FE-Optimization and data handling for Additive Manufacturing of structural parts

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Abstract

Additive Manufacturing (AM) offers high potential due to its freedom of design for structural parts. Especially in combination with FE-based topology optimization an optimal use of material and thus significant weight reductions can be expected. However, the application of AM is hampered by different additional manufacturing processes along the entire production chain and data handling induced restrictions.

Disadvantages emerge from a lack of adjustment of the entire design process for AM. First the optimization algorithms are not targeted to the opportunities and restrictions of AM – represented by design rules – like the design of support structures. Secondly, the CAD software is not adjusted to AM in particular. Creating freeform shaped surfaces based on the optimization results is significantly less convenient than building defined blocks or turning parts following the needs of conventional machining. The indispensable subsequent interpretation of optimization results regarding the design rules and the possibilities of CAD-tools counteracts optimal results.

This paper considers different approaches for a Topology Optimization (TO)-shape regaining on different sample parts including telecommunication satellite parts. An innovative design methodology is presented getting crucial for creating high quality designs.

Introduction

Emerging requirements in weight savings for fuel efficiency or performance improvement lead to a very high demand for lightweight design of parts in a broad range of industries. Especially in the areas of aerospace and racecar engineering weight reduction and performance enhancements are mandatory for commercial and sporting success. For space applications the weight reduction of structural parts is essential as not only the direct savings due to less propulsion have to be considered but additional payload can be transported into space, increasing the return of investment for the satellite mission.

One of the most promising technologies nowadays for enabling very lightweight design is the additive manufacturing (AM) technology. AM is a tool free manufacturing process and thus enables very complex designs not possible to be manufactured by conventional manufacturing. These designs are supposed to use applied material best as unused material can be omitted without raising costs but even lowering due to less material consumption.

Gaining such ‘perfect’ structures is hardly possible for designers by hand. The designer has to be supported by automatic algorithms. One method for generating these designs is the topology optimization (TO). The topology optimization is a finite element method (FEM) based calculation method that is capable of allocating material only where it is needed. [Bend03]

The combination of AM and TO carries great potential and positive impact in both directions: TO develops best shapes that are only manufacturable by AM. Though there are some hurdles to be taken in the design process. This paper details both processes, explains these hurdles and discusses different approaches of overcoming them.

Fundamentals

A broad range of manufacturing technologies is subsumed under the term ‘AM’. All of them create a part’s shape not by removing material like milling or turning, but adding material. Many of them are 2D-layer based as a complex part geometry is digitally sliced in thin layers which are than build up. For high value structural parts metals processed by the selective laser melting (SLM) can be used. In this case a thin layer of metal powder is deposited and the 2D geometry in this height is molten by a laser. After the material is solidified, the next layer is deposited and molten. Thereby step by step any complex geometry can be manufactured [Geb13]. Theoretically each layer is completely independent to the foregone. Although there are some restrictions impeding this absolute freedom, it shows the high complexity available by additive manufacturing. No tools or molds are needed and nearly everything is possible even without extra costs. [HHD06]

This high complexity in design enables using the material best. The best use of material by means of lightweight design implies a most equal stress distribution over the entire part and the use of material only where it is needed, abandoning unburdened material. Depending on the loads of a part this may come to structures with struts, sponge like material distribution or “bionic” structures. Designing these structures for complex loading conditions is nearly impossible by hand as one is not able to define the force flux analytically. The designers need to be supported by automatic working computer algorithms.

Therefore the topology optimization method (TO) can be used. The topology optimization is a method based on the finite element method (FEM) for calculating the stress and strain distribution in a part based on the loading conditions. The optimization algorithm interprets the results of a FE-Analysis and thereby optimizes the material allocation for using least material. Therefore the biggest available design space where material is allowed to be is defined. The bigger the space the better the result due to most direct force flux. [Har08] Topology optimization is already in use in many fields of engineering for gaining the best designs. For conventional machining these results have to be revised and adapted massively to enable the manufacturability. The resulting “bionic” structures with freeform surfaces and complex struts are hardly manufacturable and if required only with very high costs. Additive manufacturing is the key enabler for this technology as the additive manufacturing does not need any tools and the design is restricted by only very rare limitations. One of the simplest examples often overseen with its complexity for milling is the ability of producing very deep but small pockets without extra costs for special milling tools. More ambitious examples are complex undercuts due to most direct force flux following struts. Very voluminous designs leading to high moments of inertia and thus high stiffness can be realized by the combination of high burdened directly mapped struts with small, very filigree connecting bridges or thin but three dimensionally curved shear plates.

Beside that very smooth and “bionic” like designs are possible. As there is no limitation in complexity the surfaces and struts can flow in each other with very perfect and complex radii. One is not limited to the standard curve-radii but can design radii with very low or even without stress risings due to notch factors. The principle of optimizing notches as proposed by [Mat03] can be used best by the combination of TO and AM.

Though some limitations still have to be considered from different sides:

- process induced restrictions
- conventional post processing
- design tools

First the design has to follow some process induced restrictions anyway. In AM for metals support structures are needed between the build platform and the actual part. These are very thin and brittle structures needed to ensure the part to stay in place, reduce distortions and particularly for heat conduction from part to the build platform. These are needed at the beginning under the lowest points of a part and later on under all down facing surfaces with an angle to the build platform lower than 45° or starting volumes [ZiAd14]. Furthermore neither too small nor to big material accumulations are possible. For a safe build there has to be enough material while too big material accumulations may lead to high internal stresses causing distortions up to destruction of a part [Ada15]. As well inner cavities are possible to be build, but need a connection to the outside to remove the unused powder. Overall the dimensional accuracy and tolerances of additive manufactured parts are questionable [GiWa14]. This has to be kept in mind for TO as well as for any interfaces to other parts.

Secondly the conventional post processing has to be considered.

After the build process the part has to be removed from the build platform and the support structure hast to be removed. This can be done mainly by hand but for series production as well as for critical surfaces machinability in these areas has to be ensured. Due to the tolerances and the quality of as-built surfaces all interfaces have to be post processed with conventional machining. This is similar to casting processes [Habo14], [Tho09]. For the combination of AM and TO one has to consider the loads during conventional machining, as the resulting shapes from TO are optimal load adapted solely for the given loads. The resulting filigree shapes may not withstand the high loads from conventional machining and thereby have to be kept in mind either when setting up the TO-model or checked afterwards in FE-Analysis of the optimized part.

A further point, especially in case of integral design, is the accessibility of tools for the post processing. If an assembly is set up by different parts it might be easier to access all relevant points before assembling. If this assembly is manufactured in one step by AM it might be critical to access mounting points for correction of the surfaces as for example for washer placement.

The third point is the used software.

Common design tools are not made for high complex freeform shaped 3D-parts. Feasible freeform software exists for art designers but not for regaining and reproducing the high complex shapes of a topology optimization. These include complex surfaces with outgrowing connectors, splitting up and growing together again. For industrial use as well parametrically designed interfaces have to be used.

Topology optimization shape regaining methodologies

Even if all beforehand mentioned limitations have been considered, further manual work is needed on the TO results as they are not directly printable. The topology optimization weighs each element inside the given design space regarding its importance for the part. Thereby each element gets a density assigned from zero to one and is included correspondently in the calculation. The designer exports these results according to a chosen threshold representing feasible shapes. By this the results are not clear and usable for direct manufacturing as shown in Figure 1. These are three of the most common difficulties of topology optimization results:

- unclear results
- insufficient resolution
- insufficient design space

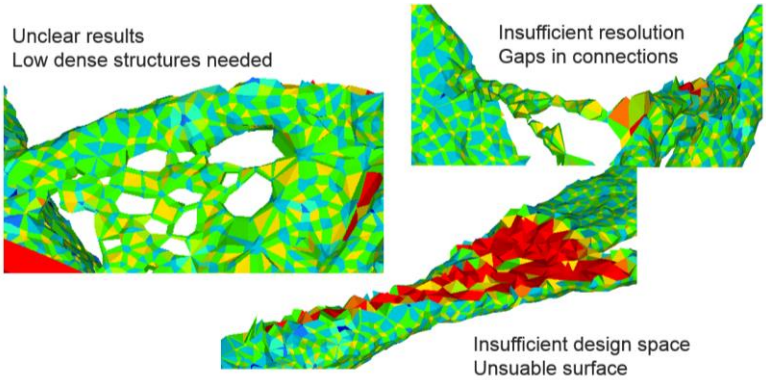


Figure 1: Examples for shape difficulties in topology optimization results

The first example shows unclear results as there is a strut with a shear plane but this plane could not be clarified to struts or surfaces but could be a perfect place for AM specific low dense structures like lattice structures. The second one shows interrupted connections due to insufficient resolution. The connection bridge between two bigger areas of the part is not closed as there are some very big elements next to very small ones leading to some elements completely not shown. This result would not be useful. The third example shows the result of insufficient design space. The inner volume of the strut is highly burdened and thereby shown red as very important. The outer shells are not that important and thereby shown green. If the exported result should have an equal stress distribution, the shown surfaces all should have the same colour and thereby importance. In this case some elements in red can be seen what is explained by missing elements in the design space. Due to the high volume of the design space the overall optimization was conducted in two steps as explained in the use case. On basis of the first iteration some elements where deleted and now it can be seen that some elements were deleted that would have been needed.

Due to these examples and further details the designer has to revise, correct and adapt the results [LiRei15].

Especially if the part is still in design process and the exact shape of interfaces or transmission points have to get updated, it is mandatory that conventional CAD-tools can interact with the data of the optimized part. If transmission points or interface shapes depend on the attached parts or vice versa, interoperability is needed. Standard CAD-tools often are based on the kernels ACIS or Parasolid and originally are made for the use of B-REP and CSG features. Though they are already updated with freeform tools for design of NURBS, they still have some problem with organic shapes. Features like NURBS, SubD or T-Splines are mathematically well described and very useful for the design of for example cars. A freeform surface organic shape part is a combination of many NURBS, each with four points and four sides. The next face has to match exactly at the other one to prevent lacks and to ensure a “watertight”, problem-free volume model [Yar13].

Designing an entire structure with these functions is a time consuming and error-prone process. One example is shown in Figure 2. The target structure is not that complicated, but due to the complex handmade shapes there are useless bulges. The part has to be divided into a great amount of single surfaces, depending on the tolerated complexity of each one. The shown problems arise from freeform splines following the optimization results that do not lead to a clear defined surface. Especially the mandatory tangentially connection to neighboring faces may cause distortion of single surfaces as the hard radii continue and result in over interpreted following splines.

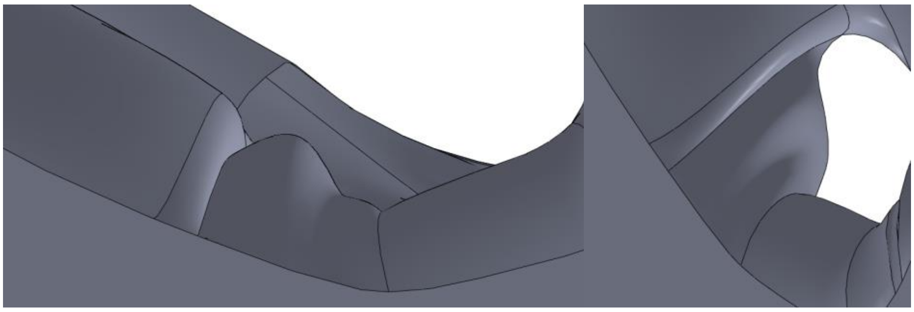


Figure 2: Unusable bulgy structure by handmade freeform shapes

Different approaches for designing optimal structures for AM have been explored in the past as shown in Figure 3 [LiRei15]. Therefore the use case described later on ("upright of a formula student racing car") was already used in the respectively relevant actual configuration of current car.

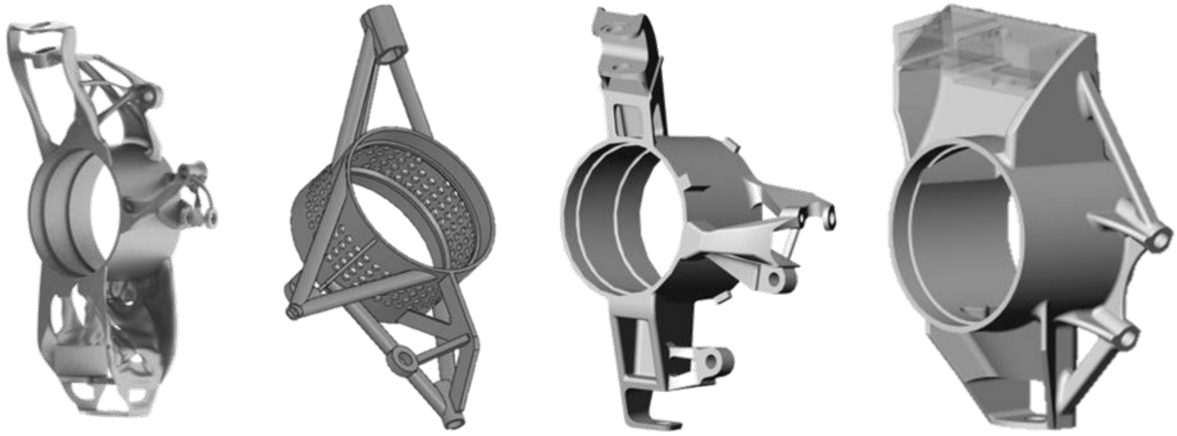


Figure 3: Different approaches designing optimal structures for AM

The first one is made by most direct use of freeform surfaces. This leads to a very lightweight design, as the TO results are implemented the most direct. Though, big disadvantages emerge from a very high effort and problems as shown in Figure 1. The second one was done without a topology optimization but based on a wire frame model, FE-analysis and conventional redesign and with regard to special direct manufacturing design rules [ZiAd14]. The results are very usable for AM but not optimal as they depend on the engineering experience and not optimization was used. The third one is based on topology optimization again but conventional CAD-features like linear extrusion were used and the design rules for reducing support and material accumulations are neglected. The fourth approach again used topology optimization and standard tools but with more lucid elements and thereby as well the TO-results as the design rules are used. Except the first approach rare freeform surfaces are used and thereby the topology optimization results with "bionic" elements are not represented best.

A typical design procedure after TO could be a retransformation to NURBS based on all elements by complex algorithms, as rudimental already implemented by common TO-software or by designer's interpretation as shown before. Both ways would not lead to perfect surfaces as automatic surfaces often keep bulkiness and difficulties with unclear results appearing as explained in Figure 1. A designer though may equalize result issues but is not capable of redesigning all complex details. Furthermore the manual work takes a very high effort. The first approach with most direct shape regaining took several weeks of hand work. Therefore a more automatic and less elaborate workflow is needed.

Summarizing, a new methodology for regaining TO result shapes is needed.

Voxel based TO shape regaining methodology

One key to solve these issues is the underlying representation methodology. Especially due to the mandatory change from B-Rep / CSG / NURBS into a polygon model for a FE-Analysis and for topology optimization this is necessary anyway. For the simulation the analytically defined and closed surfaces are meshed by a pre-processor. The result is a geometry representation based on small polygons like 2D trias or quads and 3D tetrahedrons or hexahedrons. During this transformation step information gets lost as only the position, size and shape and neighbors of each element are known. The beforehand parametrically designed structure is now fixed and all parametric dependencies are deleted. Information about defined surfaces and especially exact defined radii are no longer available. A circular hole will be presented by more or less angular elements.

A proper way to keep all desired details and remove unwished details or waviness is to stay one step longer in the alternative representation level as shown in Figure 4. The polygon model is transformed into a voxel representation. This enables an even more freeform design, as the voxels can be moved, removed and added completely free. Thereby it is as easy as in no other representation to smooth surfaces, add material where needed and design surfaces perfect for stress distribution. Low notch factors are possible as one is not restricted to circular notch forms and may design notch forms as propagated by C. Mattheck [Mat09].

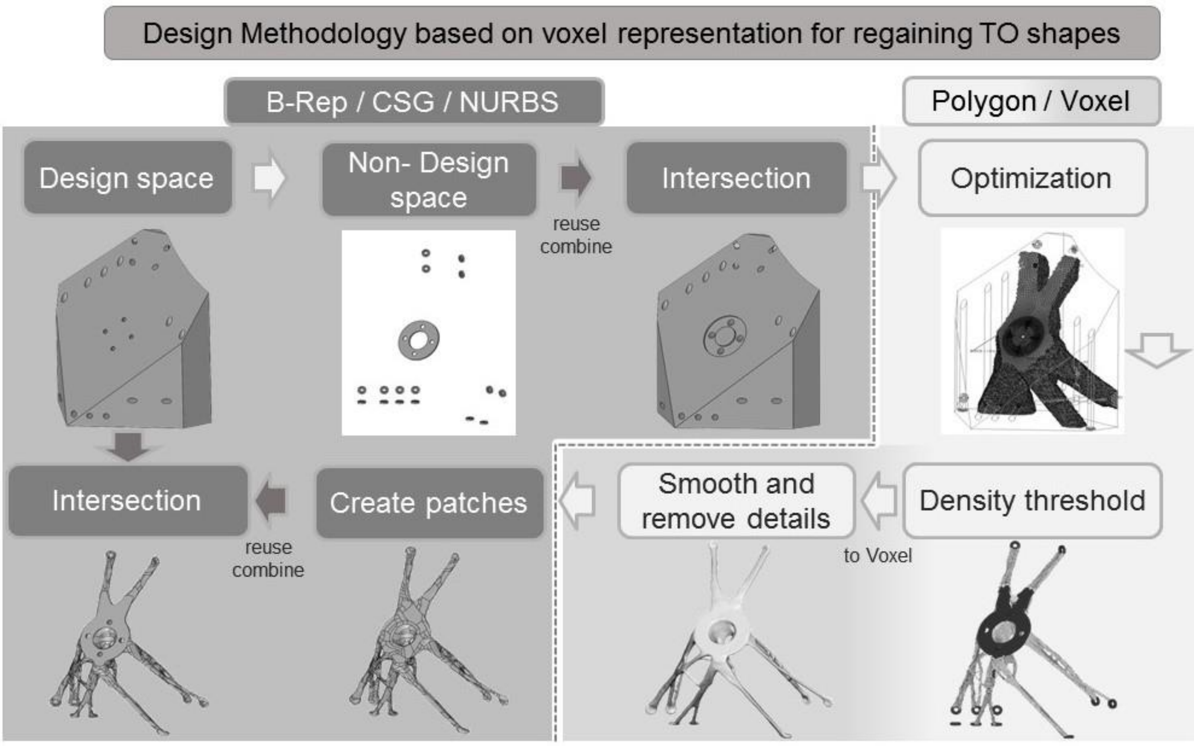


Figure 4: Design Methodology based on voxel representation for regaining

The voxel representation benefits of an inherently closed volume model. The TO-results are exported in a .stl file format that only shows surface elements as typical for stl. The single stl-triangles exactly represent the mesh of the topology optimization. Thereby the stl represents fully closed volumes without surface defects. The following modifications and transformations may cause defects and problems in data. Therefore this working dataset is filled with voxel elements. Henceforth the entire part is represented by fully closed volumes and due to the voxel technique there is no possibility of producing gaps in surface with resulting needed repair work. Furthermore, voxel can be added and removed freely. Thereby it is very easy to add needed struts that may have not been exported with sufficient material, smooth surfaces and optimize transitions between different elements. Details can be removed by smoothing and unclear results as shown in Figure 1 can be defined either as thin walls or low dense structures like lattice structures.

The voxel representation is very good in representing smooth things but it is not capable of showing sharp edges as needed for drilled holes. Therefore in the next step two different approaches have to be considered.

If a comparatively simple part is designed with only less interfaces it might be possible to circumvent this constraint and to design adequate enough surfaces with voxel technique as well. The viable sharpness depends on the chosen voxel size in terms of resolution. For bigger parts a higher resolution has to be chosen because otherwise the model is no longer processible. In this case the voxel model could be retransferred into .stl data and printed directly.

If, as already mentioned above, the part shall be used further in standard CAD tools or there is a need for parametric design of interfaces or special areas of the part, the voxel model is transferred into NURBS. These are processable in standard tools.

For complex optimization problems including inner cavities like hydraulic blocks this is mandatory to adjust the smoothed data as shown in Figure 5. While smoothing it is possible that the additional material needed for smoothing has left the design space and extends into areas where no material is allowed. This can be seen in step 2, 3 and 4 as the hole for mounting was completely closed during smoothing. On the other hand there might be material reduced for smoothing purposes from the non-design space. This can be seen in step 6 comparison. Any grey material can be seen is missing. At the strut there are some elements protruding that have been smoothed away as wished. Though, around the hole there is insufficient material left. Both, insufficient material and protruding material might hamper the correct working of the part and therefore is not permitted. Especially for complex assemblies and application sites with non-design spaces due to moving parts a correct design space is needed to ensure a proper application.

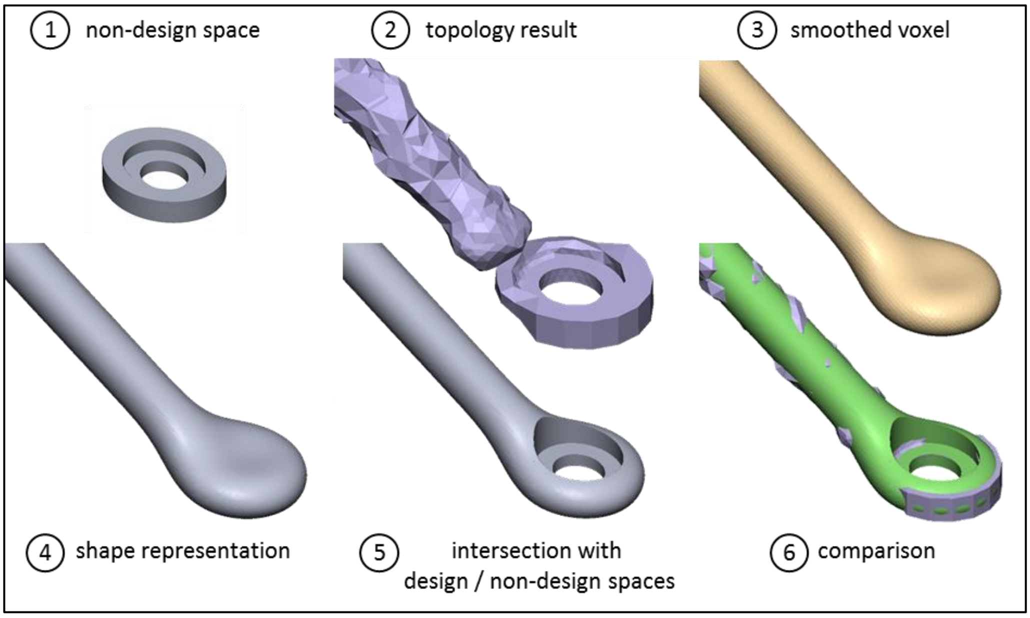


Figure 5: Workflow for combination of smoothed data with design / non-design space

The already existing design and non-design spaces represented by parametrically designed standard features are still available in the standard tools. These are now needed as shown in step 5. By use of Boolean operations on the on hand material can be added and on the other hand material can be removed to adjust and correct the smoothed shapes into usable ones.

Use Cases

Two use cases are chosen for testing and showing of proposed voxel based TO shape regaining methodology: The first one is a structural part used in telecommunication satellites, the second one is again the already mentioned upright for a formula student race car.

The considered satellite part is called "RW-Bracket" and is used to mount a reaction wheel inside the satellite. These reaction wheels can be set into rotation and thereby the satellites orientation is adjusted without using propellant. The overall structure consists of the green main bracket and three smaller blue ones as shown in Figure 6 a). This is mainly due to manufacturability and by AM the two smaller blue ones may be integrated into the Bracket. The third, bigger blue bracket has can't be integrated as it is used for other mounting purposes as well.

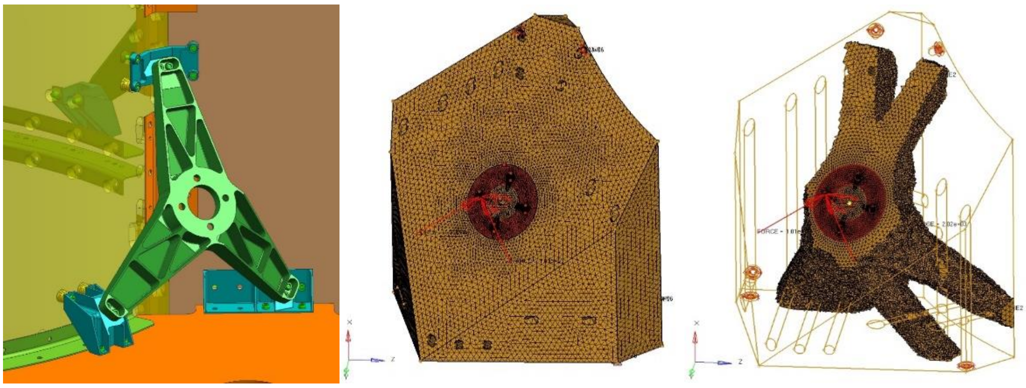


Figure 6: a) Mounted Reaction Wheel-Bracket in Satellite (without reaction wheel) b) design space c) reduced design space in second iteration

For the topology optimization first the maximum design space is defined. The bigger the design space the better the result can be as the material could be distributed best and most voluminous. Figure 6 b) shows the full FE-model including the design space in orange, the non-design space in red and the appearing forces. The non-design space is the interface towards the reaction wheel. The considered material for direct manufacturing is AlSi10Mg. Due to the size of the design space the optimization has to be conducted in two steps. Figure 6 b) shows the second iteration as the design space is reduced massively based on the optimization results of the first optimization. The optimization is constraint for a maximum displacement of 0.1 mm of the center of gravity (CoG) of the RW-Bracket. This is as well the force transmission point as the relevant forces arise from the weight of the bracket during launch. During launch as well the Eigen frequencies are very critical and therefore the bracket is restricted to a minimum first Eigen frequency of 140 Hz.

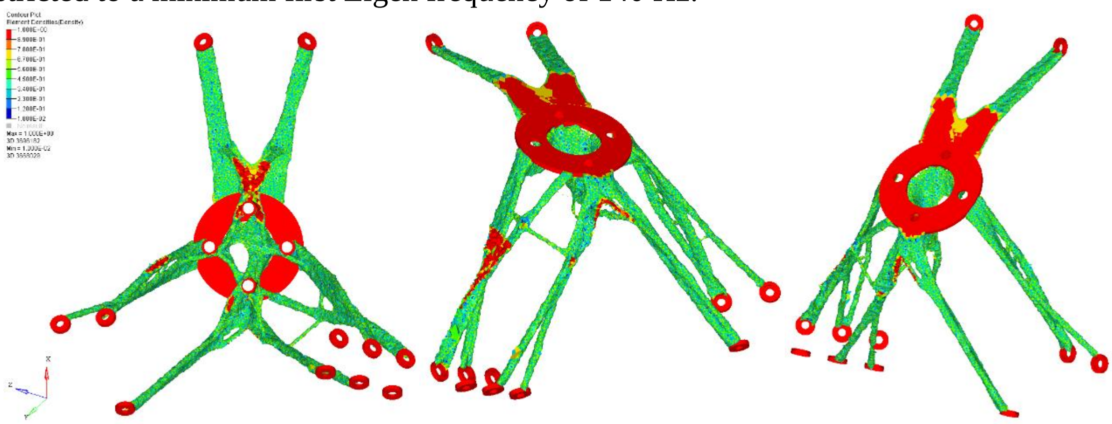


Figure 7: Topology optimization results of RW-Bracket

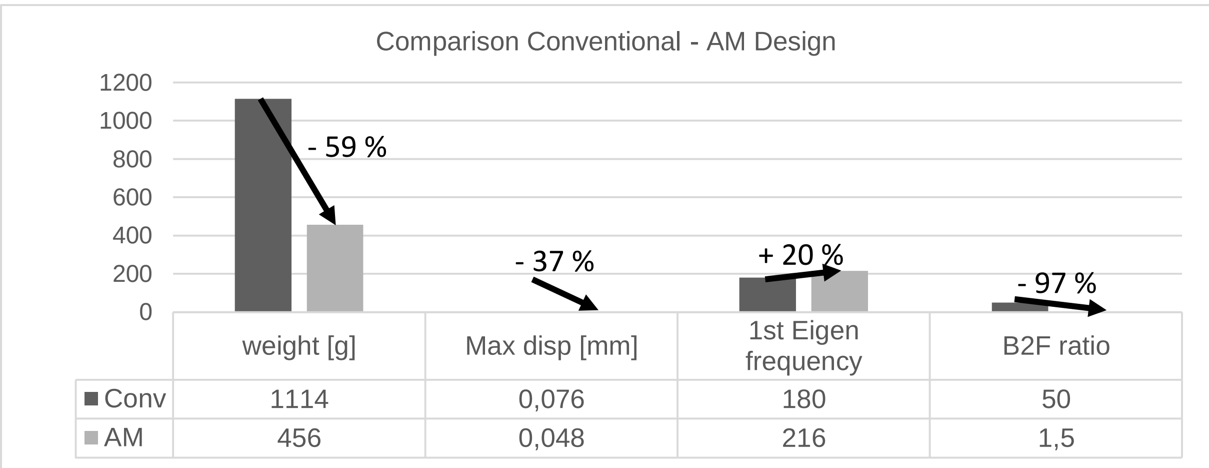
The results with a threshold value of 0.3 are shown in Figure 7. The density and importance of elements is shown by a scale from red (very important, density one) to blue (not important, density zero). Elements with a density less than 0.3 are not shown. The design is mainly driven by thin legs stiffened by small bridges. It can be seen that some of the mounting points are no longer used. Therefore a special investigation was made to ensure the appearing forces at the remaining points are not too high. This shows that the additional smaller brackets are not needed from a mechanical point of view. Producing this design conventionally is nearly impossible.

By use of the proposed voxel based TO-shape regain methodology the results where optimized and adapted and the structure as shown in Figure 8 a) is the final result. By help of topology optimization the weight is lowered by 60%, the displacement is lowered by 37% while the stiffness was increased as the 1st Eigen frequency is increased by 20% as shown in Figure 9. These good results are due to the perfect load adapted design. Figure 8 b) shows a comparison of the conventional and AM design. It can be seen that the structure follows much more direct the force flux from the reaction wheel to the mounting points. In conventional design the three legs are very voluminous but end in a very small area for connection to the smaller brackets. In AM design the voluminous and thereby stiff structure is retained directly to the mounting points. This results in stiffer but lightweight structure.

A further gain is the needed time for shape regaining. For comparison these result were tried to regain with standard CAD tools, even with modern freeform surface tools. Two weeks were spent and a feasible result was not attainable. Beside the very time consuming work the designed shapes were very bad and did not really fit to the optimization algorithms.

On the other hand, the redesign based on voxels is realizable in about one day. For further considerations, especially with regard to tight time schedules as for structural satellite parts, this should be considered.

Figure 8: a) Final RW-Bracket Design b) comparison of conventional and AM design



	weight [g]	Max disp [mm]	1st Eigen frequency	B2F ratio
Conv	1114	0,076	180	50
AM	456	0,048	216	1,5

Figure 9: Comparison Conventional – AM Design RW-Bracket

The second sample part again is the Formula Student racing car upright of this year's car from the University of Paderborn[1] similar to those presented in Figure 3. Though the requirements change during the years depending on the cars concept, the task is very good comparable and thereby the rough results over the years as well.

Over the years the computing resources got very strong. Thereby the shown optimization was done with a very high amount of elements. Hence the results are already very smooth as shown in Figure 10 a). A higher mesh resolution leads to better results especially in surface quality. Although, the described problems like gaps in connectors and unclear results will be the same with high resolution optimizations. Thereby, some details have to be defined. The result of the geometry regain is shown in Figure 10 b). It can be seen that the geometry is very close to the optimization result. With the new methodology the designer is capable to retain the structure and the mechanical principle behind the results. The outcome is a part with a very equal stress distribution over the entire structure with no critical stress risings in sharp notches as all junctions are very smooth.

This result can't be compared to a conventional design as there was no conventional design carried out. For interpretation of the quality of the design the FE-analyzed equal stress distribution can be used. As well, again the short time for shape regaining of about one day is unachievable with conventional design. Similar conventional design of previous years had shown design times of weeks, even without freeform surfaces.

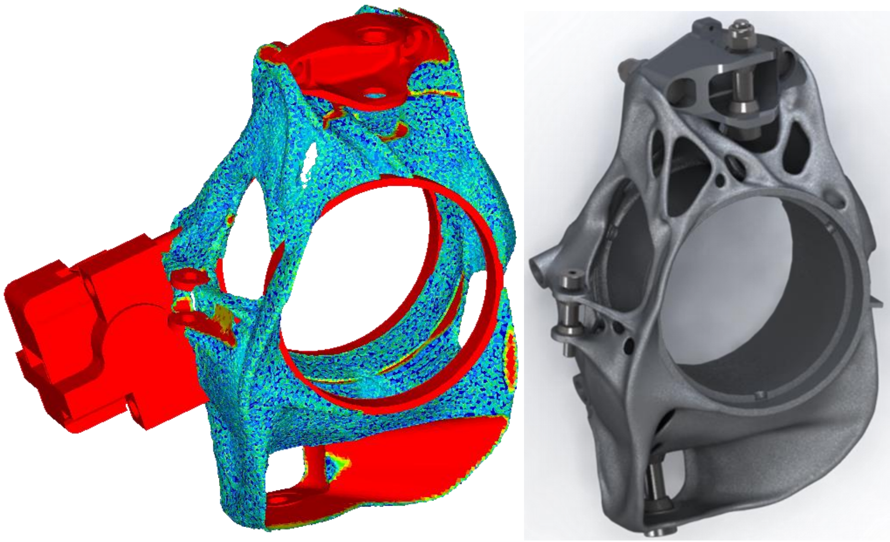


Figure 10: Upright for Formula Student racecar 2015; a) topology optimization result b) shape regain with voxel methodology

Conclusion

Additive manufacturing is a key enabling technology for the optimization of structural parts, topology optimization carries the potential to use this technology in a 'perfect' way. This combination of two strong technologies promises a higher degree of lightweight designs. Though there are some hurdles in regaining the very complex freeform surfaces calculated by topology optimization. Therefore a new methodology for voxel based topology optimization shape regaining is proposed in this paper. This methodology is capable of representing the complex structures most direct and thereby converting a digital material distribution into a clearly defined CAD model with the ability of including parametric elements for interfaces. The resulting structures offer interoperability with conventional CAD tools for parametric

[1] Formula Student is a worldwide design competition for students. Each team designs an open wheeled race car each year. The competition is made to enhance the practical education.

assembly design and for interconnection with conventionally manufacturing machines for post processing of interfaces. They represent the topology optimization results best, with low stress risings, an equal stress distribution and abandonment of unnecessary material. Furthermore very high complex designs are achievable in short time and robust 3D-data can be used in the following process steps.

The methodology was validated by hand of two use cases and the promised benefits can be achieved. Both use cases were set up in a short time with very satisfying results with regard to stress distribution and material savings. As well the actual additive manufactured parts show that the methodology works and it is possible to produce high complex shaped structure elements by use of additive manufacturing.

For gaining optimal additively manufacturable structures there is a clear need to enhance methodologies to gain shapes with low need for support structures in manufacturing process further on. This can be done either in the optimization algorithm or in the following adaption process. Changing the calculated design with regard to support structures will have impact on the degree of optimization with regard to the mechanical requirements but may result in better shapes than manual correction after optimization.

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