ECCOMAS Congress 2016
VII European Congress on Computational Methods in Applied Sciences and Engineering
J.F. Aguilar Madeira, Helder C. Rodrigues (eds.)
Crete Island, Greece, 5–10 June 2016

A METHOD FOR BI-DIRECTIONAL COUPLING OF STRUCTURE AND SYSTEM IN THE OPTIMIZATION OF MULTI-FUNCTIONAL COMPONENTS

Ajit Panesar*, Ian Ashcroft, Ricky Wildman and Richard Hague

Faculty of Engineering, University Park, University of Nottingham, NG7 2RD, UK
{*ajit.panesar, ian.ashcroft, ricky.wildman, richard.hague}@nottingham.ac.uk

Keywords: Optimization, Multi-functional Additive Manufacturing, Computational Methods

Abstract. *The driver for this research is the development of multi-material additive manufacturing processes that provides the potential for multi-functional parts to be manufactured in a single operation. To exploit the potential benefits of this emergent technology, new design, analysis and optimization methods are needed. This paper proposes a method in which a multifunctional part, consisting of a system, comprised of a number of connected functional components within a mechanical structure, can be optimized. 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. The method is demonstrated by performing a coupled optimization on a cantilever plate with integrated components and circuitry. The results demonstrate that the method is capable of designing an optimized multifunctional part in which both the structural and system requirements are considered.*

1 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 realized using additive manufacturing (AM) multi-material processes, and allows for a new AM design paradigm. The manufacturing processes, such as multi-head ink jet printing, capable of producing these parts are still under development, with considerable ongoing research into materials and process configuration. 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 multi-material manufacturing capability expands the possible design freedom from purely design of single material boundary geometry to also include material composition and functionality through the volume of the part. 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, illustrated in Figure 2, in principle, should enable in a more compact, better integrated and capable design.

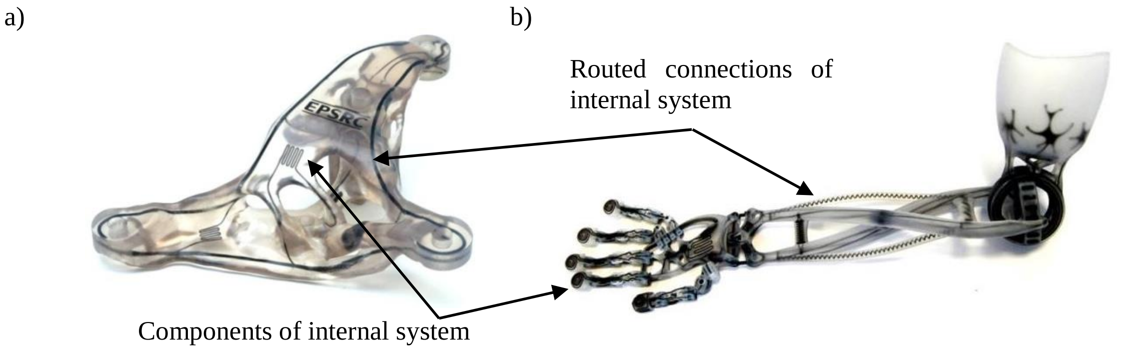

Figure 1: Multi-material jetted concept prototype - a) an example of a topologically optimized structural part with integrated internal system of placed components and the associated routing, b) a prosthetic arm with embedded systems and the associated connections between components [4].

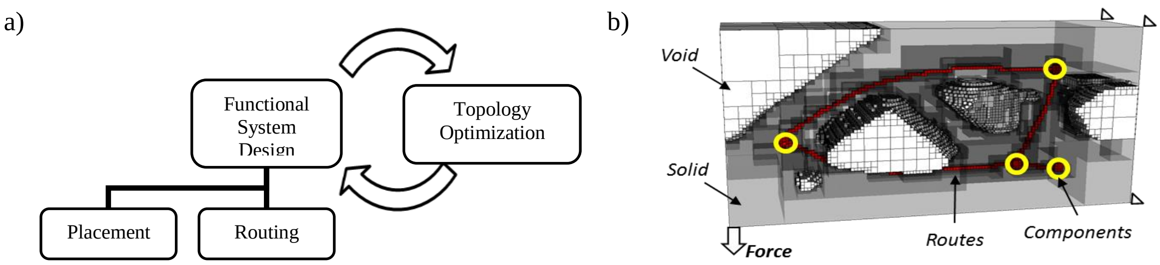

Figure 2: Coupling placement and routing optimization with structural topology optimization

The paper takes the following structure: firstly, some background information about the over-arching design framework is provided; secondly, the approach adopted for the design of functional systems is outlined; thirdly, the structure-system coupling strategy is detailed; and lastly, the appropriateness of this strategy is demonstrated by evaluating and discussing the results for example test cases.

2 BACKGROUND

The overall optimization based design framework [5] for MFAM, shown in Figure 3, has three primary strands within the structure and internal system coupling strategy: Firstly, the placement of components within the part, secondly, the routing between these components, and thirdly, accommodating the effect of integrating these components on the structural response of the part by modification of the structure using an optimization strategy. Completing the MFAM design strategy are the incorporation of design constraints and strategies employed for efficient computation of results.

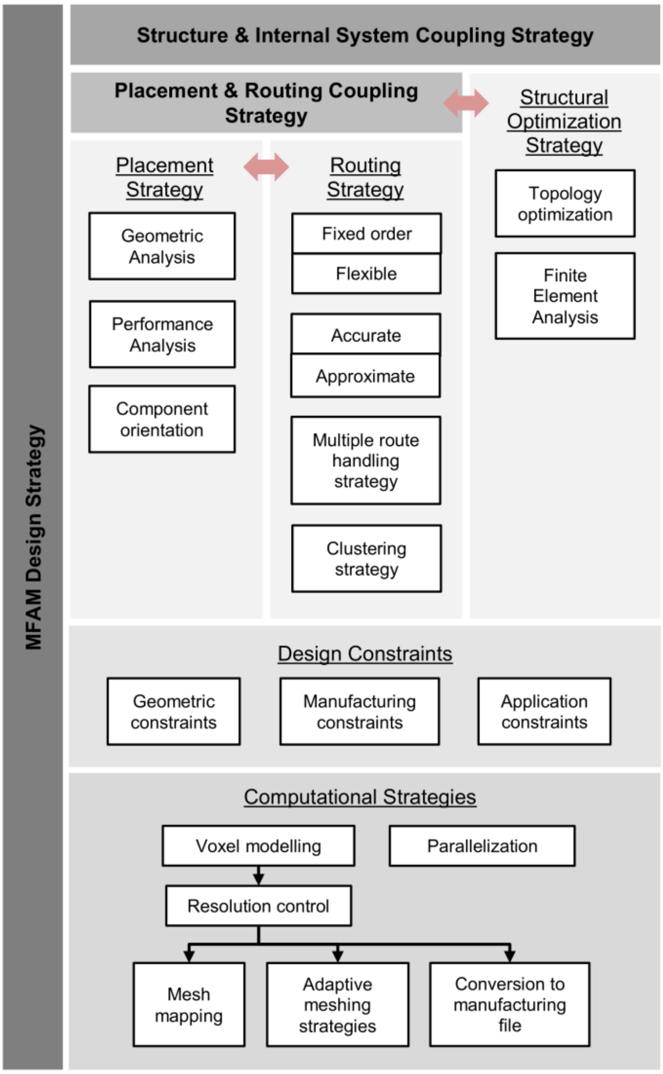

Figure 3: Overall design framework for MFAM

3 METHODOLOGY

3.1 Functional System Design

By functional system design/optimization, the authors mean the intelligent placement of components (based on some pre-determined, performance and/or geometry criterion) and generating the connections to form a circuit, commonly termed routing. 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.

One of the key enablers, making the MFAM system design possible, 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 [6][7], has been used to obtain the skeletal information of the part's topology. The reader is directed to the authors previous works [5] for details on how skeletal information is utilized for placement and routing within the context of MFAM design.

With regards to the system design considered herein, placement of the component is kept fixed (i.e. a set of pre-determined points) and the method of accurate routing as described in [5] is implemented. The system optimization problem therefore becomes a routing optimization problem where the aim is 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.

3.2 Coupling Strategy

The three primary strands of Figure 3 are used to formulate a coherent design procedure by devising suitable coupling strategies; specifically, the coupling between placement and routing, and the coupling between the structural optimization and the placement and routing. The first of these couplings could be achieved with a heuristic approach similar to those used for standard PCB or VLSI design [8], or a general purpose metaheuristic algorithm such ACO. Addressing the second of these couplings, is an approach that incorporates the effects of placement and routing methods via the finite element analysis (FEA) into a structural topology optimization (TO) algorithm.

Figure 4 shows the algorithm that couples TO routine (specifically, bi-directional evolutionary structural optimization (BESO) algorithm [3]) and a system optimization (specifically, placement of components and associated 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 system optimization could be performed, for instance, at every iteration of TO.

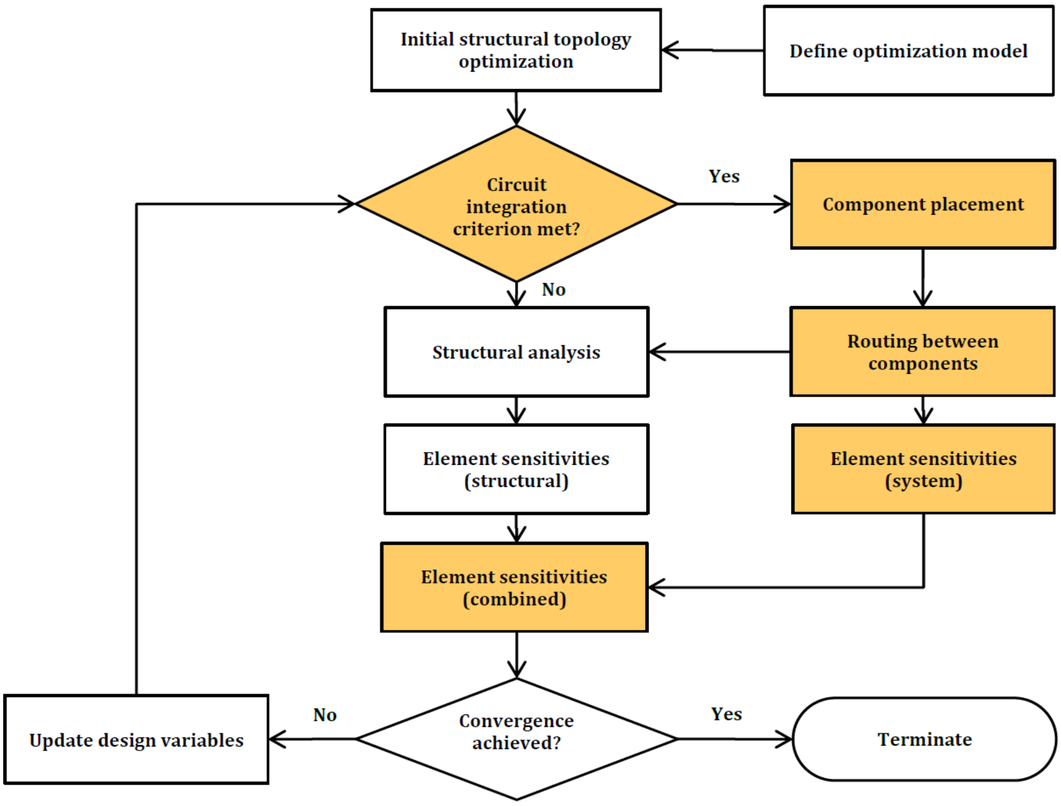

Figure 4: Flowchart showing the coupled optimization procedure

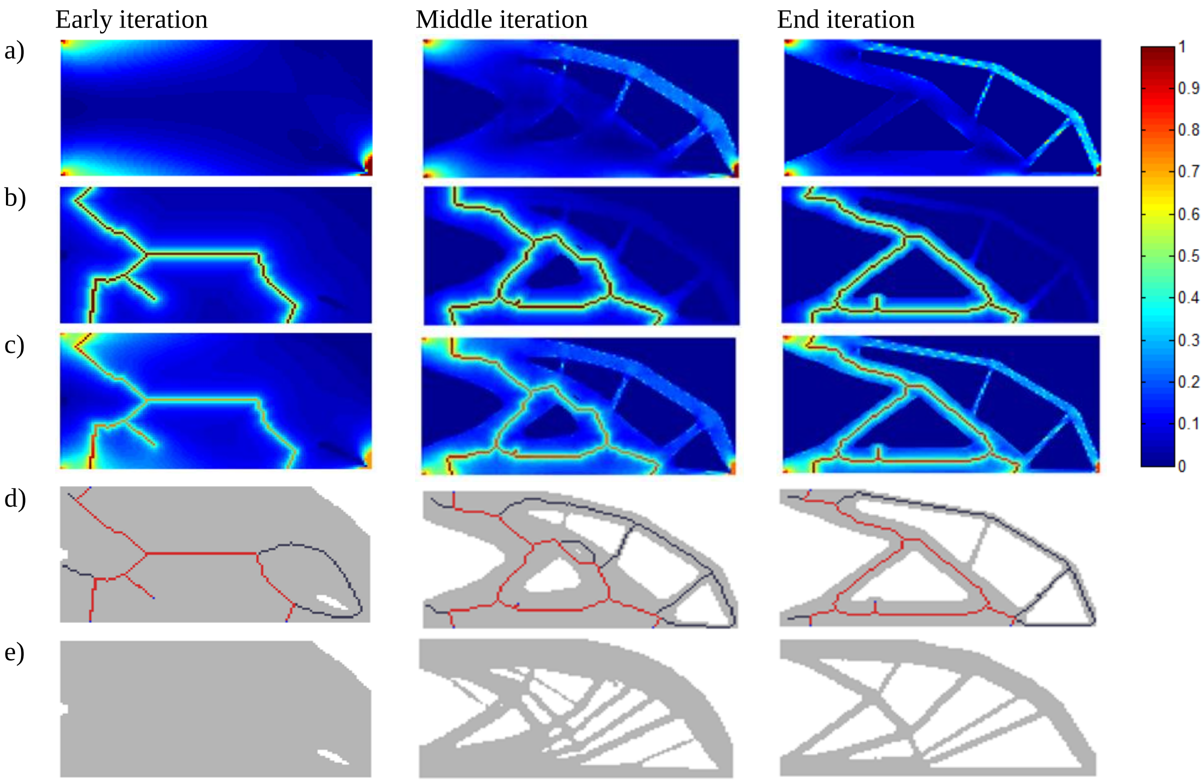

Figure 5: Effects of system integration included in the process of structural topology optimization - a) Sensitivities for structure, b) sensitivities for internal system, c) combined sensitivities, d) resulting coupled solution, and e) TO using just structural sensitivities for comparison.

This work is the natural evolution of the earlier works by the authors. The preliminary investigation of [9] (see Figure 2b) looked at integrating the system design into a structural TO algorithm such that the FEA conducted as part of TO accounted for updated material properties for regions where the components were placed and the routes were identified. Subsequently, the authors, extend this work to benefit from a bi-directional coupling between the TO and system design [10]. This is best illustrated by Figure 5 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. It is worth pointing out that in both these works, the routing was limited to what the authors refer to as approximate routing [5] (i.e. routes constrained to medial axis of the structure). This resulted in unstable evolution of the system configurations as the skeletal topology would drastically change due to the sudden dis-connectivity/disappearance in/of structural members. Therefore, with this work, the authors seek to test the robustness of the proposed coupling strategy (with improved heuristics) on problems employing accurate routing.

3.3 Heuristic sensitivity definition

The coupled optimization procedure of Figure 4 is built upon the principles of the revised BESO method [11][12]. The two key contributions made towards this coupled optimization algorithm are: a) heuristic definition for computing system associated elemental sensitivities and b) appropriate way of combining the system elemental sensitivities with that of the structural counterpart as shown by eq (1)

$$^{C}\alpha_i = \frac{^{S}\alpha_i + \lambda_1 \times (^{R}\alpha_i)}{1 + \lambda_1} \tag{1}$$

Where, $^{S}\alpha_i$ represents the normalized structural elemental sensitivities (i.e. normalized strain energies) after thresholding the outliers (i.e. at point of loading and boundary conditions) and $^{R}\alpha_i$ represents the normalized system elemental sensitivities. λ_1 is a user defined weight to control the influence/bias of the system design on the overall coupled solution.

As this work focuses on examples where the placement location of components is predetermined/specified therefore the system associated elemental sensitivities can be determined exclusively from the routing aspect of system design using eq (2)

$$^{R}\alpha_i = \frac{1}{1 + d_i} \tag{2}$$

where, d_i is the Euclidian distance between 'ith' 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.

Earlier works [10] (for example, see results of Figure 5) have indicated in the $^{R}\alpha_i$ values to be bounded and therefore $^{R}\alpha_i$ is set to zero for d_i greater than the filter radius (used for TO). Another improvement is the use of an adaptive parameter which is multiplied with $^{R}\alpha_i$ ensuring in the appropriate contributions of system associated elemental sensitivities towards the combined sensitivities (or $^{C}\alpha_i$).

4 SIMULATIONS, RESULTS AND DISCUSSION

In order to assess the appropriateness of the proposed coupling strategy, two test cases are considered, both addressing questions fundamental to this work:

Test Case - I. What influence does the updated heuristic sensitivity definition (discussed in section 0) has on the coupled solution when compared to the authors' earlier implementation of heuristics?

Test Case - II. Whether to perform (structure + system) coupled optimization or not? (By uncoupled problem, the authors mean performing TO to obtain a structure and subsequently include system design)

Test Cases considers a standard 2D cantilever problem with the left edge fixed and a vertically downward force being applied to the bottom right corner. The parameters used to simulate the test cases are reported in Table 1.

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

Table 1: Parameters used for the coupled optimization

Results for the simulation of Test Case – I are presented below. Figure 6 shows the characteristic straight-line route between two placement locations signifying the system dominated solution even though similar weighting for structure and system contributions (i.e. lamda = 1) have been used for the older heuristic definition of [10]. On the contrary, a more representative solution for the coupled problem is obtained using the proposed heuristics (see Figure 7). The main difference between solutions of Figure 6 and Figure 7 arises due to: a) the ${}^{R}\alpha_i$ values being bounded and b) the inclusion of the adaptive parameter which ensures in the appropriate contributions of system associated elemental sensitivities towards the combined sensitivities.

Results for the simulation of Test Case – II which aims to address the most important question of this work (i.e. whether to perform (structure + system) coupled optimization or not?) is shown qualitatively as Figure 8 and presented quantitatively in Table 2. It is evident after comparing the results from Table 2 that the system design benefits the most under a coupled optimization formulation.

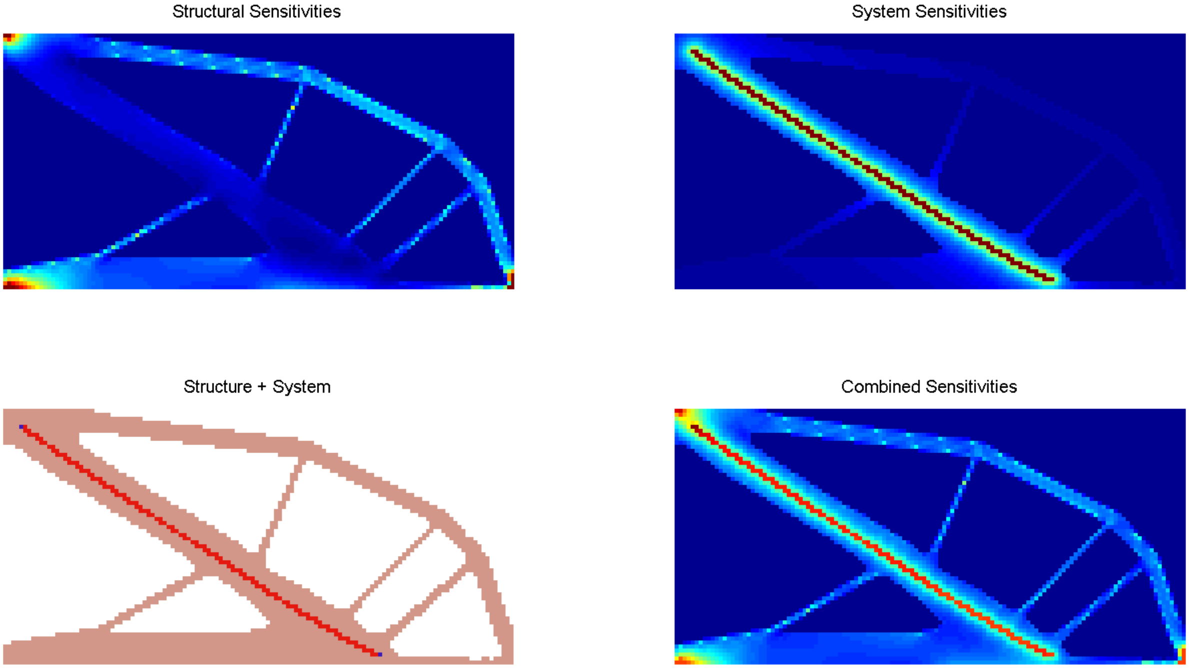

Figure 6: Results of the coupled optimization problem performed using the older heuristic definition of [10]

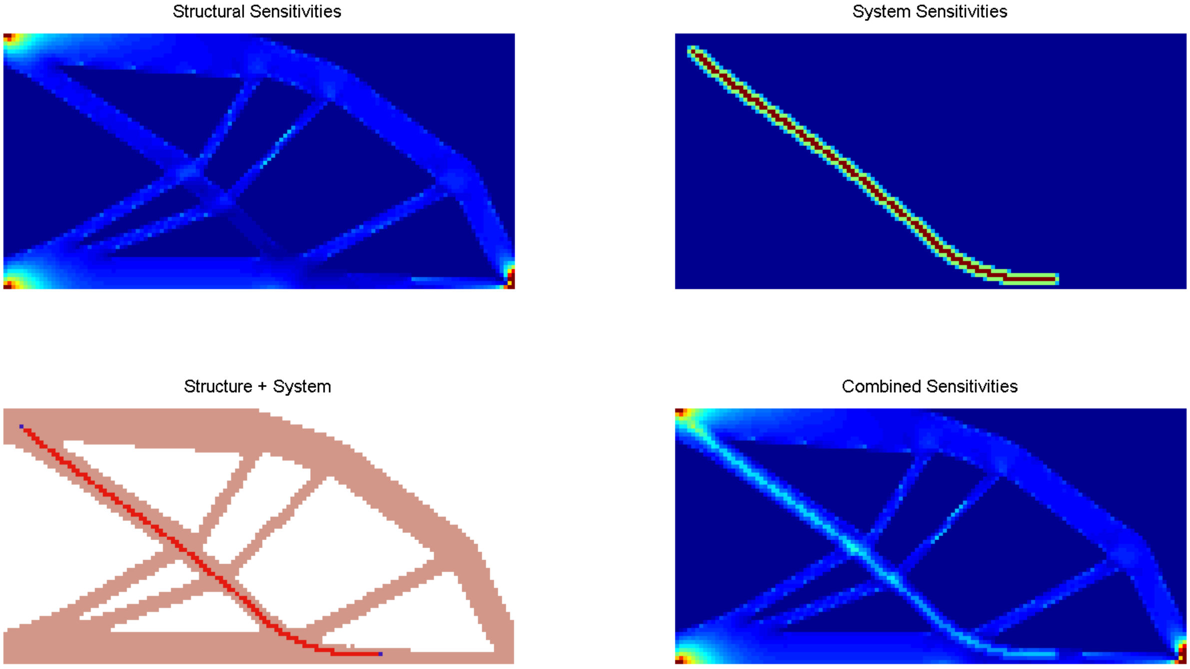

Figure 7: Results of the coupled optimization problem performed using the proposed heuristic definition

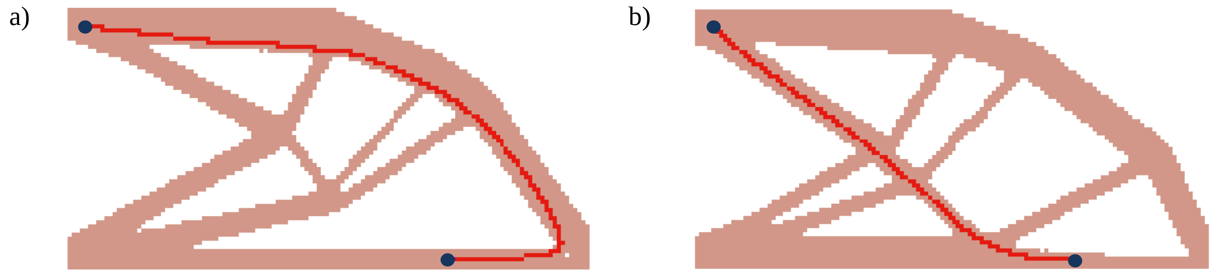

Figure 8: Comparison in results for uncoupled and coupled optimization - a) routing performed on a (converged) topology optimized structure, b) routing performed as a coupled (structure + system) optimization problem.

	Uncoupled solution	Coupled solution	difference
Path length (pixels)	196	138	30%
Total Strain Energy	39.9	40.2	<1%
Max. displacement (pixels)	76.7	77.4	<1%

Table 2: Comparison in performance between uncoupled and coupled optimization

5 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 improved heuristic definition that allows in a more appropriate coupling strategy where the structural optimization of a part is carried out in conjunction with the system design. This is achieved by accommodating the effects of system integration on the structural response of the part at every iteration within a modified bidirectional evolutionary structural optimization.

The simulation results for the evaluated 2D cantilever test cases show the suitability of the proposed coupling method where the system sensitivities, specifically routing sensitivities, are combined with the structural sensitivities for a multifunctional design problem. This work is testament to the need for developing the coupling strategy further as doing so would enable in the design of a more capable, better integrated and optimal multifunctional parts.

REFERENCES

[1] A. J. Lopes, E. MacDonald, and R. B. Wicker, “Integrating stereolithography and direct print technologies for 3D structural electronics fabrication,” *Rapid Prototyp. J.*, vol. 18, no. 2, pp. 129–143, 2012.

[2] M. P. Bendsoe and O. Sigmund, *Topology optimization: Theory, Methods and Applications*. 2003.

[3] X. Huang and Y. M. Xie, *Evolutionary Topology Optimization of Continuum Structures*, First edit. Wiley Publication, 2010.

[4] M. Amos, C.-W. Matthew, and S. Wimhurst, *3D Printed Prosthetic Arm*. Report, Univeristy of Noittingham, Nottingham, UK, 2013.

[5] A. Panesar, D. Brackett, I. Ashcroft, R. Wildman, and R. Hague, “Design Framework for Multifunctional Additive Manufacturing: Placement and Routing of 3D Printed Circuit Volumes,” *J. Mech. Des.*, vol. 137, no. 11, 2015.

[6] T. Lee and R. Kashyap, “Building skeleton models via 3-D medial surface / axis thinning algorithms,” *Graph. Model. Image Process.*, vol. 56, no. 6, pp. 462–478, 1994.

[7] M. Kerschnitzki, P. Kollmannsberger, M. Burghammer, G. N. Duda, R. Weinkamer, W. Wagermaier, and P. Fratzl, “Architecture of the osteocyte network correlates with bone material quality,” *J. Bone Miner. Res.*, vol. 28, no. 8, pp. 1837–1845, 2013.

[8] N. Abboud, M. Grötschel, and T. Koch, “Mathematical methods for physical layout of printed circuit boards: an overview,” *OR Spectr.*, vol. 30, no. 3, pp. 453–468, May 2007.

[9] A. Panesar, D. Brackett, I. Ashcroft, R. Wildman, and R. Hague, “Design Optimization Strategy for Multifunctional 3D Printing,” in *25th Interational Solid Freeform Fabrication Symposium*, 2014, pp. 592–605.

[10] A. Panesar, D. Brackett, I. Ashcroft, R. Wildman, and R. Hague, “Design optimization for multifunctional 3D printed structures with embedded functional systems,” in *11th World Congress on Structural and Multidisciplinary Optimisation*, 2015.

[11] X. Huang and Y. M. Xie, “Bi-directional evolutionary topology optimization of continuum structures with one or multiple materials,” *Comput. Mech.*, vol. 43, no. 3, pp. 393–401, Jul. 2008.

[12] X. Huang and Y. M. Xie, “A further review of ESO type methods for topology optimization,” *Struct. Multidiscip. Optim.*, vol. 41, no. 5, pp. 671–683, Mar. 2010.