

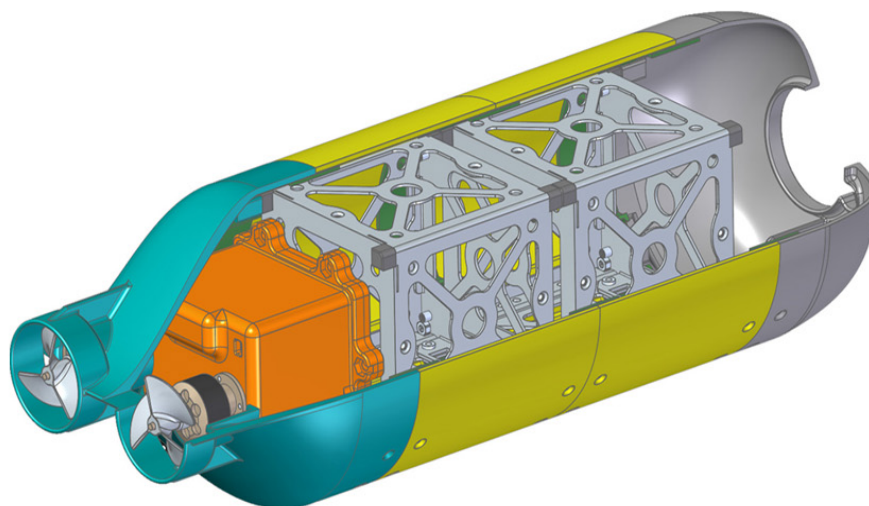


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CubeSub

A CUBESAT BASED SUBMERSIBLE
TESTBED FOR SPACE TECHNOLOGY

CHRISTIAN SLETTEBO



Abstract

This report is a Master's Thesis in Aerospace Engineering, performed at the NASA Ames Research Center. It describes the development of the CubeSub, a submersible testbed compatible with the CubeSat form factor. The CubeSub will be used to mature technology and operational procedures to be used in space exploration, and possibly also as a tool for exploration of Earthly environments. CubeSats are carried as payloads, either containing technology to be tested or experiments and sensors for scientific use.

The CubeSub is designed to be built up by modules, which can be assembled in different configurations to fulfill different needs. Each module is powered individually and intermodular communication is wireless, reducing the need for wiring. The inside of the hull is flooded with ambient water to simplify the interaction between payloads and surrounding environment. The overall shape is similar to that of a conventional AUV, slender and smooth. This is to make for a low drag, reduce the risk of snagging on surrounding objects and make it possible to deploy through an ice sheet via a narrow borehole. Rapid prototyping is utilized to a large extent, with full-scale prototypes being constructed through 3D-printing and with COTS (Commercial Off-The-Shelf) components. Arduino boards are used for control and internal communication.

Modules required for basic operation have been designed, manufactured and tested. Each module is described with regards to its function, design and manufacturability. By performing tests in a pool it was found that the basic concept is sound and that future improvements include better controllability, course stability and waterproofing of electrical components.

Further development is needed to make the CubeSub usable for its intended purposes. The largest gains are expected to be found by developing the software and improving controllability.

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Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ARC	Ames Research Center
AUV	Autonomous Underwater Vehicle
COTS	Commercial Off-The-Shelf
EJSM	Europa Jupiter System Mission
EMFM	Europa Multiple-Flyby Mission
EOI	Europa Orbit Insertion
ESA	European Space Agency
ESC	Electronic Speed Controller
FFF	Fused Filament Fabrication
JEO	Jupiter Europa Orbiter
JGO	Jupiter Ganymede Orbiter
JOI	Jupiter Orbit Insertion
KTH	Kungliga Tekniska Högskolan (Royal Institute of Technology)
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
PLA	Polylactic Acid
P-POD	Poly-Picosatellite Orbital Deployer
RTG	Radioisotope Thermoelectric Generator
SLA	Stereolithography
SEC	Stern Electronics Compartment
SLS	Space Launch System
SMI	Structural Module Interface
STM	Stern Thruster Module
VEEGA	Venus-Earth-Earth Gravity Assist

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1. Introduction

This report is a Master's Thesis in Aerospace Engineering at Kungliga Tekniska Högskolan (Royal Institute of Engineering), Stockholm, Sweden. The work described herein has been performed during an internship at the Mission Design Division of the NASA Ames Research Center, through a collaboration between the Swedish National Space Board and NASA.

Situated in Mountain View, California, the Ames Research Center (ARC) was established in 1939, as a part of what was then known as NACA and in 1958 became NASA. Initially work was focused on aerodynamic research and wind-tunnel testing, but has since expanded to cover many other disciplines such as space biology, nanotechnology, IT and human factors research. The Mission Design Division conducts early stage development of mission concepts and technology maturation to support space missions at the Ames Research Center. In recent years the Mission Design Division has focused on small satellite missions, such as CubeSats [1].

Life as we know it requires access to liquid water. Evidence of liquid water was just recently found on Mars, and the search goes on to find it elsewhere in outer space [2]. Not unique in the Solar System, Jupiter's moon Europa shows hints of a huge ocean of liquid water beneath its solid surface. Examples of other heavenly bodies suspected to hold liquid water are Ganymede, Enceladus, Titan, Callisto and Ceres. Europa however also appears to have other interesting properties which in combination with the water might provide the necessary constituents for life. Further exploration of Europa might just lead mankind towards finding extraterrestrial life, which undoubtedly would be one of the biggest scientific discovery in history. If not, there is still worthwhile knowledge to be extracted about the history of the Solar System and planetary formation by such an undertaking.

Missions headed for Jupiter's moons are currently being planned by both NASA and ESA. No earlier missions have ever aimed specifically for this neighborhood of our Solar System, and we can expect to learn greatly from them. Looking even further into the future, if the existence of liquid water on Europa can be proven, the natural next step is to investigate it in more detail. A compelling way of doing this would be to send a submersible to Europa and have it dig down to the ocean and explore it first-hand.

Still in the early stage of its development, the *CubeSub* is to become a submersible testbed for technology qualified for underwater and space environments. With the long term goal of exploring the underwater environments in outer space such as that of Europa, a huge amount technology and operational procedures must be developed and matured. To assist in this, the CubeSub is created as a tool allowing engineers and scientists to easily test qualified technology underwater. The CubeSub might also prove itself to be a valuable tool for exploration here on Earth.

First in this paper is an introductory overview of Europa and why it is of scientific interest, along with a study of currently planned missions to the Jovian system. After that follows the core subject, an in-depth presentation of the development of the CubeSub.

2. Europa

2.1 Subsurface oceans

Europa is the fourth largest moon of Jupiter, and together with the three larger Io, Ganymede and Callisto they form the Galilean moons. All four Galilean moons were discovered by Galileo Galilei already in 1610, over 400 years ago. Pioneer 10 took the first closeup photos of Europa in 1973 when passing by on its way to escape the Solar System. These photos showed a young and smooth surface with few craters, suggesting ongoing or recent activity. Patterns of fractures also indicated that the shell could move independently from the interior [3]. In 1995, data from the Galileo spacecraft gave hints of a salty ocean of liquid water underneath a frozen crust of ice. This global subsurface ocean is believed to hold more than twice as much water in it as the entirety of Earth's oceans. Figure 2.1 shows a mosaic of Europa from the Galileo mission, in which the many fractures and features can be observed.

Two of Europa's siblings, namely Ganymede and Callisto are also believed to have liquid oceans underneath frozen surfaces. Io is the one closest to Jupiter, and while not suspected to hold liquid water, it is instead extremely geologically active and its surface is dotted by hundreds of mountains and volcanoes.

Europa's underwater ocean is in part evidenced by magnetic measurements. Data from the Galileo mission implied that there is a layer of conductive material close to Europa's surface, locally disrupting Jupiter's magnetic field. The most likely explanations were found to be that either there is an ocean of conductive liquid underneath a layer of ice, or that the mantle is hot enough to necessitate a liquid

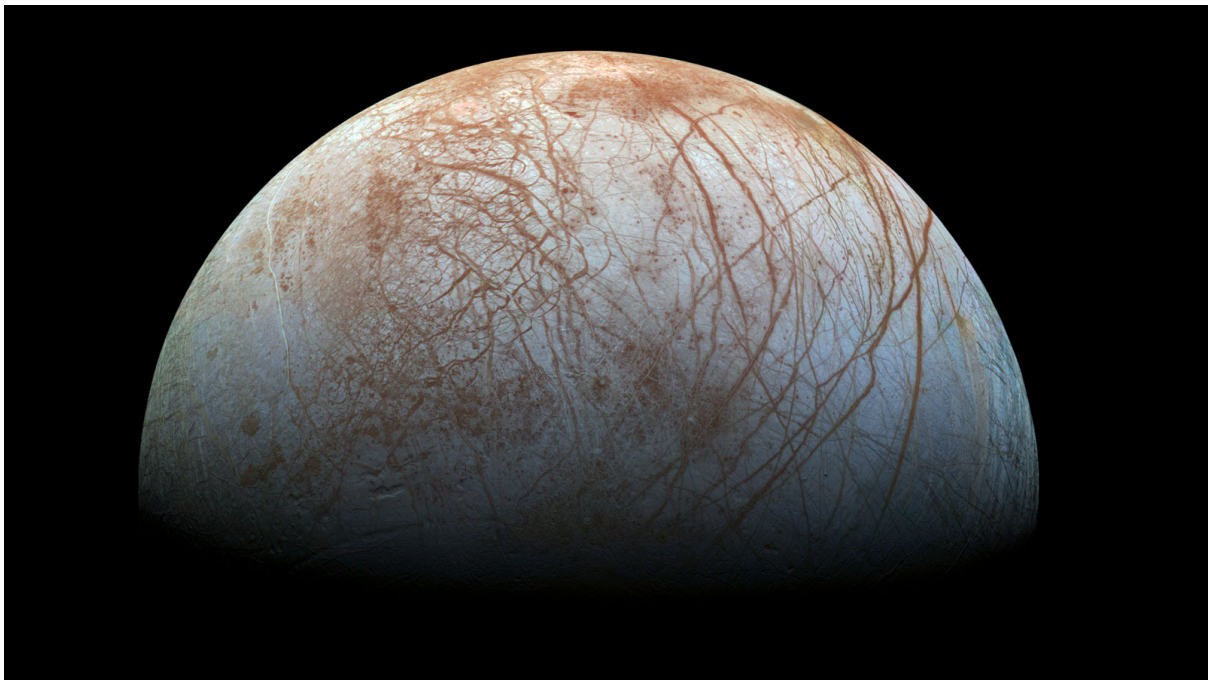


Figure 2.1: Mosaic of Europa from the Galileo mission. Courtesy NASA/JPL-Caltech

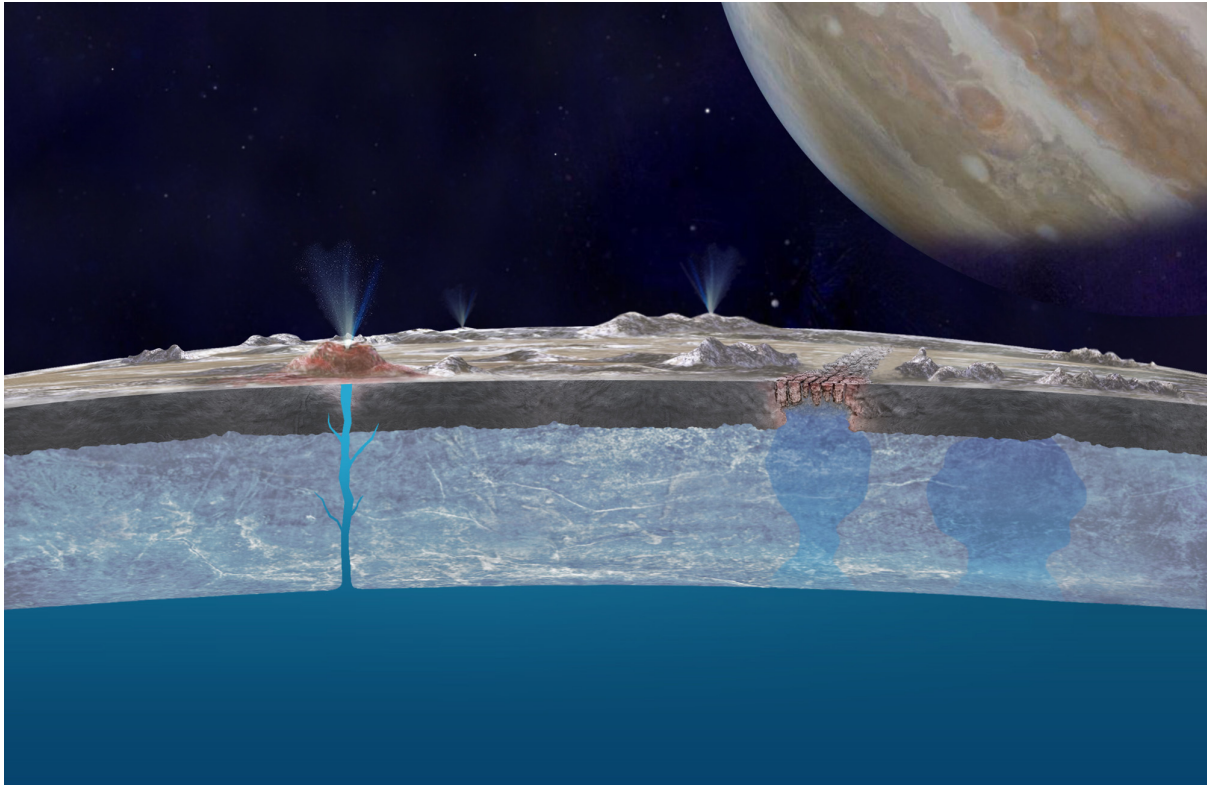


Figure 2.2: Artist's conception of Europa's icy shell and ocean. Jupiter in background. Courtesy NASA/JPL-Caltech

ocean. Another crucial observation is the tectonics seen on the surface, where the formation of cycloidal ridges and cracks are strong indicators of an ice shell that is floating on top of a liquid [4]. Moreover, in 2012 the Hubble Space Telescope observed water vapor in the south polar region, providing the first piece of strong evidence for the existence of erupting water plumes on Europa [5]. Yet, the existence of this huge subsurface ocean is not conclusively proven.

Heat is thought to be supplied to the oceans through what is known as tidal flexing or tidal heating. As Europa moves closer and farther from Jupiter in its eccentric orbit the tidal bulges rise and fall. The energy from this constant squeezing is released as heat, keeping the water liquid underneath the crust. For a lone moon this process would over time circularize the orbit and put an end to the tidal heating. However, the orbital resonance with Ganymede and Io upholds the eccentricity [6].

Exactly how Europa looks on the inside is not well-known. It is typically assumed to have an outer icy shell covering a liquid ocean, a mantle of silicate and a core rich in iron. The thickness of the ice layer is hypothesized to be anything from a few to hundred kilometers thick. Figure 2.2 shows an artist's conception of how Europa's ice shell and ocean might look. Under the thick sheet of ice is the huge ocean of water. On the left is a plume of water being ejected and on the right are two convective movements of warmer ice, ascending through the ice sheet to interact with the surface and create the visible features we have observed from afar.

2.2 Potential for life

Life as we know it can roughly be said to require three ingredients; a sustained environment of liquid water, a source of energy and the right set of chemical elements. To the best of our current knowledge Europa might very well hold all these qualities, and is as such a prime candidate in our search for extraterrestrial life. The sustained liquid environment would be supplied by the subsurface ocean and the energy by the tidal heating. Whether the chemical elements exist is not known and is one of the most important questions to be answered by missions to Europa.

Table 2.1: Selected numerical properties of Europa

Parameter	Value	Relative to	
		Earth	Moon
Radius	$1,5608 \times 10^6$ m	0.245	0.898
Mass	$4,8017 \times 10^{22}$ kg	0.0080	0.653
Orbital Period	3,551 days	0.0097	0.130
Surface gravity	$1,315$ m/s ²	0.134	0.810
Escape velocity	2026 m/s	0.181	0.851
Surface pressure	$0,1 \times 10^{-6}$ Pa	10^{-12}	300

At the bottom of the ocean water is thought to be in direct contact with the rocky mantle, possibly supplying it with the nutrients needed for life. Conditions in this area could be similar to what we find on the seafloor here on Earth. While mostly dead and desert-like, areas such as the immediate vicinities of hydrothermal vents have been found to be full of life, in spite of their to us humans very hostile environment. Such areas could be teeming with life if found on Europa [7].

No sunlight will reach down far enough to benefit potential life forms, meaning that they cannot rely on photosynthesis to get their energy. Europa sits very far away from the sun, and the covering ice sheet is thick. Life has been discovered under similar conditions on Earth in the subglacial Lake Whillans, Antarctica. In 2013, after drilling through 800 meters of ice sheet, researchers found single-celled bacteria and archaea living in this lake. Seemingly completely isolated from the rest of the world, this ecosystem works without any sunlight. The most abundant microbes were found to get their energy by oxidizing ammonium. This ammonium is thought to be sedimented remains of dead matter, deposited millions of years ago before the region froze over [8]. Little is known about these environments and ecosystems, as they are troublesome to reach and explore. Further investigations could give valuable information not only about them, but also about what we might find in space.

To increase our understanding of Europa’s habitability there are four main topics to be studied; the ocean, ice shell, chemical composition and geology. *Ocean*, is there one at all? What’s the extent and salinity? *Ice shell*, can it tell us anything about the promise of an ocean? Are there pockets of liquid water in it? How do the exchange processes between surface and ocean work? *Chemical composition*, what kinds of elements and compounds can we find and how are they distributed? *Geology*, can we say anything about recent and current activity? How do the surface formations come to be? [9]

2.3 Surface environment

Europa is in some respects similar to our own Moon. It is just over 10% smaller in radius, about 2/3 of the mass and has an almost 20% lower surface gravity. Europa is like the Moon tidally locked, meaning that one and the same side always faces its parent planet, in this case is Jupiter. Our Moon’s tidal lock to the Earth is what gives us the *near* and *far* sides. Table 2.1 presents some of Europa’s characteristics numerically and compares them to those of the Earth and our Moon [9] [10].

Just like the Moon Europa also has a tenuous atmosphere, albeit even thinner. A nearly nonexistent layer of molecular oxygen makes for a surface pressure a trillion times lower than on Earth’s surface. Production of this oxygen does not involve any biological process, but is rather a result of the harsh radiation environment. Ultraviolet radiation and charged particles trapped in Jupiter’s magnetic field collide with Europa, releasing oxygen atoms from the icy surface [11]. The virtual lack of atmosphere means that landing on Europa must be done without the use of parachutes. To reduce the speed prior to landing, thrusters must be used in a way similar to the Moon landings of the Apollo program. Additional propellant has to be brought along for this, compared to a mission that can use the “free” aerobraking to reduce its speed. Conversely, having no atmosphere also means that the difficulties associated with atmospheric entry completely disappear, the spacecraft does not need to have a heat shield.

Europa’s radiation environment has been described as the predominant challenge and life-limiting parameter for any mission that is to go there [7]. Jupiter’s incredibly strong magnetic field traps charged particles in belts similar to the Van Allen belts surrounding Earth, however the radiation in Jupiter’s belts

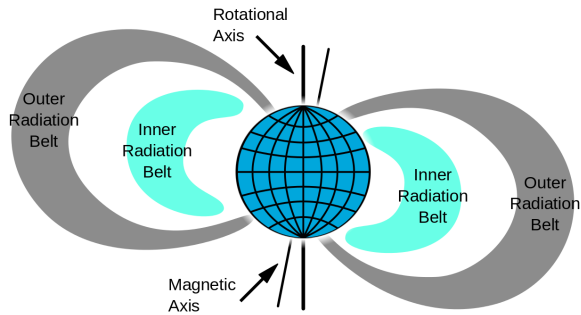


Figure 2.3: Cross sectional diagram of Earth's Van Allen radiation belts. Courtesy NASA

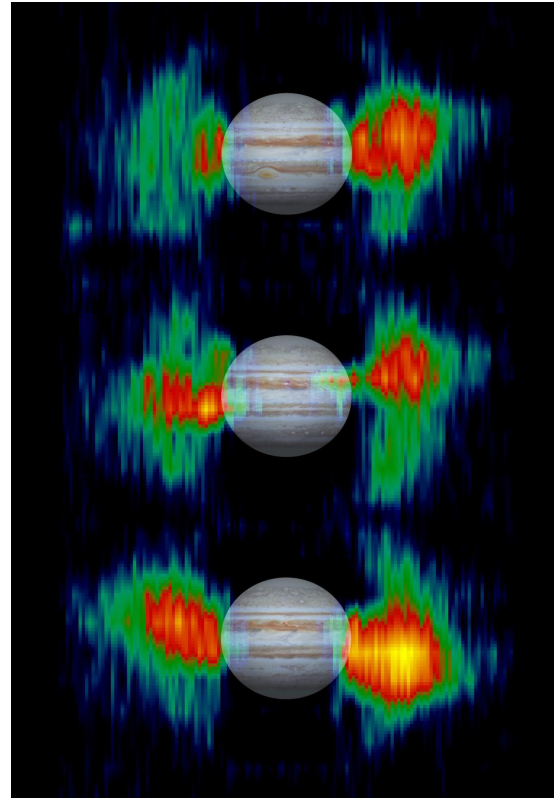


Figure 2.4: Illustration of Jupiters fluctuating radiation belts. Courtesy NASA/JPL/Space Science Institute

are orders of magnitude stronger. Figure 2.3 shows a cross sectional diagram of the Van Allen belts. Figure 2.4 shows Jupiter's radiation belts in three different positions as they rotate around Jupiter. Europa's orbit is situated within such a radiation belt. Since Europa does not have an atmosphere and only a weak magnetic field, practically all of this radiation reaches anything orbiting or landing on it. Missions must take measures to withstand this, for instance through the use of radiation resistant components, shielding and trajectories that stay out of the radiation.

3. Mission overview study

This chapter will examine some currently and previously planned missions to the Jovian system, in particular ones aiming for the moons. The goal is to identify the inherent challenges and limits of such a mission and to get a rough idea of how big a lander can be put on the surface of Europa. All the examined missions have one or more Galilean Moons as their main goals. Missions to the Galilean Moons are currently of high profile, ESA has declared the JUICE missions a Large Class project and NASA's EMFM is referred to as a flagship mission [9] [12].

In 2012 NASA declared that a dedicated mission is required to answer the principal questions about Europa [9]. No dedicated mission has ever been sent to any of the Galilean Moons, everything we know at this time has been produced by telescopes or satellites passing by on their way to other places. A large amount of completely new scientific knowledge can therefore be expected to result from any such mission.

3.1 Proposed missions to Europa

3.1.1 Lander mission - Europa Study Report 2012

The EJSM (Europa Jupiter System Mission) was proposed as a joint mission between NASA and ESA with the intent of exploring Jupiter's moons with two separate, independent spacecraft. NASA would launch the JEO and ESA the JGO (Jupiter Europa/Ganymede Orbiter respectively). Due to financial concerns the mission was canceled with NASA and ESA going separate ways with their respective submissions. NASA assembled the Europa Study Group and tasked them to find ways of considerably reducing the costs of the JEO by descoping the mission and modifying the spacecraft. A comprehensive report titled the *Europa Study Report 2012* was published in 2012 examining these possibilities [9]. ESA used the JGO as a base for the JUICE mission which is discussed later in this chapter.

Three different missions were proposed and analyzed in the report; an Orbiter, a Multiple-Flyby and a Lander. The conclusion of the study was a recommendation of the Multiple-Flyby mission as it was found to give the best price/performance ratio. Excluding the launch vehicle the costs were estimated to \$1.7B–\$1.8B for the Orbiter, \$2.1B for the Multiple-Flyby and \$2.8B–\$3.0B for the Lander, all in 2015 US dollars. Compared to the Orbiter the Multiple-Flyby was found to be able to produce significantly more useful results with the relatively small increase in cost, while the Lander was deemed too expensive and high-risk. The Europa Multiple-Flyby Mission is discussed by itself in the next section.

The report concluded that “Only a lander could accomplish evaluation of the detailed surface chemistry and mineralogy to best understand the detailed nature of near-surface organics and salts, as these investigations require *in situ* sample analyses.” [9]. When reviewed by an independent board it was however found that for a landed mission to be feasible, a precursor mission such as the Multiple-Flyby will be required to determine the landing characteristics.

Investigation of Europa's habitability was the main goal of the lander mission. This would have been realized through direct analysis and *in situ* measurements of the chemistry that cannot be done remotely. Holes would be drilled to see what can be found underneath the heavily irradiated surface, thereby determining the chemical composition and what it implies for the possibility of life. Local measurements on the ice shell would be performed to characterize its thickness, heterogeneity and if there are any dynamics between ice and water layers. The landing site was to be chosen in a geologically interesting area to perform studies of the local surface evolution. Figure 3.1 shows the lander concept presented in the Europa Study Report 2012.

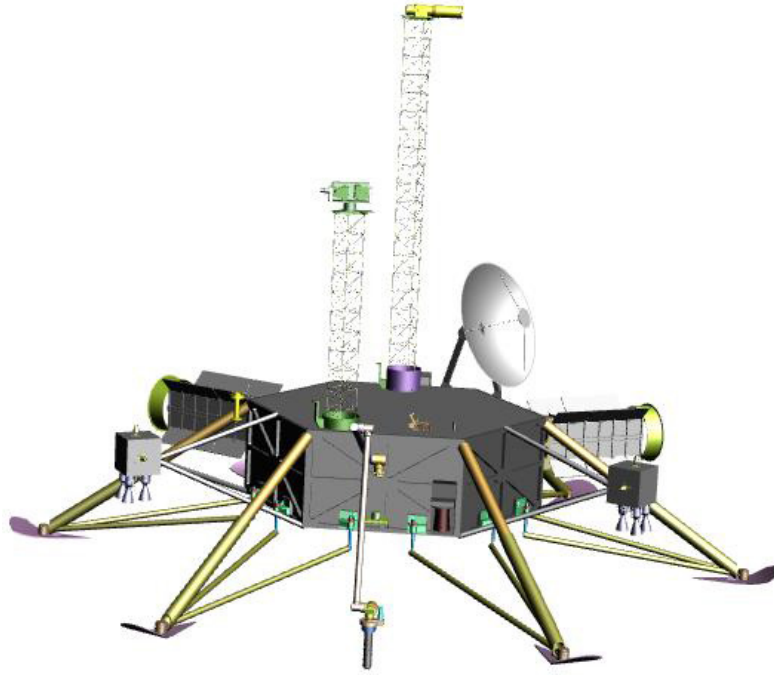


Figure 3.1: Europa lander concept, here in surface configuration. Courtesy NASA/JPL-Caltech

Launch was in the report suggested to occur in 2021, using a Delta IV Heavy to put the satellite on a VEEGA (Venus-Earth-Earth Gravity Assist) trajectory. The interplanetary transfer takes 6.4 years, followed by JOI (Jupiter Orbit Insertion) and a Jovian tour of 1.3 years before finally reaching EOI (Europa Orbit Insertion). The long Jovian tour is designed such that the trajectory between JOI and EOI reduces the radiation exposure, and involves no less than 11 gravity assists from Ganymede and Callisto.

After EOI, 30 days of reconnaissance from 200 km of altitude would follow to determine a suitable landing site. Images would be relayed back to Earth for a ground team to make a decision and upload a landing trajectory to the lander. A lander then separates from the carrier satellite and enters a 200×5 km orbit. At periapsis a deorbit burn is performed, followed by a soft landing using the thrusters. After landing, surface operations are conducted for at least 30 days which is the duration of the prime mission. The total time from launch until end of prime mission is thus slightly over 8 years.

At launch separation the complete flight system has a wet mass of 5036 kg. The lander has a wet mass of 681 kg, 122 kg of which is propellant when separating from the carrier. 34.2 kg of scientific instruments are carried and on top of this comes 12.2 kg of component radiation shielding. The instruments are mounted to a science chassis weighing 22.5 kg including shielding. All in all, this gives a total mass of 68.9 kg to be used for scientific purposes. This can be used as an approximate number for what is possible to put on Europa. The presented numbers give good system margins ($\approx 30\%$) and a lander dry mass of up to 700 kg can be allowed.

The lander would have been powered by two ASRGs (Advanced Stirling Radioisotope Generators), a power system that was up until its cancellation in 2013 developed by NASA. Solar panels were deemed unfeasible and RTGs were for reasons not specified in the report claimed to be unavailable.

With a precursor mission, the reconnaissance part could be removed along with the instruments needed for it. During these 30 days both lander and carrier would be subjected to heavy radiation, and its removal could make for a longer time on the surface and/or lessen the need for shielding. The Reconnaissance Camera is together with its shielding estimated to a mass of 35 kg, and it could either be rejected completely or simplified/scaled down to increase the scientific payload. Because of concerns regarding the uncharted surface the lander is also designed to land in a rough and somewhat unknown terrain. Better knowledge of the terrain would make it possible to optimize the lander and thereby further reduce mass and complexity.

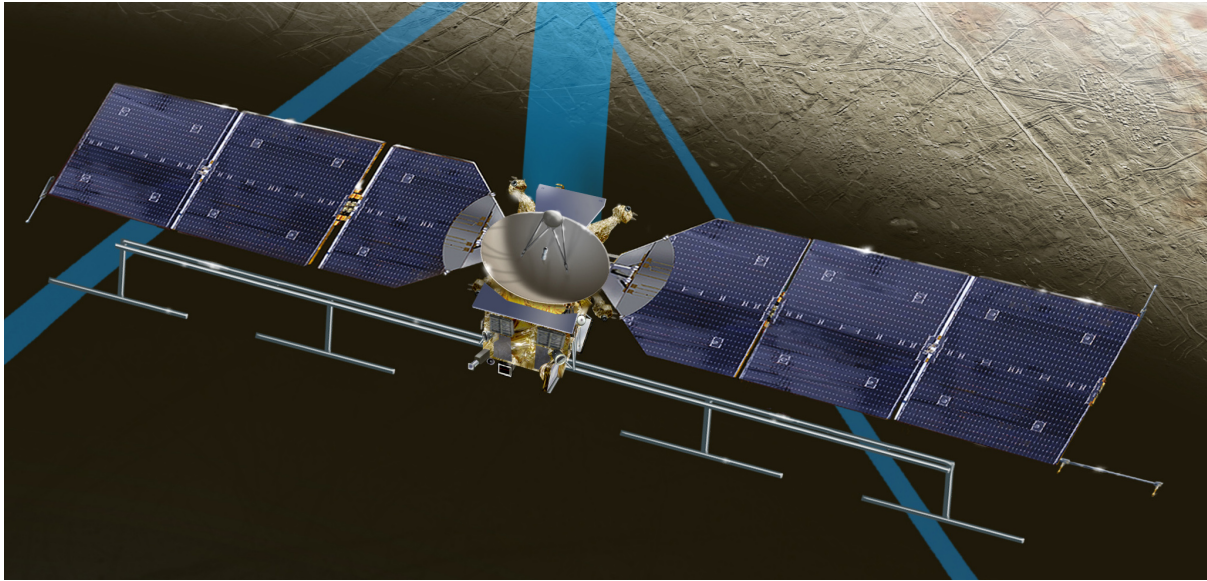


Figure 3.2: Concept illustration of the EMFM satellite. Courtesy NASA/JPL-Caltech.

3.1.2 Europa Multiple-Flyby Mission

This mission is derived from the Europa Study Report 2012, and was between 2012 and 2015 known as the Europa Clipper Mission. Figure 3.2 shows a concept illustration of the EMFM satellite. As the name implies, this mission will not go in orbit around Europa but rather perform multiple close flybys while orbiting Jupiter. This allows it to stay away from the worst of Jupiter’s radiation belts and only occasionally “dive in” to observe Europa. Through well-designed trajectories of these “dives”, almost complete coverage of Europa will be obtained. Figure 3.3 shows a concept of how such trajectories might look. Additional radiation resistance will be provided by shielding sensitive components.

The mission’s main goal is to investigate Europa’s habitability. It sets out to look for evidence for liquid water and gain more insight into the ice shell, in part through the use of an ice-penetrating radar. The interface between ocean and ice, exchange of material and variations in heat flow is to be investigated. More detailed accounts of the surface features and the chemical composition will be provided. Surface reconnaissance will be performed to find landing sites that are both safe and scientifically interesting, in preparation for an eventual lander mission.

Launch is set to be no earlier than at the end of 2021 with an Atlas V 551. NASA is looking into the possibility of using the new SLS which would delay earliest launch until June 2022. With the Atlas the transfer to Jupiter would be made with a VEEGA trajectory and a flight time of 6.4 years if choosing the launch window in 2021. The SLS would put the satellite on a direct transfer to Jupiter with a flight time of around 2 years. The direct trajectory also has the advantage of an overall reduction in complexity by removing the gravity assists as well as eliminating the thermal challenges associated with the Venus flyby. During Mission Concept Review in 2014 the SLS was found to be “far superior and the optimal solution (...) followed by the Delta IV-H and the Atlas V551”.

After JOI 3,5 years of observations and 45 low-altitude flybys of Europa follow. Power is in the baseline design supplied through solar panels with the alternative being an RTG (Radioisotope Thermoelectric Generator). The solar panels are slightly heavier than the RTG, but gives better flexibility in design and program scheduling, while also being cheaper. Wet mass is estimated to approximately 2400 kg of which 1000 kg is propellant and 100 kg scientific payload. The mission was in the Europa Study Report projected to cost \$2.1B.

3.1.3 JUICE

Based on the JGO from the canceled EJSM mentioned above, JUICE (JUper ICy moons Explorer) is a non-landing mission to the Jovian system planned by ESA. Set to launch in 2022 (with a backup possibility in 2023) by an Ariane 5 ECA, JUICE will spend 7.6 years in interplanetary transfer towards

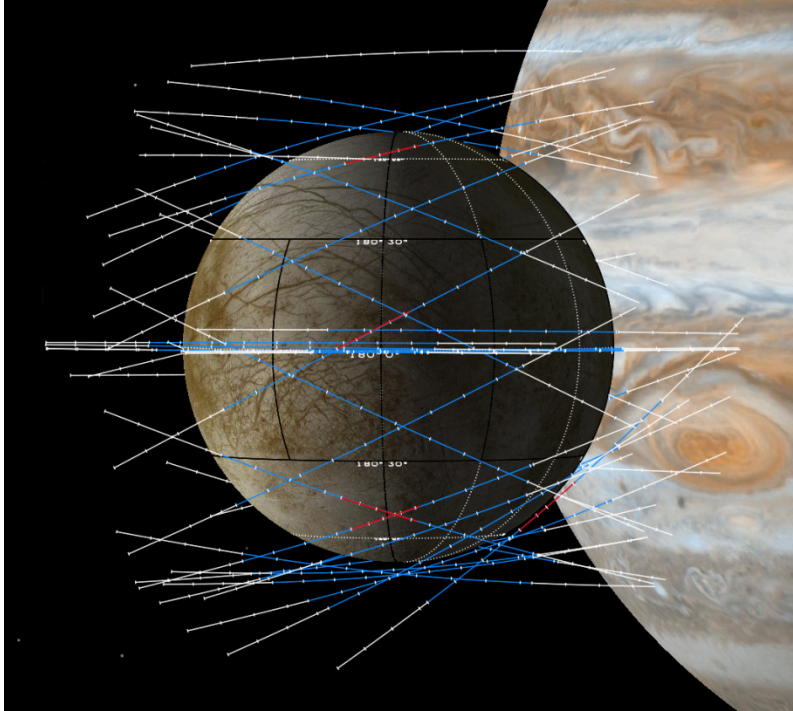


Figure 3.3: Flyby trajectories of the EMFM around Europa. Jupiter in background. Courtesy NASA/JPL-Caltech.

Jupiter through an Earth-Venus-Earth-Earth gravity assist trajectory. Including one year of JOI, 3.5 years will be spent in the Jovian system performing flybys of Europa, Callisto and Ganymede to finally enter the orbit of Ganymede. Gradually decreasing its altitude while observing Ganymede, JUICE will finally be deposited on its surface, marking the end of the over 11 years long mission [13] [14]. Figure 3.4 shows an illustration of the satellite designed for the JUICE mission.

The fundamental science goals of JUICE are to address the very broad questions about how planets form, how life emerges and how the Solar System works. More specifically, it will do so by improving our knowledge about the previously mentioned Jovian moons Callisto, Europa and Ganymede. Through the flybys JUICE will try to find further proof and data about the liquid subsurface oceans. It will look for evidence of past and ongoing geological activity and provide details about the chemical compositions of the moons. Ganymede has been chosen for the more detailed analysis at the end of the mission as it provides what ESA refers to as a “natural laboratory for analysis of the nature, evolution and potential habitability of icy worlds” [12].

JUICE will also provide more information about Jupiter’s atmosphere, magnetosphere and rings. Jupiter is an archetypal gas giant and exoplanetary system, and it can give us valuable information both about gas giants in general and the formation of our Solar System. ESA describes it as “the perfect destination for exploration of our origins” [12].

Launch wet mass is expected at approximately 4800 kg. The orbital insertions and multiple flybys give a high Δv , requiring around 2900 kg of MON/MMH (Mixed Oxides of Nitrogen/Monomethylhydrazine) bipropellant, leaving a dry mass of 1900 kg. Included in the dry mass are 11 scientific instruments that will be used for imaging, spectroscopy, in situ fields and particle measurements as well as sounding and radio science, combining to a total mass of 104 kg. According to ESA the radiation environment is the main mission challenge. To cope with this trajectories are after JOI designed to only enter into the radiation belts when necessary, and sensitive components are grouped and shielded. Between 155 and 172 kg of radiation shielding is expected. Power is supplied by solar arrays with an expected area of 60 - 75 m².

JUICE is considered a low risk mission from both technical and programmatic points of view. In 2012 BBC reported an estimated total mission cost of €1.1B (approximately \$1.2B), including the scientific instruments [15].

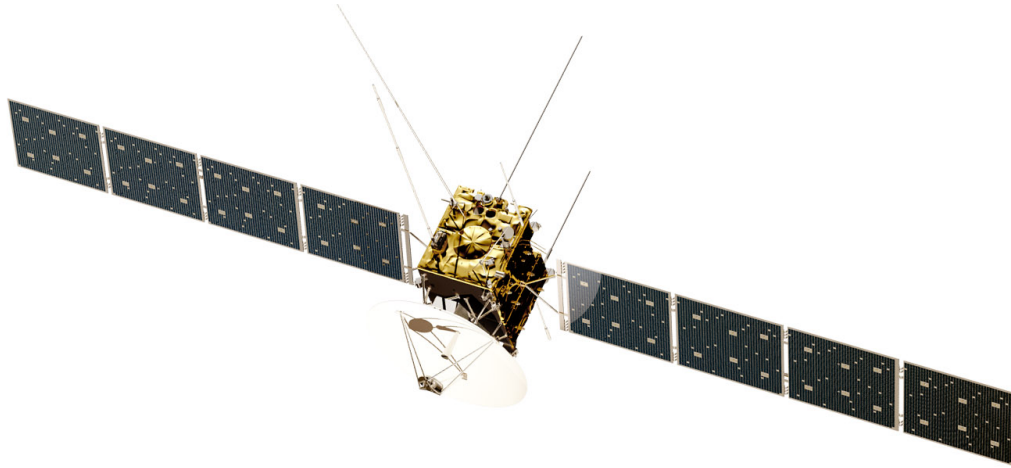


Figure 3.4: Illustration of ESA's JUICE satellite. Courtesy ESA

3.1.4 Laplace-P

Roscosmos (The Russian Federal Space Agency) has proposed a mission to orbit and land on Ganymede, formerly known as the Europa Lander. It was originally meant for Europa, but because of the radiation environment the technological and financial challenges were deemed to large and Ganymede was chosen as the new target. Just like Europa, Ganymede does not in practice have an atmosphere, disallowing the use of parachutes for landing. It has a slightly stronger surface gravity (1.428 m/s^2 vs. Europa's 1.315 m/s^2) requiring more propellant for the landing. Ganymede's orbit is situated such that the impact of Jupiter's radiation field is lessened in relation to Europa [16].

The mission consists of two probes launched separately, where one is an orbiter and the other one a lander. Launch is planned in 2023 with either the Proton or Angara launcher. Jupiter would be reached in 2029 after a VEEGA trajectory. After reaching the Jovian system, 1.5 years will be spent entering in orbit around Ganymede.

The lander is estimated to have a wet mass of 1210 kg of which 660 kg is propellant. This gives a dry mass of 550 kg, with 50 kg being scientific payload. Maneuvers for a soft landing are performed with a 3 kN hydrazine (N_2H_4) monopropellant system. Power is supplied to the lander by an RTG.

Mapping Ganymede's surface is required prior to landing, this would be done by the orbiter. Roscosmos has expressed interest in a collaboration with ESA by sharing launch vehicle and/or data with ESA's JUICE mission. Such a collaboration could obviate Roscosmos' vehicles and lessen the required work. The current status of this collaboration is unknown. Details about this mission are overall scarce and Roscosmos does not acknowledge its existence on their official website, begging the question as to whether this mission will take place or not.

3.1.5 Summary and analysis

It is apparent from the studied missions that the biggest out-of-the-ordinary challenge is the radiation environment. This results in complex trajectories and the need to shield components which in turn limits the scientific payload mass. The long distance to Jupiter is problematic as it too necessitates complex trajectories in the interplanetary transfer and long mission durations for meaningful payloads to be achievable. A signal delay of around 30 to 60 minutes also comes as a result of the distance. If using a Venus gravity assist, the thermal environment closer to the Sun becomes a concern.

A precursor mission is, if not absolutely required, highly advantageous for a lander mission. Knowing what to expect means that the lander can be optimized for a particular landing site and negates the need for in-mission reconnaissance. Having to perform reconnaissance during a mission requires the probe to carry additional instrumentation and might force it to spend more time in the radiation environment. Seeing as the EMFM and JUICE missions are likely to happen, streams of good data can be expected to be available maybe as early as mid-2020.

From the Europa Study Report lander mission it is found that up to around 700 kg is possible to land with good margins, and probably even more with a precursor mission. With the EMFM possibly using the SLS to launch to Europa in a shorter time, it is interesting to investigate what the SLS could mean for a lander mission. If using the SLS to go on the long gravity assisted transfer it would allow for a significantly heavier spacecraft and subsequent lander, instead of a reduced flight time. To get a rough idea of the mass could be put on the surface of Europa with an SLS some simple calculations are performed.

In the Europa Study Report a VEEGA trajectory is claimed to require an initial characteristic energy C_3 of around $15 \text{ km}^2/\text{s}^2$, varying slightly dependent on which launch window is chosen. The Delta IV Heavy can carry approximately 7 metric tons to this C_3 while the SLS Block 1 version is expected to be able to carry 20 metric tons [17].

The rocket equation [18] is given as

$$\Delta V = I_{sp} g_0 \ln \frac{m_0}{m_f} \quad (3.1)$$

where ΔV is the change in velocity, I_{sp} the specific impulse, g_0 the standard gravity (9.81 m/s^2), m_0 and m_f the spacecraft mass at the beginning and end of a maneuver, respectively. Rewriting (3.1) gives the mass after a maneuver as

$$m_f = m_0 \exp\left(-\frac{\Delta V}{I_{sp} g_0}\right) \quad (3.2)$$

The difference between m_0 and m_f corresponds to the propellant mass m_p required for a given maneuver. In Table 3.1 the three maneuver stages of the mission are presented, where the numbers are all taken from the Europa Study Report. The *Earth to Europa* segment contains among other things the deep space maneuvers, JOI, flyby maneuvers and EOI. When the lander separates from the carrier spacecraft in Europa orbit this segment ends. The carrier is in the Europa Study Report estimated to have a dry mass of 857 kg. For this revised mission it is assumed at 1500 kg (including propellant to sustain orbit) to account for things such as a heavier structure and larger propulsion system. *Deorbit* is a single impulse performed with a solid-fuel booster, the *deorbiter*. The deorbiter separates from the lander after the impulse, resulting in a 150 kg reduction in lander mass. Finally, *landing* is performed with the remaining mass using a hydrazine (N_2H_4) monopropellant system.

Evaluation of (3.2) using the data given in Table 3.1 and a starting mass of 20 000 kg gives the results presented in Table 3.2. Note that the masses change not only during but also between the segments due to stage separations. Judging by these calculations, it should in theory be possible to land over 3 metric tons on Europa with a VEEGA SLS mission. These calculations are performed without any safety margins, and a real mission would probably end up with around 2 - 2.5 metric tons landed. This is still significantly more than what can be achieved with a Delta IV Heavy.

Table 3.1: Maneuver data taken from Europa Study Report lander mission

Mission segment	Vehicle	ΔV [m/s]	I_{sp} [s]
Earth to Europa	Complete satellite	2870	324
Deorbit	Lander + Deorbiter	1440	290
Landing	Lander	327	236

Table 3.2: Mass estimations for Europa lander mission using an SLS launcher

Mission segment	m_0 [kg]	m_f [kg]	m_p [kg]
Earth to Europa	20000	8107	11893
Deorbit	6607	3983	2624
Landing	3833	3328	505

3.2 Ice penetration

Upon reaching Europa, penetrating through the ice is the next challenge. Depending on how thick the ice is, this can be extremely difficult or even impossible and might pose an even greater challenge than landing on Europa.

A submersible that is to reach the ocean is assumed to be transported down in a kind of drilling vessel, that upon reaching water deploys the submersible to explore. Many difficulties arise in this process. These include, but are not limited to, energy supply to the drill, surface communications, steering of the drill and whether the ice sheet can be expected to be homogeneous.

This topic, however, lies outside the scope of this paper and will not be discussed further.

4. CubeSub

4.1 Introduction

With the long term goal of sending a submersible to Europa, there is a great amount of technology and mission procedures to be developed, tested and matured. To assist in this the CubeSub, a submersible compatible with the CubeSat form factor, is being developed. The rationale behind such a concept is to provide a cheap and accessible tool for underwater testing of relevant technology, assisting in the process of further maturing the concept of a fully space qualified submersible headed for Europa. As a further clarification, the CubeSub is itself not meant for outer space, but to facilitate development of such a vessel.

The CubeSat standard is already well established, compatible technology is readily available and the know-how exists in the space industry, making it a firm ground to stand on for the CubeSub. Section 4.1.1 below further discusses the CubeSat standard.

The design philosophies for the CubeSub are the following:

- CubeSat compatibility
- Modularization
- Standardization
- COTS (Commercial off-the-shelf) components

Through these objectives, the CubeSub is expected to become cheap, readily available and flexible. Rapid prototyping through 3D-printing will be utilized in this development stage. This is both to make for quick progress in this early stage and also to explore the possibilities and limitations associated with 3D-printing a full-scale small submersible. Making sure that components are compatible with 3D-printing will be given a high priority. Some aspects of the 3D-printing technique will be discussed in greater depth in section 4.1.2 below.

The CubeSub will be used for tests in environments similar to what we expect to find on Europa, namely arctic and antarctic environments. It should thus be possible to deploy through a narrow borehole to reach ice-covered bodies of water. The development is currently in an early stage, and the CubeSub is currently aimed towards near-surface operation with no significantly elevated pressures, and is expected to run at low speeds.

The engineering goals with the work presented in this particular report are the following, the successful accomplishment of which are anticipated to result in a cornerstone for forthcoming development:

- Create a framework for the physical system architecture
- Design a concept for the structural modularization interface, namely how to mechanically connect modules
- Construct modules critical for basic operation
- Build and test a prototype

Basic operation is in this context defined as the CubeSub's ability to submerge, stay submerged and propel itself while carrying CubeSat payloads.



Figure 4.1: Empty CubeSat chassis. Courtesy CubeSat KitTM.

Whereas the CubeSub's primary objective is to further the development of underwater and space technology, it could also prove useful for Earthbound exploration. A highly standardized system utilizing well-known hardware can reduce the cost and required work load for researchers wishing to perform experiments and exploration. Users could design sensors and experiments to comply with the already well established CubeSat standard, which are then carried by the CubeSub to the region of interest. This in turn means that the end users only need to care about formulating the experiment itself and less about how to get it where they want it. This further drives the argument of making the CubeSub small and slender enough to enter tight caves or be easily deployed through a narrow ice borehole.

Although not technically CubeSats, the CubeSat-sized cubes carried by the CubeSub will also be referred to as CubeSats hereinafter.

4.1.1 CubeSat

A CubeSat is a type of miniaturized satellite built to a standardized size. The base size is 1U (U for unit), corresponding to a $100 \times 100 \times 113.5 \text{ mm}^3$ cube. A 1U CubeSat can in other words easily be held with one hand. Stacking units together give larger satellite sizes such as the also commonly used 1.5U, 2U and 3U. The same base area of $100 \times 100 \text{ mm}^2$ is retained, with the length extended accordingly. Even larger variations such as 6U and 12U also exist, which are given by placing 3U units alongside each other. Figure 4.1 shows an example of a 1U CubeSat chassis.

The CubeSat standard was developed in 1999 at California Polytechnic State University and Stanford. 2003 saw the first CubeSats launched and since then hundreds have been launched. CubeSats do not ride on dedicated launches, but rather hitchhike on larger launches with leftover space. What has made the CubeSat so popular is not only a result of the satellites themselves, but also to a great extent the P-POD (Poly-PicoSatellite Orbital Deployer) launch interface. The P-POD is a standardized CubeSat deployer inside of which up to 3U of CubeSats sit during launch. When orbit is reached and the CubeSats are ready to begin their mission the P-POD opens up to deploy them. This provides a decoupling of the CubeSats from the launch vehicle, making integration significantly easier and cheaper [19]. Figure 4.2 shows the 3U GeneSat-1 and its P-POD. The P-POD concept is in the context of the CubeSub a very interesting example of what a standardized and simple interface between the scientific instruments and studied environment can do.

With the simplified development process and thereby lowered costs, the CubeSat concept has become an enabler of space science for institutions and businesses that traditionally have not had this possibility. Many universities, including KTH, are running projects where students manage and develop real CubeSat missions [20] [21].

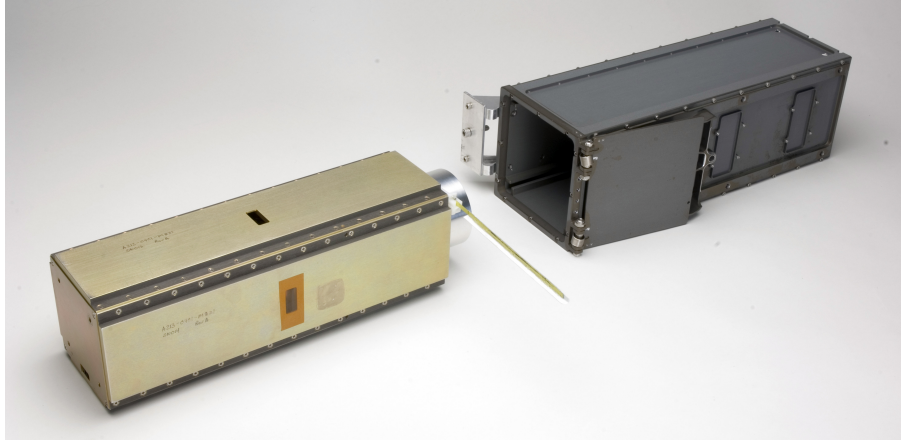


Figure 4.2: GeneSat-1 (left) and P-POD (right). Courtesy NASA ARC.

4.1.2 3D-printing

Also known by the name Additive Manufacturing, 3D-printing is currently in the spotlight due to its presumed potential to reform the manufacturing industry. It is also gaining traction among the general public thanks to the increased availability of relatively cheap printers (on the order of one or a few thousand US dollars), allowing amateurs to create complex objects at home with relative ease [22].

Many different 3D-printing technologies exist. This work has mainly involved FFF (Fused Filament Fabrication) and to a small extent SLA (Stereolithography), both of which will be discussed below. In this work, prints have been generated in the SpaceShop at NASA ARC, where a number of different printers are available.

Arguably the greatest strength of 3D-printing is the possibility to create intricate objects at a moments notice. A printer simply does not care about how complex the geometry of an object might be and as long as it is structurally sound it can in theory be printed. In reality however, 3D-printing does put some other constraints on how components can ideally be designed. The components' "printability" will be given a high priority when designing the CubeSub. What kind of properties that determine an object's printability will be discussed for each component in the coming sections followed by concluding remarks in Chapter 6, Conclusions.

A limitation inherent in the 3D-printing techniques used in this work is how components with overhangs are treated. Because components are created successively from bottom to top, overhanging features must be supported from below as they generally cannot be printed in thin air. This means that in addition to the component itself, the printer must also build the support structure as it progresses upwards. This support is then removed by the user when the print is finished.

How this support structure looks in detail is usually handled by the printer software. However where and how much is needed can be managed by the user, mainly by how the component is oriented in the print and through careful design so as to avoid overhangs. Figure 4.3a illustrates a situation where support structure is required due to an overhang. The white part has an overhang that necessitates the red support structure. This figure also shows how the angle of the overhang affects the need for support. In the lower section where the angle is low, no support is needed as such overhang can support itself. When the angle increases and finally becomes horizontal, support is required. Reorienting the component to what is seen in Figure 4.3b completely negates the need for any support structure and is as such a better orientation. In some cases, small overhangs can be printed without any support, especially when using quickly solidifying materials. Overhangs must however always be considered in the design, or it can easily become hard to remove without either damaging the component or have the support structure corrupt dimensionally sensitive areas.

The components presented in this report have all been designed and redesigned for specific printers, to suppress their weaknesses and capitalize on their strengths. Printers using different materials have been used throughout the development process. This voids any potential comparisons of the relative performances both of materials and printers, as it is hard to isolate what is an effect of the printer and what is an effect of the material.

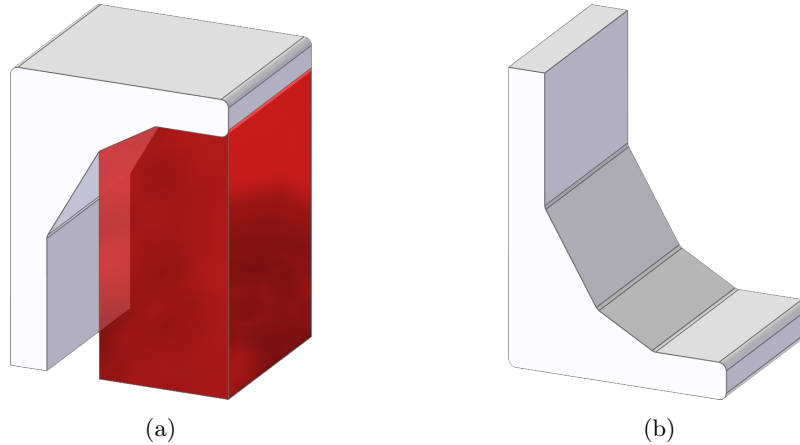


Figure 4.3: Illustration of how overhangs and orientation affects the support structure in 3D-printing.

Fused Filament Fabrication

Also known by the name FDM (Fused Deposition Modeling), FFF is the most common technology in consumer grade 3D-printers. Objects are created layer by layer through deposition of, commonly, a thermoplastic filament or metal wire. This filament/wire is heated up and extruded through a nozzle onto a base plate or “print board”. After the first layer is put down on the board, layers are successively deposited upon one another. Proper control of the temperature in this process is critical for a favorable result. Both the extruded filament and the previous layer onto which the filament is deposited must hold a high enough temperature to ensure that they fuse properly. At the same time everything should be kept at a temperature low enough to make it strong and stiff enough to hold its shape throughout the print. Furthermore, uneven heating or cooling can introduce thermal stresses. Thermal control is generally achieved through a combination of heating elements and cooling fans.

In this work, the two thermoplastics PLA (Polylactic acid) and ABS (Acrylonitrile butadiene styrene) have been printed in the consumer grade printers *UP Plus 2* [23], *Ultimaker 2* [24] and *CubePro Trio* [25]. The prices presented below were aggregated from the manufacturers’ websites 2016-01-18.

The UP Plus 2 is the smallest and cheapest of these printers, printing objects up to $140 \times 140 \times 135 \text{ mm}^3$ with a layer resolution of down to 0.15 mm. This printer cannot print full scale hull structures for the CubeSub as it is too small. Prints are made on a perforated board heated by a heating element placed centrally on the underside of the board. It sells for \$1299.

The Ultimaker 2 prints object up to $223 \times 223 \times 205 \text{ mm}^3$. It has the finest layer resolution of the three with down to 0.06 mm. The build plate is made of glass and is evenly heated by a resistance wire running underneath the whole plate. The Ultimaker 2 has been discontinued and replaced by the updated Ultimaker 2+ which sells for \$1895.

The CubePro Trio is the largest and most expensive of the three, selling for €3499 (approximately \$3900). It prints objects up to $285.4 \times 270.4 \times 230 \text{ mm}^3$ in size and has a layer resolution down to 0.07 mm. Prints are performed inside an enclosed and heated chamber. The whole object, not just the base, is thus heated evenly throughout the print. The print board is unheated.

An important aspect in the context of the CubeSub is that objects created through FFF are not necessarily waterproof. A series of points where filaments do not fuse perfectly can in combination create paths for the water to pass from one side to another. Making outer walls thicker and more dense can somewhat mitigate this risk. Acetone dissolves ABS and can be used as a surface treatment to waterproof components printed in ABS. It can also be used to repair cracks, smooth out surfaces and fuse components. [26]

The print board will be referred to as the printer’s plane and directions which are not parallel with said board will be referred to as out-of-plane. Normal to this plane is the vertical axis.

Stereolithography

SLA is a technique based on photopolymerization, a process in which a resin is polymerized, solidified, through absorption of light. By focusing light into a container of resin, layer upon layer is polymerized and a solid object grows into existence in the resin bath.

The printer that has been used for SLA printing is another consumer grade printer, the Formlabs Form1+. It has a layer resolution down to 0.025 mm and has been run with the by Formlabs provided general purpose “grey resin”. Parts up to a size of 125 x 125 x 165 mm³ can be printed. Formlabs claim that components printed with the Form1+ are waterproof [27]. This claim has not been tested in this work.

4.2 Development

This section covers the technical details of the CubeSub. First of all the starting point of the development, followed by an overview of the system architecture and design-driving decisions. After that, each module and component that has been developed throughout this work is presented. Each module and component will be described with regards to its intended function and design. The printability will be discussed, namely the specific manufacturing challenges and considerations associated with each module and component.

Apart from what is presented in subsection 4.2.1 Starting point, everything in this section has been developed in the project covered by this report and has been modeled from the ground up using SolidEdge CAD software. CAD models of CubeSats are supplied by CubeSatKitTM and used for illustration purposes [28].

4.2.1 Starting point

Prior to the beginning of the work presented in this report, some development had already been performed. The electrical and communications system architectures have been laid out and some programming has been performed. A full-scale mockup of the submersible and electronics compartments have been 3D-printed and submerged to test waterproofing and electronics packaging.

The CubeSub is designed as a traditional AUV (Autonomous Underwater Vehicle), long and slender with CubeSats stacked lengthwise. The nose cone holds optical instrumentation such as camera and lights. Engines and propellers are situated in the stern.

Modules that require control are controlled by an Arduino/Genuino Fio board. The Arduino is an open-source single-board microcontroller based on easy to use hardware and software [29] [30]. Arduino boards are available in many different shapes and have become popular tools among both amateurs and professionals wishing to control for instance a mechanism or a scientific instrument. In the CubeSub they handle things like control, data collection and internal communication.

Internal communication between modules is performed wirelessly, through XBee radios [31] mounted to the Arduinos. How the CubeSub will communicate with the surface is at this point not decided. Options include a stern mounted tether or a hydrophone. In the long term this will not be an issue as the CubeSub is to be autonomous and collected data will be recovered as it resurfaces.

Each and every module will have an individual power supply. In combination with the wireless communication this means that no cables will have to be routed between modules.

4.2.2 Key features

Before starting the development of specific modules and functions, some design-driving decisions are made. In this section these decisions and some key features are discussed.

Modularization

Central to the overall design is the modularization. The CubeSub physically consists of modules, each of which have distinct functions. Figure 4.4 illustrates the modularization concept and how modules are to be stacked together. As an example, between the Nose Cone and Stern Thruster Module it holds two Cube Modules each containing a CubeSat, followed by a set of arbitrary modules. This arrangement will

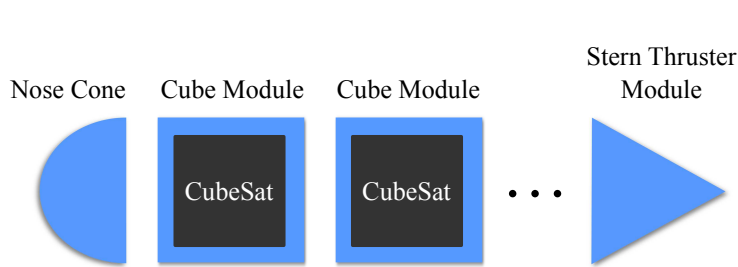


Figure 4.4: Modularization concept.

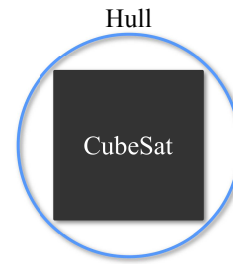


Figure 4.5: Diagram of cross section.

be up to the end user and, barring an excessive number of modules, any sequence shall in principle be possible. As was discussed earlier no cables will be needed in-between modules meaning that the only physical interface between modules will be structural. To achieve this a standardized interface must be developed that every module should comply with.

With nothing but a Nose Cone and Stern Thruster Module operation is possible, albeit a somewhat rudimentary one. These two modules are to be invariable, and once a final design is agreed upon they will not be subject to modifications between missions. For any kind of “meaningful” operation however, at least one Cube Module will be required to carry payload. With a standardized interface design it will also be possible to create additional modules to further enhance functionality.

Trim of the buoyancy will likely have to be done “ad hoc” for every different payload and set of modules, even though most of it should be cared for by mindful designing and positioning of the payload. It is thus imperative that the design allows the user to add ballast and buoyancy to the CubeSub.

Flooded interior

The CubeSub will when submerged have its interior flooded with ambient water. In other words the hull will not be waterproof, instead it will purposefully be built to take in water at deployment. This is to provide a more direct contact between payload and ambient water, through that making it easier for them to interact via windows or holes in the outer hull. Furthermore, considering that 3D-printing is to be used extensively, the manufacturing process will be simplified due to the uncertainty of its compatibility with water as discussed earlier. The main implication of this is that instrumentation sensitive to water must provide its own water- and pressureproofing. This makes for a fundamental requirement on the CubeSat payloads, similar to how they today must be able to endure the vacuum during space missions.

Cross section

Since the only hard dimensional constraint on the cross section is the CubeSat with its cubic shape, the CubeSub’s cross section can in principle be of any given shape as long as it is has room for the CubeSat. Having said that, the CubeSub is designed with a circular cross section. Shapes other than near-square and circular have for the sake of simplicity been disregarded when making this decision. Figure 4.5 illustrates the circular hull and inscribed CubeSat conceptually.

A circular cross section will, given this dimensional constraint, be stiffer and stronger when subjected to loads such as bending, twisting and radial compression. It will not have any corners in which stress concentrations might occur. Looking further into the future where a pressurized derivative might be developed, it would also be convenient if as much as possible of the design is easily adapted to what is most likely to be a circular cross section. The empty sections between CubeSat and hull created by a circular cross section can be used for beneficial functions such as buoyancy and ballast for trimming, or to extend the allowable size of the CubeSats.

A more square cross section is of course not without its advantages. It gives the possibility of a smaller wetted area and smaller frontal area which in turn gives a lower drag, with the potential drawback of being more sensitive to tangential flow. The smaller cross section also leads to less material and thus a lower mass, however the structural drawbacks might nullify this. The internal volume would be reduced and with that the water it contains. As the internal water must be accelerated with the CubeSub, this could make it faster and more maneuverable.

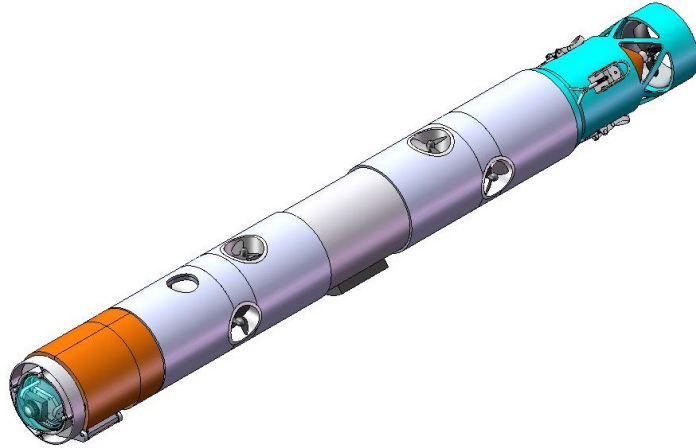


Figure 4.6: CAD model of the SCINI submersible. Courtesy Moss Landing Marine Laboratories.

Control

Control of the CubeSub will be achieved solely through the use of thrusters. In an attempt to keep the outside as narrow and smooth as possible and avoid any risks of snagging, control surfaces will not be used.

Without any control surfaces, change of pitch and yaw will be achieved using transversely mounted tunnel thrusters. Figure 4.6 shows the SCINI submersible built at the Moss Landing Marine Laboratories with such an arrangement [32]. Pitch is changed by one or more vertical thruster(s) and yaw by one or more horizontal thruster(s) pointed perpendicular to the direction of travel. With a set of two engines in each direction, this system can also be used to translate in sway and heave. As opposed to control surfaces, transverse thrusters are usable at standstill which for instance can be useful when surveying a small object from different angles.

Roll is not to be controllable, in the sense that the CubeSub will be roll stable and without any means of intentionally altering its roll orientation. Roll stability will be achieved mainly by keeping the center of mass low, which is anticipated to be more adjustable than the center of buoyancy at this stage of the development. Some additional buoyancy and ballast must be possible to add to trim the CubeSub. However so as not to make trimming unnecessarily difficult, keeping a low center of mass will where applicable be considered in the design.

4.2.3 Cube Module

The Cube Module has been designed in conjunction with the Structural Module Interface, which will be discussed in detail in section 4.2.4 below. To give the reader a better overview, the Cube Module is presented first.

Function

The Cube Module is as the name implies the module that carries CubeSats. It will serve as a self-supporting section of the hull and is as such subject to some mechanical loading. The Cube Module is the widest point of the CubeSub, thus it also drives the design of other modules as they will adhere to its width.

Design

Figure 4.7 shows the base 1U Cube Module in subfigures a, b and c, where a and c also include CubeSats. Inspired by the P-POD (Figure 4.2), CubeSats are held in place by 8 slides, a type of “tracks” running lengthwise on the inside of a cylindrical hull. These slides do not run the full length of the Cube Module, but instead terminates 6 mm before each end to give room for the Structural Module Interface ring. At each end of every slide there is also a protrusion, or “bolt pod”. Through the bolt pod runs a countersunk

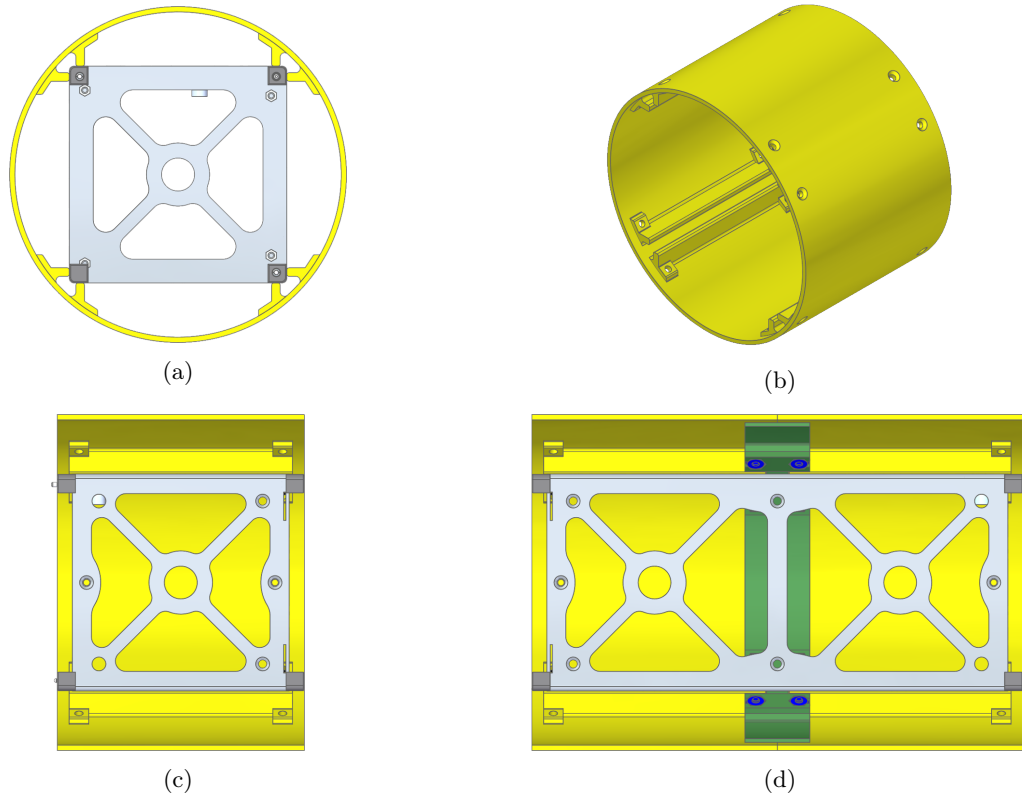


Figure 4.7: Cube Module in different views and configurations.

hole for flat headed bolts. This bolt interface will be discussed further in the Structural Module Interface section.

The Cube Module does not fixate the CubeSats in the longitudinal direction, something that is instead cared for by adjacent modules not carrying CubeSats. Each such module is designed with a “stop block” in each corner that stops CubeSats from moving along the slides. Figure 4.8 shows a close up of a CubeSat secured by a stop block in the Stern Thruster Module. Also visible in this figure is the Structural Module Interface connecting the two modules.

The base version of the Cube Module, is exactly the same length as a 1U Cube, 113.5 mm. It is also available in 0.5U, the only difference being the length which for the 0.5U is 56.75 mm. The cylinder that constitutes most of this module has inner and outer radii of 74.5 and 77 mm respectively, giving it a wall thickness of 2.5 mm. This also means that the CubeSub will be 154 mm in diameter at its widest point. The inner radius is chosen so as to give enough room for both CubeSat and Structural Module Interface. The choice of wall thickness is a result of prototype prints, where smaller thicknesses have been found too flimsy and flexible, indicating that they might break too easily.

Both ends of the Cube Module are identical, thus the direction in which it is assembled does not matter. Connecting multiple modules makes it possible to carry multiple and/or larger CubeSats. Figure 4.7d shows two Cube Modules stacked together holding a 2U CubeSat. Also visible in this picture is the Structural Module Interface connecting the two modules.

As the inside of the CubeSub is flooded with water, users can make cutouts in the walls to give the CubeSats access to the surrounding water. As was discussed earlier and visible in Figure 4.7a, a void is created between CubeSat and hull, which can be used for beneficial purposes. Based on need, this volume can be used for buoyancy and ballast. Alternatively, the allowable dimensions of the CubeSats could be increased. The best course of action is likely to be mission specific and depends on parameters such as amount and distribution of mass and the physical size of the payload.

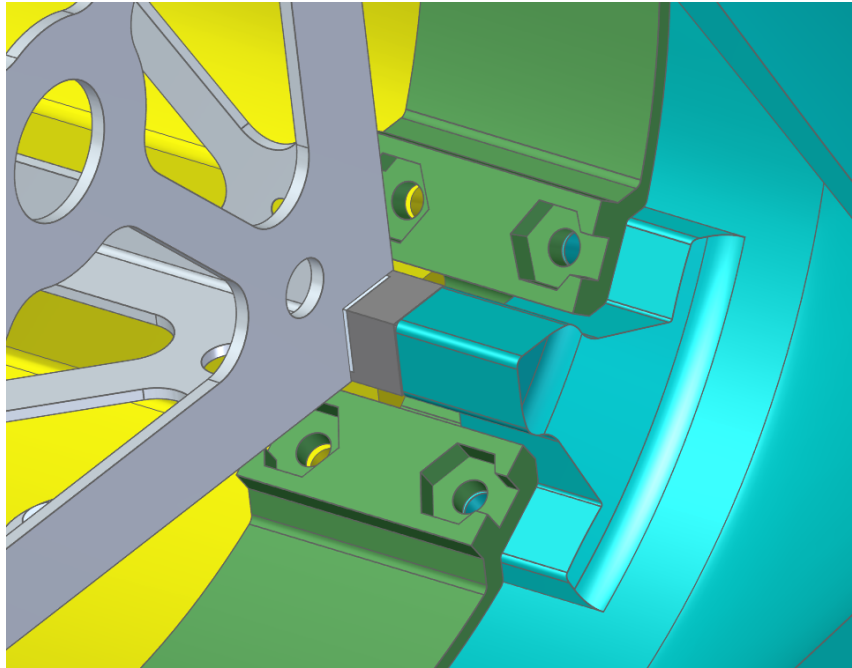


Figure 4.8: Close up illustration of a CubeSat held in place by a Cube Module and a stop block.

Printability

With a design that is overall fairly simple, printability is for the most part very good with some small details to take note of.

Two full-scale examples have been printed, one of the standard 1U size and one of the smaller 0.5U. Both were printed in the Ultimaker 2 with favorable results. The 1U took just over 20 hours to print and consumed approximately 210 grams of PLA. The 0.5U did as one would expect require approximately half the time and material. Both were printed “standing up”, with the cylinder’s central axis vertical.

Inherent in the design are some, albeit in this case small, challenges for printing. The previously mentioned slides and bolt pods that terminate before the end of the cylinder become overhangs when printed, meaning that they require a small amount of support structure.

Both prints were run with the finest layer resolution of 0.06 mm and at a relatively low nozzle speed of 30 mm/s. Running a lower nozzle speed directly leads to a lower mass flow of material which in broad terms puts less stress on the printer and filament. During these two prints, a negative side effect believed to be a result of the lower nozzle speed was observed. Intermittently, layers did not fuse perfectly, which could be an effect of the low nozzle speed giving each layer too much time to cool off before the next one is deposited upon it.

Due to problems with the printer, these prints were run without what is called *retraction*. The printer can retract when moving without extruding, over open spaces in the print where no material is to be printed. What this means is that the filament is pulled back slightly into the nozzle to prevent it from getting pulled out inadvertently when moving over previously deposited material. Without retraction a buildup of residual material can occur around edges where the nozzle transitions between printing and not printing. Figure 4.9 shows a close up of such residue observed at a completed print in the area around the end of the slides. This residue easily solidifies “in thin air” and can become fairly rigid after a couple of layers. Most of this residue can be removed by hand followed by a clean up with a rotary tool.

In the general case, small out-of-plane holes are not printed with great precision and even less so without retraction. The countersunk holes are modeled with exact dimensions to match bolts and after the print cleaned out with a handheld drill.



Figure 4.9: Residue given by non-retracting filament in Cube Module print.

4.2.4 Structural Module Interface

Function

The Structural Module Interface, hereinafter *SMI*, connects the modules mechanically. This is a standard design to which all modules adhere. A standardized interface makes the CubeSub flexible in the sense that it allows the assembly of different configurations, while also keeping the number of different components low.

Design

The SMI is perhaps best described as a low cylinder with cutouts and protrusions to make it fit the Cube Module. It covers the inside seam between adjacent modules and fixates them to each other with the use of nuts and bolts. Its outer radius of 74 mm is, with some added clearance, matched to the inner radius of modules of 74.5 mm. Apart from the bolt heads the SMI is completely invisible from the outside and only requires a screwdriver for assembly. Figure 4.10 shows three different views of the SMI and Figure 4.11 shows an SMI and two Cube Modules in assembled and disassembled states.

One SMI holds 16 bolts and nuts, or 8 per module. Due to being more available on NASA ARC, ANSI 6-32 bolts and nuts are used instead of a metric equivalent. To keep the outside as smooth as possible the holes are countersunk and the bolts are of flat-head type. As a direct result of this, a set of small protrusions, bolt pods, have been added to the insides of the modules being connected. These give the joint additional grip length, some of which is lost due to the countersink, and can be seen in Figures 4.11b and 4.12.

A bolted solution is chosen as it makes for a strong joint that is easy both to assemble and disassemble. Nuts are prior to assembly glued in place on the inside of the SMI, thus one does not need direct access to the nuts during assembly. Not only is this somewhat convenient, but also an absolute requirement to make assembly and disassembly possible as the inside is not accessible from the outside of a complete CubeSub. In a sense this solution is a substitute for threads in the ring itself. The bolts are positioned close to the slides in an attempt to make the interruption of the open space between CubeSat and hull as small as possible. In the possible case where this space is to be used, this is meant to reduce spatial constraints. Cutouts are made for the nuts to sit in, visible in Figures 4.10c and 4.11. These make it easier to position nuts when gluing, it also gives mechanical support for when the nuts are tightened.

Longitudinal cutouts are put in place to make some additional room for the slides in the Cube Module. This is a conservative approach with respect to supporting the CubeSats, allowing the slides to be almost as long as a CubeSat and thereby give it good mechanical support.

A fundamental spatial constraint is imposed by the CubeSat held by the Cube Module, none of which the SMI can intersect. Packaging around the corners of the CubeSats is compact and relatively short bolts must be used. Figure 4.12 illustrates the interaction between Cube Module, SMI and CubeSat.

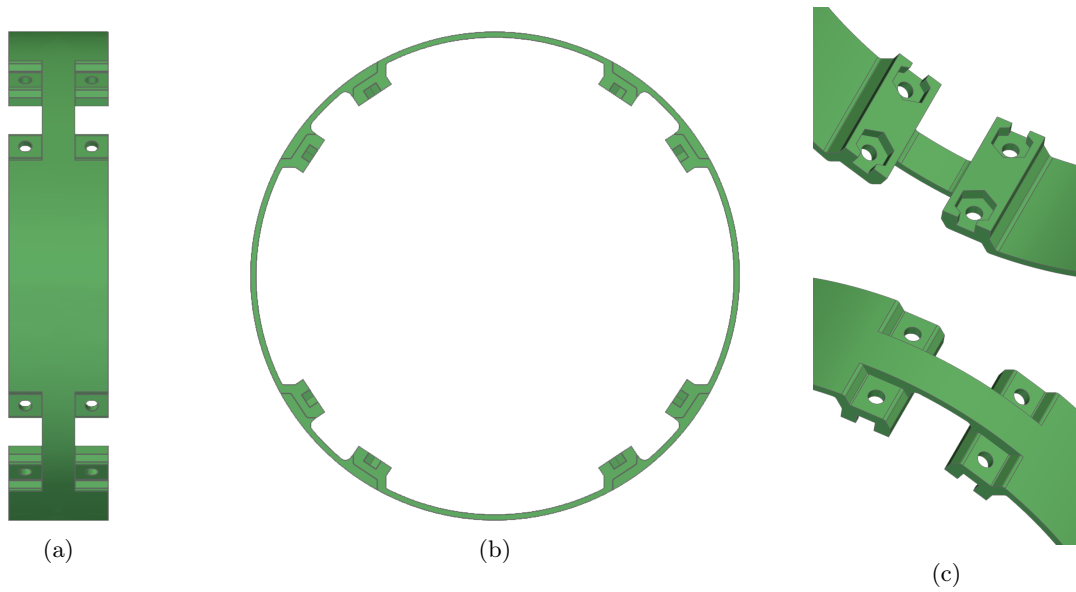


Figure 4.10: Structural Module Interface viewed radially (a), axially (b) and close-ups of bolt joint (c).

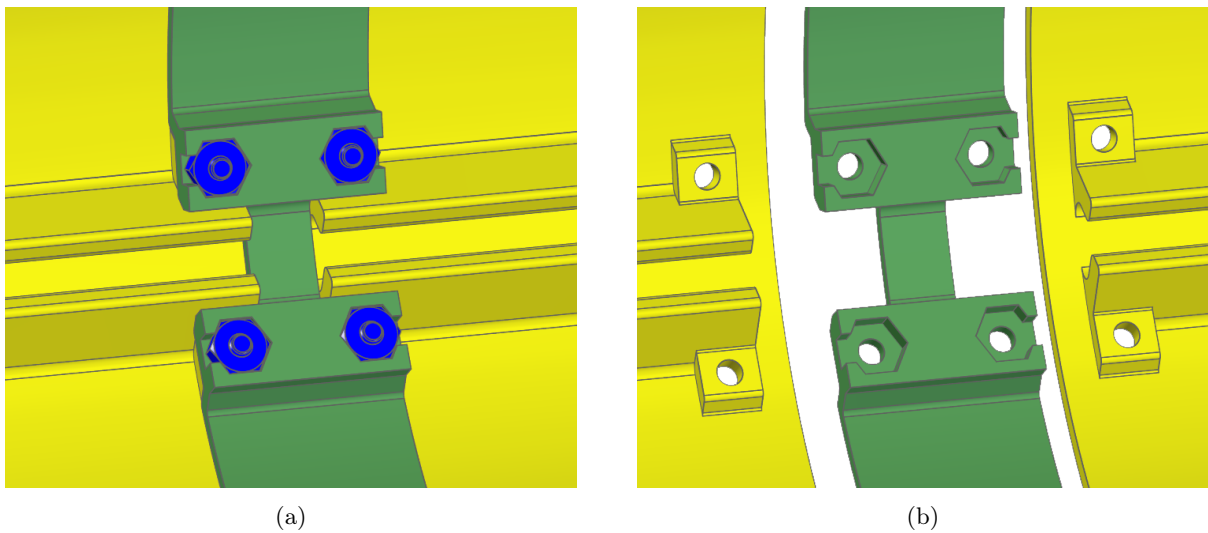


Figure 4.11: Close up of two Cube Modules and one SMI in assembled (a) and disassembled (b) states.

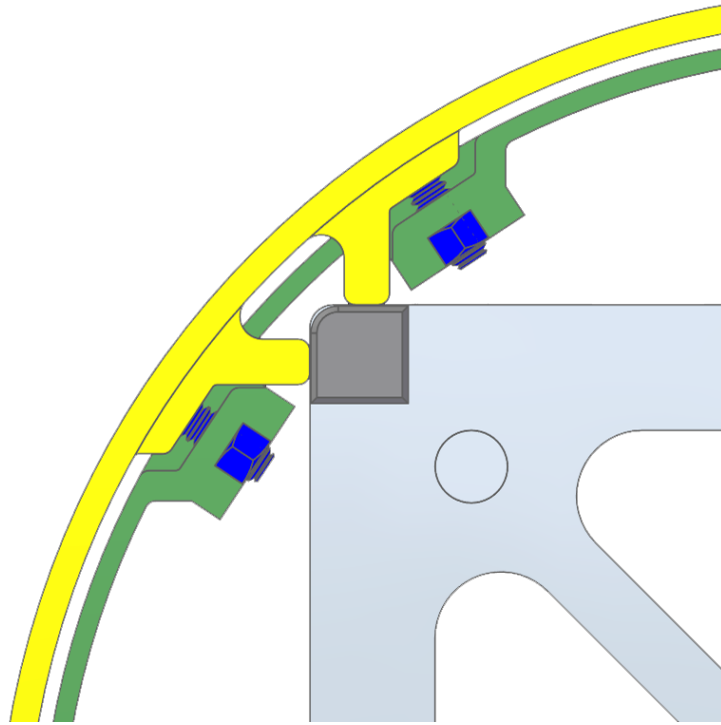


Figure 4.12: Detail view of Cube Module, SMI and CubeSat positioned on slides.

Printability

Like the Cube Module the SMI has a simple overall shape and is easily printed with generally good results. Also like the Cube Module, the SMI is best printed with its central axis vertical. The principal difficulty inherent in the design are the overhangs created by the cutouts for slides and nuts.

Printing the SMI in the Ultimaker 2 takes around 5 hours with a layer resolution of 0.06 mm and consumes 50 grams of PLA. Similar issues due to non-retraction as seen on the Cube Module occurs in the areas around the bolt holes. A few examples have been printed in the CubePro Trio with mixed results. Overall the CubePro gave a weaker and more flexible SMI than the Ultimaker 2.

4.2.5 Nose Cone

Function

The Nose Cone's primary purpose is to provide a somewhat hydrodynamic front to the CubeSub. It also has a mount for a GoPro Hero v1 camera that will be used for documentation during tests. It is in its current form relatively simple, but is expected to be revised in the future to have greater functionality. Expected additions are a more compact camera, lights and an Arduino board for control and communication. One could also add things like a sonar, or sensors to measure parameters such as temperature, pressure, salinity et cetera.

Design

The overall shape is made up of a low cylinder connected with a nearly spherical bowl. Figure 4.13 shows the front and inside of the Nose Cone and 4.14 shows a section view. Along the inside of the cylinder there are four "stop blocks" put in place to axially constrain CubeSats held by adjacent Cube Modules. Integrated in the root of each stop block are bolt pods of the same kind as in the Cube Module.

Centrally at the front is a hole for the GoPro lens and start button. Fitted to the GoPro housing is a 55 mm underwater lens, why the hole is relatively large. Inside is a fixture for the GoPro made up of three stalks with holes in the top, matching the standardized GoPro interface. The stalks are

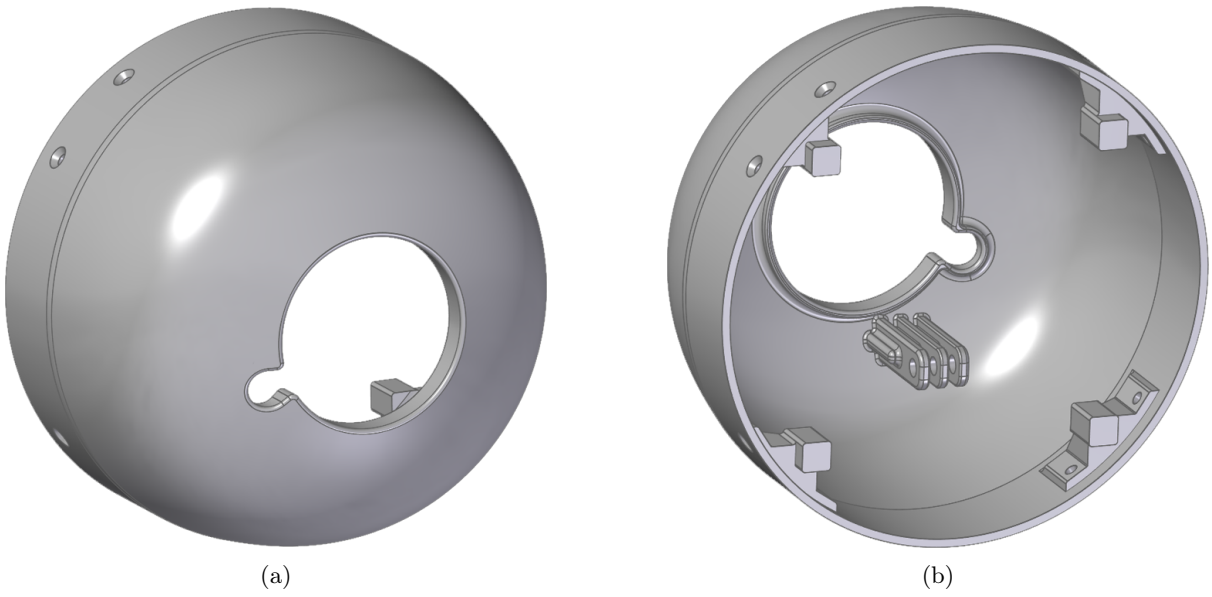


Figure 4.13: Frontal (a) and inside (b) view of the Nose Cone

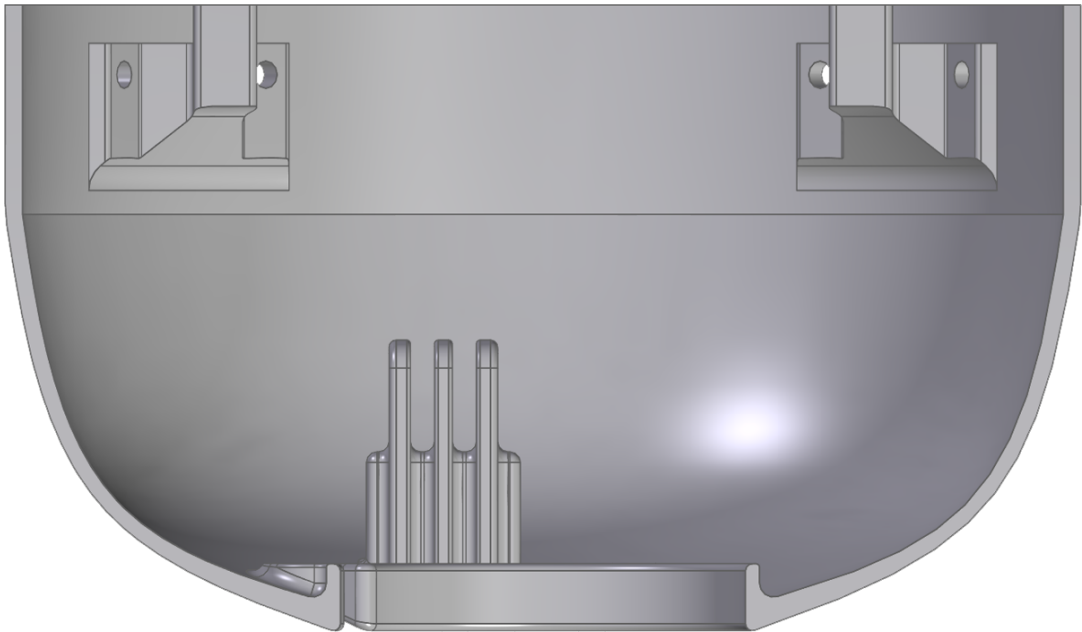


Figure 4.14: Section view of Nose Cone.

structurally connected to each other from the root to about halfway up, to make them less prone to breaking off when fitting the GoPro.

Arguably the simplest design for the bowl is a half sphere, however such a design is problematic due to the size of the GoPro. With the lens positioned exactly along the centerline of the CubeSub, one corner of the GoPro would intersect a spherical Nose Cone. To make room for the GoPro the Nose Cone is made slightly more blunt or “squared off” than a sphere. Other possible alternatives include positioning the lens off-center or making a bulge around the corner in question.

Printability

The Nose Cone is not as straightforward to print as the previously discussed modules. The first working example only came after multiple failed prints with both the Ultimaker 2 and CubePro, with the latter never managing to print a complete Nose Cone.

After two failed full-scale attempts the Nose Cone came out with a good result from the Ultimaker 2. The successful print took 20 hours and consumed 170 grams of PLA. The failures was found to be results of problems with the filament feeding. In the first attempt the filament broke off and during the second attempt it slipped out of the feeding mechanism, both of which lead to complete print failure as the nozzle was starved of material. In the third attempt the nozzle speed was reduced to 30 mm/s to give a lower feeding speed and put less stress on the filament. This is believed to have contributed to the successful result.

Multiple attempts were made in the CubePro Trio, all of which failed. The common cause of failure was that the Nose Cone came loose from the board during the print, which invariably leads to a complete failure. Factors believed to contribute to print failures are non-sufficient board adhesion, printer nozzle dragging on the part and mid-print thermal deformations of the part which in turn further amplifies the nozzle dragging. All prints failed at an early stage, less than an hour into the process. The expected printing time in the CubePro was 15 hours and approximately 170 grams of ABS would have been consumed.

Printing orientation is for the Nose Cone of great significance for the outcome, as any orientation requires a fair amount of support structure. The best orientation was found to be “face down”, with the Nose Cone standing like a fruit bowl. This is the same orientation as seen in Figure 4.14. Some support structure is required for the lower end, but the steeper upper section can be printed without support. This orientation also leaves the dimensionally sensitive GoPro fixture to be printed without any support. If printed the other way around, like a dome, a considerable amount of support on the inside of the dome would be needed. This is both time consuming and likely hard to remove. Other orientations will have the same problems with large overhangs and subsequently excessive support structures.

One difficulty with the “face down” orientation is created by the CubeSat stop blocks that stick out on the inside of the Nose Cone. Building support structure for them is not certain to give a good result as the support would not rest on the printer board, but rather on the steep inside of the Nose Cone. This issue is addressed by a chamfered transition from cylinder to stop block. What this does is provide a gradual transition, which can be printed without support structure. This can be seen in Figure 4.14. As an added benefit, the stop blocks become mechanically stronger.

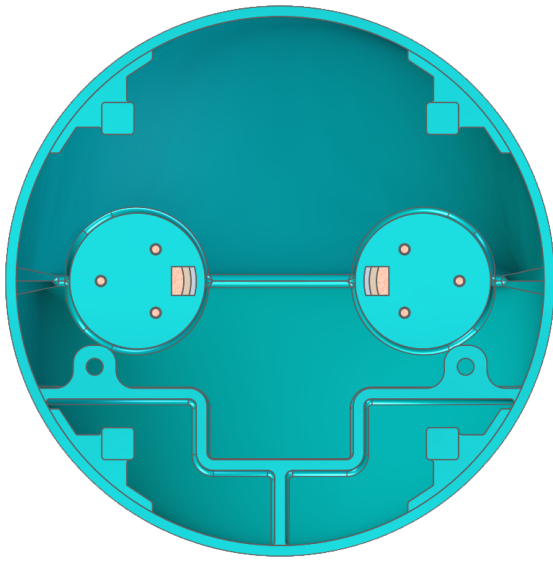
4.2.6 Stern Thruster Module

Function

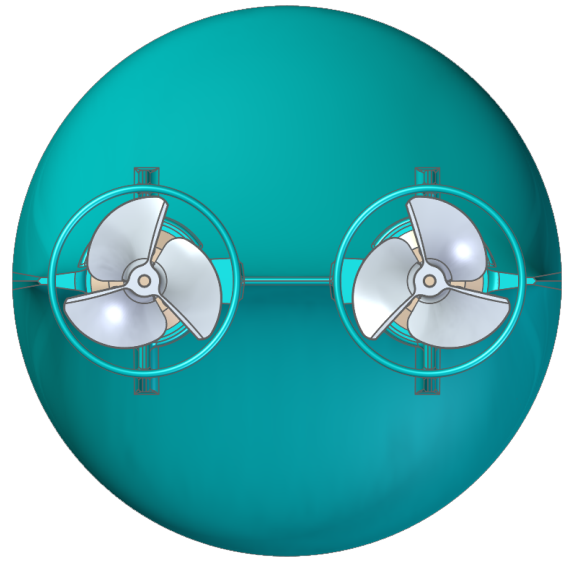
As is implied by its name the Stern Thruster Module, hereinafter *STM*, is to be the main provider of thrust and is positioned at the back end of the CubeSub. It holds engines, batteries and an Arduino board to control the engines. In future revisions the *STM* might also be the attachment point for a tether, which would then require some additional subsystems to handle and distribute the tether data.

Design

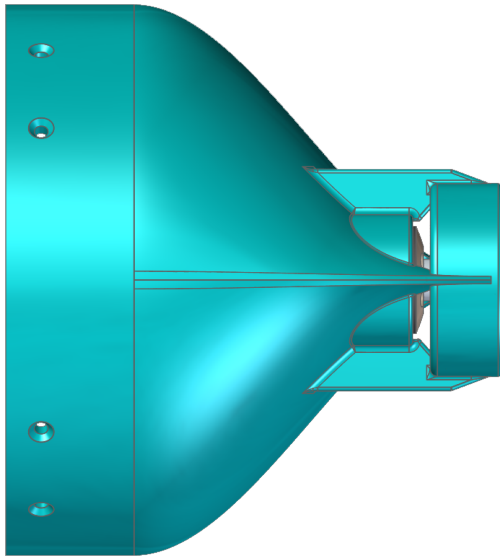
The *STM* is in a number of respects similar to the Nose Cone. It is based on the same low cylinder which in this case is connected to a lofted wedge-like shape. Along the inside of the cylinder are the same CubeSat stop blocks. Situated at the tapered end are two engine mounts with nozzles. In these



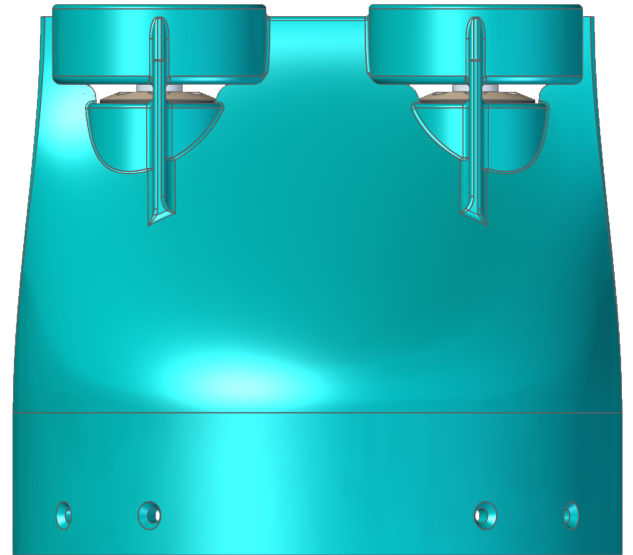
(a)



(b)



(c)



(d)

Figure 4.15: Front (a), back (b), side (c) and top (d) views of Stern Thruster Module.

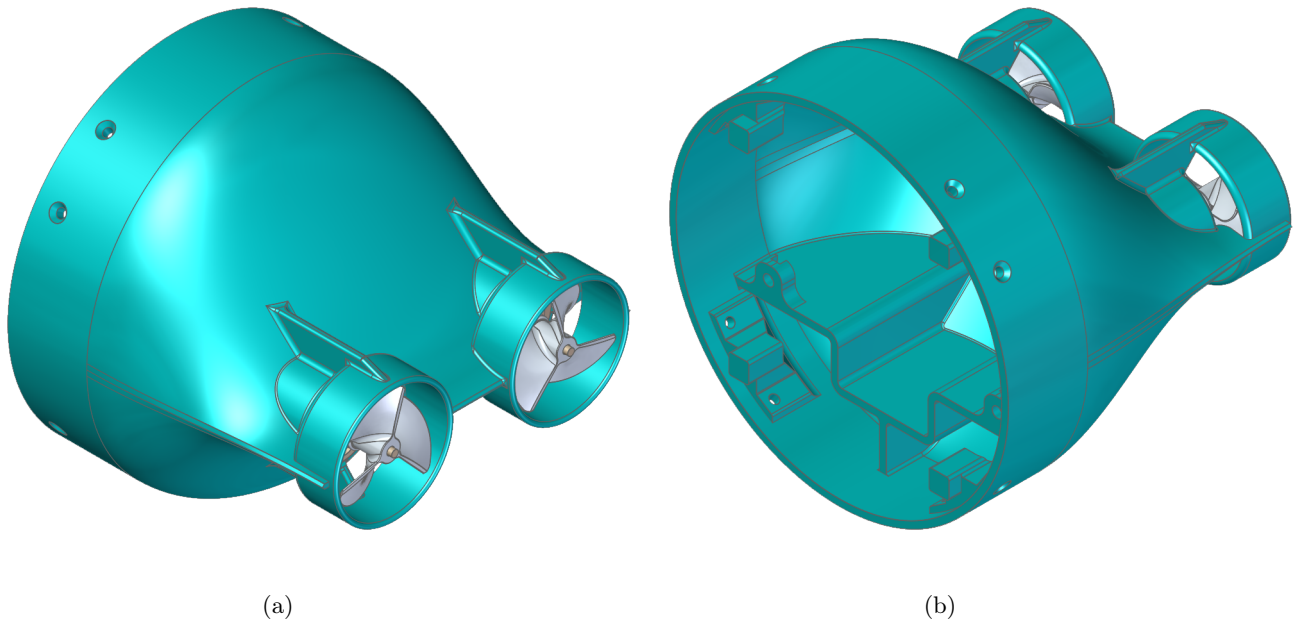


Figure 4.16: Isometric views of the aft (a) and forward (b) facing sides of STM.

mounts sit two brushless engines, which are counter-rotating so as to cancel each other’s roll moment. Figure 4.15 shows four orthographic views of the STM and Figure 4.16 two isometric views.

Solutions with one and four engines have been considered. The single engined concept was rejected due to the non-cancelable roll moment and expected weak thrust. A set of COTS engines and propellers had already at an earlier project stage been acquired, and the STM is designed to utilize these. Had this not been the case a larger single engine could have been used to achieve the same thrust as the current solution. With four engines the roll moment can be canceled and more thrust can be achieved, but at the cost of high mass and power consumption. Furthermore, the packaging is expected to be challenging with four engines and it was as such also rejected.

An important aspect of the design is, loosely speaking, the overall “smoothness” of the STM. The flow of water supplied to the propellers should be of good quality to ensure high propulsive efficiency. To keep the form drag low the flow should also stay attached, something a smooth shape helps facilitate by keeping pressure gradients small. Because of this the STM has been designed to have an overall shape that is free of abrupt geometric changes.

At the tapered end of the wedge are two wells, at the bottom of which the engine mounts are found. The mounts have three screw holes and a slot for the engine wiring. Each engine is threaded with three M2.5 holes, and screws are inserted from inside the STM. Nozzles in the form of straight cylinders encircle the propellers for protection and to reduce the risk of snagging. The engines are positioned such that they are directly exposed to water, however the manufacturer Turnigy claims that they are waterproof.

The mechanical interface to which the Stern Electronics Compartment (section 4.2.7) is connected comprises most of the inside. This interface is made up of a seating matching the shape of the compartment and two “ears” to which the compartment is fixated with ANSI 6-32 bolts. On the backside of the ears there are cutouts for nuts similar to those seen on the SMI (Figure 4.11). This seating can be seen in Figures 4.15a and 4.16b.

Printability

Due to the complex shape and many features the STM is currently the most complicated part of the CubeSub to print. One example has been printed successfully in the Ultimaker 2, which with a nozzle speed of 30 mm/s and a layer resolution of 0.06 mm took 42 hours. 340 grams of PLA was consumed.

The STM is best oriented with its nozzles pointing directly upwards. This gives a large footprint on the print board and thus provides a strong foundation for the rest of the print. One might think that it would result in large amounts of support structure, however the walls of the wedge are steep enough

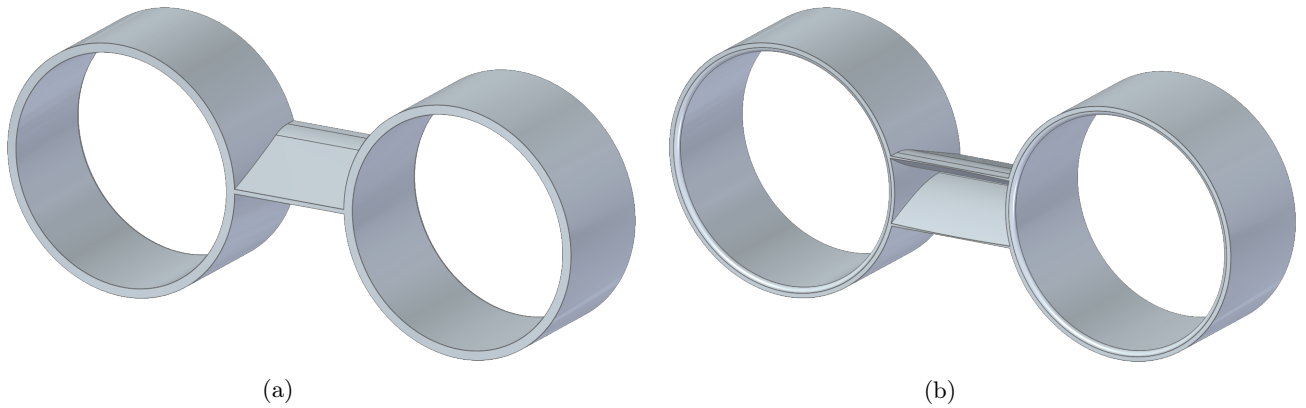


Figure 4.17: Aft (a) and forward (b) facing sides of ad hoc nozzle unit.

not to require support. Support is required for the plane surfaces on the engine mounts and electronics compartment shelf. The engine mounts have the capability to be very flat on the outside which in turn enables the placement of propellers to be performed with good precision.

Orienting the STM with nozzles downward would make for a less sturdy starting point. Engine mounts would have support structure on the outside, possibly hard-to-remove, in the engine wells. Furthermore, the ears made for the electronics compartment are at risk of low fidelity on the inside where the nut is positioned. Other orientations have been disregarded due to expected excessive support structures.

The nozzles proved problematic for printing. The Ultimaker 2 was unable to build support structure resting on the steep wedge, whereas the UP Plus 2 did so without problems when a small scale test was performed. Because of this, the nozzles were removed from the STM model prior to printing and thereafter printed separately in the UP Plus 2. Figure 4.17 shows the ad hoc nozzle unit that was designed for this purpose. The section connecting the two nozzles is made to match the wedge between the engines, and then glued in place onto this wedge. The prongs that originally support the nozzles were kept in the design to reduce the risk of debris entering the nozzles during operation.

Printing the nozzles by themselves also proved somewhat challenging. Multiple prints failed due to the nozzle unit coming loose from the board. This is believed to be due to a combination of thermal stresses and non-sufficient board adhesion. By enclosing the printer in a box to increase the surrounding temperature and making small design modifications to increase the contact area between printer board and nozzle unit, the print succeeded. The nozzle unit was oriented with the nozzles' central axes vertical and the tapered end of the wedge facing down into the board. This orientation leaves the dimensionally critical inside free of any support structure or overhang residues. The successful print took just under 4 hours with a layer resolution of 0.15 mm and consumed 22 grams of ABS.

4.2.7 Stern Electronics Compartment

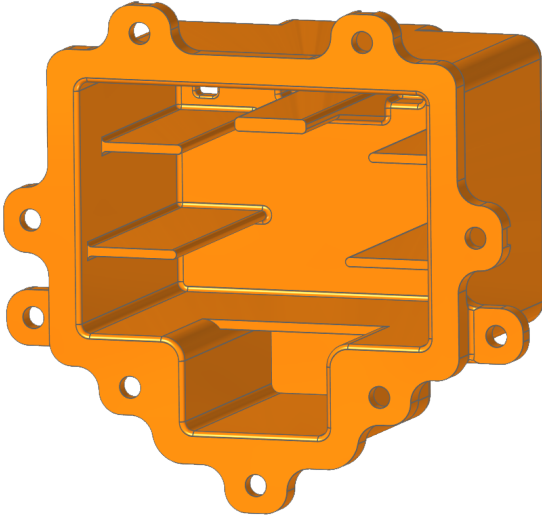
Function

The Stern Electronics Compartment, hereinafter *SEC*, holds all the electronics required to control the engines in the STM. It provides waterproofing for the electronics, required due to the STM being flooded with water. The SEC is not designed to withstand elevated pressures and to keep the STM compact the SEC is made to be both compact in itself and packaged tightly inside the STM.

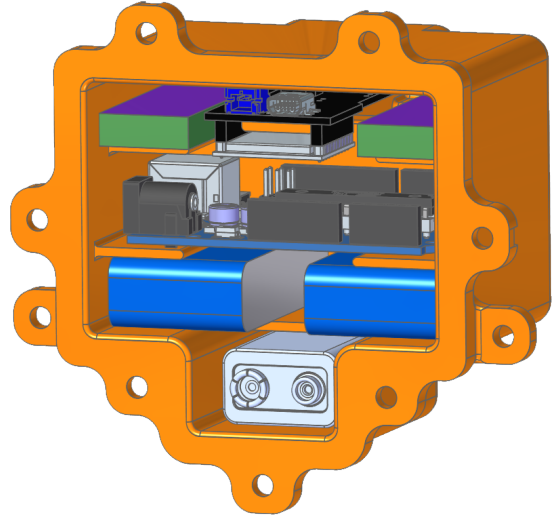
Inside the SEC sits one 9 V battery, two 7.4 V LiPo batteries, two ESCs (Electronic Speed Controllers), one Arduino Uno or Fio and cables to connect it all. The possibility to have either an Arduino Uno or Fio is to increase the flexibility in the early development stages. Future revisions are expected to use the Fio board only.

Design

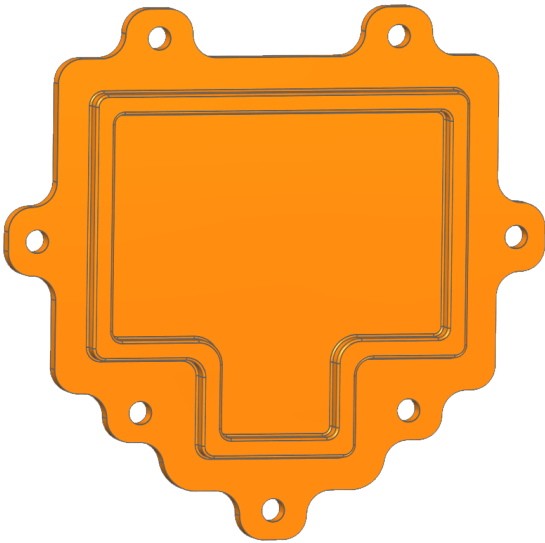
The SEC is fairly simple in design with an overall “boxy” shape and a bolted on lid to keep the water out. The shape is given by the components it is to contain. It is seated in the STM on a shelf tailored



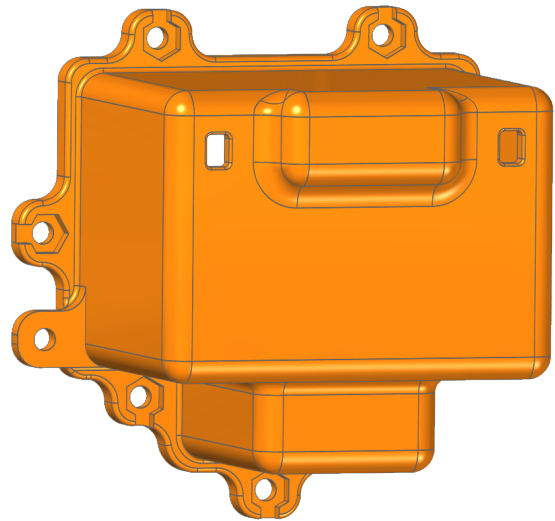
(a)



(b)



(c)



(d)

Figure 4.18: Empty (a) and full (b) SEC, lid (c) and back side (d).

to the shape of its lower end and attaches with two ANSI 6-32 bolts and nuts to the “ears” on said shelf. Making the SEC a fully integrated part of the STM was considered in the design process, but rejected to make the SEC more flexible in design and easier to work with during operation. The outer walls are 3 mm thick, a number determined by simple leak-tests of boxes with different thicknesses.

Figure 4.18 gives a visual overview of the SEC. Subfigure a shows the empty SEC from the front. Subfigure b shows the SEC with all components inside. At the top level are two ESCs (corners) and one Arduino Fio with an XBee module (middle). Beneath them lies an Arduino Uno. Under the Uno are two LiPo batteries which power the engines via the ESCs. At the bottom is the 9 V battery driving the Arduinos. As was previously mentioned only one of the Arduinos will be used at once, thus freeing up some space to pack wire excess in. Subfigure c shows the the lid and subfigure d shows the rear of the SEC.

To be able to fit the SEC as low as possible in the wedge-shaped STM, the space for the 9 V battery is shallowed slightly. This is possible thanks to the 9 V battery being shorter than the LiPo batteries. Similarly, the Arduino Fio requires an extended depth and is placed at the top of the SEC where the dimensions of the STM allow for it. To keep the center of mass low, the heavy batteries are placed as low as possible. The lighter Arduino and ESCs are placed high.

Components sit on tailored shelves, not clamped but instead held in place by the internal geometry of the SEC, wires and other components. Given that the CubeSub is unlikely to perform any violent maneuvers, the SEC and its contents are not expected to be subjected to heavy mechanical stresses. On the back side are two holes for cables from the ESCs to the engines, see Figure 4.18d. After cables have been routed through these holes they are sealed with a sealant such as silicone or similar.

The lid is attached with seven ANSI 6-32 bolts and nuts. A “lip” matching the inner edges of the SEC runs along the inside of the lid, see Figure 4.18c. Around this lip and opening of the SEC are flat areas onto which a gasket can be fitted. Like the SEC walls, the lid is 3 mm thick.

Printability

The SEC and its lid has been printed with generally good results, the lid especially so, in the UP Plus 2.

Printing an SEC takes 17 hours and consumes 150 grams of ABS. Orienting the SEC with its opening facing straight upwards has been found to give the best results. No support structure is needed on the inside, and good flatness on the lid interface can be achieved which is an important aspect of the waterproofing. Holes are parallel with the printer’s plane and can as such be printed with high accuracy.

Attempts to print the SEC with a slight tilt were made to reduce the amount of support structure and investigate whether it affects the development of cracks between layers. Support structure was as expected slightly reduced, however at the cost of significantly more cracking. Furthermore the flatness of the opening face was found to be worsened along with the the accuracy of the holes.

Sharp corners that lie in the printer’s plane have been avoided in the design. Earlier iterations often developed an abundance of cracks between layers in the corners, a problem to which small corner radii are believed to have contributed significantly. Outer and inner in-plane corners are given 5 and 3 mm radii respectively. Acetone can then be used to seal occasional cracks.

The lid is easily printed with very good results. It takes 5 hours to print and consumes 36 grams of ABS. Oriented with the lip facing upwards, no support is needed. Flatness is very good and bolt holes have high accuracy.

4.2.8 Propellers

Function

The COTS propellers that had been purchased earlier in the project were later found to be mechanically incompatible with the engines. Furthermore only propellers of one rotational direction had been acquired. A set of counter-rotating propellers compatible with the engines have therefore been developed.

Design

The overall design of the propeller is heavily inspired by the COTS propeller. It is 15 mm long and has a diameter of 48 mm. There are three blades, each created by a helix with increasing radius. The blades on the COTS propeller are lightly cupped, something not included in this design. At the bottom of the

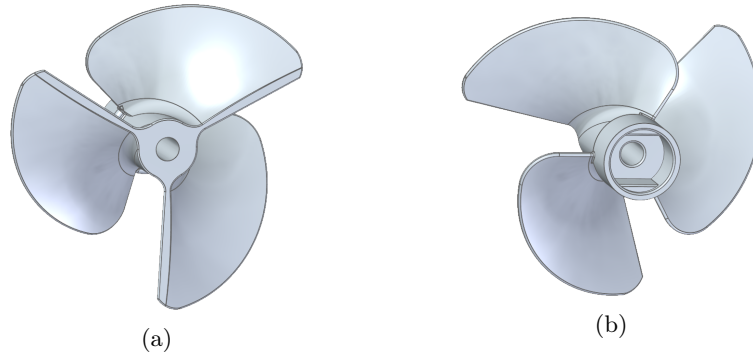


Figure 4.19: Front (a) and back (b) views of propeller.

hub is an interface matching the engine's that locks the engine and propeller rotationally. The threaded engine shaft runs through the hub and at the top a nut locks the propeller axially. Figure 4.19 gives two views of the propeller, the rightmost of which also shows the engine interface.

Printability

Prints were performed in the FFF printer UP Plus 2 and the SLA printer Formlabs Form1+. In both cases results were generally good, but with some differences. Small modifications to the design of the COTS-propeller have been made to make it more fit for printing. The blades have been made thicker along with the interface between blade and hub.

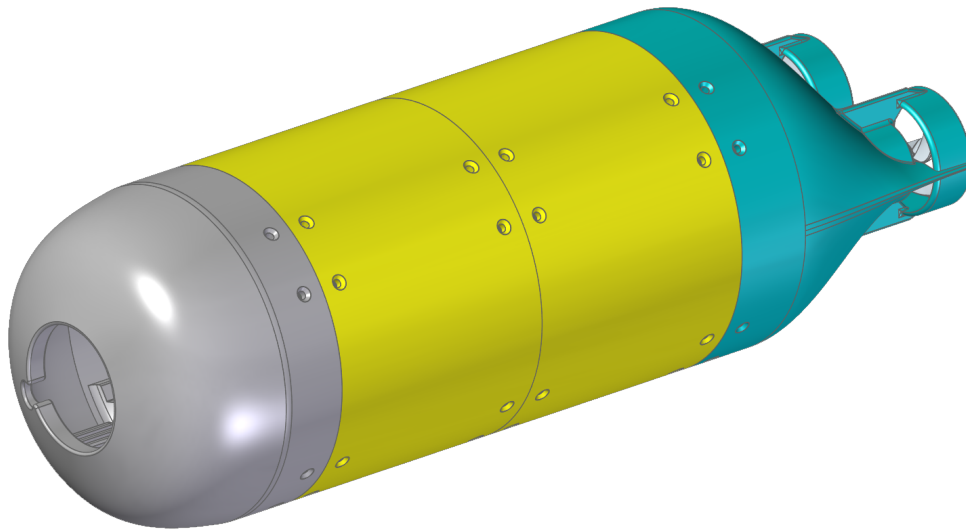
Printing one propeller with a layer resolution of 0.15 mm in the UP Plus 2 takes 40 minutes and 4 grams of ABS. Orientation was found to be very important with the FFF technique. Attempts were made with the propeller "lying down", in other words with its hub axis vertical. This orientation gave unsatisfactory results, with the main problem being that the blades require plenty of support structure which is then very hard to remove without damaging the blades. Orienting the propeller such that the hub's axis is horizontal instead proved successful. The support structure must still be removed with great care from the delicate propellers, but thanks to smaller contact patches between propeller and support it is nonetheless possible.

Rotating the propeller about its hub when in this orientation makes for further alterations. The trailing edges of the blades should be kept from sitting perfectly horizontal, as this was found to make it hard to remove the support without damaging the hydrodynamically important trailing edge. Moreover, the non-isotropic material properties of 3D-printed objects makes for a propeller where the three blades all have slightly different mechanical properties. Some care should be exercised so as not to make any one blade much weaker than the others. The surface is somewhat rough which likely has a negative effect on performance. No acetone treatment was attempted but is expected to improve the smoothness.

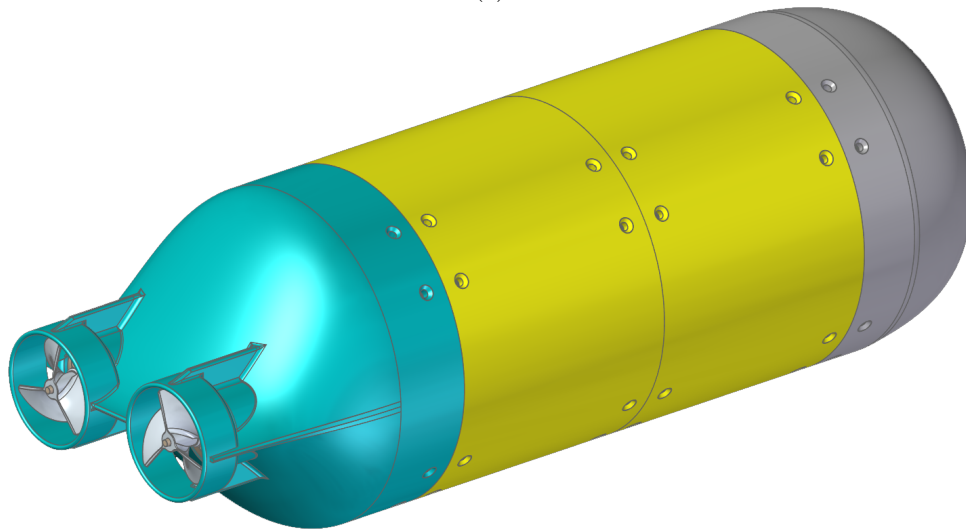
With the SLA printer Formlabs Form1+ set to a layer resolution of 0.05 mm one propeller takes just under 2 hours to print. In successful prints the finer layer resolution is noticeable along with the overall smoother finish in comparison to the UP Plus 2. The blades are also more flexible and less brittle. The Form1+ handles the support structure in a different way, making it possible and advantageous to orient the propellers with the hub vertical. Completely failed prints occurred intermittently, with the main problem being that large chunks of the blades break off during the print. Occasionally there was also residue stuck to the blades which was hard to remove. Usually this residue did not make a propeller unusable but is assumed to significantly worsen its performance.

4.2.9 Assembly

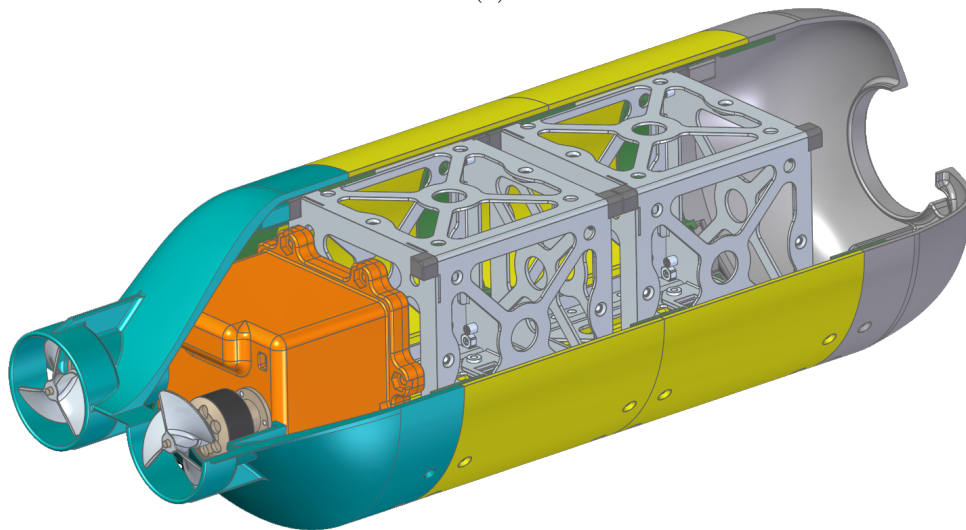
With the modules presented in the sections above (and some software), basic operation is possible. Figure 4.20 shows an assembly meant to exemplify a full CubeSub, assembled with two Cube Modules carrying one 1U CubeSat each. Subfigure c shows a section view, in which the two CubeSats are visible, as well as the SEC sitting in the STM. This configuration is 456 mm long and has an empty mass of approximately 1.6 kg, including a GoPro camera, engines and electronics and excluding CubeSats. Like all configurations the outer diameter is 154 mm.



(a)



(b)



(c)

Figure 4.20: Front (a), rear (b) and section (c) views of an assembled CubeSub.

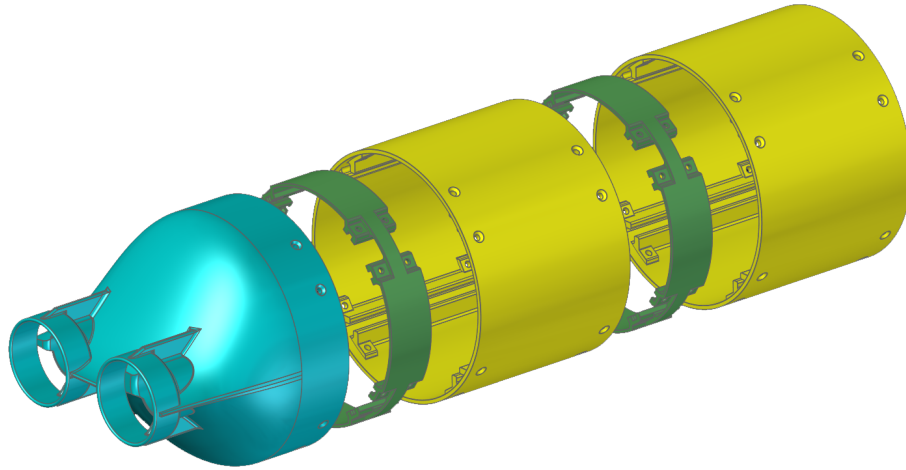


Figure 4.21: Exploded view of an STM, two Cube Modules and two SMIs

Figure 4.21 shows an exploded view of the modules in Figure 4.20, apart from the Nose Cone. This figure demonstrates how the modules are stacked together to form the CubeSub. It also shows the modularity, as any one of the two Cube Modules could easily be replaced by some other type of module that adheres to the standard interface.

4.3 Pool test

A test was performed in the swimming pool in the NASA Ames Research Park. The test was overall successful with some learning points for future development. Only basic submersible operation was tested, meaning that no payload was carried.

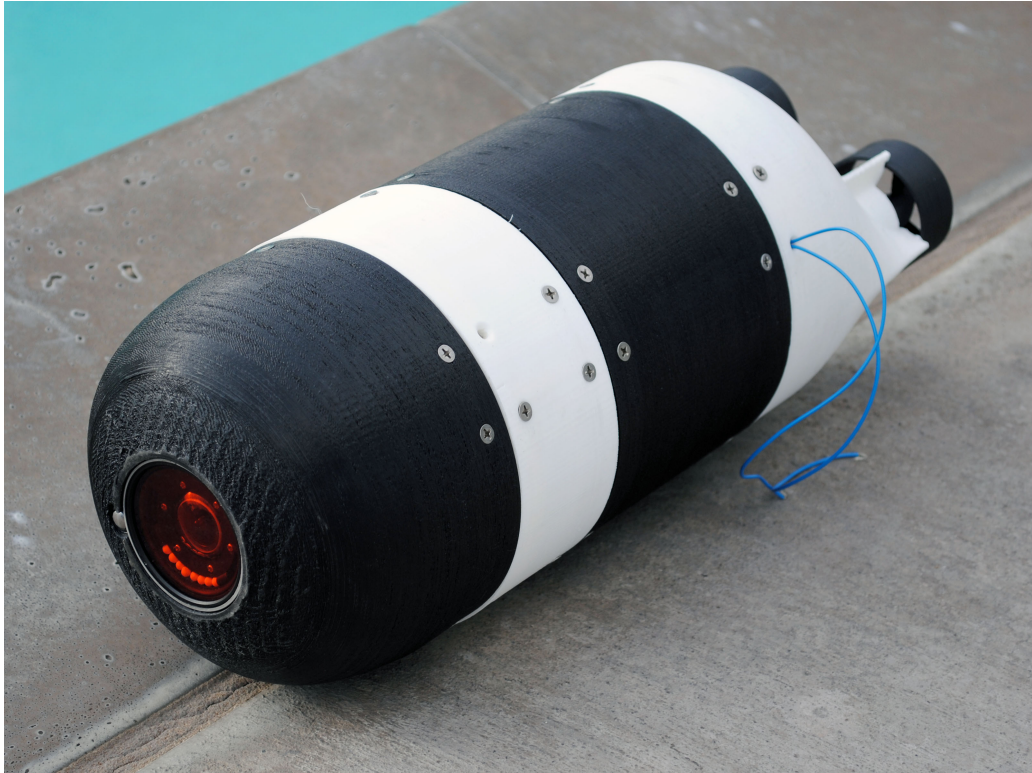
Figure 4.22 shows the CubeSub right before testing. The visible modules are the Nose Cone (with GoPro camera), one 0.5U Cube Module, one 1U Cube Module and the Stern Thruster Module with the ad hoc nozzle unit. The tested configuration was 400 mm long and weighed approximately 1.7 kg. If looking closely at the Nose Cone in subfigure a, one can discern the rough and streaky remains of the support structure around the GoPro lens. The SEC was put in a plastic bag for additional waterproofing as no gasket was used between box and lid.

The Arduino Fio was programmed with a predefined scheme for the engines to run. The cord that can be seen peeking out of the STM in Figure 4.22 was used to start and reset the Arduino and with it the scheme. During the test the engines cut out multiple times, only to come back a few moments later. It is not known why this happened, but similar behavior has been observed when testing the engines on land. When working, the engines were set to run at maximum speed. The ABS propellers printed in the UP Plus 2 was used during the test, none of which showed any signs of damage after the test and performed as expected.

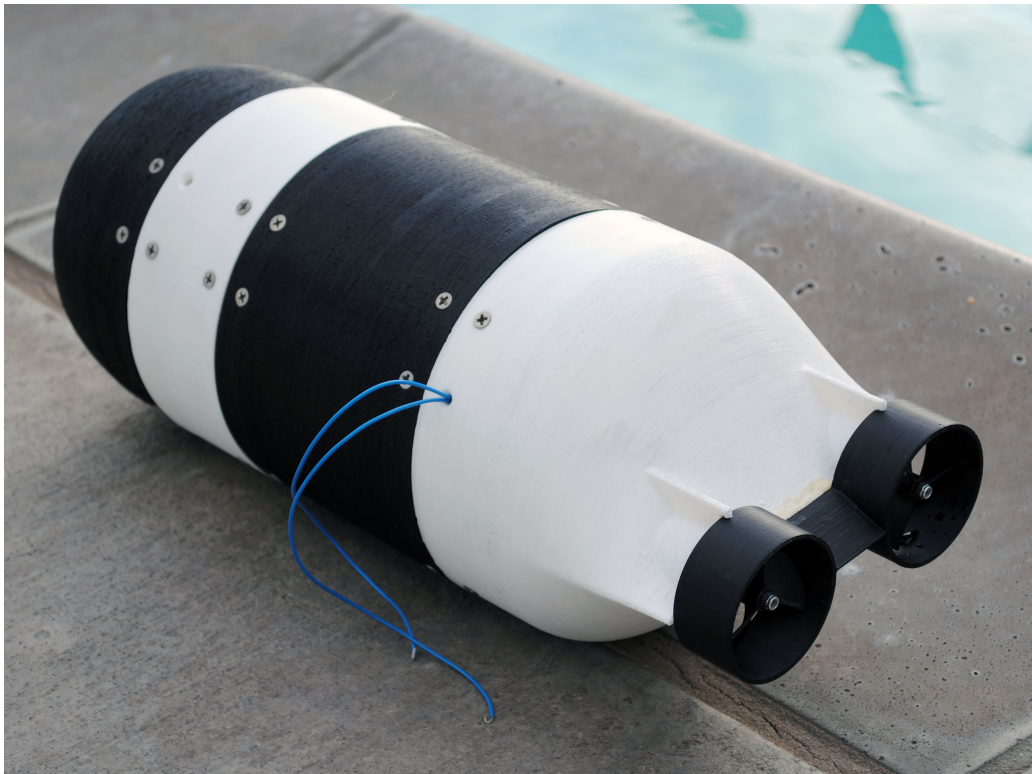
A 1 lb (454 grams) diving weight and a 16 fl oz (473 ml) bottle filled with air was used for roll stability and buoyancy control. The diving weight was put at the bottom of a Cube Module without any clamping and moved back and forth to trim the pitch. The bottle was wedged in place in the “ceiling” between long bolts sticking out from the SMI. Together these two additions are nearly neutrally buoyant and as such they do not affect the total buoyancy significantly. Buoyancy of the CubeSub was very close to neutral when completely flooded. Yaw stability was unsurprisingly found very poor. The CubeSub flailed around without any apparent heading, an issue likely compounded by the problems with the engines and water jets in the swimming pool.

The hull structure worked as expected. It was easily assembled and held together well mechanically. A few of the bolt holes were left open to let in water quickly at the beginning of the test. The gap between GoPro lens and Nose Cone as well as the gaps between the modules also provided openings for the water to flow in.

The test ended after approximately half an hour due to the electronics failing. More specifically, water reached the inside of the SEC and thereby incapacitated the electronics. When opening the SEC after the test, water poured out from it. It appeared as if the SEC had been full of water during a significant part of the test, as the water flowing out was discolored to a brown/green tint and the 9 V contacts had buildups of rust-like material on them. The obvious conclusion from this is that waterproofing must be improved. It is not known where most of the water leaked in. Possible entryways include the gap between lid and box, holes for engine cables, unseen cracks and through porosities in the walls.



(a)



(b)

Figure 4.22: Front (a) and rear (b) view of the CubeSub assembled for pool testing.

5. Discussion

5.1 Missions to Europa

Considering the already extreme costs of non-landing missions to the Jovian system (on the order of a billion US dollars), the cost of a mission that is to land, drill and deploy a submersible on Europa can only become exorbitant. Furthermore, the technological challenges of such a daunting mission can be anticipated to be enormous. On the whole, a mission of this kind will be a gigantic undertaking on most levels. This of course makes it all the more alluring and exciting, especially so in combination with the chance of finding extraterrestrial life.

During the writing of this report, the 2016 budget for NASA was released. This budget directs an additional \$175 million towards the EMFM and mandates that it includes a lander [33].

5.2 Design afterthoughts

Generally, the CubeSub concept appears feasible and fulfilling the project's goals should be possible after further development.

The extensive use of and deliberate design towards 3D-printed manufacturing is potentially a great strength of the CubeSub. It means that anyone with access to a large enough 3D-printer, such as the Ultimaker 2, can build a near-complete submersible to assist in the development or put it to good use. With that said, some components might be better suited for other manufacturing techniques. The Cube Module for instance has a simple overall shape that presumably could be made from a long tube, cut to desired length. CubeSat slides could subsequently be "bolted on" by some means. Solutions like this might make for a cheaper and/or mechanically stronger end product.

The decision to have a flooded inside of the CubeSub should be carefully analyzed before progressing all too deep into further development. If at a later stage the CubeSub is to aim for greater depths, the flooded design could become unpractical for reasons that at the time of writing have not been considered or are unknown. This is an open question, flooding could likewise prove highly advantageous.

Continued use of Arduino boards is recommended due to the ease of use and it being an open-source platform. This makes them ideal in an application like the CubeSub which is made for a wide range of users with varying levels of knowledge, working towards different goals requiring easy modifications.

5.3 Suggested development

This section will present some ideas and suggestions for how and where to continue the CubeSub development. This includes modifications to existing modules, the development of completely new modules and overall system improvements. All modules presented in this report are still open for modifications and improvements.

Perhaps the largest gains at this stage is to be found in the electronics. A system that allows a user to control the CubeSub from the surface or a simple autonomous control system would greatly improve the functionality of the CubeSub and take it much closer to its intended use as a test bed. It would drive the development of other subsystems by enabling tests to be performed in their intended environment.

On a related note, a software framework compatible with the concept of modularity must be devised. It should allow a user the simple inclusion or removal of existing modules as well as the possibility for developers to easily include new modules into the CubeSub framework.

The finer numerical details of the design such as wall thicknesses and corner radii have been chosen on an estimation and trial-and-error basis and should be treated as such. Future development should see these values as first approximations and can if deemed necessary be optimized.

5.3.1 Improvements to presented modules

To improve controllability, a linear actuator could be accommodated in the voids of one or more adjacent Cube Modules and used to control the pitch angle during a mission. The addition of vertical stabilizers to the STM would likely improve yaw control and stability.

As observed in the pool test the SEC must be developed further. The possibilities and limitations of its waterproofing abilities should be examined. In the long term it should be built to withstand elevated pressures to allow the CubeSub to go deeper.

For additional control and less dependence on transversal thrust, an STM with vectorable thrust could be considered. This can be achieved by mounting the engines on gimbals and steering them with servos. Furthermore, additional thrust can be achieved by shaping the already existing nozzles in the STM, an example of thrust increasing nozzles are Kort nozzles [34]. Similarly, more careful propeller design would improve performance. Seeing as the nozzles were problematic to print in the Ultimaker, their design should be considered in future revisions. The ad hoc nozzle unit worked well and could be the way forward in this matter.

The Nose Cone can be improved upon through the integration of components such as a purpose-built camera, lights, sonar, thermometer and/or pressure sensor. In its current design it provides a relatively large volume of open space free to be used for beneficial functions, some of which also could be used for buoyancy.

The slides on which the CubeSats rest in the Cube Module could likely be made shorter, while still giving sufficient support to the CubeSats. This would offer more space to the SMI which, if needed, could then be made stronger.

The SMI could possibly be reduced in size. The current design consists of a cylinder with 16 bolt holes, grouped together in four corners. A possible modification to this design would be to remove the material between the groups. What would be left are a set of “splice plates” holding the modules together, meaning that the SMI is no longer a single ring but rather four small separate pieces. This would make an SMI easier to manufacture and replace. The smaller size means that it can be created with smaller printers such as the UP Plus 2. Less material is consumed and printing times are reduced. Furthermore, if only a small section of the current SMI were to break for some reason, the whole ring might require replacement. If a small connector breaks, only that particular unit needs to be replaced.

5.3.2 Additional modules

Given the CubeSub’s modularity, increased functionality can be achieved with relative ease through the construction of new modules. Following are some suggestions for future modules.

Transverse Thruster Module

With the CubeSub’s current system design a module like this is required for full control. A concept draft is presented in Figure 5.1. It is a simple design with two perpendicular and offset tunnels crossing straight through a cylindrical hull. Inside each tunnel sits an engine and a propeller. This design leaves a large amount of open space usable to house batteries and control systems. Foams could be added to make the module neutrally buoyant and thus easier to include in a mission. Similar to the other modules not carrying CubeSats this concept has the CubeSat stop blocks integrated with the bolting interface.

Another possibility is to integrate these functions into the Nose Cone and/or the Stern Thruster Module.

Buoyancy Module

With heavier payloads the voids in the Cube Module might not be enough to make the CubeSub neutrally buoyant. A simple solution to this would be to modify a Cube Module and fill it with a low density closed cell foam, such as the expanded polyurethane seen on the SCINI [32]. It could be made available

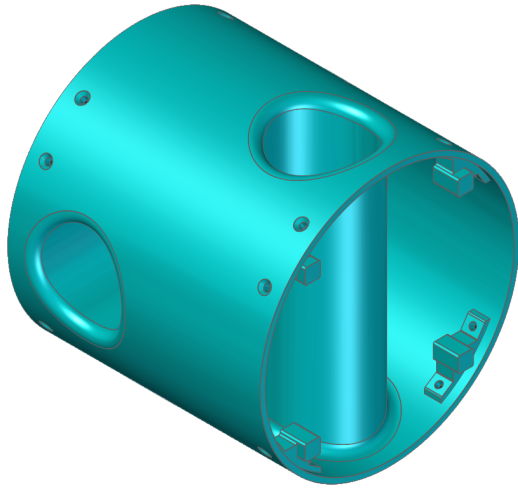


Figure 5.1: Transverse Thruster Module concept

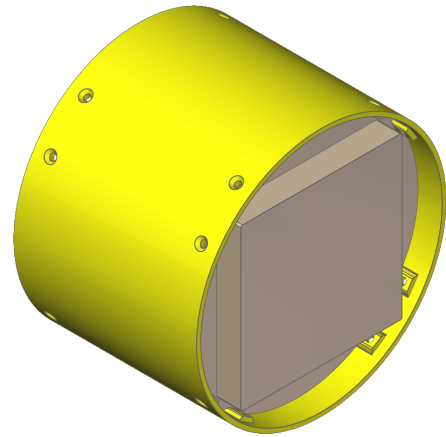


Figure 5.2: Buoyancy Module concept

in the 0.5U and 1U sizes already established by the Cube Module, and would become an off-the-shelf buoyancy booster. Such a module could be positioned at any longitudinal position in the CubeSub and would thus also be usable for coarse pitch trimming.

Figure 5.2 shows a concept draft of such a module. It is based on a Cube Module where the CubeSat slides have been removed. The open space is filled with foam, which in addition to providing buoyancy also is shaped to provide longitudinal constraint to adjacent CubeSats.

Further ideas

Augmentations of the Cube Module could extend the capabilities of the CubeSat payload. One example of such an improvement would be to have a module that in some way allows the CubeSats to rotate around the CubeSub's longitudinal axis. This would allow for something like a camera or sonar to "look around" and see even more. Another interesting concept would be a solution to allow for the underwater deployment of CubeSats. A CubeSat could then be dropped off on a lakebed or released to float up to the surface and take measurements on its way there.

Another version of the STM with more engines or more powerful ones could be of interest if running missions with larger CubeSub assemblies or in strong currents.

It should in principle be possible to construct a sort of "hinged" module, such that the CubeSub would be allowed to twist and bend itself. This could perhaps be useful when navigating tight corners in underwater caves.

6. Conclusions

6.1 Europa missions

Two high profile missions, NASA's *EMFM* and ESA's *JUICE*, are currently aiming for the Jovian system in the 2020's. Roscosmos may or may not also be launching a similar mission, *Laplace-P*, in the same time frame. Up until recently none of these were to land on Europa, however EMFM has in the the 2016 NASA budget been mandated to include a lander. *JUICE* will end with a crash landing on Ganymede. The biggest challenges for these missions are the long distance from the Earth to Jupiter and the intense radiation fields of Jupiter.

Simple calculations based on NASA's landing mission concept indicate that it is possible to land up to around 2500 kg on Europa's surface, if using the SLS as a launch vehicle.

6.2 CubeSub

6.2.1 Concept

The CubeSub concept has in this work been moved forward. In particular its mechanical system architecture, hull structure and modularity concept. The CubeSub is a modular submersible testbed compatible with the CubeSat standard. It is intended as a tool in the development of a space qualified submersible, that perhaps is to be used in the purported subsurface ocean on Europa or a similar environment. The CubeSub is also in itself believed to be usable as a tool for exploration on Earth, which could also provide valuable data for a future Europa submersible.

The overall form is similar to that of a common AUV, a slender shape with a camera in the front and engines in the stern. It has a circular cross section, is 154 mm in diameter at its widest and of variable length. Its inside will be flooded with water to facilitate the interaction between CubeSat payloads and surrounding water. Between Nose Cone and Stern Thruster Module, modules can be stacked together in an arbitrary sequence and number to fit the needs of the user. Each module is powered individually and communicates wirelessly, making them easy to replace and rearrange. Figure 6.1 shows an example configuration of the CubeSub.

Modules required for basic operation have been developed, along with a compartment for electronics and a set of tailored propellers. Table 6.1 presents these modules and components with data from successful prints. A full scale prototype has been manufactured and tested successfully. It was found that the current concept could perform basic operation and that improvements are to be found in controllability and waterproofing.

In its current state the CubeSub is still in need of further development to make it usable either as a testbed or exploration tool. The largest improvements are expected to be found in controllability and software. Thanks to the CubeSat standard already being nailed down, payloads can however be developed in parallel with the CubeSub.

6.2.2 3D-printing

3D-printing has been used extensively throughout the development and has enabled quick progress and great freedom in the design. It has offered great flexibility and adaptability, the tailor-made propellers and ad hoc nozzle unit being good examples of this.

Table 6.1: Overview of developed modules and manufacturing data. Masses include support structure. Data for the Stern Electronics Compartment includes that of the lid.

Component	Printer	Print time	Material	Mass
Ad hoc nozzle unit	UP Plus 2	4 h	ABS	22 g
Cube Module 1U	Ultimaker 2	20 h	PLA	210 g
Cube Module 0.5U	Ultimaker 2	10 h	PLA	105 g
Nose Cone	Ultimaker 2	20 h	PLA	170 g
Propeller	UP Plus 2	40 m	ABS	4 g
Stern Electronics Compartment	UP Plus 2	17 + 5 h	ABS	170 + 36 g
Stern Thruster Module	Ultimaker 2	42 h	PLA	340 g
Structural Module Interface	Ultimaker 2	5 h	PLA	50 g

Contrarily, it also puts some constraints on how components can ideally be designed. Aspects which must be considered throughout the whole design process from drawing to completed print include, but are not limited to, component orientation, layer fusion, overhangs, surface flatness, desired dimensional tolerance, print board adhesion and corner sharpness.

Four consumer-grade 3D-printers have been used in the manufacturing of the full scale prototype, three of which use the FFF technique and one the SLA technique. Out of the three FFF printers, two generally performed well and produced functional components; the *UP Plus 2* and the *Ultimaker 2*. The *CubePro Trio* that was also used consistently failed to produce anything at all and when it did the results were of unsatisfactory quality. The SLA printer *Formlabs Form 1+* was only used to print propellers and did so with mixed results. All components used during the test were produced in the Ultimaker 2 and the UP Plus 2 printers.

Waterproofing is found to be a nontrivial issue with 3D-printing and should be investigated further.

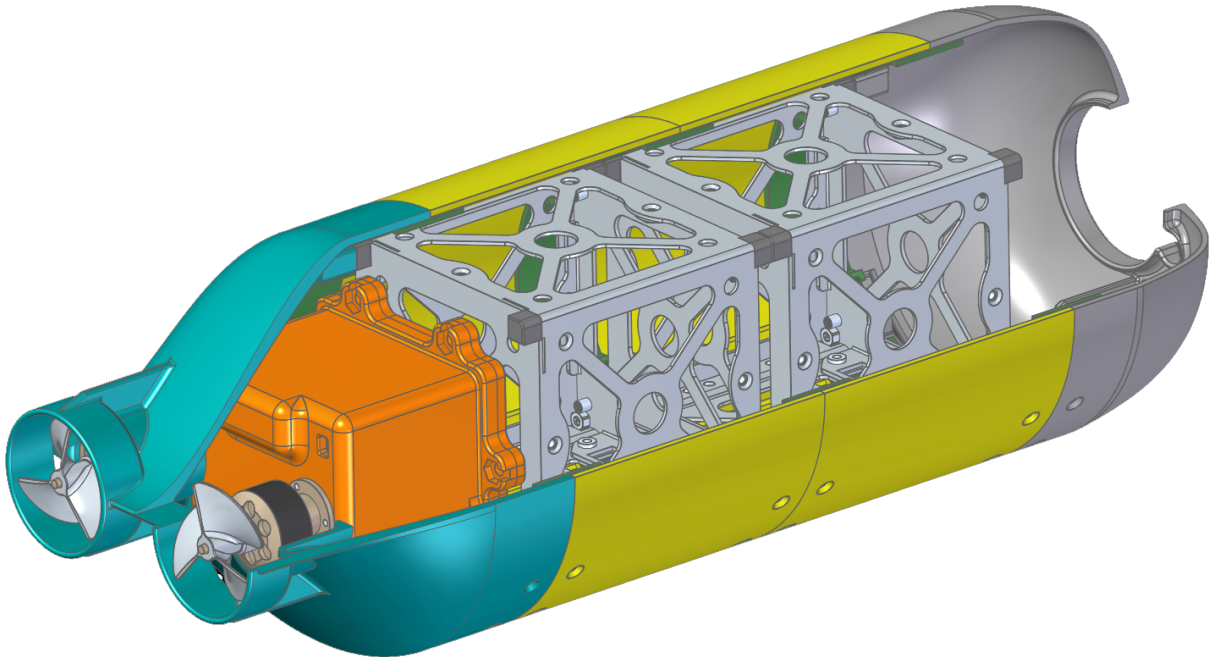


Figure 6.1: Section view of an example configuration of the CubeSub.

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