AN OPTIMIZATION BASED DESIGN FRAMEWORK FOR MULTI-FUNCTIONAL 3D PRINTING

D. Brackett, A. Panesar, I. Ashcroft, R. Wildman, R. Hague

Faculty of Engineering, University Park, The University of Nottingham, NG7 2RD, UK

Abstract

This work investigates design analysis and optimization methods for the integration of active internal systems into a component for manufacture using multi-material 3D printing processes. This enables efficient design of optimal multifunctional components that exploit the design freedoms of additive manufacturing (AM). The main contributions of this paper are in two areas: 1) the automated placement and routing of electrical systems within the component volume and, 2) the accommodation of the effect of this system integration on the structural response of the part through structural topology optimization (TO). A novel voxel modeling approach was used to facilitate design flexibility and to allow direct mapping to the 3D printer jetting nozzles.

1 Introduction

This paper presents and evaluates a framework for the design of multifunctional components to be made using additive manufacturing (AM) multi-material processes. By definition, a multifunctional component must have multiple uses, such as structural and electrical functions. An example of this is a structural health monitoring component such as that shown in Figure 2. While processes capable of physically realizing these components are still under research, a variety of techniques have been proposed, primarily using stereolithography and direct write / print technologies. The reader is directed to Lopes *et al* 2012 [1] for a history of work carried out in this area. The EPSRC Centre in Innovative Manufacturing in Additive Manufacturing at the Universities of Nottingham and Loughborough, UK, has the development of multi-functional 3D printing processes as one of its main aims. This Centre aims to achieve this in two primary ways, via ultrasonic consolidation (UC) and by multi-material jetting.

While work has been ongoing within the AM community to develop the manufacturing processes to achieve multifunctional AM (MFAM), there appears to have been little work carried out on developing the design systems to exploit the design freedom these processes will provide, hence, the Centre also focuses on design and analysis methods to enable this. Current placement and routing techniques are designed for printed circuit boards (PCBs) used in planar (2D) or stacked planar (2.5D) arrangements. Opening up the design space to allow true 3D placement and routing without the need for a PCB allows more compact and capable systems. Some work has been carried out on 3D routing, primarily on cable / hose routing in large scale structures [2-14], but there appears to be no work on devising a design system tailored for MFAM incorporating optimal placement and routing.

With this work there were two general intentions defined from the outset. Firstly, it was preferred to remain within the voxel modeling environment where possible. This was because the

intention was to use the jetting AM process for the printing of the system. The array of jetting nozzles of this process allows a direct mapping of raster based file formats such as a bitmap to the nozzles. This eliminates manual CAD techniques, including the need to covert to the STL file format and associated slicing, which is well known to be cumbersome. By using voxels, no slicing is necessary and the workflow can be made significantly more efficient. Secondly, specifying design intent through the volume of a part is difficult, especially when working with voxels. To alleviate this problem, where possible, the design optimization process was automated based on the design requirements and analysis of the components' geometry and performance.

This paper presents an optimization based design framework for multi-functional 3D printing with an aim to contribute to two primary goals: firstly, the efficient placement and routing of components within the 3D volume, and secondly, taking into account the effect of these components on the structural response of the part and the subsequent optimization of the system within a general purpose voxel environment. This paper takes the following structure: Firstly, the framework methodology is outlined; secondly, this is demonstrated with some example test cases; and thirdly, the method results are evaluated and discussed.

2   Framework

The framework of this work is outlined in Figure 1. This shows a coupling between a topology optimization routine and the placement and routing optimization. The ultimate aim of this work is to be able to intelligently optimize the design of a multifunctional component to be made using multi-material jetting processes such as that shown in Figure 2. This tool will be essential in exploiting the geometric design freedom of AM processes and the additional functionality design freedom of MFAM.
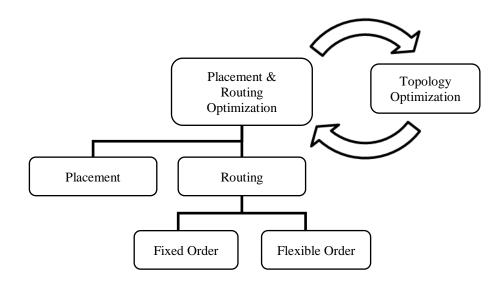

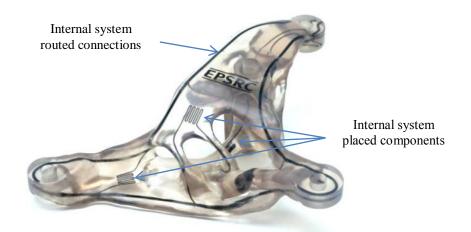Figure 1 – Framework for coupling placement and routing with topology optimization (TO).

Figure 2 – Example multi-material jetted concept prototype of a topologically optimized structural part with integrated internal system of placed components (in this case strain gauges) and the associated routed connections.

3   Placement and Routing Optimization Methodology

This section will discuss the method adopted for the placement of components, the associated routing between them and the optimization strategy.

3.1   Placement Method

Once the 2D restriction of planar PCBs for component placement is removed, the components can be placed anywhere within the volume of the part, and the design space is greatly increased. Efficient ways of determining appropriate component positions are therefore required which currently do not exist. Two placement approaches were investigated based on assessment of the components geometric requirements and performance characteristics.

3.1.1   *Topological / Geometric Analysis*

Topological or geometric assessment of the structure can be used to ensure appropriate placement of monitoring components within it. The proposed approach makes use of topological skeletonization [15] to represent the components' topology. In 2D, this generates a medial axis that approximately represents the center lines of the structural members. In 3D, a medial surface can also be generated. Both the medial surface and axis reduce the quantity of geometric information (i.e. dimensionality) required to represent the topology.

The skeleton can be used to characterize the topology, for instance, by identifying the joints of the skeleton and splitting it at these points, individual lines approximately representing each topological member are generated. Once the member centerlines have been isolated, the midpoints of these members can be found which can be used to form the locations for the placement of the internal components. By using a finite difference approach to calculate the

gradient of the member, strain gauges can be oriented in the direction of the members' longitudinal axis. This approach assumed that it is best that the strain gauges be placed on the central axis of the member, however, many other placement strategies could be implemented just as easily using this general approach. The topological skeleton and the associated joints and member midpoints are shown in Figure 3.
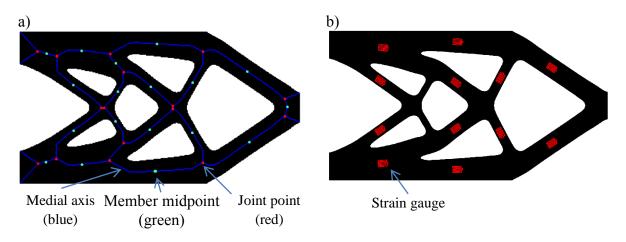
a)

b)

Medial axis   Member midpoint   Joint point
(blue)   (green)   (red)

Strain gauge

Figure 3 – a) Topological skeleton (medial axis) used to place internal components, and b) strain gauges mapped onto member midpoints and aligned with orientation of member.

3.1.2   *Performance Analysis*

For many components, the internal system and sensors will be used to provide some assessment of the components' performance in-service. The sensors could, therefore, be placed based upon the expected loading scenario. For example, areas of high strain may be considered to be appropriate locations for strain gauges. By carrying out performance analysis of the component, these regions can be identified and through manipulation of the analysis results, regions of suitability can be isolated, as shown in Figure 4.
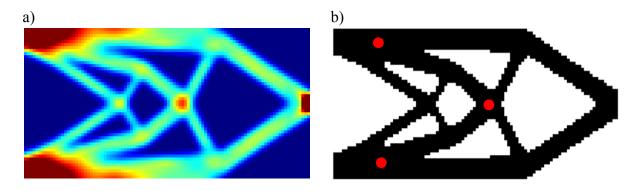
a)   b)

Figure 4 – Thresholded and masked strain energy distribution for component placement.
a) Strain energy analysis distribution (red = high, blue = low), and
b) centroids (red) of isolated regions for sensor location.

3.1.3   *Placement Constraints*

While the medial axis retains member length information, it does not retain information about the width of the topological members. A secondary stage can be carried out to calculate this lost information and once the topology has been quantified in this manner, with design constraints defined to ensure a feasible optimized design. As an example, sensors may be required in structural members most susceptible to buckling; this susceptibility is governed by member length and width. The member length can be defined as the total number of pixels in each skeleton member, which can be isolated by identifying the joints of the skeleton.

The width of each member was calculated as follows. Using the midpoints of each isolated skeleton member, the Euclidean distance from these points and the void regions was calculated. The minimum of these values is therefore the shortest distance from the midpoint to the boundary, and the width is then calculated as twice this distance. This method is shown in Figure 5. Owing to the skeletonization method, in some regions, generally towards the end of structural members where short members lie close to the boundary, the width value can be underestimated, as highlighted in Figure 5. While it is unlikely that very short skeleton members would actually be utilized for placement purposes, this characteristic is actually beneficial to the placement constraint and is a conservative measure.
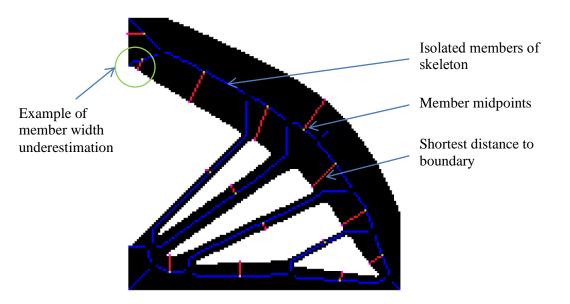

Figure 5 – Measurement of topology member width.

3.2   Routing Method

Once the internal components have been placed, the next task is to generate the connections to form a complete circuit, commonly termed routing. The routing is achieved by identifying the shortest paths between components subject to design rules / constraints. The following stages form the backbone of the routing tool:

1. Volume (uniform) discretization – This is a numerical necessity as there is no other viable means of quantifying routes, at least from an optimization viewpoint.
2. Shortest path identification between two components – This is done for all pairs of components that may be connected to each other. A 'multi-stencil fast marching' algorithm, which works on the same principle as Dijkstra's algorithm, [16] is used at this stage.
3. Optimal network of paths between multiple components – This stage becomes relevant when components can be connected in a flexible order. Ant colony optimization (ACO) [17] is implemented to solve this combinatorial problem to identify the optimum solution.

The tool developed for the purpose of routing optimization aims to improve the circuit efficiency through minimization of resistance which is proportional to conductive track length (and in doing so minimizes the utilization of conductive tracks as well). This is, in principle, achieved by identifying the shortest paths (conductive tracks) between components subject to design rules / constraints. Doing so increases the overall circuit efficiency, as both the inter- and intra- connections for systems are optimized.

3.2.1 *Routing Constraints*

The main constraints imposed on the routing optimization were to avoid obstacles and void regions and to have a minimum spacing between routes (to avoid interference between circuits). Control of the track width was also incorporated into the method to ensure the required levels of conductivity and insulation were achieved. These would not have a significant effect on the routing optimization and so they were included at the post processing stage only.

3.3 Topology Optimization Method

The placement of electronic systems within a component has potential implications on the performance of the component from a structural point of view, with potential reinforcing or weakening effects. The optimal internal circuit arrangement is also interdependent of the structure that surrounds it, and so the design of the structure and of the internal system should be concurrent. Specific weightings can be applied to control the effect to which each consideration has on the result. Therefore, the placement and routing was carried out within a topology optimization routine. The optimization problem is multi-objective in nature, for example, to minimize structural compliance and minimize circuit length (correlated with resistance), subject to a volume fraction constraint. Initially, this was implemented in a single objective model with the optimization being governed by the structural response, but with the effect of the integrated system on the structural performance taken into account.

3.3.1 *Optimization Strategy*

To establish an initial approximation to the optimal topology, the structural optimization iterations were carried out first. After a particular criterion was met, e.g. x number of iterations, x convergence tolerance met, the internal circuit was introduced and taken into account structurally for subsequent iterations. The Young's modulus of the elements (Table 1) representing the routing and strain gauges replaced those of the structure in the structural analysis model and the strain energy was calculated based on these values. The circuit and structure was then allowed to

change with the intention of converging to an optimal solution. Following each structural optimization iteration, the placement of the components was determined, followed by the routing of the electrical connections between them. This approach is summarized in Figure 6. The structural optimization was carried out using the BESO (Bi-directional Evolutionary Structural Optimization) topology optimization strategy [18]. This approach was used because of its inherently discrete nature and also because of its simple integration with other local structural analysis responses such as stress, when compared with density based approaches such as [19].

The BESO code was used with a commercial finite element analysis (FEA) solver, specifically RADIOSS by Altair Engineering. For improved efficiency a quadtree (2D) or octree (3D) decomposition mesh was used with multi-point constraint (MPC) averaging equations for the hanging nodes.

Function	Material	Young's Modulus, E (GPa)	Young's Modulus, E (scaled)	Poisson's Ratio, v
Structure	Steel	200	1.0	0.3
Void	Air	1E-4*	5E-7	0.3
Wiring	Copper	117	0.585	0.3
Insulation	Polyethene	0.3	1.5E-3	0.3

Table 1 – Material properties used for structural analysis. *Bulk modulus used for air.
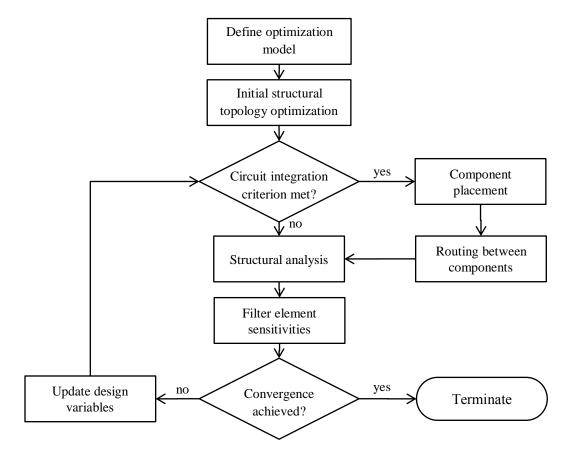

Figure 6 – Flowchart showing integration of internal system design with BESO topology optimization algorithm.

4   Simulation and Results

In order to demonstrate the multi-functional optimization method presented above, two test cases are presented. The first is in 2D and demonstrates the incorporation of the effect of the integrated system on the mechanical performance of the component. It also demonstrates the intelligent placement method based on the topological skeleton. The second test case is in 3D and demonstrates the more advanced capabilities of routing with both fixed order and flexible order connection requirements.

With both internal systems, the primary consideration was circuit efficiency, which is affected by the circuit resistance and interference from other parts of the circuit. The resistance is affected by the circuit length, its cross-sectional area, and the material resistivity. The interference is affected by proximity to other conductive tracks / components.

4.1   2D Test Case

This test case represents a component requiring structural health monitoring. This was achieved by using integrated strain gauges at various locations to provide feedback to the system. This would enable the identification of unexpected high loading so that catastrophic failure can be avoided, e.g. by limiting functionality of the system to reduce loading on that component.

The placement and routing methods were integrated with the BESO structural topology optimization method as outlined in Figure 6. In this case, the initiation of the placement and routing was carried out after the topology had converged. The remaining iterations of the optimization could then take account of any effect of the gauges and circuitry on the structure and make topological modifications accordingly. The material property values used for the optimization are contained in Table 1. The placement criterion was to place the sensors in the three longest members, based upon member assessment from the automated skeletonization routine. In this case the optimal connection order was found at each iteration by evaluating the total circuit length for all combinations. The topology optimization loading and design domain is shown in Figure 7. The results of the topology optimization with the placement and routing included are shown in Figure 8.
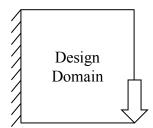

Figure 7 – Model design domain with loading and boundary conditions.

a)

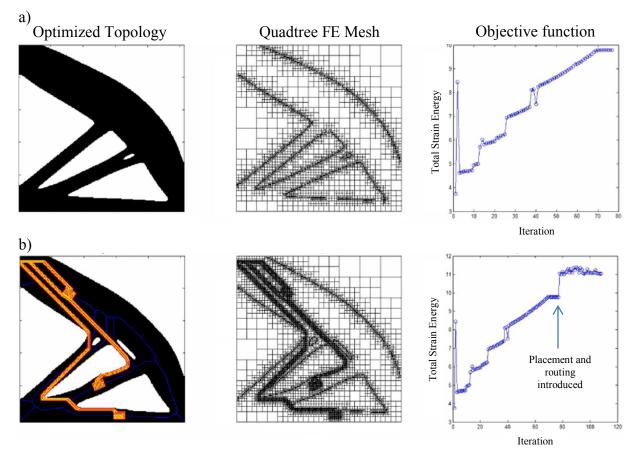| Optimized Topology | Quadtree FE Mesh | Objective function |

Figure 8 – a) Topology optimization with an adaptive quadtree mesh until converged, and b) subsequent introduction of strain gauges at skeleton member midpoints and associated routing to single point.

4.2   3D Test Case

For this 3D case, the placement of the components was determined manually a priori. The topology optimization was subsequently carried out based on a compliance minimization with a volume fraction constraint. This topology was then used to carry out the 3D routing stage. The connection scheme of the various internal components is presented in Figure 9. Here, the red lines indicate a fixed order connection (i.e. where the order of connectivity between a group of components is defined) whereas the blue lines represent a flexible order connection (i.e. where a group of components are interconnected but their interconnectedness is not strictly defined).

Figure 10a and b present the results for the 'fixed order' and 'flexible order' connection schemes, respectively. Figure 10c shows the combined sets of routes to produce the optimized internal system within the optimized topology. It can be seen that some routes traverse through void space between disconnected portions of the structure. This is because in this example, the internal components were allowed to be load bearing as it was assumed they would be printed at the same time. A mechanism using dilation and Boolean operations was implemented to enable routes to travel around the internal components that blocked routes through the structure.

a)

Additional component connection points

Optimized topology

Sensor connection points

b)

| Component set 1 |

| Sensors set 1 |

| Component |

| Component set 3 |

| Component |

| Component set 2 |

Red = fixed order
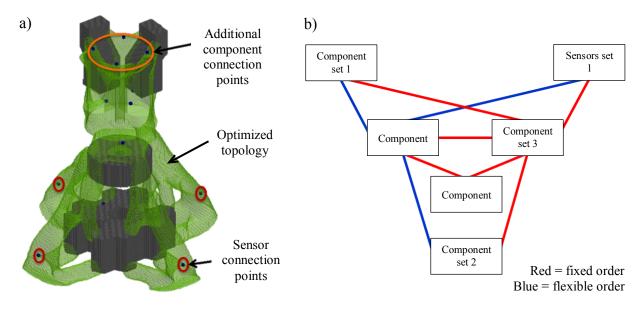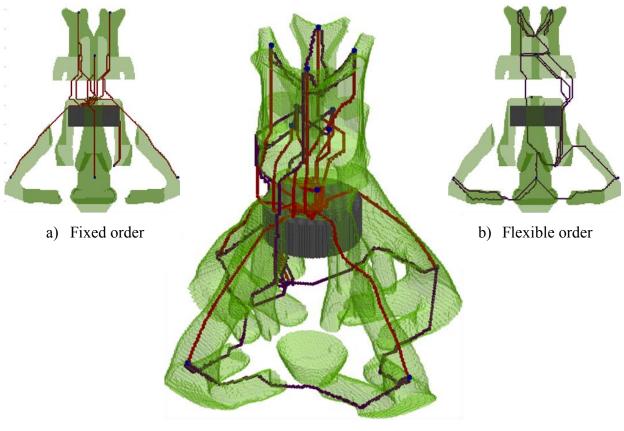Blue = flexible order

Figure 9 – a) Topology optimized structure (green) with manually placed components, and b) component connection order schemes (fixed / flexible) for routing.

a) Fixed order

b) Flexible order

c) Routed network

Figure 10 – Routing optimization results.

5   Discussion

The results from the two test cases have demonstrated the effectiveness and robustness of the outlined methodology. This section provides an overview of the issues with the current approach and proposes improvements.

5.1   Placement

From initial investigations, the intelligent placement approach was found to have two main issues. Firstly, placement of strain gauges at joints is problematic due to the multi-directional nature of the strain. This would likely require several uni-directional strain gauges at different orientations. Secondly, the thresholding values required to accurately isolate the high strain regions require tuning to the particular problem. Because of these issues, the second approach of placing the strain gauges in individual topological members using skeletonization was implemented for the initial work. Another alternative would be to couple the two methods so that both geometric and performance analysis features were used as a basis for intelligent placement.

5.2   Routing

Two main issues were observed from this routing approach. Firstly, the order in which the connections were made can have a large effect on the resulting total circuit length. Secondly, the routing is constrained by the structure itself. Modification to the structure to improve the routing efficiency could be beneficial, especially where very thin members are on the shortest routes for several components.

Addressing the first of these issues, a straight forward approach that was evaluated was to try all possible combination orders and select the order with the lowest sum of the circuit lengths to carry forward to the structural analysis. This is a combinatorial problem with an order of complexity of n!, where n is the number of connection points. Existing PCB routing approaches use a 'push and shove' approach to iteratively modify routes that are blocking subsequent routes. This approach could be used, however, it should be realized that in full 3D routing it is unlikely that previous routes would have such a significant effect on subsequent routes and so was not considered a significant problem.

The second issue can potentially still be present in 3D routing. To tackle this issue, a heuristic approach was taken to locally dilate parts of the structure based on the positions of previous routes. In the example shown in Figure 11, it can be seen that the shortest distance for all three strain gauges would be through the thinnest member, though this member can only accommodate a single route through it. By dilating this route further and modifying the structure accordingly, subsequent routes can also pass through this member.
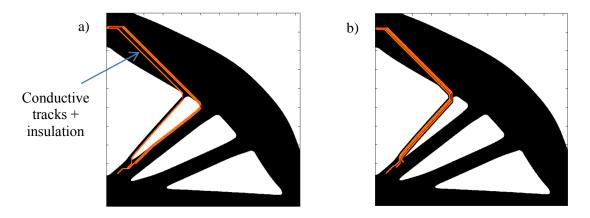
Figure 11 – Effect of local dilation strategy on circuit efficiency.
a) Routes without local dilation, b) routes with local dilation

5.3   Topology Optimization Integration

A more integrated approach is ultimately required for linking with the structural optimization process. The initial implementation took account of the mechanical properties of the integrated components and conductive tracks on the total compliance of the structure. The quadtree decomposition meshing strategy used for the analysis enabled a much reduced computational burden for the topology optimization process.

5.4   Internal Component Design

The design freedom enabled by AM provides opportunities to create non-traditional component geometries. For example, a standard strain gauge would have predefined terminal locations. Note that in this case, these have not been predefined as these were defined by the routing of the connections to these components to avoid overconstraining the routing. More significant changes include having strain gauge coils in multiple dimensions such as those shown in Figure 12. This geometry could be aligned with the longitudinal axis of structural members, particularly thin members that could not contain this number of coils in planar form. More importantly, it offers the potential for more compact and better integrated system designs.
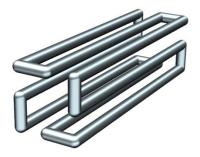

Figure 12 – Example of design freedom in creating a compact 3D strain gauge
to be placed in thin structural members.

6   Conclusions and Next Steps

This paper has presented work on the development of an automatic placement and routing methodology to be used in the design and optimization of multifunctional structural components. The results from the two example test cases have demonstrated the effectiveness and robustness of the outlined methodology. The capability of this method allows the exploitation of the manufacturing capability under development within the AM community to produce 3D internal systems within complex structures.

The primary next steps of this work are to improve upon the topology optimization coupling approach and to establish procedures for direct control of the jetting process to facilitate simpler design to manufacture processes.

7   Acknowledgements

8   References

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