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Design optimization for multifunctional 3D printed structures with embedded functional systems

A. Panesar[1], D. Brackett, I. Ashcroft, R. Wildman, R. Hague

Faculty of Engineering, The University of Nottingham, Nottingham, NG7 2RD, UK, [1]ajit.panesar@nottingham.ac.uk

1. Abstract

This paper presents an optimization based approach for the design of additively manufactured (AM), or 3D printed, multi-material parts with embedded functional systems (for example, a structural part with electronic/electrical components and associated conductive paths). The main contribution of this paper is the coupling strategy that enables the structural topology optimization (TO) of a part to be carried out in conjunction with the internal system design. This is achieved by accommodating the effects of system integration on the structural response of the part within TO. This work aims to demonstrate that the presented coupled optimization approach provides improved designs for 3D printed circuit volumes (PCVs) which provide benefits including: optimal system design, miniaturization, circuit encapsulation (protection) and tailored structure-system performance.

The coupled optimization strategy outlined in this work consists of: 1) a placement method used to determine suitable component locations (influenced by information extracted from the skeleton i.e. medial axis of the structure), 2) a routing method for optimal shortest distance connections between points (here, Dijkstra's algorithm is used to route between two fixed points by tracing skeletal members), and 3) integration into a TO routine taking account of the effect of routing on structure and vice-versa. This paper will report the developments made on the proposed coupled optimization strategy by detailing how the results from automatic placement and routing techniques are considered for the TO.

2. Keywords: additive manufacturing, 3D printing, multifunctional devices, topology optimization.

3. Introduction

A multifunctional part, by definition, has multiple uses, such as structural and electrical functions, for example, a structural health monitoring (SHM) part. Multifunctional designs could be physically realized using additive manufacturing (AM) or 3D printing multi-material processes which are still under development. A variety of techniques have been proposed, primarily using stereolithography and direct write/print technologies and 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 University of Nottingham, UK, has the development of multi-functional 3D printing processes, specifically multi-material jetting, as one of its main aims. The Centre also focuses on developing design optimization strategies and methods to enable this multifunctional design paradigm.

The motivation for this work lies in the realization of the ultimate aim which is to be able to intelligently optimize the design of a multifunctional part, such as the concepts included in Figure 1. Such multifunctional AM (MFAM) designs require coupling of the embedded system optimization (i.e. intelligent placement of system components and the associated routing) with a topology optimization (TO) routine (i.e. structural optimization technique that iteratively improves the material layout within a given design space, for a given set of loads and boundary conditions [2][3]). This coupling, in principle, should enable in a more compact, better integrated and capable design and is the focus of this paper.

The paper takes the following structure: firstly, the strategy for optimization of multifunctional design is outlined; secondly, the details of 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.

4. Methodology

4.1 Coupling Strategy

Figure 2a shows a coupling between a TO routine (specifically, bi-directional evolutionary structural optimization (BESO) algorithm [3]) and a system optimization (specifically, placement of components and associated connection routing). This coupled optimization strategy is essential to fully exploit the design freedoms offered by MFAM. The main reason for the choice of BESO was the well-defined solid-void representation provided at every iteration within the TO which meant that the internal system optimization could be performed at every iteration of TO (if necessary). In previous works [4][5], the authors demonstrated a single direction coupling of the aforementioned optimization strategy. This preliminary work looked at integrating the system optimization into a structural TO algorithm such that the finite element analysis (FEA) conducted as part of TO accounted for updated material properties for regions where the components were placed and the routes were identified. In this paper, the authors extend this work to benefit from a bi-directional coupling between the TO and internal system optimization. This is best illustrated by Figure 3 wherein we can observe the use of elemental sensitivities from both the structural and system aspect of our design to update the design variables for subsequent optimization runs.

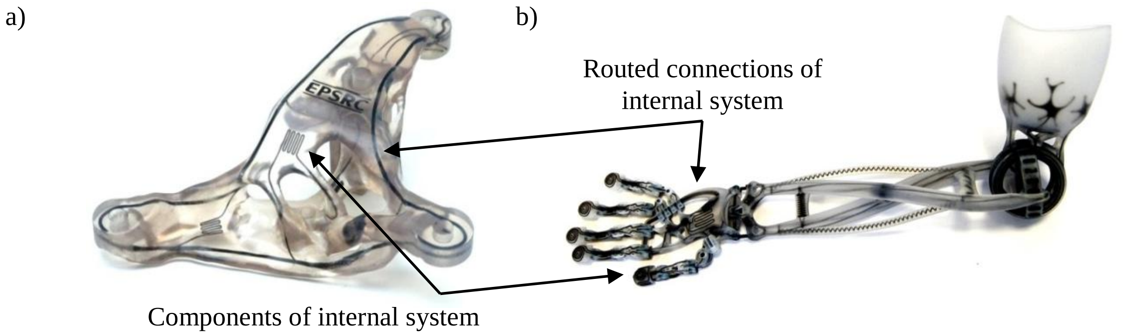

Figure 1: Multi-material jetted concept prototype - a) an example of a topologically optimized structural part with integrated internal system of placed components and the associated routing, b) a prosthetic arm with embedded systems and the associated connections between components [6].

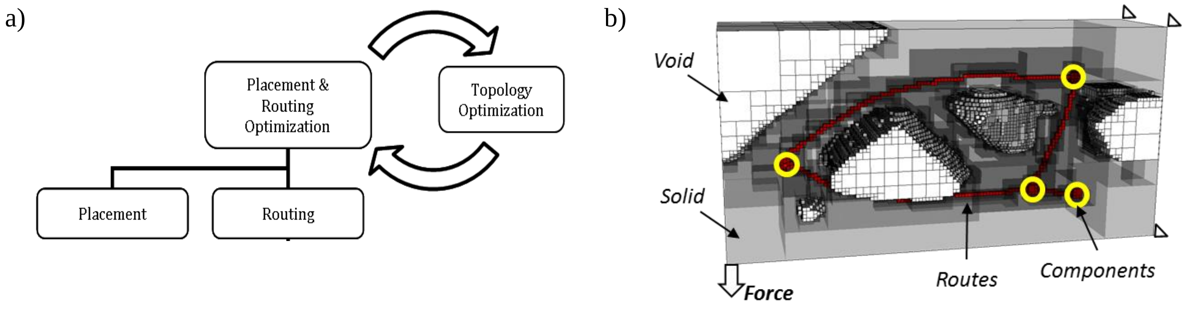

Figure 2: Coupling placement and routing optimization with structural topology optimization

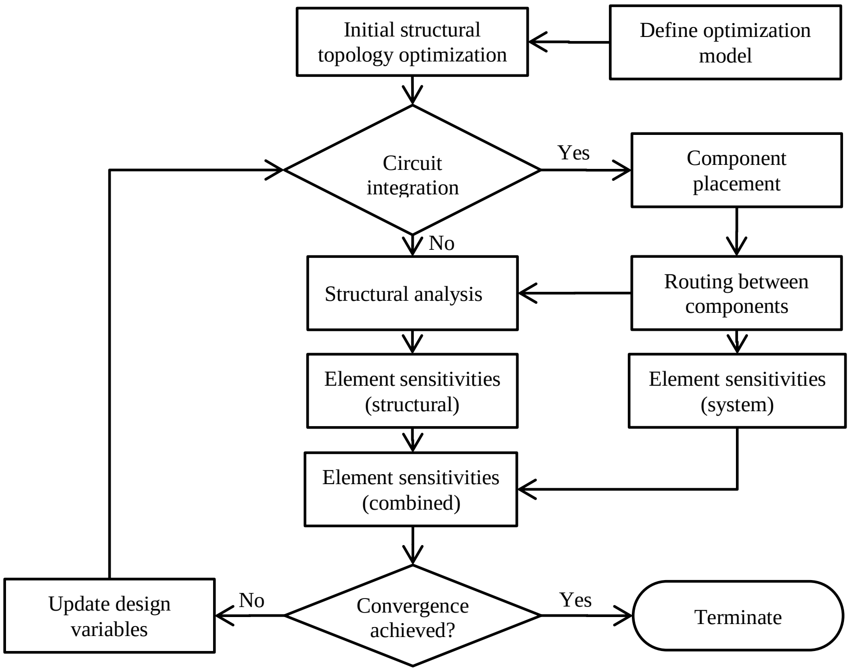

Figure 3: Flowchart showing the coupled optimization procedure

4.2 System Optimization: Placement and Routing Methodology

In this work, system design/optimization means the intelligent placement of components (based on some performance and/or geometry criterion) and the associated connection routing. A wide range of automated placement and/or routing techniques have been employed in numerous fields, including electronics, civil (buildings), aerospace, navigation systems, and artificial intelligence (robotics). The electronics community has benefited significantly from advancements in these techniques and this is evident from the highly miniaturized and optimized very large scale integration (VLSI) and printed circuit board (PCB) designs. Although 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. The reader is directed to the authors previous works [4][5] for details on the placement and routing strategies/techniques within the context of MFAM design. Currently, PCBs within electronic devices are limited to a stacked 2D (i.e. 2.5D) paradigm [7], however, with the development of multi-material AM the design of functional devices in true 3D, termed printed circuit volumes (PCVs), can be considered. The 3D placement of internal components and the associated routing of connecting tracks should enable more compact, better integrated and capable MFAM systems.

One of the key enablers for MFAM system design is the skeletal information. This can be obtained through the process of skeletonization which 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 [8][9], has been used to obtain the skeletal information of the part's topology. For this study, the medial axis is used to obtain appropriate orientations of placed components in accordance with the approach outlined in [5] and to identify the optimal routes.

With regards to the system design considered herein, 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. 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, 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.

In this study, a MATLAB [10] implementation utilizing the Dijkstra's algorithm [11] is employed to route between two points by tracing members on the medial axis. This approach is described by the following steps:

1. Obtain the medial axis for the current structural topology.
2. Compute the length of each medial axis member (i.e. branch point to branch point).
3. Identify the link and the points on it that are nearest to the placement location. Find the distance from the aforementioned points to the branch points of the link they lie on (see Figure 4).
4. Develop a graph (network) representing the path finding problem.
5. Solve the graph problem using Dijkstra's algorithm.

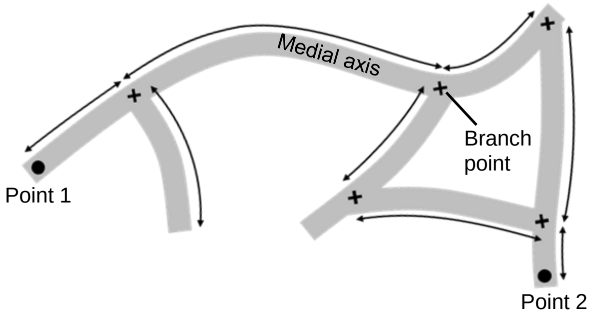

Figure 4: Routing method: shortest path identification based on the medial axis. Distances between points are represented by double ended arrows.

4.3 Coupled Optimization Procedure

The combined elemental sensitivity of an element within the design domain or ' ${}^{i}\alpha$ ', as outlined in Figure 3, is computed using Eq.(1)

$$ {}^{i}\alpha = \frac{{}^{i}\alpha_1 + \lambda\ {}^{i}\alpha_2}{1 + \lambda} \tag{1} $$

where, α_1 represents the normalized structural elemental sensitivities (i.e. normalized strain energies) after thresholding the outliers (e.g. at the regions where the loads and boundary conditions are applied), α_2 represents the normalized system elemental sensitivities, and λ is a weighting factor influencing the relative importance of the structural and system sensitivities.

For this study, a heuristic was defined (Eq.(2)) for the computation of internal system elemental sensitivities.

$$ {}^{i}\alpha_2 = \frac{1}{1 + d_i} \tag{2} $$

where, d_i is the Euclidian distance between 'i^{th}' element within the design domain and the closest point from it on the routed paths. Doing so, assigns a value of '1' to those elements which form a route and a lower value for elements that are further away from the routed paths.

As combined elemental sensitivities 'α' is used for updating the design variables in our modified BESO implementation, it can therefore be claimed that the objective function being minimized in this problem is $\sum\ {}^{i}\alpha$.

5. Simulation, Results and Discussion

In order to assess the proposed coupling strategy, a test case with the problem definition of Figure 5, is considered. Herein, four pre-placed components (based on the static arbitrary performance map of Figure 5a – two components at maximum values and two at minimum values) are chosen with the component connection topology of Figure 5b. Table 1 details the parameters set for the coupled optimization formulation (modified BESO) for the considered test case of Figure 5.

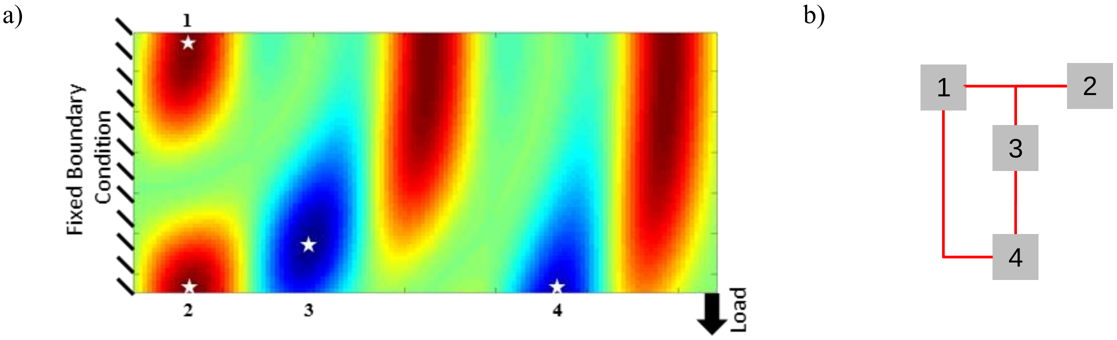

Figure 5: Problem definition a) four components placed within the design domain based on a static external performance map for the considered cantilever problem b) topology of the connected components defining the system configuration.

Table 1: Parameters used for the coupled optimization formulation

Parameter	Description	Value
λ	Parameter used for the single objective weighted sum formulation	1
$E_{Structure}$	Modulus of elasticity used for structure	1
E_{Void}	Modulus of elasticity used for the void region	1e-6
E_{System}	Modulus of elasticity used for system	1e-3
ν	Poisson's ratio used for all materials	0.3
R_{min}	Filter used to avoid checker-boarding	2
er	Evolution rate used for BESO	2%
Vol_{frac}	Target volume fraction used for optimization	40%
$Iter^{limit}$	Number of optimization iterations after which the process is terminated	60

Figure 6 shows the sensitivities of the structure and internal system as well as the combined sensitivities from which the design variables are updated (c), plus the optimized structure and system results (d) and the results from the TO with just structural sensitivities (e). Figure 7 shows the history of the artificial objective function calculated as a weighted sum of the structural and system sensitivities. Optimization progress was observed to be generally stable with only a few discontinuities over the history which correspond to sudden changes in the structural members selected for routing through.

In the coupled results (Figure 6d), the skeleton is shown with the red portions representing the actual routes used (overlapping routes are allowed at this stage in the design process). It was observed that the structural members that had routes within them had increased thickness that those that didn't and in comparison with the reference structure for which there are two contributing reasons. The first reason is that the routes affect the mechanical performance of the structure due to a lower Young's modulus being used for the material property of those elements in the FEA and so the structure is thickened up to compensate. The second reason is that due to the heuristic nature of the internal system sensitivity definition where the sensitivities are linked to Euclidean distance from the medial axis (Eq.(2)), the combined sensitivities for those regions of the structural members are higher than they would be otherwise which affects the design variable update.

The differences in the evolution of the solutions between the coupled structure and system optimization problem, and the structure only TO can also be observed. It can be seen that the structural topology looks identical for the early stages in both optimization problems. This can be understood by examining the element removal criterion, i.e. lower ${}^{i}\alpha$ values, and as medial axis is going to be well within the mostly solid structure, one can expect similar elements being chosen for removal. However, with removal of more material from the structure, the influence of system elemental sensitivities can be witnessed and it is evident that the coupled formulation has a significant effect on the material layout for the structure.

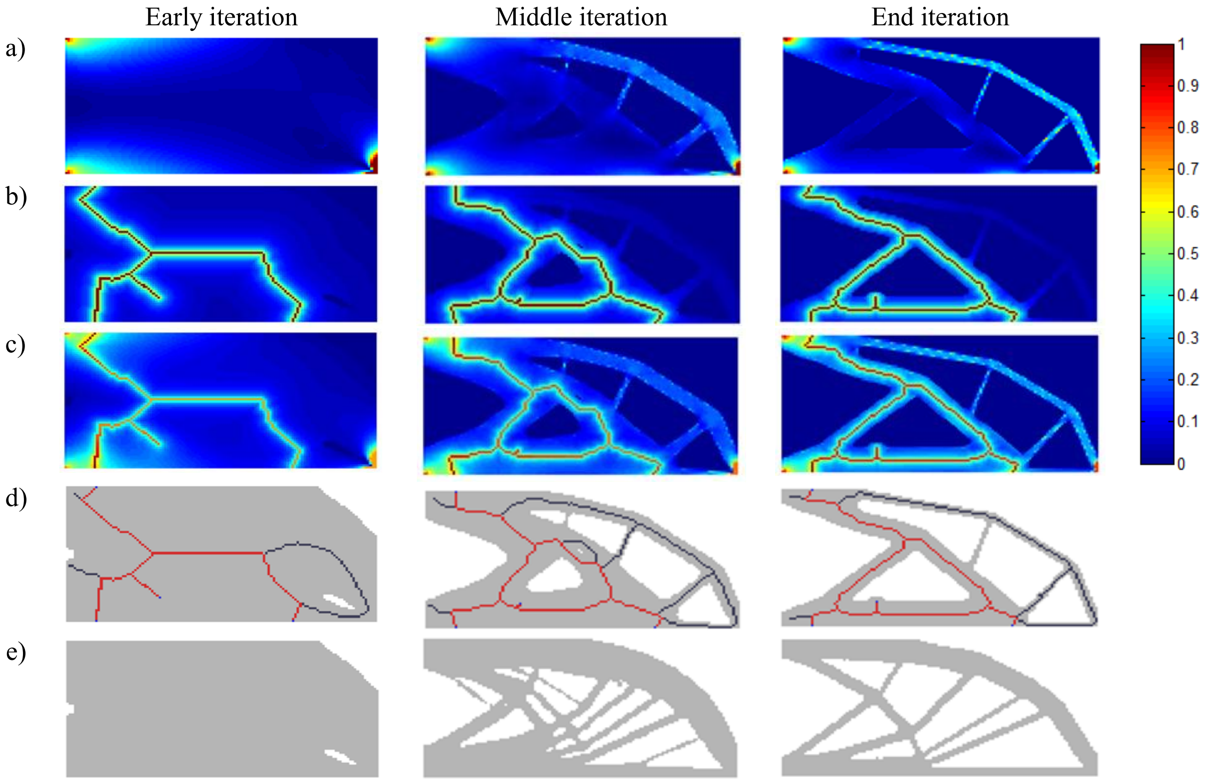

Figure 6 – a) Sensitivities for structure, b) sensitivities for internal system, c) combined sensitivities using Eq.(1), d) resulting coupled solution, and e) TO using just structural sensitivities for comparison.

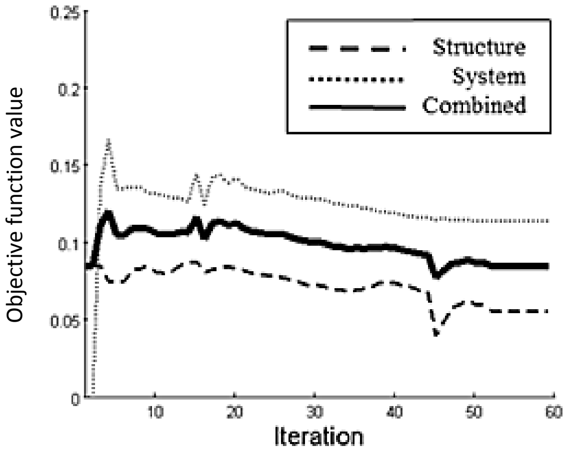

Figure 7 – Objective function formed as a weighted sum of the structure and system sensitivities.

6. Concluding Remarks

This paper has presented a coupled optimization formulation for the design of additively manufactured multi-material parts with embedded functional systems (e.g., a structural part with electronic/electrical components and associated conductive paths). This marks a significant step towards being able to exploit the design freedom offered by these manufacturing processes.

The main contribution of this paper is the coupling strategy that enables the structural TO of a part to be carried out in conjunction with the system design through the use of combined structural and internal system sensitivities, based on the routing between components placed based on a performance map. Following each structural optimization iteration, the placement of the components was determined, associated routing performed, and the design variables then updated for the next iteration of the TO phase.

The results have demonstrated that the method through the evaluation on a 2D cantilever test case for a simple connection topology. There is work to be done on tuning the heuristic internal system sensitivity definition to ensure it is not inappropriately biasing the structural member thickness through the use of the 'distance from medial axis' measure. The next steps are to evaluate this method on a non-static performance map that changes in response to changes in the structure.

7. Acknowledgements

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8. References

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