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CLOSED-WALLED TOPOLOGY OPTIMIZATION OF AN ADDITIVELY MANUFACTURED MOTOR BRACKET FOR AN UNMANNED CARGO AERIAL VEHICLE

JASPER RIESER AND MARKUS ZIMMERMANN

Technical University of Munich
TUM School of Engineering and Design, Department of Mechanical Engineering
Laboratory for Product Development and Lightweight Design
Boltzmannstr. 15, 85748 Garching, Germany
e-mail: jasper.rieser@tum.de, web page: https://www.mec.ed.tum.de/lpl

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Abstract. Compared to conventional intuition-based design, topology optimization (TO) provides considerable mass savings by clearing excess material from lightly loaded regions of a structural part. The remaining material may be distributed in a purely truss-like fashion, or in the form of a closed-walled design consisting of flat plates or curved shells with variable thickness. Unless buckling is of critical concern, closed-walled designs are in general more efficient than trusses which makes them particularly interesting for challenging applications in lightweight design. However, closed-walled designs obtained by topology optimization are still the exception rather than the rule. This paper investigates the applicability of the recently developed selective penalization approach to the design of a motor bracket for an unmanned aerial vehicle (UAV) to deliver defibrillators which is currently being developed by the HORYZN student initiative at the Technical University of Munich. The optimization results are closed-walled designs as desired. A comparison to a truss-like design as well as to a conventional off-the-shelf motor bracket reveals that the closed-walled design even outperforms the topology optimized truss-like design by additional 3% in terms of stiffness-to-weight ratio. Moreover, it provides a streamlined housing protecting the motor cables and contributing to the reduction of aerodynamic drag at cruise speed. Another key finding of this case study is: Depending on the specific optimization problem, and a suitable build orientation provided, closed-walled designs may lower the amount of necessary sacrificial support structures or may even be almost self-supporting. For the closed-walled motor bracket design we found a reduction by more than 25% compared to the truss-like design. This did not require limiting the freedom of design by imposing any additional constraints. The motor bracket was successfully manufactured from aluminium alloy using laser powder bed fusion (LPBF) followed by removal of support structures and CNC machining of functional surfaces.

1 INTRODUCTION

Adapting the design of mechanical parts to precisely specified load cases, boundary conditions and design requirements results in tailored parts that often have significantly lower mass.

This has been the earliest and probably still is the most important application for topology optimization (TO) which over the years has become a standard tool to solve structural optimization problems of this kind. TO-based parts are commonly composed of a few manually designed engineering features such as bores and mounts that are connected by a smooth truss structure. Although such optimized parts are already considerably more efficient than conventionally designed parts, they are still not optimal. As it has been pointed out by [7], closed-walled designs exhibit a stiffness-to-weight ratio which is at least equal to but usually significantly larger than that of a similar truss. In contrast to a truss, which consists of straight bars under tension and compression, a structure is called closed-walled if it consists to a relevant degree of surface elements under biaxial stress.

In the context of density-based topology optimization, such as the popular SIMP method [1], the emergence of closed-walled designs is subject to certain conditions. Contributing factors that can favour convergence towards closed-walled design are the use of a continuation scheme and a more conservative tuning of the optimizer. However, first and foremost, the mesh must be chosen sufficiently fine with respect to the yet unknown part design. It is indeed fairly common that the finite element size of a typical practitioner's mesh is much larger than what would be needed to represent even the walls with the smallest thickness. Especially for problems with large design domains and low material volume fractions the required number of elements quickly exceeds the acceptable limits.

To make closed-walled designs feasible also in large design domains while still keeping the computational effort manageable, different approaches have been proposed that work without excessive mesh refinement during the TO step. In this paper, we employ the two-step optimization procedure by [6] to design a lightweight motor bracket for a UAV. The first step of the optimization procedure is a density-based topology optimization on a fixed mesh. Unlike the classical SIMP method, the stiffness of intermediate densities is only penalized in thick-walled or void regions but a linear interpolation is used for thin geometrical features. The optimizer takes advantages of this selective penalization in such a way that the design is driven towards a discrete 0-1 material distribution only in the penalized regions whereas thin features can still have intermediate density without compromising efficiency.

The motivation for allowing only thin features to have intermediate density is that their dimension in thickness direction is small when compared with other dimensions. This allows to convert the elements with intermediate density into solid elements by a local shrinking in thickness direction which leads to a morphed mesh with a material volume close to the target value but without changing the design's overall shape excessively. This conversion is done in the second step of the optimization procedure by computing the linear elastic deformation of the design under imposed inelastic shrinkage strains while being connected to an elastic foundation. Finally, a smooth, manufacturable CAD geometry is build manually from this morphed mesh by reverse engineering.

Exploiting a greater freedom of design by using TO for part design is usually not without its challenges. In fact, a considerably higher geometrical complexity of the part is the price to be paid for any mass saving and performance gains. This can become a severe drawback since geometrical complexity is a critical issue with respect to manufacturing. In these cases, it can be worth considering additive manufacturing (AM), as long as part or batch size restrictions do not apply. While geometrical complexity is not necessarily a problem for AM, particular attention must be paid to down-facing surfaces with an angle less than some critical angle. For

LPBF and AlSi10Mg a critical angle of 45° measured from horizontal is commonly assumed. To be printed successfully, faces with smaller angles need temporary support during the build process. A large amount of these sacrificial support structures increases build time, powder consumption and post processing effort, since support removal can be a laborious task leading to a fairly low productivity. A straightforward and simple approach to prevent this is to replace sacrificial support structures by permanent walls integrated into the part design ([2]). Since these permanent walls are added to a given design only for the sake of improving manufacturability, their contribution to part performance, such as mean compliance, will most likely be poor. Thus, this strategy is fully recommended only where the additional mass of permanent walls is not of crucial importance. A more advanced approach is to modify the structural members to reduce the amount of overhanging faces instead of adding separate walls subsequently. Several methods of this kind have been development to consider overhang restrictions during TO, see for instance [4, 3]. It is not surprising that the latter approach leads to designs which provide a better trade-off between loss of mechanical performance and reduction of sacrificial support structures. However, driving the solution towards support-free designs, regardless whether this is done by explicitly adding constraints to the optimization problem or through the use of a customized filtering scheme, will always limit the freedom of design and will lead to a lower stiffness-to-weight ratio compared to a design not considering overhang angles at all.

As it has been exemplified in [6] by means of a simple MMB-beam problem, TO-based truss designs can usually not be expected to be self-supporting by default. Interestingly, switching to a closed-walled design does not only improve the stiffness-to-weight ratio, but also has the potential of reducing support structures considerably. In this paper we explore the applicability of the two-step optimization procedure presented in [6] beyond the somewhat simplified academic test-cases shown therein. In particular, we raise the question whether the benefits of closed-walled designs can in fact be obtained also for a more complex, practical engineering problem.

2 DESIGN PROBLEM

Our study discusses the topology optimization, detail design and additive manufacturing of a motor bracket for the new UAV developed by the HORYZN student initiative at the Technical University of Munich. The concept design is shown on the left of Fig. 1. To achieve the ambitious design goals with respect to payload and range, lightweight design rules are strictly followed for every newly developed component of the vehicle. The motor bracket was selected for a detailed design study due several reasons. First and foremost, a relevant mass saving potential was identified compared to a conventional bracket. This assumption was further supported by the required number of 4 identical brackets per UAV, which also justified the additional design efforts. Moreover, the motor brackets is located within and may obstruct the air flow of the rotor, which is why a compact and streamlined design is to be preferred. The same argument applies to the impact on drag during cruise. The motor bracket is also known to be subject to intense vibrations, which demands for a careful re-design of the interfaces and connections between motor, motor bracket and boom. Lastly, providing a convenient mounting option for the housing of the electronic speed control (ESC) would be desirable.

The available design domain is visualized in Fig. 2 together with two kinds of engineering features modelled as fixed-solid domains. The sleeve connector loosely clamps around the boom made of carbon fiber-reinforced polymer (CFRP) and a firm connection is achieved by

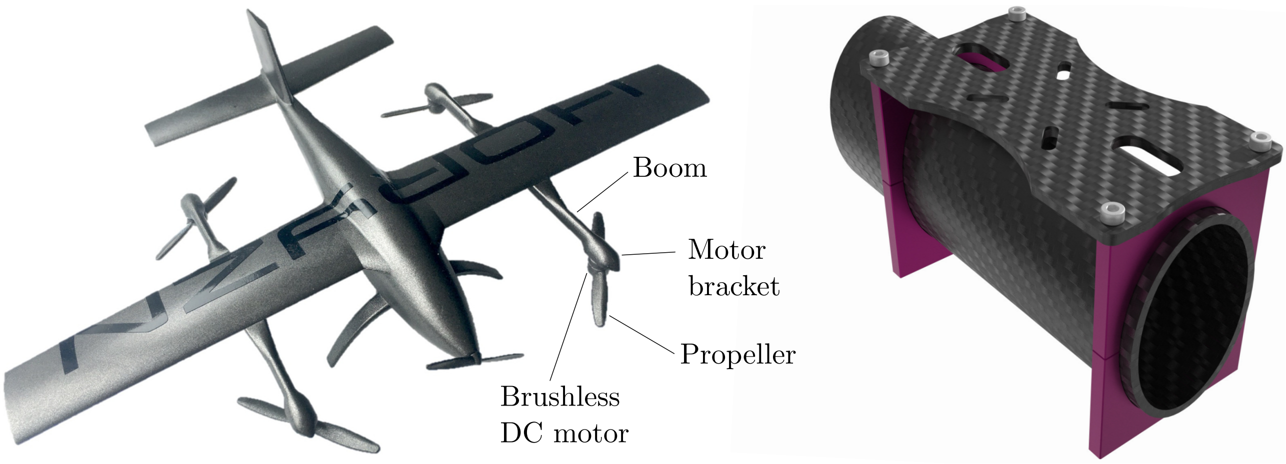

Figure 1: Early stage concept design of the new UAV (left) and conventional motor bracket (right).

adhesive bonding. A layer of glass fiber is used to protect the aluminium of the motor bracket against galvanic contact corrosion. The thin sleeve connector has a length of 30 mm to provide a large bonding area, its wall thickness increases linearly from 0.8 mm to 1.5 mm. Four cylindrical motor mounts are provided to attach the stator of the brushless DC motor to the motor bracket using M4 hexagon socket head cap screws. Suitable channels have been cut into the box-shaped design domain to ensure there is enough space for placing and fastening the screws. Another cut-out passes through the design domain in x-direction for assembly of the ESC and to provide convenient access to the inner of the boom.

Based on preliminary estimations and experience gained from the previous UAV generation, an allowable mass of 32.5 g was set by the HORYZN conceptional design team. This is precisely 75% less than a comparable off-the-shelf motor bracket used before and shown on the right of Fig. 1. Maximum von Mises stresses must stay below yield strength $R_{p0.2} = 210\,\text{Mpa}$ with a factor of safety $FoS = 1.5$. Similar to the boom, the objective for the motor bracket is to maximize stiffness in z-direction to resist the lift force $F = 165\,\text{N}$. The lift force is evenly distributed over the mating surfaces of the four motor mounts. The motor has a fairly strong stator machined from aluminium with four threaded holes and a a clean, flat mounting face. Its stiffness contribution to the entire assembly is significant and can not be neglected. It is taken into account during the optimization of the motor bracket assuming a simple tied contact at the matings surfaces. Similarly, the adhesive bond at the inner surface of the sleeve connector is simply modelled as a fixed support.

3 RESULTS

For the case study presented in this paper, we implemented the two-step optimization procedure by [6] in Matlab to generate the closed-walled designs using selective penalization. The same parameters were adopted if not otherwise specified. Results are compared against truss designs based on the classical SIMP method which were found using the 3D topology optimization code by [5]. The topology optimization problem of the motor bracket is solved using a mesh of regular hexahedrons with an element size of 1 mm, $1.5 \cdot 10^5$ active design variables and $5.3 \cdot 10^5$ displacement degrees of freedom. With classical SIMP the design converges towards a discrete 0-1 truss, see Fig. 3a. Each of the two outer cylindrical mounts which are further away

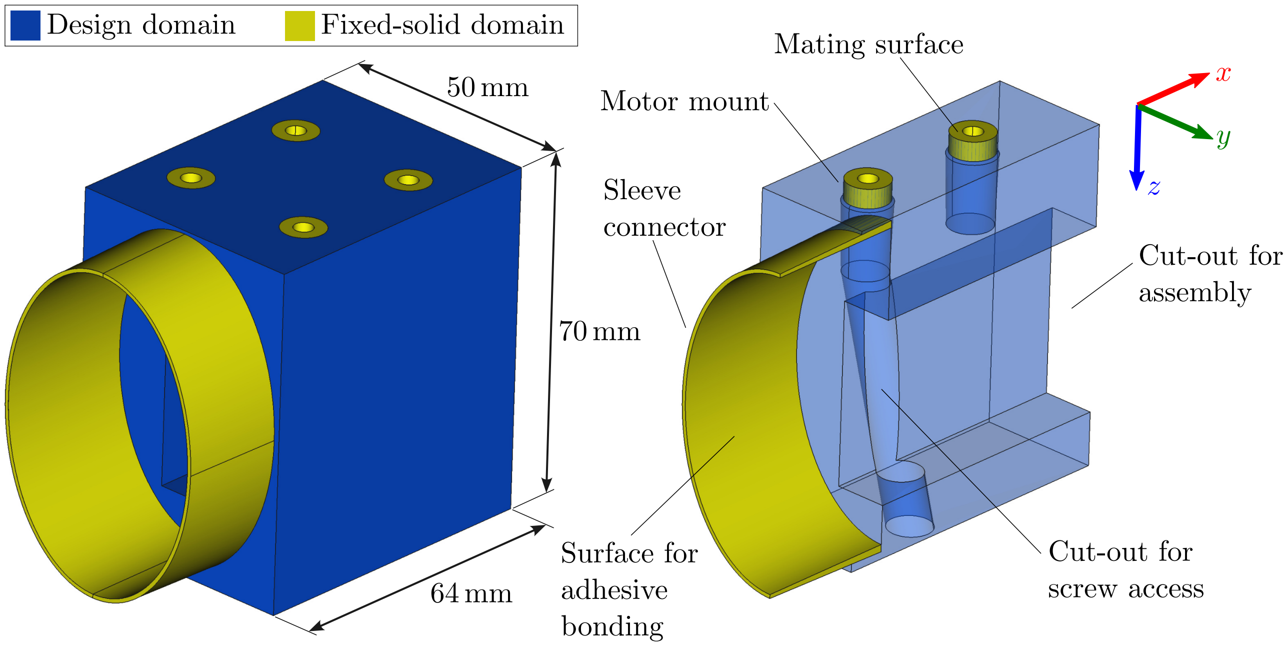

Figure 2: Outer view (left) and transparent cross-sectional view (right) of the design domain and fixed-solid domains for topology optimization of the motor bracket.

from the boom is supported by a thick bar connecting the mount to the sleeve connector. This bar is not straight, but exhibits two slight bends where smaller diagonals bars are attached to it.

In contrast, when making use of the two-step optimization procedure, a variable-thickness-sheet-like structure is obtained instead of discrete bars. The topology resulting from the first step is shown in Fig. 3b. Due to the selective penalization, it obviously still contains a large amount of intermediate densities which are further processed in the second step leading to the morphed mesh shown in Fig. 3c.

Both the discrete truss and the closed-walled morphed mesh were reverse engineered into solid, smooth CAD geometries. An image of the latter illustrating also the attachment to the boom is provided in Fig. 4. All designs are symmetric with respect to the x-z-plane.

To verify designs are in compliance with the mass constraint we computed their mass based on an AlSi10Mg average density of $2.7\frac{\text{g}}{cm^3}$. To assess and compare the structural efficiency of the different design variants, we computed the scaled compliance as the product of the design's mean compliance multiplied by its mass. The values are listed in Tab. 1. Relative differences to the respective baseline design are indicated in parentheses for easier comparison. It can be seen from the first two rows, that the TO result based on selective penalization predicts a reduction of the scaled compliance by 8% compared to the truss design. The third row reveals that the mesh morphing does not exactly conserve the material volume, and likewise mass, but the difference is not significant and can in fact be partly attributed to the removal of void elements. We intentionally do not provide a compliance value for the morphed mesh, as it is rather an intermediate step towards a manufacturable CAD geometry. Values for the post-evaluation of the final CAD geometries have been computed using body-fitted tetrahedron meshes with element size $\leq 1\,\text{mm}$ and can be read from the two bottom rows.

While for the truss the scaled compliance computed for the CAD geometry closely matches

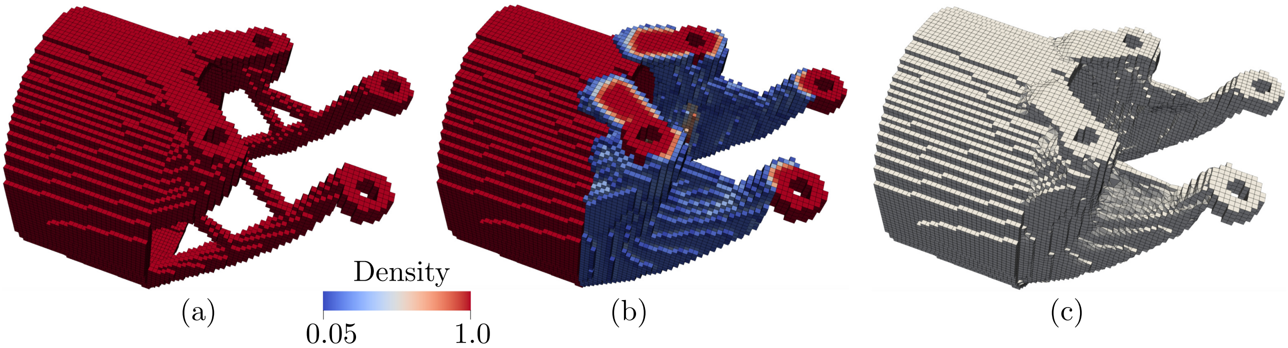

Figure 3: Topology obtained using classical SIMP **a**, topology obtained using selective penalization before **b** and after mesh morphing **c**.

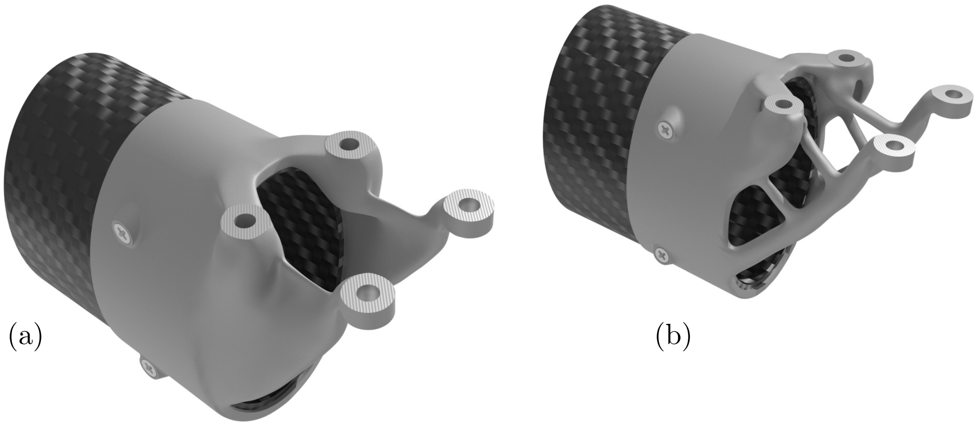

Figure 4: Final design of the truss bracket **b** and the closed-walled bracket **a** fitted to the CFRP boom. Two protruding bosses with countersunk bores have been added to the sleeve connector. Their purpose is to seat countersunk screws used to fasten the ESC inside the boom.

Table 1: Mass, scaled compliance and supported surface area of the optimized designs found using the classical SIMP method and the selective penalization approach.

	Figure	Mass in g	Scaled compliance in Nmm·g	Surface area requiring support in mm^2
Classical SIMP	3a	32.5	12.63 (100%)	-
Selective penalization	3b	32.5	11.62 (92.0%)	-
Morphed mesh	3c	32.2	-	-
Truss CAD geometry	4b	31.2	12.57 (99.5%)	413.7 (100%)
Closed-walled CAD geometry	4a	31.1	12.17 (96.3%)	302.2 (73%)

the value from the TO step, one observes a deviation by about 4% for the closed-walled design. This is more than the deviations reported for the academic benchmark cases in [6], where the shape of the design domain and the loading is not overly complex allowing the optimized structure to evolve freely. Thus, we attribute the deviation to the more complicated design domain of the motor bracket. The underlying assumption of the selective penalization approach

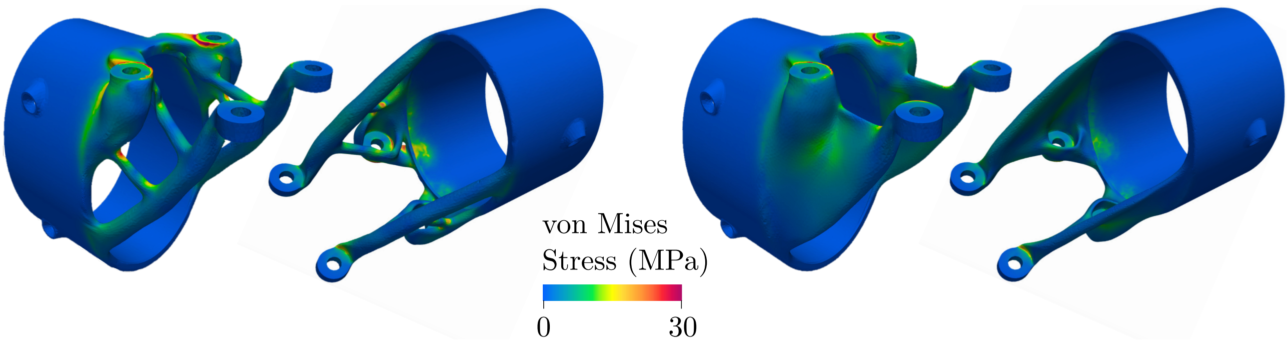

Figure 5: Stress analysis for the truss design (left and middle left) and the closed-walled design (middle right and right).

is that for a linear relationship between Young's modulus and density the stiffness of a wall-like feature does not change when the wall thickness is increased as long as the density is reduced by the same factor. This appears reasonable for axial rigidity and shear rigidity, but it clearly overestimates out-of-plane bending stiffness. Although individual wall-like members even partly subject to bending are unpreferable, they may sometimes still be the best compromise in particular if the available design domain is confined due to cut-outs. For the motor bracket discussed here, this is likely what happens e.g. near the two mounts which are closer to the sleeve connector. The topology tightly wraps around the cylindrical screw access cut-outs indicating that an undisturbed formation of a more efficient topology is impeded. Nevertheless, the closed-walled design still exhibits a notable improvement of more than 3% with respect to scaled compliance when compared to the truss design. A linear elastic stress analysis has been performed taking into account the lift force and additionally the maximum motor torque of 5030 Nmm. Stresses remain below the specified allowable as shown in Fig. 5. Stress peaks arising along the edges of the motor mounts are mainly the result of the simplified modelling of the motor and its attachment to the mounts.

Another relevant aspect of the design variants is their required amount of sacrificial support structures during the LPBF process. While a minimum of support structures is always needed to firmly fixate the part on the build plate as well as to ensure heat is conducted away properly, it is a common goal to reduce their use as much as possible. Assuming a critical angle of 45°, we have computed the part orientations with respect to the build plate which minimize the surface area requiring support. Non-self supporting sharp bottom edges are supported by a support structure of 1 mm width. The optimal orientations, which were computed for each design variant individually, are almost identical and visualized in Fig. 6. In contrast to the bottom faces of the compact truss members, marked by a white arrow in Fig. 6a, the closed-walled design benefits from the much smaller amount of support structures required at the bottom line of the otherwise self-supporting thin wall, see the white arrow in Fig. 6b. As stated in the column on the far right of Tab. 1, the surface area of the closed-walled CAD geometry still requiring support is 27% smaller compared to the truss.

It is worth mentioning, that closed walls, although not explicitly demanded, are a desired feature since they form a streamlined fairing. It does not only offer aerodynamic advantages but also partly encloses and protects inner components like the motor wires. The closed-walled design has finally been printed successfully by LPBF from AlSi10Mg alloy. Post-processing steps included de-powdering, manual support structure removal, blasting for surface roughness

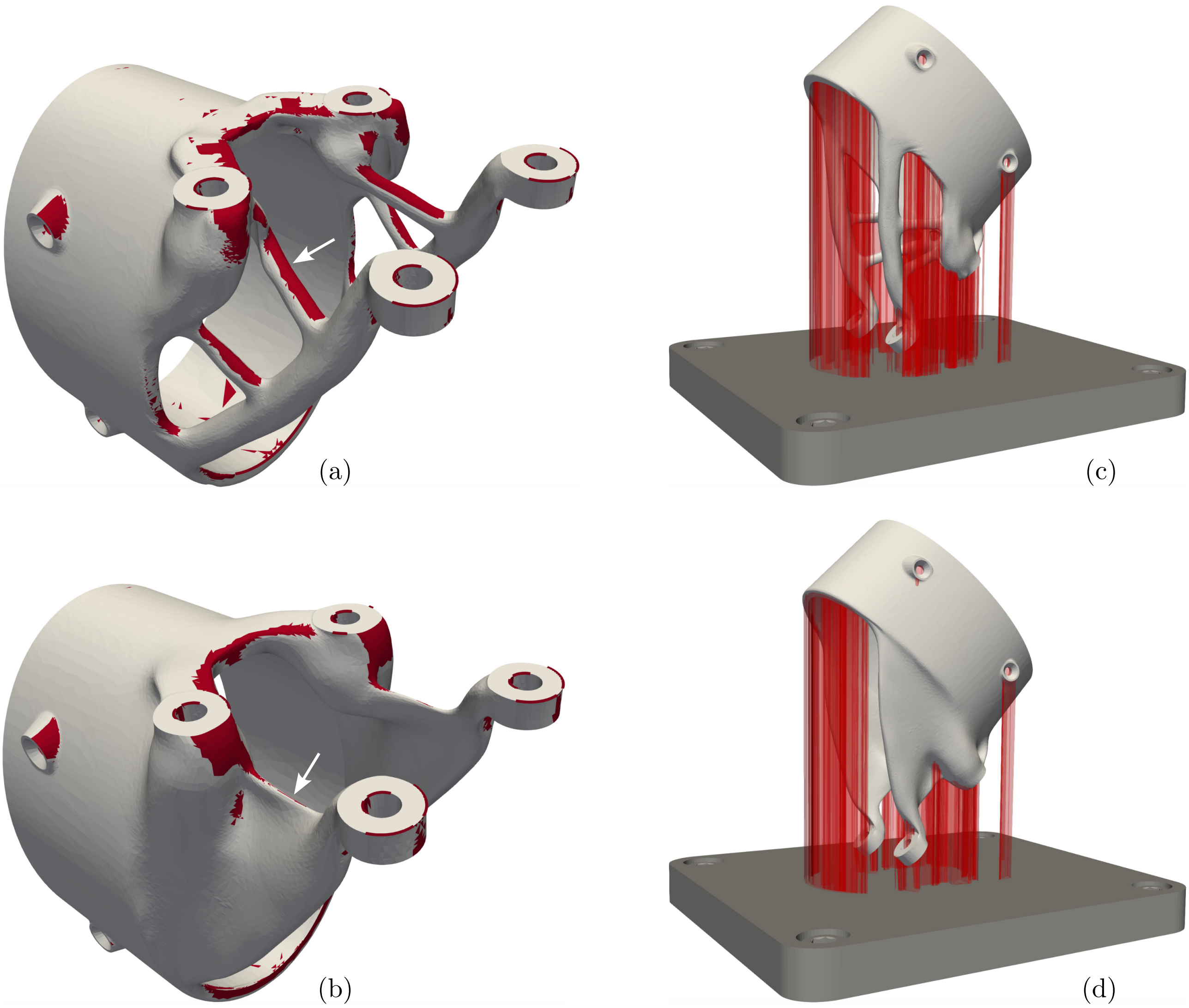

Figure 6: CAD geometries of the truss **a** and closed-walled design **b**, surfaces requiring support are highlighted in red. Optimal part orientation on the build plate and support structures for the truss **c** and closed-walled design **d**.

improvement and CNC post machining of functional surfaces. Results are shown in Fig. 7.

4 CONCLUSIONS

We have presented a case study on the design, optimization and manufacturing of a motor bracket for the new cargo UAV by the HORYZN student initiative at the Technical University of Munich. We generated a closed-walled and thin-walled lightweight design by successful application of a recently developed topology optimization approach which does not require particularly fine meshes to fulfil this task. While the benefits of closed-walled designs with respect to structural efficiency have already been demonstrated by several authors, we highlight especially the potential of closed-walled designs to improve manufacturability by reducing the necessary amount of support structures, which is an important cost driver in additive manufacturing. From this case study we draw the conclusion that the benefits of closed-walled designs

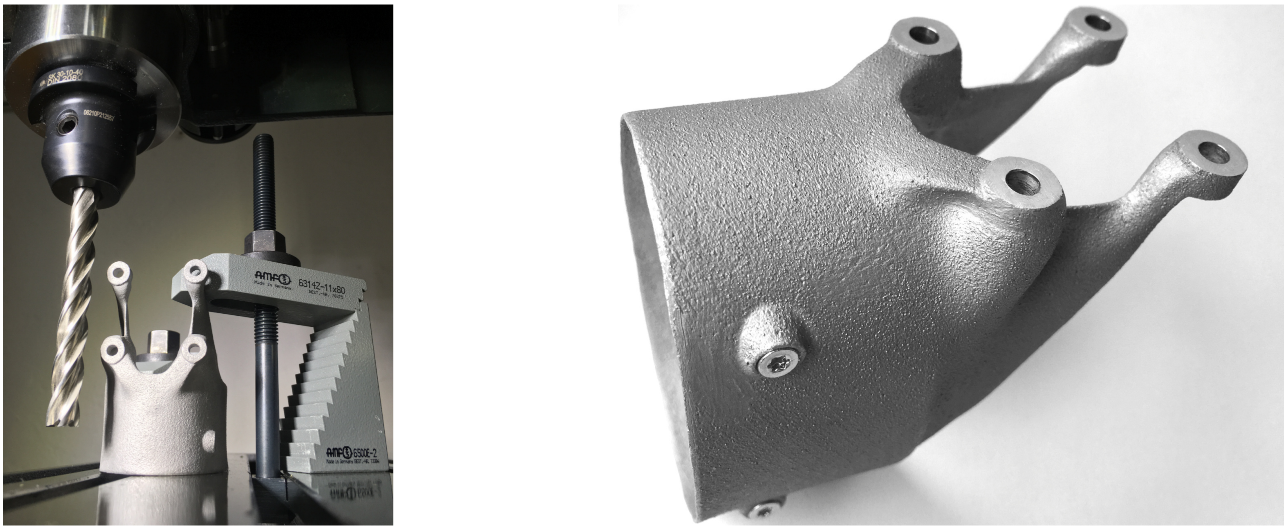

Figure 7: Post machining of functional surfaces (left) and finished part (right).

can be threefold: First, closed-walled designs offer superior stiffness-to-weight ratios not only for simple benchmark problems, but also for more complex use cases of practical relevance. Second, they can potentially be produced by additive manufacturing with considerably less support structures. Third, in some applications closed walls are a welcome feature serving secondary purposes like protection or aerodynamic at zero additional weight.

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