MULTI-COMPONENT TOPOLOGY SYNTHESIS FOR POWDER BED ADDITIVE MANUFACTURING

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ABSTRACT
Topology optimization for additive manufacturing has been limited to designing parts smaller than the printer's build volume. To enable the design of structures larger than the printer's build volume, this paper presents a gradient-based multi-component topology synthesis for designing structures assembled from components made by powder bed additive manufacturing. The manufacturing constraints on the maximum allowable build volume (which is limited by the machine specification), the elimination of enclosed holes (which will trap un-melted powders inside), and the minimum printable feature size are modeled and incorporated in a gradient-based multi-component topology optimization framework. As a result, the manufacturability of each constituent component is satisfied. Numerical results of multi-component topology designs optimized for the minimum compliance subject to powder bed additive manufacturing constraints are presented. The resulting multi-component designs unlocked richer design space for early-stage topology exploration.

INTRODUCTION
Additive manufacturing is a class of manufacturing processes that produce structures by adding layer-upon-layer of materials. It is capable of fabricating structures with complicated shapes, which can be difficult, if not impossible, for traditional manufacturing processes. Additive manufacturing shares with topology optimization a similar trait that facilitates innovative designs through the relaxation of constraints on component geometries. Topology optimization therefore has become an effective tool for designing structures made of additive manufacturing [1–3].

Although additive manufacturing is more flexible than traditional processes in terms of what shapes can be made, there are still certain restrictions. First, a component cannot be made if it physically exceeds the printer's maximum allowable build volume. The build volume is defined as the maximum size (in length, width and height) of an object that an additive manufacturing machine can produce. For powder bed processes, the build volume restriction is rather significant due to their strict powder bed size limits. This restriction has limited their applications to produce relatively small parts. A second design guideline is that enclosed holes should be avoided. Because the un-melted powders trapped inside of any enclosed holes cannot be removed from the component once it has been built. Finally, the minimum feature size determined by the machine’s minimum printable feature size should be explicitly controlled.

If structures are designed in the multi-component manner, the design freedom dramatically increases thanks to the new interpretations of manufacturing restrictions. For example, a structure exceeding the maximum build volume, which cannot be made as a single piece, can now be produced as an assembly of multiple components. A multi-component structures with “global” hollow features can now be manufactured as well, as long as each constituent component has no “local” enclosed holes therein. These new interpretations of manufacturing restrictions unlock the possibility of designing structures with more complex geometry and better performance, taking full advantage of the benefit of additive manufacturing and topology optimization. Conventionally, the component decomposition is
often treated as an arbitrary manual decision after the overall structural design is complete. The method presented in this paper intends to realize the simultaneous optimization of the overall structural design and component decomposition for structures assembled from additively-manufactured components.

DESIGN FIELD

There are two layers of design fields, as shown in Fig. 1. The first layer is the density field $\rho$ as a common field for all components, which describes the overall base topology. The second layer is the membership vector field $m = (m(1), m(2), \ldots, m(K))^T$ where $K$ is the prescribed, maximum allowable number of components. $m(k)$ is the fractional membership of a design point in the design domain to the $k$-th component. Both $\rho$ and $m(k)$ can take continuous values ranging between 0 and 1. All design fields were regularized with the PDE-based filtering and the Heaviside projection following [4]. In order to ensure the unique selection of the component for each design point, an additional important criterion needs to be satisfied at the end of optimization. The membership to only one component converges to 1 while the memberships to all other components converge to 0. The discrete material optimization (DMO) method was used in this paper to satisfy this criterion.

MANUFACTURING CONSTRAINT MODELING FOR POWDER BED ADDITIVE MANUFACTURING

Manufacturing constraints for the maximum build volume and the elimination of enclosed holes are modeled. Both constraints are applied at the component level. For most existing manufacturability-driven topology optimization, manufacturing constraints have always been applied at the overall base topology level.

Maximum allowable build volume

The build volume of a powder bed additive manufacturing machine is usually given as a machine specification, defined by its maximum allowable length, width, and height. In the computer graphics community, there are works discussing partitioning 3D printable parts based on a specified maximum build volume limit [5,6]. However, these works only dealt with partitioning of given geometries. Also, the partitioning was treated as discrete problems, and often solved by heuristic non-gradient optimization methods.

To compute each component’s bounding box sizes, the oriented bounding box (OBB) is used following [7,8]. Bounding box axial directions can be extracted by a weighted principal component analysis, which will determine the orientation of the bounding box. The size of the bounding box is computed through the maximum approximation of all projected slack locations.

Elimination of enclosed holes

For conventional, single-piece topology optimization, the virtual temperature method has been proposed to generate simply-connected structures [9,10]. However, when enclosed holes are not allowed in the entire single-piece structure, the use of topology optimization becomes somewhat questionable, since the advantage of topology optimization over the sizing and shape optimization is its capability for adding (and removing) holes and exploring shapes with different connectivity.

To eliminate holes enclosed within each component, the virtual temperature method is generalized, to make it applicable to multi-component topology designs. Instead of prohibiting enclosed holes in the entire single-piece structure, the generalized constraint only prevents hole formation within each component.

OPTIMIZATION FORMULATION

The multi-component topology optimization for additive manufacturing problem is formulated as the minimization of structural compliance subject to constraints on the volume fraction, the maximum allowable build volume, and the absence of enclosed holes for each component. As demonstrated in Fig. 2, a design domain $D$ is chosen so that loads and boundary conditions can be applied. Then the problem is defined as finding the optimal material distribution and component decomposition simultaneously within $D$. Suppose that A (in blue) and B (in red) in Fig. 2 are two components, for instance, this particular decomposition is infeasible, since component A does not satisfy the enclosed hole constraint while component B does not satisfy the build volume constraint (assuming the dot rectangle is the prescribed, maximum allowable build volume).
The overall optimization formulation can be summarized as follows:

\[
\begin{align*}
\text{minimize} & \quad F \\
\text{subject to} & \quad \int \rho \, d\Omega - \bar{V} \leq 0 \\
& \quad \rho \in [0, 1]^D \\
& \quad \text{for } k = 1, 2, ..., K: \\
& \quad l^{(k)} - \bar{L} \leq 0 \\
& \quad w^{(k)} - \bar{W} \leq 0 \\
& \quad h^{(k)} - \bar{H} \leq 0 \\
& \quad t_{\text{max}}^{(k)} - \bar{T} \leq 0 \\
& \quad m^{(k)} \in [0, 1]^D 
\end{align*}
\]

where \( F \) is the structural compliance objective; \( \rho \) and \( m^{(k)} \) are the density and membership design field; \( K \) is the prescribed, maximum allowable number of components; \( \bar{V} \) is the volume fraction constraint limit; \( l^{(k)} \), \( w^{(k)} \) and \( h^{(k)} \) are the approximate oriented bounding box length, width and height for component \( k \); \( \bar{L} \), \( \bar{W} \) and \( \bar{H} \) are the build volume length, width and height constraint limits; \( t_{\text{max}}^{(k)} \) and \( \bar{T} \) are the approximate maximum temperature for component \( k \) and its constraint limit for the elimination of enclosed holes manufacturing constraint using the generalized virtual temperature method.

The nonlinear, constrained optimization problem in Eq. (1) was solved by the method of moving asymptotes [11]. The sensitivity analysis followed the standard adjoint method and was implemented using COMSOL Multiphysics.

**NUMERICAL RESULTS**

**2D cantilever**

To show the multi-component topologies optimized for different prescribed build volume limits, a cantilever example was used. Its design domain \( D \) and boundary condition settings are presented in Fig. 3(a). The maximum allowable number of components was set as \( K = 4 \). The volume fraction constraint limit was set as \( \bar{V} = 0.5 \).

Figure 4 presents four designs with different prescribed build volume limits. Their maximum allowable build volume (defined as rectangles in this 2D example) is presented in Figure 4(e). Topology (a) was generated by conventional, single-piece topology optimization where a rectangle in the size of its initial design domain (2 by 1) was needed to cover the entire geometry. By prescribing the maximum allowable build volume as \( \bar{L} = 1.5 \) and \( \bar{W} = 0.6 \), a three-component topology (b) was obtained. The outcome number of components was less than the maximum number allowed as one of the components became unused. It demonstrated the robustness of the formulation that the outcome number of components could converge to a number different from the prescribed \( K \). This was not the case for topology (c) where the prescribed build volume was too small to have a three-component design with sound structural performance. Therefore, a four-component design was generated with the prescribed limit set as \( \bar{L} = 1.0 \) and \( \bar{W} = 0.4 \). Finally, a narrow build volume was set as \( \bar{L} = 2.5 \) and \( \bar{W} = 0.3 \) for the case of topology (d). For all multi-component designs (b-d), there were no enclosed holes in any decomposed component. However, the conventional, single-piece design (a) had four enclosed holes, which did not satisfy the powder-bed additive manufacturing constraints. The four designs had different base topologies in order to satisfy the corresponding prescribed build volume limits while maximizing their structural performance.

**3D simply-supported center loading**

To demonstrate the proposed multi-component topology synthesis applied to a 3D problem, a simply-supported center loading example was used. Its design domain and boundary condition settings are presented in Fig. 3(b). The maximum allowable number of components was set as \( K = 3 \). The volume fraction constraint limit was set as \( \bar{V} = 0.3 \).
For comparison, conventional topology optimization (without manufacturing constraints) was used to generate the single-piece result, as shown in Fig. 5(a). Due to the symmetry, only a quarter design domain was optimized. An enclosed hole was generated in the middle of the optimized structure. According to the powder-bed additive manufacturing constraint, un-melted powders will be trapped inside, and cannot be removed from the component once it is built. It has also previously been reported that for ultra-high resolution topology optimization results, many local hollow features can appear [12]. The build volume required for this part is equal to its initial design domain bounding box (2 by 2 by 1).

The multi-component topology shown in Fig. 5(b) was optimized in the full design domain without applying any symmetry boundary conditions. A smaller and narrow rectangular build volume limit of $L = 3.0$, $W = 1.2$ and $H = 0.8$ was specified. By slicing the larger blue component, it can be seen that there is no enclosed hole inside. Therefore, its overall base topology is different from that of the single-piece topology in order to satisfy the prescribed build volume limit and the elimination of enclosed holes manufacturing constraints.

CONCLUSIONS

This paper presented a multi-component topology synthesis for designing structures assembled from components made by powder bed additive manufacturing. The weighted principal component analysis was used to limit the size of each component to be kept within the prescribed, maximum allowable build volume limit. To avoid the formation of enclosed holes in each component, the generalized virtual temperature method was implemented. The minimum length scale was controlled by the design field regularization.

Both 2D and 3D examples were discussed for compliance minimization multi-component topology designs subject to powder bed additive manufacturing constraints.

REFERENCES


