Deutscher Luft- und Raumfahrtkongress 2017
DocumentID: 450298

# RISK REDUCTION AND PROCESS ACCELERATION FOR SMALL SPACECRAFT ASSEMBLY AND TESTING BY RAPID PROTOTYPING

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## Abstract

Changes due to design flaws impose major costs, delays and high risks on any spaceflight project. The later the change, the riskier and more expensive it is. System changes due to failures detected during spacecraft assembly are usually one of the last hardware flaws to be found and therefore impose major risks on the overall project. Traditionally, this is overcome by metal or wooden mock-ups early in the process. However, to respond to design changes in a fast manner and to properly explore the remaining options by building multiple full size mock-ups in a short time interval, rapid prototyping was used by the authors. This paper provides lessons learned of the Munich Orbital Verification Experiment II (MOVE-II), related to rapid prototyping technologies used during the development phase. MOVE-II is the second CubeSat mission of the Chair of Astronautics at the Technical University of Munich (TUM).

Early in the design process, a 3D printed structural model of the CubeSat was built to verify the CAD model, the assembly strategy, and to track down potential system level design deficiencies. By doing so, minor and major flaws concerning integration of the satellite were found in an early project phase. Furthermore, multiple design alternatives were 3D printed during the development process, not only exploring different solutions but also defining cable paths and cable lengths and evaluating the corresponding assembly process. In difference to traditional methods, 3D printing allows for a shorter implementation time span of different design options. In addition it was possible to conduct dress-rehearsals of the integration procedure early on in order to save time in later project phases, and without potentially harming expensive hardware. Due to the early integration of the prototype, Ground Support Equipment (GSE) and specific tools could be defined ahead of time. The biggest non-technical benefit was, that the physical model simplified communication of problems and possible configurations as well as introductions to the system. Display material was always available for the developing team, either for presentations of the project or for recruitment of new team members. The paper concludes with a brief assessment of the limitations of rapid prototyping technologies for risk reduction and process acceleration. Assessment of mechanical functionality as well as mechanical fits are limited due to production tolerances. Therefore the deployment mechanism of MOVE-II could not be tested sufficiently. Finally, future improvements are shown for upcoming CubeSat missions of the TUM.

## 1. INTRODUCTION

Initiated in 2006, the MOVE CubeSat Program of TUM has run with the main goal of hands-on education of undergraduate and graduate students since then. The program's first satellite, First-MOVE, was launched in late 2013 and operated in space for a month [1]. Funded by the German Aerospace Center (DLR) as an educational project, the goal of MOVE-II [2] is to build and operate a 1U-Cubesat capable of supporting a scientific payload, evolving the subsystems that were developed in-house for First-MOVE and applying the lessons learned [3] from the project. Furthermore, MOVE-II should demonstrate a magnetorquer based 3-axis stabilized bus [4] for future science and technology verification missions and should be capable of processing and downloading large amounts of data using the in-house developed Nanolink protocol [5]. As the scientific payload, the degradation of a 4-junction solar-cell prototype will be measured in orbit [6]. The MOVE-II satellite is depicted in Fig. 1.

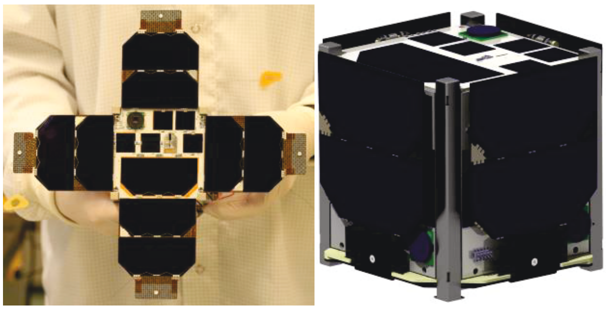

Fig. 1: MOVE-II in Deployed (left) and Launch Configuration (right)

Applying the lessons learned we manufactured a 3D printed mechanical representation of the satellite at an early stage. This prototype helped verifying the CAD model and the assembly strategy, and tracking down potential system level design deficiencies. By doing so, we found minor and major flaws concerning the integration of the satellite in an early project phase.

Being on the forefront of innovation in spaceflight, many CubeSat missions have implemented additive manufacturing in their design process. Propulsion systems [7], embedded electronics [8] and radiation shields [9] for CubeSats were developed in the past and one future mission will be “made in space”, using the 3D printer aboard the International Space Station [10]. A more detailed evaluation of the impact of additive manufacturing on the CubeSat development process can be found in [11].

This paper is organized as follows: Chapter 2 gives an overview of the MOVE-II satellite and its subsystems. In chapter 3, the 3D printed prototype is described in detail and some of its use cases are presented. Chapter 4 presents all rapid manufactured GSE that was used during the MOVE-II project. Chapter 5 describes the advantages of having a demonstration object for internal and external presentations and discussions. Finally, in chapter 6, we conclude with an overall evaluation of using rapid prototyping in a student CubeSat project and give an outlook.

## 2. SATELLITE DESCRIPTION

MOVE-II’s subsystems are stacked onto each other in +z direction. The so-called Antenna Deployment Mechanism (ADM) on the bottom of the satellite hosts the antennas during the start and releases them after deployment. In stored configuration a redundant shape memory alloy hold-down and release mechanism, called 2SMARD, holds the ADM in position. For UHF and VHF antenna deployment, 2SMARD releases the ADM and two mechanical springs push it down. In parallel to the ADM movement, the so-called Flappanels flip open and the antennas jump out. This mechanism was developed to avoid a long lasting reset procedure, as in burn wire mechanisms. The active attitude control is performed by magnetorquers, implemented in the Printed Circuit Board (PCB) Sidepanels and Mainpanel of the Attitude Determination and Control System (ADCS). Additionally, those Sidepanels host all the sensors needed to determine the attitude of the satellite (sunsensor, magnetometer, acceleration sensor…) and carry additional solar cells. The magnetorquers in the Sidepanels, Mainpanel and Toppanel allow to generate a three-dimensional magnetic field to stabilize the satellite. All the internal boards are connected by the standard PC/104-plug in a stacked configuration. The stack and the Sidepanels are mounted together using four rails and the so-called Topframe and Bottomframe. The four rails host deployment pins, by which the satellite is switched off during launch. An exploded view drawing of the satellite is shown in Fig. 2.

## 3. 3D PRINTED PROTOTYPE

We manufactured a 3D printed structural model of MOVE-II early in the design process (Fig. 3). Being a mechanical representation of satellite, it had no electrical functionality. The intentional purpose of this prototype was to prove the mountability of our satellite and to determine the final cable paths. For the boards we chose the Fused Deposition Modeling (FDM) technology. Some components on the boards were implemented by plastic or wooden blocks glued on the boards. We also produced a prototype of the frame by laser sintering, as FDM did not yield the required accuracy. The Side- and Flappanels were simply cut out of polymer or carbon fiber reinforced

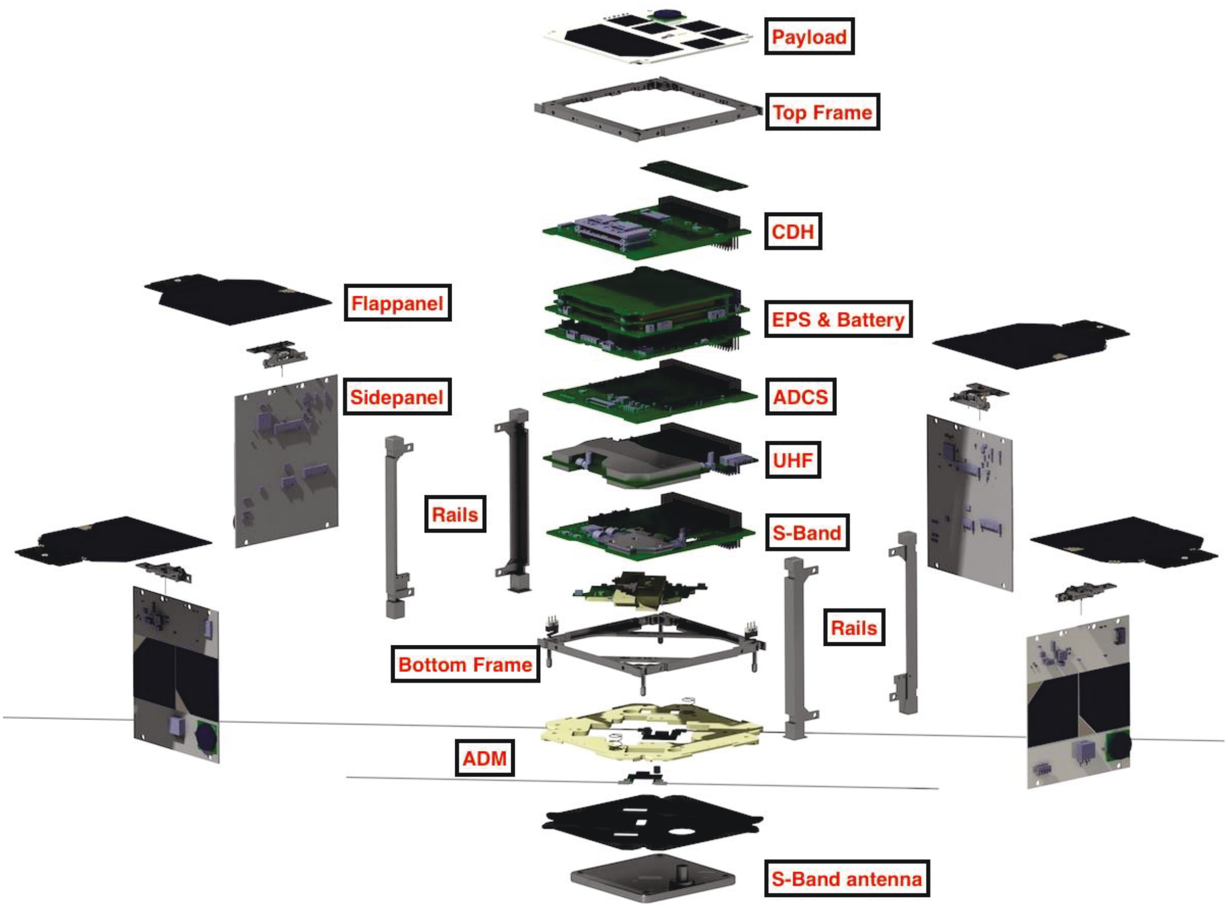

Fig. 2: Exploded View of MOVE-II

polymer plates to facilitate the production.

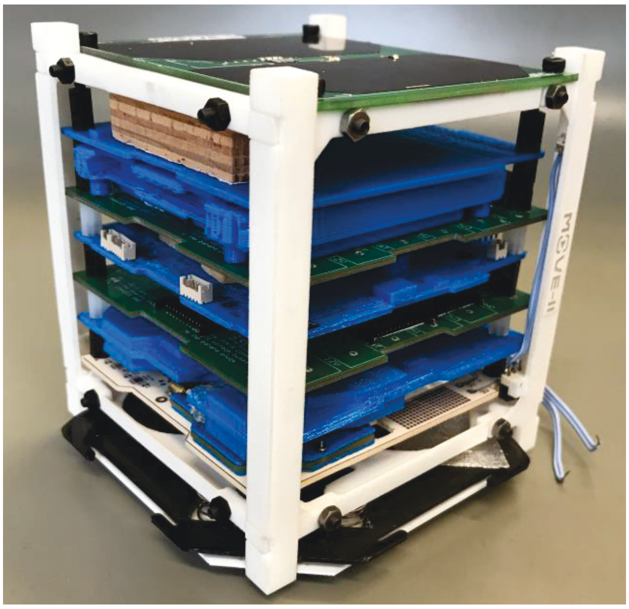

**Fig. 3: 3D Printed Structural Model of MOVE-II**

### 3.1. Proof of Functionality

With this prototype, we were able to prove the basic functionality of the deployment mechanism. Since the mechanical properties of the additive manufactured plastics are not comparable to the aluminum of the final product, the achieved tolerances were not representative. The frame bent too much under the load of the ADM springs, causing the mechanism to jam and failed deployment. This problem was later solved by using two instead of four push-down springs. Although not completely successful, the tests proved that the system could be integrated as intended and the basic functionality of the self-developed deployment mechanism.

### 3.2. Definition of Cable Paths

For the definition of cable paths and lengths, we were able to speed up the traditional process (CAD) by defining paths and lengths with help of the 3D prototype. Gluing plugs on their later positions on the PCB mockups allowed us to specify all cables and verify their mountability, volume budget and compliance to minimum bending radii. The result was a complete, verified wiring definition half a year before the Engineering Model hardware was available. We decided to use flat ribbon cables as often as possible to avoid squeezing them during assembly and increase the stiffness of the cables. That decision also forced us to reverse the pin assignment on the Sidepanels. Due to detection of this problem in our 3D prototype, we were able to make that decision early. Thus, the design change on the Sidepanels had neither financial nor scheduling impacts.

The HF cables' definition turned out to be more challenging than the connections to the Sidepanels. These cables have to move during the deployment of the satellite and have bending radii only one order of magnitude below the CubeSat's side length. The HF signal is dampened in case the cable is bent with a shorter radius. The cable lengths and paths could be defined via the 3D prototype in less than a day's work. We also found a mechanical collision between the lowest board of the stack and the plug of the S-Band antenna in the launch configuration of the satellite.

After having all cables planned on the 3D prototype, we built the complete cable harness for the Engineering Model. Only one cable had to be slightly modified, so time and money were saved during the assembly of the Engineering Model by defining the cable harness beforehand.

### 3.3. Detection and Remedy of Collisions

We were able to assess design changes very fast and without causing cost overruns, project delays or even harming expensive hardware. As volume is the most limited resource on CubeSats, we had to change the distances between the boards in our stack multiple times. Minor collisions, not detected in CAD, were detected on our prototype and the resulting design changes were fed back to the PCB-designers. Volume restrictions and cabling also inflected the decision where to put an additional module on the upper board of the stack (command and data handling subsystem). Using a rapid prototyped module stack, we were able to assess multiple possible options and choose the best.

### 3.4. Detection and Remedy of Problems in the Assembly

To assure an easy integration we tested the assembly of the satellite several times with the 3D prototype, exposing issues early on. We had to lengthen some of the cables to allow an integration without stressing them, leading to a more complex cable laying strategy. These cable-related integration steps could be easily developed and exercised with the 3D prototype. Also, different subassembly strategies concerning the Side- and Flappanels were explored. To remove the Sidepanels safely, we first have to remove the Flappanels to avoid damage on the Flappanel solar cells. The first idea was to glue the hinge between Flap- and Sidepanel on both sides to the panels. With this solution, the only way to take the two panels apart was to remove the bolt of the hinge. Being made of polyether ether ketone (PEEK), the bolt could be worn down doing that. So we decided to glue just the Flappanel side and to attach the whole Flappanel-hinge subassembly by screws to the Sidepanel and the frame.

The 3D prototype helped us a lot with creating the integration procedure and the corresponding documentation. The main document was ready before the first integration of the Engineering Model started.

## 4. GROUND SUPPORT EQUIPMENT

Due to the early integration of the prototype, GSE and specific tools could be defined ahead of time.

### 4.1. Stands for Satellite Integration

To allow an easy and reproducible cable laying of the antenna cables, the ADM has to be mounted on the bottom frame before mounting the S-Band board. To hold the ADM in place, the rails are required. A GSE set of 3D printed rails (Fig. 4) with some additional features was manufactured. They share their attachment point to the bottom frame with the original rails but do not exceed the bottom frame towards the stack side and have a lip to hold the ADM in place. An additional feet to avoid having the whole satellite weight on the ADM completes these set of GSE-rails.

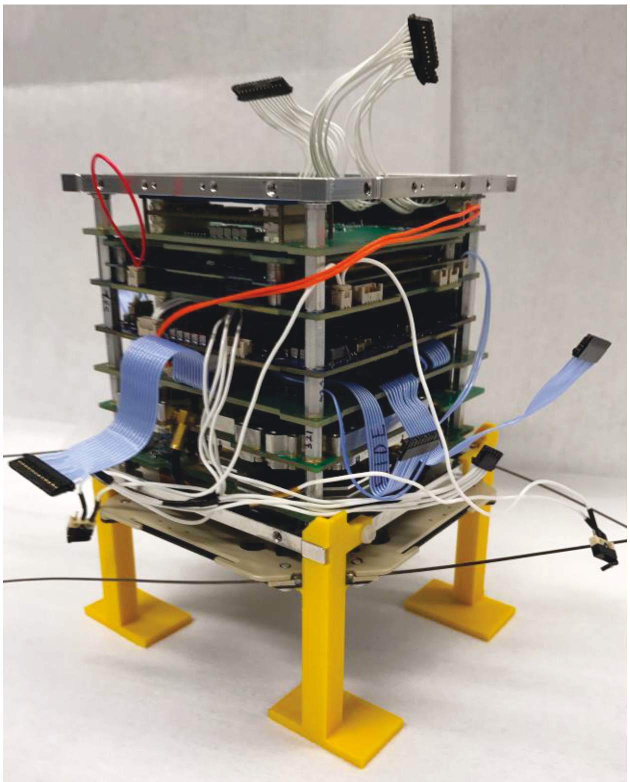

Fig. 4: MOVE-II Satellite Stack on GSE Stands

To let the satellite stand on the rails instead of the ADM after taking the placeholder rails away, we designed further stands for integration and testing purposes. The first type of stand is a flat one (Fig. 5) which allows us to put the satellite on it during assembly.

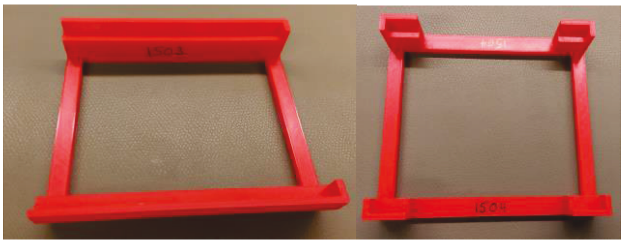

Fig. 5: Flat Type of Stands for Integration and Testing

This type of stand has one disadvantage: Placing the satellite on it also triggers the deployment pins, making it impossible to operate the satellite. For that reason, we built a second type of stand (Fig. 6) which allows us to place the satellite onto its rails without pressing the deployment switches. Furthermore, the test stand was heightened for our Thermal Vacuum Chamber (TVAC) test campaign, to place the satellite in the field of view while being inside the TVAC. Traditional solutions like cables or strings would not have allowed us to simulate a complete launch phase (with releasing the deployment pins and a collision free deployment). With an integrated pin-release mechanism, this stand allows us to do a full dress rehearsal of launch, LEOP and mission operations inside the TVAC.

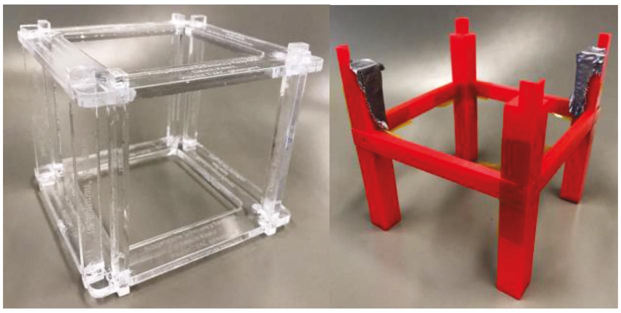

Fig. 6: Adapted Type of Stands for TVAC Testing

## 4.2. Mounts for Tests

As the performance of our magnetorquers is limited, we need to avoid magnetisable parts on our satellite and estimate the residual dipole before launch. For this purpose, a Hall effect sensor had to be placed above the evaluated part in a specific distance. A 3D printed stand for the probe allowed accurate positioning, making the measurements reproducible and comparable. To test the sun sensors of our ADCS, the satellite was placed on a turntable and illuminated it with a sun simulator. For that purpose we produced a specific stand for a turntable (Fig. 7) to place the satellite safely on it. We were able to simulate different sun vectors and figure out if they were measured correctly. We produced protective caps for the sun sensors to avoid breaking their cover glasses while handling the satellite.

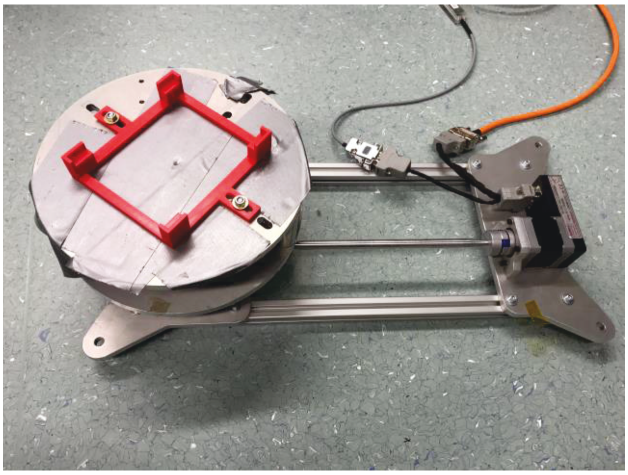

Fig. 7: 3D Printed GSE for Turntable Testing

## 4.3. Reset Mechanism

Resetting the hold down and release mechanism without any type of additional device was not possible without risking to damage the satellite. So we developed a fixture that holds the Flappanels in place while the ADM is closed by hand. That fixture was produced with FDM in several parts to speed up the production time. The fixture has four adjusting screws, allowing us to position the Flappanels right under the slits in the ADM, where they are held in position during the start. With this tool we are able to reset the satellite within ten minutes.

## 5. PROJECT PRESENTATION

It is very difficult to describe a system as complex as a satellite that just exists in CAD files. Having a real piece of hardware makes it much easier to introduce our satellite to new members. With the 3D printed prototypes, we are able to show our deployment strategy and also our structure composition on a model of the same size as the real satellite. Having a physical representation of the satellite in an early project phase was very helpful to acquire new team members. We were able to show that a satellite can be as small as a CubeSat and we were able to explain what it actually does in space. We could observe the motivation of some potential team members to contribute in our project rising after they had the prototype in their hands. Finally, the 3D printed prototypes turned out to be also useful for public relation purposes. We are able to show the satellite in a very detailed version without having to fear to damage operational hardware.

## 6. CONCLUSION

Using 3D prototypes early on turned out to be a productive source of discussion within the project. The difficult cable laying strategy of the antenna cables was discussed more than once by examining the different possibilities on the prototype. Also writing the integration procedure was a lot easier by actually doing dry runs on 3D printed prototypes in advance of doing it with operational hardware.

In summary, it turned out that rapid prototyping is a powerful tool for student projects building a small satellite. It allowed us to rapidly build a physical representation of our satellite to evaluate the design. We were able to implement changes very fast and thereby judge different design options early in the process. Thus, we hope to implement the techniques learned during the MOVE-II development in future projects.

## ACKNOWLEDGEMENTS

The authors acknowledge the funding of MOVE-II by the Federal Ministry of Economics and Energy, following a decision of the German Bundestag, via the German Aerospace Center (DLR) with funding grant number 50 RM 1509.

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