STRATHCUBE: THE DESIGN OF A STUDENT CUBESAT USING CONCURRENT ENGINEERING METHODS

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ABSTRACT

With the role of concurrent engineering (CE) becoming more important to the success of companies, it is vital that engineering students are able to understand and apply this concept. In this regard, the University of Strathclyde regularly offers its students opportunities to learn about this process through practical-based CE workshops. The results from a student-based CE study of a CubeSat are therefore outlined, including the effectiveness of the session as a learning experience for students. Through collaboration and teamwork, the student team produced a feasible design concept which achieved most of the prespecified objectives. Additionally, it was determined that the learning outcomes of the study were widely met, despite it taking place virtually due to COVID-19.

1. INTRODUCTION

Concurrent engineering (CE) is commonly applied as a systems design approach during Phase 0/A feasibility studies of space missions in order to decrease development time and the need for multiple design reworks. The process enables various activities to be run simultaneously by employing multidisciplinary groups to design space systems in a collaborative and timely manner, through the complete sharing of product data and instantaneous interactions of different disciplines [1]. However, although CE is not an essential practice within the space sector, it is a well-established means for developing early space system design concepts. Today, the role of CE towards the success of companies is becoming increasingly more important in order to reduce lead times, produce a higher quality of product, lower production & manufacturing costs and fulfil customer requirements [2]. For this reason, it is vital that university students are well-versed in the concept in order to boost their career prospects in the field of aerospace engineering [3].

In this regard, the University of Strathclyde has its own Concurrent Design Facility (CDF) called the Concurrent & Collaborative Design Studio (CCDS). The CCDS is used for all CE activities within the university, with several space mission design studies having already taken place, such as the MÌOS and NEACORE concepts [4,5]. It was opened in October 2015 and is located within the Technology & Innovation Centre (TIC) in Glasgow. The facility consists of 18 workstations, each of which are equipped with Linux (Ubuntu 14.04) and Windows 7 operating systems. Both the European Space Agency (ESA) Open Concurrent Design Tool and RHEA Group's Concurrent Design & Engineering Platform 4 - Community Edition (CDP4-CE) are used as central design tools hosted on an Ubuntu 14.04.4 virtual server.

Whilst CE is not currently offered as part of any module within the University of Strathclyde at present, several extracurricular initiatives have been put in place to actively encourage student participation. For example, the Aerospace Centre of Excellence offers students the chance to propose their own mission concepts and hosts regular concurrent design challenges which are open to students from all levels and disciplines across the university. The aim of such initiatives is to bolster learning by providing students with a practical working knowledge of the CE process. This allows the students to gain a range of valuable skills beyond their core studies, which helps prepare them for the world of work after university, increasing their employability.

Consequently, this paper presents the final design of a Phase 0/A feasibility study that was undertaken for the STRATHcube mission (a student CubeSat concept in development at the University of Strathclyde) and the effectiveness of the CE session as a learning experience for students. The study utilised the CCDS, with 29 undergraduate and postgraduate students participating under the guidance of experienced researchers. However, due to the COVID-19 pandemic, the facilities were accessed remotely by the participating students, adding a different dimension to the learning activities.

2. BACKGROUND

2.1 Project Motivation

The concept of developing a CubeSat at the University of Strathclyde was proposed by a student association known as the Strathclyde Aerospace Innovation Society (StrathAIS). In October 2019, a working group was established within the organisation to investigate the feasibility of developing such a spacecraft, with the ultimate goal being to enter the ESA: Fly Your Satellite! (FYS) competition. This competition seeks to support student developers in building, testing, integrating, and launching their designed satellite. The project can be entered at Phase C (detailed design), or Phase D (production and functional testing). Therefore, a CE session was undertaken for Phase 0/A of the project to rapidly develop an initial design that would act as a springboard for the student team to build upon, with a Critical Design Review (CDR) planned for late 2020.

2.2 Payload Selection

Based on the recommendations of the StrathAIS working group, it was proposed that the objectives of the mission should align with cutting-edge research at the University of Strathclyde. As such, three key objectives were defined for the satellite: to track space debris using a novel antenna; to measure the effect of re-entry on the satellite using basic sensors; and to demonstrate Wireless Power Transmission (WPT).

A major problem facing space missions is space debris in Low Earth Orbit (LEO). This debris is primarily tracked from the ground using radar [6,7] but is currently only capable of detecting debris with a diameter larger than around 1 cm. Therefore, smaller debris particles must be modelled and hence have significant uncertainties associated with their motion [6,7]. Mounting a radar on a CubeSat could potentially be more effective in accurately detecting space debris, due to its significantly greater proximity [7]. There would also be the potential to detect smaller debris particles than are currently possible from the ground. Therefore, the main focus of the mission was dedicated to this detection to help improve current space debris catalogues. The primary payload would be a novel 3D Phase Antenna as part of a passive radar system. The system would use satellites, such as the SpaceX Starlink constellations, as a reference for reflection and analyse occultations in the radio signal to identify debris.

The secondary payload intended to observe interactions between the CubeSat and the atmosphere during the re-entry phase. This data would be crucial for improving the sizing and design of future re-entry thermal protection systems. Currently, even the best experimental facilities are not able to provide a complete set of re-entry flow conditions. ESA have created the AeroThermoDynamics & Design for Demise (ATD^3) group to research this. In 2018, ATD^3's QARMAN mission completed its demise and expect to release their results later this year [8]. To collect the relevant data, a combination of: Spectrometers, Heat Flux and Pressure Sensors, and Pressure Chambers were proposed.

As a third experiment, the feasibility of WPT to CubeSats was planned. This would involve positioning one of the spacecraft's solar panels in range of a laser beam transmitting from the International Space Station (ISS). Demonstrating WPT from the ISS would provide new opportunities for CubeSats to increase their power reserves and therefore allow for the possibility of extending mission lifetimes.

3. MATERIALS & METHODS

3.1 Concurrent Design Session

As part of the University of Strathclyde's Concurrent Design Challenge series, StrathAIS contacted the Aerospace Centre of Excellence to request a CE study for the STRATHcube mission. In preparation for the session, a multidisciplinary cohort were split into teams to design each satellite subsystem. Each sub-team comprised of at least one postgraduate and one undergraduate student. Postgraduates were selected for the challenge and assigned to a sub-team based on prior CE experience and their field of research. Undergraduate students who had expressed a desire to participate were assigned to the subsystem that they had expressed the most interest in contributing to. Mission and payload requirements were derived from the ESA FYS design specification [9]. These requirements and constraints were used as a framework in CDP4-CE during the session to ensure the design would always be suitable for its future goal of being launched in the FYS program.

Each day would start with a design recap, aimed at updating the whole team on the day's objectives and latest information. Each team would then continuously iterate their design, detailing all relevant components in CDP4-CE. Since the CCDS is still a relatively new facility which is mainly used by students, the methodology applied within each CE study run at the university has thus far been based upon the ESA CE philosophy, as exemplified through ESA Academy's CE challenge [10,11]. At the end of each day, a design briefing was held, allowing the team to share and consolidate the day's progress.

Communication was a key component of the study to ensure that each part of the rapidly changing design progressed cohesively. Despite this, being unable to physically congregate in the CCDS due to social distancing measures introduced in the wake of COVID-19 meant that the session was instead held over Zoom. These less than ideal circumstances proved a challenge for the team and made communicating effectively even more critical. Wilson & Berquand [12] detail how the team adapted specific aspects of the CE process to compensate for this.

3.2 Trade-Off Analysis

A trade-off analysis was undertaken to determine whether a propulsion system would be needed and if the main payload, a 3D phase array antenna, could be hosted on a 3U CubeSat. If the antenna could not be accommodated, an alternative payload such as a patch antenna could provide similar, but less performant, measurements. Therefore, 6 potential design options were considered, as illustrated in Figure 1. However, due to the limited time available for the study, only three of these were eventually explored. The selected options, shown in green, were the following:

- **Option 1:** No propulsion system, 3D Phase Array antenna, 3U
- **Option 2:** Propulsion system, 3D Phase Array antenna, 3U
- **Option 3:** Propulsion system, Patch Antenna instead of 3D Phase Array antenna, 2U

The remaining design options were discarded from the study based on the advice of the study advisors and basic logic. In this regard, it was already known that the 3D phase array antenna could not fit on a 2U structure.

However, if a patch antenna could be accommodated on a 2U structure, then there would be no need to design a 3U CubeSat. Despite this, although a passive CubeSat with a smaller payload would be less challenging than accommodating the larger phase array, it would vastly reduce the mission's scientific capabilities.

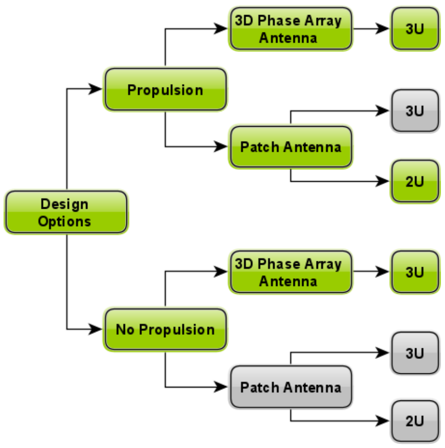

Figure 1: Design options explored (in green) during STRATHcube feasibility study

A propulsion system critically increases the complexity of a CubeSat mission, as well as incurring a substantial cost. A need for propulsion was mainly considered due to early Ballistic Coefficient (BC) estimations, which suggested that a propulsion system may be required to extend the mission lifetime. In addition, during the study, the Japanese partner assembling the primary payload (the 3D phase array antenna), confirmed that the instrument could be accommodated on a 3U structure and that it could be contained in a volume of 1U.

3.3 Systems Engineering

For each of the four iterations of the CubeSat design, mass and cost budgets were prepared for the spacecraft. In each instance, the ESA "Margin philosophy for science assessment studies" [13] was applied at both a system and subsystem level. Participants were responsible for applying the relevant subsystem margin based on how proven the applied technology is in terms of its Technology Readiness Level (TRL) before committing their values to the CDP4-CE tool. The students were encouraged to use a conservative value in case of doubt. A system level margin of 10% was then applied by the system engineers.

For the first design iteration, only a preliminary mass was estimated for the default option of a 3U body with a 3D Phase array antenna and a propulsion system. This was due to the aforementioned 6 potential design options for the satellite having not yet been defined. For the second design iteration, a mass budget was comprised for each of the 3 shortlisted design options. Before commencing the final two design sessions, it was apparent that the first design option (passive 3U bus with a 3D phase array antenna) would be the only one necessary to continue investigating as the other two shortlisted options were deemed infeasible. Therefore, a final mass budget was detailed for this option only.

As requested by the StrathAIS team, a cost budget was prepared for the satellite. This was generated based on a combination of specific product costs and cost estimation relationships using an in-house developed tool called the Strathclyde Space Systems Database (SSSD) [14]. It was assumed that the cost of developing the antenna payload itself should not be included in the cost budget. A margin of 5-20% was applied to each subsystem in accordance with its TRL, before applying a 10% system margin. As was the case for the mass budget, all three design options were costed for the end of Iteration 2. For the final two design sessions, the first design option was the only to be costed.

In line with the sustainability objectives of the CubeSat, the SSSD was also used as part of a wider Life Cycle Sustainability Assessment (LCSA). As such, the environmental, social and economic life cycle impacts were modelled for each design option throughout the study to keep participants informed of the evolving sustainability impacts of the mission as it developed over the course of the week. In this regard, the SSSD was used to compile the life cycle inventory based on information and data deposited to the CDP4-CE as well as SSSD default values/methodology, expert judgement and literature reviews.

3.4 Learning Experience for Students

As well as assisting the StrathAIS students to produce an initial design of their mission concept, the CE session itself was also intended to act as a training and learning activity. This is because practical-based learning has been shown to improve student engagement and outcomes [15]. In this sense, from participating in the CE session, the students were expected to gain industry-relevant knowledge and experience, thereby allowing them to climb further up Bloom's taxonomy [16].

However, the virtual dimension of the study added a new perspective to the traditional approach adopted within the CCDS. In this regard, whilst research by Swart indicates that distant-learning engineering students thrive in practical workshops [17], the system engineers found that maintaining adequate levels of participant interaction was a particular challenge for the virtual CE session in the absence of a physical CDF [12].

With that in mind, defining the benefits of the study as a learning experience for students is an important consideration to ensure that the students have not been adversely affected by the new constraints imposed upon them through the implementation of social distancing measures. For this reason, on completion of the study, the Director of the Aerospace Centre of Excellence evaluated the quality of the final mission design whilst a research survey was confidentially distributed to the students in order to gather their feedback. The findings have been used to benchmark the success of the study as a learning experience, whilst providing important information for continual improvement.

4. RESULTS & DISCUSSION

4.1 CONOPS Refinement

One of the critical design requirements for STRATHcube was a mission lifetime of at least 6 months. The Mission Analysis team had to determine whether the CubeSat could stay above re-entry altitude for this long without propulsion. This was achieved by performing a parametric study, varying the CubeSat's deployment conditions and BC, the latter being the most important factor in the orbit's decay. It was eventually found that, for the proposed orbit and range of BC, the spacecraft would indeed survive for the minimum lifetime.

However, the potential benefit of including a propulsion system to aid the mission lifetime was still to be evaluated. A propulsion study performed by the Mission Analysis team concluded that any feasible propulsion system could, at best, only extend the mission by 15 days. It was therefore decided to discard the possibility of using a propulsion system.

Mission Analysis also conducted a proximity study to check that the WPT experiment was feasible to perform. This experiment would take place between a range of 50 to 100 km away from the ISS. Depending on the final value of the BC, the spacecraft could stay within the 100 km proximity for a maximum of 3 weeks. This was deemed to make the WPT experiment feasible.

For the re-entry experiment, there were originally two possible mission objectives: obtain stagnation temperature data and observe the destruction of the spacecraft's solar panels at altitudes lower than 130 km, or to obtain stagnation properties and species information of the upper atmosphere between altitudes of 200 km and 120 km. The first of these would have required a 1U section of the CubeSat to house a large and delicate heat sensor. Due to the nature of its operation, this sensor would need a certain amount of attitude stability to provide correct readings. Unfortunately, the Attitude and Orbit Control System (AOCS) sub-team found no commercially available solution for re-entry stability to fit a CubeSat. Coupled with the communications antenna being required to be placed on the end of the same 1U section where the sensor would be housed (essentially blocking it), this led to the second option being chosen.

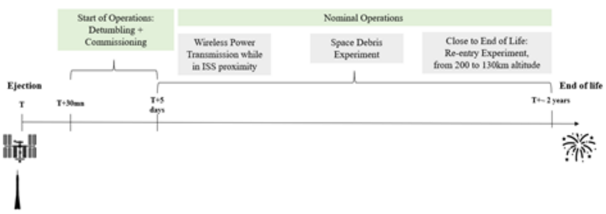

Figure 2: The refined CONOPS for the STRATHcube mission

Figure 2 above shows the refined CONOPS timeline for the STRATHcube mission. Studies performed during the session proved that even without propulsion, the mission could last up to 2 years, depending on the BC. Due to a lack of a propulsion system, the WPT experiment would be conducted first while the spacecraft is in the required proximity to the ISS. Then for most of the mission lifetime, the space debris tracking would be carried out. Finally, at end of life before demising, the upper atmosphere readings would be taken.

4.2 Trade-Off Analysis & System Results

The trade-off analysis found that, of the three shortlisted design options, only one would be feasible to continue with: Option 1, a passive 3U bus with an integrated 3D phase array antenna. This was due to the Mission Analysis team determining that a passive system would comply with the minimum lifetime requirements, as well as the conclusion that a compatible propulsion system would not significantly extend the lifetime of the mission. Discarding the propulsion options relieved the power budget, enabling the allocation of more of the mass budget to the re-entry (secondary) payloads and made the mission more cost realistic for a student project.

The final mass of STRATHcube, including system and subsystem margins, was 3776 g. This was 5.6% lower than the maximum for a standard 3U CubeSat, as is required for ESA: FYS. The mass evolution of each design option across all iterations is shown in Figure 3.

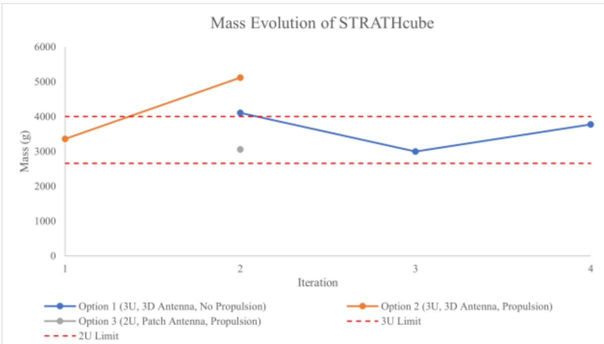

Figure 3: Mass Evolution of STRATHcube Design Options

Option 2 was found to rise significantly above the 3U mass limit after the second iteration was a key factor in its elimination as a potential design option. Option 3 was discarded after only one initial mass estimation given that having a 3D antenna was prioritised over a propulsion system. It can be seen that design Option 1 decreased 27% in mass from Iteration 2 to 3. This was due to an initial overestimation in the mass of the thermal system and a reduction in the solar array sizing based on the LCSA results. The mass of the system then rose again by 21%, largely due to a significant change in the configuration of the 3D antenna payload.

The final cost estimate for the satellite, including the appropriate margins, was £73,920. The largest associated costs were those of the deployable solar panels and ADCS system. Options 2 and 3, which both used a propulsion system, were costed at £202,660 and £172,454, respectively. As was the case for the mass budget of these two options, these costs were far greater than could be deemed feasible given the estimated budget of the student team. The estimated costs at the point that the designs were frozen are presented in Table 1.

Table 1: Design option budgets and their major cost elements

Design Option	Estimated Budget at NPV	Budget Distribution *(Values over 20% only)*
1	£73,920	**33.02%** Integrated ACDS System **26.46%** Deployable Solar Cell
2	£202,660	**40.08%** Micropropulsion system **32.66%** Deployable Solar Cell
3	£172,454	**47.10%** Micropropulsion system **38.38%** Deployable Solar Cell

In terms of LCSA, it was found that the environment is the most negatively affected sustainability dimension. This was primarily caused by mineral resource depletion from the extraction of Ge used as a substrate in the solar array, human toxicity caused by the dioxins released in the Ge substrate production and water consumption during turbine use in electricity production which is consumed during design stages, AIT and ground stations. As such, actions were taken during the CE study to lower these impacts, with a particular emphasis on reducing the mass of the solar arrays as much as possible. This resulted in the sustainability impacts of the final mission design becoming negligible across each impact category over its entire life cycle. In this regard, when comparing the overall life cycle sustainability impacts against other CCDS mission studies, on average, STRATHcube was the found to be the most sustainable CubeSat designed at the University of Strathclyde to date. Whilst the absolute results will remain confidential for now, the relative life cycle results can be seen in Figure 4 below.

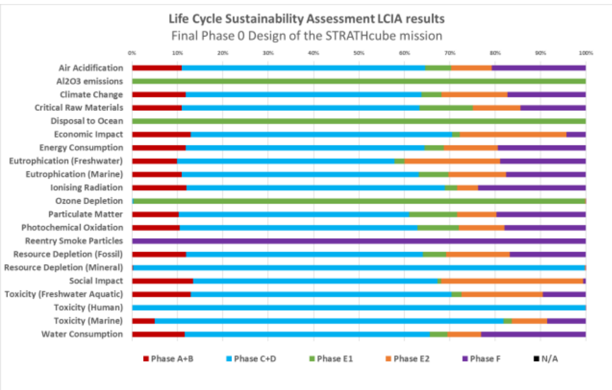

Figure 4: Relative LCSA results of the STRATHcube mission

4.3 Feedback & Research Survey Findings

In the evaluation of the final mission design quality, the Aerospace Centre of Excellence Director stated that he was very satisfied with the outcome of the STRATHcube study and commended the students on their tremendous work and the great results achieved. He concluded by stating that although the design completeness was not quite at the level typically achieved by industry or ESA, given that the majority of the team consisted of students with no previous experience or background skills in CE, the team produced a solid and sound design concept. Additionally, in his opinion, the study reached a very similar level of design completeness to previous Phase 0/A feasibility studies conducted within the CCDS. This indicates that the virtual nature of the study did not affect the overall design quality produced by the students.

Finally, the student research survey specifically asked students how the experience benefitted them and what they would recommend for future CE training and learning studies. The feedback revealed that all students had a positive experience and benefitted from their participation to some degree, with many citing that they had enjoyed the opportunity to work on a practical engineering project with support and guidance from PhD students and researchers. Other commonly cited benefits included increased levels of industry-relevant knowledge, the practical experience as an effective learning method for advancing professional development and skill enhancement, with particular reference to space system design, teamwork, communication, organisation and technical competencies. A word map of the key phrases from the feedback can be seen in Figure 5.

Figure 5: Word map of key phrases from the student feedback

In terms of recommendations, two main themes were derived from the student research surveys. The first related to communication. In this regard, it was felt that more must be done to compensate for communication difficulties in the absence of a physical CDF. This was because the students often felt disconnected or were reluctant to speak up. The second recommendation was for a longer period to be assigned for preparatory work prior to the CE study to allow for better efficiency from the first iteration. In particular, the respondents felt that the CDP4-CE had a steep learning curve and that the payload requirements were not fully defined before the design session began, which added uncertainty and reduced their understanding of the process as a whole.

5. EVALUATION & FUTURE WORK

5.1 STRATHcube mission

The original payload for the re-entry experiment was unfortunately not possible because suitable stability technology for CubeSats does not currently exist. Carrying this flaw through several design iterations was not ideal for the session as more time could have been used to further explore design for demise techniques. This reiterates the need for clearer, pre-agreed objectives and constraints for the payloads in short CE sessions. In the future, the team plans to use design for demise methods to provide simulated data to compare against the sensor readings.

Although Mission Analysis proved that the spacecraft could stay within the 100 km for approximately up to 3 weeks, it is still unclear what the real timeframe would be due to a lack of initial deployment conditions. More detailed information about the ISS' deployment mechanism is required to ascertain whether there is enough time to perform the WPT experiment at different distances as planned. To ensure that the future trajectory of the CubeSat is safe and not in danger of colliding with the ISS or any other major objects in LEO, higher fidelity models and simulations of the spacecraft's motion will need to be performed moving forward.

The open-ended nature of the initial goals of the study - in that the group did not know whether the CubeSat would be 1, 2 or 3U, or whether there would be any advantage in using a propulsion system - meant that conducting a trade-off analysis was critical. This method was also extremely effective in simultaneously not making the Phase 0/A study too prescriptive; whilst still focusing the efforts of the student team to consider only a shortlist of options. Eliminating certain options was based on the engineering judgement of the experienced systems engineers, emphasising the benefit of the team structure that was selected. Therefore, within any future STRATHcube CE session, it should be ensured that similarly experienced systems engineers are in place to advise on such matters.

As can be gathered from the fluctuation in the mass between successive iterations, the solution did not converge as is customarily desirable for a CE study. The largest changes in mass for the selected design option occurred in the payload, due to changes in its configuration late in the study. A recommendation, therefore, for future studies of a similar nature would be to have a primary payload that is more concrete in its definition from the outset. This would remove the uncertainty of potential changes which the payload design may have on other subsystems and the system as a whole.

It was found that using a propulsion system was extremely prohibitive from a cost perspective. Further work to reduce the cost of £73,920 includes evaluating the feasibility of manufacturing certain components in-house and finding more suitable alternatives. The costed components will also be checked for compatibility with one another by completing a comprehensive system architecture. This will likely involve contacting suppliers for further information and for quotations. Work is underway to potentially mitigate some aspects of the satellite cost by sourcing local partnerships with CubeSat manufacturers. Future STRATHcube CE studies will need to consider the potential further costs associated with the latter stages of development, namely testing, integrating, and launching the satellite.

Lastly, from a sustainability perspective, it is recommended that the use of Ge in the solar arrays is addressed as a priority if possible. This could be achieved by switching the solar arrays to a type which do not use Ge or by minimising the mass of the solar arrays as far as possible. Optimisation of the workload and electricity use consumption at each life cycle stage may also be investigated.

5.2 Concurrent Engineering for Student Learning

Overall, the STRATHcube CE study provided vital support to StrathAIS with regard to their student project, whilst also giving them a vital insight into the space systems design process. In this regard, the virtual dimension of the CE study did not appear to adversely affect the learning outcomes or student engagement based on the evaluation of the final mission design quality and the student research survey feedback. This reaffirms the findings of Swart, that distant-learning engineering students thrive in practical workshops [17], despite a reduction in participant interactions being identified in comparison to physical CE studies [12].

However, the student recommendations will be used to continually improve future CE sessions to further enhance student learning and produce mission concepts with a higher design completeness, closer to the level typically achieved by industry or ESA. In this regard, the system engineers will ensure that a more appropriate and user-friendly communication platform is used within future CE sessions whilst further actions will be taken to reinforce team cohesion. Additionally, although it will not be without its challenges due to the time commitment required by students for this extracurricular activity, potentially extending the study preparatory period beyond a few days will also be investigated.

6. CONCLUSION

A fully virtual CE session was successfully utilised to complete a Phase 0 feasibility study of the STRATHcube mission, a University of Strathclyde student CubeSat concept. It was determined after considering several options that the most suitable configuration for the satellite would be a passive 3U enclosure and a sophisticated primary payload. An initial design was completed for each subsystem such that all were compatible with the constraints associated with the selected design option. It could subsequently be concluded that the satellite would feasibly be able to meet most of the mission objectives initially specified. Crucially, the participating students were exposed to the virtues of CE first-hand, gaining invaluable experience whilst also advancing their own student project. This was reflected in the positive feedback garnered through a comprehensive research survey. Further work is already underway to complete a detailed design of the satellite and its subsystems. A second CE session is planned to complement the satellite's detailed design phase and will also consider how a build process could be achieved.

7. ACKNOWLEDGEMENTS

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8. ABBREVIATIONS AND ACRONYMS

AOCS	Attitude and Orbit Control System
ATD^3	AeroThermoDynamics & Design for Demise
BC	Ballistic Coefficient
CCDS	Concurrent & Collaborative Design Studio
CDF	Concurrent Design Facility
CDR	Critical Design Review
CE	Concurrent Engineering
COVID-19	Novel Coronavirus Disease 2019
CPD4-CE	Concurrent Design & Engineering Platform 4 – Community Edition
ESA	European Space Agency
FYS	Fly Your Satellite
ISS	International Space Station
LCSA	Life Cycle Sustainability Assessment
LEO	Low Earth Orbit
StrathAIS	Strathclyde Aerospace Innovation Society
STRATHcube	Space Debris Tracking, Re-entry Analysis and Wireless Power Transmission Student Partnership CubeSat
SSSD	Strathclyde Space Systems Database
TIC	Technology & Innovation Centre
TRL	Technology Readiness Level
WPT	Wireless Power Transmission

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