
  - **Proved feasibility** and within remits of university research
  - Initial system sizing and design (**passive gyroscopically spin-stabilised sailcraft**)

- Preliminary design by Geragidis [5]
  - Demonstrated feasibility of deployment on a **Mars transfer orbit**, verified by GMAT
  - Provided a **design envelope for future work**

- Preliminary structural design by Montete [6]
  - Preliminary structural model for spin-stabilised and boom deployment design concepts, modelled in ABAQUS
  - Wrinkling analysis and effect on performance
  - Proved **passive tracking to be unfeasible, need active tracking**

[4] Hotston-Moore, E. (2019) Feasibility analysis of a solar sail propelled spacecraft for extrasolar trajectories, [5] Geragidis, F. (2021) Preliminary design of a solar sail propelled spacecraft for extrasolar trajectories, [6] Montete, P. (2021) Preliminary structural design of a solar sail propelled spacecraft for extrasolar trajectories

Mission scenario - Trajectory

- Passive gyroscopically spin-stabilised sailcraft deployed at apoapsis of Mars transfer orbit
  - See Figure 4

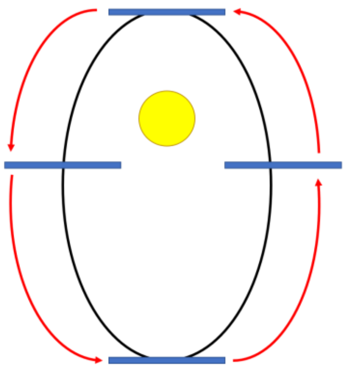


Fig 4: Orientation of sailcraft over orbit. Not to scale.

- **Periapsis falls and apoapsis rises** with each pass due to sail plane orientation remaining planar
  - See Figure 5

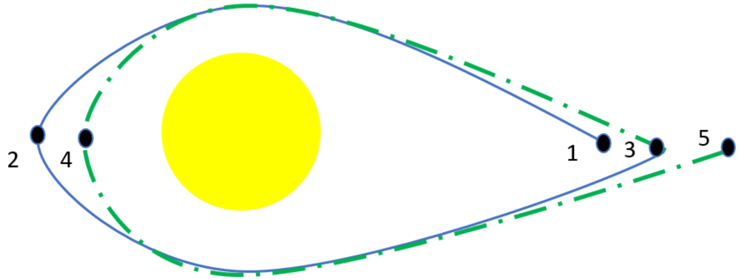


Fig 5: Evolution of orbit over time. Not to scale.

Thesis Objectives

1. Further-refine the solar sailcraft's preliminary design
    1. Validate the usage of a **standard CubeSat specification**
    2. Defining the **requirements and sizing** of each subsystem
    3. Update the power and **mass budget**

2. Explore the solar sailcraft's **attitude stability** over the mission

Sailcraft Design

Sailcraft Design

1. Mass sensitivity study
2. Hub sizing
    1. Internal layout
    2. Stowage of sail
3. Subsystem sizing
    1. Attitude determination and control (ADCS)
    2. Command and data handling (C&DH)
    3. Telemetry, tracking, and command (TT&C)
    4. Power
        - Validation of subsystem sizing
4. Sailcraft mass budget

Mass sensitivity study

Table 1: Design envelope of key parameters of the sailcraft [5]

Parameter	Minimum	Design	Maximum	Units
A_{sc}	7.6	12.4	$\boxed{28.6}$	m^2
l_{side}	2.739	3.493	5.320	m
m_{sail}	21.584	35.216	81.224	g
ω_{sc}	0.32	0.49	0.63	RPM

- Need to find ideal mass range based on size range from design envelope
- Chosen to use **maximum sail size** for largest thrust from SRP
- Tested masses of [2, 3, 4, 5, 6, 8] kg in GMAT

[5] Geragidis, F. (2021) Preliminary design of a solar sail propelled spacecraft for extrasolar trajectories

Mass sensitivity study

Table 2: Mass sensitivity study results from GMAT simulations

Mass (kg)	Maximum Apoapsis (AU)	Time to Apoapsis (years)	Closest Approach (AU)	Time to 121 AU (years)
2	23.99	27.94	0.07	58.65
3	4.85	10.05	0.18	62.04
4	6.97	15.61	0.13	52.70
5	11.01	23.62	0.09	55.70
6	21.43	40.30	0.04	72.96
8	9.17	32.27	0.14	98.60

Mass sensitivity study

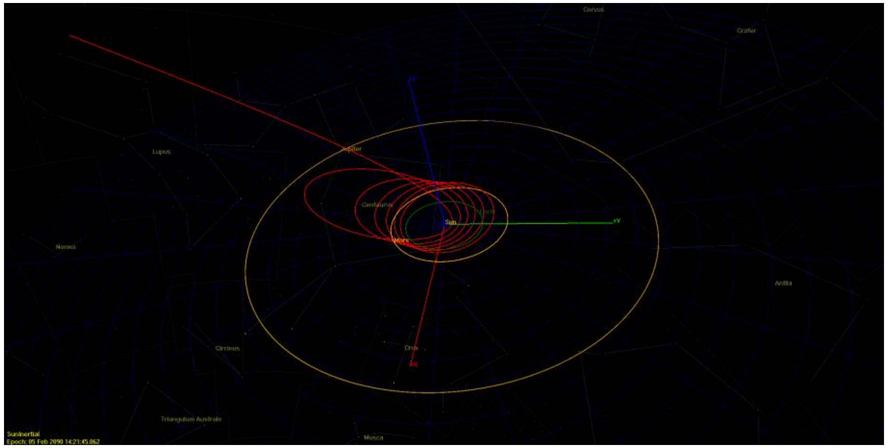


Fig 6: GMAT simulation using sailcraft mass of 3 kg.

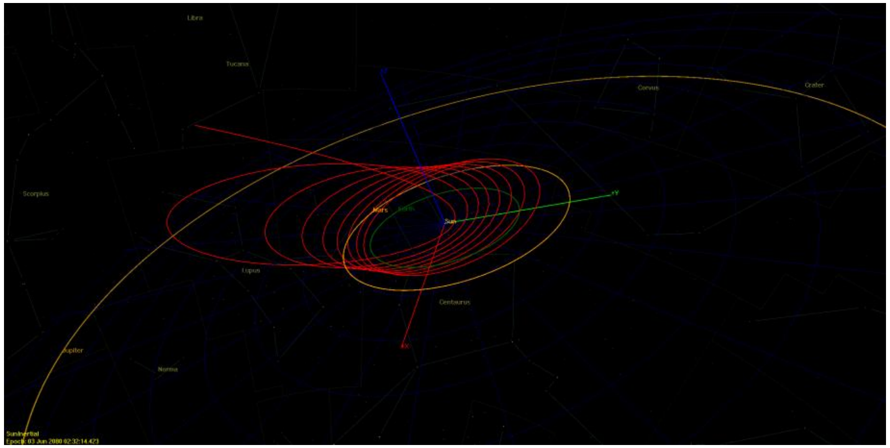


Fig 7: GMAT simulation using sailcraft mass of 4 kg.

Hub sizing

- Chosen **target mass of 3.99 kg** to fit within **3U CubeSat**

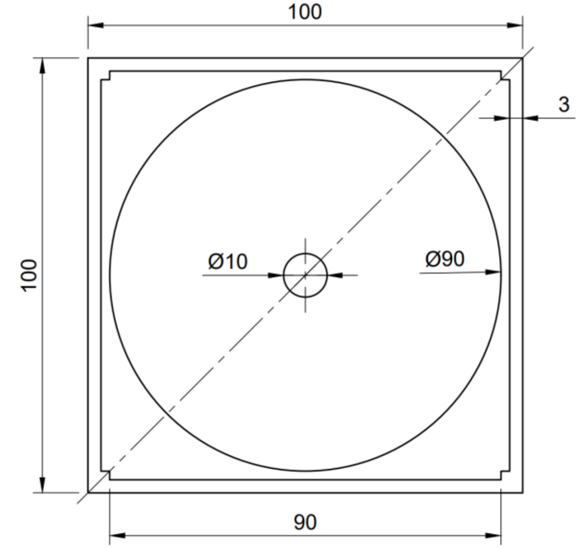


Fig 8: Internal layout of spool setup in bottom unit.

- Sail to be stowed around a spool in bottom unit (see Figure 8 for sizing)
  - **8.93 mm** space between stowed sail and outer wall
    - Assuming perfect wrapping and tip weight, leaves enough slack room for practical use

Attitude determination and control

- Proposed use of passive gyroscopic stability → no control considered

- Choice of attitude determination: **Miniature spinning sun sensors**
  - Used previously in IKAROS
  - Placed at top and bottom of sailcraft's spin axis

- Supplementary data from solar cells and panels can also be used for attitude determination when sun sensors are out-of-view

Table 3: Properties of a Miniature Spinning Sun Sensor by Redwire Space [7]

Mass (kg)	Power rating (W)	Field of view (°)	Radiation tolerance (krad)
< 0.25	< 0.5	± 87.5	100

[7] Miniature Spinning Sun Sensor (±87.5°) | satsearch

Command and data handling

- Utilised for storing mission data from ADCS and Power, timekeeping, health monitoring and data processing
  - Data to be relayed by TT&C

- Considered generic COTS on-board computer by ISISPACE

Table 4: Properties of a generic on-board computer (iOBC) for space missions [8]

Mass (kg)	Power rating (W)	Data Storage (kB)
0.1	0.4	512

[8] ISIS On Board Computer - ISISPACE

Telemetry, tracking, and communication

- Need to be able to track sailcraft from Earth until it is on escape trajectory

- Key tracking parameters
  - Max distance from earth → 7 AU
  - Closest approach time → 19 years

- Goals
  - **Tracking distance limit → 7 AU**
  - **Active mission lifetime → ≥19 years**

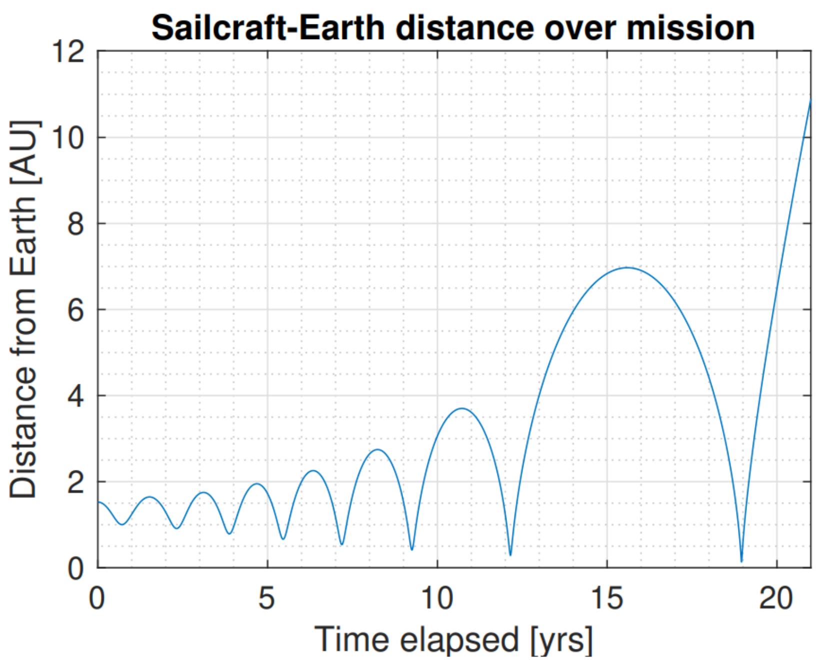


Fig 9: Distance between Earth and Sailcraft over the duration of the active mission

Telemetry, tracking, and communication

Table 4: Properties of X-Band patch antenna by EnduroSat [9]

Mass (g)	RF Output Power (W)	Frequency Range (MHz)	Half Power Beam Width (°)
2.2	≤ 4	8025-8400	74

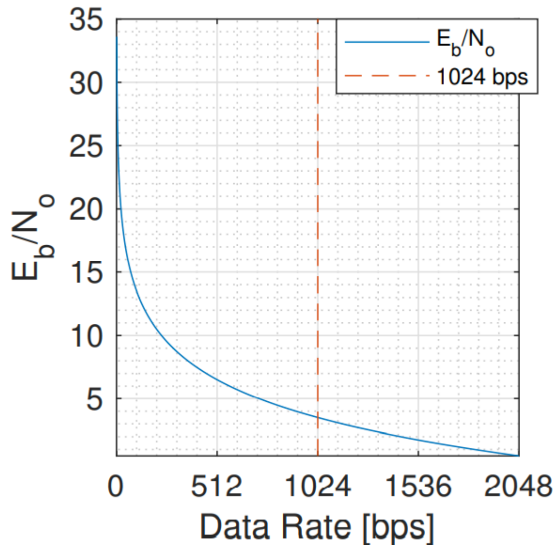


Fig 10: Energy-per-bit noise ratio variation with path length of 7 AU

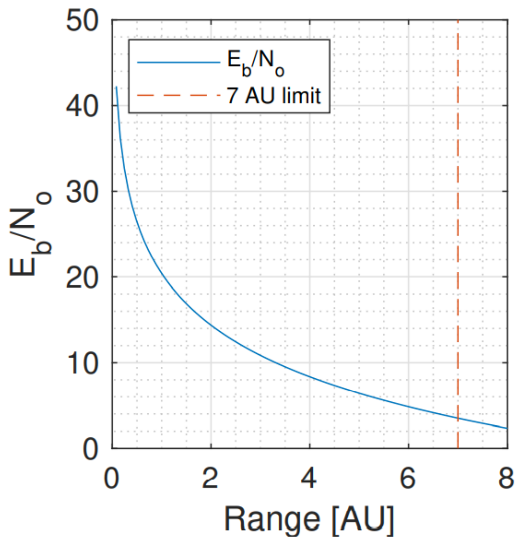


Fig 11: Energy-per-bit noise ratio variation with data rate of 1024 bps

Telemetry, tracking, and communication

- Chosen TT&C setup meets tracking limit goal
  - Data rate of 1024 bps → **225 kB transmission in 30 minutes**

- Modulation: BPSK Reed-Solomon Plus R-1/2, K=7 Viterbi decoding
  - Lower limit of 3 dB
  - With data rate of 1024 bps, worst case energy-per-bit noise ratio is 3.5 dB

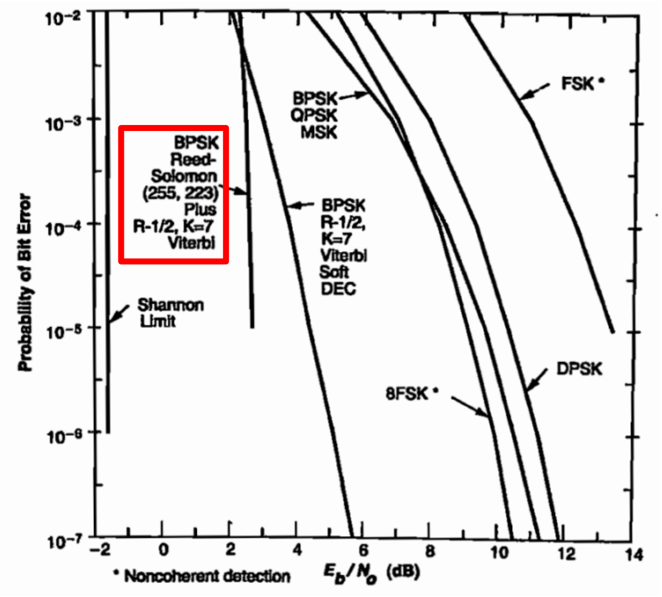


Fig 12: Bit error probability as a function of energy-per-bit noise ratio [10]

[10] Wiley J. Larson. Space Mission Analysis and Design. Kluwer Academic Publ, Dordrecht [u.a.], 3. ed., 6. print. edition, 2004. ISBN 1881883108.

Power

- Batteries → **1.2 kg of LiCFx** cells (360 Wh capacity)

- It was found during analysis that **two methods of solar power generation** are required for prolong the energy capacity for the mission lifetime goal
  - **Solar panels** on each CubeSat door
  - **Thin-film solar cells** on sail
    - 14.97 m^2 on side facing sun on apoapsis/deployment ($90° < \theta < 270°$)
    - 0.1 m^2 on side facing sun at periapsis ($0° < \theta < 90°$, $270° < \theta < 360°$)

Power

Table 5: Power budget of the sailcraft system

Component	Power (W)
Propulsion	0
ADC	0.25
CDH	0.4
TTC	4
Sum	4.9
Margin	10%
Total	**5.12**

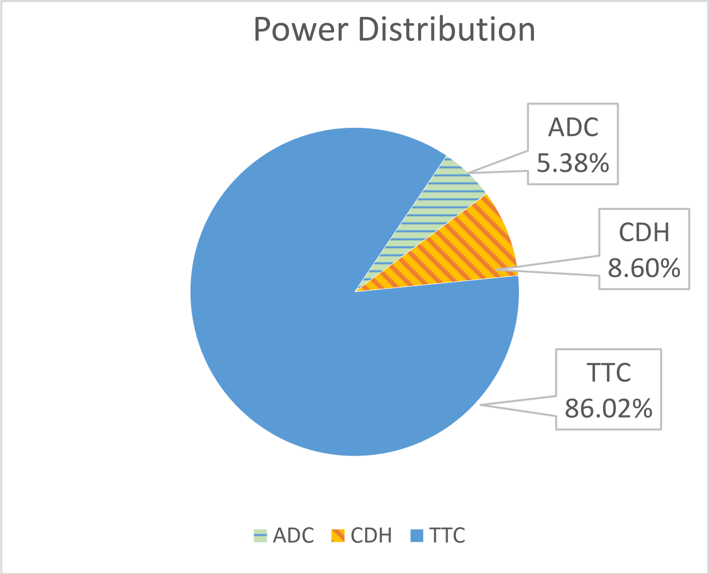


Fig 13: Pie chart showing distribution of power by subsystem

Power

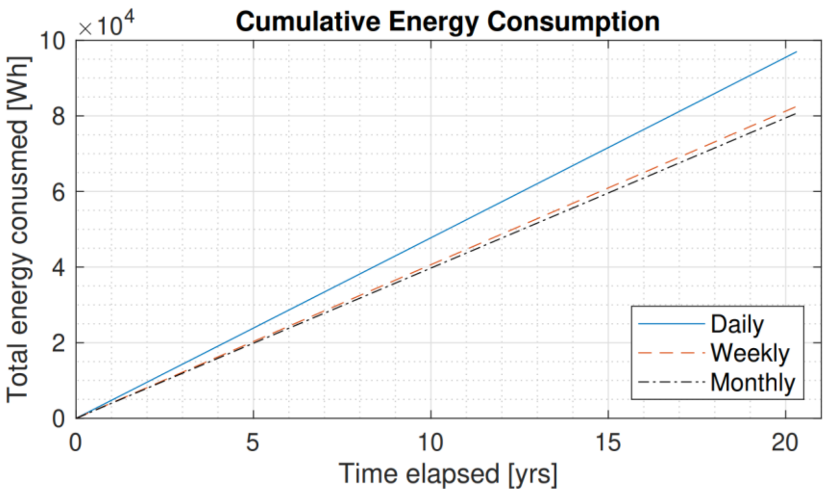


Fig 14: Energy consumption of the system with daily, weekly, and monthly tracking rates

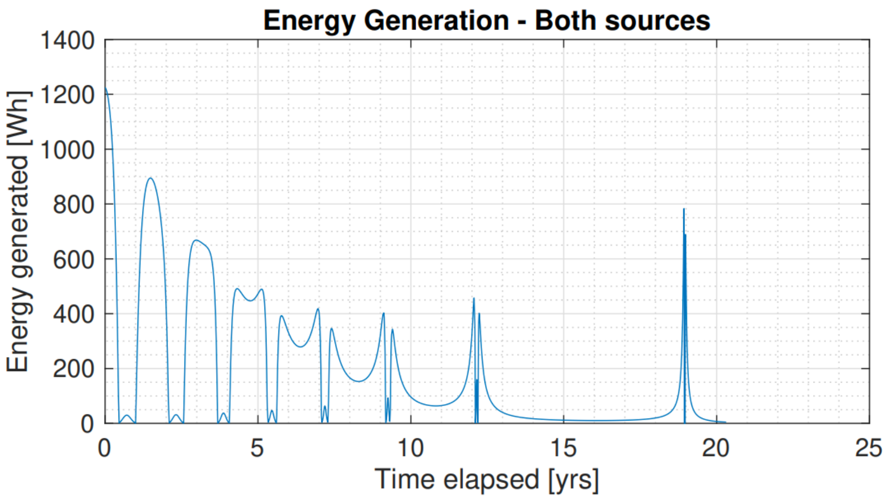


Fig 15: Energy generation of the entire system during the mission

Power

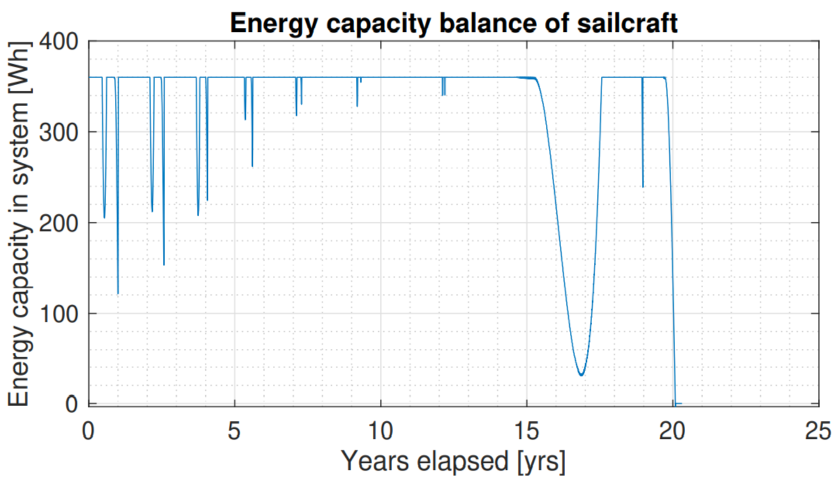


Fig 16: Energy capacity balance over the duration of the active mission

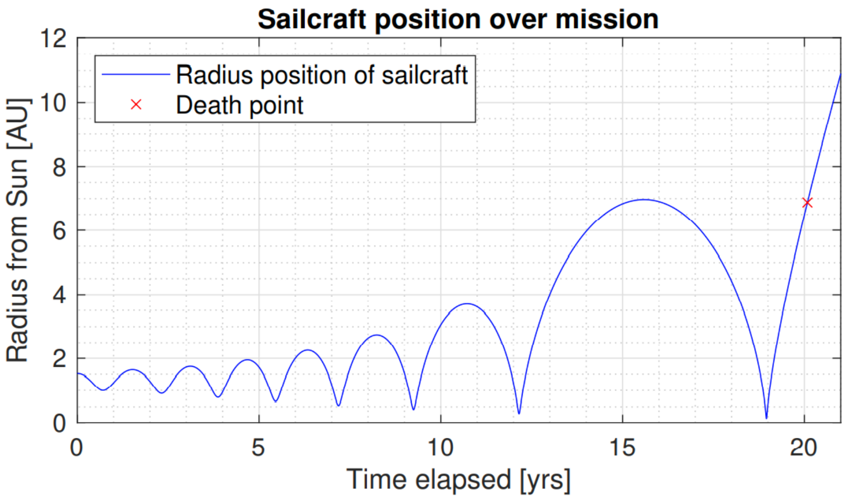


Fig 17: Distance between the sailcraft and Sun with indication of death of the system due to loss of energy capacity over the duration of the active mission

Mass budget

Table 6: Mass budget of the sailcraft system

Component	Mass (kg)	Percentage of Mass (%)
Structures	0.852	21.36
Power	2.554	64.02
ADCS	0.500	12.53
TT&C	0.002	0.05
Propulsion (Sail)	0.081	2.04
Total	3.989	100

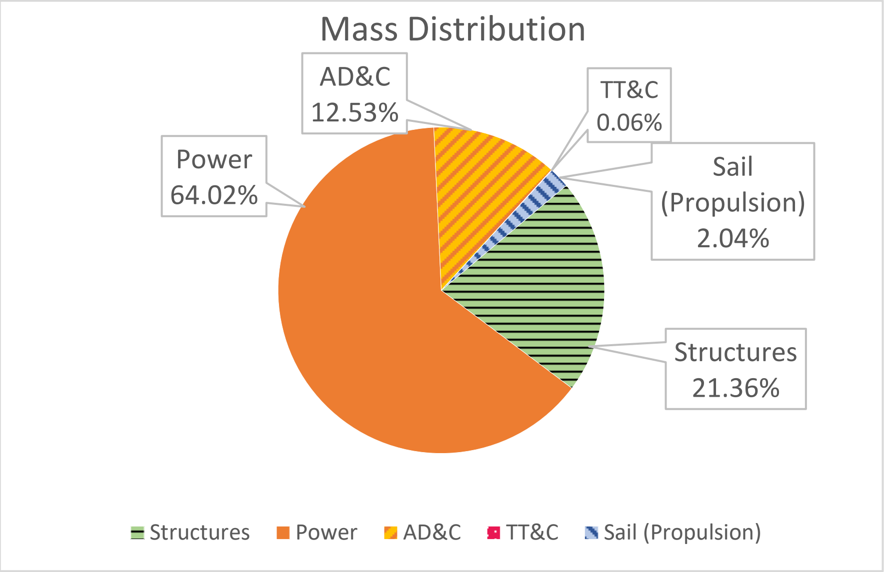


Fig 18: Pie chart showing distribution of mass by subsystem

Attitude Sensitivity Study

Sailcraft Design

1. Problem setup
    1. Theory
    2. Assumptions
    3. Moment of inertia
    4. Method validation

2. Center of gravity offset study

Problem setup – Theory

- Euler's dynamic equation of motion → $\boldsymbol{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{I}\boldsymbol{\omega} = \boldsymbol{T}$

- Assuming sailcraft is spin-stabilised with axisymmetric geometry, the imparted angular acceleration can be found using:

$$\dot{\omega}_1 = \frac{T_1}{I_1}$$
$$\dot{\omega}_2 = \frac{T_2}{I_2}$$
$$\dot{\omega}_3 = 0$$

Problem setup – Theory

- Solar radiation pressure (SRP) varies across the sail, creating a center of pressure offset from the origin

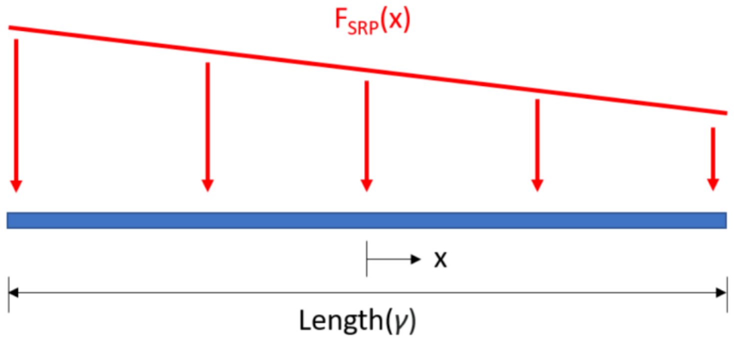


Fig 19: SRP variation across sail. Not to scale.

- Torque can be calculated about each principal axis using:

$$T_x = F_{SRP,tot}(x_{c_p} - x_{c_g})$$
$$T_y = F_{SRP,tot}(y_{c_p} - y_{c_g})$$

Problem setup – Assumptions

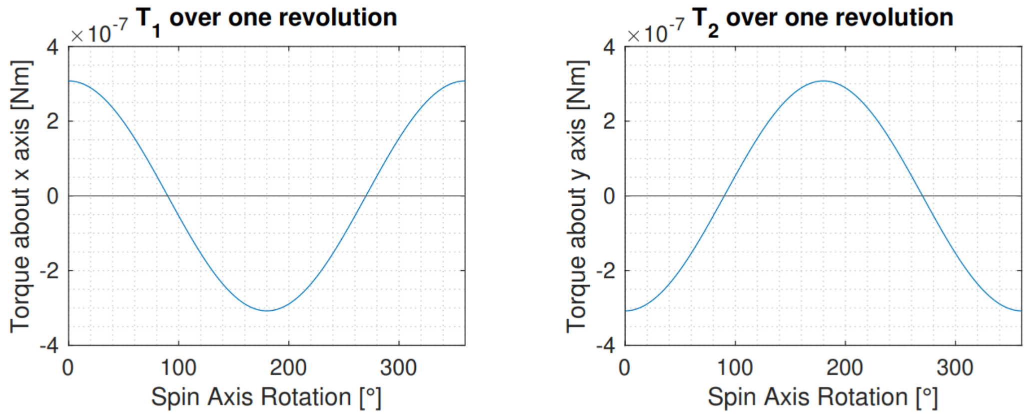
1. **Sail is the only body** in consideration during attitude calculations
   - CubeSat structure is neglected as it is only a preliminary study to determine effect of SRP on sail orientation over time

2. **Perfect deployment** and spin orientation of sailcraft at apoapsis
   - Sail face is perpendicular to orbital plane and normal to the Sun-Sail vector at apoapsis

3. **Mass assumed to be uniformly distributed** about CubeSat and about sail respectively

Problem setup – Method validation

- Assuming a **zero center-of-gravity (CoG) offset** and due to the axisymmetric geometry of sail, the center of pressure will rotate about the origin such that the **induced torque should cancel out over one rotation**



(a) Torque variation about x-axis over 1 revolution.

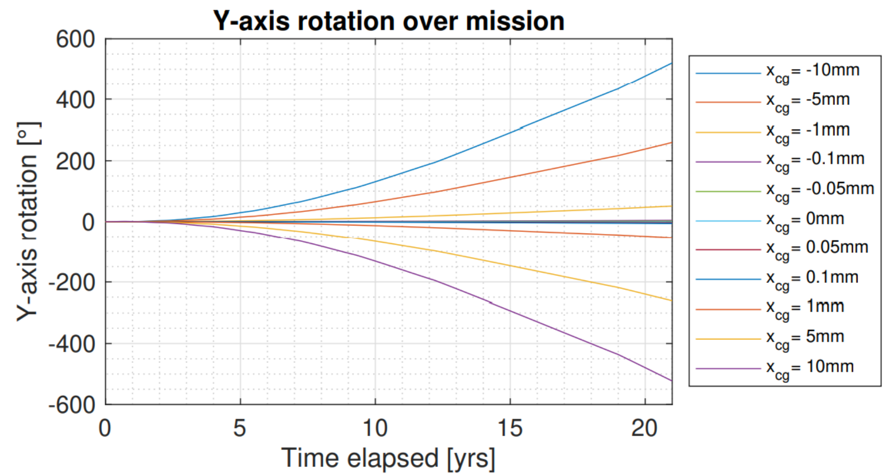
(b) Torque variation about y-axis over 1 revolution.

Fig 20: Torque variation about principal axes at radius of 0.12 AU, and α = 90°.

Center of gravity offset

- A range of CoG offset were investigated:
  - [-10, -5, -1, -0.1, -0.05, 0, 0.05, 0.1, 1, 5, 10] mm

(a) Rotation about X-axis over the duration of mission.

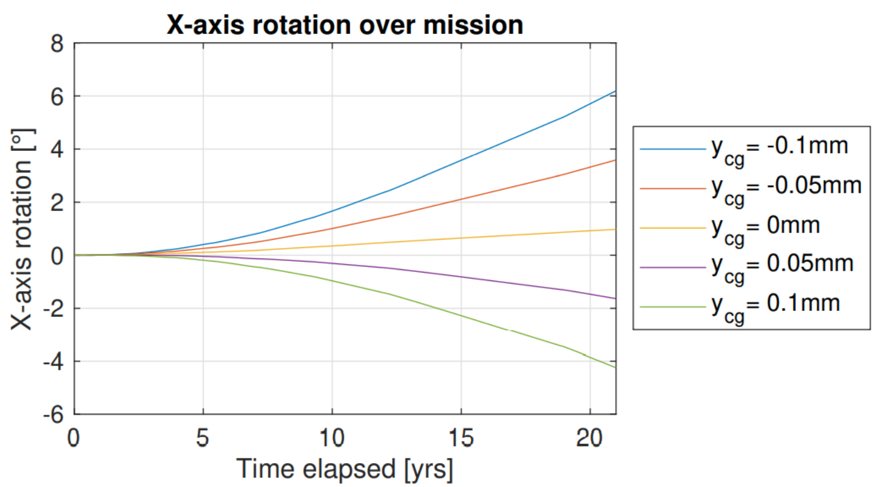


(b) Rotation about Y-axis over the duration of mission.

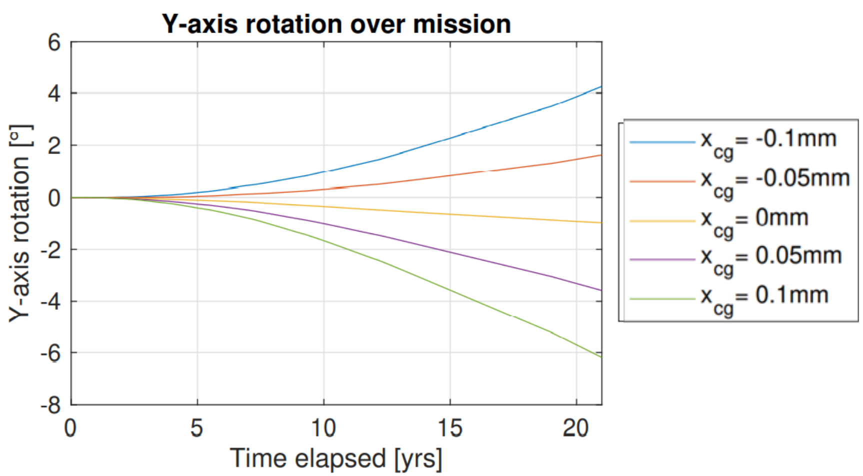
Fig 21: Rotation about principal axes over duration on mission based on varied CoG offset.

Center of gravity offset

- A range of CoG offset were investigated:
  - [-10, -5, -1, **-0.1, -0.05, 0, 0.05, 0.1**, 1, 5, 10] mm



(a) Rotation about X-axis over the duration of mission.



(b) Rotation about Y-axis over the duration of mission.

Fig 23: Rotation about principal axes over duration on mission, focusing on the successful CoG offset range of -0.1 to 0.1 mm.

Conclusions

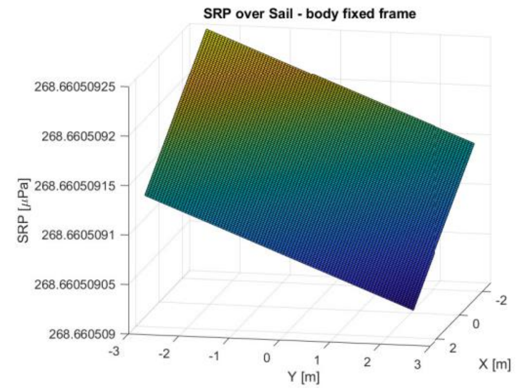
1. Sailcraft was designed to **fit within 3U CubeSat** with a validated subsystem sizing, including **capability for active tracking.**

2. Attitude sensitivity study found that with realistic CoG offsets, the sailcraft would diverge from its ideal orientation, resulting in **failure of the mission.**

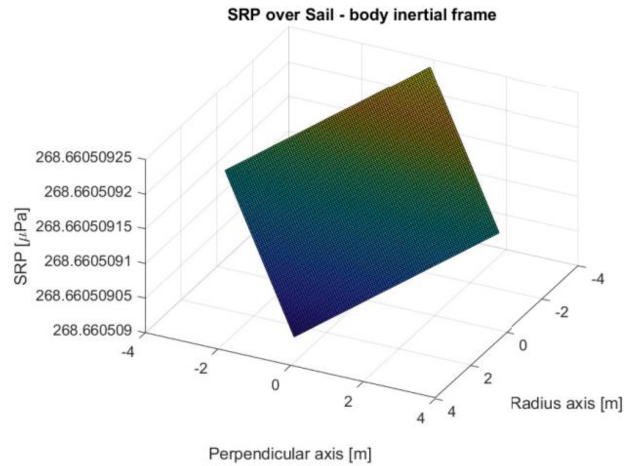
3. **Active attitude control system** needs to be implemented in a future iteration, also using a larger CubeSat specification to accommodate for the additional mass and volume. Can consider using larger sail with a revised design envelope analysis.

4. Consider **interplanetary missions** for its shorter timescale, immediate utility, and as a proof of concept for larger missions like extrasolar trajectories.

Appendix



(a) SRP Variation in body fixed frame where orientation is $\gamma = 45^\circ$ and $\alpha = 45^\circ$.



(b) SRP Variation in body inertial frame where orientation is $\gamma = 45^\circ$ and $\alpha = 45^\circ$.

Figure 20: SRP variation over sail in different reference frames at $r = 0.13$ AU.

The center of pressure of the SRP can be calculated by calculating the X-axis and Y-axis centroids (1st moment of area) using the expressions in Equations (18).

$$x_{c_p} = \frac{\int_{x_{min}}^{x_{max}} x\, F_{SRP}(x)\, dx}{F_{SRP,tot}} \tag{18a}$$

$$y_{c_p} = \frac{\int_{y_{min}}^{y_{max}} y\, F_{SRP}(y)\, dy}{F_{SRP,tot}} \tag{18b}$$

where $F_{SRP,tot}$ is the net force acting on the sail, which can be calculated using Equation (19).

$$F_{SRP,tot} = \int_A F_{SRP}\, dA \tag{19}$$

Finally, the formula for calculating torque about each principal axis on the sail is expressed in Equations (20).

$$T_x = F_{SRP,tot}(x_{c_p} - x_{c_g}) \tag{20a}$$

$$T_y = F_{SRP,tot}(y_{c_p} - y_{c_g}) \tag{20b}$$

These values can be used to calculate the angular acceleration from Euler's dynamic equation of motion in Equations (16). These can then be calculated at every time instance and integrated over time to obtain the resultant angular velocity, and integrated again to obtain the resultant rotational change about each axis.

Table 9: The distribution of mass and volume to give an averaged effective uniform density of the CubeSat and the sail to be used for computing $\boldsymbol{I}$ in Fusion 360.

Body	**Mass (kg)**	**Volume (m^3)**	**Effective Density ($kg{\cdot}m^3$)**
CubeSat	3.290	0.003	1096.713
Sail	0.699	5.72e-5	12222.448

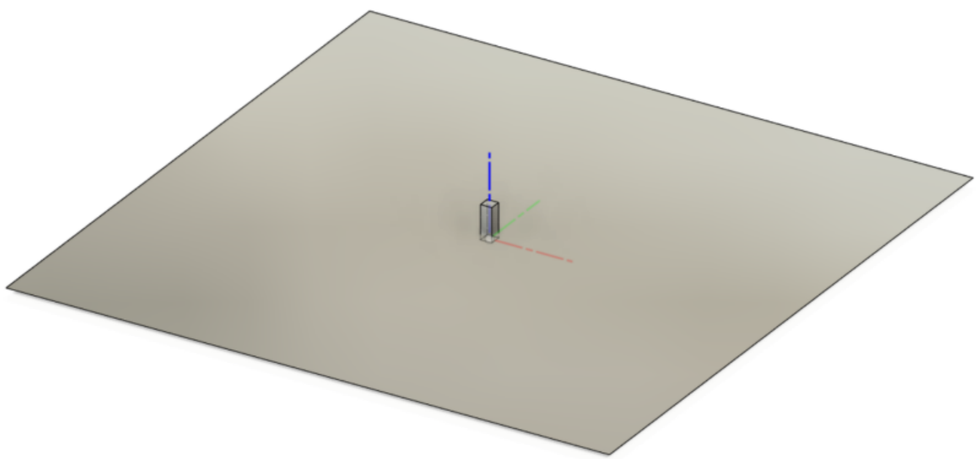
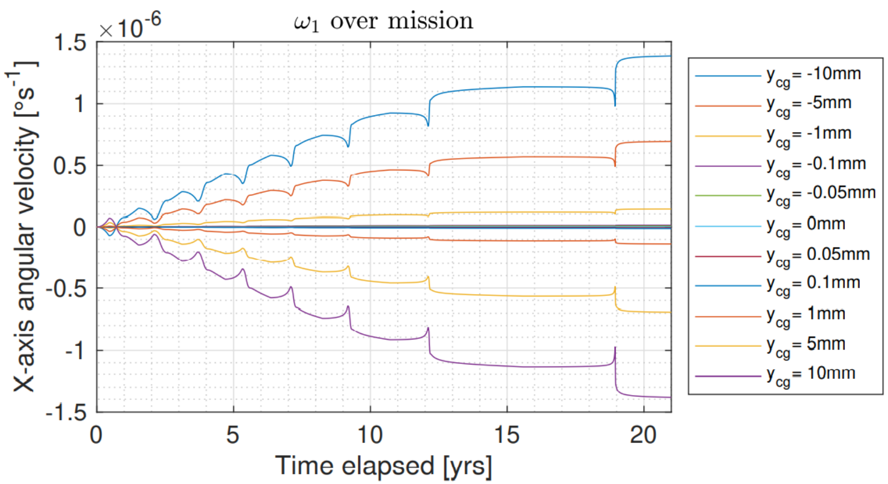


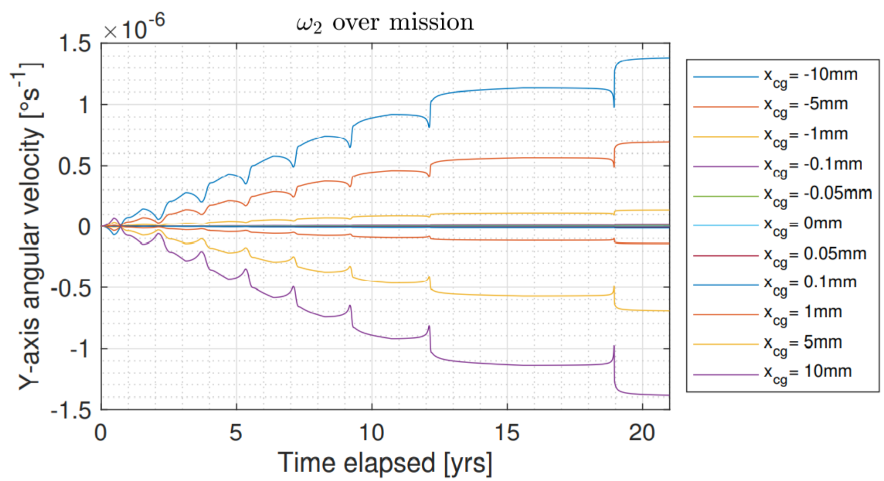
Figure 22: CAD of sailcraft used in calculating the moment of inertia about the origin.

Table 10: Rotation change about X and Y axes varied by CoG offset.

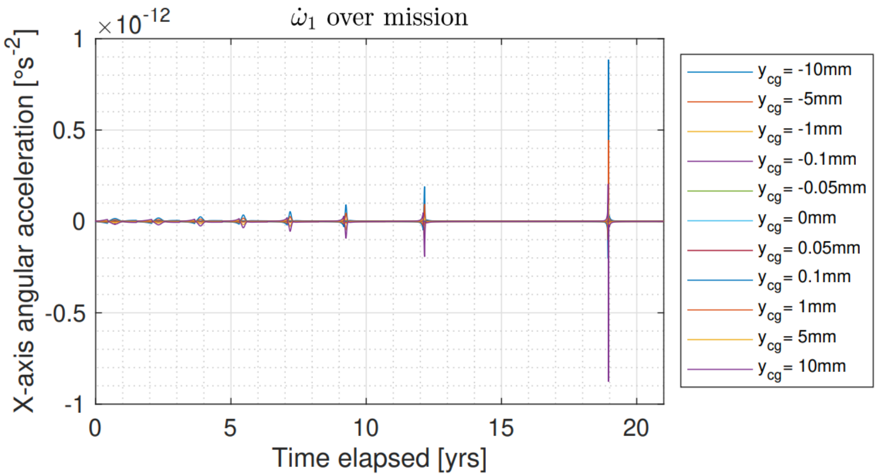
CoG offset (mm)	X-axis rotation (°)	Y-axis rotation (°)
-10	520.87	522.82
-5	259.95	261.90
-1	51.21	53.16
-0.1	4.24	6.19
-0.05	1.64	3.58
0	-0.97	0.97
0.05	-3.58	-1.64
0.1	-6.19	-4.24
1	-53.16	-51.21
5	-261.90	-259.95
10	-522.82	-520.87



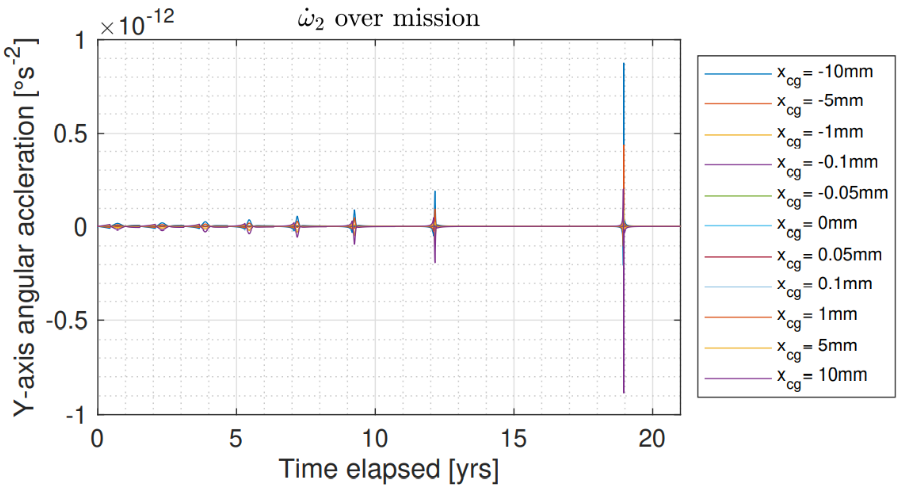
(a) Angular velocity about X-axis over the duration of mission.



(b) Angular velocity about Y-axis over the duration of mission.



(a) Angular acceleration about X-axis over the duration of mission.



(b) Angular acceleration about Y-axis over the duration of mission.

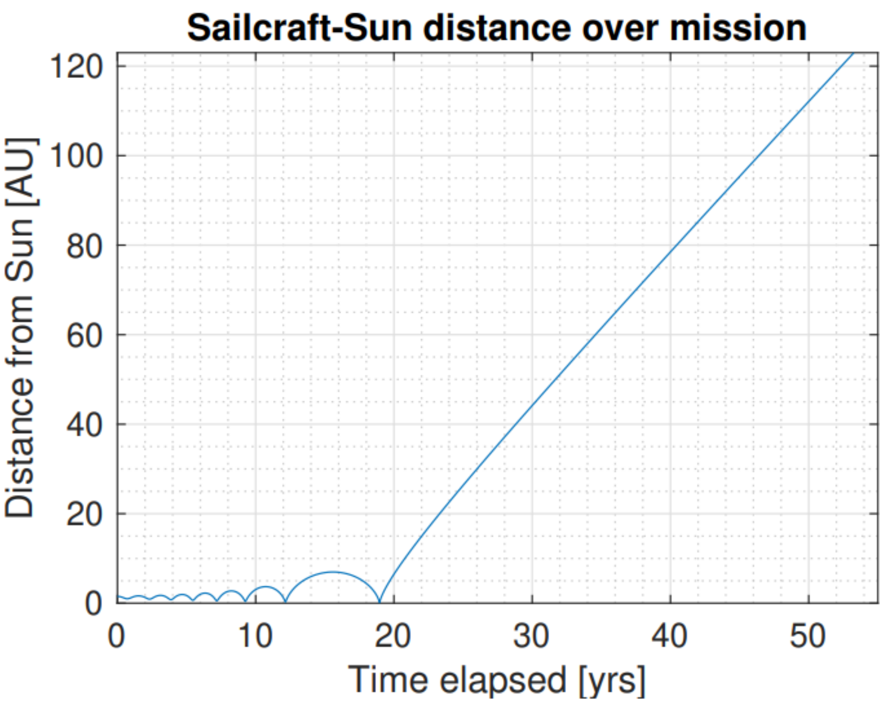


Figure 29: Distance from Sun over the mission.

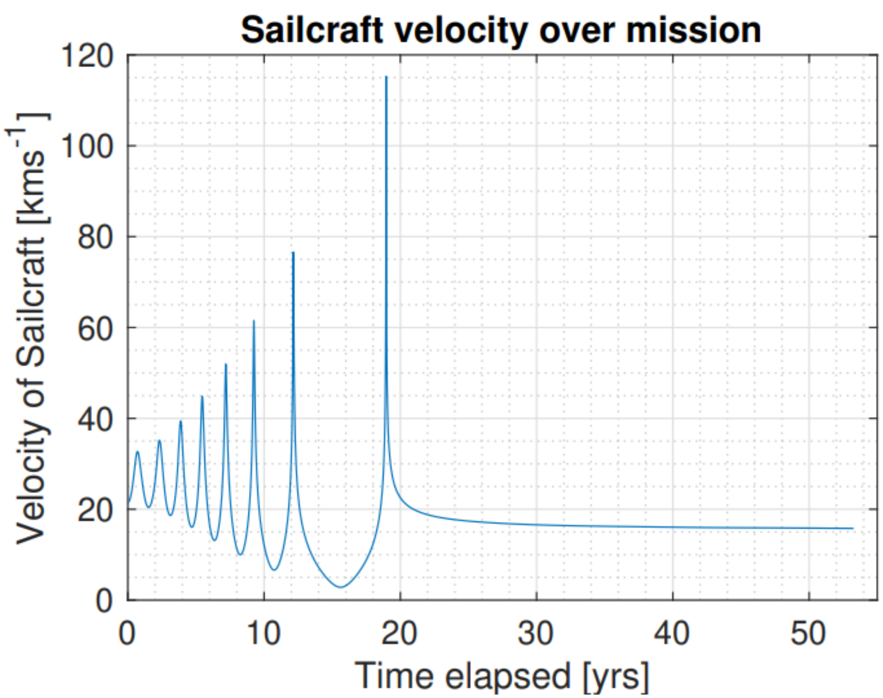


Figure 30: Magnitude of velocity in Sun inertial frame over the mission.

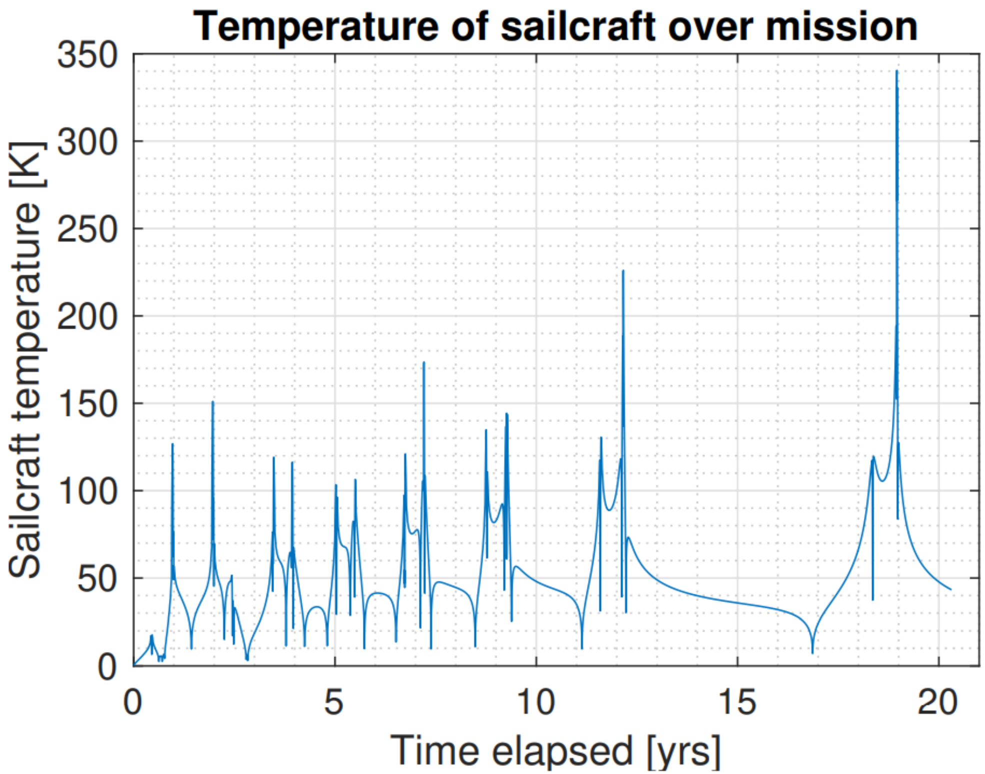


Figure 31: Temperature over the duration of the active mission.

Problem setup – Reference frames

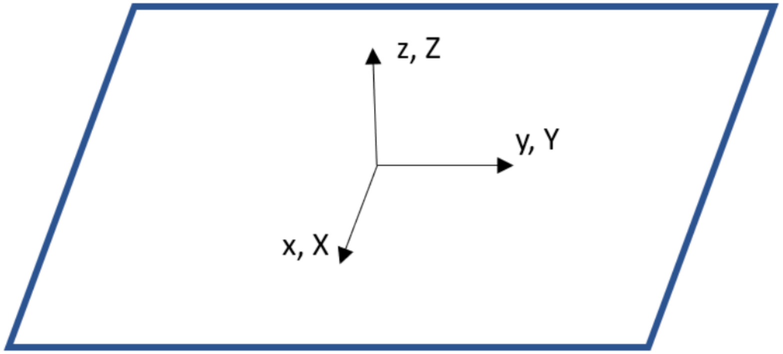


Fig 20: Body-fixed frame when body-inertial frame coincide, $\gamma = 0°$.

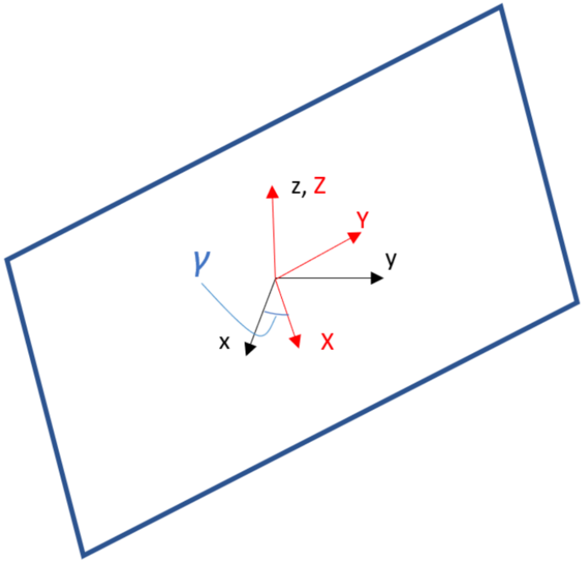


Fig 21: Body-fixed frame when body-inertial frame when sail is rotated by γ.

Problem setup – Reference frames

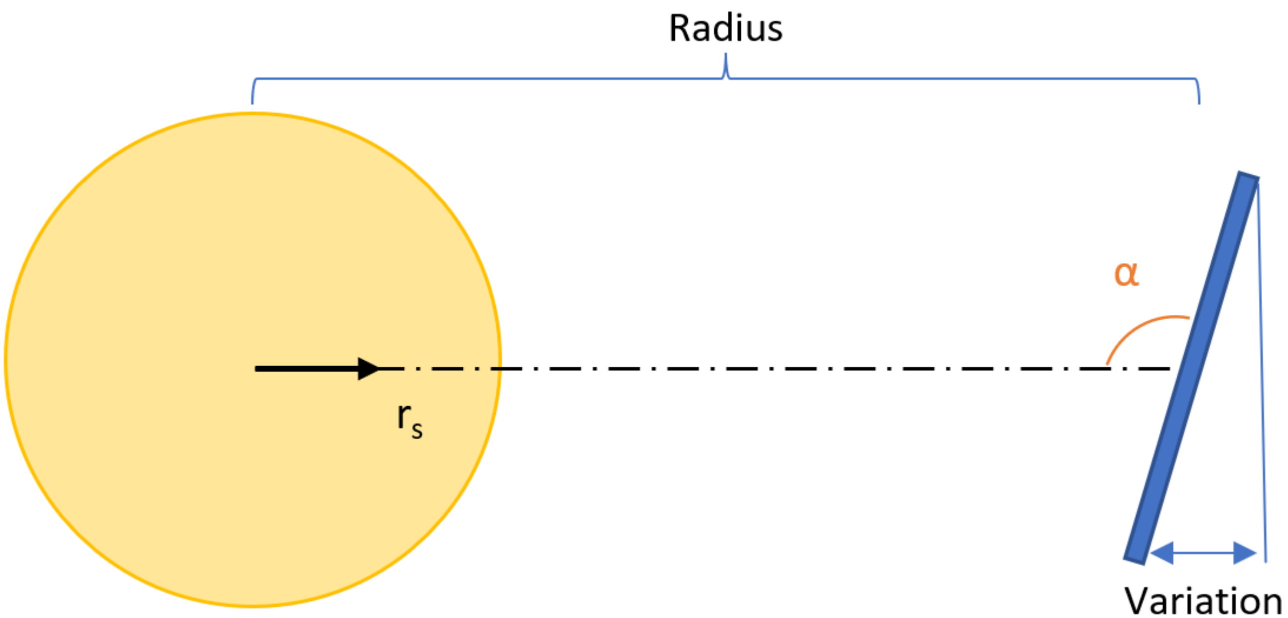


Fig 21: Sun-inertial reference frame showing definition of angle of attack, *α*.

Problem setup – Moment of inertia

- Moment of inertia about origin was calculated using simplified CAD of sailcraft
- CubeSat body and sail moments of inertia were summed together
  - Intermediate axes values are negligible

- Moment of inertia utilised in following analysis is as follows:

$$\begin{bmatrix} 3.3452 & 0 & 0 \\ 0 & 3.3452 & 0 \\ 0 & 0 & 6.6646 \end{bmatrix} 10^{13}\,\mathrm{kg}\cdot\mathrm{m}^2$$

Future Work

Future work

1. Designing and validating an active attitude control system as part of ADCS
2. Updated reference case trajectory with new design iteration
3. Construction of an integrated attitude and orbit propagation simulator
4. Construction of a FEA model of sail and detailed CAD of sailcraft for simulations
   - Revised structural analysis on sail with thin-film solar cells implemented on sail
5. Design of the carrier spacecraft and CubeSat deployment system
6. Component level design of each subsystem
7. Consider exploring alternate mission concepts (interplanetary missions)