Modular Horizons: Open-Source Innovation in CubeSat Design with the VIBES Project

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***Abstract*—The VIBES satellite research program of the City University of Applied Sciences Bremen aims at bringing the consumer electronics revolution to space to improve the performance of spacecraft. The paper "Modular Horizons: Open-Source Innovation in CubeSat Design with the VIBES Program" explores possibilities for creating CubeSat architectures using modular units applicable to standard sizes ranging from 1U to 12U and beyond. While a 1U configuration includes essential subsystems such as power distribution, a battery board, and an Onboard Computer (OBC), larger variants like 12U can accommodate additional components such as advanced Attitude Determination and Control System (ADCS), orbit-keeping systems, and payloads. The use of unified and standardized core elements enables a flexible, scalable, and sustainable approach to CubeSat development. By developing this architecture as an open-source project, the technology can be used by other CubeSat developers and is planned to be implemented in future VIBES spacecraft.**

***Index Terms*—satellite, research, consumer electronics, modular, design, cubesat, subsystem, scalable, open-source, spacecraft**

I. Introduction

THE research program Visionary Ingenuity Boosting European Spacecraft (VIBES) aims to improve the performance of satellites with modern technologies by using efficient and powerful components as they are used in smartphones and making them applicable for spaceflight. The program envisages the development, launch, and operation of multiple spacecraft to display the quality of the developed technologies. The program is focused on enabling an environment for hands-on learning and establishing a knowledge base on how spacecraft are developed, built, verified, launched, and operated.

Since Bremen has a strong local aerospace industry, VIBES is making use of it and promoting cooperation. VIBES is a program of the Institute of Aerospace Technology (IAT) of the City University of Applied Sciences Bremen (HSB) and was established by Prof. Dr. Antonio García in 2021. Currently, the VIBES team, consisting of students and researchers of the IAT, is working on their first spacecraft called VIBES Pioneer [1].

A. VIBES Pioneer Mission

VIBES Pioneer is a 3U CubeSat that carries a camera and a new type of measurement system as its primary payload. The measurement system was developed by the VIBES team using MEMS sensors (micro-electromechanical systems) from the automotive industry to detect perturbations emitted by moving parts of a spacecraft. By analyzing the data gathered with this Microvibration Measurement System (MVMS), image data can be optimized and the operation modes of the spacecraft adjusted.

As a secondary mission objective, VIBES Pioneer utilizes a software-defined radio developed at the IAT for increased communication capabilities.

VIBES Pioneer will launch into a 500 km sun-synchronous orbit on the second flight of Rocket Factory Augsburg's RFA ONE, a launch opportunity that was granted to the VIBES team by the German Space Agency.

Building on the technological foundation and lessons learned from the VIBES Pioneer mission, the next phase of the program seeks to not only advance satellite performance but also to optimize how such systems are designed and assembled. One promising approach in this direction is the adoption of modular architectures.

This paper will explore the possibility and benefits of the development of a modular configuration, with a view to implementation on future VIBES missions. The idea for the design of the modular system for CubeSats and for the provision of 3D files for the construction of the CubeSats in CAD (computer-aided design) software with the help of an open-source platform is based on a modular system built on aluminum profiles. Various profile sizes and corresponding components allow for the realization of a wide range of projects. In a similar way, it should be possible to select a CubeSat size, e.g., 2U, and filter all the components that can be used for the specific CubeSat size. The provision of 3D data, construction plans, circuit diagrams, and documentation is intended to simplify the construction of CubeSats.

B. VIBES' Mechanical Interface

The CubeSat is iteratively developed by implementing three functional structural thermal models (STMs) with a different degree of functionality. The final version (V3) is the most detailed version and represents the flight model in terms of the structure.

The primary structure consists of two identical side frames, top and bottom plates, four identical ribs, and four threaded mounting rods. Together with the side frames, the bottom and top plates as well as the ribs define the basic structure, as shown in figure 2. The side frames are attached to the ribs and the top and bottom plates. In addition, the top and bottom plates fixate the mounting rods. These serve as an interface between the printed circuit boards (PCBs) and the structure. Spacers are utilized as a mechanical interface to stack the PCBs and create a bus system. The spacers wrap around the PCBs as well to establish and preserve their spacing from one another. Four wall panels, as well as the top and the bottom panel, seal the satellite and protect the satellite's internal components: they unfold, as shown in figure 1, to deploy the solar arrays.

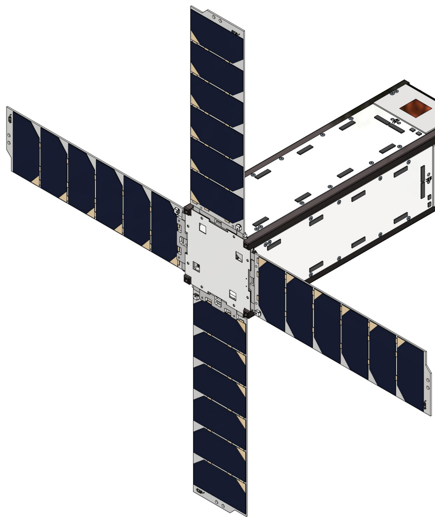

Fig. 1. VIBES Pioneer in Unfolded Configuration.

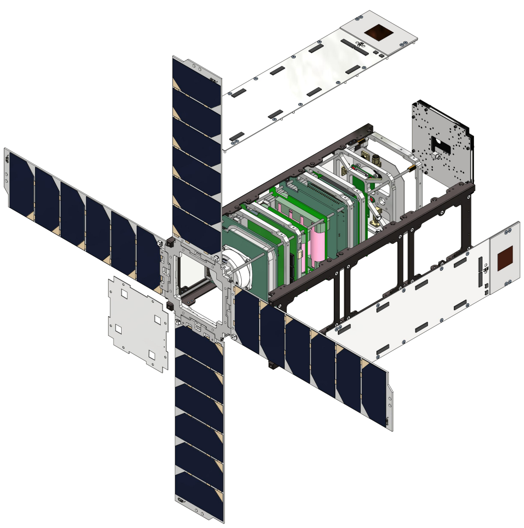

Fig. 2. Internal Structure of the VIBES Pioneer CubeSat.

II. State of the Art

CubeSat structures adapt to the diverse needs of space missions. Monolithic structures are characterized by being built from a single piece or shell. Such structures provide integral support for all satellite components; possess high mechanical strength due to the absence of joints or assemblies; have lower complexity during assembly; and are suitable for small-sized CubeSats with simple configurations and standard payloads [2].

Modular structures consist of multiple panels that are assembled to piece together the satellite structure. Their repair and upgrade ability, as well as the chance to make them bigger and more complex, make them desirable.

Card slot systems are designed with slots that allow electronic cards and other components to be inserted and secured in predetermined positions. They provide easy access to internal components and improve thermal and cable harness management. Such structures are ideal for CubeSats that incorporate multiple electronic boards or interchangeable modules.

Custom structures are characterized by meeting unique mission-specific requirements and incorporating specialized geometries and materials. They offer the possibility of incorporating advanced or experimental technologies, as well as optimizing particular functions. They are commonly used in research and development missions that require unconventional structural solutions.

Structures manufactured by additive manufacturing use 3D printing techniques to create complex structures with materials such as polymers and metals. They are characterized by weight reduction through optimized designs, the possibility of producing complex geometries that would be difficult to achieve with traditional methods, and reduced costs and production times. They are used for applications requiring rapid prototyping, lightweight structures, or customized designs.

The choice of structure type for a CubeSat depends on factors such as the size of the satellite, the complexity of the mission, the payload requirements, and the conditions of the space environment to which it will be exposed. Over the last decade, modular structures have revolutionized the design and assembly of CubeSats, offering flexible, scalable, and efficient solutions for a wide variety of space missions. These structures allow for simplified integration of subsystems and modules, accelerating development times and reducing costs [2].

EnduroSat, a leading manufacturer of CubeSat platforms, offers a range of CubeSat structures that are designed to be lightweight, rugged, and easy to assemble to maximize available space and enable customizable configurations. Manufactured from space-grade aluminum alloys, they are fully compliant with the CubeSat standard, support a payload of up to 24 kg, and feature vertical and horizontal assembly options. EnduroSat states that the robust design is guaranteed to last during its launch and space operation. The structures can be delivered with installed roller switches on their rails, making them compatible with ISS deployment. Furthermore, EnduroSat offers personalization options like nuts and modular configurations [3]. Besides structures, the company also supplies transmitters, antennas, OBC, EPS, solar panels, and customizable equipment for different CubeSat configurations.

The open-source CubeSats community has outstanding projects: LibreCube's goal is to promote participation in space exploration through the creation of freely available hardware and software [4]. OreSat, created by the Portland State University Aerospace Society (PSAS), is a fully open platform designed for interdisciplinary student groups whose goal is to provide an accessible foundation for designing and building CubeSats [5]. PyCubed, developed by Carnegie Mellon University's Robotic Exploration Laboratory (REx), is an open-source software and hardware framework designed to simplify the creation of CubeSats, particularly for devices with restricted space mission experience. EQUiSat, created by Brown University students, is a 1U CubeSat that acts as a teaching and technology showcase project, making it easy for others to replicate its subsystems on a limited budget [6]. These projects are evidence of the increased interest in open cooperation in the creation of CubeSats, fostering accessibility and innovation in the field of space exploration [7].

The future of CubeSats is being shaped by these technologies, encouraging the use of modular frameworks to optimize satellites' design, scalability, and capacity for adaptation.

III. Modular Structure

The idea of introducing a modular system is one of the proposals for a future mission of the VIBES program. The use of universal connectors and connecting elements and the use of identical components for different CubeSat sizes as far as possible can speed up the construction of new CubeSats of different sizes: modular systems are designed to facilitate the transition from compact platforms such as 1U CubeSats for basic educational purposes to larger proof-of-concept missions such as 12U or even 24U platforms and simplify their construction. By dividing the electronics into 0.5U segments and fixing the PCBs with PCB standoffs, the removal of parts of the satellite for testing or repair purposes is considerably simplified compared to the previous use of threaded rods.

We must take special care when designing the modular system to ensure that the elements can accommodate as many CubeSat sizes as possible. This approach ensures the creation of a clear system, preventing the waste of development potential due to duplication. A design study was carried out; the main purpose was to find out how a CubeSat structure can be set up in which as few components as possible are required for a large number of different CubeSats.

IV. Design Survey

We conducted a design study to transfer results from the 3U VIBES Pioneer CubeSat to the modular system. To ensure the viability of various CubeSat sizes, the design study used the 2U size instead of 3U. The emphasis was on how to realize diverse CubeSat sizes while also ensuring that the components match the various CubeSat sizes.

The ribs have been proven to be suitable for various CubeSat sizes. It is possible to build 1U, 1.5U, 2U, and 3U ribs in the same way. The CubeSat design specifications demand different ribs for the 6U and 12U sizes, as the footprint in the xy plane deviates as soon as neighboring U's occur. A 6U CubeSat contains three units in the $z-$axis, two on the $x-$ axis, and one in the $y-$axis. In contrast, 1U, 1.5U, 2U, and 3U in the xy plane each have one unit. When two units occur in the $x-$ or $y-$direction, the width of the rib increases from 100 mm to 226.3 mm, rather than simply doubling. This value corresponds to a footprint of 226.3 mm in both the x and y dimensions for the 12U CubeSat. The 6U structure will contain ribs measuring 2 units by 1 unit, as well as 1_2 units by 1 unit, to allow components to be attached. 1_2 unit means that it is a unit that is derived from the total size of two adjacent units. Figure 3 shows two connected 1_2 unit by 1 unit ribs at the top, as they can be used in a 6U CubeSat, and a 1 unit by 1 unit rib at the bottom.

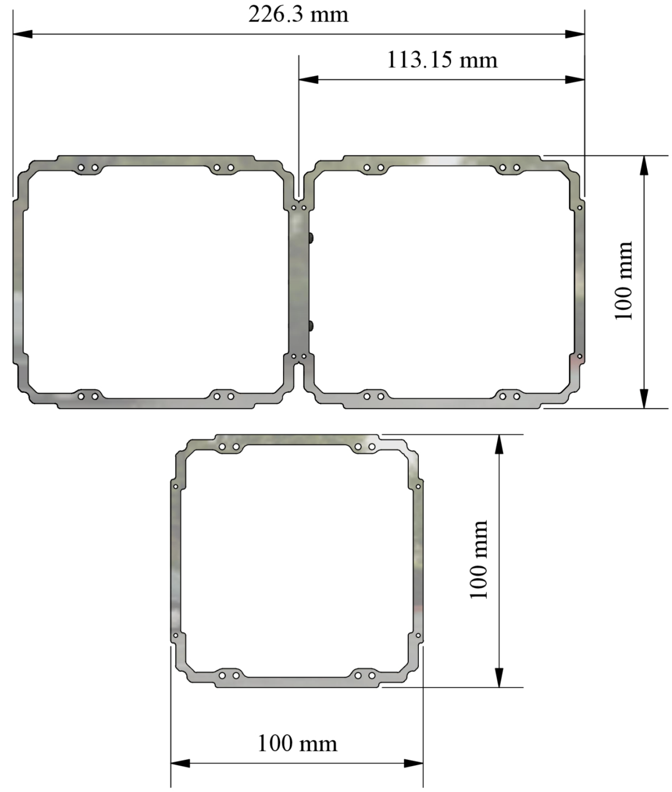

Fig. 3. Connected 1_2 unit by 1 unit ribs (top) and 1 unit by 1 unit rib (bottom).

A 1_2 unit is half the size of 226.3 mm. Bolting the 1_2 unit by 1 unit ribs together produces a rib with the same size as a 2 unit by 1 unit rib. This configuration allows for the creation of fastening sites and the introduction of intermediate reinforcements. The same goes for the 12U CubeSat. Connector elements unite the ribs in the y direction. Figure 4 illustrates the disassembly of a connecting part. The length of the connecting parts varies with the CubeSat size in the $z-$direction. It is possible to use the same frame elements for 6U and 12U. Smaller sizes require separate frame elements since their sizes differ in the $z-$direction. The frame components provide the option of fixing ribs every 0.5 units. The actual distance between fastening choices varies with the overall size in the $z-$direction [8].

The electronic components should be compatible with all CubeSat sizes. To achieve this, we must devise an electrical connection mechanism for the circuit boards, as well as a fastening method within the framework. Future development will focus on implementing electrical connections. The 3U CubeSat VIBES Pioneer presently has a 120-pin connection. However, this connecting approach has resulted in a loss of space due to the 120-pin connector's height.

Further development aims to simplify satellite integration. The design study used PCB standoffs rather than continually holding the PCBs in the $z-$direction using threaded rods and spacers, as was done with the CubeSat VIBES Pioneer. The PCBs are organized into 0.5-unit-high blocks, which are then installed in the structure from the side. This method allows individual blocks to be removed from the satellite for maintenance and testing without having to disassemble the entire CubeSat.

Figure 4 illustrates how to remove a PCB block: it shows how the fastening screws of the rib connecting element are first unfastened.

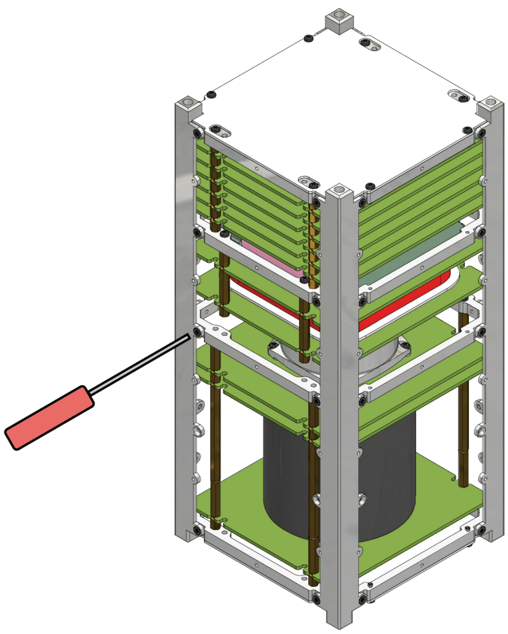

Fig. 4. Initial step to remove PCB block on a 2U CubeSat with modular architecture: loosening of the rib connecting element's screws.

Loosening the fixing screws of the PCB block is next. The PCB block is attached to two ribs with a total of 8 screws. Four screws are accessible from below and four from above using a screwdriver. Each rib has eight fixing holes, but only four are needed for a PCB block per rib. We double the number of holes per rib to accommodate a second PCB block. In this way, the PCB blocks can be detached separately from the structure. Figure 5 shows the loosened connecting element and the loosening of one of the fastening screws of a PCB block.

Figure 6 shows the lateral removal of the PCB block. The CubeSat structure undergoes simultaneous removal of several PCBs. PCB standoffs maintain the connection between individual PCBs. After removing the PCB block, it is possible to disassemble it to replace components or conduct tests.

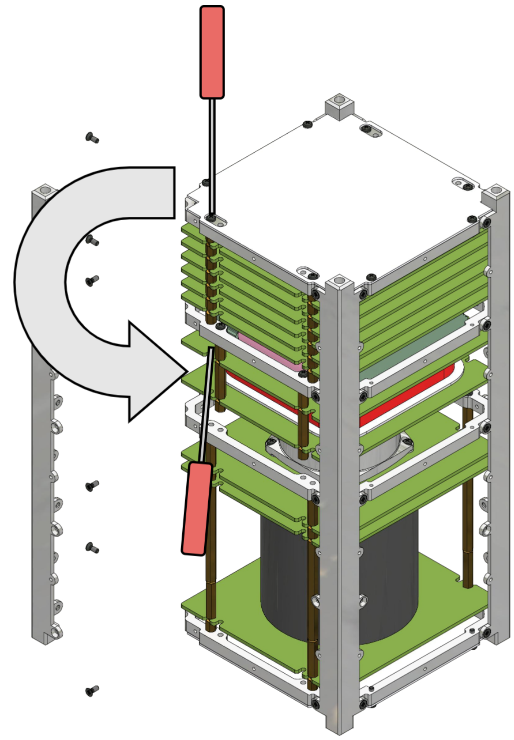

Fig. 5. Loosening the screws of the circuit board block.

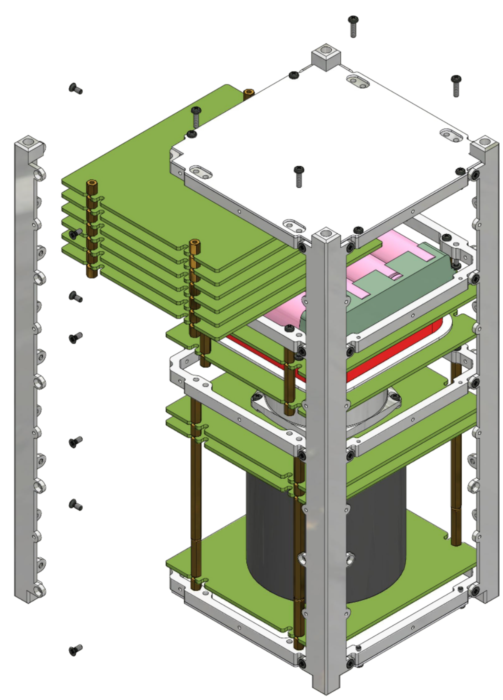

Fig. 6. Removing the circuit board block.

V. Open-Source Tool

The next section explores initial ideas for the website's structure and the distribution of component data. The website's approach is based on a modular system for aluminum profiles that is often used to create a wide variety of designs. In this system it is possible to download aluminum profiles and other components based on a certain grid as 3D files and to combine them in a CAD software to create a new design.

A. Allocation of Proper CubeSat Components

In the aluminum profile modular system, there are multiple profiles based on different grids. One grid, for instance, is 20 mm by 20 mm. The simplest profile has this cutting surface and varies in length. Other profiles are built on this 20 mm by 20 mm grid, with cutting surfaces of 40 mm by 20 mm, 40 mm by 40 mm, and so on. Connection sets and other compatible components are available in sizes to fit the grid. Other frequent grid sizes are 30 mm by 30 mm and 40 mm by 40 mm. Users can choose the components, adjust their lengths as needed, and add holes and threads. Some providers then offer 3D file downloads for use with CAD software. The components are subsequently combined into a machine, test stand, or other structure using CAD software.

The open-source website is intended to take a similar technique, where it should be possible to download 3D files to assemble them into CubeSats of different sizes in CAD software. The website also includes documentation, KiCad files, component inventories, and production files for the circuit boards. KiCad is an open-source EDA (Electronic Design Automation) software for designing circuit boards.

The website allocates the appropriate CubeSat size to a component upon its insertion. Figure 7 shows the assignment of the search parameters to the components. Figure 7 exemplifies a rib and a battery board: the rib is suited for CubeSat sizes 1U, 1.5U, 2U, and 3U, while the battery board's electrical design allows it to accommodate sizes ranging from 1U to 12U. We also included the component category as an additional parameter.

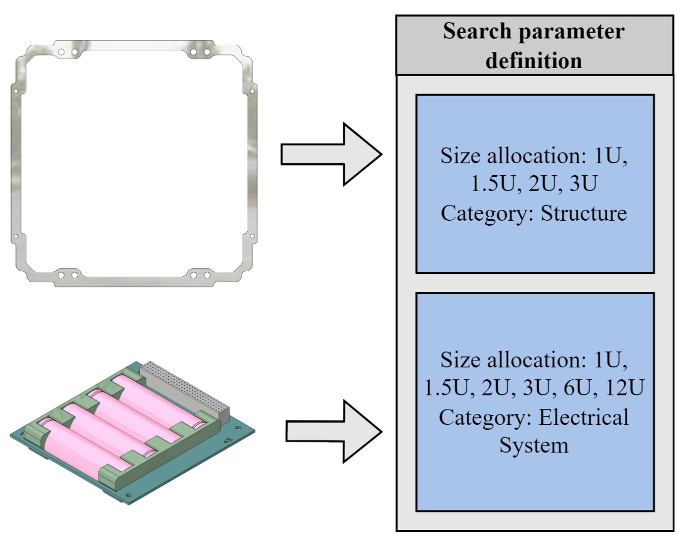

Fig. 7. Assignment of the filter parameters to the components.

Figure 8 shows the filtering of the available CubeSat components according to satellite size. For instance, once 2U is selected, the platform shows all components and assemblies suitable for this size.

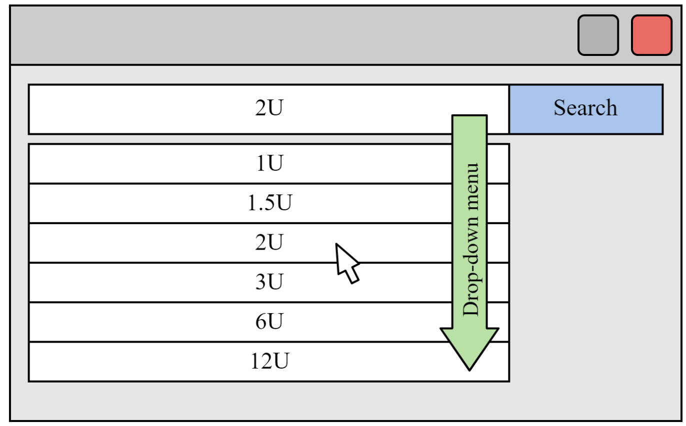

Fig. 8. Application of the CubeSat size filter.

Figure 9 presents a list of components along with an example project for a 2U CubeSat after applying the size filter. We apply a second filter to narrow down the component search more precisely. The application includes a further subdivision into categories.

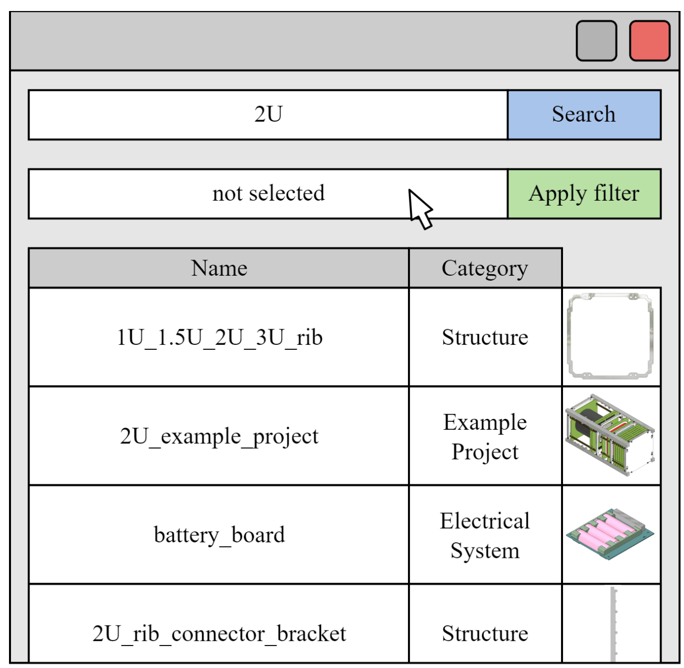

Fig. 9. List of components and assemblies suitable for a 2U CubeSat.

To apply filtering in subcategories, the category can be selected in Figure 10. This categorization is based on the CubeSat subsystems. As a result, the website follows the project's internal structures and allows external developers to find components for their area of work.

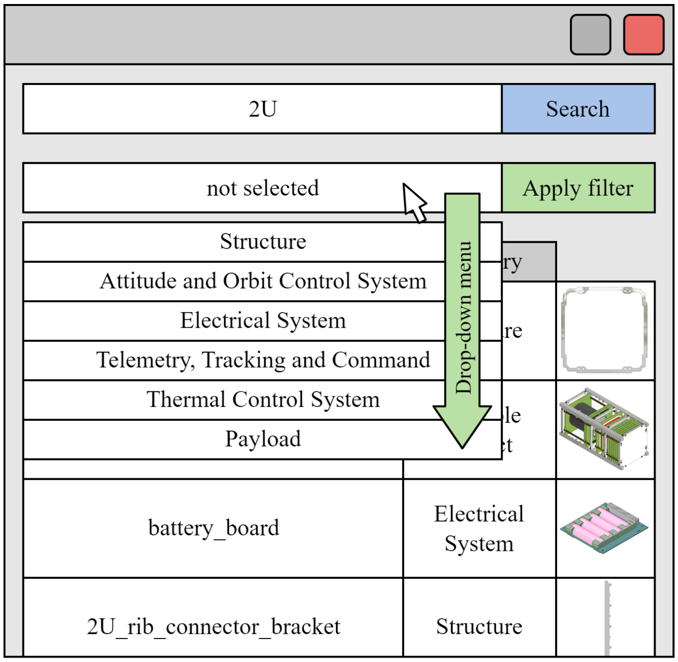

Fig. 10. Application of filtering according to categories.

B. Using the Components to Construct a CubeSat

To access the construction plans, documentation, and 3D data of a required component, a component is selected from the list and clicked. The website then displays an overview page for the component. The 3D files, KiCad circuit diagrams, and other relevant documents can be downloaded in this window. A sketch of the overview page is shown in Figure 11.

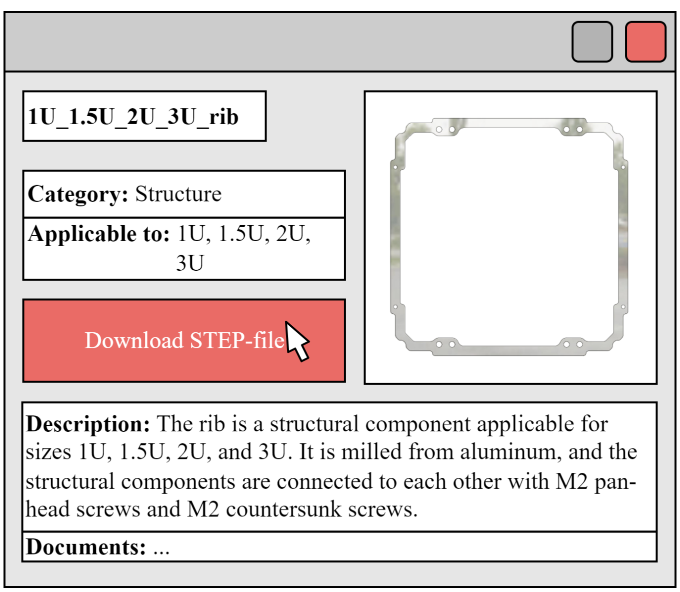

Fig. 11. Further documentation and 3D files are available to download.

If a 3D file is downloaded successfully, a message is displayed to inform the user that the file has been downloaded, as shown in Figure 12.

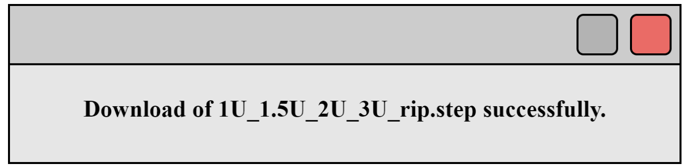

Fig. 12. Message about successful download of 3D file.

The downloaded component file can now be used to construct a satellite. To achieve this, the 3D file is inserted into CAD software. Various CAD programs can utilize the STEP (Standard for the Exchange of Product Model Data) file format. The CAD software uses the pre-designed components to construct a CubeSat. In this way, development costs for basic components can be saved, and more resources are available for the development of complex payloads or other new developments in the field of CubeSats and satellites in general. Figure 13 shows a sketch of the construction of a 2U CubeSat in the CAD software using the downloaded component.

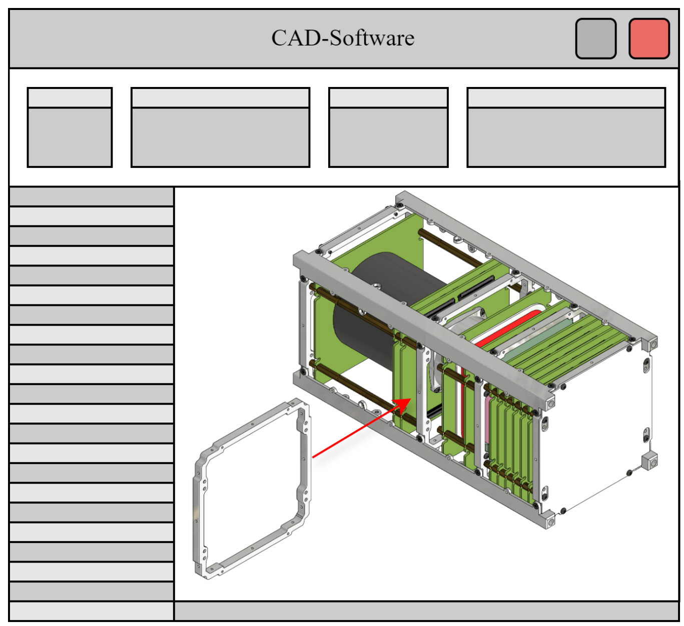

Fig. 13. 2U CubeSat downloaded file in CAD Software.

C. Use and Contributions from External Developers

The open-source platform should be open for users to expand the modular system. The input from the CubeSat project at the City University of Applied Sciences Bremen serves as the basis. We invite users to contribute their developments to the open-source platform. The contributions go through a review process and are then released on the website. At the same time, users can communicate errors or comments on existing components, which can then be corrected or taken into account. This approach aims to create a modular system that evolves as a collaborative project, improving with increased use. The loop between the VIBES research program and users or contributors is shown in Figure 14.

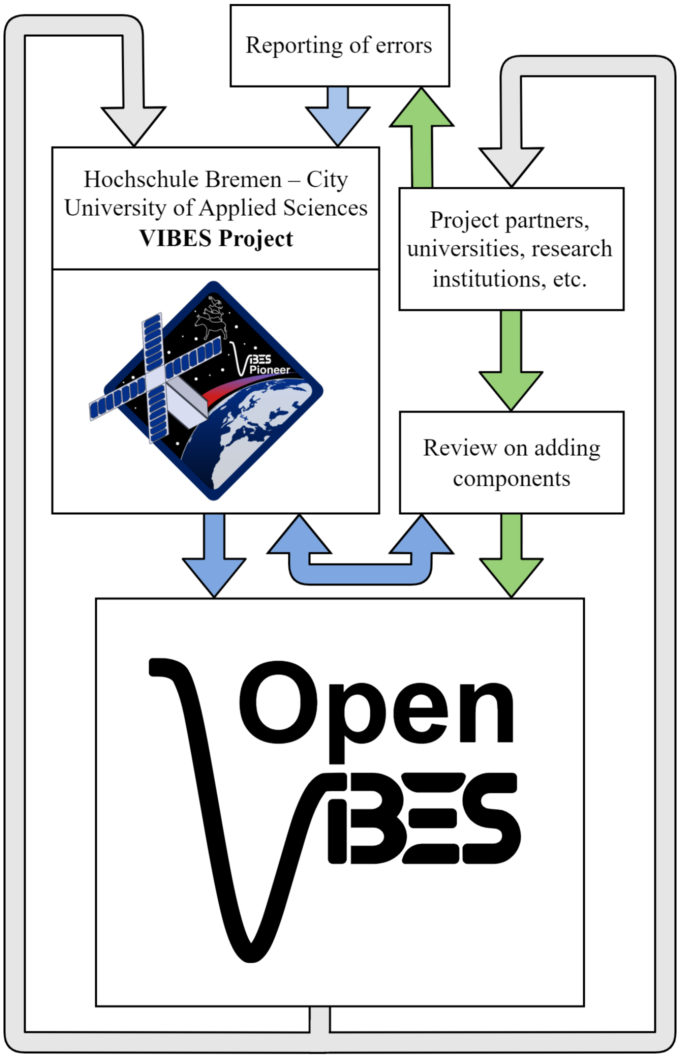

Fig. 14. Feedback flow of all-users contribution to the open-source platform.

The modular architecture's open-source approach aims to increase the impact of satellite missions by sharing designs, methodologies, and results with scientists while also allowing for continuous development and improvement by future team members of students and researchers at the City University of Applied Sciences Bremen.

In the initial phase of open-source tool deployment, this technique will be available at the IAT, allowing students and staff to use and contribute to the project's development.

We will create an internet platform to reach a larger audience and make these resources available to CubeSat developers worldwide. Users will be able to simply traverse this site, selecting the CubeSat size and examining the accessible structural and electronic components.

The platform will have KiCad projects for electronic circuits, 3D files of the components, and documentation. The site will make it easier to start unique projects by providing components according to the desired CubeSat size.

In addition to providing access to space technology, this open-source methodology promotes international cooperation, creativity, and the continued development of modular CubeSat constructions. This program may eventually reach more colleges and research teams, resulting in an even more dynamic and reachable space exploration ecosystem.

VI. Conclusion

In summary, this paper addresses the exploration of the development of a modular structure for CubeSats within the framework of the VIBES research program, highlighting its potential as an open tool for the scientific, academic, and technological community. Based on the experience gained in the VIBES Pioneer mission, the evolution toward more scalable, reusable, and adaptable designs that allow the efficient integration of subsystems and the customization of configurations for future missions has been proposed.

The concept suggests a perspective built on modular elements, universal connectivity, and available digital resources such as 3D files, electronic schematics, and technical documentation, all integrated in an open-access platform. This digital tool allows selecting the size of the CubeSat and filtering compatible components.

The approach seeks to lower development costs, speed the design and assembly processes, and make it simpler for the scientific community, particularly academics and students, to participate. It not only boosts innovation within the Institute of Aerospace Technology at the City University of Applied Sciences Bremen but also lays the foundation for a global collaboration that drives space exploration from an accessible, sustainable, and cooperative perspective.

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