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Topology Optimization for DfAM with Build Area Constraints

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***Abstract*—** The ever-increasing demand for lightweight and structurally efficient components and assembly-based systems has led the aerospace industry to adopt computational tools and additive manufacturing (AM) techniques to advance their designs. Compared to traditional manufacturing methods, AM enables the production of components with complex geometries whose material layout is optimized using topology optimization. Despite this advantage, design for additive manufacturing (DfAM) methods remain underdeveloped. Currently, most DfAM methods are limited to redesigning components that fit within the build volume of an AM machine. The objective of this work is to introduce a novel method that incorporates AM build area constraints with movable partitioning rectangles.

A case study is performed on a cantilever beam example as a proof-of-concept for the proposed approach. Preliminary results demonstrate the efficacy of the optimization scheme in decomposing a structure into components that satisfy the geometric limits of the AM build plate, while minimizing the structural impact of joints in the decomposed design.

This work introduces a novel TO-oriented DfAM method used to redesign two-dimensional structures that do not fit on an AM build plate, by decomposing it into several components. Successful development of this optimization method will allow aerospace engineers to generate lightweight and structurally efficient assembly-based systems that better satisfy AM machine capabilities.

Keywords- DfAM, topology optimization, additive manufacturing, build area constraint, 3d printing, feature optimization

I. INTRODUCTION

Over the last few years, aerospace engineers have turned to computational tools and additive manufacturing techniques to further advance their designs to reach new structural performance heights. Topology optimization is a numerical tool used to determine where material should exist within a design space to obtain the best structural performance [1]. Additive manufacturing is widely adopted with TO tools to exploit its design freedom and produce high performing structures that would otherwise be unattainable with conventional manufacturing processes.

Despite the benefits of AM, the maximum allowable length, width, and height of an AM machine limits the structures that can be redesigned for AM. Many TO for DfAM methods have been proposed over the last few years to impose design requirements to satisfy AM system performance limitations. However, these studies have mainly focused on the development of single component redesign and consolidation design methods for components that fit within the AM machine [2]. To produce the airbus Light Rider frame shown in Fig. 1, the topology optimized design needed to be partitioned into components to be manufactured using AM. However, no mathematical approach was used to decompose the structure into components that satisfied the AM build volume requirements. The development of part decomposition methods for DfAM, a method of splitting a single component into several parts, is crucial to overcome this obstacle.

One existing approach uses the Multi-Component TO (MTO) framework to obtain optimized structures made of several components that satisfy the maximum AM build volume [3]. This method uses an element-wise design variable (DV) method to simultaneously optimize the material layout and design of components. However, this method can be computationally expensive with large models and does not account for the structural impact of including joints in the assembly, which can result in the generation of unsatisfactory designs.

The objective of this work is to introduce a novel method that incorporates AM build area constraints with movable geometric features, referred to as partitioning rectangles in this paper. The idea is to use the geometric representation of the partitioning rectangles in the problem formulation to determine the best position for the partitioning rectangles to decompose the structure, such that each component satisfies the AM limitations. This method, which optimizes the explicit geometric parameters of features that are mapped onto a fix

Figure 1: Airbus Light Rider manufactured with AM in separate components [4].

grid, has been termed as feature optimization by Wein et al. Refer to their review paper for a thorough explanation on feature-mapping and a detailed review of existing studies that use this methodology [5]. This solution method has the potential to reduce the computational burden associated with the MTO framework, as well as generate structurally efficient solutions that consider joining methods.

The paper is organized as follows: Section II describes the basic idea of the proposed methodology. Then Section III presents and discusses the effectiveness of the methodology by evaluating the results obtained on a cantilever beam. Finally, Section IV discusses main conclusions for the current work.

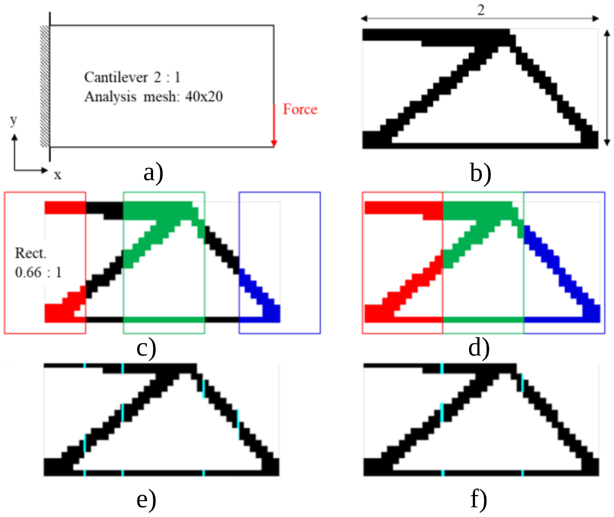
II. METHODOLOGY

A. *Overview*

The proposed method is divided into two subproblems. First the topology design of a structure is optimized. Second the layout of the partitioning rectangles in the design is optimized for structures larger than the AM build area. For simplicity, this paper only considers the translation of the center x-coordinate of each partitioning rectangle as a designable variable. By splitting the approach into two subproblems, the behavior of the latter method can be isolated and studied more closely. Figure 1 demonstrates the basic idea behind this methodology.

B. *Build area constraints via partitioning rectangles*

Partitioning rectangles are used to directly control the size of each component in the structure so that each comply with the AM machine build plate limitations. This is done by setting the length and width of each partitioning rectangle to correspond to the maximum allowable build area on the AM machine. Using the example in Fig. 1, the area of the AM build plate is $\frac{1}{3}$ the size of the cantilever beam. Therefore, three partitioning rectangles are initialized on the design space to satisfy this constraint, as shown in Fig. 1c.



a) b) c) d) e) f)

Figure 2: Basic idea of proposed methodology. a) cantilever beam example, b) topology optimized results, c) initialized partitioning rectangles for feature optimization, d) possible result after feature optimization, e) and f) representation of joints at partitioning rectangle edges.

Fig. 1d demonstrates a potential result after optimizing the x-coordinate location of each partitioning rectangle. Note all structural elements, identified with black, fall within a partitioning rectangle identified in red, green, and blue. This means that the structure is fully decomposed, and each component can be manufactured using the AM machine.

C. *Joint model*

The edges of the partitioning rectangles represent the partitioning lines that splits the structure into parts that fit inside the AM machine. Joints are modelled at the partitioning rectangle edges to model the structural impact of assembling a multi-component system. This is demonstrated in Fig. 1e and 1d where the structural and joint material elements are represented with black and blue, respectively.

D. *Problem formulation*

The problem statement for topology optimization is based on a minimum compliance problem subject to a volume fraction constraint. For density-based optimization with solid isotropic material with penalization, the design variables are the elemental densities. For feature optimization, the design variables are the centroid x-coordinate positions for each partitioning rectangle. The problem formulation for feature optimization can be mathematically expressed as the minimization of compliance subject to a decomposition constraint. The objective function drives the optimization scheme to find the optimal position of each rectangle such that the structural impact of joints on the overall performance is minimized. The decomposition constraint is developed to ensure that all the structural material falls inside a partitioning rectangle.

III. CANTILEVER BEAM EXAMPLE

A. *Model Setup*

A 2D cantilever beam example is used to demonstrate the capability of the proposed methodology. The design domain, boundary condition, and loading condition is shown in Fig. 3. It is assumed that the structural material is isotropic with the Young’s modulus, density, and Poisson’s ratio chosen to be that of steel. For feature optimization, the joint material properties are taken to be 15% weaker than the structural material properties. The topology and feature optimization problems are solved using an in-house computational tool that interfaces with an FE analysis software. The well-known MMA optimizer is employed to solve both subproblems.

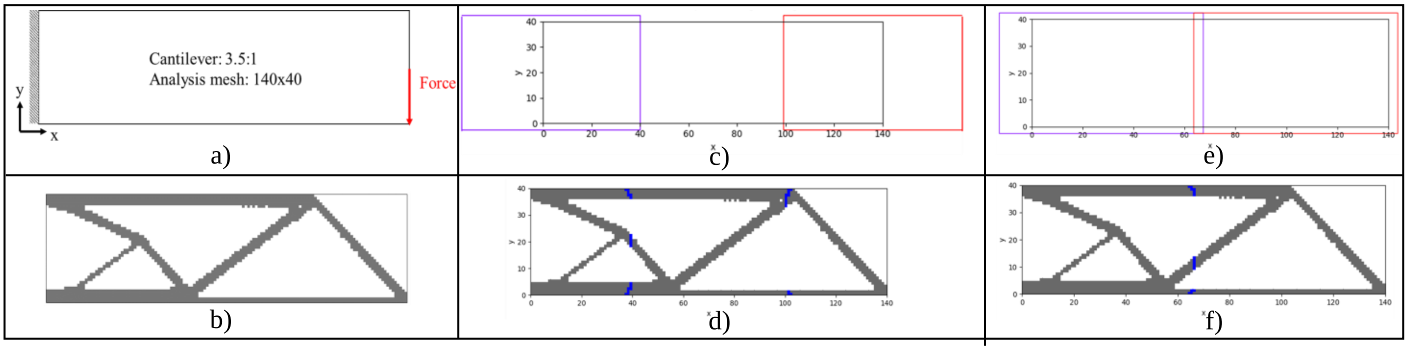


Figure 3: Topology and feature optimization results on cantilever beam. a) cantilever beam example with a 140x40 FE mesh, b) TO result for a 30%VF steel cantilever beam, c) explicit parameters of partitioning rectangles at iter 0, d) result at iter 0, e) explicit parameters of partitioning rectangles at iter 16, f) optimal result at iter 16.

Fig. 3b shows the topology optimized structure to be used for feature optimization. This results in a structure with compliance of 1108.28 J and 30% volume fraction. The feature optimization problem corresponds to a minimum compliance problem subject to a 0.5% decomposition constraint. A small constraint value is chosen to aid with convergence as it allows 0.5% of the structural mass to fall outside of a partitioning rectangle. The following section discuss the results obtained in two simple case studies:

B. Results and discussion

To study the effectiveness of the proposed methodology, an AM build plate constraint of 0.57 is used. Therefore, two partitioning rectangles are initialized with a width and height of 80x45 to satisfy this limitation. The height of the rectangles is set to be greater than 40 to avoid placing unwanted joints at the top and bottom edges of the design domain. The initial centroid x-coordinate positions for the partitioning rectangles are 0.01 and 139.99. The initial explicit parameters for the partitioning rectangles are demonstrated in Fig. 3c. In this design, the purple rectangle is set to have precedence over the red rectangle. This is setup to avoid the use of overlap constraints. The post-processed result of mapping the partitioning rectangle edges onto the fixed grid is shown in Fig 3d.

The optimized result for the proposed methodology is shown in Fig. 3e and 3f. The optimal position of rectangles 1 (purple) and 2 (red) are 27.28 and 107.22, respectively. The structure is decomposed into two parts, each with similar dimensions of approximately 70x40 satisfying the build area constraint. Joints (shown in blue) are placed between both structural components (shown in grey). It is worth noting that the number of design variables using this approach is only 2, which is a significant reduction from the number of DVs required with an element wise DV method.

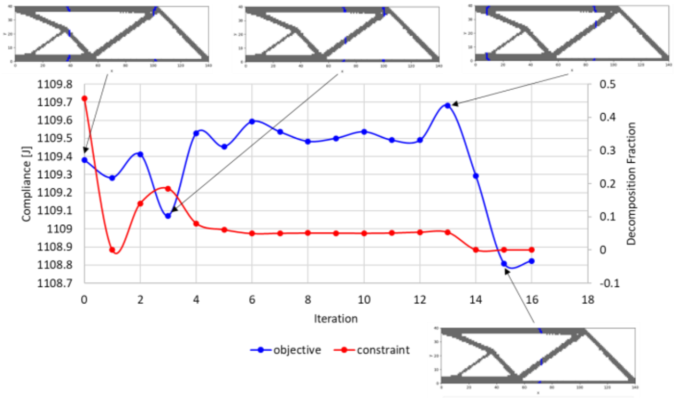


Figure 4: Function value history plot

The iteration history of the objective function and the constraint function are plotted in Fig. 4. The values converge after 16 iterations with an optimal compliance value of 1108.82 J. The compliance of the structure increased by 0.045% with the consideration of joints. While this affects the structural performance of the structure, the designer obtains a result that can be manufactured using the AM machine. Further, it can be observed that the objective value is unstable throughout optimization. This is due to the appearance of more/less joints as the partitioning rectangles move from one section of the beam to the next, where more/less structural material is converted to joint material properties.

IV. CONCLUSION

This paper presents an overview of the proposed TO for DfAM method that incorporates AM build area constraints to the TO problem by using movable partitioning rectangles. In this approach, the x-coordinate position of each partitioning rectangle is optimized to describe the decomposition and distribution of joints within the structure. The use of these features reduces the number of design variables required for optimization. This solution method has demonstrated the potential to generate structurally efficient multi-component designs that satisfy AM build plate limitations, while considering the structural implications of including joints. The benefits of allowing the partitioning rectangles to move, rotate, dilate, and shrink will be presented in future works.

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