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Design framework for multifunctional additive manufacturing: Coupled optimization strategy for structures with embedded functional systems

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The driver for this research is the development of multi-material additive manufacturing processes that provide the potential for multi-functional parts to be manufactured in a single operation. In order to exploit the potential benefits of this emergent technology, new design, analysis and optimization methods are needed. This paper presents a method that enables in the optimization of a multifunctional part by coupling both the system and structural design aspects. This is achieved by incorporating the effects of a system, comprised of a number of connected functional components, on the structural response of a part within a structural topology optimization procedure. The potential of the proposed 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

Single-material additive manufacturing (AM) processes, such as selective laser melting, enable the design of geometrically complex parts. Multimaterial additive manufacturing (MMAM) further expands this design freedom to include the spatial variation of material composition and enable multifunctionality through the volume of a part. Multifunctionality, by definition, necessitates the embedding of active sub-components in order to deliver additional functional capability, such as electronic, electro-mechanical, optical, electromagnetic, chemical and thermal [1]. MacDonald and Wicker [1], in a recent review article, identified multifunctional additive manufacturing (MFAM) as a pivotal technology in advancing the future of AM. Efforts have been made by researchers to develop hybrid systems to achieve MFAM, one such example is the work by Lopes et al. [2] where stereolithography and direct print technologies are combined to realize additively manufactured electronic devices. Such hybrid approaches often require multiple machine/print-restarts and additional manual or automated accompanying procedures. Conversely, multi-head inkjet printing, a promising MMAM process allows for MFAM designs to be realized with greater degree of manufacturing freedom in a single operation by co-depositing structural and functional inks. Recent works [3–5] have demonstrated the potential of jetting for electronics applications and highlighted the considerable ongoing research into materials and process development for MMAM.

Steps towards exploiting the design freedoms of AM have also been made. OpenFab [6] defined a procedure to efficiently grade mechanical properties through the volume of a part and Ponche et al. [7] proposed a three step global design approach with the aim of better integration of the design requirements (functional specification) with the AM process. However, there has been little work carried out to date on developing the design philosophies to realize novel MFAM concepts. The authors consider a closer interplay between the MMAM and topology optimization (TO – a structural optimization technique that iteratively improves the material layout within a given design space, for a given set of loads and boundary conditions [8]) key to progressing the MFAM design paradigm. One direct beneficiary of this is the area of 3D printed electronics, as fabrication of rugged structures that embed non-traditional electronic systems in an arbitrary form become possible [2,9]. This approach has the potential to pave the way for lightweight, more compact, better integrated and more optimal designs.

TO with embedded components has been investigated previously for the "integrated layout design" problem [10–13], where the aim has been to find both the optimal placement and orientation of components and the optimal configuration of the material simultaneously. This was achieved by iteratively changing the geo-

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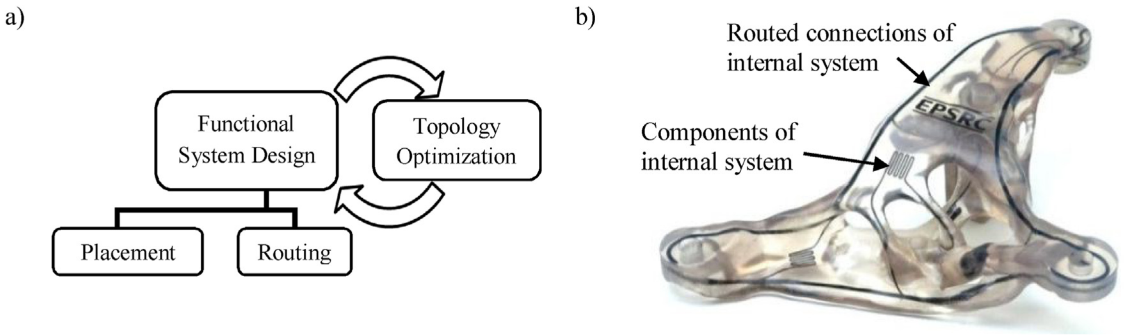

Fig. 1. Multifunctional design – a) top-level diagram showing coupled optimization of structures with embedded system, b) multi-material jetted concept prototype showing an optimized structural part that embeds an internal system (comprised of placed components and the associated routing) intended for the purpose of structural health monitoring.

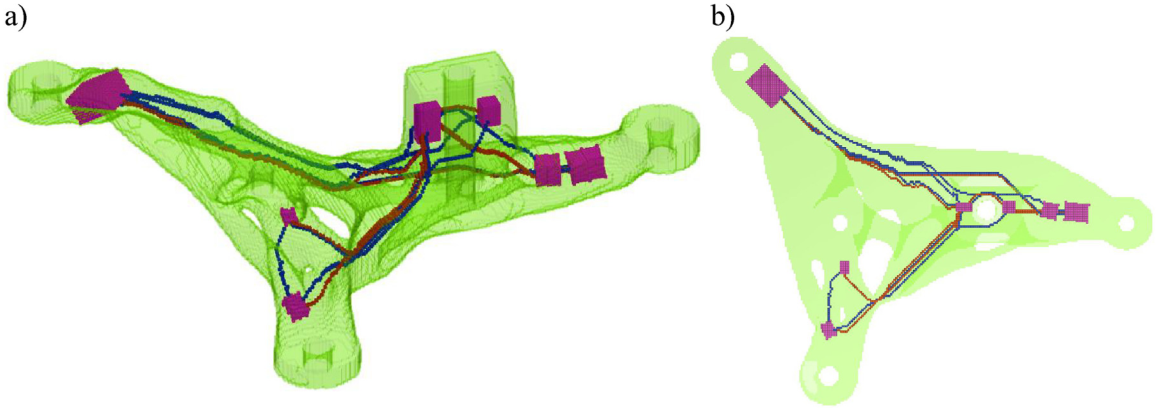

Fig. 2. Example of a TO automotive component (transmission mount) with embedded systems – demonstrating 3D placement of components and associated routing a) perspective view, b) top view.

metrical design variables describing the location and orientation of components within a TO regime. In all the reported instances, the implementation remained limited to the inclusion of rigid components that solely intended to enhance the structural performance. Therefore, this works seeks to make a step forward towards the inclusion of functional components (or a system) in a structure enabling the optimization of a MFAM design. To realize this aim, i.e. optimize the design of a multifunctional part, coupling both the system design (which is based on a functional performance i.e. not limited to only capturing structural or mechanical behaviour) and structural design, as illustrated in Fig. 1, is needed.

Earlier work by the authors detailed a MFAM design framework [9] to realize a functional system, specifically aimed at 3D Printed Circuit Volume (PCV) applications i.e. printed electronics in true 3D – not limited to, for example, printing on surfaces as in [2] or the stacked 2D (i.e. 2.5D) Printed Circuit Board (PCB) paradigm [14]. This work presented methods for the intelligent placement of functional components at suitable sites, and the associated routing for the conductive pathways within a part manufactured using multi-material jetting. Moreover, efforts were made to integrate these aspects of system design into a TO procedure such that the finite element analysis (FEA) conducted as part of a TO accounted for the updated material properties, reflecting system attributes [15]. Subsequently, this was extended to benefit from a bi-directional coupling between the TO and system design but the implementation remained limited to a specific routing method and suffered from robustness issues [16].

The capability for designing MFAM concepts for PCV application is in its infancy and therefore this work focuses on developing a generic coupled optimization strategy for the realisation of structures with embedded functional systems that are intended for manufacture using multi-material jetting. The paper takes the following structure: firstly, a description of design for functional systems is provided; secondly, the structure-system coupling strategy is presented; thirdly, the heuristic definition of the system sensitivities is detailed (so that one can tackle a bi-directional structure-system coupling); and lastly, the appropriateness and robustness of this strategy is demonstrated by evaluating and discussing the results for example test cases.

2. Methodology

A voxel modeling environment is chosen for seamless transition between system design, numerical analysis and manufacture as they all rely on discretized volumetric space [9]. Specifically, voxels for system design, hexahedral elements for FEA and 2D pixels with associated layer thickness in the raster-based (bmp) file format employed in jetting. Adoption of the voxel modeling environment eliminates the need for manual computer-aided-design operations, including conversion to the common STereoLithography file format and associated slicing, which is well known to be cumbersome and error prone.

2.1. Functional system design

The key enablers for making the functional system design possible are: (i) intelligent component placement and (ii) the associated connections routed between them. For simplicity, these are referred to as placement and routing. Although advancements in PCB design has led to the development of several graph algorithms