INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

FEATURE BASED INTERPRETATION AND RECONSTRUCTION OF STRUCTURAL TOPOLOGY OPTIMIZATION RESULTS

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Abstract

The application of structural topology optimization is a common computer aided method to define the ideal design of a mechanical part. However, the problem remains, that the optimized component in its triangulated surface form cannot directly be used as model in the CAD based product development process. Due to different design aspects (even when using additive layer manufacturing technologies) the result needs to be interpreted and converted into a parametric feature based CAD model. After all, the current standard method is a time consuming, long-winded manual reconstruction.

To put this right, this paper presents a semi-automatic approach to support the design engineer. The tool provides a way to interpret and reconstruct three dimensional topology optimization results as a parametric feature based CAD model. This approach automates the manual proceeding in order to generate a high quality solid CAD part. The functionality is demonstrated in a case study by an optimized and reconstructed motorcycle swing arm.

Keywords: Computational design synthesis, Computer aided design (CAD), Optimisation, Embodiment design

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

Additive Layer Manufacturing (ALM) and individualised on demand production are hot topics in product development. ALM (or 3D printing) affects all important engineering aspects, like lightweight design, production volume, cost and sustainability. This production technology removes a lot of traditional manufacturing constraints and uses significantly less raw material than traditional subtractive machining. In addition cost-intensive tools and casting moulds are no longer required. ALM is perfectly suited for low volume lightweight parts and is already successfully established to manufacture parts for current aircraft generations. According to (Keniston, 2014) it took only two months for an aircraft nacelle hinge bracket from a proposal to its inclusion on an aircraft. Costs and supply lead time dropped by 70%.

On the other hand an ALM based production on demand process enforces a high level of product maturity in the virtual design stage. For lightweight applications the design engineer needs to define a product design which ensures both the given functional requirements as well as an optimal ratio of stiffness to weight. Engineering tools like structural topology optimization allow a fast generation of an optimal initial design that meets these requirements (Bendsoe and Sigmund, 2003). Topology optimization is successfully used for casting parts (Harzheim and Graf, 2005) and delivers its full potential for additive layer manufactured parts (Tomlin and Meyer, 2011). ALM allows a higher design freedom, so most areas of the topology optimized design proposal can be maintained. In spite of the given design freedom, the initial design proposal of topology optimization has to be interpreted and reconstructed in the CAD system to allow an integration of functional or design requirements. (Emmelmann et al., 2014) for example uses CAD interpretation of optimized design proposals to integrate bionic shapes into the resulting design. For this purpose parametric feature-based CAD models are used because of its advantages over the triangulated mesh representations. Predefined parameters and shapes can easily be adjusted by features or modified and updated to new requirements or design aspects, like manufacturing, function, aesthetics or ergonomics.

The current industry standard for conversion of topology optimization results into a feature-based CAD model is the manual reconstruction by a design engineer. This process is suitable for very simple or strongly constrained topology optimization problems, like rotationally symmetric or somehow rectangular shaped parts which are easy to remodel. Complex shapes with the design freedom of ALM parts on the other hand lead to a time-consuming and mostly not very accurate process by using manual reconstruction. A precise reconstruction of the design proposal generated by topology optimization could be reached by using reverse engineering tools for scanning - which is usually not required, because it leads to an exact copy of the design proposal, which in turn leads to a very coarse design. Especially ALM and casting parts should feature a streamlined, somehow bionic, design, which can typically be reached by a manual feature-based interpretation of the topology optimization result. Figure 1 for instance shows a topology optimized valve train rocker arm of a combustion engine and its manually interpreted design. Due to manufacturing and functional restrictions it was not feasible to precisely reconstruct the result but to interpret the shape manually.

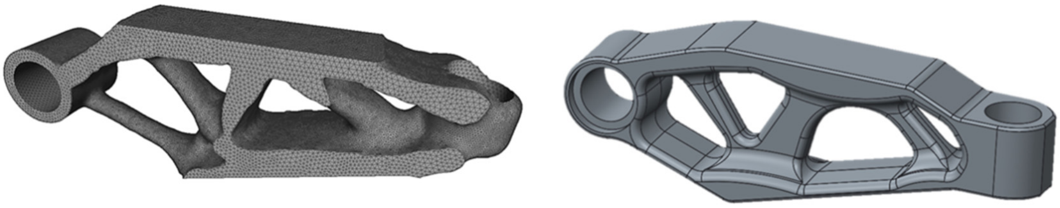

Figure 1. Optimized design proposal and interpreted CAD model of a valve train rocker arm (Stangl et al., 2013)

For these reasons reconstructing topology optimization results by using typical reverse engineering tools cannot be recommended for a productive environment. This paper focuses on bridging the gap between a time consuming manual CAD interpretation and an unwanted reverse engineering by presenting a semi-automatic approach for a feature-based interpretation and reconstruction of three dimensional topology optimization results as parametric CAD model.

2 STATE OF THE ART

A typical proceeding in performing a topology optimization is shown in Figure 2. It is divided into three main steps. During CAD pre-processing the CAD model of the design space is created, which is subsequently used for the optimization step. The optimization itself is also divided into a pre-processing, a processing and a post-processing step.

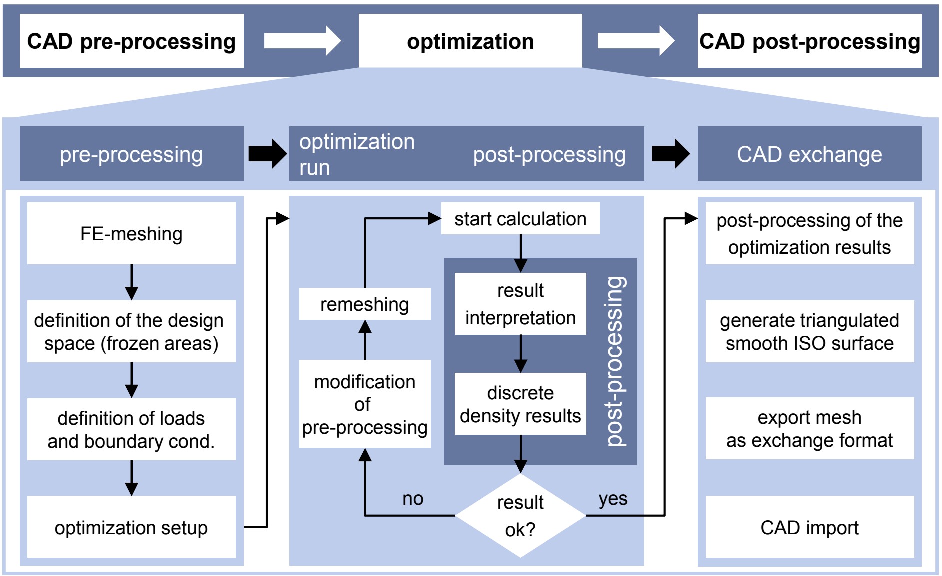

Figure 2. Topology optimization steps based on (Hessel, 2003)

A finite element model is needed for the structural optimization. It is generated by conventional finite element tools and extended by a topology optimization setup. After performing the optimization run, discrete density results are generated during post-processing. The density results represent the optimized shape. During the CAD exchange step, the results are smoothed and exported as triangulated surface meshes. This surface mesh is typically reimported in the CAD environment. The optimization and exportation process is perfectly integrated into industry standard software tool chains. However, the already mentioned reconstruction of a feature-based CAD model has to be performed manually due to the lack of specific tools.

To solve this problem of an automatic or semi-automatic reconstruction, several approaches have been developed. They can generally be divided into two categories: spline surface based and parametric volume based reconstruction methods. Whereas reverse engineering approaches for 3D surface scanning methods can be assigned to both categories, but rather to surface based methods.

The methods presented by (Tang and Chang, 2001), (Hsu and Hsu, 2005) and (Koguchi and Kikuchi, 2006) are all based on a similar surface reconstruction approach. They all involve creating several B-Spline cross sections along one or up to three directions of the world reference frame through the density results or the smoothed mesh. These cross sections are then swept along the corresponding coordinate axis to generate NURBS (Non -Uniform Rational B-Spline) surfaces that represent the optimization result. All methods are able to create CAD surface models of simple beam optimization problems. Nevertheless the disadvantage of these methods is the resulting 3D model itself. A model based on NURBS faces is only a surface representation which is hard to control interactively by the design engineer. Not only the high number of B-Spline cross sections and control points, but also the lack of a typical feature tree does not allow the typical geometry manipulation possibilities a design engineer would expect. This representation is less than ideal for a post interpretation and adaption of the geometry to certain design aspects. It would even be easier to use a mesh processing framework like the one presented in (Möbius and Kobbelt, 2012) and directly modify the triangulated surface of the optimization result, but this approach can neither bypass a manual CAD reconstruction.

Reverse engineering tools for 3D surface scanning applications allow an automated conversion of triangulated surface meshes or point clouds into CAD surfaces and partially into solids. Like investigated by (Kuang-Hua Chang, 2012) automatic feature recognition of these tools only works well for geometric primitives and primitive surfaces - which a topology optimization result rarely includes. Nevertheless these tools need a high level of experience and won’t directly lead to a parametric feature-based CAD model. The reverse engineered surface model can lower the conversion effort but the manual steps for a solid conversion in CAD still remain high.

To include more of the capabilities a feature-based CAD model offers, (Larsen and Jensen, 2009) developed a volume based method for converting topology optimization results into parametric CAD models. This is done by gradually removing material from the CAD model of the design space model. Predefined templates, like sweep and extrude features, are used to remove material at the same position the optimizer does. The sections needed for the features are generated for each spatial direction of the world reference frame. Their methodology was successfully tested for generating parametric CAD models for several optimized beams. However the section generation along the main axes of the optimization result has a great practical disadvantage. Cross-sections of resulting local structures, like single ribs, a design engineer would like to adapt, do not depend on their section. It concurrently depends on the surrounding holes represented by the generated features. Especially by taking complex ALM structures into account, there is a missing link between the essential parameters the design engineer considers and the parameters of the generated CAD features. Additionally the section generation by using the spatial directions of the world reference frame cannot be used to represent undercuts that are readily possible for additive layer manufactured parts. Although the approaches mentioned above provide promising results, the discussed problems prevent a full integration of reconstruction approaches in the CAD based design process and need to be solved.

3 NEW APPROACH FOR FEATURE-BASED RECONSTRUCTION OF TOPOLOGY OPTIMIZATION RESULTS

Instead of using a subtractive modelling process by cutting features away from a base solid, this paper provides a new approach to the design engineer. It allows a semi-automatic CAD reconstruction and interpretation of the optimized geometry from inside out. The idea is to generate a curve-skeleton that represents the topological shape of the optimization result and subsequently using the curves of the skeleton as a reference for an additive modelling process with 3D solid features. This approach is strongly related to the proceeding of a manually interpretation and reconstruction of topology optimization results. Due to the fact that all parameters and references are modifiable during and after reconstruction, the presented approach has the advantage that an adaption of the design is continuously possible. The new approach for a feature-based reconstruction of topology optimization results follows six main steps (Figure 3).

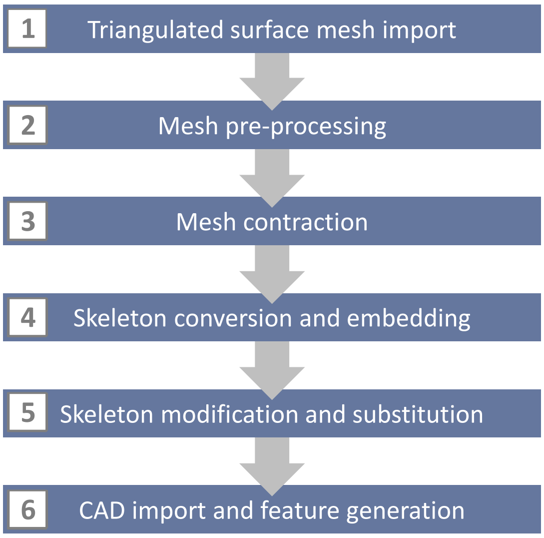

Figure 3. Feature-based reconstruction process

Starting from a typical topology optimization process (section 2) the result is imported as a triangulated surface mesh in an auxiliary application in the first step. This result mesh, which has been generated by the optimization software during the optimization process, is generally meshed with an irregular edge length. The irregularity could be even larger if a data reduction was performed. This means that flat sections or areas with a small curvature are only approximated with a very low number of nodes to reduce the size of the mesh file. The resulting irregular mesh is suitable for a manual reconstruction process, but would lead to poor results using the provided approach. 5000 or more vertices are recommended for the skeleton extraction process (Au et al., 2008). For this reason the surface of the optimization result is consistently remeshed with equilateral triangles in the second step, using the isotropic remeshing algorithm presented by (Botsch and Kobbelt, 2004). The next two steps are essential for extracting the skeleton.

Extensive research on curve-skeleton extraction can be found in relevant literature. Curve-skeleton extraction methods can be classified in two main categories, volumetric and geometric methods depending on the used data representation. Volumetric methods are the pioneer methods. They use a voxelized representation for thinning by iteratively removing boundary voxels or use a discretized field function to determine the voxels of the medial surface that can be converted to a skeleton. According to (Au et al., 2008) and (Sobiecki et al., 2013) volumetric methods all share the same drawbacks. These methods are computationally intensive, numerically unstable and potentially loose details. In contrast geometric methods have the advantage to work directly on polygon meshes or point sets without pre-sampling the data into a volumetric model. Although there are several methods in this category, only the newest and state of the art contraction-based methods are considered for the reconstruction approach. (Sobiecki et al., 2013) compared six recent contraction-based curve-skeletonisation methods against several quality criteria on a set of complex 3D shapes. The method of (Au et al., 2008) performed very well in all criteria. From the design point of view all generated skeletons show a very good topological representation of the input mesh. For this reason Au's method was selected for the provided reconstruction approach.

To illustrate the contraction-based skeleton extraction, a simple double torus (Figure 4) is used in this section. The full reconstruction process is shown during an optimization study of a motorcycle swing arm in section 4.

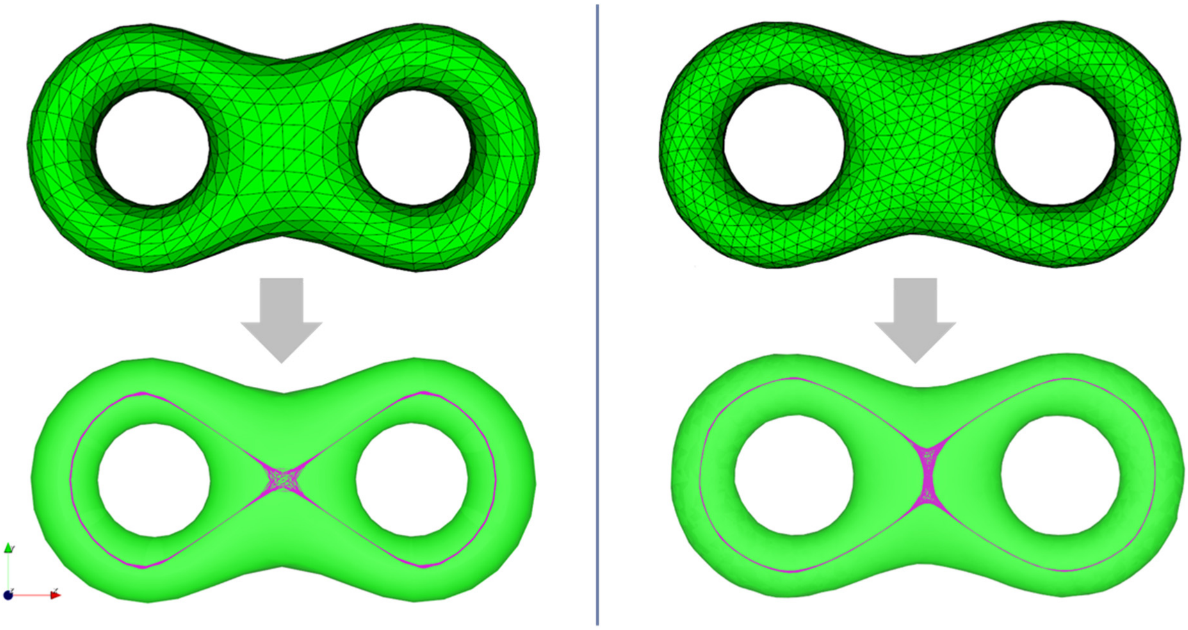

Figure 4. Mesh pre-processing and contraction

Using Au's method the imported surface mesh is contracted into a (nearly) zero-volume skeletal shape in step three by applying implicit Laplacian smoothing with global positional constraints. The mesh contraction retains the topological shape of the original mesh and does not modify the mesh connectivity.

Like shown in Figure 4 the contraction step can clearly be improved by isotropic remeshing of the original mesh e.g. with a target edge length defined to 2% of the bounding box diagonal length. The resulting contracted shape of the remeshed mesh is not only smoother but also matches the topology of the input data significantly better. Visually the contracted shape is a 1D skeleton, but however its connectivity is remains the same as in the original mesh.

In order to convert the contracted mesh into a one dimensional curve skeleton a connectivity surgery process, which was also presented by (Au et al., 2008), is performed in the fourth step. Edge collapses are applied to the contracted mesh in order to remove all faces from the degenerated mesh while preserving the shape of the contracted geometry and the original topology using a cost function. It cannot constantly be guaranteed that the contracted mesh lies within the original geometry or is correctly centred, especially where large differences in the object's thickness occur. Therefore the embedding of the skeleton is also improved in the fourth step. Figure 5 shows the converted skeleton and the improved embedding of the skeleton.

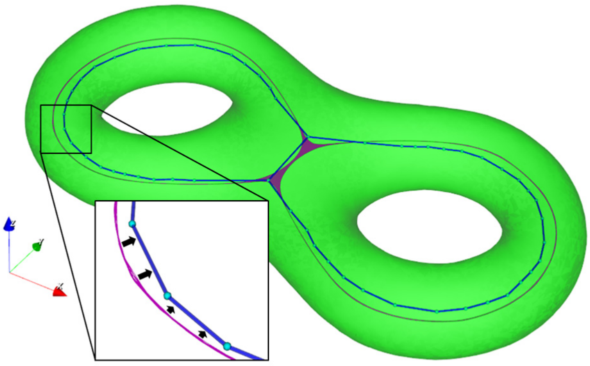

Figure 5. Skeleton conversion and improvement of skeleton embedding

In addition to improve the centeredness, each skeleton node is moved to an approximate centre of its corresponding region of the mesh, which was mapped during the skeletonisation process. (Au et al., 2008) developed their skeleton extraction method mainly for skinning animation. But the skeleton may have a more complex branching structure than the anatomical branching structure of a model. To simplify the branching structure they also presented a merging step for adjacent nodes. This step was not implemented in the reconstruction approach because it falsifies the topology of the optimization result.

Including the fourth step, the feature-based reconstruction approach can be performed fully automatic. For a high-quality of reconstruction and interpretation some user input for modification and substitution of the generated skeleton curves is necessary or advisable in the fifth step. Like shown in Figure 6 for example, it is necessary to delete orphan or undesirable skeleton curves (dotted line) or nodes that are not needed for the CAD reconstruction. Furthermore several skeleton curves have to be combined or substituted by splines.

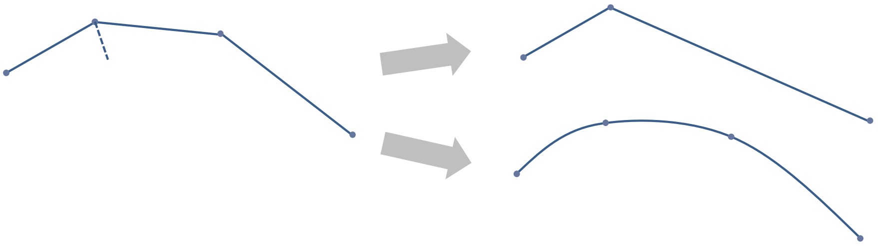

Figure 6. Modification and substitution of the skeleton

For interpretation purposes of the topology optimization result, the auxiliary application currently allows the following user-modification steps to the skeleton:

- Repositioning of skeleton nodes and curves
- Clean-up of orphan or undesirable skeleton curves
- Combination and splitting of skeleton curves
- Substitution of polygonal skeleton curves by splines or straight lines

The last step of the process is the transfer of the user-modified skeleton to the CAD system. This is done via a simple exchange file format. Currently solid sweep and blending features, which are pre-defined as user-defined-features, are inserted into the skeleton curves in the CAD system. The cross sections of the features can be user-selected and are geometrically fitted to the optimized mesh. In the next section, the whole process is presented in detail by a case study.

4 CASE STUDY

4.1 Demonstrator: Optimization of a motorcycle swing arm

To demonstrate the feature-based reconstruction approach in practical use, an optimization study is performed. This study focuses on the front swing arm of a motorcycle (1), shown in Figure 7. The main objective of the topology optimization is to maximize stiffness of the swing arm design, in order to get good driving characteristics, and simultaneously reduce mass for a dynamic acceleration and braking behaviour of the motorcycle.

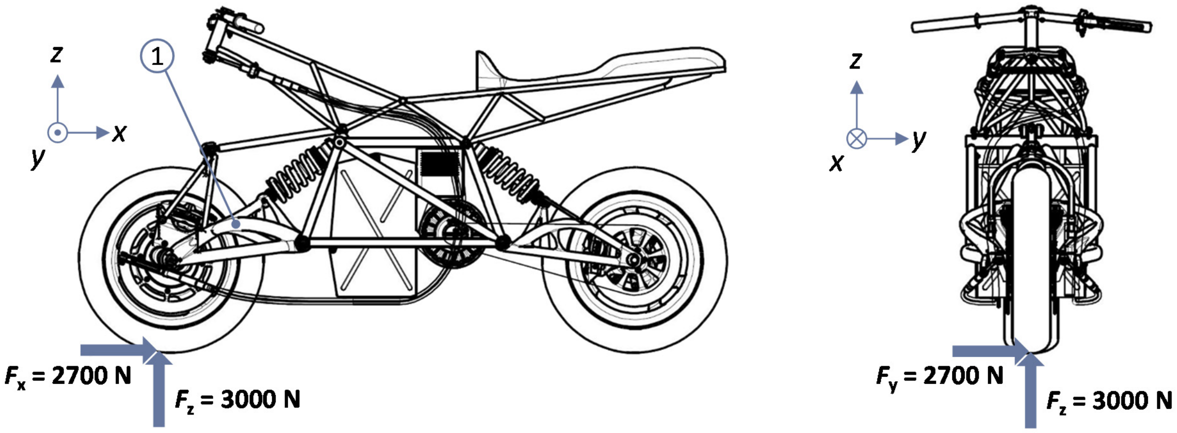

Figure 7. Case study: optimization of a motorcycle swing arm

The relevant load cases for the suspension and chassis design of a motorcycle are the extreme running conditions. With reference to the front swing arm of the presented motorcycle concept, the extreme load case occurs if the driver performs an emergency braking during a turning manoeuvre. The loads for this driving condition (Figure 7, left side) are defined for a heavy rider and include safety factors. Based on the motorcycle load case, a free body diagram can be determined, which is shown in Figure 8 for the design space of the swing arm.

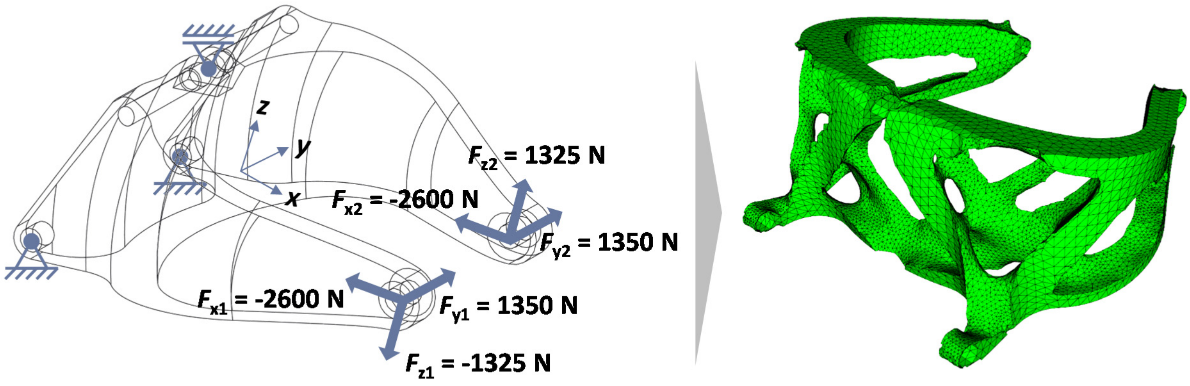

Figure 8. Design space, load case and optimization result

Based on the objective (maximize stiffness), the design space is also maximized, taking surrounding components during motion into account. To define an appropriate finite element model for the optimization step, which reproduces the given situation of the swing arm, the design space is constrained at the chassis bearing holes, like presented in the figure above. Including all loads and a material definition (AlCu4SiMg), the FE-model can be used to define a topology optimization setup using the commercial software suite TOSCA.Structure 8.0. For the use case the objective function of the optimization task is to "minimize weighted compliance of the structure" while not exceeding a given lower volume constraint of 25% of the original design space volume. The asymmetric load case of the swing arm would produce an asymmetric optimization result. To obtain a symmetric geometry, a plane symmetry constraint is applied to the optimization model along the global z-x-plane. As the later component should be designed for manufacturing with ALM, no demold- or other manufacturing-constraints are defined. The optimization job was performed with the sensitivity-based algorithm of TOSCA.Structure. Figure 8 shows the smoothed topology optimization results on the right side, which are exported as a triangulated surface mesh for the reconstruction process.

4.2 Semi-automatic reconstruction of the swing arm

According to the presented approach the optimized surface mesh is imported in the auxiliary application, remeshed, contracted and simplified to a curve skeleton. The embedded skeleton and the contracted mesh inside the optimization result are shown in Figure 9 on left side.

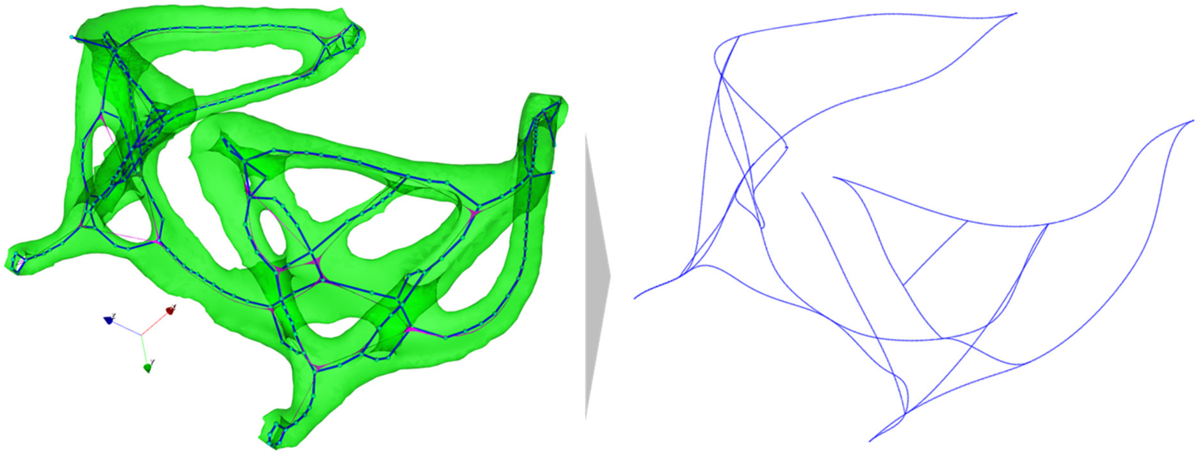

Figure 9. Contracted mesh, embedded skeleton and resulting skeleton

To produce a high-quality feature reconstruction (and interpretation) result, the modification functions of the auxiliary application mentioned above are used to clean-up the generated skeleton. The first step is to delete the contracted curves of the swing arm's bearing points because these areas of the component should be modelled manually in the CAD environment. Furthermore, curves or orphan regions which should not be represented as solid sections in the later CAD model are deleted. The last essential skeleton modification step is to combine the relevant skeleton curves which should be represented by one feature and substitute the polygonal skeleton curves by spline curves. The result of these steps is shown in Figure 9 on the right side. This user-modified skeleton is transferred for feature insertion into the CAD environment.

The feature insertion process is performed by using swept blend features, which generate a solid volume by a combined sweeping and blending of multiple cross sections along a middle line. Currently the swept blend features are pre-defined with a starting and end cross section as user-defined-features (UDF) that accept a middle line reference. For a CAD model the dimension of the cross sections can be controlled by parameters. For the swing arm model UDFs with elliptical cross sections are used. Figure 10 shows the insertion of the swept blend UDFs and the reconstructed model.

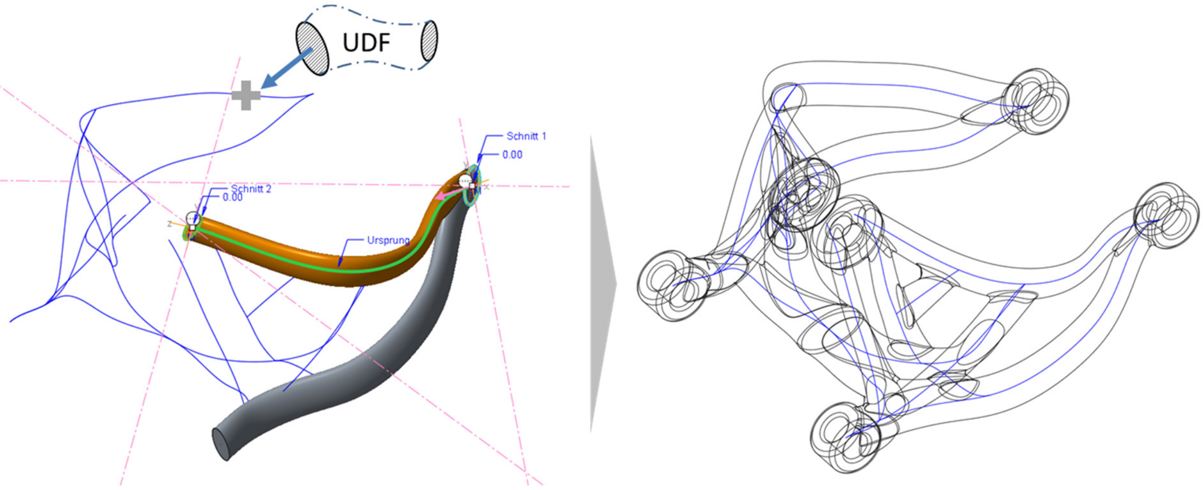

Figure 10. Insertion of solid features on the skeleton segments and reconstructed model

At the current state of the implementation, the dimension of the beginning and end cross section of the feature is fitted by a middle value determined by the skeleton-mesh mapping, which was generated during the mesh to skeleton conversion process (see section 3). As the inserted features are only referenced by the global defined skeleton lines, the model remains fully modifiable like a manually created parametric CAD model. After the insertion of the main solid features further finishing of the model, e.g. by adding fillets and bearing holes has to be done manually by the user.

4.3 Comparison of the reconstruction results

During the case study the mesh of the optimization result was not only reconstructed using the presented approach. It was also manually interpreted and reconstructed by a designer without knowledge of the presented reconstruction approach. The resulting CAD model is shown in Figure 9 on the left side, the model reconstructed with the presented semi-automatic approach on the right side. To enable a comparison between the two models, elliptical cross sections were used for both reconstruction strategies.

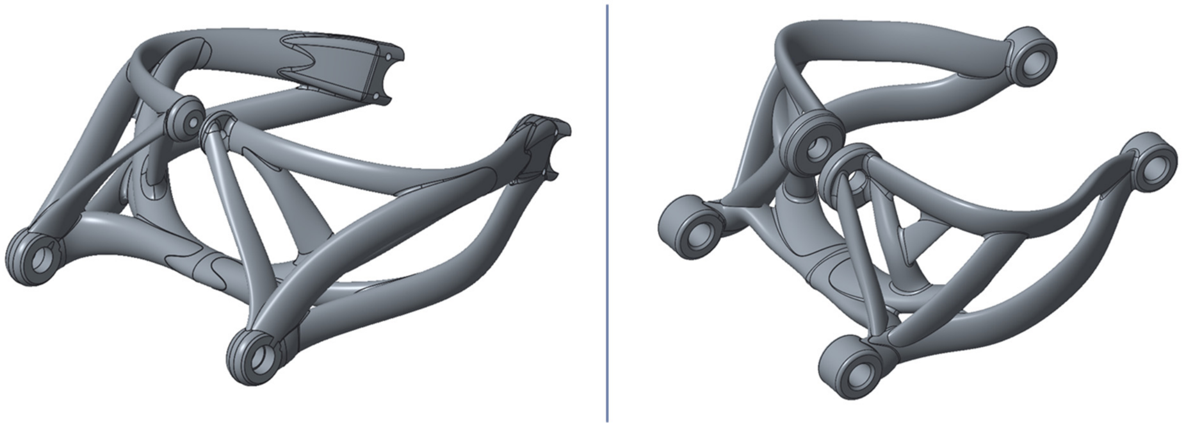

Figure 11. Manual interpreted CAD model vs. semi-automatic reconstructed CAD model

Compared to the optimization result (Figure 8) the left model has been reconstructed with a higher design freedom: Transitions between different trajectories of the component were relocated. Moreover smaller bars have not been reconstructed by the design engineer. Furthermore the dimension of the cross sections are slightly small compared to the optimized geometry. The right model seems to be a more accurate reproduction of the optimization result but imitates an amount of design flexibility a design engineer would consider during a manual interpretation. The main difference between the two strategies is the significant reduction of the required time to interpret and reconstruct the model: It took about three work days to interpret and reconstruct the optimization result manually. The most time-consuming step was the manual creation of the references for the features. In contrast, it took only half a working day (several iterations were needed to simplify and substitute the curve skeleton) to reconstruct the swing arm using the semi-automatic reconstruction approach.

5 SUMMARY AND OUTLOOK

This paper presents an approach which allows a semi-automatic feature-based reconstruction and interpretation of three dimensional structural topology optimization results. It has been shown on the basis of a case study that the proposed approach can be fully integrated as intuitive and time saving interpretation tool in a productive environment. In contrast to other methods the presented approach allows a user-modification or post-interpretation in every single design step. Furthermore the reconstruction process imitates the manual proceeding and the generated features put parameters a designer would consider into account. Thus the result of the reconstruction process is a high-quality parametric feature-based CAD model. Compared with an exclusively manual reconstruction strategy, the main advantages are the significant time savings, the more accurate reconstruction and a more independent design process on the individual experience of the design engineer. The presented approach is currently being advanced - especially the insertion of features. To offer higher design flexibility, further machining features, like rotational or blending features and a wider choice of feature cross-sections will be implemented. For sweeping and blending features the number of feature cross sections will be selectable. Another further development concerns the analysis of the mapping between the 1D skeleton and the original mesh. The purpose is to benefit from the mapping not only to dimension the cross sections geometrically, but to determine mechanical replacement values for the selected cross sections, like area moments of inertia. In order to extend the field of application and take constraints given by classical manufacturing methods, like welding, casting or forging into account, further development and testing will be realized.

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ACKNOWLEDGMENTS

The authors thank FE-DESIGN for supporting this research by providing the optimization software TOSCA free of charge.