Design Optimization Strategy for Multifunctional 3D Printing

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Abstract

An optimization based design methodology for the additive manufacture of multi-functional parts (for example, a structure with embedded electronic/electrical systems and associated conductive paths) is presented. This work introduces a coupled optimization strategy where Topology Optimization (TO) is combined with an automated placement and routing approach that enables determination of an efficient internal system configuration. This permits the effect of the incorporation of the internal system on the structural response of the part to be taken into account and therefore enables the overall optimization of the structure-system unit. An example test case is included in the paper to evaluate the optimization strategy and demonstrate the methods effectiveness. The capability of this method allows the exploitation of the manufacturing capability under development within the Additive Manufacturing (AM) community to produce 3D internal systems within complex structures.

1 Introduction

This paper presents and evaluates an optimization strategy 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, e.g. a Structural Health Monitoring (SHM) component. While manufacturing processes capable of physically realizing these components are still under development, a variety of techniques have been proposed, primarily using stereolithography and direct write/print technologies. The reader is directed to [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, UK, has the development of multi-functional 3D printing processes as one of its main aims. This Centre aims to achieve this is via multi-material jetting.

While work has been ongoing within the AM community to develop the manufacturing processes to achieve Multi-Functional AM (MFAM), there appears to have been little effort to develop design philosophies/tools tailored to exploit the design freedom associated with MFAM, hence, the Centre also focuses on developing design and analysis methods to enable this. The motivation for this work lies in the realization of an ultimate aim which is to be able to intelligently optimize the design of a multifunctional part, particularly within the scope of optimal placement and routing. The optimized 3D placement of internal components and associated routing would enable more compact, better integrated and capable MFAM systems. This concept is illustrated by the examples in Figure 1.

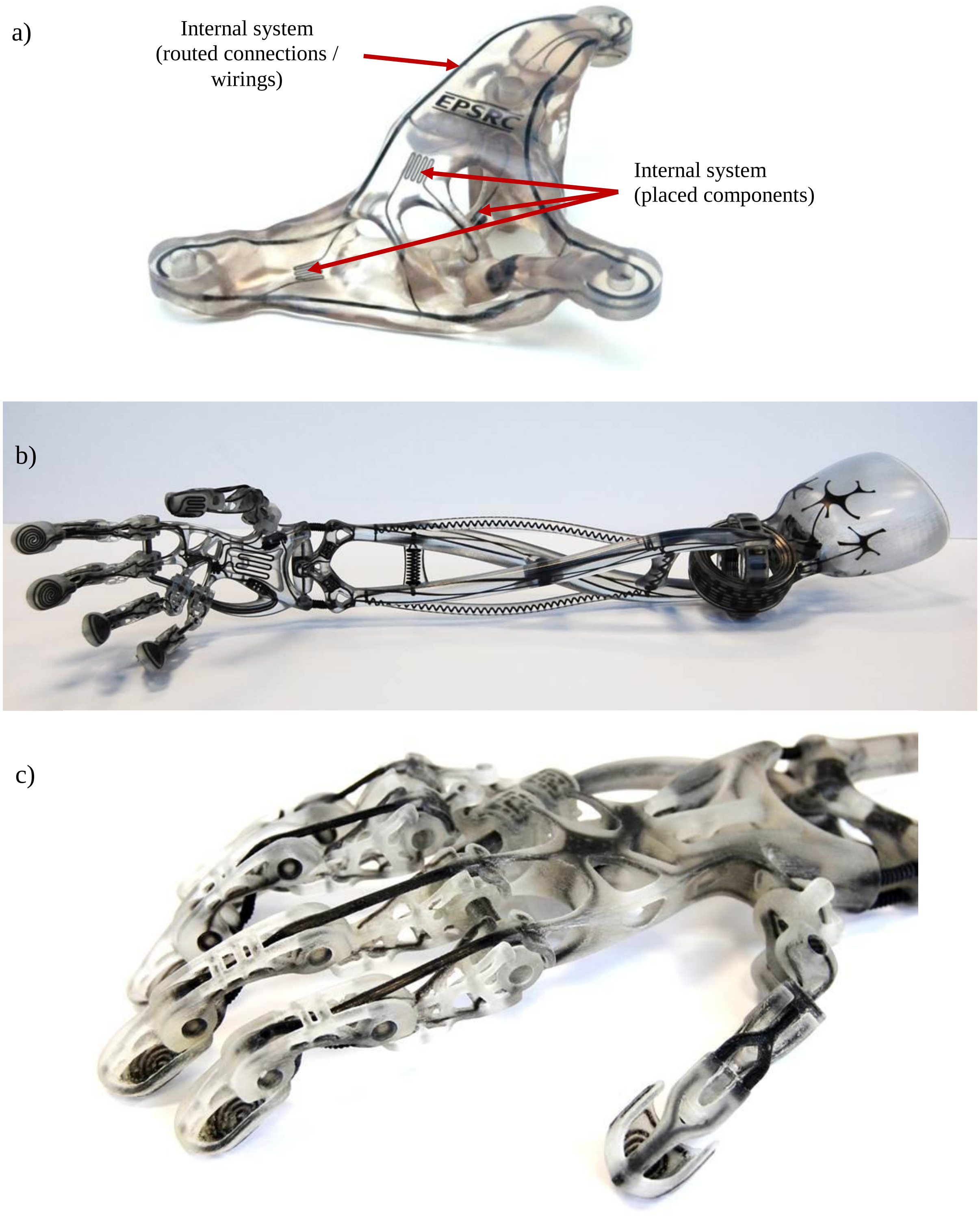

Figure 1: Multi-material jetted concept prototype - a) an example of a topologically optimized structural part with integrated internal system of placed components and the associated routing, b) a prosthetic arm with embedded systems and the associated routing [2], and c) a zoomed-in view of the prosthetic arm highlighting the complexity of the hand.

Imparting such functionality to a MFAM part can be best achieved by coupling a placement and routing optimization with a Topology Optimization (TO) routine which is a structural optimization technique that iteratively improves the material layout within a given design space, for a given set of loads and boundary conditions [3][4][5][6]. Automated placement and/or routing techniques have been employed in numerous fields ranging from: electronics, civil, aerospace, navigation systems, and artificial intelligence (robotics). In principle it would be best to perform placement and routing in one step as placement has significant repercussions on the routing but due to the nested dependencies these can be more efficiently (in terms of computational expense) tackled independently. To this end, several graph algorithms and mathematical methods, as reported in [7][8][9], have been developed and implemented. Many of these strategies have been adapted and coupled with global optimization algorithms such as Genetic Algorithms (GA) and Ant Colony Optimization (ACO) to solve optimization problems in other fields. Examples include pipe/cable routing [10][11][12][13] and optimum placement for SHM [14][15].

To facilitate the attainment of the overarching aim, which is to optimize the design of a multi-functional part, this work presents a coupled design optimization strategy. The paper takes the following structure: firstly, the strategy for optimization of multifunctional design is outlined; secondly, the details of the placement and routing approaches, and the coupling strategies are discussed; and thirdly, the appropriateness and effectiveness of the strategy is demonstrated by evaluating and discussing the results for an example test case.

2 Strategy: Design optimization for multifunctional 3D printing

Figure 2 shows a coupling between a TO routine and a placement and routing optimization. This coupled optimization strategy is essential to exploit the design freedoms offered by MFAM.

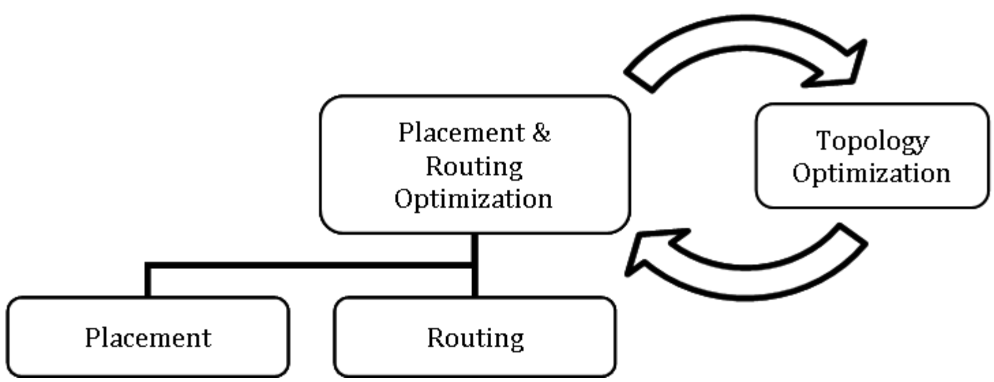

Figure 2: Strategy for coupling placement and routing with topology optimization.

In previous work [16], the authors demonstrated the capability of the aforementioned coupled optimization tool for a 2D test case of SHM. This preliminary work looked at integrating the placement and routing methods into a structural TO algorithm so that the optimization takes account of any effect that the placed components and circuitry has on the structure and makes according topological modifications. In this paper, we present the extension of this capability to 3D. Figure 3 shows an example that adopts the framework of Figure 2 wherein we have a one-to-one communication between the structural analysis and placement and routing optimization. Note that the solid part of the structure is removed to allow the internal routing and components to be viewed.

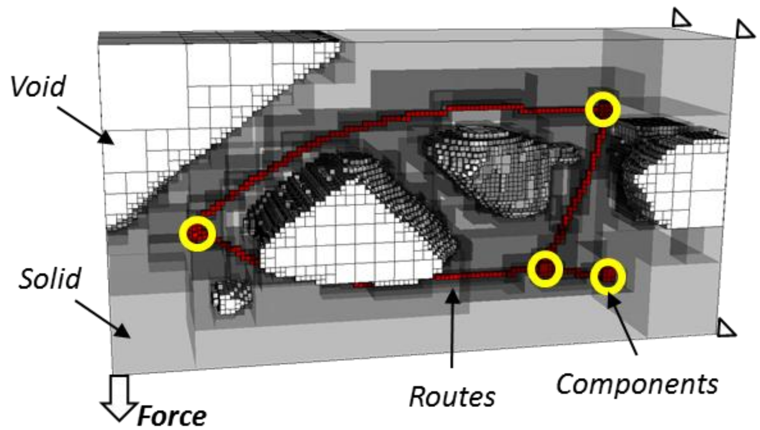

Figure 3: An example demonstrating the coupled optimization strategy of Figure 2.

3 Methodology

In order to exploit the increased design freedom offered by MFAM design, strategies suitable for: 3D placement and routing, and its efficient coupling with TO need to be devised.

3.1 Voxel modelling environment

A voxel modelling environment (where a voxel represents a cube in space) was considered for this study. This choice enables direct mapping to the raster based file formats used in AM, such as the bitmaps used in jetting. This eliminates the need for manual CAD operations, including conversion to the common STL file format and associated slicing, which is well known to be cumbersome and error prone. In addition, working in the voxel environment offers great flexibility as it enables in simple mesh mapping between different stages of the process to allow different modelling resolutions for control over accuracy/detail. This mesh mapping can be best achieved through the use of foreground meshes that are compatible with (i.e. an offspring of) a constant background mesh. We term this multi-resolution mesh philosophy as the Multiple Compatible Mesh Method (MCMM). To illustrate the usefulness of the MCMM, consider an example where a fine resolution is used for structural optimization, a coarse resolution for placement and routing optimization, and a very fine resolution for manufacturing. In doing so, we make the overarching design, optimization and manufacturing process, more efficient.

3.2 Placement and routing methodology

Figure 4 provides a top-level description of the proposed placement and routing methodology. Placement of the component involves: identifying potential locations; identifying the orientation for the component under consideration; and finally assessing the location suitability for this component. Routing involves: separating the component connection by type; computing shortest paths for pairs of components as described in Figure 4; and finally solving the combinatorial network problem (if one exists).

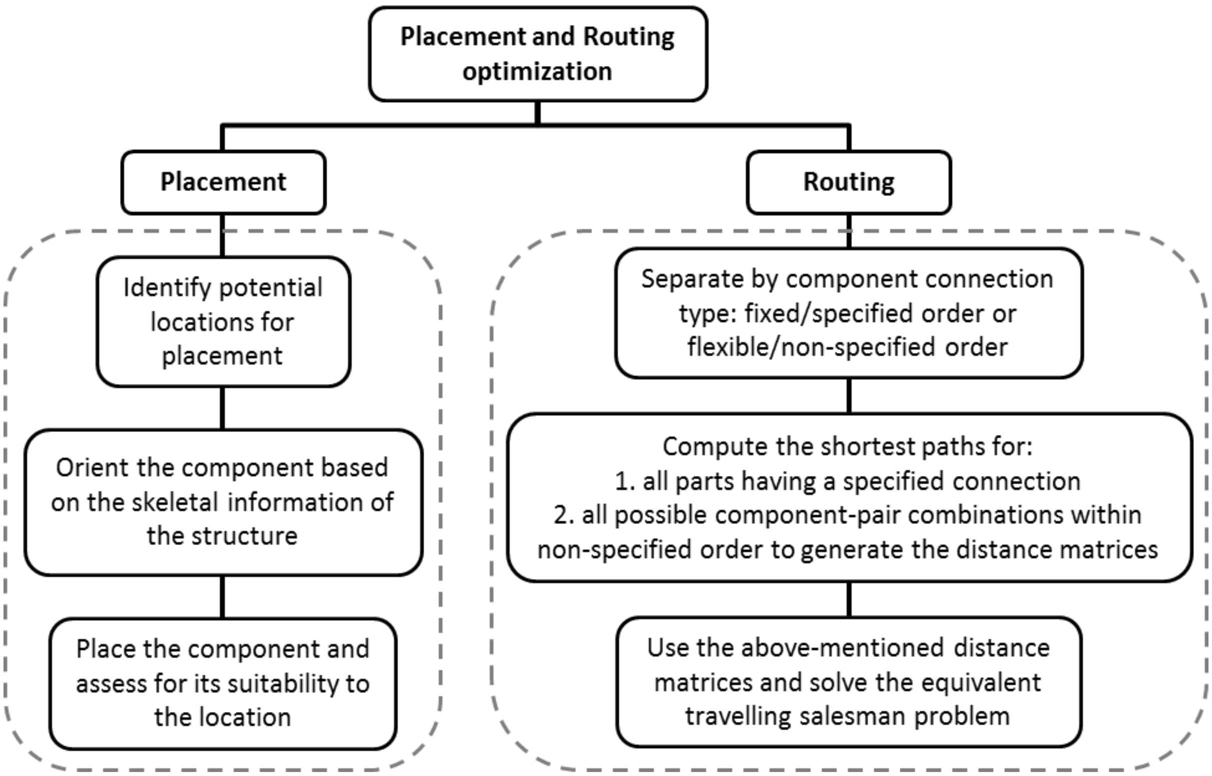

Figure 4: Description of the placement and routing strategy.

3.2.1 Skeletonization: characteristic information regarding the geometry

Skeletonization is the general name given to a process which reduces the quantity of geometric information (i.e. dimensionality) required to represent a structure whilst preserving the essence of the topology. In 3D, this means a 2D medial surface and a 1D medial axis. A thinning algorithm, as detailed in [17][18], has been used to obtain the skeletal information of the part's topology. For this study, the medial axis is of particular importance as it is used to obtain appropriate orientations of placed components.

3.2.2 Placement strategy

In order to automate the component placement, we propose a placement strategy that, in principle, capitalises on both the performance and geometric aspects by coupling them. These two aspects have been outlined in Table 1 and are discussed in-depth in the following sections.

Table 1: Geometry and Performance based placement strategy

Geometry Based			Performance Based	
Medial axis	Volume	Specified	Structural response	On other physics (e.g. thermal)
e.g. when good component encapsulation is desired and/or a measure of member deflections is needed.			e.g. thermocouples may be placed at high temperature regions.	

1. Performance characteristics – for many structures, the internal system of components and sensors can be used to provide some assessment of the structures' performance in-service. For example, consider Figure 5, which shows a structure subjected to an external heat stimuli. In order to effectively monitor the thermo-structural response of this structure, two thermal sensors are placed at the hot spots, a Central Processing Unit (CPU) in the cold spot (to process data from all sensors) accompanied by a thermal sensor to monitor the temperature of the CPU and four strain gauges in the key structural members.

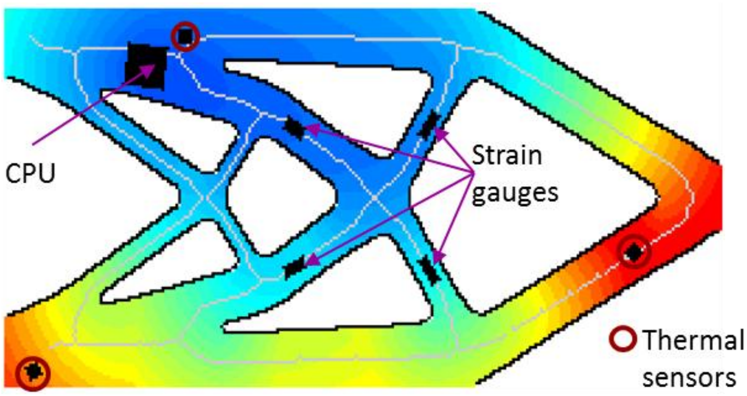

Figure 5: An example demonstrating component placement based on performance measures.

2. Geometric features – for many structures, the internal system of components and sensors might be required to be placed such that they are well encapsulated within the structure and also monitor the structural performance of the geometric members. Another example of geometrically important part location is an external sensor, such as an optical sighting or measurement device. The components could, therefore, be placed based upon the skeletal information of the geometry such as the medial axis. Doing so reduces a 3D volume to a network of 3D lines upon which the placement can be based, thereby significantly reducing computational expense. In addition to the aforementioned approach, one could adopt a more generic, unconstrained approach where the whole design volume can be exploited for placement. This would be computationally more expensive as it operates on the whole 3D structural volume so it is recommended to identify a set of somewhat uniformly distributed random placement locations within the volume of the part to use for component placement. The procedure for doing this involves initially selecting a set of random points within the part volume, constructing a Voronoi decomposition from them, and then identifying the centroids of these regions which define the new point set.

The approach adopted in this study for the placement of components is summarized by the flowchart of Figure 6. Details of this approach can be found in [19].

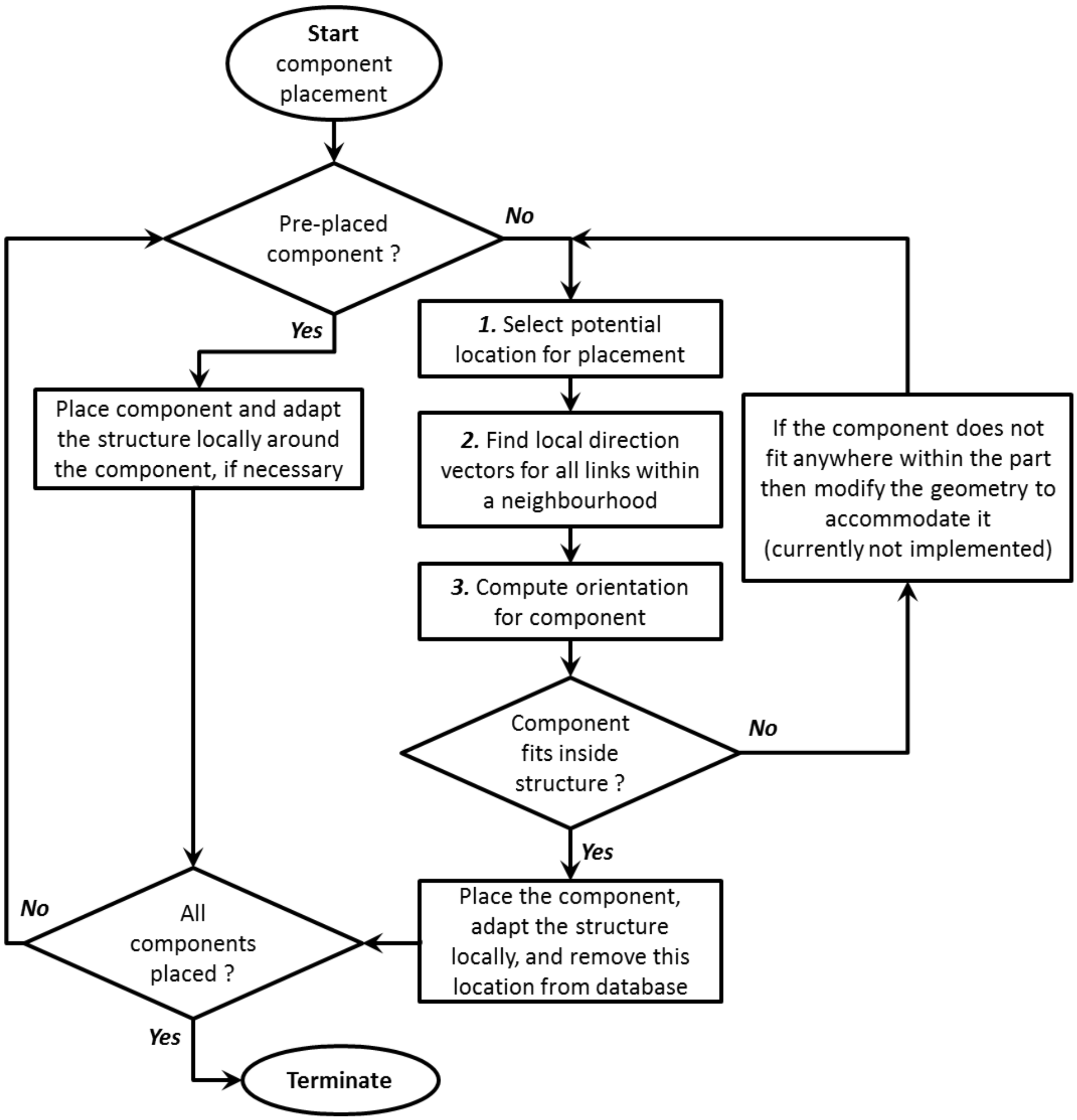

Figure 6: The placement methodology

3.2.3 Routing strategy

Once the internal components have been placed, the next task is to generate the connections to form a circuit, commonly termed routing. The routing optimization aims to improve the circuit efficiency by lowering resistance, which is proportional to the conductive track length. This is, in principle, achieved by identifying the shortest paths between components subject to design rules and constraints. By doing so, we also minimize the utilization of the conductive track material.

The main constraints imposed on the routing optimization were to avoid obstacles (e.g. internal components and void regions) and to have a minimum spacing between routes (to avoid electrical interference). Control of the track diameter was also incorporated into the method to ensure the required levels of conductivity and insulation could be achieved.

A MATLAB implementation [20] of the Fast Marching (FM) method [21] was used to identify the shortest route between any two considered components and an in-house implementation of Ant Colony Optimization (ACO) [22] was used for solving the combinatorial network problem (as described in Figure 4). The robustness of ACO has been well documented [22]. Furthermore, benchmarking of the in-house ACO code was carried out using standard TSPs taken from [23][24] for which the minimum tour lengths were known and the implementation enabled in converged solutions within reasonable iterations (i.e. computational effort).

3.3 Coupled optimization procedure

As discussed by the authors previously [16], it is beneficial to first establish an initial approximation to the topology by using sufficient TO iteration until a particular criterion was met (e.g. x number of iterations or x convergence tolerance met) and only then coupling the TO with the placement and routing optimization. Herein, a one-to-one communication between the TO and placement and routing optimization is considered. It is proposed that following each structural optimization iteration, the placement of the components is determined, associated routing is performed, and subsequently the design variables are updated accordingly for the next iteration of the TO phase, however, there are numerous variations to this overall philosophy that may be preferred in certain applications. This approach is summarized in Figure 7.

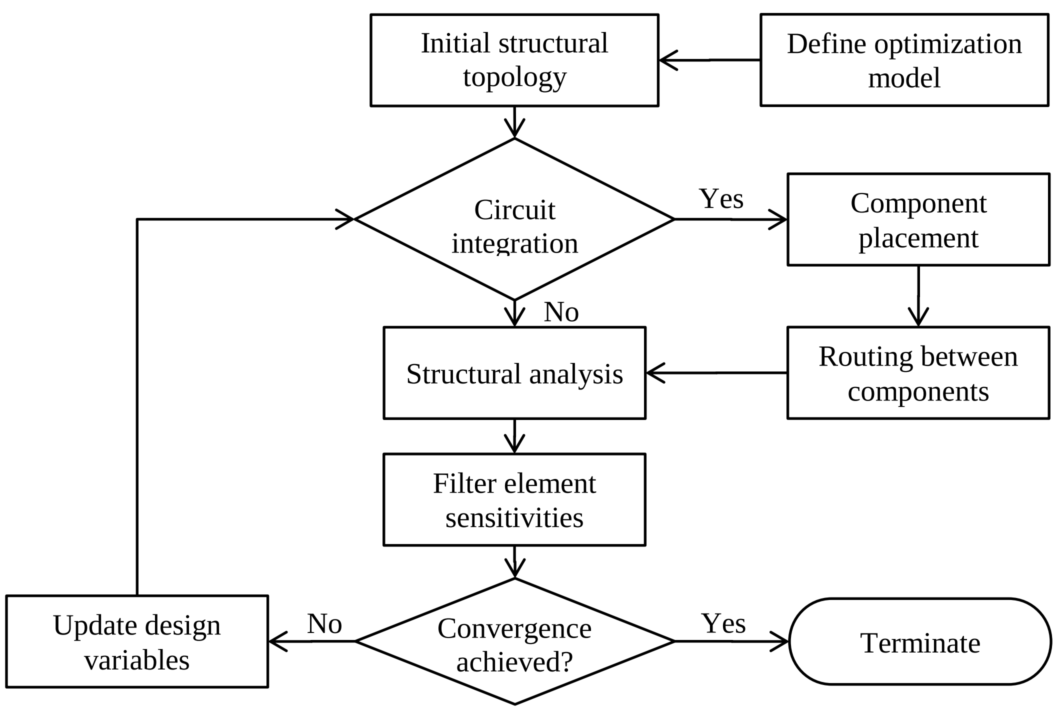

Figure 7: Flowchart showing the coupled optimization procedure

For the structural analysis model, the Young's modulus of the elements representing the structure, void, placed components and wiring were updated in accordance to Table 2. Here, λ_1 and λ_2 are parameters that govern the property of the components and wiring by bounding them to those of the structure and void. A commercial Finite Element Analysis (FEA) solver [25] was used to perform the structural analysis.

Table 2: Material properties used for structural analysis

Function	Young's Modulus, E	Poisson's Ratio, v
Structure	1	0.3
Void	1E-4	0.3
Components	$\lambda_1 \times Structure + (1-\lambda_1) \times Void$	0.3
Wiring	$\lambda_2 \times Structure + (1-\lambda_2) \times Void$	0.3

3.4 Improving computational efficiency

To allow for an efficient optimization procedure, approximations were made without compromising the accuracy at the FEA stage. This was achieved by utilizing a hierarchical mesh decomposition strategy, specifically quadtree (2D) or octree (3D) decomposition (see Figure 8a), which consisted of three key concepts.

The first of these concepts is a dual mesh system, which allows decoupling of the design variables (background mesh) and the analysis (foreground) mesh to enable flexibility of the mesh configuration. This background mesh was of constant predefined resolution and remained unchanged throughout the optimisation. At each optimisation iteration, the analysis results from the foreground mesh were mapped onto the background mesh prior to the stage of updating the design variables. At each iteration of the optimisation a completely new mesh was generated based on the aforementioned conditions using the updated design variables.

The second concept is the decomposition procedure which generated the adapted analysis elements from the design variable mesh. The primary condition used to determine when an element should be split was if there was some level of heterogeneity in the corresponding area of the background mesh. Constraining this decomposition were three primary parameters, namely, the minimum and maximum element dimensions and the maximum number of adjacent elements to any one larger element edge (2D) or face (3D). The differing effects of these parameters on the efficiency and efficacy of the analysis and optimisation stages are discussed and recommendations made for parameter combinations are given in [26].

The third concept is the use of multipoint constraint (MPC) equations to allow the use of hanging nodes in a mesh with undistorted elements by defining their relationship to their surrounding reference nodes. This approach enables a relationship between the foreground and background meshes to be maintained, which is a necessary requirement for the Multiple Compatible Mesh Method (MCMM).

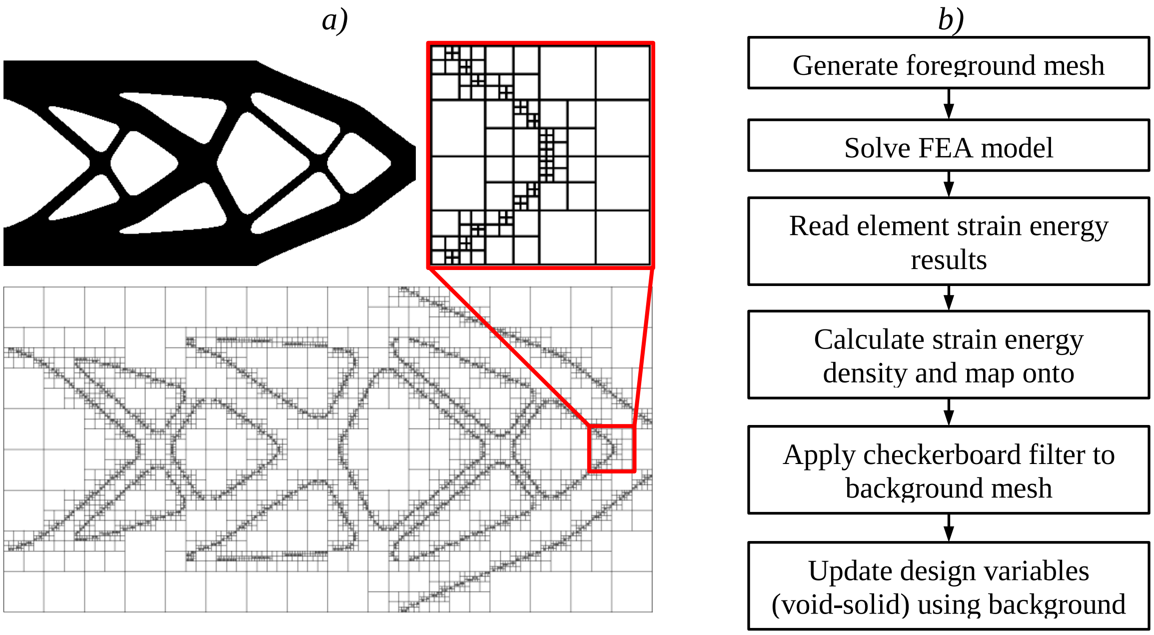

Figure 8: a) An octree decomposed topology used for analysis,
b) Integration of meshing procedure into BESO TO routine.

The revised bi-directional evolutionary structural optimisation (BESO) method [27][28] was used for this work, primarily, because it made identification of boundaries straightforward as the structure is inherently discrete throughout the optimisation (due to the two possible design variables values). As a non-uniform mesh was used for this work, the sensitivity number included the effect of the element size; the strain energy was mapped onto the background mesh elements after dividing by the foreground element area or volume to get the strain energy density [4]. The rest of the procedure is typical for the BESO methodology from the aforementioned sources. The overall optimisation procedure used for this work is summarised by the flowchart in Figure 8b.

4 <u>Simulation Results and Discussion</u>

The test case of Figure 9 is considered to evaluate and better understand the proposed coupling strategy. In this example, the structural criteria of Figure 3 (i.e. same boundary and loading conditions) with four internal components that are all connected to one another is considered. The placement of the components is chosen to be on the mid-points of the medial axis members (refer [19] for details). It was decided to incorporate the automated placement and routing into the coupled optimization at 50th iteration and terminate the coupled optimization at 70th iteration. This was done so that the structure was reasonably well-defined before considering the internal system integration.

The results provide an insight into the strategy employed for coupling of the TO with the placement and routing approach. It is evident from the evolution of the solution that the proposed strategy is appropriate for the design of MFAM parts but it is the effectiveness of this strategy which is in question. This strategy has successfully demonstrated the capability to automate the placement of components and generate the optimal routing. Nevertheless, more work needs to be done to improve its effectiveness as the internal system configuration was found to be erratic despite the objective function (i.e. total strain energy) being reasonably stable. The reason for this erratic behaviour is principally because of the criterion used for placement (midpoint of medial axis members). To overcome this, two procedures can be adopted. Firstly, a system to track the placed components could be used which should allow for more stable internal system configuration changes as the optimization progresses. Secondly, the internal system could be introduced gradually to the structure with the values of λ_1 and λ_2 (in Table 2) slowly varying from 0 to 1 over the iteration history (unlike the constant value chosen for this study).

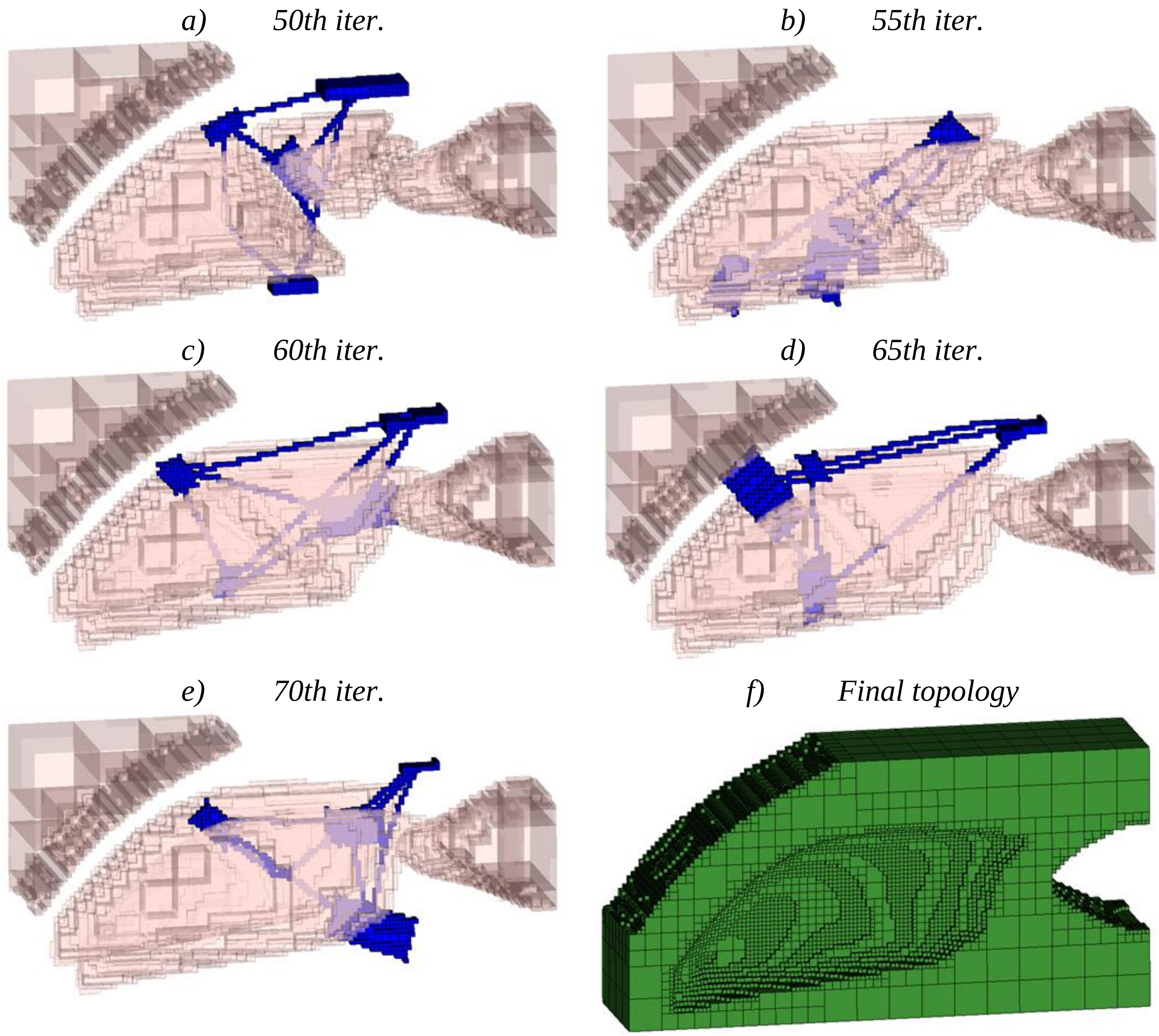

Figure 9: Results for test case 1 – coupled optimization strategy
Internally placed components and associated routing shown for
a) 50th iter b) 55th iter c) 60th iter d) 65th iter e) 70th iter f) final topology

Devising a tool to facilitate the intelligent placement of components is challenging; not only is the tool required to place components at potential sites but to also place them such that the associated routing length is minimized. Therefore the automated placement and routing methodology can be extended to include more advanced features such as: a combinatorial optimization scheme to identify the best placement configuration that minimizes total circuit length; and the capability to locally adapt the structure for a more effective routing that can result in the total route length being minimized further (this is especially important when several shortest routes pass via or would benefit passing via the same thin member).

Moreover, 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 over-constraining the routing. More significant changes include having strain gauge coils in multiple dimensions such as those shown in Figure 10. 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.

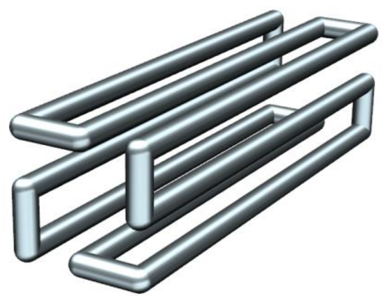

Figure 10 – Example of design freedom in creating a compact 3D strain gauge to be placed in thin structural members.

5 <u>Concluding Remarks</u>

This paper has presented a coupled optimization strategy where a topology optimization method is combined with an automated placement and routing approach for the design and optimization of multifunctional AM parts. The proposed placement approach capitalizes on both the performance and geometric aspects of the considered part. A medial axis based component orientation scheme is proposed for an appropriate alignment. With regards to routing length minimizing problem, a FM method in conjunction with an ant colony optimization algorithm was used. Adaptive meshing, specifically, Octree decomposition is employed to obtain computational leverage in the coupled strategy. The result from the example test case demonstrated the appropriateness of the proposed coupling strategy. The capability of the placement and routing 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 devise strategies for closer integration of the placement and routing methods with the topology optimization procedure.

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