72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021.

IAC-21-E2,4,2,x66554

STRATHcube: A Student CubeSat that Encourages the Sustainable Usage of Space

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Abstract

The 'NewSpace' revolution has led to more launch opportunities and cheaper off-the-shelf components. As a consequence, the rate at which objects are being launched into orbit has significantly increased. A large proportion of these new objects are due to satellite mega-constellations, and concern is growing over the congestion of the space environment. However, a positive associated with the democratisation of space is that CubeSats, a standardised nanosatellite, are becoming increasingly technically capable. STRATHcube is a student-led CubeSat in development at the University of Strathclyde that seeks to mitigate the problem of space debris with two novel technology demonstrations: in-orbit space debris tracking and measuring fragmentation during atmospheric re-entry. This paper will present the design of the CubeSat and the learning experience of the student team. A trade-off analysis was conducted to determine the optimum configuration of the CubeSat in terms of viability and scientific value. A broad range of configuration options with different payload capabilities and properties were initially considered. By completing a high-level design for each option, a baseline and a more technically ambitious choice were selected. A detailed design process was then able to be undertaken for the CubeSat subsystems, in parallel with the design of the payloads and their experiments. As the first student CubeSat development at the University, strategies such as interactive workshops were used to give undergraduate students practical experience of designing and building a space mission. The challenges associated with developing STRATHcube in parallel with two ambitious experiments will be assessed, particularly given the student-led nature of the project. From the trade-off analysis and detailed design process, it was determined that the CubeSat's primary payload will use passive bi-static radar technology to demonstrate in-orbit space debris tracking, which could eventually decrease the minimum size of debris currently able to be catalogued. A secondary payload that will gather flight data on the spacecraft's fragmentation during re-entry was determined as feasible but posed significant challenges for the design of several subsystems. The results of a survey measuring the success of the methods used to train the students involved in the project are presented. It is hoped that the CubeSat's design will enable it to contribute to space debris mitigation and encourage the sustainable usage of space.

Keywords: STRATHcube mission, CubeSat, space debris, satellite fragmentation, trade-off analysis, education

Acronyms/Abbreviations

Concurrent Design & Engineering Platform 4 - Community Edition" (CDP4-CE), Commercial off-the-shelf (COTS), Design for Demise (D4D), Design Iteration (DI), Debris Risk Assessment and Mitigation Analysis (DRAMA), European Space Agency (ESA), Low Earth Orbit (LEO), Passive Bistatic Radar (PBR), Satellite Design Competition (SDC), Space Situational Awareness (SSA), Strathclyde Aerospace Innovation Society (StrathAIS), UK Students for the Exploration and Development of Space (UKSEDS)

1. Introduction

1.1 Motivation

With the advent of private rocket companies and growing space activity, the number of satellites launched into orbit around Earth has dramatically increased. This "NewSpace revolution" [1] has paved the way for satellite mega-constellations and increased accessibility to space. Historically, space missions have operated under the "Big Sky Theory" [2], believing that space is so vast that there is little risk of objects colliding with each other. Therefore, the consequences associated with leaving objects in orbit with no end-of-life strategy were not considered. However, with increased space activity, concern is growing over the congestion of the space environment. The accumulation of space debris from the first satellite launch in 1957 to 2015 is illustrated in Fig. 1.

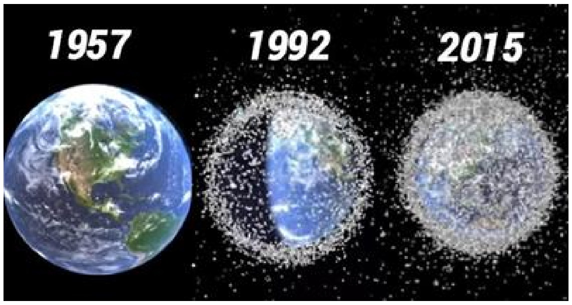

Fig. 1. The evolution of space debris from 1957 to 2015

LEO, the closest orbital region to Earth, extending to an altitude of 2,000 km, is becoming congested at an alarming rate due to its optimal proximity for Earth observation and low latency data transfer. At the beginning of 2020, ESA catalogued nearly 14,000 objects in LEO, with only around 3,000 of these being active satellites [3]. Space debris forms the remaining 11,000 objects catalogued; however, it is estimated that the true number of debris in orbit stands at over 128 million. The term space debris refers to any artificial object that is not operational in orbit, including defunct satellites, rocket bodies, and fragments created from explosions and collisions [4]. Most debris are millimetres in size, but still pose a significant risk to the nominal operation of ongoing satellite missions in the event of a collision, due to the hypervelocity orbital speeds of 7-8 km/s speeds in LEO.

One potential outcome of the debris problem is Kessler's Syndrome. Kessler's Syndrome predicts that if the number of objects in space reaches a critical value, a single collision could start a chain event, ending in an artificial debris ring around Earth. If intervention is not introduced to mitigate against the debris environment, future access to space will be limited, as any satellite launched could be quickly destroyed by collision with debris. As a result, Space Situational Awareness (SSA) was an initiative developed for space debris mitigation [5]. As part of SSA, the risk posed by debris to current spacecraft operations and ground infrastructure must be assessed to ensure the longevity of the space environment.

SSA is concerned with two primary areas for space debris mitigation: the accurate tracking and cataloguing of debris to prevent collisions with active satellites, and the removal of debris to minimise the growing congestion in populated orbits [5].

Debris tracking is currently carried out in ground-based facilities on Earth using radar and optical technology. However, the minimum debris size that can be tracked and catalogued in LEO from these facilities is typically limited to 10 cm. Therefore, millions of pieces of debris potentially go undetected, which could result in a catastrophic collision with an active satellite [6, 7].

Debris removal has become a requirement in recent years, with regulations introduced that state objects must be safely removed from highly congested orbits within 25 years of their mission's end [8]. As many small-to-medium sized satellites are unable to carry additional propulsion to relocate themselves to graveyard orbits – orbits in which spacecraft are unlikely to cause a collision - disposal through atmospheric re-entry is preferred [9]. However, there is potential for satellites to survive re-entry and impact Earth.

To minimise the risk of a satellite surviving re-entry a process known as Design for Demise (D4D) has been introduced to the satellite design process, requiring satellite developers to consider the end-of-life phase of missions alongside the spacecraft design [10]. These processes rely on upper atmosphere orbit propagators to indicate the time and location that a satellite will re-enter Earth's atmosphere, and re-entry analysis tools to predict the probability of a satellite's survival following re-entry and the associated risk [11] [12]. These tools, however, tend to underestimate satellite survivability and therefore understate the associated risk, limiting our ability to accurately predict and minimise the risk of a re-entry event using D4D processes [13].

1.2 STATHcube Project Overview

The growing debris population and associated SSA initiative provides the basis for the STRATHcube mission. STRATHcube aims to positively contribute to ongoing research in space debris mitigation for the sustainable usage of space through the development of a CubeSat platform. CubeSats are a standardised nanosatellite made up of 10x10x10 cm 'units', or 1U. These platforms have made space missions more accessible, reducing their typical cost and development time by using standardised Commercial off-the-shelf (COTS) components. As such, CubeSats have become central to many research missions and are ideal for STRATHcube's objectives [14].

STRATHcube will have two payloads on board, developed to target the current limitations in SSA, addressed above. STRATHcube's primary payload will demonstrate an in-orbit debris detection method to show the potential to better track and detect debris from orbit compared to the current capabilities of ground-based facilities [15]. This demonstration will test a signal processing algorithm developed by researchers at the University of Strathclyde to detect debris. STRATHcube's secondary payload is concerned with the end-of-life phase of the spacecraft. It aims to provide flight data for the development and validation of D4D processes to reduce uncertainties present in their satellite survivability and risk prediction.

STRATHcube was proposed by members of the Strathclyde Aerospace Innovation Society (StrathAIS), with the aim of developing and launching the first Scottish student-led CubeSat, using recognised spacecraft design procedures. To achieve this goal, the CubeSat will undergo a development process that takes place over several years. This process begins with an initial feasibility study and preliminary design; followed by a more rigorous detailed design that is verified by testing and construction; before ultimately moving to launch and operations.

STRATHcube's feasibility study was completed in May 2020, through a virtual Concurrent Engineering Session organised by StrathAIS and the University of Strathclyde [16] [17]. The study involved 29 undergraduates and PhD students, under the guidance of experienced researchers. The feasibility study was extremely successful as the project was deemed viable and the scientific areas for both payloads were outlined.

It was determined from this session that the primary payload for STRATHcube would be an antenna system for detecting space debris in-orbit, acting as a technology demonstrator for an algorithm being developed at Strathclyde. The secondary payload would consist of a sensor package to attempt to improve the design for demise process by collecting data during the CubeSat's re-entry.

1.3 Paper Scope and Aims

This paper will detail the aims that were specified for the satellite following its feasibility study, and the progress that has been made toward these aims to date. The scope will be limited to the completion of a thorough preliminary design of the CubeSat, its payloads, and its subsystems.

Trade-off analyses were used extensively to progress the design of STRATHcube. Initially, an iterative, system-level trade-off analysis was conducted. The aim of this high-level trade-off was to consider a wide range of concepts for the configuration of the satellite and its mission, and then gradually reduce them down over the course of four design iterations. It was desirable for there to be two remaining options following the final iteration: a 'baseline', more conservative option, and an 'ambitious' option. A more detailed design process could then occur at a subsystem level, in order to select the single most feasible design option for the satellite.

Throughout the development of the CubeSat platform, the design of both payloads and their experiments was progressed from concept to a feasibly operable technology demonstration. An abridged summary of this process will be given, with particular emphasis placed on the challenges that were experienced at a system level due to the novel and ambitious nature of the payloads.

Given that STRATHcube will be a multi-year long project, it will be necessary for numerous students, of varying backgrounds and experience, to contribute to its development over its lifetime. Therefore, the final objective of this paper will be to detail the methods that were implemented to teach undergraduate students in the fundamental principles of nanosatellite design; and to critically assess their success.

2. Design Trade-Off

Trade-off analyses are commonly used in spacecraft systems engineering to compare the characteristics of different candidate system architectures or configurations [18]. The aim of any trade-off analysis is to identify the best solution for the system, measured against a defined set of assessment criteria.

2.1 System-Level Design Trade-Off

The system-level trade-off analysis consisted of four design iterations (DI's), each of approximately two weeks in duration. It was critical to ensure that the trade-off conducted by the team was both exhaustive and quantitative. During each iteration, the team worked concurrently to define a high-level design for each subsystem for every candidate configuration. Key design parameters - such as mass and power - were inputted to RHEA Group's "Concurrent Design & Engineering Platform 4 - Community Edition" (CDP4-CE), such that parameter modifications and progress could be tracked and managed by the system engineers.

Before the trade-off commenced, a shortlist of potential CubeSat configurations was compiled. Options were specified primarily based on possible payload configurations, with the primary payload prioritised. The categories of the primary payload considered were limited to either 'Basic' or 'Advanced', depending on the capability of the antenna hardware used. Three different possible options were considered for the Secondary. Initially, these were labelled as 'Advanced', 'Moderate', and 'Basic', respectively, based on their relative complexity. The justifications for these labels are outlined in section 4.1.

Due to its high impact on the CubeSat design, the inclusion of a propulsion system was considered when defining the trade-off analysis options, although as a secondary factor. Initial form factors from 1-6U were estimated based on the results of the feasibility study [16].

DI1 started with ten possible configurations. Due to greater knowledge at a system level, the ten options were heavily modified, and then reduced to nine possible configurations for the start of DI2. The options studied from DI2 onwards are presented in Table 1.

Table 1. Summary of possible STRATHcube configurations considered in the high-level trade-off

Option	Form Factor	Primary Payload	Secondary Payload	Propulsion
1	1U	Basic	Basic	No
2	2U	Basic	Basic	No
3	2U	Basic	Basic	Yes
4	2U	Basic	Moderate	No
5	3U	Basic	Advanced	No
6	3U	Advanced	Basic	No
7	3U	Advanced	Basic	Yes
8	3U	Advanced	Moderate	No
9	3U	Advanced	Advanced	No

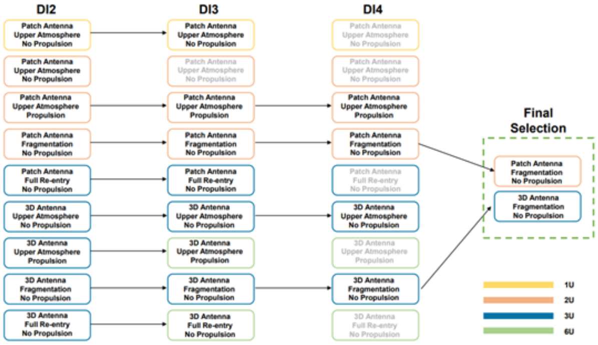

Fig.2. Summary flowchart of the high-level trade-off

As shown in Fig. 2, the two final options selected both aimed to undertake the 'Moderate' fragmentation re-entry experiment, as it was concluded to provide the best balance between feasibility and scientific value for the secondary payload. One option used the more 'Advanced' 3D antenna as the primary payload, and hence required the larger 3U bus. The other, 2U option, used the better-defined 'Basic' patch antenna. It was concluded that the effectiveness of the propulsion system in extending the duration did not justify its mass, cost, or power requirements.

The obtained result was the desirable scenario from the outset, in that one of the final options represented a more ambitious primary payload configuration, as it used the 'Advanced' 3D antenna option, whereas the other was deemed more achievable as it would use a patch antenna. The impact of this result is discussed in detail in section 3.

2.2 Subsystem-Level Design Trade-Off

Once the final two candidate configurations had been identified, the trade-off analysis moved from a system-level to a subsystem-level. As has been discussed, the ultimate goal of this stage was to move from the two options detailed in section 2.1 to the single best option for the STRATHcube project. In order to make this decision, both candidate configurations brought forward had to be scrutinised at both a system and subsystem level to evaluate and select the more suitable option overall.

The subsystem-level trade-off analysis was split into two DI's. At the end of each DI, the design of every subsystem was updated for both of the final two candidate options, based on the more detailed analysis that had been carried out by the team. The necessary components for each subsystem were also selected. By the end of the second DI, both of the final two CubeSat designs could be critically evaluated, and the best option was selected.

At the conclusion of the final DI, the optimal configuration for STRATHcube was deemed to be the "baseline" option that had been earlier. This option consisted of a 2U structure, a patch antenna for the Primary Payload, and the fragmentation re-entry experiment for the Secondary Payload. The main reason this option was selected over the 3U alternative was driven by the primary payload, which will be discussed in more detail in section 3. This decision was coupled with the 3U option being consistently over the allowable mass in both DI1 and DI2 of the subsystem-level trade-off, despite best efforts to reduce it.

3. Primary Payload Progression

3.1 Primary Payload Concept

The primary payload of STRATHcube will contribute to space environment sustainability through the tracking of space debris in-orbit. The motivation for performing such in-orbit tracking is that the debris is far closer to the target, and hence smaller pieces of debris could potentially be detected. There are several reasons for this improvement, including the reduced effects of the Doppler shift due to lower relative velocities between the CubeSat and the debris; as well as lower losses due to the signal no longer having to travel through the atmosphere.

The method that will be used by STRATHcube to perform in-orbit tracking is based on on-going research at the University of Strathclyde, which was sponsored by the UK Space Agency and ESA [19]. The principle, Passive Bistatic Rader (PBR), uses 'backscattering', whereby a receiver, the CubeSat, will intercept radar signals destined for Earth coming from a transmitter – an 'illuminator of opportunity', in the form of a satellite constellation overhead. If a piece of debris is in the way (the target), it has been demonstrated as feasible to propagate the motion [15], as well to estimate as the size and shape of the debris [20]. This concept can be visualised in Fig. 3.

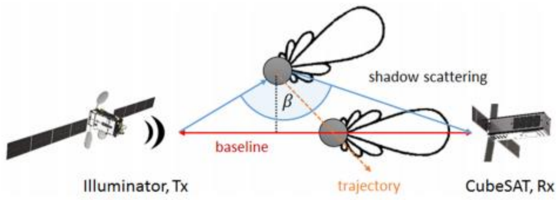

Fig. 3. CubeSat PBR space debris tracking concept. Credit: [15]

The selection of an illuminator of opportunity was essential in progressing the primary payload design, as the on-board debris-tracking antenna is required to receive signals at the operational frequency of the illuminator satellite(s). It was desirable for the illuminator of opportunity to be part of a large constellation to increase link availability. The Iridium Constellation was selected as the illuminator of opportunity due to its reliability and availability.

3.3 Primary Payload Platform Integration

Developing the primary payload from a concept to a feasible technical solution was critical to the STRATHcube design process. Two hardware options for the primary payload were explored concurrently throughout the system- and subsystem-level trade-offs outlined in section 2. The first used a novel 3D phase array antenna, and the second a COTS patch antenna.

The 3D antenna featured onboard the 'ambitious' STRATHcube option identified at the end of the system-level trade-off. This label was due to the hardware still being in the early stages of its development, in association with researchers at Strathclyde. The 3D antenna was expected to be able to track space debris more effectively, and provide better experimental data. However - as is to be expected from a new technology - several of the 3D antenna specifications were yet to be defined. This lack of information led to several crude estimations being made by the team in order to design and size the supporting CubeSat platform.

Estimates for essential 3D antenna design parameters - such as mass, power, and dimensions - would often fluctuate significantly based on new information becoming available. A key example was the working estimate for the 3D antenna power consumption increasing by a factor of 10 from one DI to the next. Even with conservative margins having been applied, such an increase had an extremely significant impact on the design of the supporting subsystems, given the limited nature of the CubeSat platform.

Due to the interdependency of spacecraft subsystems, such an increase in power required would not only increase the demands on the power generation subsystem. Adding the extra solar panels necessary would increase the overall mass of the CubeSat, limiting the mass available to other subsystems - and hence their capabilities. A substantial cost increase would also likely ensue.

Once an appropriate illuminator of opportunity had been selected, choosing a patch antenna capable of completing the mission posed far fewer issues to the overall spacecraft design. Patch antennae are inherently compact, meaning their associated mass and dimensions do not contribute significantly to the mass budget or restrict the volume available to other components. Further, the patch antenna selected consumed far less power than the 3D antenna. Given that solar panels are one of the most expensive pieces of CubeSat equipment, choosing the patch antenna would have the knock-on effect of substantially reducing the overall cost of the satellite.

Therefore, although the 3D antenna would likely have been a more impressive technology demonstration of in-orbit space debris tracking, the impact that its selection would have on the satellite as a whole had to be traded-off. It was concluded that the 3D antenna was not yet in an advanced enough stage of its development to be a viable option, leading to the selection of the far cheaper and less complex COTS patch antenna.

4. Secondary Payload Progression

4.1 Secondary Payload Concept

During the system-level trade-off analysis, refining the concept for STRATHcube's secondary payload was a critical activity. It was known from the satellite's feasibility study that it would provide flight data during atmospheric re-entry to improve D4D models. What data would be collected, how it would be collected, and how the CubeSat would send this data to ground were all to be determined.

Three options for the secondary payload were initially considered. The first would measure the atmospheric density of the lower thermosphere from an altitude of 250 – 90 km. The second would record aerothermal measurements in the most destructive phase of re-entry, similar to the QARMAN mission [21]. These two options were differentiated based on their measurement capability and hence complexity, leading to their labelling of 'Basic' and 'Advanced', respectively, as was discussed in 2.1. The final option, labelled as 'Moderate' in terms of complexity, would have a sensory package for in-situ measurements but would also seek to determine when the solar panels broke away (fragmented) from the CubeSat structure during re-entry.

As was outlined in 2.1, it was decided that both candidate STRATHcube configurations considered during the subsystem-level design trade-off would feature the fragmentation experiment. The first reason for this decision was that the 'Basic' concept was adjudged to be of less scientific interest to the project's academic, whereas the 'Advanced' package was estimated to be too complex, costly, and similar to previous missions. Secondly - to the best of our knowledge at the time of writing - no mission has ever been attempted to detect the fragmentation of a specific piece of equipment. Therefore, if successful, the data collected would be highly novel and potentially useful to improve D4D models - significantly adding to the appeal of the experiment.

An artistic illustration of the secondary payload experiment is shown in Fig. 4. STRATHcube is considered to come to the end of its nominal operation, where the primary payload and all major supporting subsystems are active, at approximately 170 km. At this altitude modelling suggested the Attitude Determination and Control System (ADCS) will no longer be able to counteract the environmental disturbance torques. Therefore, the satellite solar panels were designed to be re-configured in-orbit (Stage 1) to provide aerodynamic stability during the secondary payload experiment. The impact of including this capability on the satellite will be discussed in detail in 4.2.

During Stage 2 of the fragmentation experiment, sensors will collect data on the re-entry environment, and communication will be established with the Iridium constellation such that data can be transmitted. Using this method is necessary due to communications 'blackout' which is experience during re-entry meaning that communication with a ground station is not possible.

ESA DRAMA (Debris Risk Assessment and Mitigation Analysis) simulations were used to make an initial prediction for when solar panel fragmentation and complete demise would occur. During Stage 3 of the experiment, methods to detect the solar panel fragmentation will be attempted, before complete destruction of the satellite occurs. This demise represents Stage 4 of the secondary payload experiment, and the end of the STRATHcube mission.

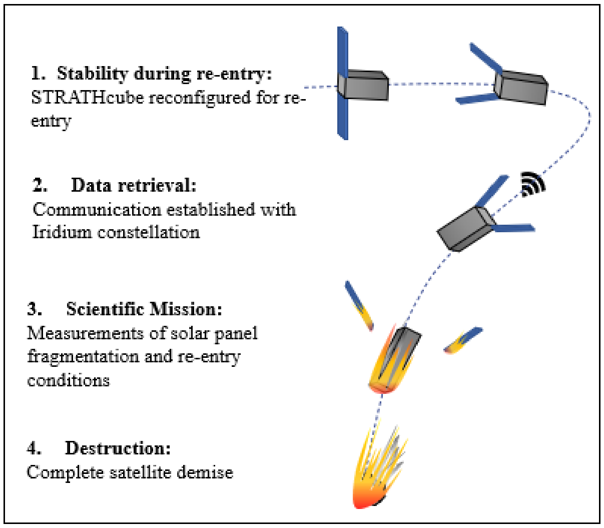

Fig. 4. Artistic illustration of the secondary payload experiment concept

4.2 Secondary Payload Platform Integration

Integrating a feasible concept for the secondary payload onto the satellite platform had a profound impact on the configuration of STRATHcube throughout its entire design process. Unlike for the primary payload, the same experiment would not be undertaken by the different secondary payload options that were considered during the system-level trade-off. As a result, the rate of progress in characterising the secondary payload hardware between successive DI's was limited, given that the concept for each different experiment had to first be refined. Consequently, progress as a system level stalled given that the platform was designed to enable the payloads to carry out their experiments. Therefore, the decision to take only the fragmentation experiment into the subsystem-level trade-off was based largely on engineering judgement of the project system engineers, secondary payload manager, and the project supervisor.

As has been discussed, only a high-level design for the fragmentation experiment existed at the beginning of the more detailed, subsystem-level trade-off. Therefore, as the design of the secondary payload began to mature, the design of the supporting subsystems was required to progress almost in parallel with the payload itself.

An example of the CubeSat design rapidly changing at a system level due to progression in the secondary payload was after the introduction of the requirement for the satellite to remain aerodynamically stable during the fragmentation experiment. The only feasible solution was quickly identified as passive stabilisation by means of reconfiguring the CubeSat solar panels in-orbit. The shape and size of the CubeSat solar panels changed drastically as a result, which required mission analysis, AOCS, and power to perform significantly more detailed analysis and calculations to determine how to make the new design feasible. Additionally, re-configurable CubeSat solar panels are not available to buy off-the-shelf, meaning that a custom solar panel deployment mechanism had to be designed, as shown in Fig. 5.

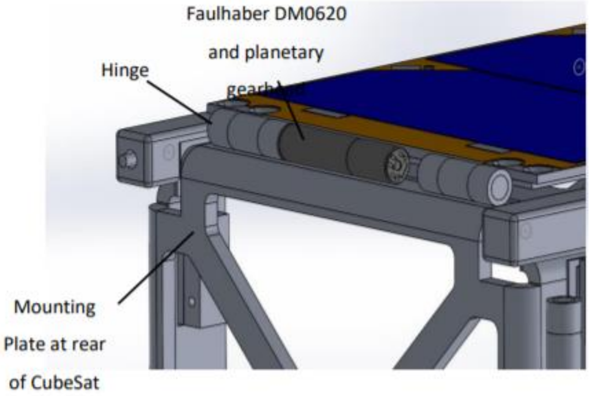

Fig. 5. The geared stepper motor and hinge mechanism designed to enable solar panel reconfiguration.

Despite the challenges associated with undertaking the fragmentation experiment as a part of the STRATHcube mission, and the rapid subsystem development that was required, at the stage of the design that was reached it was deemed to be feasible. One benefit of the secondary payload is that it will not interfere with the operation of the primary payload, given that it takes place at the mission's conclusion. Therefore, the inclusion of the secondary payload will not jeopardise the mission as a whole.

5. Educational Impact on Students

5.1 Group Master's Thesis

The STRATHcube project has been developed thus far by a team of 6 students working toward a master's group thesis. Given that the ultimate aim for STRATHcube is for it to be launched into LEO, it would be difficult to find a university project as challenging, rewarding, and practical in the context of space systems design in the real world.

The Director of the Aerospace Centre of Excellence at the University of Strathclyde, Professor Massimiliano Vasile, was the primary customer and supervisor for this project. When asked to comment in the official grading of the thesis, he noted "[the level of] technical content is very high for the time they had and the difficulty of the project" and "the group worked very well together, [they were] very well organised, with constant communications and regular reviews". Therefore, in his opinion, the progression of the design using a group of Master's students was more than satisfactory, as it ultimately resulted in a "very comprehensive, well-structured [design] report".

This appraisal demonstrates that the educational benefits of CubeSats are still significant, over 20 years on from their inception as tools for learning by professors at Cal Poly [14] – given that the team went from knowing little of nanosatellite design to delivering a feasible proposal for a relatively complex mission concept. Given the additional enforced challenges associated with working together entirely virtually due to the COVID-19 pandemic, the team regard the progress made to be especially pleasing.

Following the success of using this team structure, a new group of Master's students has been approved to lead the next phase of the project this coming academic year. Additionally, two bachelor's students will complete their individual dissertations on a specific aspect of the satellite's design.

The focus of the students continuing the project will shift to the physical testing and calibration of STRATHcube components – with a particular emphasis on the payloads – using a 'FlatSat' purchased for the team's use. Such testing will allow them to consolidate the CubeSat's design and make final component selections, such that a full build can begin.

5.2 The 'STRATH^2' Initiative

Perhaps an equally significant impact of the STRATHcube project on the education of Strathclyde students has been through an initiative dubbed 'STRATH^2'. The project was named as such because of its purpose to teach students in the earlier stages of their undergraduate degree the principles of nanosatellite and space systems design.

A group of 11 junior students were delivered weekly interactive workshops on various spacecraft subsystems by members of the STRATHcube team. The junior team were then challenged to apply their new skills by entering the UK Students for the Exploration and Development of Space (UKSEDS) Satellite Design Competition (SDC) [22]. The SDC 2020-21 requested proposals on a simplified lunar CubeSat concept, with a detailed requirement specification.

The impact that being a part of this team had on the learning experience of the students involved was critically assessed. All were invited to complete a detailed survey, consisting of numerical ratings from 1-10 and comments. A summary of the questions posed, and the average rating, is given in Table 2.

Table 2. Summary of STRATH^2 team survey

Question	Average Rating
How much did you enjoy being part of the StrathAIS CubeSats team this year?	8.83
How beneficial do you think being part of	8.67

the StrathAIS CubeSats team will prove to be in university learning experience?	
How useful do you think the interactive training workshops were or will prove to be?	7.67
To what extent do you think being part of the StrathAIS CubeSats team will make you want to participate in more space related projects?	9.17
To what extent do you think working toward the UKSEDS Satellite Design Challenge throughout the year was beneficial to your experience?	8.33
How interested were you in pursuing a career in the space industry **before** being a part of the StrathAIS CubeSats team?	5.83
How interested are you in pursuing a career in the space industry **after** being a part of the StrathAIS CubeSats team?	8.67
How interested are you in being a part of StrathAIS this coming academic year?	9.17

When asked to rate their enjoyment of being in the team out of 10, all but one team member gave either a 9 or 10 rating. The same is true of how beneficial the students believe the experience will prove to be in the context of their university learning experience. These results demonstrate not only that participating in the STRATH^2 project enhanced the skillset of the students as budding space engineers, but also that they had fun while doing it. Several of the students cited being taught specialist topics of interest that are not part of their curriculum is what generated their excitement to learn. As a result, their motivation to test these newfound skills by engaging in their competition entry increased.

Although the feedback was positive overall, it was clear that improvements could be made to the interactive training workshops. Several of those surveyed highlighted that the workshops were not in depth enough to gain a significant understanding of the topic. One student surmised "I think that personal initiative is the only way towards acquiring knowledge one can apply in their work." This finding shows the importance of allowing the students to develop their skills by giving them ownership of their own project. Further, it suggests that one of the reasons they enjoyed the experience so much overall was that it was different to traditional learning methods, such as lectures and tutorials.

The extent to which the students had developed in their knowledge of nanosatellite design over the course of the project was made clear during the 'Competition Day' of the UKSEDS SDC. Following a 25-minute presentation and Q+A session to a panel of UK industry experts, the StrathAIS team were adjudged to have produced the best Extended Design Report (the final of three milestones to be requested throughout the year for the competition) and were awarded 2nd overall. The achievement is especially impressive given that the Strathclyde team, who knew next to nothing of CubeSat design at the beginning of the project, were competing against several other top UK Universities, many of whom consisted largely of postgraduate students.

More generally, the team members reported that their interest in pursuing a career in the space industry had gone up significantly compared with before they had started the project; a 49% increase on average. One 3rd year student stated:

"Before working with the team, I always assumed the space sector would be fairly inaccessible, with few roles being available. However, over the last year I have come to realise how large the sector actually is and how quickly it is growing."

The impact of the STRATH^2 initiative is, therefore, clearly not limited to the university experience of the students; it is possible that it will help to shape their future career path too. Given the proportion of the students who wish to pursue further space-related projects during the remainder of their studies (two will be completing their bachelor's dissertations on STRATHcube this year), it is likely that their enthusiasm to contribute to the development of the space industry will only grow.

6. Discussion and Conclusions

Throughout the project, trade-off analyses were used extensively to iterate upon the design at a high, system-level, and a more detailed, subsystem-level. This approach was largely beneficial, as the nine possible CubeSat options which were considered at the beginning of the project were reduced to two at the conclusion of the system-level study. The intended outcome of this high-level trade-off was reached, in that through quantitative decision making the two options which remained represented a 'baseline' and an 'ambitious' configuration.

However, it was found that at times the progression of the secondary payload was delayed. Delays were – understandably – cause by the range of experiments which were considered during the high-level trade-off. As a result, none were of sufficient detail. An important consequence of this delay was that the overall system progress also stalled. Therefore, during the subsystem-level trade-off, when only the fragmentation experiment was considered, progress of the supporting subsystems had to be made in near parallel.

Furthermore, the 3D antenna option was not well defined throughout the project. Often key parameters, such as mass and power, fluctuated from DI to DI, which adversely affected the capabilities of other subsystems.

A key lesson learned by the team is, therefore, the importance of having well-defined payloads before commencing the design of a spacecraft platform. For STRATHcube, this issue could have been addressed by undertaking a more in-depth initial feasibility study for the satellite, or a separate feasibility study for the proposed instruments. Additionally, potentially scheduling less DI's throughout the design process could have been beneficial to reduce the pressure on each team member, allowing them to instead delve deeper into their respective area of responsibility. However, given the challenges associated with developing the platform design in parallel with the payloads, that a feasible system design was produced, incorporating achievable primary payload and secondary payload concepts, can be considered an achievement.

Although there is much work still to be done on the design and verification of STRATHcube, the success of using a master's group thesis to progress the project was such that the team structure will be continued this academic year. In addition, two further students will complete their bachelor's thesis on an aspect of the design, meaning that there will be enhanced continuity for those participating in the project in the coming years.

The STRATH^2 initiative has demonstrably enhanced both the learning experience and the enjoyment of students in the earlier years of their studies, by introducing them to CubeSat design. It is evident that the extent of the knowledge that the students gained, given the success they enjoyed in the UKSEDS SDC, where they competed at a national level.

Most crucially, however, it was clear from the feedback of the STRATH^2 students that they were far more enthused about working on future space projects or pursuing a career in the space industry than they were at the beginning of the project. This conclusion seems to reflect findings that CubeSat initiatives have directly led to an increased number of Science, Technology, Engineering and Mathematics (STEM) students actively pursuing a career in the space sector in the US [23]. Therefore, it is hoped that the future is not only bright for STRATHcube, but for the future of the space industry in Europe; given the number of academic institutions who pursue similar student space programmes.

Acknowledgements

The STRATHcube team (Ciaran Jenkins, Lewis Creed, Julie Graham, Sam Kirk, Douglas McGarrity, Gary Stewart) would firstly like to thank Prof. Massimilano Vasile. His expertise, guidance and enthusiasm has been instrumental since STRATHcube's inception and throughout its progress since. Secondly, our sincerest thanks go to Dr. Andrew R. Wilson, who has continually been willing to provide invaluable feedback and advice (even at short notice). Finally, thanks go to Mr. Rory Hope for his leadership of the STRATH^2 initiative; responsible for inspiring Strathclyde students to get involved in CubeSat design.

Sponsors

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