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DA VINCI SATELLITE – ELEVATING EDUCATION

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Abstract

The Da Vinci Satellite is a 2U CubeSatellite that is being developed with the goal to inspire and enthuse the youth to learn more about technology and space travel. The team at Delft University of Technology consists of over 80 Bachelor and Master students from disciplines such as Aerospace Engineering, Computer Science, Electrical Engineering and Applied Physics. There are also multiple Precision Engineers part of the team, that have joined from the Leiden Instrumenten Maker School (LIS) in the Netherlands. Through working on the satellite and educational modules, the multidisciplinary team focuses on demystifying space and making it a fun and engaging subject for children in primary schools and high schools. That is why the satellite harbours two novel custom-made payloads on board; the Dice Payload and the BitFlip Payload.

The Dice Payload consists of a small chamber with five small aluminium dice of different colours, which will be used by primary school children. In collaboration with the LIS, a special mechanism has been designed to ‘roll the dice’ in microgravity and clamp them such that a picture of the numbers can be taken with the Earth as a backdrop. After the design, manufacturing, and assembly of the parts, the payload underwent a series of tests. These tests have included multiple 0g flight tests and a vibration test. Through the extensive testing, there have been iterative design changes to improve the payload’s overall performance and design.

The second payload of the Da Vinci Satellite is the BitFlip Payload. This novel payload recently has been tested in a proton accelerator facility at the Paul Scherrer Institute. This subsystem is a stack of PCB’s with SRAM that has been designed for high school students. High school students can send a picture of themselves to the satellite where the data will be stored on the SRAMs. Because of the radiation environment in LEO and the susceptibility of the memory, bitflips will occur. These changes in the information from a 1 to a 0 (or the other way around), will result in the information of the picture being changed. When the picture has been compressed using a compression algorithm such as GIF, JPEG, or PNG interesting effects can occur. Once the student will receive the altered picture, they will be able to compare it with the original and learn about space, radiation, compression algorithms, and electronics.

Acronyms/Abbreviations

ADCS	Attitude Determination and Control System
COTS	Commercial Off-The-Shelf
DVS	Da Vinci Satellite
EPS	Electronic Power System
ESA	European Space Agency
FYS!	Fly Your Satellite!
LIS	Leiden Instrumenten Maker School
NLR	Royal Netherlands Aerospace Center
OBC	On-Board Computer
VSV	Vliegtuigbouwkundige Studievereniging

1. Introduction

In recent years, the development of CubeSats has been primarily driven by the need to reduce costs in the space industry. With their smaller mass, reduced volume, and standardized component sizes, CubeSats offer a streamlined, cost-effective approach to satellite development and deployment. These compact, modular satellites provide a unique opportunity to make space exploration more accessible to younger generations, serving as a conduit for fostering interest in space science and technology. The Da Vinci Satellite (DVS) [1], a 2U CubeSat currently under development at Delft University of Technology, demonstrates this potential by emphasizing the educational purpose, which represents a novel approach for CubeSat applications.

The primary aim of the Da Vinci Satellite project is to inspire and engage the next generation in fields such as technology, engineering, and space exploration. By assembling a multidisciplinary team comprising over 80 Bachelor and Master students from diverse disciplines, including Aerospace Engineering, Computer Science, Electrical Engineering, and Applied Physics alongside precision engineers from the Leiden Instrument Makers School (LIS), the project fosters an environment of collaboration and innovation. This team works collectively not only to design, build, and test the satellite, but also to develop comprehensive educational content aimed at making STEM subjects engaging and accessible for primary and high school students. This content includes books, videos, online learning platforms, and presentations, covering a wide range of topics beyond just space science. It focuses on various aspects of science and engineering, with the goal of inspiring students to pursue STEM fields while also educating them on critical issues like the effects of climate change.

The satellite features two innovative payloads, the Dice Payload and the BitFlip Payload, designed to offer hands-on educational experiences, allowing students to interact with real-world space phenomena. This paper provides a detailed examination of the Da Vinci Satellite project, with particular emphasis on the design, development, and testing of its custom payloads.

Beyond its educational purpose, the project has offered the development team critical insights into systems engineering, while highlighting the technical challenges associated with developing space-based technologies. The knowledge gained through the satellite's development underscores the complexities of space-related projects and can be beneficial to other student teams aiming to make use of CubeSats for education, research or other new applications. Finally, the experience gained from Fly Your Satellite! and the comparative design in CubeSat development are also discussed in this paper.

2. Da Vinci Satellite Mission

In 2019, the VSV 'Leonardo da Vinci', which is the study association of the Aerospace Engineering faculty at the Delft University of Technology, celebrated its 75^{th} anniversary. Established in 1945 and with approximately 2500 members, it aims to serve the interests of its members through their study and career phases [2].

Part of the anniversary was the creation of the Da Vinci Satellite project, which aims to contribute to the educational needs of children and students all around the world. The Da Vinci Satellite mission is to inspire and enthuse children and students through the development of an educational satellite, with additional educational content being developed in parallel.

As space has become an integral part of our daily lives, it has significant societal implications. This is why the Da Vinci Satellite project is teaching children about space from an early age onwards so they can become inspired and motivated to discover the world, including technology, societal challenges, global climate challenges and sustainability.

The educational modules developed by the DVS team will be accessible globally, free of charge, in multiple languages, and available both offline and online. These modules have undergone an extensive testing phase in collaboration with schools in Delft and Rotterdam as a crucial step for demonstrating their suitability for classroom use and ensuring they meet the needs of both students and teachers. Additionally, once the official DVS website is launched, it will provide a full online learning environment with interactive modules targeting high school and primary school students. Teachers will have access to the necessary tools and teaching materials directly through the website, as well as the ability to connect with the DVS education team for additional support.

Space is generally seen as a challenging subject to understand. The Da Vinci Satellite project aims to demystify space and provide insights into its multidisciplinary aspects, making engineering and STEM as a whole more accessible for the future generations. The goal is to demonstrate that these fields are not as daunting as they may seem, sparking curiosity and interest in STEM from an early age on, and equipping the young students with a foundational understanding of STEM subjects. This will empower them to confidently tackle complex challenges in their personal lives and upcoming academic careers, thereby preparing the next generation of problem solvers and innovators, all under the motto "*Elevating Education*."

3. Payloads of the Da Vinci Satellite

To actively engage students from primary and high schools, the CubeSat is equipped with two custom developed payloads; the Dice Payload and the BitFlip Payload. Both of these payloads can be seen in Fig. 1, with the

BitFlip Payload on the left and the Dice Payload on the right. The Dice Payload came to be after a nationwide competition in the Netherlands, where the team asked primary school students the question "What would you like to see/do in space?". One of the standout answers was, "Play a game!". Inspired by the idea, the team collaborated with the Leidse Instrumentmakers School (LIS) in Leiden to bring this vision to life, which resulted in the Dice Payload. This payload consists of a special mechanism that is able to throw five dice in microgravity. The system then clamps the dice and takes a picture of the numbers on the dice with the Earth in the background.

The second payload, known as the BitFlip Payload, was specifically designed to engage high school students in an interactive and educational space experiment. This payload allows students to send their own photographs to the Da Vinci Satellite, where the images are exposed to the space environment, particularly the elevated levels of radiation. Due to the high radiation, bitflips (changes in the digital data) will occur, altering the images. After a designated period, the students receive their altered photographs and can compare them to the originals, providing a hands-on opportunity to learn about the effects of radiation, electronics, space, and programming.

Both payloads are designed to inspire children of various ages, helping them realize that the topic of space can be something for them as well. This is intentionally done in a way that is accessible, engaging, and enjoyable. In addition to participating in a personalized or entertaining space experiment, students can also deepen their understanding of space history and science through the website and educational modules that the Da Vinci Satellite team is developing in parallel with the satellite.

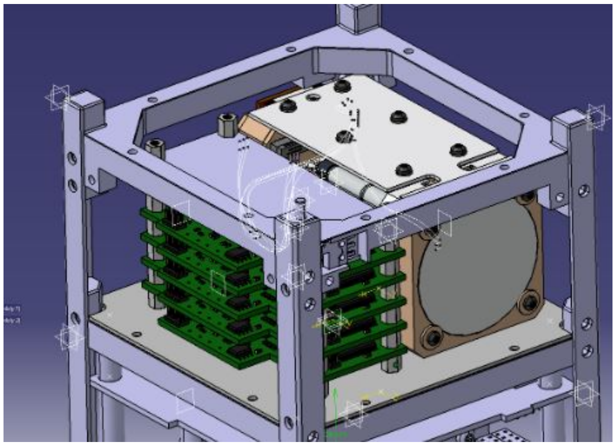

Fig. 1. The two payloads of the Da Vinci Satellite, BitFlip Payload(left) and Dice Payload(right)

3.1 Functional Architecture Dice Payload

The Dice Payload that can be seen in Fig. 2 and Fig. 3 is controlled by an Arduino Pro Mini. This Arduino is in turn controlled by the OBC, which will communicate with the Arduino using I2C. The Dice Payload uses two sets of two motors. The first set is used to move the slider, and this way, clamps the dice in between two glass windows. The second set is used to spin the sweeper that prevents the dice from stacking during clamping and to later give the dice momentum and this way throw the dice. Because the Arduino is not able to provide enough power to these motors it is connected with a motor driver that is able to manage the two different groups of motors individually. Another job of the Arduino is switching on the LED's and making sure they have the right light intensity to see the dice and to counter for example the albedo effect. There is a special small camera with autofocus that is connected to the OBC which is able to take pictures of the clamped dice. The five dice of the Dice Payload all are anodized to have a different colour that has been carefully picked out such that colour blind children are also able to distinguish the different dice.

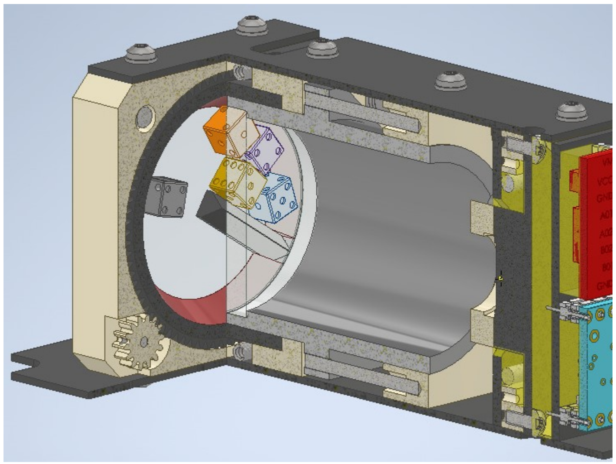

Fig. 2. Render of Dice Payload

In general the Dice Payload makes use of two mechanical sub-parts; namely the slider and the sweeper mechanism. The slider mechanism uses two DC motors and two spindles to move the slider forward. Within the slider one of the optical windows is glued using space grade epoxy. By moving this slider forward the dice are clamped in between the two optic windows and this way a clear picture can be taken where the amount of eyes on the dice can be easily seen. The second mechanism is the sweeper mechanism that uses DC two motors with two smaller gears to turn the sweeper. This sweeper makes sure that during clamping no two dice are stacked on each other as this would be non desirable for both the motor and the picture that is being taken. Once the optical windows move away from each other and the dice are released the sweeper mechanism is now used to spin around and by doing so give the dice a certain momentum. This way the dice get a random motion and the dice are 'thrown'.

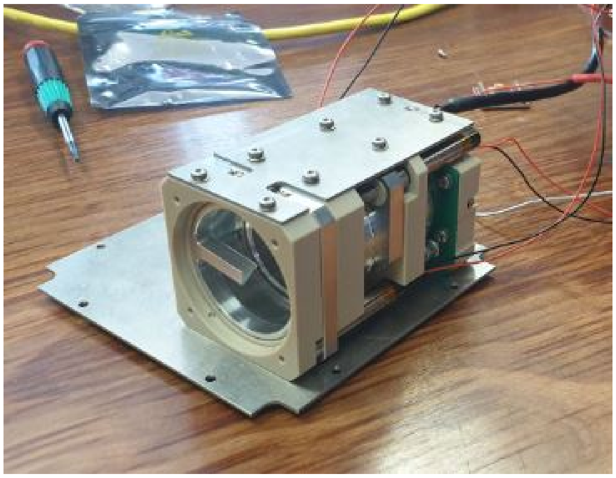

Fig. 3. The assembled Dice Payload, picture taken before iterations from the 0g flight test

To play a game with our satellite the Dice Payload uses a game cycle that is divided into three steps. Roughly the goal is to make sure that the dice are clamped, the picture can be taken and that the dice are 'thrown' again.

Game cycle in three steps:

1. When the Arduino gets the signal from the OBC, the motors will make the slider move forward. This way the freely moving dice in micro gravity will be clamped in between the two optic windows(pieces of glass). At the same time another set of motors will make the 'sweeper' spin around in such a manner that it collects all the dice, and makes sure they are not stacked.
2. The LED's will light up with the desired light intensity. Next the OBC sends a signal to the camera that will take a picture of the clamped dice. This picture will be sent to the OBC where it will be stored for the time being.
3. In the last phase the two optic windows will again move away from each other and the sweeper will rotate to give the dice a certain random motion and this way 'throw' the dice.

3.2 Functional Architecture of the BitFlip Payload

In total there are 5 PCB's that will be connected via a daisy chain that will together form the BitFlip Payload. The Data of the pictures will be stored on the 3 SRAM chips CY62167EV30LL) on every board that will go via the ARM-microcontroller Cortex-M4 (STM32L471RGTx). The size of the BitFlip payload is 40.5 X 75 X 45 mm with 48 Mbit per board, so 30 MBytes in total.

When someone uploads a picture to our website to be sent to the BitFlip Payload, this file will first be compressed using the desired compression algorithm. The metadata will be saved by us but will be excluded from the data that will be sent to the Da Vinci Satellite since a bit flip in this data will just result in something that can not be displayed. Once the data has been picked up by our satellite a copy will be saved on the OBC (On Board Computer) it will also be saved on the SRAM of the BitFlip Payload. This SRAM is not radiation hardened, such that the data is exposed to space radiation and bitflips can occur. Once a specific experiment has been performed (for example keeping the picture stored on the payload for different amounts of time) the corrupted picture will be compared with original version. Only information about flipped bits will be sent down back again so we use limited space in the downlink data budget. Back on earth the information about the flipped bits will be superimposed on the original picture (that also again includes the metadata). Now the person will be able to visually compare their original with the bit flipped picture. The engineering model of the BitFlip Payload is shown in Fig. 4.

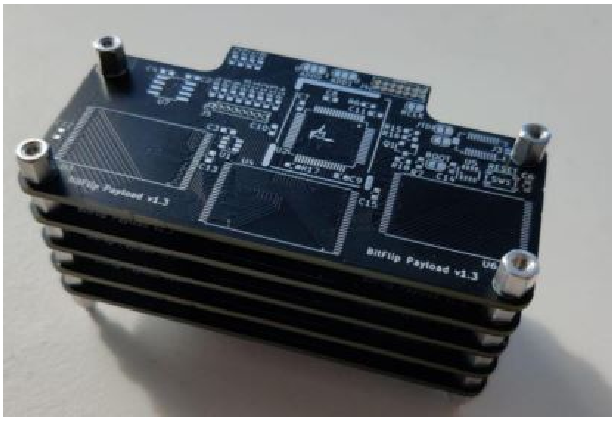

Fig. 4. Engineering model of the BitFlip Payload

3.3 Testing of the Payloads

As both payloads of the Da Vinci Satellite are custom-designed and built subsystems, thorough testing is essential to assess their responses under various conditions. Specifically, it is critical to evaluate how these payloads will perform in the unique environments of the launch and space. Key tests include the vibration test to simulate the launch environment, the 0g tests to assess the Dice Payload's functionality in a microgravity environment, and the radiation test to predict the occurrence of bit flips in the Bitflip Payload under space radiation.

In the sections below, a general overview of these tests and the corresponding results will be presented.

3.3.1 0g Tests - Dice Payload

The Dice Payload is a custom made payload that will function in a reduced gravity environment in space. The whole idea of the Dice Payload is that children are able to 'play a game in space' with 5 dice that are floating in microgravity that can be randomnised and clamped to take a picture of the numbers on the dice. To verify the functionality of the mechanism responsible for "throwing" (randomizing) and clamping the dice, testing in a microgravity-simulating environment is required. For this purpose, a 0g flight test was conducted.

During a 0g flight, an aircraft performs parabolic maneuvers, creating brief periods of microgravity, in the case of the conducted test, approximately 10 seconds per parabola. In the initial 0g flight test, 15 testruns were performed to evaluate the Dice Payload's mechanisms. TThere were two goals during the tests: to determine the optimal operating speeds for the mechanism's movement to clamp the dice, and to assess the spindle's rotation speed necessary to provide sufficient momentum to randomize the dice.

The test came out to be extremely useful, as the team found an unexpected design flaw. The spindle, designed to randomize the dice and prevent stacking during clamping, was instead contributing to the stacking of dice. This issue, as shown in image Fig. 5, resulted in one of the dice being positioned on the sweeping mechanism (left), preventing the sled from moving fully forward and causing an improper clamping configuration compared to a correct clamp (right).

Fig. 5. Pictures taken during the 0g flight test of stacked dice(left) and a successful clamp(right)

Following the 0g flight test, the payload team reviewed the test footage in detail and identified two critical weak points in the sweeper design: the large flat surface at the base of the sweeper arm and the flat edge on the sweeping side. The large surface area at the base allowed dice to land and stack, particularly due to the run-out radii from the milling process located there.

To prevent stacks and mitigate these issues, two solutions have been devised that the team continued to test with:

- Adjusting the geometry of the sweeper:
  The upper surface of the sweeper arm was reduced, and the floating surface was angled at approximately 55°. This reduction minimizes the landing area for the dice, decreasing the likelihood of stacking. The angled surface ensures that if a die lands on the arm, it will slide off due to the combination of the arm's movement and the surface incline, preventing obstruction.
- Manufacturing the sweeper arm separately from the drum:
  By manufacturing the sweeper arm as a separate component from the drum, greater flexibility in shaping the arm was achieved. This allowed for the removal of radii in the corners, significantly reducing the size of the upper surface and further minimizing stacking potential.

Both problem areas where design modifications were performed are illustrated in image Fig. 6. A second, smaller 0g flight test was conducted to validate these changes, leading to the final new design of the sweeper mechanism that can be seen in Fig. 7 . Another additional change was the implementation of 4 stop switches mounted on the sides of the Dice Payload to sense if there are stacked dice as the slider mechanism would in that case not be fully moved forward.

3.3.2 Vibration Test - Dice Payload

To ensure a satellite's survivability during launch, it must withstand significant vibrations and shocks. These forces are particularly critical for custom payloads like the

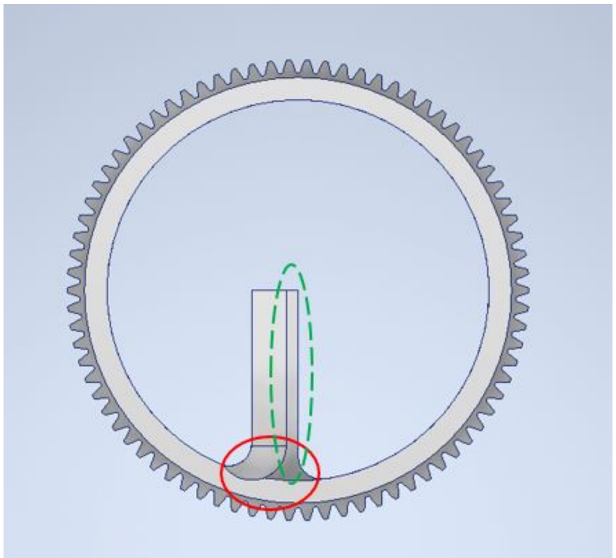

Fig. 6. Problem areas as identified in the 0g flight test, manufacturing radius(red circle) and upper surface(green dashed circle)

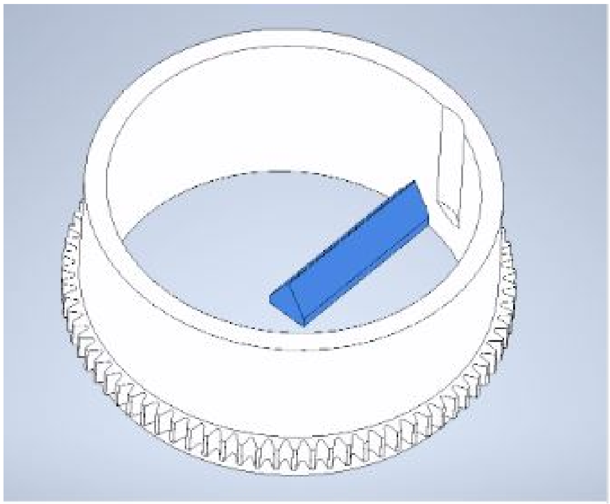

Fig. 7. The redesign of the sweeper mechanism of the Dice Payload

Da Vinci Satellite's Dice Payload, which contains loose components (dice). To evaluate the payload's ability to endure these conditions, a vibration test was conducted to simulate the launch environment.

The team performed the vibration test in 2023 at the Royal Netherlands Aerospace Center (NLR) in Marknesse. For this, a custom fixture was fabricated to securely mount the payload onto the shaker table. Pre-test checks were performed to ensure all systems were functioning as expected and sensors were placed at key locations on the payload to capture relevant data during testing.

The Dice Payload was tested along three axes (X, Y, and Z) using two methods: random vibration testing and sine vibration testing. In the random vibration test, the shaker table vibrated at multiple frequencies, closely simulating the dynamic environment of a rocket launch. Random vibration testing is considered one of the most accurate methods for replicating the conditions experienced during launch. Sine vibration testing was also conducted to evaluate the effects of resonance conditions. In this test, the table vibrated with progressively smaller movements, simulating resonance buildup and decay.

After each axis test, a performance test was conducted to verify the functionality of the payload's clamping and throwing mechanism. This test involved a full operational cycle of the Dice Payload, in which the dice were thrown and then clamped again. These performance tests ensured that the payload remained operational and that no components were hindered by the vibrations experienced during testing.

Following a full day of testing across all axes, the Dice Payload successfully passed both vibration and performance tests. Which marked an important milestone in validating the payload's readiness for spaceflight.

3.3.3 Radiation Test - BitFlip Payload

The main goal of the BitFlip Payload is to help educate students in the Netherlands and all around the world about space and let them interact with it in a playful manner. The engagement occurs via the payload, providing students with the opportunity to observe images they send into space undergo distortion due to bitflips induced by space radiation. As a payload meant for space, our primary objective during the radiation test of the BitFlip Payload was to make sure that the basic feature of the payload would work in space. This meant putting the payload into a radiative environment and make sure that our payload could detect occurring bit flips in its memory and report those bit flips to an on-board computer. This would also help us find any flaws in our system and make any necessary improvements. The second objective of the payload test was to better characterize the memory chips, consisting of SRAMs, to better simulate the bitflips expected in orbit. This could be done by finding the cross-section of the chip, using the spectra of the planned orbit, and third party softwares to determine the expected rate of bit flips for our mission. A third objective was to evaluate the behavior of the payload in both static and dynamic states, comparing the system's response when actively reading data versus when in a rest state.

The radiation test was conducted at the Proton Irradiation Facility at the Paul Scherrer Institute, with support from the RADNEXT program. The PIF utilizes a proton beam with energy degraders to produce a controlled mono-energetic beam, directed at a single board from the Bit-Flip Payload, which will eventually comprise at least five stacked boards, each containing three SRAMs. To achieve the characterization objective, a collimator was used to focus the beam on a specific SRAM chip. The board was mounted on an XY frame, oriented perpendicular to the proton beam, enabling targeted irradiation of different chips without needing to reposition the payload. During static testing, the SRAMs were loaded with a specific bit map and read only after irradiation under controlled conditions (time, flux, and energy). For the dynamic tests, the entire board was irradiated, simulating conditions more closely resembling those encountered in space. This approach allowed for observation of how the payload might fail under mission conditions and how recovery from such failures might be managed. A collimator was used to irradiate the entire board, including the nearby STM32 processor, which controls read/write operations on the SRAM and could also be affected by radiation.

In total, 43 tests were conducted over two days. Of these, 22 tests involved static irradiation of individual chips, while 21 tests involved dynamic irradiation of the entire board. The static tests resulted in 15 successful detections of bit flips, while seven runs failed due to errors, leading to data loss. For the dynamic tests, 13 runs yielded bit flip data, while eight experienced errors. During the dynamic tests, a significant increase in single-event upsets (SEUs) was observed, with more than 100 bit flips occurring at once during data reads, compared to the 1–2 bit flips typically observed over a 3–5 second interval. This unexpected behavior led to uncertainty about whether the bit flips affected neighboring memory locations or were distributed randomly across the chip. Further analysis is required to determine whether this behavior is related to the density of traces, which could cause current to jump between traces, triggering unintended write actions.

With respect to the primary objective, the test successfully demonstrated the payload's ability to report bit flips in its memory, despite some runs failing to produce bit flip readouts. These failures provided valuable insights for improving the payload's robustness, leading to both design modifications and adjustments in data handling protocols. Regarding the characterization of the SRAM, the results remain inconclusive, and the cross-section versus linear energy transfer (LET) for the chip has not yet been accurately determined. Preliminary findings suggest an increased frequency of bit flips in the MeV range, though further analysis is required to confirm these observations quantitatively. The ongoing investigation is expected to facilitate the development of a simulation model for the payload using software such as SPENVIS and OMERE. This model aims to improve predictions regarding the occurrence, location, and quantity of bit flips during the mission. Notably, the experiment revealed significant differences in the behavior of the payload between static and dynamic configurations, enhancing understanding of its performance in space. Efforts are ongoing to investigate these variations and explore potential strategies for mitigation or operational use.

4. Fly Your Satellite! - 4th Edition

As of March 2024, the Da Vinci Satellite team is participating in the fourth iteration of ESA Education's Fly Your Satellite! (FYS!) programme. This programme is the result of a close collaboration between ESA and universities from ESA Member States, Canada, Latvia, Lithuania, Slovakia and Slovenia. It is targeted towards university student teams, based in ESA member states and cooperating states, who are developing CubeSats or PocketQubes. Throughout the programme, the participating students are guided through the typical space mission development cycle by ESA experts, offering students the unique opportunity to gain practical experience in a real space project from cradle to grave.

The following chapter will explain the motivation of the DVS team to participate in the entry contest for the FYS! programme and describe the application and selection process. Thereafter, the current state of the project within the FYS! timeline will be illustrated.

4.1 Motivation for the Application

The main motivation for participating in the Fly Your Satellite! programme is to learn from the expertise and insights of ESA specialists. With the satellite nearing integration and the project entering the very critical Assembly, Integration, and Verification phase, implementing standard practices for spacecraft development and receiving support from experts will greatly help with ensuring that the Da Vinci Satellite project is successful. Next to that, it is an amazing opportunity for the students of the team to learn the working methods adopted in professional space programmes and develop professional skills that will prepare them well for a career in the space industry. Participation of DVS in the Fly Your Satellite! programme constitutes a substantial infusion of knowledge and technical expertise from ESA experts to current and future members of the student team.

Next to the knowledge and support of ESA professionals, the team is seeking support during the testing campaign. The Dice Payload had already undergone successful zero-gravity and vibration tests, and the functionality of the BitFlip Payload was shown through the radiation test. With preparations for the environmental test campaign intensifying while the project advances, the team will benefit greatly from the access to test facilities and support for the upcoming vibration and thermal-vacuum test.

The last thing that the team looks forward to is a launch opportunity when the satellite meets all requirements to be accepted for launch. While the team was already looking into launch providers on its own, ESA will support the DVS team greatly, by acquiring a launch opportunity.

4.2 Application and Selection Process

As part of the deliverables required in order to apply for a spot in the FYS! programme all candidates must provide an extensive proposal document. The proposal documentation created by the DaVinci Satellite team covers:

- The high-level description of the mission, including mission objectives, Concept of Operations and an explanation of how the data from the satellite will be used in the educational programme of Da Vinci Satellite project, benefiting university, high-school and elementary school students alike.
- Design definition and justification for the whole satellite, its subsystems, and Ground Segment, as well as all analyses and simulations performed in support of the engineering decisions and trade-offs taken by the team up to that point.
- Status of Assembly, Integration and Verification activities, including the planned verification approach and model philosophy.
- Information on the overall project organization, including team composition, project schedule, interfaces with external partners, a budget breakdown, and major technical and managerial risks.
- Comprehensive list of Technical Requirements developed by the DVS team and an assessment of the level of compliance with technical requirements stipulated by the ESA Fly Your Satellite! Team, presented in form of a compliance matrix.

4.3 Progress of the Project with regards to FYS!

The project timeline within Fly Your Satellite! resembles the mission phases common in real space projects. The ESA mission phases and their main objectives are briefly described in Table 1. As mentioned, the FYS! programme focuses on supporting student teams through assembly, integration and testing, launch and operations, as well as disposal of the satellite. This corresponds to the project phases D, E and F.

Table 1. ESA mission lifetime cycle

Mission Phase	**Description**
Phase 0	Concept Study and Mission Definition
Phase A	Mission Feasibility and Project Planning
Phase B	Preliminary Design Definition
Phase C	Detailed Design Definition
Phase D	Qualification and Production
Phase E	Operation
Phase F	Disposal

4.3.1 Previous Mission Phases of DVS

In the development cycle of the Da Vinci Satellite, Phase 0 was performed by a team of bachelor students as part of the final graduation group project in the frame of the aerospace engineering study programme. Additionally, the team organized a competition for primary school students, inviting them to design satellite payloads based on their interests. This led to the creation of the dice payload concept. Phase 0 ended in Summer 2018 with the final review of the graduation project.

In early 2019, phase A was initiated, which marks the official beginning of the DVS as a student team. Next to the efforts proving the mission feasible and creating a technical development timeline, a lot of effort also went into setting up the educational programmes for primary and high school student.

Later that year, the project has transitioned into phase B, with both the design of the satellite and the educational programme being developed by the students, as well as an active business and communications team organizing regular meeting with the project stakeholders and engaging with primary school and high school teachers.

With the Detailed Design Kick-off in late 2020 and the Preliminary Design Review in summer 2021, the project officially entered phase C. With the two payloads being developed in-house, a focus was put on refining and finalizing the payload design during phase C. To this end, the design iterations have been supported by multiple development tests, for example zero-g flight tests for the dice payload, testing the functionality of the mechanisms in microgravity conditions, or the radiation testing of the BitFlip Payload, as described in 3.3. At this point, preparation began for the next big milestone, system integration and testing, starting with functional testing of software drivers. Additionally, the flight hardware was procured. The application for the FYS! programme was done in the final stages of phase C. With admission into FYS!, DVS is now preparing to enter the next phase of the satellite development life cycle together with ESA.

4.3.2 ESA FYS! Timeline

The Fly Your Satellite! programme is structured similarly to the ESA mission phases but is tailored to meet the educational goals of university student teams [3]. The programme phases correspond to the standard project phases D and E, covering satellite assembly, integration, testing, launch, and operation. The timeline is influenced by various factors such as team performance, mission complexity, and available launch opportunities. Below is an overview of the project phases as they align with our CubeSat mission development.

Phase D1: Build Your Satellite! This phase, with a duration ranging between 0.5 to 1.5 years, began following the successful selection of our team into the FYS! programme. For our team, the phase kicked off with our participation in a Training Workshop with other Fly Your Satellite! student teams at the ESA ESEC Galaxia site. Next to very informative lectures about the typical AIV process and test campaign of a CubeSat, we performed a run-through of actual thermal vacuum and and vibration tests at the CubeSat Support Facilities. Because the tests were performed on dummy payloads, not the actual satellite, this experience allowed us to make mistakes and learn from them, so that we can prepare better for the actual test campaign. The first major milestone is the so called Kick Off Review, during which all aspects of the design of our mission will be examined by ESA experts in the frame of an official review process. The reviews serve to consolidate our CubeSat Design Definition and Justifications, as well as our Assembly, Integration, and Verification (AIV) plan. During this phase, we are responsible for the manufacturing, assembly, and integration of the CubeSat. The satellite will undergo thorough inspections to verify compliance with dimensional and physical requirements. Functional tests will be performed covering all operational modes. A special focus is given to FlatSat testing, with the purpose of verifying that all the interfaces between the satellite subsystems and components are compatible and can communicate among each other. The phase concludes with a Functional Test Review (FTR) which will serve as a critical milestone for transitioning to the environmental testing phase.

Phase D2: Test Your Satellite! Following the completion of Phase D1, the project enters Phase D2, which typically lasts 0.5 to 1 year. During this phase, we will perform environmental testing on our satellite, including vibration and thermal vacuum tests, in ESA's facilities at ESEC Galaxia. These tests aim to confirm that the satellite can withstand the conditions of launch and space environments. By the end of this phase, we aim to pass the Flight Acceptance Review (FAR), a key milestone to ensure the satellite is ready for launch. During this process, all results from the environmental test campaign, compliance with regulations and preparations for launch are reviewed. Successfully completing this review will grant us access to the next stage of the FYS! programme, leading us toward the launch opportunity.

Phase E1: Launch Your Satellite! The next phase, which spans 3 to 6 months, involves all necessary preparations for the launch. During this phase, ESA will offer our team a launch opportunity. Our tasks include delivering the flight hardware, integrating the satellite into orbital deployers, and performing any additional integrated tests required by the launch provider. At the conclusion of Phase E1, the satellite will be launched into orbit, marking the completion of this phase.

Phase E2: Operate Your Satellite! After the satellite is deployed in orbit, Phase E2 begins. This phase focuses on satellite operations, during which we will operate our CubeSat from the TU Delft ground station, collect mission data, and analyze the results. The phase concludes with a Post-Flight Review and Lessons Learned workshop, where we will present our findings and experiences to ESA and other participating teams.

5. Comparative Design in CubeSat Development

Student teams face unique challenges in CubeSat development due to limited resources and expertise. This chapter compares the component-driven design approach taken by student teams, like Da Vinci Satellite, with the more requirements-driven approach used by industry and explores how student teams adapt their systems engineering strategies through creative problem-solving, outsourcing, and efficient testing procedures.

5.1 Component-Driven Design

Industry projects have the financial flexibility to select components based on strict mission requirements. This selection process involves rigorous trade studies, lengthy supplier evaluations, and the development of custom (in-house) subsystems. Companies sometimes produce up to 80% of their subsystems in-house [4], creating tight control over the quality, design and reliability of their CubeSats. This ensures that the components are tailored to meet precise mission requirements and helps maintain high standards of reliability.

In contrast, student teams often lack the technical expertise and facilities to design complex subsystems in-house, necessitating a reliance on outsourcing and commercial off-the-shelf (COTS) components from sponsorships, donations, or affordable purchases. For example, companies like ISISpace, Hyperion, and Eurocircuits provide specialized subsystems such as power systems, communication systems, and PCBs. Outsourcing gives student teams access to advanced technologies that would otherwise be hard to develop themselves, but they also lose some of the customization options and detailed control that comes with in-house development.

While some components, like the payloads and databoards, are custom-made for the mission, other subsystems do not exactly fit the CubeSat's specific needs. For example, the team's Attitude Determination and Control System (ADCS) exceeds the mission's requirements, which at first seems beneficial but introduces disadvantages such as increased power consumption and volume. The team in turn works around these disadvantages by minimising the ADCS usage, since our pointing requirements are low, thereby sparing power. Similarly, DVS initially opted for an Electrical Power System (EPS) Type A [5], because of an offer ISISpace made. But due to the offer being early in the development cycle, the predicted power consumption that was not completely accurate to the actual power consumption. This means that only a little amount data can be downlinked without exceeding the recommended limit on the Depth of Discharge of the batteries, which would in turn decrease the satellite's lifetime due to battery degradation. Operation of the Dice and BitFlip Payload results in a lot of data throughput due to the amount of pictures that will be sent, so DVS is looking into upgrading to the EPS Type B and thus carrying a battery pack with 4 Li-ion cells instead of only 2. This gives us the opportunity to downlink more data, which means more payload interaction for the high school and primary school students, as well as an increased lifespan. This change of EPS however changes the Mass Moment of Inertia (MMOI) of the CubeSat, necessitating a change in stacking of subsystems and another structural review.

This highlights the financial constraints and adaptability required when student teams follow the component-driven design while still trying to tailor the subsystems as good as possible to the mission's need. At the same time, students learn how to communicate technical specifications with vendors, manage supplier relationships, and deal with the complexities of integrating outsourced components into the overall system.

5.2 Testing Procedures

Due to budget and time constraints, student teams must also adopt shorter and more efficient testing procedures compared to the rigorous testing phases employed by industry teams. While industry projects have the resources for extensive validation and testing, student teams prefer to focus on quick, targeted iterations. These iterations help teams rapidly gain insights into the performance of their CubeSat systems while adhering to tight deadlines.

The Assembly, Integration, and Verification (AIV) process, for example, involves fast-paced, hands-on learning, with students working to validate their designs as efficiently as possible. Since resources for professional-grade testing facilities are often limited, students often design DIY setups, or leverage partnerships with external labs. This process allows students to gain valuable experience in testing protocols, environmental simulations, and verification procedures, even if their resources are limited compared to industry projects.

Testing is more than just validation, it is a critical learning opportunity. Not only does it ensure that the CubeSat systems function as expected, but it also provides hands-on experience with the kind of testing protocols used in industry. Students learn about the importance of planning, conducting tests with precision, and interpreting test results to refine their designs. This hands-on experience helps bridge the gap between educational CubeSat projects and professional industry practices.

6. Conclusion

In conclusion, the development of the Da Vinci Satellite has been an incredible learning experience, highlighting the unique challenges faced by student teams in CubeSat projects. The project has provided valuable insights into systems engineering, particularly through a component-driven approach that required the creative integration of commercial off-the-shelf (COTS) in contrast to the industry standard, which is the requirements-driven approach.

Despite the challenges of limited in-house capabilities, the team has successfully designed, built, and tested two unique educational payloads, the Dice Payload and the BitFlip Payload. The Dice Payload is designed to allow primary school students to engage in a microgravity dice-rolling experiment, taking images of the dice with Earth as a background. The BitFlip Payload, intended for high school students, demonstrates the effects of space radiation on data stored in SRAM chips, turning digital bit flips into an educational tool about radiation and electronics. Both payloads have undergone extensive testing, including zero-gravity and vibration tests for the Dice Payload and radiation testing for the BitFlip Payload, to validate the design and ensure mission readiness.

Participation in the ESA Fly Your Satellite! program has further enriched the team's experience by providing access to professional guidance and test facilities, helping ensure that the satellite meets the high standards required for space missions. Da Vinci Satellite is currently at Phase D2: Test Your Satellite!, where we are looking forward to performing the environmental tests, including vibration and thermal-vacuum tests, to simulate launch and space conditions.

The Da Vinci Satellite project not only demonstrates the technical capabilities of our student team but also emphasizes the educational impact of the mission, aimed at demystifying space, not only for Dutch primary and high school students, but for students around the world. With launch preparations well underway, we look forward to seeing our satellite reach orbit and fulfill its mission to engage and educate the next generation of space enthusiasts.

Disclaimer

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The views expressed herein by the authors can in no way be taken to reflect the official opinion of the European Space Agency.

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