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The Design of a Fragmentation Experiment for a CubeSat During Atmospheric Re-entry

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Abstract

Space debris mitigation has become essential for the continued use of space. The removal of satellites from Low Earth Orbit by uncontrolled atmospheric re-entry is a recommended space debris mitigation practice. However, to ensure this is safe, Design for Demise processes are required to predict the risk of a satellite surviving re-entry using re-entry analysis tools. These tools tend to under-predict the risk of satellite re-entry due to limited success recording flight data on early re-entry missions. The most prevalent uncertainty in re-entry analysis tools that is yet to be measured is satellite fragmentation. As such, STRATHcube, a student-led CubeSat project for Space Situational Awareness developed at the University of Strathclyde, aims with its secondary payload to provide flight data investigating the conditions under which solar panel fragmentation occurs. This experimental payload aims to utilise the flexibility a CubeSat platform provides, developing and testing an initial framework for on-board satellite monitoring during atmospheric re-entry. In this paper the initial design and development of this experiment is addressed. A discussion of the challenges encountered when designing a CubeSat for re-entry studies is also undertaken. These challenges include limited available mass, power, and volume inherent to a CubeSat mission, as well as satellite instability, communication blackout and high aerothermal and dynamic loads experienced during re-entry. The sensor platform developed to monitor the solar panels and record re-entry measurements for heat transfer, temperature, velocity, and attitude are also detailed. A trade-off between imaging and the use of electromechanical break switches to monitor fragmentation during re-entry is considered. With these activities, STRATHcube's atmospheric re-entry experiment aims to develop a framework for fragmentation studies, with the obtained flight data allowing for the greater validation and verification of satellite fragmentation in re-entry analysis tools.

Keywords: Atmospheric re-entry; Satellite fragmentation; CubeSat; Aerodynamic stability; STRATHcube mission

Acronyms & Abbreviations

COTS	Commercial off-the-shelf
D4D	Design for Demise
DRAMA	Debris Risk Assessment and Mitigation Analysis
DSMC	Direct Simulation Monte Carlo
IMU	Inertial Measurement Unit
LEO	Low Earth Orbit
MEMS	Micro-Electro-Mechanical System
PSS	Payload Support System
SSP	Scientific Sensor Platform

1. Introduction

Satellites were once launched and left in orbit under the 'Big Sky Theory', which assumed the risk of collisions in orbit between man-made objects was negligible [1]. Today however, it is widely accepted that satellites, especially in Low Earth Orbit (LEO), must be disposed of within 25 years of their mission's end to minimise space debris accumulation [2]. Without these measures, it is expected that collisions between space debris and operational satellites will jeopardise our future access to space, as described by Kessler's Syndrome [3].

Uncontrolled atmospheric re-entry is commonly used to remove small-to-medium sized satellites from LEO [4]. These satellites must undergo Design for Demise (D4D) prior to launch, a process carried out to simulate a satellite's trajectory as it re-enters Earth's atmosphere and predict its associated risk using re-entry analysis tools [5] [6]. Satellite developers are required to adjust their satellite's design or mission if the predicted risk exceeds NASA's acceptable casualty risk [7]. However, the re-entry analysis tools used for this purpose are known to understate the risk of a satellite's re-entry, minimising the effectiveness of these processes [8].

Extensive work has been carried out in literature to identify the uncertainties in re-entry analysis tools which contribute to these inaccurate predictions [9] [10]. From these studies, it may be concluded that the process for which a satellite breaks up during re-entry, termed its fragmentation, most significantly impacts the probability of a satellite's destruction known as its demise [11].

The earlier a satellite breaks up into individual fragments, the higher likelihood of demise. Lips, Koppenwallner et al. found a 35% fluctuation in results when the fragmentation altitude was varied in object-oriented re-entry analysis tools used for D4D [6]. In these tools, satellite breakup is modelled as a simultaneous, single event at a predefined altitude demonstrated by Fig 1. After this point the trajectory of each resulting fragment is propagated individually using the re-entry analysis tool [2].

This simplification originates from visual observations of re-entry events, currently our only means of observing and understanding satellite fragmentation.

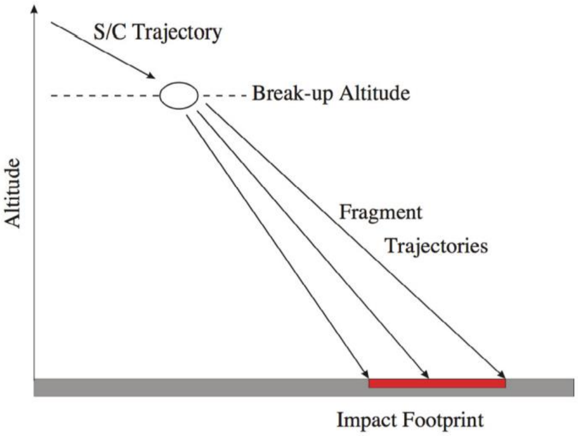

Fig 1. Satellite Fragmentation Process in Object-Oriented Re-entry Analysis Tools [12]

Fig 2. Observation of the Hayabusa Spacecraft During Atmospheric Re-entry [13]

Fig 2 is an example of these observations, where the Hayabusa spacecraft is seen to re-enter Earth's atmosphere. In the first image, the spacecraft is a singular object, as expected, but following a high energy event, captured in the centre image, the spacecraft is seen to decompose into fragments. Observations such as these have been used to generalise the breakup altitude in object-oriented re-entry analysis tools as approximately 78 km [5]. Although these images give an indication of the point at which total fragmentation takes place for the most generalised cases, they do not convey the conditions under which fragmentation occurs. The obtainment of such information is the subject of this paper.

Flight data from re-entering satellites may be used to gain more information and enrich our understanding of the re-entry environment [12]. In the past however, very few re-entry studies produced adequate scientific observations, restricting the validation of re-entry analysis tools to only a few cases. Ground-based experiments also yielded limited results, due to a difficulty simulating the high energy processes for re-entry in a laboratory environment [13] [14]. The high failure rate and cost of these missions led their decline for a number of decades. However, the recent widescale adoption and increased technical capabilities of standardised CubeSats offer an alternative platform for atmospheric re-entry studies [15].

The form factor and standardisation of CubeSats allows atmospheric re-entry experiments to be developed at a lower cost and redundancy than previously possible [16]. CubeSat missions such as QARMAN [17] and EntrySat [18], belonging to the Von Karman Institute's QB50 constellation have exhibited the potential for CubeSats in tackling the challenges presented by atmospheric re-entry experiments.

With this in mind, we aim to demonstrate the concept and design of an experiment to record the conditions under which solar panel fragmentation occurs for a CubeSat during atmospheric re-entry. This experiment is the secondary payload of the 2U STRATHcube platform, an initiative developed by students at the University of Strathclyde to design, build and launch the first Scottish student-led CubeSat [19]. This experiment is the first known attempt to record satellite fragmentation during atmospheric re-entry, and if successful will allow us to further develop re-entry analysis tools, alleviating some of the prediction uncertainties impacting D4D processes.

The design and development of the fragmentation experiment is divided into 6 sections in this paper. In Sections 2 - 4 an overview of the challenges associated with re-entry, the concept of operations and conceptual design for the fragmentation experiment are discussed, respectively. The design of the supporting systems required for the experiment is provided in Section 5 and for the sensor platform in Section 6. The paper concludes with a review of the current progress and further work for the fragmentation experiment in Sections 7 and 8.

2. Challenges of Re-entry Experiments

Experiments to study atmospheric re-entry need to overcome several challenges to record and recover viable scientific observations.

2.1 Satellite Demise

Satellites re-entering Earth's atmosphere are expected to be destroyed prior to impact. This limits the time available to record and transmit scientific observations. In some missions such as QARMAN, additional thermal protection systems are used to maximise satellite survival and lengthen the experiments duration [20].

This is not feasible nor necessary for STRATHcube, with the mass and volume budget available for the fragmentation experiment limited on the 2U CubeSat platform. The experiment was developed with this in mind, aiming to studying solar panel fragmentation, which is expected to occur during early re-entry to ensure sufficient measurements are recorded prior to demise. As a result, STRATHcube will re-enter Earth's atmosphere without additional thermal protection, simulating typical space debris re-entry.

2.2 Blackout Zone

Shortly after a satellite re-enters Earth's atmosphere it encounters the Blackout Zone, where communication with ground stations is not possible. This occurs as satellites travel at hypersonic speeds, leading to shock wave formation and flow dissociation on front of the satellite. The ionised particles that surround satellites during this high energy phase of re-entry prevent any communication with ground stations [21].

There are two other data retrieval methods for re-entry experiments: data may either be transmitted during re-entry via a satellite constellation or stored on board the CubeSat in a 'survival unit', designed to withstand re-entry and be recovered upon impact [17].

The STRATHcube fragmentation experiment will use data transmission during re-entry as a means of data retrieval. This approach has a limited impact on STRATHcube's overall design, requiring fewer resources compared to the 'survival unit' concept. As such, the risk of transmission failure and subsequent data loss during re-entry using this approach was deemed acceptable.

2.3 Stability

Satellites must re-enter Earth's atmosphere without tumbling otherwise recorded measurements are not meaningful for atmospheric re-entry studies.

Multiple methods for stabilisation are available for CubeSats, but in this case a passive stabilisation system is required, as active systems are unable to provide stability during re-entry without significant power draw [22]. Hysteresis and magnetic stabilisation systems are also not effective given the disturbing forces felt during re-entry [23].

Passive aerodynamic stabilisation systems used in re-entry studies such as QARMAN [17] and the U.S. Navy Research Laboratory's Space Darts [24] have proved effective. In these cases, the satellites solar panels are reconfigured into a 'shuttlecock' position to shift the centre of pressure behind the centre of mass, providing aerodynamic stability [22]. This approach, illustrated in Fig 3, will be used to provide stability for the fragmentation experiment.

Fig 3. Render of STRATHcube in the 'Shuttlecock' Configuration for Atmospheric Re-entry

3. Concept of Operations

The fragmentation experiment is the concluding phase of STRATHcube's mission, as shown in the Concept of Operations in Fig 4. The experiment has three distinct stages. In the first stage, STRATHcube is readied for atmospheric re-entry. This is expected to occur at approximately 170 km (t2 in Fig 4) when early indications of atmospheric re-entry are identified by the onboard Attitude Determination and Control System (ADCS). At this time the solar panels will be reconfigured into the 'shuttlecock' position to provide aerodynamic stability during re-entry.

In the second stage of the fragmentation experiment the sensor platform is operational, and re-entry data collection begins. This is expected to commence at approximately 150 km, 5 hours after t2. Recorded scientific data will be transmitted via the satellite constellation during this stage. Using the European Space Agency's (ESA) object-oriented re-entry analysis tool DRAMA (Debris Risk Assessment and Mitigation Analysis), an initial prediction for solar panel fragmentation and satellite demise have been made. The melting temperature of the solar panel CubeSat connection was used as a fragmentation trigger for this case, a feature available in DRAMA-3.0.3. The results shown in Fig 5 estimate the first solar panel will break away from the CubeSat bus at 107 km, 10.7 minutes after conventional atmospheric re-entry begins at 125 km (t3 in Fig 4).

The third stage of the fragmentation experiment is the failure of the onboard components required for re-entry measurements and/or communication. This signals the end of the experiment. Complete satellite demise is then predicted to occur at approximately 16.5 minutes after

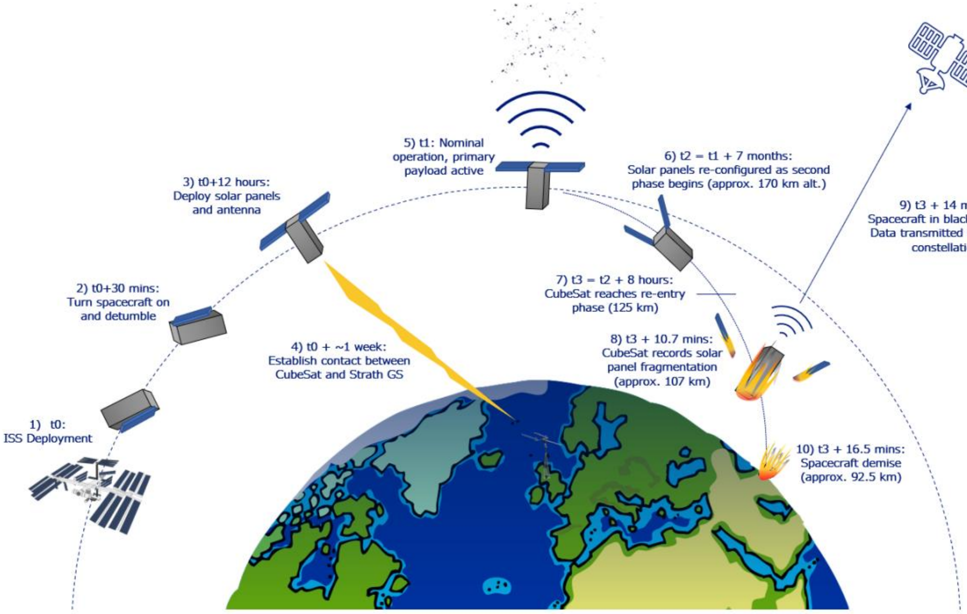

Fig 4. Concept of Operations for the STRATHcube Mission

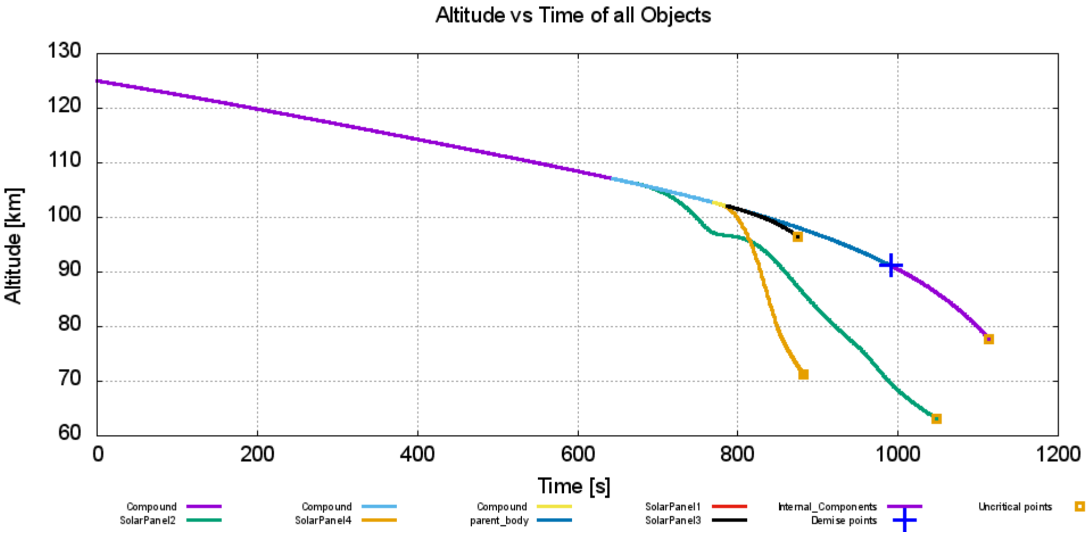

Fig 5. DRAMA Re-entry Analysis Tool Predictions for STRATHcube During Atmospheric Re-entry

atmospheric re-entry began. This a conservative timeline used to provide an estimate of the maximum length of the experiment to determine the required power budget. In reality, solar panel fragmentation may be expected to occur prior to DRAMA's prediction.

4. Conceptual Design Overview

For design purposes, the fragmentation experiment was divided into two subsystems: the Scientific Sensor Platform (SSP) and the Payload Support System (PSS).

The SSP is responsible for all measurements recorded for the duration of the experiment. Whilst the PSS refers to the requirements imposed upon the CubeSat's design to overcome re-entry challenges and support the optimal operation of the SSP.

The resources available to the fragmentation experiment as the secondary payload on the 2U CubeSat guide the design decisions made in this paper. As such, compact components with low mass, volume, and power draw, that are preferably space tested and commercially available were selected where possible for the experiment. Additionally, the scientific sensors must also be able to provide reliable measurements whilst operating in low density, high enthalpy and high temperature flow expected during re-entry.

5. Payload Support System

The design of the passive stabilisation and telecommunication systems required for the experiment

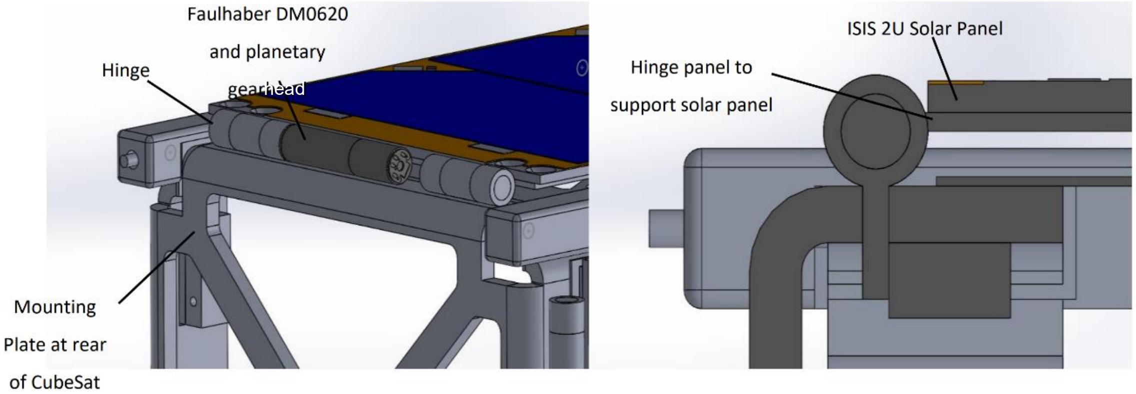

Fig 6. Geared Stepper Motor and Hinge Mechanism for STRATHcube Solar Panels; Attached to CubeSat Structure (Left) and Cross-Section (Right)

and referred to in Sections 2.1 and 2.2 were critical components included in the Payload Support System.

5.1 Telecommunications

The proposed data retrieval solution uses the Iridium Constellation as an intermediary telecommunication link. This allows data to be sent during re-entry via a live dial-up connection to the constellation where it can later be downloaded conventionally at a ground station.

Relaying data via Iridium during re-entry is a well-researched method, having been carried out by the SCUBEE [25] and Suborbital Flight Communication and Fire Box projects [26], and is intended to be used for the QARMAN CubeSat mission [17]. In fact, the PicoPanther project found that the Iridium constellation provided the best coverage for their proposed LEO CubeSat [27].

The Iridium Core 9523 modem, along with a development board and a helical Iridium compatible antenna will be used for communications during the fragmentation experiment. This modem board has a data rate of 2.4 kbps, suitable for short burst data transmission and has proved successful when used on NASA's Re-entry Breakup Recorder [28] and in the MiniCarb mission in LEO [29].

5.2 Passive Stabilisation System

The passive aerodynamic stability system for STRATHcube requires a tailor-made solar panel deployment mechanism. This allows the solar panels to be redeployed to an angle of 135 degrees to provide aerodynamic stability prior to atmospheric re-entry. This angle was informed by previous successful missions [22] [24].

Conventional, deployable solar panels lock in only one configuration, commonly perpendicular to the CubeSat. In STRATHcube's case, the solar panels must lock in two positions, for nominal operations in orbit and for atmospheric re-entry.

The proposed deployment mechanism for STRATHcube comprises of a geared stepper motor which will power a hinge fixed to the back of each solar panel and mounted inside the CubeSat as shown in Fig 6 [32] [33]. A solenoid lock placed on the inside surface of the CubeSat, extruding into carefully positioned indents in the back panel, can provide a physical lock for each configuration. The solenoid lock will continue to secure the solar panel in either deployed position without continuously powering the stepper motor.

This design requires further development but is outlined here due to its relevance in the design of the fragmentation experiment solar panel monitoring strategies, referenced in Section 6.1.2.

6. Scientific Sensor Platform

The Scientific Sensor Platform aims to monitor the solar panels for signs of fragmentation and record the heat and motion history of the CubeSat during re-entry. These three measurements are key parameters used to determine the probability of a satellite's demise in re-entry analysis tools and therefore are expected to sufficiently characterise the fragmentation event [5]. Further measurements to characterise re-entry could be included in future on a mission with greater mass, volume, and power availability.

6.1 Solar Panel Monitoring

There are two potential approaches to monitor STRATHcube's solar panels during re-entry; imaging to observe the solar panels and/or electromechanical break switches to monitor the connection between the solar panel and the CubeSat [34]. For the fragmentation experiment to be successful the chosen approach must provide sufficient information of the solar panel condition for the duration of the experiment.

6.1.1 Imaging

Onboard imaging during re-entry is an ideal approach to monitor CubeSat fragmentation. As there is no prior knowledge of the exact mechanism for fragmentation, imaging allows the event to be observed without any prior assumptions.

Imaging may be carried out visually or thermally. ESA's e.deorbit mission demonstrates the benefits of thermal imaging [35]. Comparing the thermal and visual images of the satellite in Fig7, thermal imaging more effectively captures details of the satellite in orbit.

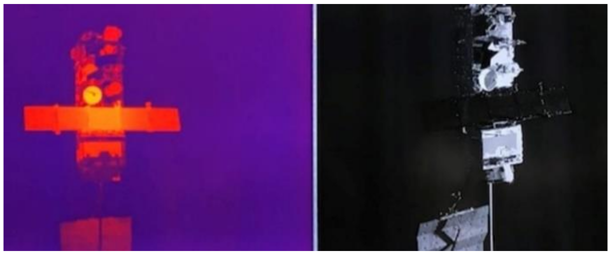

Fig 7. ESA's e.deorbit Imaging Comparison of Derelict Satellite [36]
(LHS: Thermal Imaging, RHS: Visual Imaging)

There are a higher number of "commercial-off-the-shelf" (COTS) space grade visual cameras for CubeSats, but these are typically designed for Earth observation, and therefore, use camera lenses to increase the field of view, not required for STRATHcube. This increases the mass and form factor of visual cameras.

Compared to the possible visual cameras, the Mosaic Thermal imaging camera was selected for the fragmentation experiment. This camera is expected to provide effective imaging, for a lower pixel count, power, and volume. Although the Mosaic camera has not been tested in space, it has promising shock loading and further testing will be used to confirm its suitability.

The most challenging aspect of imaging is transmitting the results frequently enough prior to satellite demise. There are two options for this; the first involves compressing and transmitting the image and the second uses an object-detection Machine Learning algorithm that will be developed and trained on-ground prior to launch, to analyse images captured during atmospheric re-entry.

For the first option, minimising image size and therefore data transmission time is an essential parameter to the experiment's success. It is expected with the current communications package (outlined in Section 5.1) approximately 50 seconds is required to transmit a single image with 50% data compression. This prevents imaging from being a sufficient method for solar panel monitoring with the current configuration.

However, in the future an alternative higher data rate modem that allows for timelier image transmission may make this approach more feasible. The Iridium 9770 modem is a promising solution with a data rate of 88 kbps, allowing a single image to be transmitted within approximately 5 seconds with 50% image compression. This modem has a larger relative mass, power, and volume which prevented it from being used currently on STRATHcube. Further investigation into alternative solutions suggests potential for smaller scale high data rate modems like the Iridium 9770 to become available in coming years, as their application on CubeSats and drones increases.

The second option, which considers the development of a Machine Learning algorithm for object detection would improve imaging feasibility. This approach involves the analysis of images captured during re-entry, allowing a short data burst to be transmitted opposed to the full image, to inform on whether the solar panels were seen. The feasibility of such an approach on STRATHcube will be investigated further in the coming years to ensure sufficient and timely computational power is available during atmospheric re-entry.

6.1.2 Electromechanical Break Switches

Electromechanical break switches are a less data, mass, and power intensive approach to monitor the solar panels during re-entry. The concept was developed with the objective of placing a mechanism at each solar panel hinge to indicate whether the hinge had broken during re-entry. This approach, therefore, relies upon the assumption that solar panel fragmentation results in, or is due to hinge failure or deformation. Although solar panel hinge deformation may be expected for complete fragmentation, the forces which act, and the resulting deformation cannot be confirmed prior to this experiment.

The design of the electromechanical break switches takes advantage of the solar panel hinge locking mechanism detailed in Section 5.2. The idea is to integrate the electromechanical break switch into the pre-existing solenoid lock circuit at each hinge, in the form of a latched relay.

The latched relay will remain closed when the hinge is locked as expected, however when significant force is applied during re-entry, the solar panels are expected to be pushed backward, resulting in eventual fragmentation, and breaking the solenoid lock. When the lock is pushed sufficiently far from its operational position it will complete a circuit which sends a resulting electronic pulse, actuating the latched relay. The relay will open when this occurs, sending a signal to the on-board computer to alert it that the lock has broken and therefore, solar panel fragmentation is assumed to have occurred.

Although requiring further development to test and integrate the concept, if successful electromechanical break switches present a low-cost solution that will greatly increase solar panel monitoring information. Given the limitations for imaging during re-entry at this time, electromechanical break switches are the favoured sole solution for solar panel monitoring. It is recommended however, that a dual solution that incorporates imaging and the electromechanical break switches be proposed in the future to maximise the fragmentation experiments effectiveness.

6.2 Heat History Measurements

Heat history refers to the convective heat transfer measurements that will be recorded during re-entry. The sensor platform designed for this purpose must be capable of detecting changes in flow temperature below 150 km altitude. This may be done either using a dedicated heat flux sensor or thermocouples to measure the temperature applied to the sensor and find the resulting heat flux.

Most missions use thermocouples as they are cheaper and more compact so can be distributed across the CubeSat, maximising heat flux measurements. However, using thermocouples to determine heat flux requires the development of a calibration curve. This method results in high measurement uncertainties. Given, re-entry analysis tools rely on heat flux as a parameter for demise, thermocouple measurements will not be solely relied on during the experiment [37].

Instead, a dedicated heat flux sensor will be used to record heat flux, which can later be converted to flow temperature. The HFS-4 heat flux sensor, which has an embedded K-type thermocouple was selected for this purpose. Given re-entry analysis tools use stagnation point heat flux to determine heat transfer across the satellite, the sensor will be positioned at the stagnation point on the CubeSat's front face, secured with an epoxy to guarantee thermal contact [2].

Two thermocouples will also be placed at the solar panel hinge to provide a greater understanding of the conditions leading to fragmentation. This choice maximises data output, whilst avoids reliance on thermocouple measurements. The SA1XL-KI-SRTC K-type thermocouple probe will be used as it is expected to meet all mission requirements, allow for easy positioning at the solar panel joint and operate under high temperature flow.

6.3 Motion History Measurements

Motion history refers to the measurement of velocity, orientation, and altitude during re-entry.

6.3.1 Velocity Measurements

Freestream velocity is currently measured using a pressure sensor platform first proposed by the SASSI^2 re-entry mission [37] [39]. This platform resembles a pitot-static probe, measuring freestream velocity from the pressure difference between three pressure ports whose inlets are angled to the flow stream.

Three MKS Instruments MEMS (Micro-Electro-Mechanical System) 905 MicroPirani gauges placed within settling chambers to prevent high energy flow from directly striking the sensor are used for this purpose. The pressure ports must be located on the front face of the CubeSat like the heat flux sensor, due to the free molecular nature of the flow affecting the entirety of the front face.

In addition to these sensors a spectrometer is required to identify the species present and determine freestream velocity. Further information of the design of this platform may be accessed from SASSI^2 documentation [37].

6.3.2 Attitude Measurements

An Inertial Measurement Unit (IMU) was selected to detect translation and rotational accelerations during re-entry. This measurement will give an indication of the stability and orientation of STRATHcube [39]. The UM7-LT Orientation sensor was selected for this purpose. This sensor has previously been used on similar re-entry missions. It has low mass, volume and cost compared with the other IMU's typically used on CubeSats. In the future if the on-board computer has suitable IMU capabilities there is the potential to utilise it for measurements rather than having a dedicated sensor.

6.4 Electronics Design

In addition to the telecommunications package, a processing board and Analog to Digital (ADC) converter are required for the fragmentation experiment.

A Raspberry Pi Pico processing board was selected for data processing during re-entry. These have been utilised on similar missions and have relatively low power and mass.

An ADC converter is also required for the heat flux sensor, pressure sensors and thermocouples. These components produce an analogue signal that must be amplified and converted to a digital signal prior to processing and transmission. An ADC Pi was selected for this purpose.

7. Further Work

The fragmentation experiment detailed in this paper will be developed further in the future to test and validate the initial design concepts outlined here. In particular, the solar panel deployment mechanism and electromechanical break switch design will be advanced through testing and further electronic design.

The integration and verification of the remaining fragmentation experiment sensors will also be undertaken in the future. This includes the possible selection of a high data rate modem board compatible with image processing if available and the specification of the Scientific Sensor Platform duty cycles.

Additionally, further modelling to characterise the re-entry conditions using the Direct Simulation Monte Carlo (DSMC) method will be beneficial in validating the Scientific Sensor Platform design in the future.

Moreover, high fidelity simulations will be considered to confirm the planned 'shuttlecock' re-entry configuration guarantees aerodynamic stability for STRATHcube.

8. Conclusions

The general concept and design of a novel experiment to investigate solar panel fragmentation during atmospheric re-entry for a 2U CubeSat platform is discussed in this paper. As described, the CubeSat must be designed to overcome the challenges of the re-entry environment, remaining stable and communicating via a satellite constellation. The sensor platform must also be developed to accommodate the high energy re-entry flow and stringent mass, power and volume requirements imposed by the CubeSat.

The experiment was divided into the Payload Support System and Scientific Sensor Platform to aid its design as part of the STRATHcube project. Through this distinction, the Payload Support System preliminary design includes the passive aerodynamic stabilisation system, whereby the solar panels are reconfigured for stability, communication via the Iridium Constellation during re-entry and using no additional thermal protection to lengthen mission lifetime, allowing STRATHcube to simulate space debris re-entry more closely.

Progress for the Scientific Sensor Platform includes the selection of the sensors required to record the heat flux, velocity, and attitude during re-entry. A dedicated heat flux sensor, thermocouples, Pirani Gauge pressure sensors, spectrometer and Inertial Measurement Unit are used for this purpose. Lastly, solar panel monitoring concepts were investigated. These include the use of imaging or the tailor-made electromechanical break switches employed at the solar panel CubeSat joint. For the time being electromechanical break switches will be relied upon for solar panel monitoring given constraints on image transmission.

To summarise, progress to date for the fragmentation experiment is promising, with future work expected to further advance and reinforce the experiments design. The eventual launch and deployment of this fragmentation experiment onboard STRATHcube is expected to provide a new opportunity to understand the re-entry environment. This will allow re-entry analysis tools to be enhanced to further reflect the observations made with these activities, strengthening the predictions relied on during Design for Demise processes.

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