Additive Manufactured Structures for the 12U Nanosatellite ERNST

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ABSTRACT

One of the emerging technologies in recent years is additive manufacturing. It promises unprecedented design freedom in both modeling and rapid manufacturing. We are reaping the benefits of additive manufacturing for our 12U nanosatellite ERNST by printing the optical bench that supports the spacecraft payloads. We design the structures by using a finite-element numerical approach for optimizing the topology with respect to 1) available design space, 2) payload interfaces, 3) mechanical launch loads, and 4) thermal loads generated by the cryocooler of the MWIR main payload. We cope with the latter by integrating a pyramidal structured radiator surface in the optical bench as a functional element. Making use of the selective laser melting technique, we manufactured the first version of the optical bench for the engineering model of the ERNST spacecraft from AlSi10Mg alloy. Vibrational testing proved the suitability of our multidisciplinary design approach and the production quality. We are currently implementing the next version of the ERNST optical bench including spacecraft design changes and using Scalmalloy®, a material developed for additive manufacturing that provides high tensile strength and low thermal expansion. This marks a next step on the way to the application of additive manufactured components in space.

INTRODUCTION

Small satellites have been and continue to be predestined for on-orbit demonstrations of space technology. The cost-effective and quick access to space through small satellite missions allows for a timely low-risk verification of new components for the spacecraft industry. Yet, a small satellite mission itself may benefit from the higher performance of advanced technology. This also applies to additive manufacturing, which is currently driving the innovations in production technologies not least in the aerospace sector. A lot of research is currently underway to establish additive manufacturing as a design and production method for space applications. However, some features of the current state of the art of additive manufacturing limit their application in space missions with stringent quality assurance regulations. These are, in particular, the surface roughness and the heretofore-limited knowledge of the mechanical behavior and anodizing procedures of the layered, additive manufactured parts compared to conventional machined parts. The benefits of additive manufacturing are obvious. It allows complex designs with almost no compromises with regard to production. Integrating different components and their functionalities in one part saves both production and assembly time. This makes additive manufacturing an interesting option for small satellites with highly integrated design and short implementation phases on the one side and a higher risk tolerance with tailored engineering requirements on the other side. To reap the benefits and demonstrate the application of printed metallic structures with integrated functional elements specifically but not exclusively for small satellites, we include additive manufactured structures in our nanosatellite mission, ERNST.

THE 12U NANOSATELLITE ERNST

The German nanosatellite ERNST is a 12U platform based on CubeSat technology. It relies on advanced CubeSat products for attitude determination and control, communication, on-board computer, and power distribution and storage. These commercial components are integrated on a common backplane board with four tailored PC/104 stacks[1]. The spacecraft bus components are completed by deployable structures: solar arrays that provide 60 Watts beginning-of-life power and a de-orbit dragsail to ensure the sustainable use of the orbit environment. The bus components occupy less than half of the space available within the 12U primary structure that consists of classical machined profiles (indicated in blue in Figure 1). The rest of the space is available for various payloads.

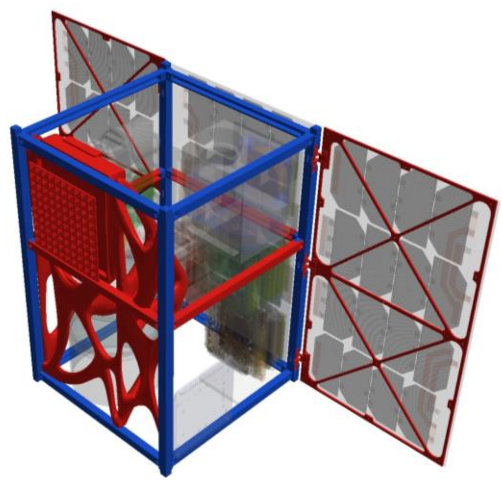

Figure 1: ERNST 12U Nanosatellite structures

The idea behind ERNST is to provide an agile and modular satellite bus that uses the advances of the CubeSat market dynamics with sophisticated standardized bus components while providing sufficient space and power for more complex instruments through its 12U format. We achieve payload flexibility by including an FPGA-based data processing unit and high-data-rate X-band transmitter in the standard bus on the one hand. Additive manufacturing, on the other hand, is the means by which we design custom-made structures for quickly integrating the instruments. For its demonstration mission, with the launch planned for early 2021, ERNST carries on-board multiple instruments: 1) an actively cooled mid-wavelength infrared (MWIR) imager, 2) a visible imager, and 3) a radiation detector for in-situ monitoring of energetic particle fluxes and total dose in orbit.

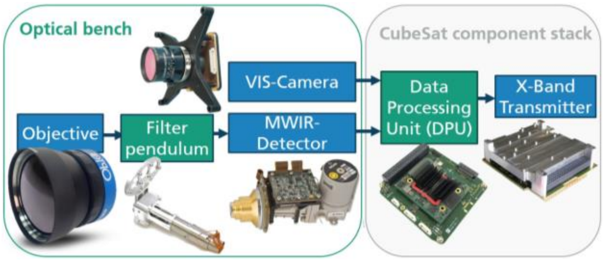

Figure 2: MWIR imager components

The high-resolution MWIR imager has two scientific objectives: 1) monitor the Earth surface in two spectral bands, and 2) detect missile launches during their boost phase[2,3]. This main payload includes an IR-objective, a filter pendulum for switching between different spectral regions, an infrared detector with integrated Stirling cryocooler and a data processing unit (DPU) as shown in Figure 2. Besides the DPU, which is integrated in a stack with other CubeSat components, all payload components are mounted on the additive manufactured optical bench.

ADDITIVE MANUFACTURED STRUCTURES

The main function of the optical bench is to provide a mechanically stable support for the MWIR payload components and the visible imager. Its mechanical stiffness must be sufficient to avoid any interference of the instrument performance by mechanical and thermal loads. The structure and the optical path between the IR-objective and the IR-detector must be robust against launch vibrations and the thermal loads in orbit. The main source of heat (and substantial vibrations due to motor vibration) at the optical bench is the Stirling cryocooler. While it keeps the MWIR detector at 77 K operating temperature, its hot end emits a considerable part of the consumed input power (i.e. 10 Watts during initial cool down). Figure 3 shows the results of thermographic measurements of the unsupported MWIR-detector in vacuum. We stopped its operation when it reached 85°C at the hot side after 40 minutes to prevent it from overheating. The optical bench needs to absorb and transfer this heat input from the payload.

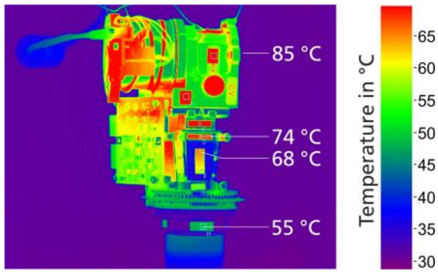

Figure 3: MWIR-detector interface temperatures

Additive manufacturing enables us to integrate functional elements for heat transfer and emission in one part of the optical bench. These functional elements include a radiator surface facing free space and the heat-transfer structure connecting it to the hot end of the cryocooler. We considered integrating capillary heat pipes inside the optical bench for efficient heat transfer. However, the thermal analysis showed that we meet the requirements even without dedicated heat-transfer devices by using the thermal conduction within the ERNST structures[4]. Thus, we decided to keep the ERNST design simple and keep the idea of structurally integrated heat pipes for configurations in which it may become necessary.

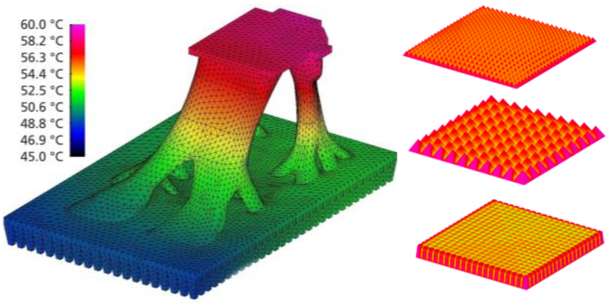

Figure 4: Heat transfer and emission structures

Figure 4 shows results of the thermal analysis for the structural elements of the optical bench that transfer the heat from the detector hot end (on top) to the space-facing radiator (bottom). The spatial thermal gradient between space-facing side and payload side is 7.5 °C[5]. We achieve a high heat emission output by giving the radiator surface a three-dimensional geometry. Its three-dimensional blunt pyramidal geometry effectively increases the emission surface area while keeping a small base area. Different design versions (thermal emission gain) are shown to the right in Figure 4. The optimized version increases the net power emission by 36.5 % compared with a plane surface[5].

DESIGN PROCESS

Since manufacturing constraints become obsolete with additive manufacturing, the structural design can be driven by the functional and performance requirements alone. We use a finite-element numerical approach for optimizing the topology with respect to the loads and boundary conditions for the optical bench[6]. The goal is a lightweight structure that is robust against deformations under vibrational loading and ensures a fast and homogeneous temperature transfer. We perform simulations using Altair's OptiStruct including its Solid Isotropic Material with Penalization[7] approach for topology optimization as well as its coupled thermal-structure analysis capabilities[8].

Figure 5 shows the overall design process. First, we define the payload components to be mounted on the optical bench and the mechanical loads acting on the system during rocket launch (plus qualification margins) and the thermal loads occurring during operation in orbit. Then, we identify the design space, i.e. the volume that is available for placing structures after removing non-design areas that are needed to accommodate other components or to allow access to it.

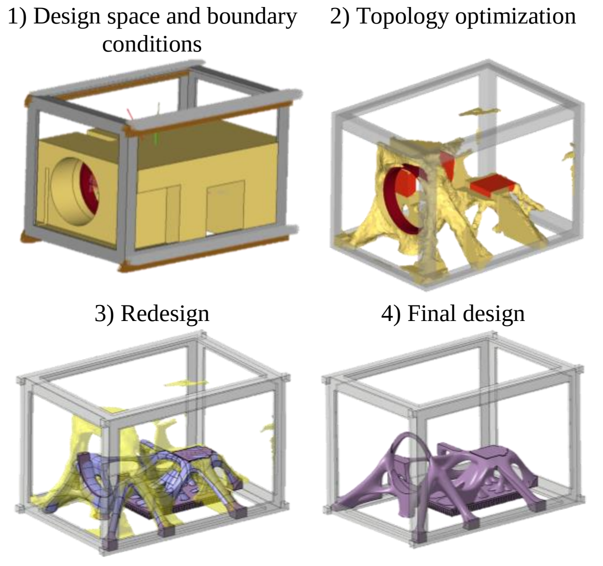

Figure 5: Design process

We combine standard acceleration and vibration loads and define a stiffness goal with the first eigenfrequency >100 Hz. The solution of the optimization task as shown in Figure 5 has a bionic appearance with relatively high geometric complexity. We simplify the geometry and include functional design elements for mounting (for components and for post-processing) in a hybrid CAD approach[9]. This combination of non-parametric and parametric CAD concepts enables easy design changes in the optimized structure. Finally, we verify the adequacy of the final design of the optical bench by numerical frequency response and thermal analysis. The maximum root mean square von-Mises stress response found is four orders of magnitude lower than the yield strength of the aluminum alloy.

MANUFACTURING

We use the well-established powder-bed layering method, the selective laser melting (SLM) process as shown in Figure 6. A laser beam (1) melts metallic powder particles in the selected cross section of the structure being manufactured (5). After having processed one layer with a typical thickness of 30 through 90 microns, the platform (4) is lowered accordingly. The coater (2) then applies a new top layer of powder and the laser operation starts again. Thus, the powder bed (3) increases layer-wise, while the top layer stays within the laser-focus-level, additively fusing cross sections together.

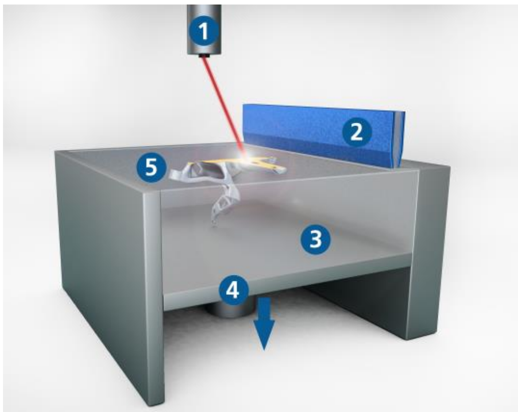

Figure 6: Powder-based layering method by SLM

The quality of the additive manufactured structures depends on coupled process parameters: the power, scan speed and scan pattern of the laser beam, build orientation, powder properties and layer thickness. We use an industrial, high-quality system, the EOS M 400, as shown in Figure 7, to produce the ERNST structures at Fraunhofer EMI. It is able to process structures with maximum $400 \times 400 \times 400\ mm^3$ volume and provides 1000 Watts laser power.

No specific preparation of the facility is needed with respect to the design of the structure to be printed. More specific set-up time is only necessary when changing the material. We used standard aluminum alloy, i.e. AlSi10Mg, for manufacturing the first version of the optical bench for the ERNST engineering model. For the next version, which reflects changes in the spacecraft component design and their allocation, we will use an advanced material, Scalmalloy®. This AlMgSc alloy was specifically developed for additive manufacturing using selective laser melting. A specific

Figure 7: Additive manufacturing facility

microstructure through precipitation phases provides high tensile strength as well as low thermal expansion, thus, increasing the stability of the optical bench when compared to the previously used aluminum alloy[10]. No effect on the heat transfer capability is expected, as the thermal conductivity of Scalmalloy® is as high as with the aluminum alloy. Figure 8 shows the printed optical bench with integrated MWIR payload components.

Figure 8: Additive manufactured optical bench

Strictly speaking, the production of the optical bench is not merely generative but a hybrid process that includes sanding and machining in post-processing. Specifically, we sandblast the complete optical bench after additive manufacturing and carry out grinding and tapping at the component interfaces. Thus, we effectively get the best of both worlds.

VERIFICATION

We optimized the manufacturing process parameters in terms of surface quality and production time. We verified the conformance of the produced structural element by vibrational testing. Figure 9 shows the optical bench installed on the shaker table for testing the horizontal axis. The comparison between the numerically predicted and the experimentally determined frequency response in Table 1 shows an appropriate conformance, with small deviations stemming from non-ideal coupling to the shaker table.

Table 1: Optical bench eigenfrequencies

Mode	Testing	Simulation
1	440 Hz	446 Hz
2	550 Hz	524 Hz
3	975 Hz	991 Hz
4	1093 Hz	1027 Hz
5	1228 Hz	1281 Hz
6	1482 Hz	1432 Hz
7	1669 Hz	1634 Hz

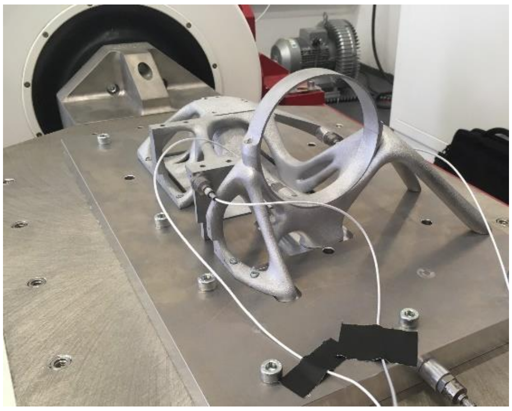

Figure 9: Optical bench shaker setup

We will continue testing with the completed ERNST engineering model with installed components and the next version of the optical bench made from Scalmalloy. Moreover, we plan to perform thermal-vacuum testing to verify the thermal performance of the optical bench and its integrated radiator element.

CONCLUSIONS

Additive manufacturing enables structures that are virtually impossible to produce with traditional machining. We take advantage of the benefits of this technology to produce a custom-designed optical bench that is used to integrate various payload components in the payload compartment of the 12U nanosatellite ERNST. Thus, we achieve a flexible satellite bus design for various payloads. For the design process we apply a hybrid topology optimization approach to find an optical bench layout that 1) is robust against the combined vibrational and static acceleration loads during launch, and 2) transports and emits substantial thermal loads of a cryocooler payload. Specifically, we functionally integrate thermal transfer elements and a radiator surface that is highly emissive through a three-dimensional surface structure. Manufactured using an advanced selective laser melting facility, we verified the appropriate quality of the additive manufactured structures by vibrational testing. We are currently updating the optical bench design, taking into account design changes of the spacecraft and introducing Scalmalloy® as the new material with high strength and thermal stability. The results achieved so far prove the suitability of our multidisciplinary design approach and mark a next step on the way to the on-orbit application of additive manufactured spacecraft components.

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