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INSTITUTE OF AEROSPACE ENGINEERING

LETECKÝ ÚSTAV

PROPOSAL OF THE MODULAR SUPPORT EQUIPMENT FOR THE CUBESAT INTEGRATION

KONSTRUKČNÍ NÁVRH MODULÁRNÍHO PŘÍPRAVKU PRO INTEGRACI CUBESATU

MASTER'S THESIS

DIPLOMOVÁ PRÁCE

AUTHOR Bc. Ondřej Kukla

AUTOR PRÁCE

SUPERVISOR Ing. Jan Vaverka

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Assignment Master's Thesis

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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Proposal of the modular support equipment for the CubeSat integration

Brief Description:

CubeSats are small satellites with the standardized dimensions and weight, suitable for in–orbit experiments and new technology demonstration. Each satellite is composed of one or more cubic modules (called "unit" – U) with an approximate size of 10x10x10 cm. The satellites are integrated utilizing dedicated platforms – MGSE (Mechanical Ground Support Equipment), often available as 1U–3U. However, the integration of the bigger CubeSats requires scalability of the support equipment used. An adaptive design of the MGSE is one of the possible ways to ease the development of the bigger, more sophisticated CubeSats.

Master's Thesis goals:

The main objective of the thesis is a design proposal of the adaptive Mechanical Ground Support equipment, enabling an integration of the 1U – 12U CubeSats.
– review of the MGSE used in space engineering,
– study of the specific CubeSat MGSE used for the integration,
– an analysis of the currently available products and conceptual proposal of the modular MGSE,
– concept selection and design proposal of the modular 1U – 12U MGSE for CubeSat.

Recommended bibliography:

CAPPELLETTI, Ch., BATTISTINI, S., MALPHRUS, B. ed. CubeSat Handbook: From Mission Design to Operations. USA: Academic Press, 2020, 498 s. ISBN 978-0128178843.

YOST, B., WESTON, S., ed. State-of-the-Art: Small Spacecraft Technology. Ames Research Center, Moffett Field, California: Small Spacecraft Systems Virtual Institute, 2020, 327 s. ISBN NASA/TP—2020–5008734.

CubeSat 101: Basic Concepts and Processes for First-Time CubeSat Developers. NASA: NASA CubeSat Launch Initiative, 2017, 96 s. Dostupné také z: https://www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf

Deadline for submission Master's Thesis is given by the Schedule of the Academic year 2021/22

In Brno,

L. S.

doc. Ing. Jaroslav Juračka, Ph.D. Director of the Institute	doc. Ing. Jaroslav Katolický, Ph.D. FME dean

ABSTRAKT

Cílem diplomové práce je vytvořit konstrukční návrh modulárního integračního přípravku CubeSatů. V textu níže jsou obecně představeny CubeSaty společně s komerčními přípravky pro jejich integraci. Finální konstrukční řešení bylo zvoleno na základě porovnání zvolených parametrů a informací zjištěných z průzkumu trhu. Návrh byl úspěšně vytvořen a k práci jsou připojena 3D data a výkresová dokumentace.

KLÍČOVÁ SLOVA

CubeSat, MGSE, přípravek, integrace

ABSTRACT

The aim of this diploma thesis is to create a design of Mechanical Ground Support Equipment for CubeSat integration. In the text below, CubeSats are generally introduced together with commercially available products for their integration. The final design was chosen based on a comparison of parameters and results from the market research. The design itself was successfully created, 3D data and drawings are attached to the work.

KEYWORDS

CubeSat, MGSE, jig, integration

ROZŠÍŘENÝ ABSTRAKT

Tato práce se zabývá vývojem zařízení, které slouží k integraci CubeSatů. CubeSat je typ satelitu, který je normalizovaný a podle standardu *CubeSat Design Specification* má momentálně 6 různých velikostí. Vyvíjený přípravek musí být modulární, aby ho bylo možné použít na všechny velikosti. K návrhu takového zařízení bylo nutné provést rešerši a zjistit, jaké mají tyto satelity rozměry jednotlivé velikosti, k čemu slouží a jaké věci se na ně běžně integrují.

V první části diplomové práce je provedena rešerše, která objasňuje odpovědi na tyto klíčové otázky. V návaznosti na zjištění základních informací byl proveden průzkum trhu, který odhalil provedení přípravků používaných k integraci jednotlivých výrobců. Obecně se dají tyto přípravky rozdělit na dva typy. Tyto typy se liší ve způsobu upnutí CubeSatu na statický a dynamický. Statický typ umožňuje upnutí bez možnosti jakéhokoliv pohybu, na druhou stranu dynamický typ umožnuje rotaci kolem jednotlivých os satelitu. Dále všechny tyto přípravky umožňují integraci v horizontální i vertikální poloze satelitu. Některé přípravky slouží jen pro integraci menších velikostí, kdežto některé nemají žádné omezení týkající se velikosti integrovaného satelitu. V závěru této kapitoly je provedena analýza potenciálu trhu těchto malých satelitů, která má za úkol zjistit, jak moc jsou relevantní částí vesmírného průmyslu a zda má vůbec smysl zabývat se tímto druhem satelitů z ekonomického hlediska. Analýzou bylo zjištěno, že je to atraktivní část průmyslu, která každoročně navyšuje počet vypuštěných zařízení a existuje zde potenciál růstu do budoucna. V diplomové práci jsou také představeny hypotézy, které předpovídají trend na několik následující let a výsledkem je, že i do budoucna se počítá s každoročním přírůstkem vypuštěných zařízení v řádu desítek kusů.

Jelikož cílem diplomové práce je provést návrh konstrukčního řešení a průzkum trhu ukázal, že existuje několik typů zařízení, tak v následující kapitole bylo provedeno koncepční řešení obou typů z cenového a ergonomického hlediska. V potaz byla brána také jednoduchost manipulace s jednotlivými velikostmi CubeSatu, a také jednoduchost zařízení pro případ, když bude třeba změnit velikost integrovaného satelitu. Výsledkem této kapitoly je výběr statického přípravku, jelikož je levnější na výrobu a jednodušší na vývoj. Dále je snadněji modulovatelný pro integraci různých velikostí satelitu. Jeho nevýhodou je neergonomická manipulace s velkými CubeSaty jako například 12U, které mohou dosahovat váhy až 24 kg. U satelitů této velikosti bude také integrace více časově náročný proces, než v případě použití dynamického přípravku. V návaznosti na rozhodnutí, jaký typ zařízení bude navrhnut, proběhl návrh designu přípravku. V konstrukční kapitole je popsáno, v jakém prostředí bude přípravek použit, dále byl proveden výběr materiálu a byla také zvolena vhodná ochrana před elektrostatickým výbojem. Po provedení této vstupní analýzy přišel na řadu popis konstrukčního řešení. Jak 3D data, tak výkresová dokumentace byly vytvořeny v softwaru Autodesk Inventor Professional 2021.

Výsledné řešení se skládá z hliníkového plechu s drážkami, s lineárním vedením. Lineární vedení obsahuje díry na kolíky. Do těch děr v lineárním vedení se vloží buď vertikální, nebo horizontální segment s kolíky podle potřeby integrované polohy CubeSatu.

This thesis was written in cooperation with S.A.B. Aerospace s.r.o.

BIBLIOGRAPHIC REFERENCE

KUKLA, Ondřej. Konstrukční návrh modulárního přípravku pro integraci CubeSatu [online]. Brno, 2022 [cit. 2022-02-21]. Available at: https://www.vutbr.cz/studenti/zav-prace/detail/139811. Diplomová práce. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Letecký ústav. Vedoucí práce Ing. Jan Vaverka.

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AUTHOR’S DECLARATION ON THE ORIGIN OF THE WORK

I declare that I have written the master’s thesis *Proposal of the modular support equipment for the CubeSat integration* on my own according to the advice of my superior Ing. Jan Vaverka, and using the sources listed in references.

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Author’s signature

CONTENTS

INTRODUCTION

CubeSat is a standardized small satellite that has become a popular launched spacecraft due to its affordability. These spacecraft consist of several subsystems such as an electrical power system that supplies and distributes power to the spacecraft, or a navigational system that helps with the location determination of the satellite, and these subsystems must be assembled to create a functional spacecraft. The Assembly process of the subsystems is a difficult task where the safety of the components must be ensured. To help to meet safety requirements Mechanical Ground Support Equipment (MGSE) is developed. It helps to meet not only safety requirements but also reduces the time needed for the assembly process. Because CubeSats have become so popular according to the price and availability of components, companies in the space industry consider its platform as an alternative to the current approach when it comes to developing a small new satellite.

The thesis consists of a theoretical part where are described Ground Support Equipment (GSE) used generally in space and especially in the CubeSat sector. It follows with a market overview, that introduces commercially available devices. The part ends with a market potential analysis which helps to reveal how much are CubeSats a relevant part of the space industry. It determines what is the current trend of launching CubeSats, which sizes launch the most and if CubeSats are interesting in economical point of view. Figure 1 highlights the phase of the CubeSat development related to the thesis.

The second part of the thesis is a practical part which compares basic designs of MGSE in the market overview. Final solution was chosen based on given attributes such as price or ergonomics. The design of the proposed device is described in the last part of the thesis.

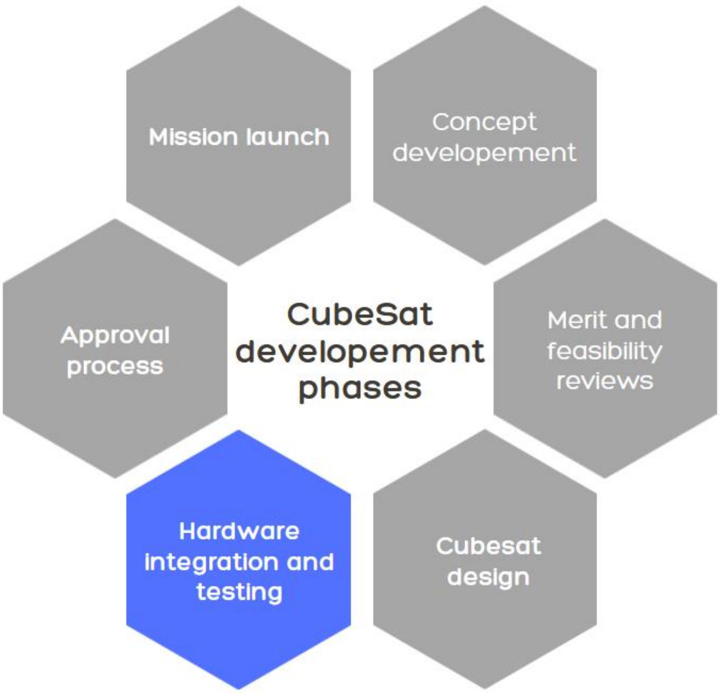


Figure 1 Highlighted phase of the CubeSat development related to the thesis [1]

1 STATE OF THE ART

1.1 GSE in the space industry

Ground Support Equipment (GSE) is a non-flight product used on the ground to assemble, integrate, test, transport, access, handle, maintain, measure, calibrate, verify, protect or service a flight product. GSE contains both hardware and software [2]. General types of GSE are Mechanical (MGSE), Electrical (EGSE) [3], and Optical (OGSE) [4]. Types of GSE with their purposes are shown in Figure 2.

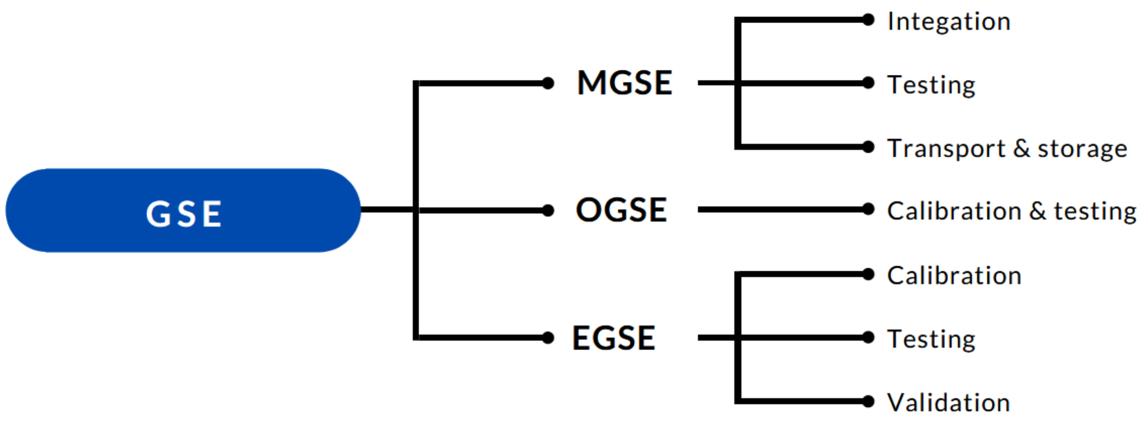


Figure 2 Types of GSE with their purpose [2][3][4]

1.1.1 MGSE

MGSE is a supportive jig that is designed to help with the integration of subsystems into the structure of a spacecraft in a cleanroom. It can also help with basic mechanical testing, which means verifying the functionality of subsystems, such as deployable antennas or solar arrays, although specific tests such as vibration tests or acoustic tests require special testing devices. MGSE also includes lifting and turning devices as well as a variety of adapters for vibration tests or thermal testing. Another field of application is storage & transport. An important fact to mention is that MGSE is used for integration of all types of spacecraft such as satellites, rockets, International Space Station modules, and all kinds of payloads [5].

MGSE can be also divided by the type of mounting to static and dynamic. Static means that the spacecraft is not allowed to move while it is mounted in the MGSE. Dynamic allows rotating the spacecraft. Another division is by the position of the mounted spacecraft to vertical or horizontal.

Custom MGSE for integration

Because of the different sizes, shapes, and masses of spacecraft, there is no universal integrational solution in the MGSE segment. Overall, there are plenty of developers who offer a custom solution of MGSE to the customer's requirements. An example of developers with focus on custom made solutions with their heritage is listed in Table 1.

Table 1 List of developers with focus on custom made solutions with their heritage

Developer	***Origin***	***Heritage***	***Reference***
SENER Aerospacial	Spain	Euclid, Biomass	[6] [7]
High Performance Space Structure Systems	Germany	JUICE, METOP	[8]
Space Structures	Germany	ExoMars 2016 EDRS-C	[9]
Rostock System-Technik	Germany	Bartolomeo	[10]

The Euclid satellite which will help with the research of the properties of dark energy, belongs to the large spacecraft category with a mass of over 2000 kg. For this spacecraft, 13 MGSE items are being developed. Some are used for lift the satellite in different configurations, to manage horizontal and vertical integrations or for gravity adjustable module to position the centre of gravity [6].

Platform Bartolomeo is a European external platform attached to the Columbus module of the International Space Station. Its purpose is to host external payloads. To make a proper assembly, it was necessary to develop a set of MGSE for integration and testing. In Figure 3 are shown the Euclid satellite and the Bartolomeo platform with their MGSE [9].

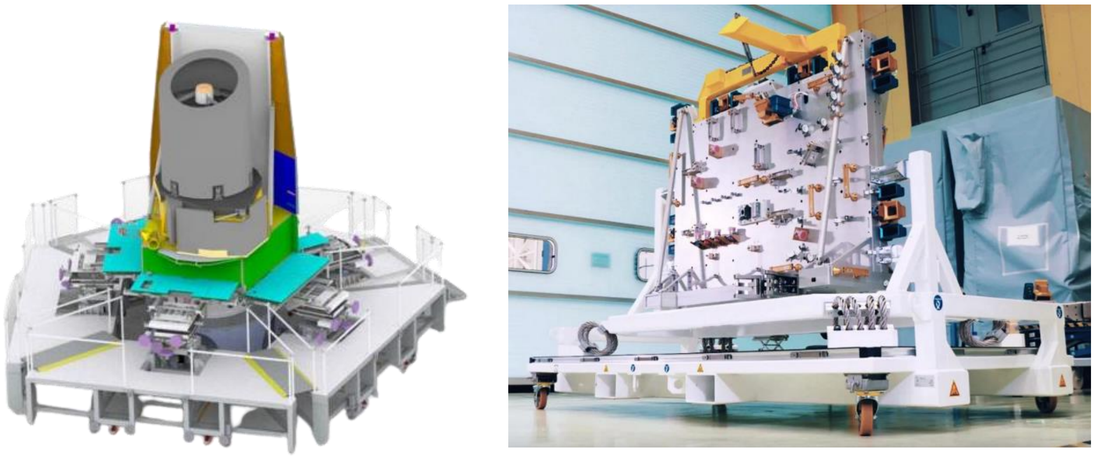


Figure 3 The Euclid satellite (left) [6] and the Bartolomeo platform (right) [10] with their MGSE

Commercial MGSE for integration

There are several developers who do not offer custom solutions only. They have tried to standardize their products to offer a commercial solution with a low amount of additional engineering to satisfy customer's requirements. The main type of an MGSE used for integration in space industry is a multipurpose trolley. It allows moving the spacecraft to vertical as well as horizontal positions. Examples of other MGSE are hoisting & lifting devices and a variety of adapters such as adapters for vibration testing.

In Table 2 are listed developers of commercial solutions for integration with projects they participated on. APCO Technologies is a provider of devices for a rocket assembly and payloads up to 5 tonnes. They provided MGSE for European launchers such as VEGA, Ariane 5, or Ariane 6. Other developers have built their heritage on MGSE used for satellite integration [11].

Table 2 List of developers with a commercial solution with their heritage

Producer	***Origin***	***Heritage***	***Reference***
APCO Technologies	Switzerland	Ariane 5, Ariane 6, VEGA	[11]
Beyond Gravity	Switzerland	Copernicus, PACE	[12]
GRADEL	Luxembourg	EDRS, Proba-3	[13]

Figure 4 shows a multipurpose trolley that is used to assembly medium or large spacecraft and compares it to MGSE which is used to assembly CubeSats. Spacecraft in the multipurpose trolley can be mounted in horizontal as well as vertical position and allows 90° tilt and 360° rotation.

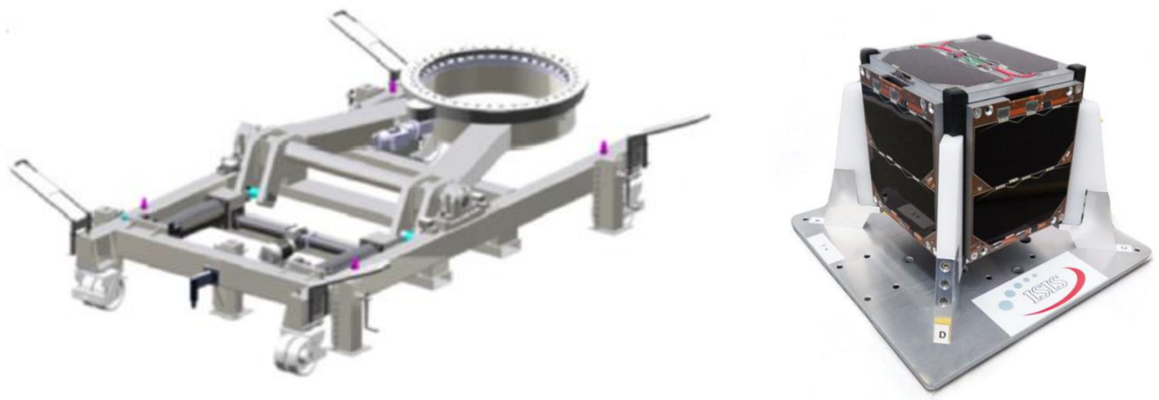


Figure 4 Multipurpose trolley (left) [11] and MGSE for a CubeSat integration (right) [14]

MGSE for transport & storage

Another type of MGSE are storage & transport containers. They can be pressurized or non-pressurized. These devices are designed for a long-term storage of satellites, subsystems, or their transport. The MGSE may contain a controlled environment system for the spacecraft. The controlled environment means that the container can control multiple parameters such as temperature, humidity, and concentration of particles in the air. The typical configuration of a spacecraft transport and storage container is a base frame, a thermally insulated tub and a removable lid. Controlled environment is maintained by passive thermal insulation, active thermal control units, and air filtering systems. For container autonomy, a combustion generator is a part of the environmental package. They include a damping system to reduce damage from several sources such as vibrations or shocks [15].

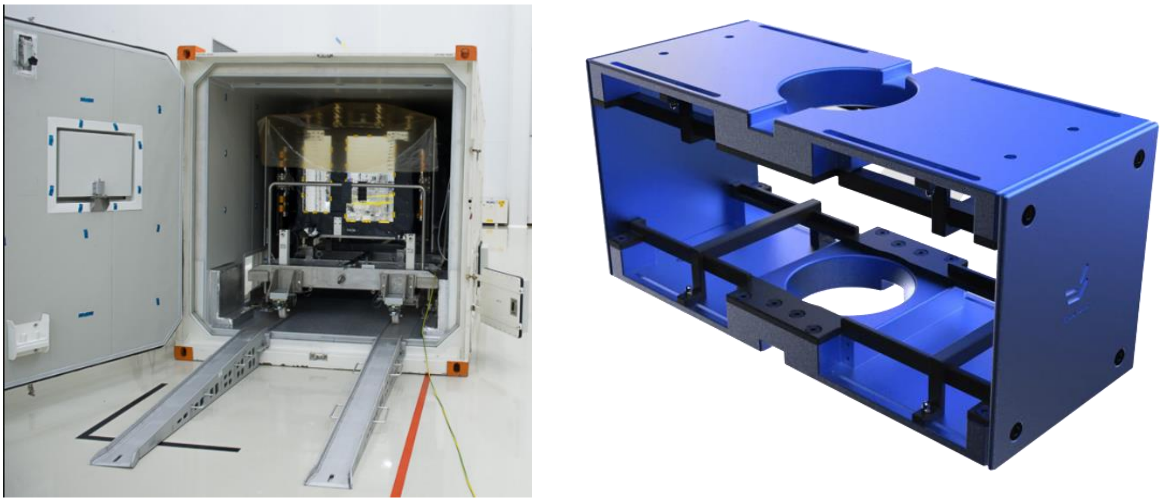


Figure 5 Transport container for a medium spacecraft (left) [16] and for a 3U CubeSat (right) [17]

Figure 5 shows a comparison of containers for a medium spacecraft and a CubeSat. On the left side, there is the transport container for the Galileo satellite (675 kg). On the right side, there is a CubeSat transport container which can host spacecraft up to 3U (up to 6 kg). The CubeSat container does not contain environment control [17].

1.1.2 EGSE

EGSE is an integrated support equipment used to validate and test the functionality of electrical subsystems before launch. It is a combination of software and hardware that performs testing of a spacecraft, by simulating the interfaces of missing systems to assure full compatibility once integrated within the overall platform. Testing includes external elements such as antennas related to communications as well as onboard elements such as computer or battery systems. Figure 6 shows integrated EGSE devices [3][18].

Figure 6 Examples of integrated EGSE units [3][18]

1.1.3 OGSE

By the definition, OGSE can be classified as MGSE, because it is used for testing and calibration of instruments, but developers usually divide these into two types. These test benches must be flawless in terms of optical performance and mechanical stability to calibrate an optical system, such as telescopes or mirrors to the optimal performance. Figure 7 shows a device called Multi-Optical Test Assembly which is an OGSE including a three-mirror telescope. The main purpose is to determine optical performance depending on the performed simulations [19][20].

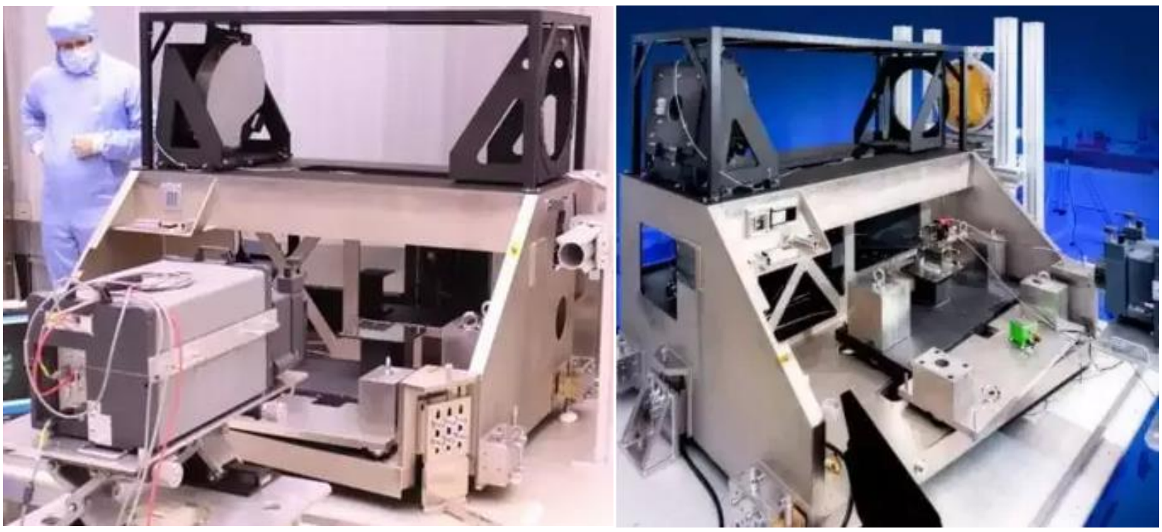


Figure 7 Multi-Optical Test Assembly OGSE unit [20]

1.2 CubeSats

1.2.1 Overview of spacecraft categories

From a general definition, a satellite is a moon, planet, or object orbiting a planet or a star. Types of satellites are:

- *Natural* – a natural object that orbits a planet, a moon, or another body in a solar system
- *Artificial* – a human-made object which orbits celestial bodies and takes pictures, is used for communication or to predict weather conditions

Artificial satellites can be divided by mass or by their purpose. In Table 3 are shown general types of satellites based on their mass. CubeSats generally belong to the small satellites (SmallSats) category which is grouped into five categories from femtospacecraft (< 0,1 kg) up to minispacecraft (10 - 100 kg). First launched CubeSats were small spacecraft with a mass slightly above 1 kg, so they were classified as nanospacecraft. Current standard CubeSats can weigh up to 24 kg and the higher mass pushes CubeSats also to the microspacecraft category, but the title nanosatellites stuck to them from pioneer CubeSats [21][22].

Table 3 General types of satellites based on mass [23]

Class	*Platform mass [kg]*
Large spacecraft	> 1000
Medium spacecraft	500 – 1000
Small spacecraft	< 500

Figure 8 shows further categorization of small spacecraft.

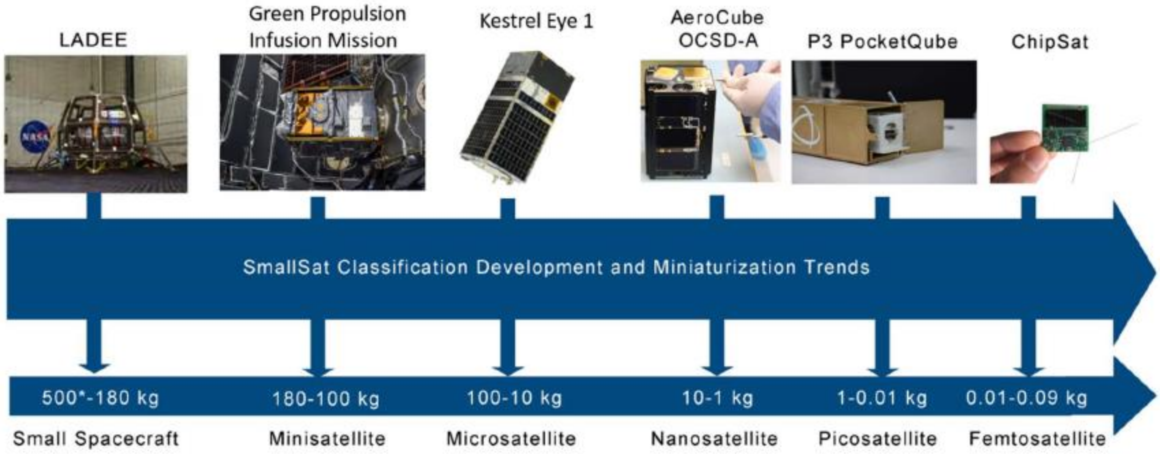


Figure 8 Classification of SmallSats based on mass [24]

There are several purposes of CubeSats. The scientific purpose is the most common because testing new technologies on small satellites is economically advantageous than running tests on bigger ones. Other purposes include observation of the Earth, planetary exploration, or fundamental Earth and space science such as measuring required physical activity. These roles, each with an example, are described in more detail below [1].

As alternative platforms for space instruments - Enhancing traditional satellites roles such as observations of astronomical targets such as the Sun, exoplanets, or galaxies [25].

RaInCube, 6U, 2018 - Uses the first radar that used to track weather conditions [25].

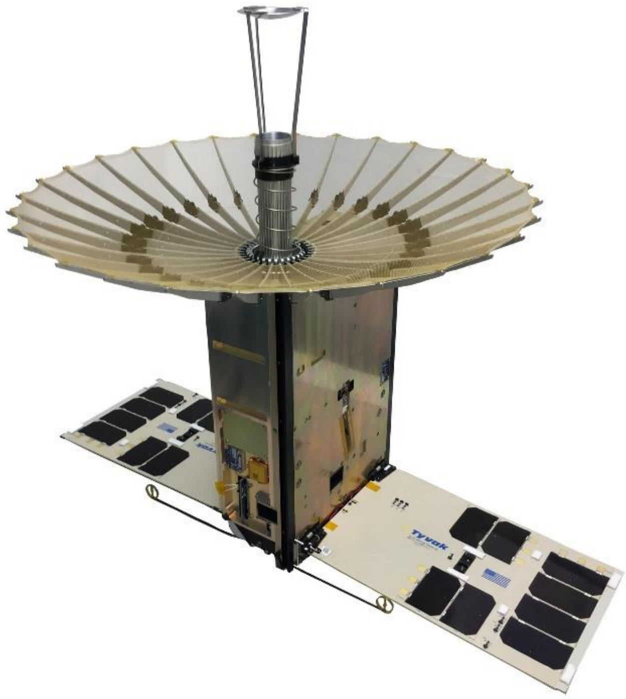


Figure 9 RaInCube CubeSat [26]

As alternative platforms for space experiments - Enabling varied industry sectors access to space as an environment. Materials science, radiology, and pharmacology are examples of these sectors [25].

ASTERIA, 6U, 2017 - First successful exoplanet detecting CubeSat equipped with COTS systems for providing necessary pointing accuracy [25].

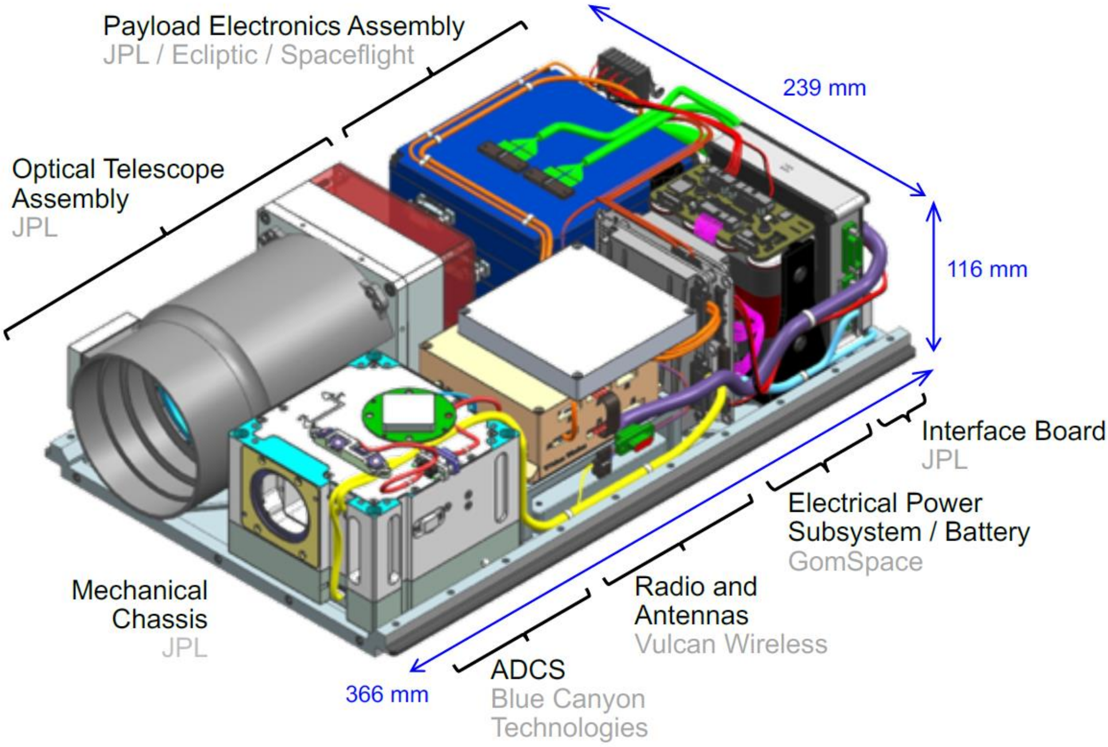


Figure 10 ASTERIA CubeSat [27]

As affordable technology-demonstrators and proof-of-concept platforms - Lower resources needed for development with a possibility to use already designed components, have made CubeSats a natural application as technology demonstrators for several new technologies such as communication systems, solar cells, etc.. These satellites are also used for demonstrating new mission concepts [25].

LightSail 2, 3U, 2019 - Tested controlled solar sailing in LEO onboard a CubeSat [25].

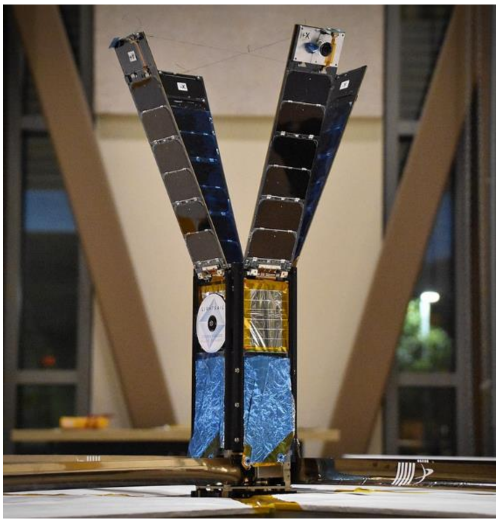


Figure 11 LightSail 2 CubeSat [28]

As payloads outside of Earth's orbit - To support bigger spacecraft with additional measurements or to place instruments in favourable orbits that would need to separate launches [23].

MarCO, 2x 6U, 2018 - The first interplanetary CubeSat mission [25].

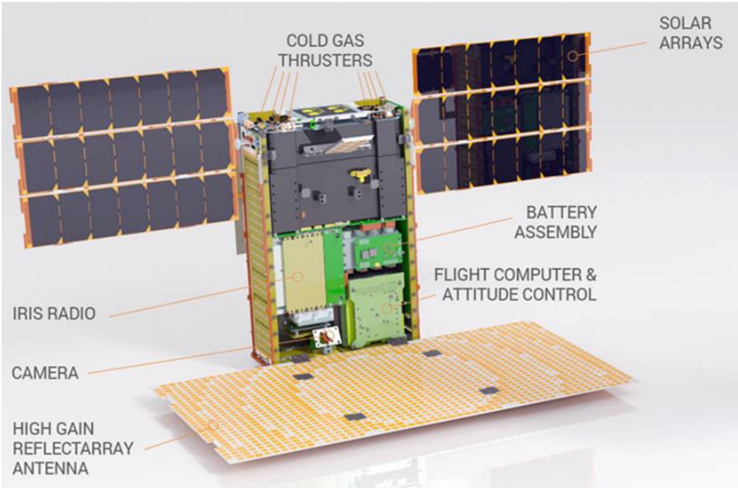


Figure 12 One of the MarCO CubeSats [29]

The realization of mega-constellations at achievable prices - The standard design specification and advanced CubeSat industry has aided some spacecraft to be cheaper and easier to mass-produce. Mass production is a significant aspect of a constellation to stay as cheap as possible. With more spacecraft in a constellation, it is easier to achieve more coverage, greater redundancy, or provide a shorter revisit time [25].

Planet Labs - A provider of series of various SmallSats and CubeSats to image the Earth in high-resolution images — useful in agriculture, forestry or it has been used for mapping. The Dove constellation of 3U CubeSats currently counts more than two hundred spacecraft units [25][30].

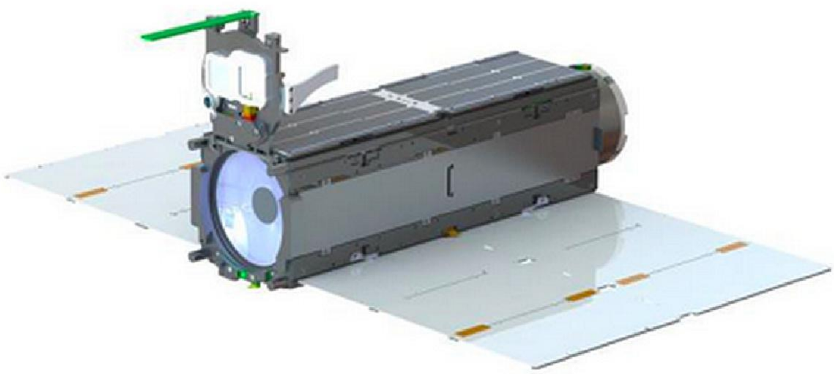


Figure 13 The Dove CubeSat [30]

The variety of missions and applications that CubeSats can manage has led them to be considered the economical way to reach space. From the initial idea that CubeSats are a great tool to gain new experiences with satellites in education, they have been adopted by the biggest organizations such as space agencies or military organizations. The CubeSat standard has grown to a relevant sector of the space industry thanks to the evolution of COTS, services, and mass production [25].

1.2.2 Standard

CubeSat is a type of small satellite that must meet specific criteria concerning weight, shape, or size for example. The CubeSat Design Specification standard form factor is defined as a U (unit). 1 unit is a 10cm cube with a mass up to 2 kg. The current standard counts 6 sizes while starting with the 1U and ending with 12U. The individual sizes are shown in Figure 14. The main objective of the standard is to provide specific information about the design such as mechanical, electrical, or operational [22].

The standard helps to reduce development time and costs. With the standard for companies, it is possible to develop universal components which can be widely used with only a small additional development to match customer's requirements. The result is that CubeSat is using these universal parts to become less expensive than a customized spacecraft. The standardization also helps to reduce costs associated with deployment due to their size and shape [1].

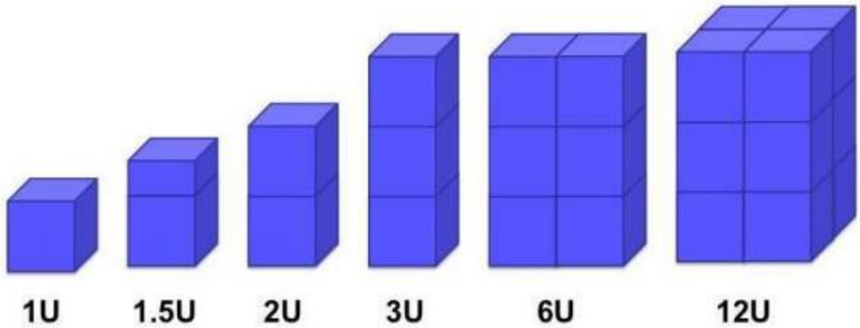


Figure 14 Current state of the CubeSat family [24]

The specification describes other mechanical, electrical, and operational requirements. The mechanical part specifies for example an additional volume of CubeSats called Tuna cans, the surface roughness of rails, position of the centre of gravity, and the surface treatment of rails. The electrical part describes when the power system should be activated, the use of deployment switches, and removal before fly pins. The operational part helps to meet legal obligations and to ensure safety for other CubeSats [22].

1.2.3 Subsystems of a CubeSat

This part introduces subsystems of CubeSat which are essential to the proper functionality of the spacecraft. For the optimal use of a spacecraft the optimal environmental conditions, such as ambient temperature, must be secured. Many of these systems rely on electrical energy so there must be a system that can provide the electricity to the crucial parts. Sometimes it is needed to relocate the satellite, therefore, it must have a propulsion system. These systems work as a life support for the payload. Figure 15 shows essential subsystems needed in a CubeSat.

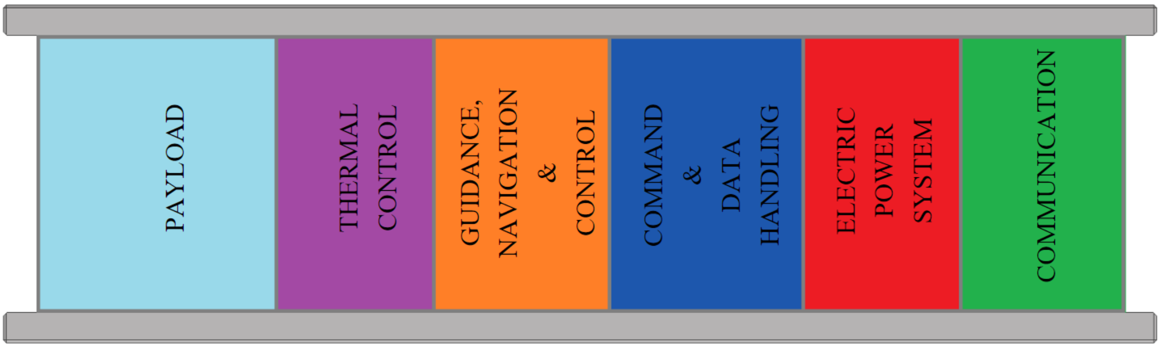


Figure 15 Scheme of essential subsystems of a CubeSat [24]

Structure

The primary structure is a frame dominantly made of an aluminium alloy. Other parts such as subsystems, solar panels, or reinforcements are attached to the structure. Most of the primary structures are machined from aluminium alloy 6061 or 7075. These structures contain flexible mounting points for connection with other components. Currently, 1U, 3U, and 6U frames are the most common choice. However, 12U frames are becoming more widely available [24]. Figure 16 shows examples of these structures.

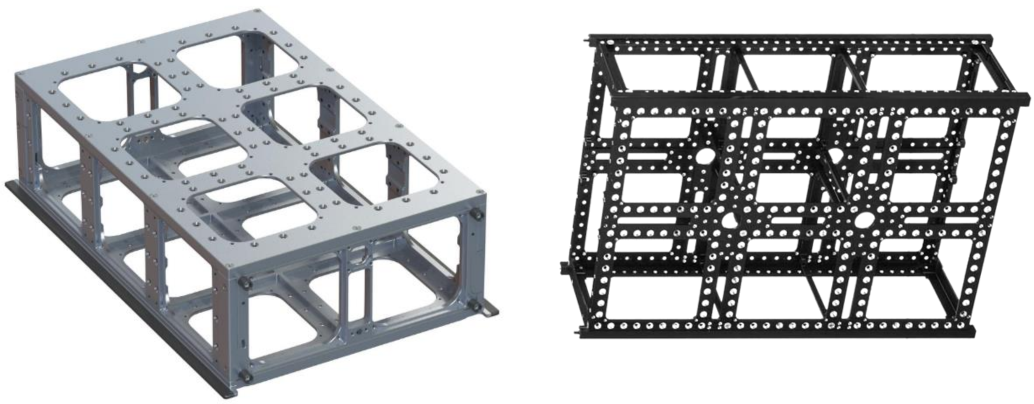


Figure 16 Examples of primary structures [24]

Communication

The communication system is a fundamental unit of each spacecraft. It allows the spacecraft to communicate with a ground station on the Earth and transmit information. It also works oppositely and allows the satellite to receive commands from the Earth or another spacecraft. The system consists of the ground segment and the space segment. The ground segment are one or more ground stations located on Earth, and the space segment is a spacecraft. Communication can be performed by radio frequency or optical. Figure 17 shows an antenna used on a CubeSat with a PCB for its control [24].

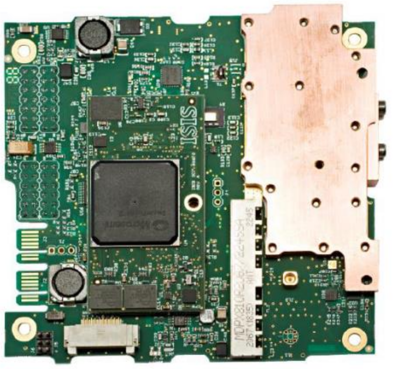
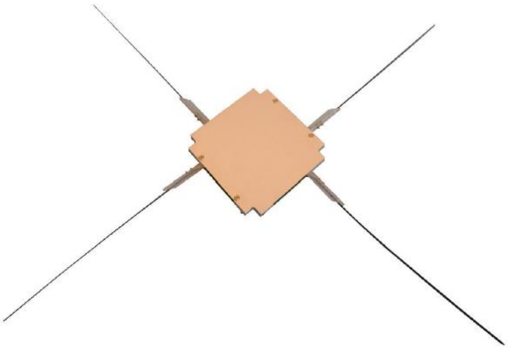



Figure 17 PCB (left) [31] and a deployable antenna (right) [32]. Both developed by ISISPACE

Electrical Power System

The Electrical Power System (EPS) is a subsystem containing electrical power generation and distribution unit, as well as storage which is implemented by a battery or a supercapacitor. It usually takes a large volume and mass in a spacecraft. Power generation technologies consist of photovoltaic panels or arrays. These components include photovoltaic cells. Power storage technologies usually consist of batteries or supercapacitors. There are two types of batteries - primary and secondary. Primaries are single-use batteries while secondaries are rechargeable. The power management and distribution system help with the power control of the spacecraft. Figure 18 is an example of a modular EPS consisting of three printed circuit boards and a battery pack [24].

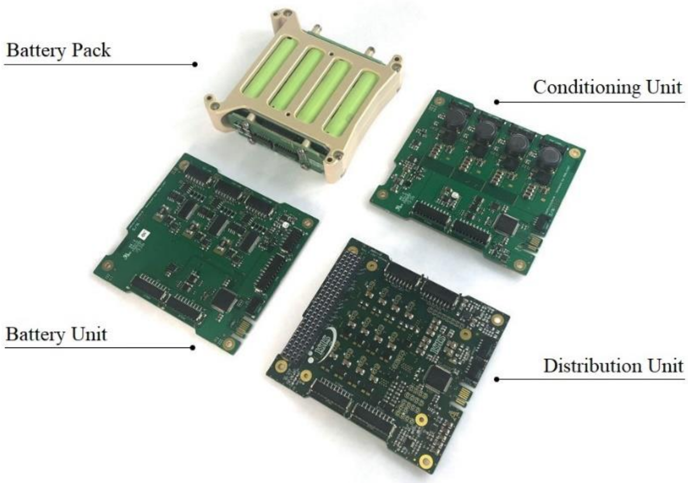


Figure 18 Example of modular electrical power system developed by ISISPACE [33]

Command & Data Handling

The processing requirements are easily handled by the current generation of microcontroller and the current technology is advanced enough. It is already in use and will be used in the upcoming years. Currently there are produced highly integrated and modular systems that contain the compute unit, memory, and the ability to support a variety of inputs & outputs for the CubeSat class of small spacecraft. Figure 19 shows a highly integrated board with a processor, memory, and several connectors [24].

Figure 19 Highly integrated board from AAC Clyde Space [34]

Guidance, Navigation & Control

The Guidance, Navigation & Control (GNC) is a system composed of an attitude determination part and a part used for its control. The attitude is determined with sensors such as sun sensors, star trackers, horizon sensors, etc. To change spacecraft's direction and speed are used actuators such as magnetic torquers, thrusters or reaction wheels. Every system includes sensors like accelerometers which measure velocity. When required velocity change is achieved the manoeuvre is stopped [24]. Figure 20 shows a guidance, navigation & control unit which contains three reaction wheels to provide a 3-axis control, sun sensors with a nadir sensor and a magnetic torquer as the actuator. These components are integrated on appropriate PCB stack.

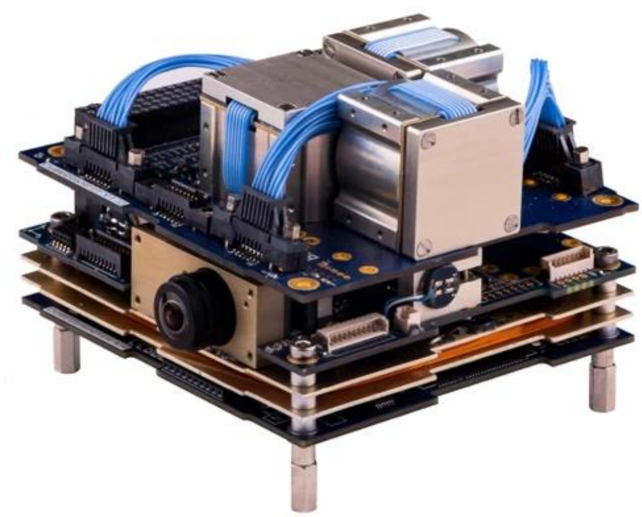


Figure 20 GNC unit [35]

Thermal control

Every component of a spacecraft has a range of acceptable temperatures which must be kept securing the functionality of the satellite. Temperature can be regulated by passive or active technology. Passive thermal control means that the temperature of a component is controlled without any source of power. The main advantage of these systems is lower mass and volume than can be achieved by active thermal control components. As examples of such systems can be mentioned insulation, heat pipes, or coatings. On the other hand, active thermal control uses power to maintain the temperature of a component. The advantage of these systems is that they can secure tighter temperature ranges of a spacecraft than the passive ones. Electric coolers or electrical resistance heaters are common examples of such devices. An example of a passive thermal control device is in Figure 21. It is a copper thermal strap. Copper is usually used because it has good thermal conductivity [24].

Figure 21 Thermal strap [36]

Propulsion

Propulsion is an optional subsystem. In-space small spacecraft propulsion technologies are categorized as chemical or electric. Chemical systems are usually applied when high thrust is needed, or rapid manoeuvres are required. Chemical systems continue to be the in-space propulsion technology of choice when their total impulse capability is sufficient to meet mission requirements. Electric propulsion devices have fractional thrust compared to chemical, but on the other hand, these systems can provide greater total impulse [24].

1.2.4 Assembly procedure

This part provides a preview of how a CubeSat assembly process can look like. For this purpose, PW-SAT2 was chosen which is a 2U CubeSat developed by the Faculty of Power and Aeronautical Engineering Warsaw University of Technology launched in 2018. The CubeSat was chosen due to its available documentation. The payload of the satellite was a deorbit system (deployable sail) as a technology demonstration [37]. The satellite is shown in Figure 22.

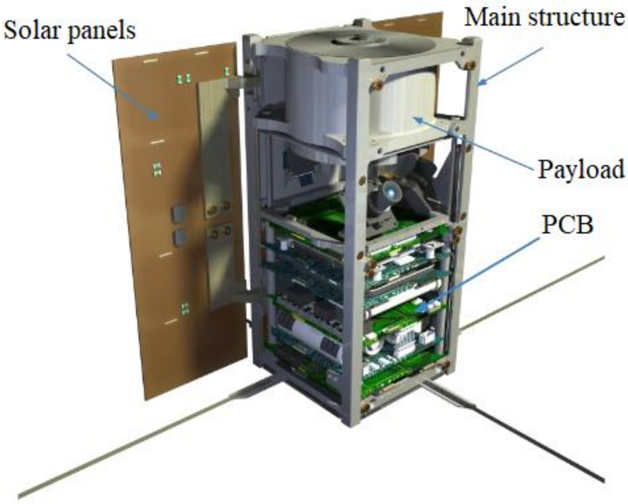


Figure 22 PW-SAT2 [37]

Firstly, printed circuit boards (PCBs) were assembled. The PW-SAT2 accommodates PCBs that belong to communication system (COMM), electric power system with accumulators (EPS + ACCU), attitude determination and control system (ADCS), on board computer (OBC) and last is servicing the payload (PLD). On the bottom, there is an antenna (ANT). These boards are mounted on 4 rods with spacers to separate them. Figure 24 shows assembled PCB stack [37][38].

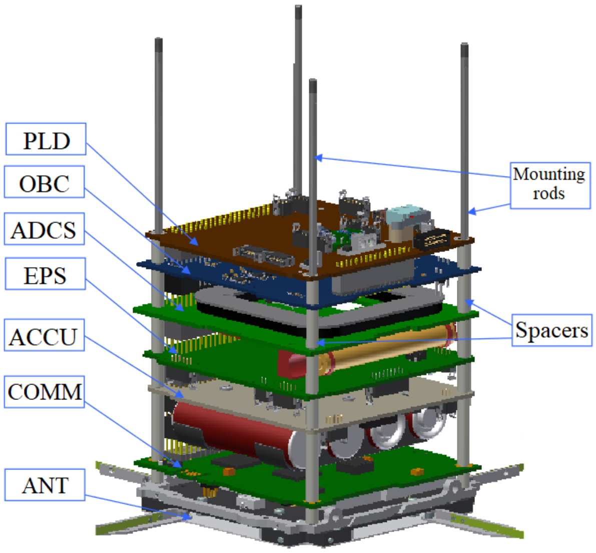


Figure 24 Assembly of the PCB stack [37]

The following step was to add the secondary structure (SS) to improve strength of the structure. The structure has also mounted points for cameras (CAM1 and CAM2). Third step was placing the sail module on top of the secondary structure. The payload module contains sail release mechanism (SRM), container and cover. Figure 23 shows these two steps. After completion of the PCB stack could be the assembly moved to a horizontal MGSE where these were executed. When it was assembled together, the harness could be applied [37][38].

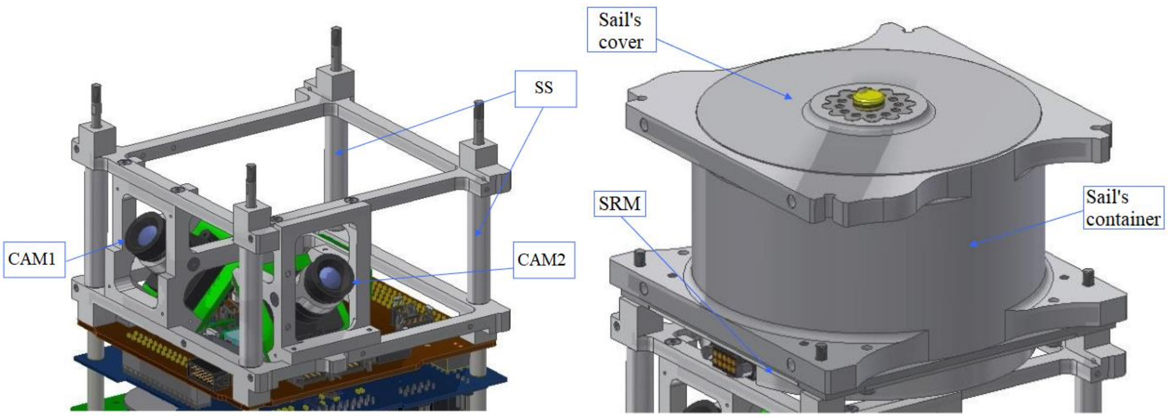


Figure 23 Assembly of the secondary structure without the payload (left) and with the sail unit (right) [37]

Fourth step was to mount the primary structure rails with hinges and sleeves for connection with interface to connect solar array deployable system. Final step was to add external parts such as camera wall, shield, and solar panel & solar arrays. When the payload and the PCB stack were integrated together, the assembly could be moved to a horizontal MGSE where were executed last two steps [37][38]. These steps are shown in Figure 25.

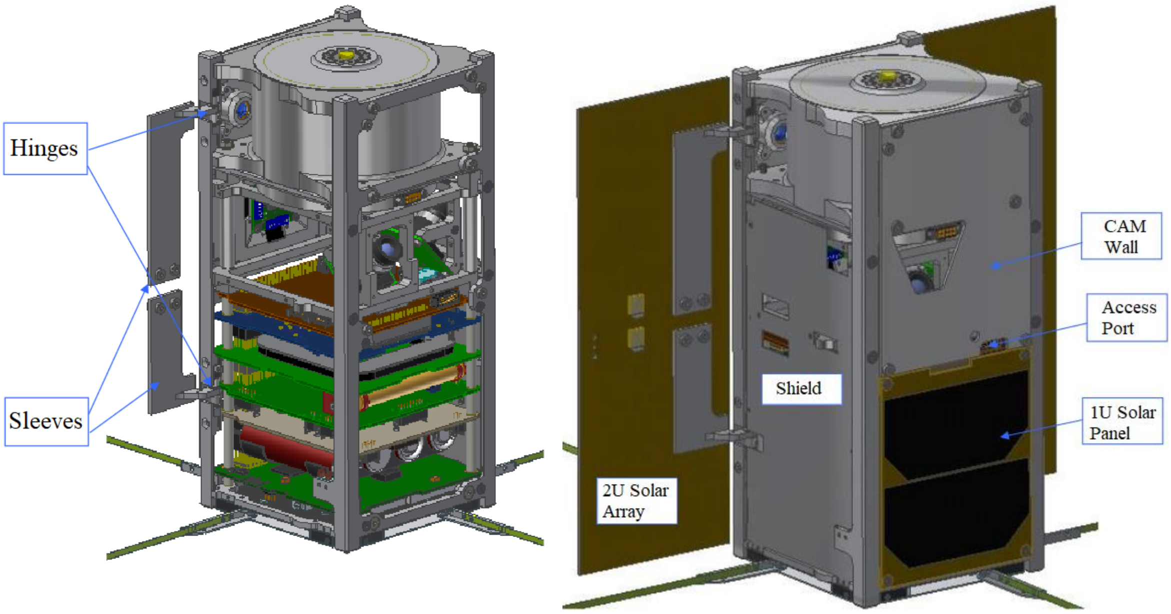


Figure 25 Adding the primary structure (left) and the solar system with shielding (right) [37]

1.3 MGSE for CubeSat integration

MGSE for CubeSat integration is created to both facilitate and shorten the assembly process while satisfying the quality requirements. It reduces the damage to the satellite system during handling. Any manual activity with a satellite must be done with care. Nevertheless, it consumes resources due to necessary activities like reporting and safety procedures included in the original not-optimized process shown in Figure 26. Implementation of the appropriate tool may help to reduce steps as well as the effort and required resources needed to achieve the goal. It shortens the procedure of manipulating the satellite when all manual activities are performed, such as mounting components inside the satellite and performing tests [39]. These MGSEs are divided into static and dynamic.

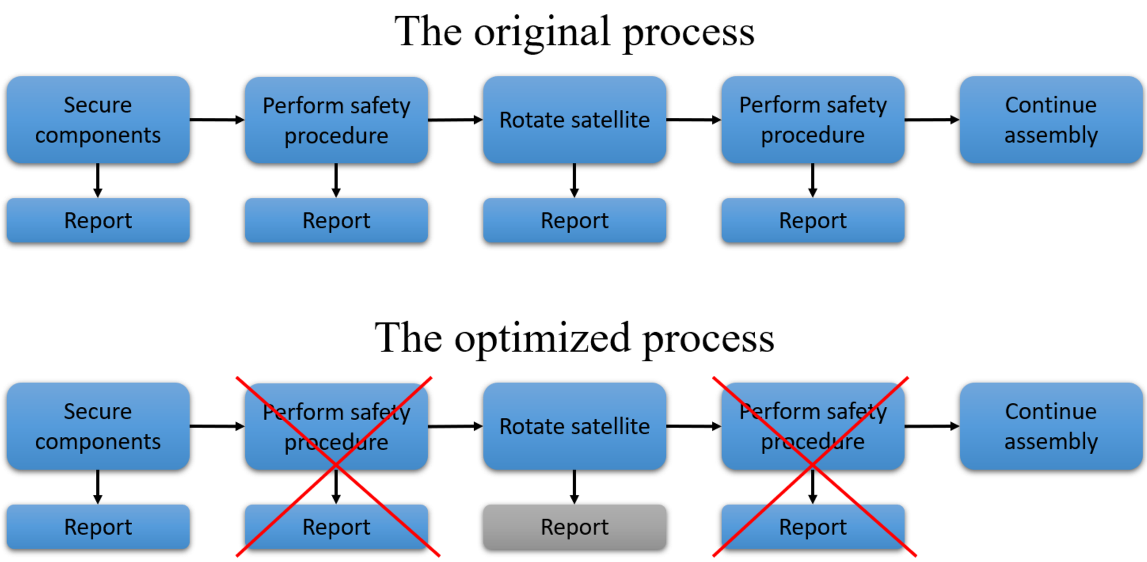


Figure 26 Optimalization of assembly process [39]

1.3.1 Design

Static

Static design of MGSE means that CubeSat is mounted in a jig in a fixed position with no ability to rotate. For rotation of the satellite, it is needed to demount it, rotate it, and then mount it again to the required position. This type of device consists of a metal sheet with holes or grooves for segments which can fix a required position of a satellite. In the sheet, there are also holes for a grounding connector, because Electrostatic discharge (ESD) can damage sensitive electronic devices during the integration. Most of the parts are made of an aluminium alloy. Non-metal parts such as covers on segments are made of polymer material. These covers prevent causing damage to the primary structure. Figure 27 shows a static design, where is a base plate with segments which can mount a CubeSat in different positions.

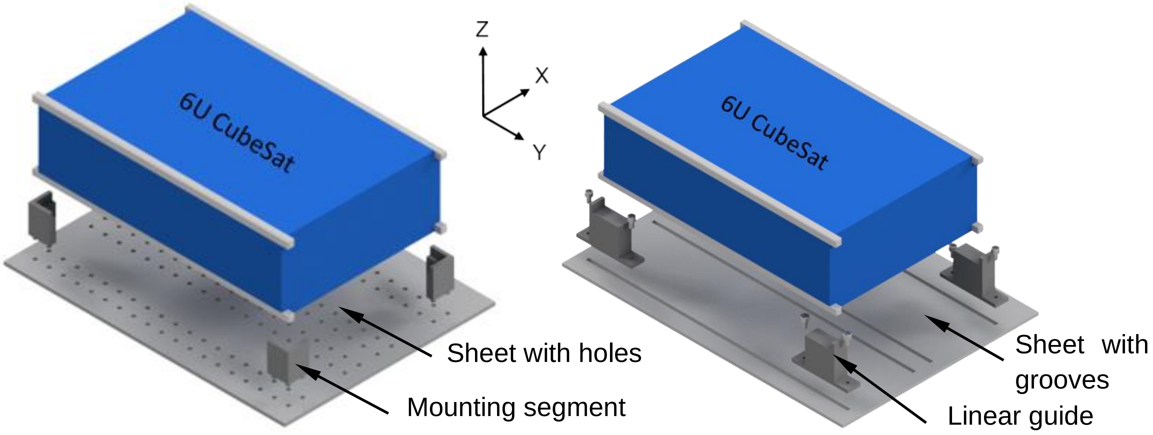


Figure 27 Static MGSE for CubeSat integration with a system of holes (left) and a linear guide (right)

Dynamic

Dynamic MGSE is a device which has from 1 to 3 degrees of freedom and allows to rotate a satellite within a single mount. This device consists of a body with an arm or a simpler rotational mechanism such as bearings with a locker to fix the satellite in a desired position. This type of device also contains a grounding connector. Figure 28 shows a design of the MGSE which can rotate a satellite about two axes. In the device is mounted a 6U CubeSat and axes of rotation are highlighted with red colour.

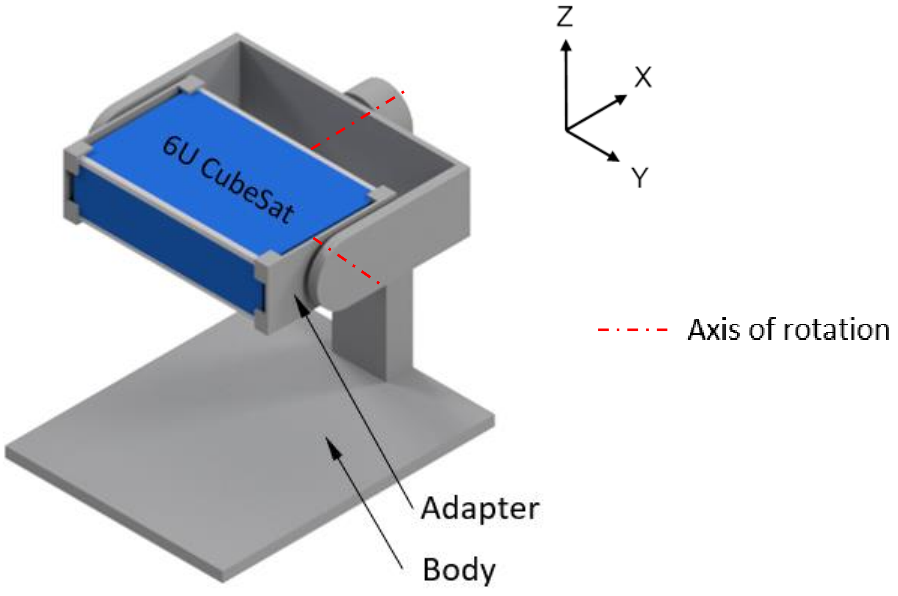


Figure 28 Dynamic MGSE for CubeSat integration with two axes of rotation

1.3.2 Market research of MGSE

ISISPACE

They have developed a static MGSE for horizontal and vertical integrations of a CubeSat in range from 1U to 3U. Devices consist of aluminium alloy base plates where are inserted jigs using holes. Jigs are equipped with a polymer cover made of Polyoxymethylene Copolymer (POM-C). The cover serves as electrical insulator and protects the structure of the satellite. All the devices also contain two grounding connectors to connect grounding cable. Parts are screwed together. Price of the ISISPACE jig set is 2500 € and it contains 1U horizontal, 2U - 3U horizontal and 1U - 3U vertical MGSE. In Figure **29** is shown the set where in the front, there are horizontal jigs and in the back is the vertical jig [40].

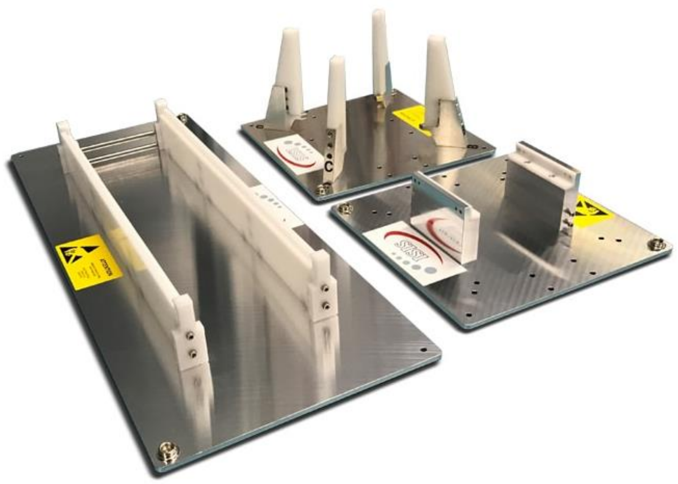


Figure 29 The MGSE set for integration from ISISPACE [40]

LatAmSAT

Their solution is an equivalent of ISISPACE. It is a static MGSE which consists of an aluminium alloy base plates where are inserted segments. Used materials are an aluminium alloy for metal pieces and Teflon (PTFE) for plastic pieces. Price of the set of three jigs is 2350 €. Figure 30 shows the LatAmSAT product line where from left to right, there is up to 3U horizontal, 1U horizontal, and 1U - 3U vertical MGSE. Figure 30 shows their line-up [41].

Figure 30 Set of LatAmSAT MGSE units [41]

EnduroSat

They offer a multifunctional static device. It serves as MGSE used for integration as well as protective housing while transport is needed. Figure 31 shows configuration used for integration with 1U CubeSat, and configuration used for transport. The jig can mount CubeSats in range from 1U to 3U. The jig is also modular and is made up of five modular component parts that are screwed together. This design approach allows to use the same parts for different configurations. Metal alloys as well as plastic materials are used on the jig. Metal parts are made of aluminium 6 series and are blue anodized. The jig parts which are in contact with the satellite are all made of POM-C, which is a high friction resistive material. This material prevents the mounted CubeSat from being scratched. Pricing for this device is 2900 € [17].

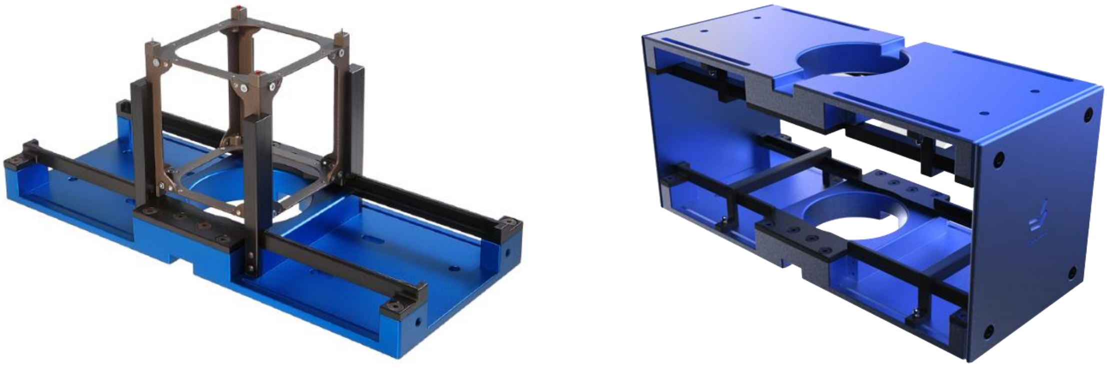


Figure 31 Multifunctional MGSE for integration (left) and transport (right) made by EnduroSat [17]

SPACEMIND

They offer two static jigs which are compatible with all standard sizes from 1U to 12U. First jig called GSE00 is a modular MGSE easily reconfigurable in 1U - 3U vertical as well as horizontal stand. Vertical and horizontal rail holders are made of Polyamide (PA6). Second jig GSE12 is compatible with structures up to 12U. Both devices have a ground connection. Both devices are shown in Figure 32. Pricing for these devices is 1500 € for GSE00 and 4300 € for GSE12 [42][43].

Figure 32 GSE00 (left) [42] and GSE12 (right) [43]

STM

STM solution is called Modular Assembly Table (MAT). It is a static device which allows to mount CubeSats vertically or horizontally in range from 1U to 12U. It consists of a set of holes where the jigs are put and screwed to the base plate. It consists of grooves as well, where sliding adjustable supports are inserted. There are also used metallic and non-metallic materials. Metallic parts such as base plate and jigs are made of an aluminium alloy, and non-metallic parts such as plastic cover on jigs to prevent any damage to the satellite structure are made of PTFE. Figure 33 shows the MAT in configuration where all jigs are mounted. In this configuration the device can weigh more than 6 kg. Two handles are added for easier manipulation. There is an option for anodization of metal parts. Price of this device is unknown [44].

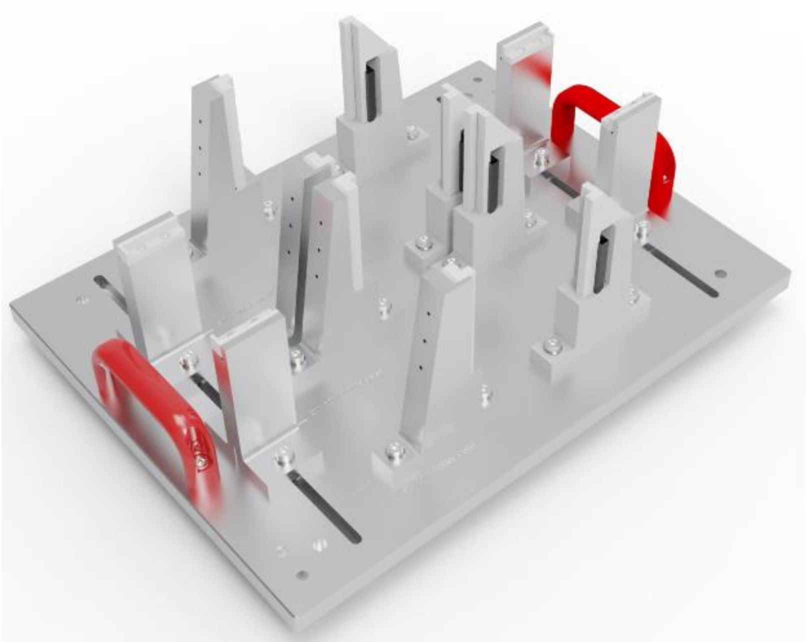


Figure 33 Modular assembly table [44]

MURB Space

3D MGSE is a dynamic type of MGSE which allows to rotate the satellite in 3 axes. Each axis has a locking mechanism. The jig is highly universal because the adapter can be modified according to the satellite requirements. Because of the modularity, any sized and shaped CubeSat can be mounted in the jig. This device also has an integrated communication interface, so it is possible to communicate with the satellite. It also can supply a satellite with the electrical power. The device is shown in Figure 34. Price of the device is 5500 € [39].

Figure 34 3D MGSE with mounting options [39]

Custom MGSE

There are also custom-made solutions. Nevertheless, there is no available information about them. Figure 35 shows two examples of custom MGSE used for CubeSat integration. On the left is MGSE of 6U MarCO CubeSat and on the right is MGSE used for integration 3U VZLUSAT-2 [45][46].

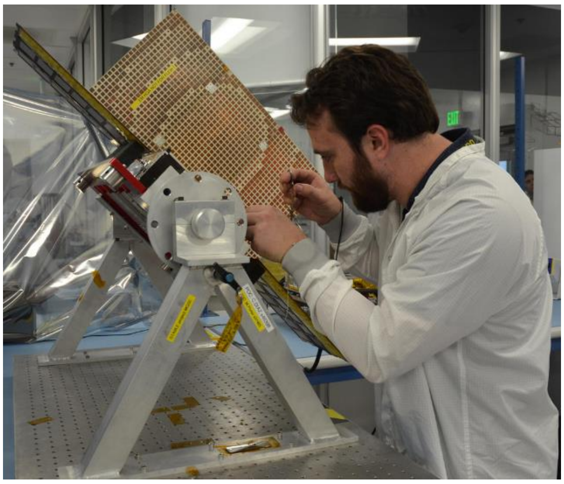


Figure 35 Custom MGSE for MarCO CubeSat (left) [45] and VZLUSAT-2 (right) [46]

Summary

Table 4 Summary of the market research

Manufacturer	***Type***	***Device***	***Size***	***Price [€]***	***Material***	***Reference***
ISISPACE	Static	2x HMGSE 1x VMGSE	1U–3U	2500	Aluminium POM-C	[40]
LatAmSAT	Static	2x HMGSE 1x VMGSE	1U–3U	2300	Aluminium Teflon	[41]
EnduroSat	Static	Jig	1U–3U	2900	Aluminium POM	[17]
SPACEMIND	Static	GSE00 GSE12	1U–12U	1500 4300	Aluminium PA	[42][43]
STM	Static	MAT	1U–12U	Unknown	Aluminium Teflon	[44]
MURB Space	Dynamic	3D MGSE	1U–12U	5500	Aluminium Unknown	[39]

2 MARKET POTENTIAL OF CUBESATS

This chapter consists of market analysis and forecast. The analysis determines what is the trend of launching CubeSats and what are the most popular sizes. Forecast makes a preview of the situation for upcoming years. This chapter jointly reveals the relevancy of CubeSats in the space industry.

Kulu et al. [47] maintains a database where he keeps the information about launched CubeSats and some other types of satellites. The launching of nanosatellites started in 1998. Launching CubeSats started a few years later in 2003. Until the end of the year 2021, there were 1802 nanosatellites launched of which 1667 were CubeSats. That means out of all nanosatellites, 92 % are CubeSats. Progress of launched nanosatellites compared with CubeSats over time is shown in Figure 36 [47][48].

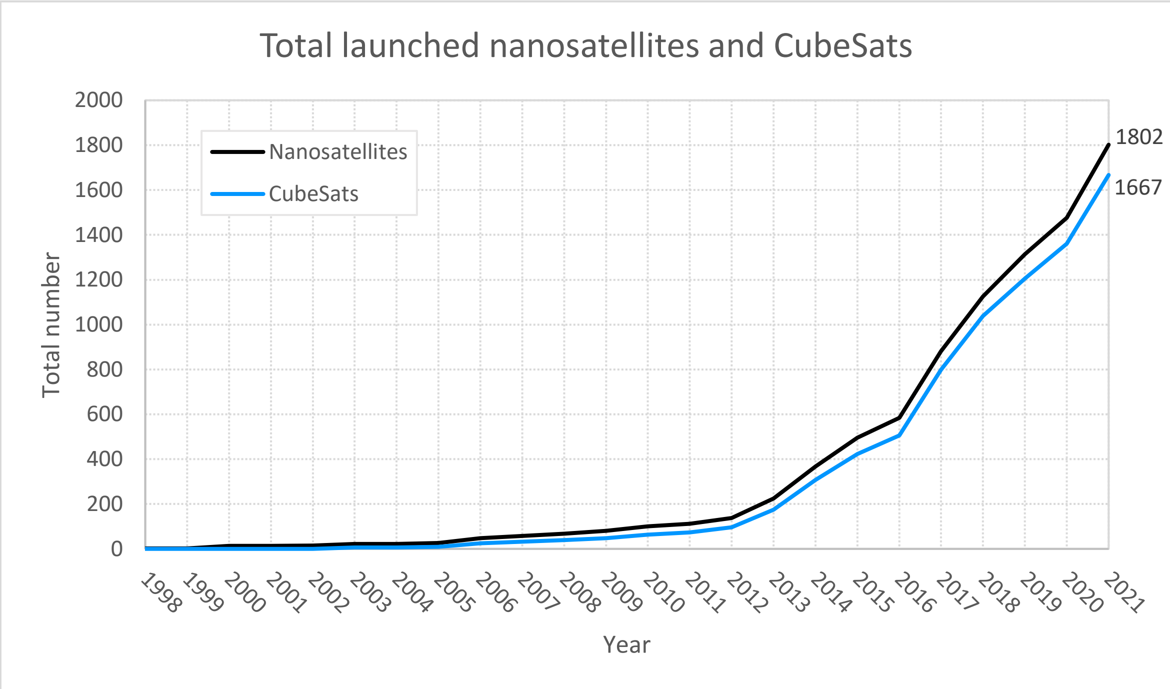


Figure 36 Numbers of launched nanosatellites over time [47][48]

From the chart can be deduced that curves have a growing tendency, so CubeSats strengthen their position within the space industry. Among 1667 launched CubeSats there were 1512 standard and 140 non-standard spacecraft, which means the standard form factor creates more than 90 % of all launched CubeSats. The CubeSat standard started with only 1U but over time it has evolved and accepted new sizes. The first new member of the family has been 3U. Later, have been accepted 1,5U, 2U, and 3U, and the latest additions have been 6U and 12U. So, the standard currently contains 6 sizes and any different size counts as non-standard [47][48].

The most used standardized size has been the 3U with 932 satellites launched so far. On the second place has been the 1U with 253 launched pieces. Surprisingly, the third most used size has been the 6U even though the first launch of the size was in 2014 with 162 6U launched spacecraft [47][48]. It was demonstrated that 6U CubeSat which can weigh up to 12 kg can perform missions equivalent to microsatellite in range of mass from 50 to 150 kg [49].

Beyond the current family, 140 CubeSats were launched. The most used non-standardized format has been the 0,25U with 128 launched satellites. Other sizes have been launched insignificantly. Figure 37 shows information about all types of launched nanosatellites in more detail [47][48].

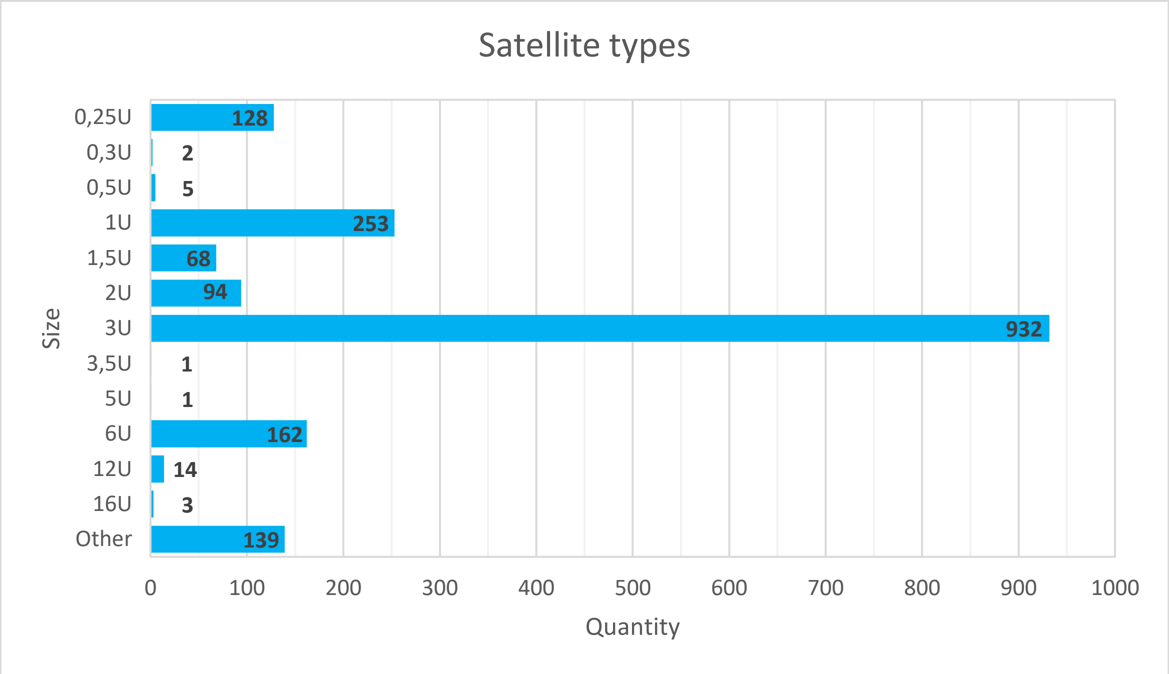


Figure 37 Types of launched nanosatellites [47][48]

The number of launched 3U is highest of all platforms but it does not mean that there orbits 932 independent 3U CubeSats. A lot of satellites work together as a constellation. These constellations can consist of units to thousands of spacecraft. Table 5 shows an overview of big constellations of CubeSats to demonstrate their impact to total launched numbers [47][48].

From the table is obvious that CubeSats which are part of a constellation make a big part of the total launched satellites. For example, 121 out of 128 0,25U CubeSats belong to the SpaceBEE constellation. Another case is that the two biggest 3U constellation - Dove and Lemur - make more than 30 % of all launched 3U spacecraft [47][48].

Table 5 CubeSat constellations [47][48]

Developer	***Constellation***	***Size***	***Quantity Launched / planned***
Planet	Dove	3U	200+ / 150
Spire	LEMUR	3U	150 / 150
Swarm Technologies	SpaceBEE	0,25U / 1U	121 / 150
Kepler Communications	GEN1	3U / 6U	15 / 140
GeoOptics	CICERO	6U / 12U	7 / 50
Fleet Space	Alpha	3U / 6U	6 / 140

Figure 38 shows the distribution of types of spacecraft that make a constellation. The most popular type of spacecraft are CubeSats with more than 40 %. It can be even more than that because about 15 % of constellations have currently unknown specific sizes but are most likely to be CubeSats [47][48].

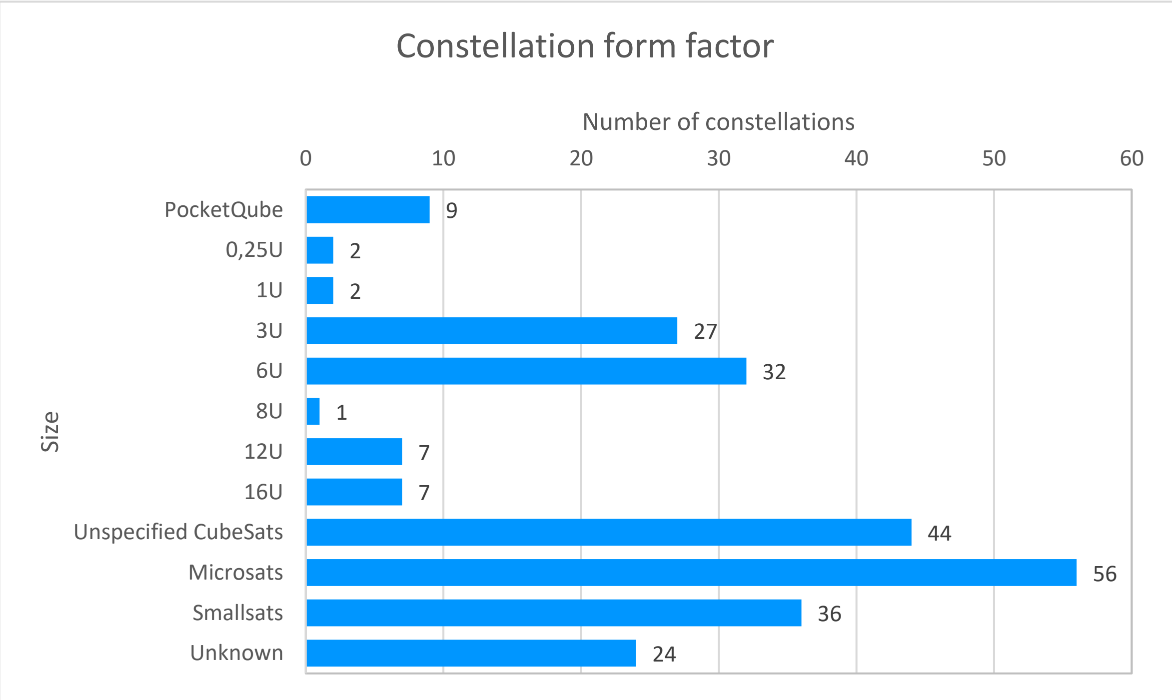


Figure 38 Constellation form factor [47][48]

Even though the most popular size is 3U, there is announced more constellations with 6U form factor.

Also, ways how are small satellites delivered to space makes them even more attractive platform due to a lower pricing. Generally, CubeSats are a secondary payload. They are transported to the space as a rideshare payload or piggyback payload. Both types are a secondary payload. The secondary payload is a minor payload which needs an adaption to launch conditions such as launch date or final orbit. These downsides are compensated with a lower price for the launch. Today's rideshare flights can deliver to an orbit more than one hundred spacecraft during a flight [50][51][52].

2.1 Future of CubeSats

From the market research is clear that CubeSats are a fast-growing part of the space industry. Figure 39 shows forecasts of several developers with its evolution over time. The most actual forecast from January 2020 counts with more than 2500 launched nanosatellites from 2022 to 2028 which is even more since they have begun, although the previous one from 2018 predicted slightly higher numbers. One of the reasons might be the virus Covid-19 because it has affected the entire world since it has started in 2019. Despite this unfavourable information, number of announced nanosatellites to be launch in the year 2022 has exceeded all forecasts by about 30 %. For next years, the latest forecast predicts an increase of the launched satellites by about 20 % per year although the current number of announced spacecraft is a fraction of that. Among the announced spacecraft are counted those which have booked a place on a rocket. The process of booking is handled in a matter of months before the flight. So that can be a reason why are current numbers so low [48]. Figure 40 shows launching year of announced constellations.

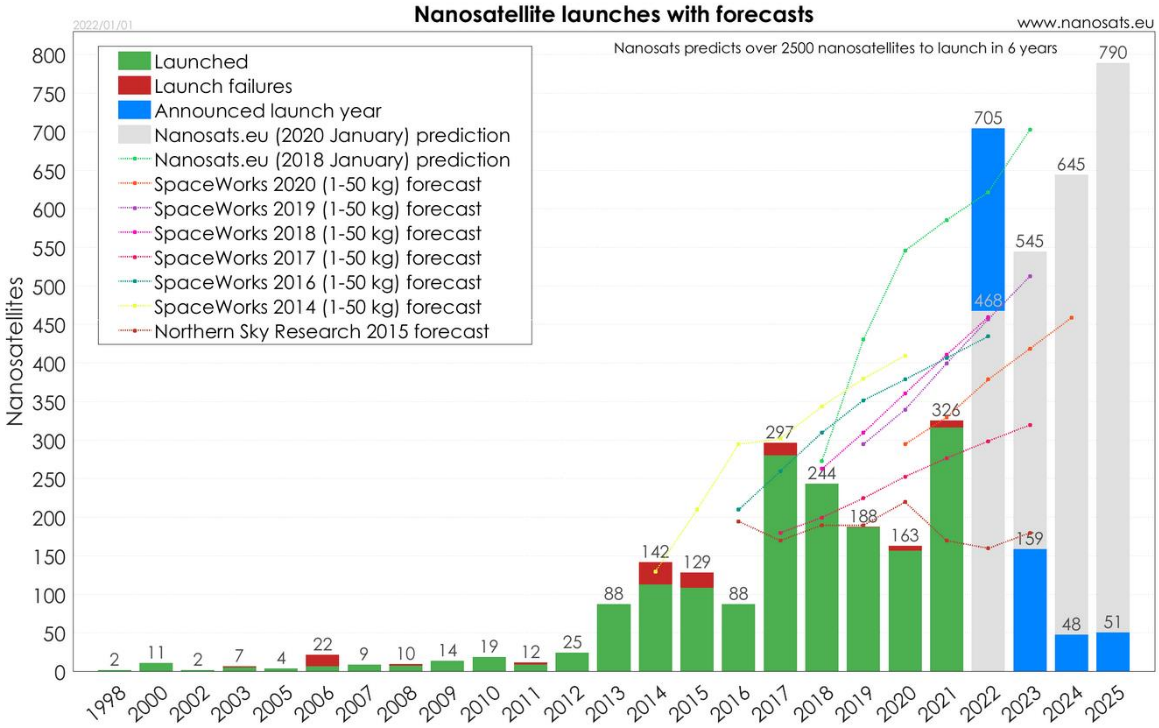


Figure 39 Constellation first launches [48]

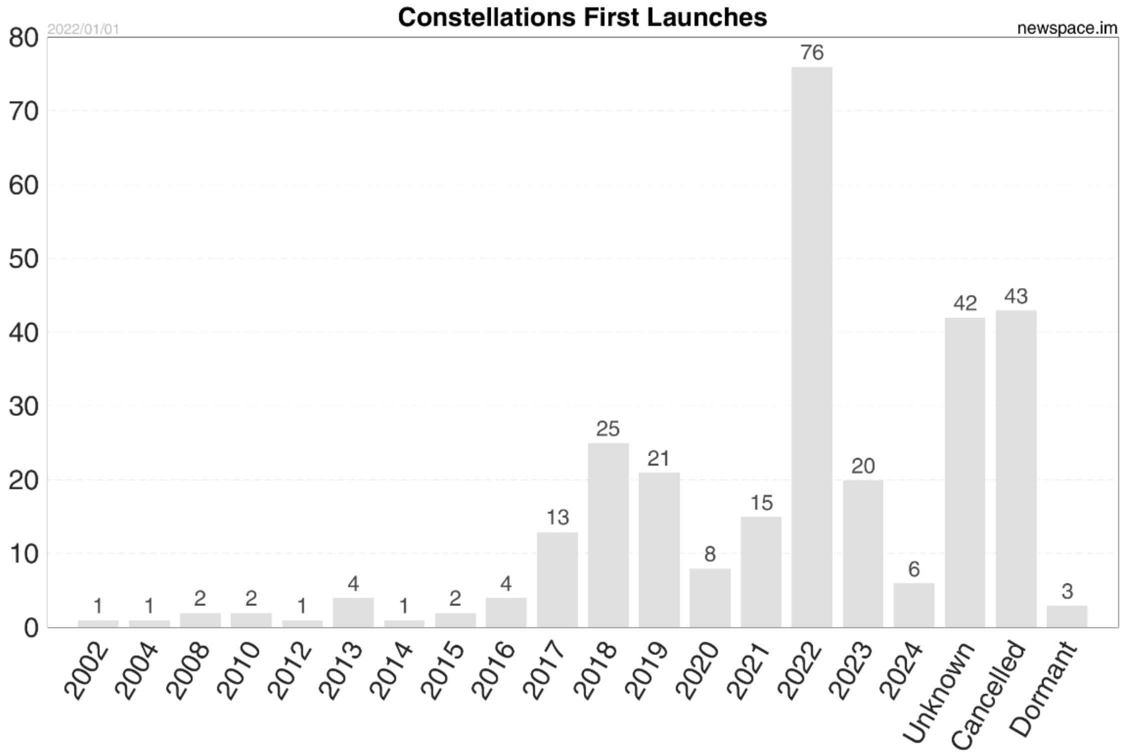


Figure 40 Nanosatellite launches with its forecast [53]

3 PROBLEM ANALYSIS AND AIM OF THE WORK

3.1 Analysis and evaluation of the literature review

CubeSats are part of SmallSats with a wide range of applications. Their journey started in 2003 when 6 satellites were launched. 307 CubeSats were launched in 2021 and the forecast predicts that number of deployed satellites will increase. The forecast done by *Nanosats.eu* was exceeded by 116 %. In few next years until 2025, the same forecast predicts a 15% increment of launched CubeSats per year. It can be deduced that CubeSats are a valid area of interest in the space industry because the number of launched spacecraft is growing by more than 15 % increment.

In general, large and medium spacecraft use MGSE developed especially for purposes of the spacecraft. Because integrational jigs are only a tool in the spacecraft lifetime process there is not much information available. On the other hand, commercially available solutions such as multipurpose trolleys or lifting devices are also an option which can fit. The second type of MGSE is storage & transport containers which ensure a controlled environment for the spacecraft.

Basic types are static and dynamic. Static has a simple design but does not allow rotation with the spacecraft. It is cheaper to develop a static device, but the integration will be more time-consuming. The dynamic is the opposite to the static because it allows to rotate a satellite but it takes more resources to produce and develop. Also, they are distinguished into two types by the integrational position of the spacecraft to vertical and horizontal. Commercial solutions are mostly designed for integration 1-3U form factor. Jigs for 6-12U are not yet common even though these sizes have a big potential. These devices meet the requirements of the work but with a price over 4000 € for the cheapest one, it is unacceptable to use.

3.2 Aim of the work

The main goal of the thesis is to propose the MGSE for 1-12U CubeSat integration. A comparison of two basic types needs to be completed in order to choose a final solution. The comparison needs to be performed by specified parameters such as price, adaptability between sizes or ergonomics for the service. Also, there will be compared integrational processes with and without the MGSE to demonstrate its benefits. The result of the comparison is a single solution which will be developed. Another output of the work are 3D data and drawings.

4 CONCEPTIONAL DESIGN

This part describes crucial characteristics which reflect what type should be chosen as the final design.

4.1 Adaptability

Adaptability evaluates the accessibility to a satellite during the integration. The first paragraph of each type describes the ability to rotate a satellite during one mounting. This influences the total time needed for the integration process. The second paragraph describes an ability to modulate into a state where it would be possible to integrate a CubeSat in a different position such as vertical or horizontal. It also evaluates the ability to mount a different size of CubeSat.

Dynamic

The rotating mechanism of the MGSE with two degrees of freedom is an effective solution both in terms of access during one mounting and the number of dismounts required during the entire assembly process. It gives access to sides without top and bottom parts during a single mount or the opposite – it gives access to the top and the bottom, but two sides are inaccessible because they are mounted in the adapter. This is an advantage for the integration of bigger units such as 12U because they can weigh up to 24 kg and manipulation with these spacecraft cannot be easy. Therefore, any kind of rotation instead of remounting is a time-saving aspect. Ability to rotate a satellite can be also time-saving in the process of a connecting harness.

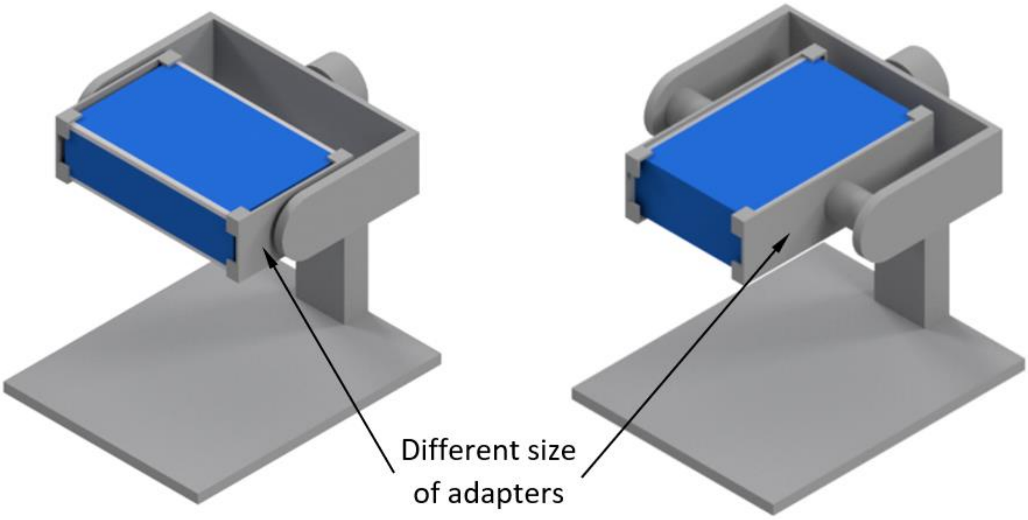


Figure 41 Access to sides (left) and access to top and bottom side (right) with a need of different adapters

Modulation of this type of design is more problematic. Technically, for each size of a CubeSat and position on the integration, a separate adapter is needed. For example, switching a 6U CubeSat means that also adapters need to be switched. Figure 41 shows an example of a 6U CubeSat where adapters with different sizes are needed to get an access to all sides.

Static

Static MGSE is not as efficient as dynamic in accessibility to a satellite during one mount, so this type needs a demount-rotate-mount process more often. This does not mean necessarily a problem for smaller units. Sizes up to 3U are small and light and manipulation with them can be handled by one hand. The demount-rotate-mount process can be more problematic and time-consuming.

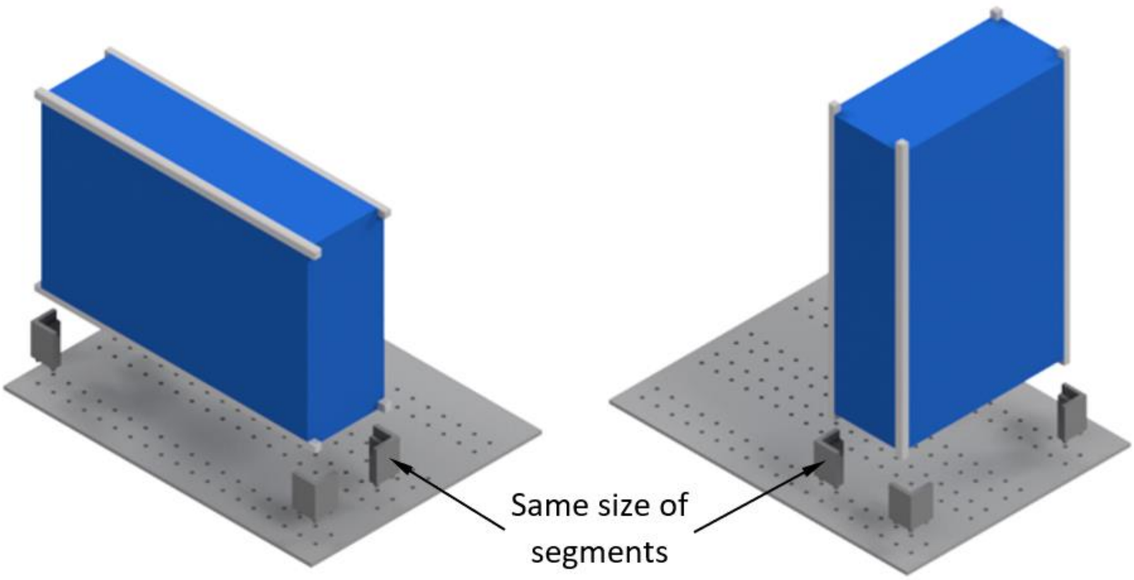


Figure 42 6U CubeSat in different positions using same adapters

In terms of mouldability this type is a more efficient solution. Theoretically, one set of segments can be used any position of integration, no matter what size is integrated. That is shown in Figure 42. Practically, there are different sets of segments for horizontal and vertical position because a CubeSat in the vertical position needs ensure more stability than in the vertical position.

4.2 Ergonomics

This part describes how difficult is to operate MGSE for a person who would integrate a satellite. Some characteristics of ergonomics were described in the previous part intended for adaptability because these parts are closely connected. Generally, the integration of smaller satellites is less demanding in terms of time and physical strength because a 1U CubeSat can weigh up to 2 kg and its maximal dimension is 113 mm. On the other side of the CubeSat standard range is a 12U CubeSat which can weigh up to 24 kg and its maximal dimension is 366 mm.

Dynamic

A dynamic MGSE allows rotation, turn, or tilt of a satellite to a more desired position by an integrator to make the assembly process more comfortable. It also reduces the number of remounting because it gives access to a bigger part of a satellite and thus increases safety and time saved during the integration. This applies to bigger CubeSats such as 6U and 12U. A disadvantage is that a dynamic MGSE has a bigger dimension than a static one.

That can feel uncomfortable during an assembly process of a CubeSat such as 1U or 2U and using such a big jig for integration. Figure 43 shows the difference between the biggest and the smallest standard CubeSat in the dynamic MGSE.

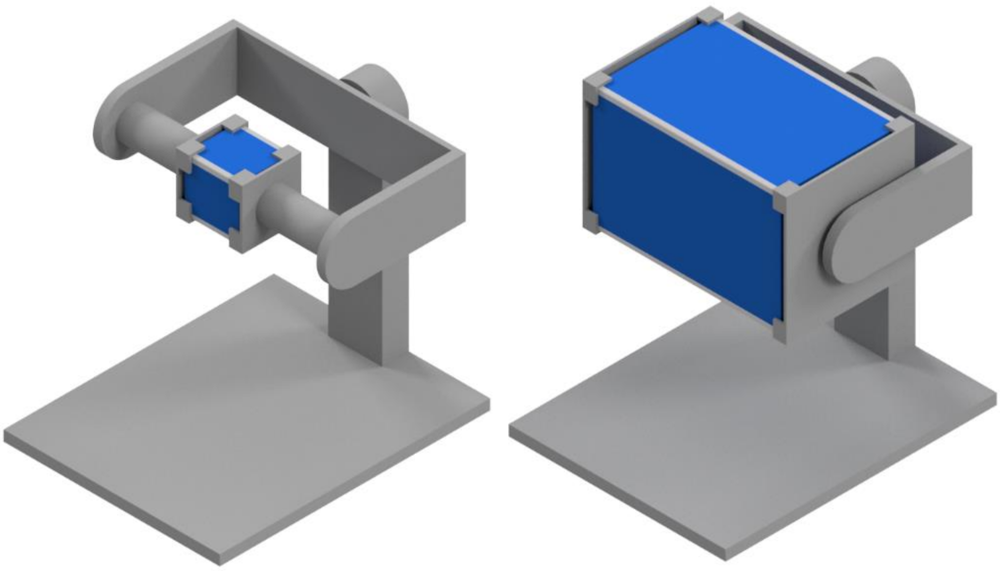


Figure 43 1U (left) and 12U (right) CubeSat in the dynamic MGSE

Static

A static MGSE fixes a satellite in a position on a table with limited access to the sides of a CubeSat and with no ability to adapt to desires of an integrator. To make the assembly process more comfortable a satellite needs to be remounted or the device needs to be manually rotated. This action is no problem when a small CubeSat is integrated. To perform the demount-rotate-mount process with a 12U satellite weighing 24 kg can be a task for several persons. On the other hand, size of the MGSE is more compact compared to the dynamic. Figure 44 shows the difference between the biggest and the smallest standard CubeSat in the dynamic MGSE.

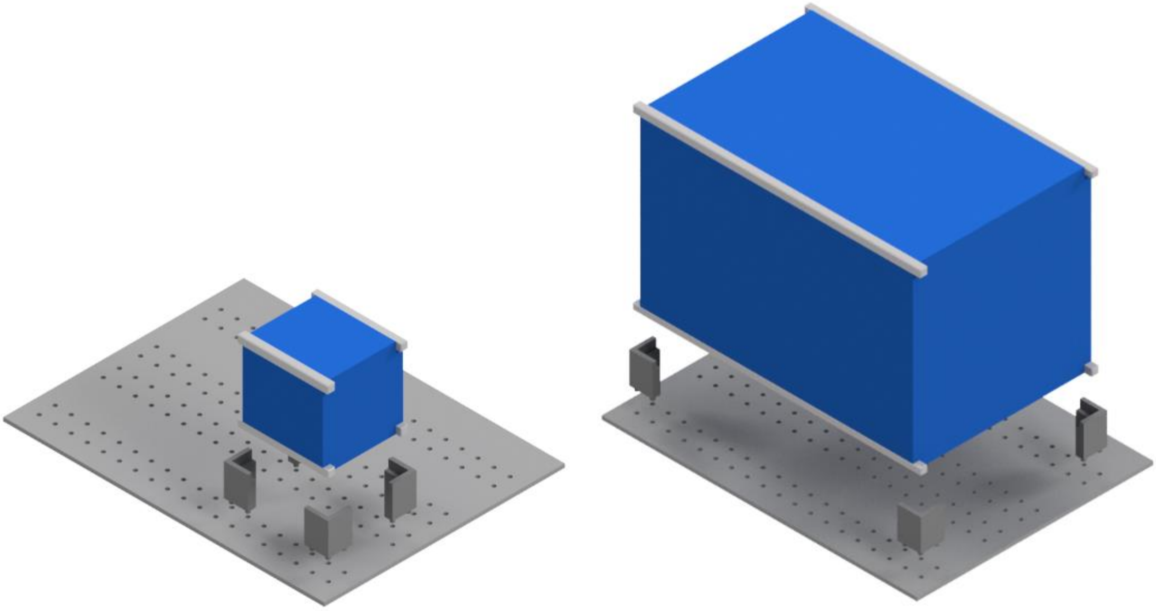


Figure 44 1U (left) and 12U (right) CubeSat in the static MGSE

4.3 Result

The market research showed that a static MGSEs in range a from 1 - 12U are cheaper compared to dynamic.

In terms of adaptability was found out that the dynamic provides better access during the integration but overall needs more adapters to mount all the sizes. The static requires more often the demount-rotate-mount process because it has limited access to sides of a satellite. On the other hand, it needs less components to mount all sizes. Also, rearrange the static MGSE for a different size is a less complex task, so the modulability is better there.

From the ergonomics point of view, the dynamic is more suitable for bigger sizes because they are heavier and rotating them is a more comfortable process. To rotate a big CubeSat such as 12U the device must be robust and integration of smaller sizes such as 1U may be a non-ergonomic process. The static design may has smaller dimension compared to the dynamic which is favourable for integration of small CubeSats such as 1U - 3U. Bigger sizes are heavier, and the demount-rotate-mount process may be non-ergonomic.

Because of the dynamic design reduces number of needed mounts, the integration process is less time-consuming there. All the compared parameters are summarized in Table 6 where the + symbol shows more suitable solution. In ergonomics are written suitable sizes for integration.

Table 6 Summarization of compared parameters

Parameter	***Static***	***Dynamic***
Price	+	-
Accessibility	-	+
Modulability	+	-
Ergonomics	1U – 3U	6U – 12U
Time-consumption	-	+

As the proposed type was found more suitable for the 1 - 12U the static MGSE because it is cheaper to produce, and its mechanical design does not contain complex subsystems such as rotational mechanism. The dynamic type should be considered in a situation where a company plans to build a constellation with a high number of satellites. There can be considered the total time savings during the integration process as an advantage.

5 CONSTRUCTION SOLUTION

This chapter concludes a detailed description of the proposed solution. As the first step, the need was to determine dimensions of all standard CubeSat sizes to get the general dimensions. These dimensions were acquired from the CubeSat standard. Attachment 9.1 shows all CubeSat sizes with their dimensions. The integrational process usually happens in a cleanroom where special furniture and tools need to be used. For a CubeSat integration, a workbench needs to be used. MGSE needs to be designed to fit on a workbench. Figure 45 shows a workbench with dimensions 900 x 1500 mm. On the workbench during the integration an MGSE needs to be placed, components for integration, tools used for integration and an EGSE to verify the functionality of subsystems. Software Autodesk Inventor Professional 2021 was used to realize 3D data, drawings, and renders.

Figure 45 Example of a workbench use in a cleanroom [54]

5.1 Material selection

The second task was to figure out what material should be used. Commercial devices contain metal parts, as well as non-metal parts. In some cases, metal parts were made of an aluminium alloy EN AW-6061. Prefix AW stands for wrought material and the 6000 series means that it is an alloy with Si and Mg. Due to these elements, the alloy is easily heat-treatable, weldable, machinable, corrosion-resistant and suitable for anodization. Anodizing is a chemical-thermal process that creates a protective oxide layer on the surface of a part, which increases corrosion and wear resistance [55]. An alternative to the EN AW-6061 is EN AW-6060, AW-6063 or EN AW-6082.

The alloy EN AW-6060 is widely used in applications with small loads. However, low strength characteristics are compensated with great machinability, surface quality with the ability to coat [56]. The alloy EN AW-6063 is suitable for applications with modest loads. The rest of the characteristics are similar to the previous alloy [57]. The alloy EN AW-6082 is suitable for high loaded applications [58]. All these alloys are commonly available in form of sheets, plates, or rods [59].

Table 7 compares the basic characteristics of alloys. Materials were compared in T6 temper which means that annealing and artificial ageing was applied [60]. Then in Table 7 are parameters rated with grades from 1 to 6 where the lower grade the better suitability. The scale is used from datasheets of materials.

Table 7 Comparison of metal materials

Material	*Tensile strength [MPa]*	*Machinability*	*Anodizing*	*Corrosion resistance*	*Ref.*
EN AW-6060	170	2	1	1	[56]
EN AW-6061	260	2	1	2	[55]
EN AW-6063	195	2	1	1	[57]
EN AW-6082	310	2	2	2	[58]

Polymer materials such as PA6, POM or PTFE were used for non-metallic components. Aluminium alloys have sufficient mechanical properties for milling such as tensile strength which can be multiple times higher than plastic materials. So, these polymer materials were investigated, and the result is summarized in Table 8. Compared parameters were tensile strength and ESD safety. ESD safe material prevents electrostatic charge from building up. Type of surface resistance determines if a material is ESD safe or not. There three types of surface resistance types [61]:

- *Conductive* – Materials with low electrical resistance. They allow the charge to flow easily to another conductive object.
- *Dissipative* – Materials with a controlled way of the flow of charge. The flow of charges is slower than conductive materials. These are ESD materials.
- *Insulative* – Materials with a high electrical resistance prevent or limits the charge flow across their volume to another object.

The result of the investigation is that PTFE does not fit in terms of tensile strength which is only 28 MPa and there is a higher risk of plastic deformation than other compared materials [62]. PA6 has the highest tensile strength which is almost 72 MPa but it is not an ESD safe material [63]. POM-C has a tensile strength of 65 MPa which is similar to PA, but it is also an ESD safe material, so the final design was chosen for this material [64]. This material is commonly supplied in the form of bars, plates, and sheets [65]. Information is gathered Table 8.

Table 8 Comparison of plastic materials

Material	*Tensile strength [MPa]*	*ESD safety*	*Reference*
PTFE	28	No	[62]
PA6	71,9	No	[63]
POM-C	65	Yes	[64]

5.2 Electrostatic discharge protection

Electrostatic discharge is the release of static electricity when two objects come into contact. Many ESD's are below the threshold of human perception but can be still harmful to electronic components and can cause total damage and hidden effects that can fail the component [66]. Due to this reason, appropriate protection needs to be applied. Sometimes, the integrational process of a CubeSat is realized in a cleanroom where a grounded anti-static mat is placed on an integrational bench. Figure 46 shows cases when ESD protection is applied on an MGSE. Also, a person who is doing the process integration wears a grounded antistatic wrist strap to eliminate the risks of ESD [67][68]. The jig is equipped with an ESD button for cases where the environment does not include a grounded surface such as an antistatic mat.

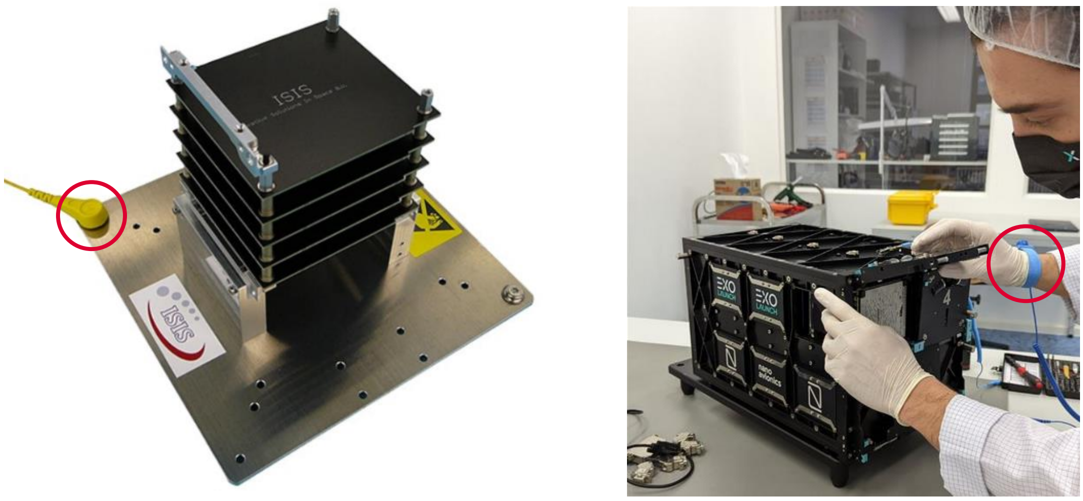


Figure 46 ESD plug (left) [67] and ESD wristband (right) [68]

There are two types of ESD studs which are male and female. For this application was chosen male type because grounding cables usually have the opposite one. Another division is by installation type into riveted and screwed. Riveted comes in a pack consisting of an upper and a lower part which need to be riveted together with a special tool [69][70]. Screwed comes in a pack that consists of the upper part and a screw. There is no need of special tools for assembly, but the surface of the surface must be countersunk for a screw head. For the final design was chosen screwed ESD plug because it is easier to assemble and chosen model is 067-1007, made by MULTICOMP, which has an M3 internal thread supplied with a Phillips screw. The set is shown in Figure 47 [71].

Figure 47 ESD plug 067-1007 [71]

5.3 Design of proposed MGSE

The device should be easy to manufacture, reconfigure and operate. As was described in chapter 4, the final solution is a static MGSE.

The design consists of a universal part which is the same for both horizontal and vertical mounting. This universal part is shown in Figure 48. The universal part consists of a 4 mm thick base plate made of EN AW-6061, which has three grooves with mounted sliding mechanisms, handles for easier manipulation and an ESD stud. The sliding mechanism has two holes on top which are prepared for a horizontal or vertical jig. From the bottom of the base plate, there are T-shaped nuts to allow the slider to be fixed in the desired position by tightening the screws. Screws on sliders serve as a locking mechanism where tightening screws fix the slider on the position. The sliding mechanism was chosen over the system of holes because it can easier fit non-standard sizes. In Figure 48 sliders are deployed at distance of 6U or 12U and if it is needed, there is a clearance of 18 mm for additional manipulation.

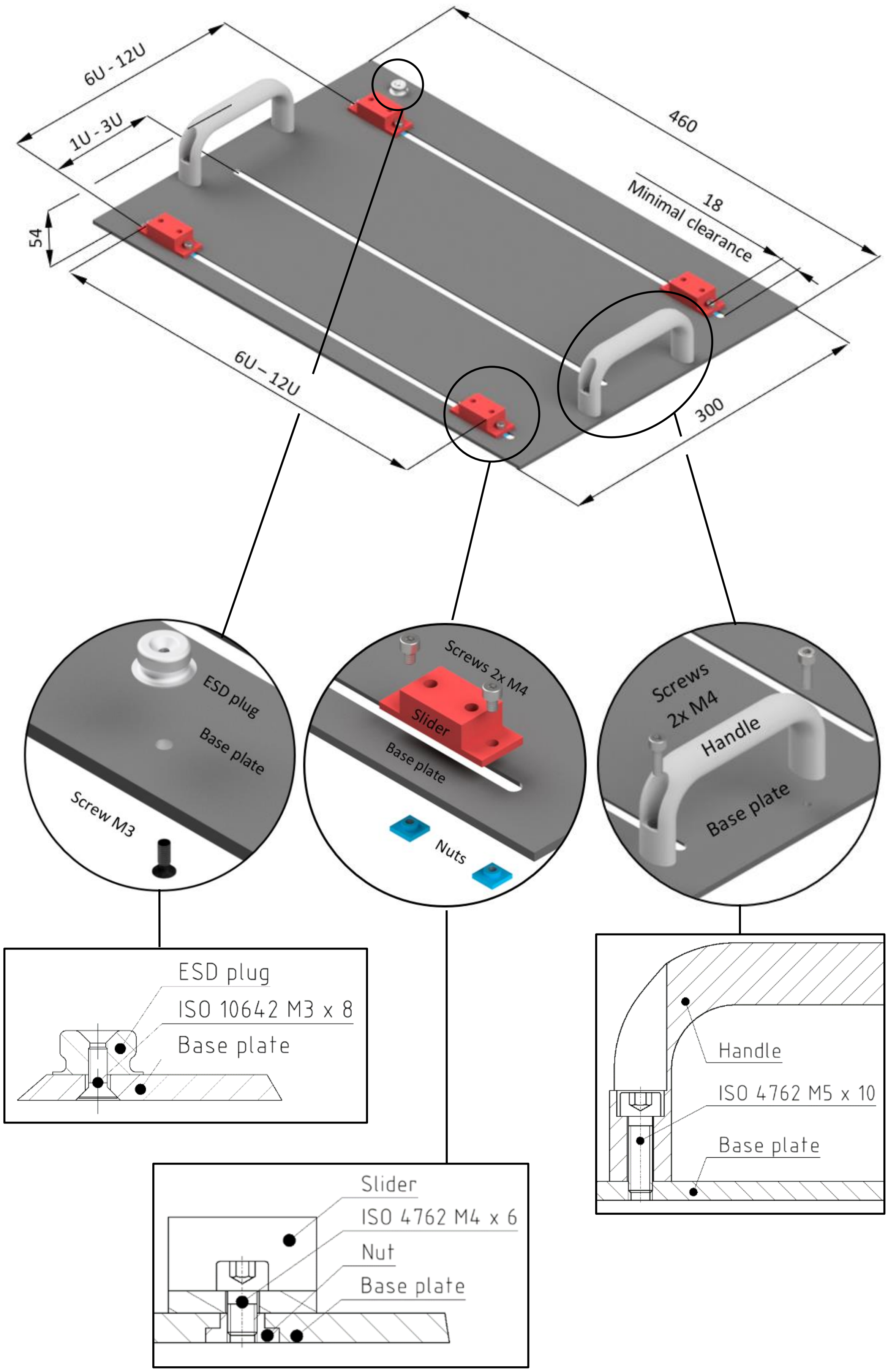
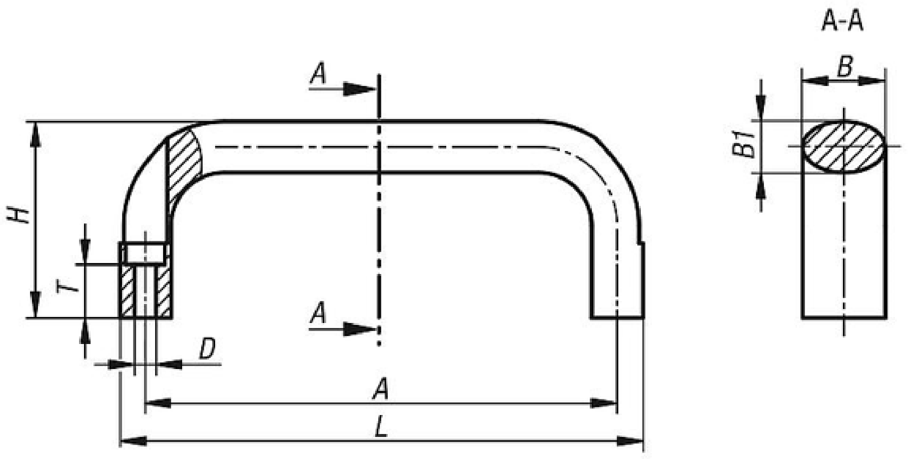


Figure 48 Description of the universal part of the design

The device contains two handles which are purchased items. The chosen type is called Pull oval handle with numbering 06920-11000105 and is made by Norelem. It is an oval handle made of aluminium EN AW-6060 with a black powder coating. This type of handle can lift up to 100 kg. Specification of the handle is described in Figure 49 [72].



Handle dimensions

A [mm]	*B [mm]*	*B1 [mm]*	*D [mm]*	*H [mm]*	*L [mm]*	*T [mm]*	*Load capacity [N]*	*Colour*
100	21	13	5,5	50	113	13,6	1000	Black

Figure 49 Dimensions of the handle [72]

5.4 Horizontal MGSE

The horizontal MGSE consists of universal part and another segment which is added to the slider. Figure 50 shows a 6U CubeSat in horizontal position and a detail of the horizontal segment where machined parts are together with their material.

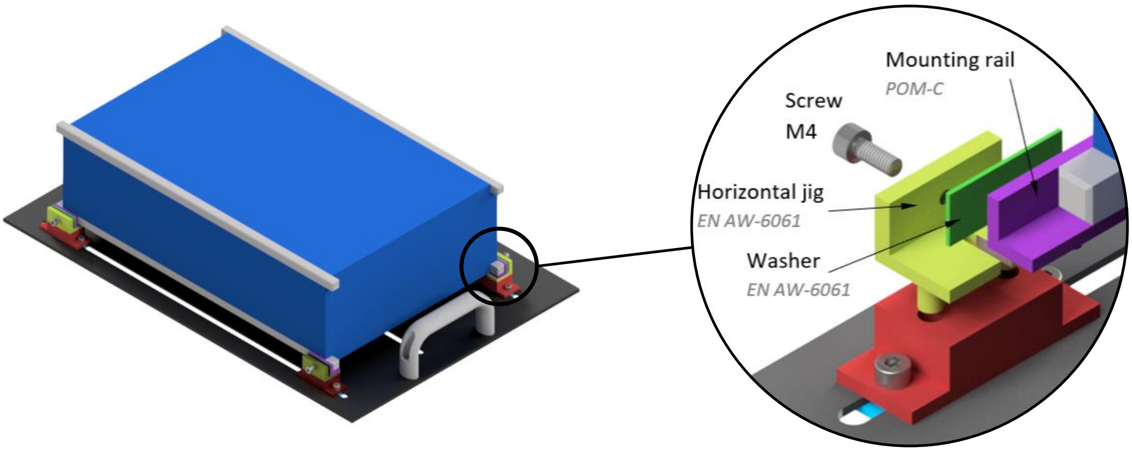


Figure 50 Description of the horizontal segment

The horizontal segment consists of three parts and a screw. There are two holes in the slider where fit pins are machined on the horizontal jig. In this case, an overlap fit Ø5 H8/h9 was chosen which is a recommended combination as a sliding fit with a small clearance and it is also used for centering parts [73]. The horizontal jig also contains a hole with M4 thread with ISO 4762 screw which serves as a locking mechanism. Tightening the M4 screw pushes the washer with the mounting rail which applies a force to a CubeSat and fixes its position. The washer prevents causing damage from the screw to the mounting rail. The distance between the satellite and the base plate must be large enough to fit fingers there during laying a satellite on the horizontal jig. Also, there must be enough space for fitting the Allen key for tightening M4 screws. Clearance during the tightening process shows Figure 51.

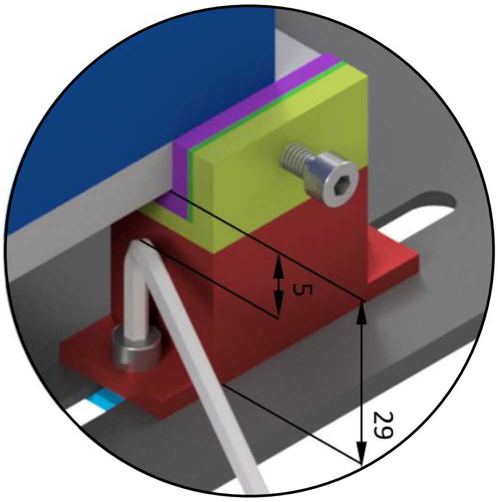


Figure 51 Clearances when a CubeSat in the horizontal position is mounted

The clearance between the horizontal jig and washer is given by the M4 screw and it varies in range from 0 to 4 mm. There is a groove in the horizontal jig which reduces the degrees of freedom of the mounting rail and serves as a linear guide. Before mounting a CubeSat there is no need for a sophisticated setup of the MGSE. Only the distance of the sliders needs to be set which depends on the integrated size. The locking mechanism in the horizontal segment can stay unlocked as is shown in Figure 52. There is still 5 mm of the bearing surface before tightening.

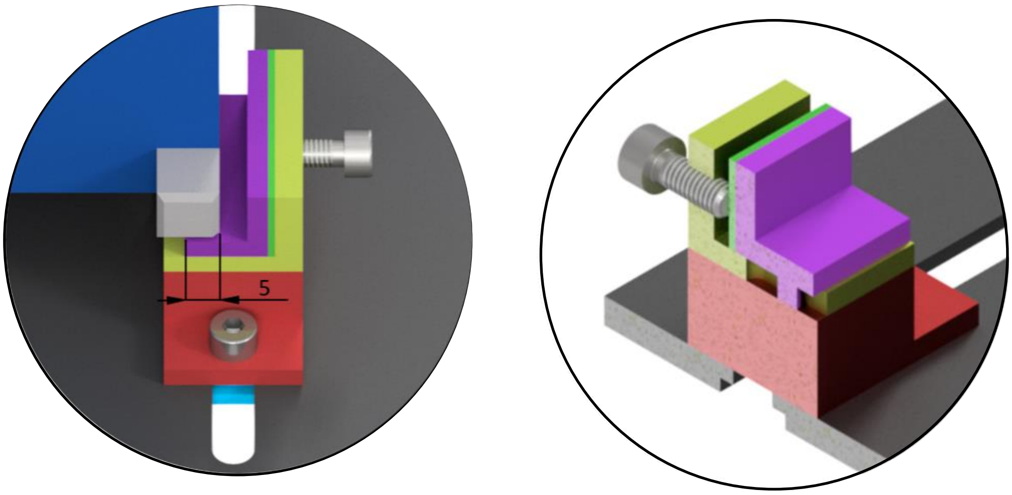


Figure 52 Minimal length of the bearing surface (left) and the cross-section of the locking mechanism (right)

5.5 Vertical MGSE

The vertical MGSE consists as well as the horizontal MGSE of the universal part and a segment which is added to the slider. Figure 53 shows a 6U CubeSat in the vertical position and a detail of the vertical segment where machined parts are together with its material. A different segment with a higher mounting rail was designed to provide better stability during the integration.

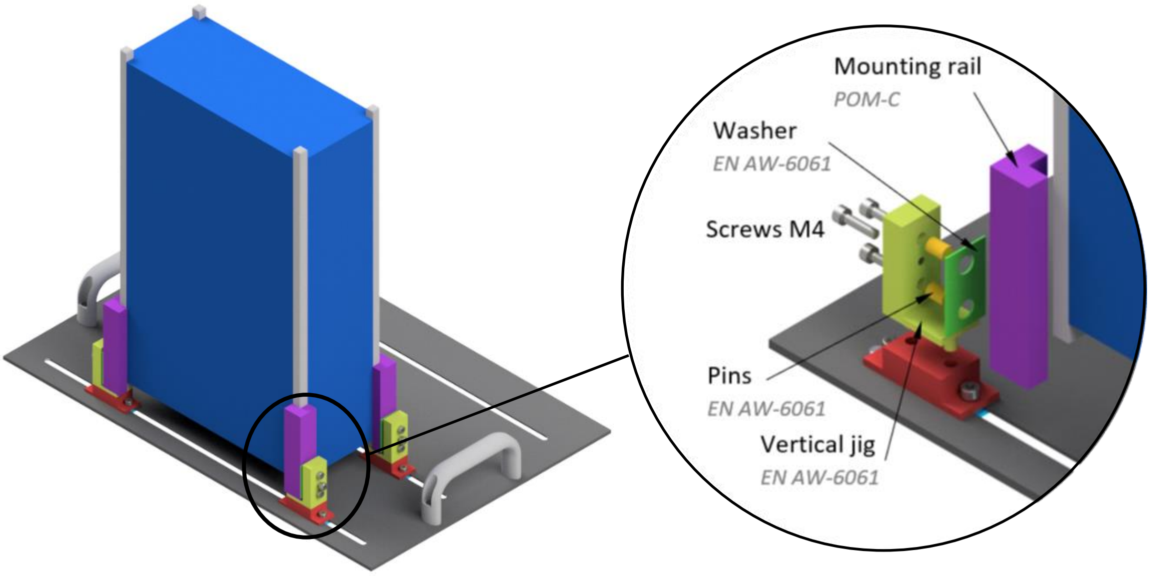


Figure 53 Description of the vertical segment

This segment consists of four parts and a screw. The mounting principle is the same as in the horizontal segment. The vertical jig contains two pins which are inserted into holes in the slider. The same type of fitting as at the horizontal is used here. The vertical jig contains three holes where two of which are used for joining pins to the vertical jig with screws. The middle one contains M4 thread and serves as a locking mechanism. Tightening the M4 screw pushes the washer with the mounting rail which applies a force to a CubeSat and fixes its position. The washer prevents causing damage from the screw to the mounting rail. The mounting rail contains two holes to be able to fit pins. The chosen fit is Ø6 H8/h9 as a commonly used type of fit [70].

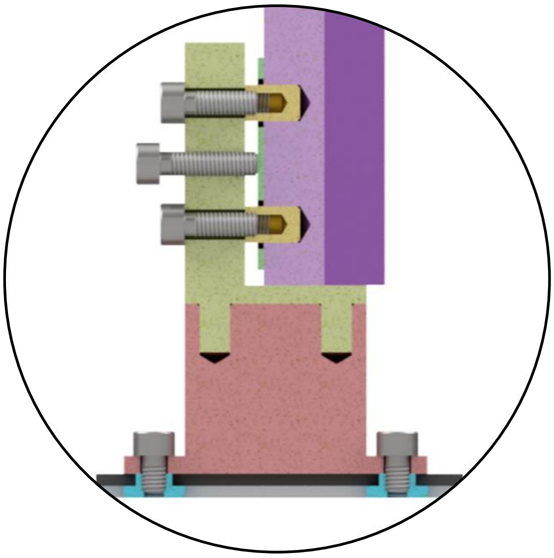
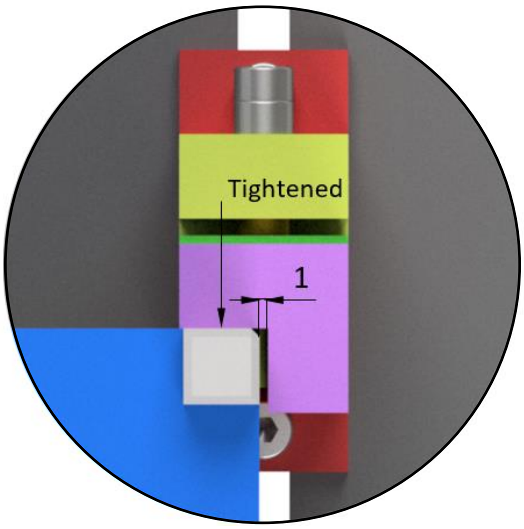


Figure 54 The cross-section of the vertical segment

Figure 54 shows a cross-section of the horizontal segment inserted on the slider. The tight grip is only from the side where is the locking mechanism. The second side serves only as a guide and helps with the stability of bigger CubeSats such as 6U and 12U. Mounting rails prevent unwanted tilting of a CubeSat during the integration. Figure 55 shows the clearance and dimensions of the bearing surface of the horizontal segment.



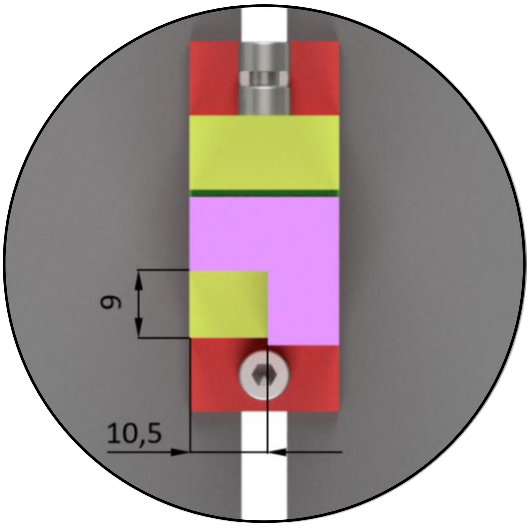


Figure 55 Clearance (left) and dimensions of the bearing surface (right) of the vertical segment

6 CONSCLUSION

This thesis was written in cooperation with S.A.B. Aerospace s.r.o. It deals with a development of a device which is used for integration of CubeSats. CubeSats are a standardized type of satellite. The CubeSat Design Specification currently has 6 sizes. Most likely, the number of standardized CubeSats will increase in the future because larger normalized satellites are getting popular. To design such a device, it was necessary to conduct a research and find out what the dimensions of each CubeSat sizes are and what subsystems are usually integrated into them.

The first part of the thesis contains the research where this information is gathered. After the general information was processed, the market research was made, which revealed individual manufacturers and their design. These products can be generally divided into two categories. The first category compares mounting method of a CubeSat into static and dynamic. Static allows mounting without the possibility of any movement and, on the other hand, dynamic type allows rotation around chosen axes. The second category compares position of integration to vertical and horizontal. Some of the manufacturers focus on sizes up to 3U and some have no restriction on the size of an integrated satellite.

The second part of this thesis was a market analysis of the CubeSat sector. Purpose of this part was to reveal how CubeSats are popular and relevant parts of the space industry. As a result, it was confirmed that CubeSats are an attractive part of the industry, proved by increasing number of the launched satellites every year. With increasing number of launched CubeSats, demand for MGSE will increase. In the thesis, shown forecasts which predict an annual increase as well.

In the third part, of the thesis comparation of introduced designs was made. As a result the static design of MGSE was selected as the proposed design. It was selected based on the price, the adaptability, and the ergonomics parameters. Also, complexity of the mechanical design was considered.

The last chapter with the proposed design describes the environment in which the product is intended, suitable materials and ESD protection were chosen. When all the variables had been solved, a description of the design came up. The resulting solution consists of the aluminium base plate with grooves which serves as a linear guide for the slider. The linear guide contains holes for pins. Both, the vertical and the horizontal segments with pins should be inserted into the slider which depends on required position of a CubeSat.

Proposed MGSE fulfil objectives of the thesis. In addition, non-standard sizes can be mounted due to sliding mechanism of the chosen design. This thesis could serve as an input for work where is described the assembly process of a CubeSat. What types of operations are needed during the integration and what kind of MGSE is needed for these operations.

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8 LIST OF ABBREVIATIONS

ANT	Antenna
ACCU	Accumulators
ADCS	Attitude determination and control system
CAM	Camera
COMM	Communication module
COTS	Components of the shelf
EGSE	Electrical ground support equipment
EPS	Electric and power system
ESD	Electrostatic discharge
GNC	Guidance, navigation, and control
GSE	Ground support equipment
LEO	Low Earth Orbit
MAT	Modular assembly table
MGSE	Mechanical ground support equipment
OBC	On-board computer
OGSE	Optical ground support equipment
PA6	Polyamide Nylon
PCB	Printed circuit board
PLD	Payload
POM-C	Polyacetal copolymer
PTFE	Polytetrafluoroethylene
SRM	Sail release mechanism
U	Unit

9 LIST OF ATTACHMENTS

9.1 Drawing of CubeSats

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