Structural Adaptation through Stiffness Tuning

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Abstract

Adaptive design strategies have been employed to improve structural performances in terms of load-bearing efficiency and energetic impact as well as to achieve multi-functionality. In this work, we investigate a passive adaptation strategy that employs variable stiffness in robotically printed materials. This paper focuses on the design and robotic fabrication of a chaise longue that can change shape to function as both recliner and chair depending on user requirements. The approach is unique in the way computational design is linked with robotic production. In this context, the design of the chaise longue is not limited to a formal process, but extends to the synthesis of the material distribution layout in order to achieve the intended functional behaviour.

Keywords

structural adaptation, adaptive design strategies, robotic printing

Introduction

Most engineering structures and products are overengineered as a result of being designed to meet strength and rigidity requirements to withstand worst-case loading scenarios which, in practice, occur very rarely. The conventional approach to cope with these requirements not only creates significant material waste, but also restrains structural and architectural design. Instead, structures could employ adaptation through controlled shape changes in order to counteract the effect of loads (e.g. stress, deformation) and achieve multi-functionality.

Previous work has shown that state-of-the-art adaptive design strategies can be employed to lower the environmental impact of structures while achieving a higher level of structural efficiency, e.g. to increase the height of tall buildings as well as the span of bridges and self-supporting roof systems (Teuffel, 2004; Senatore, Duffour, Hanna, Labbe, & Winslow, 2011; Senatore, Duffour, Winslow, & Wise, 2018; Senatore, GDuffour, & Winslow, 2018). Adaptive design strategies in combination with additive manufacturing at high spatial resolution (micro-scale) have been implemented to synthesise products with specific material behaviour, for instance for orthotropic foams (Martinez, Song, Dumas, & Lefebre, 2016; 2017). However, in practice, the application of these techniques is still limited.

In this work, a passive adaptation strategy, which employs variable stiffness in robotically printed materials, is investigated. This work focuses on the design and fabrication of a chaise longue that changes shape as a result of deformations induced by the weight of a user as shown in Fig. 1. The shape change is designed to accommodate both seating and a near-supine position for sleeping. The design of the required structural adaptation is implemented by tuning material stiffness through material pattern differentiation.

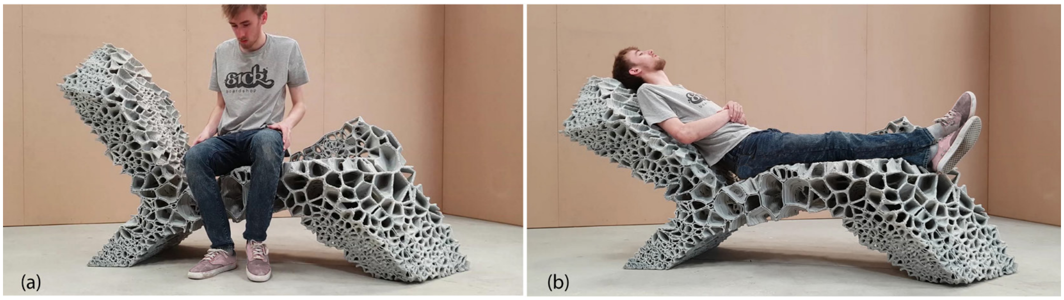

FIGURE 1 Chaise longue shape change from (a) sitting to (b) lying down obtained by tuning the stiffness through material deposition.

The chaise longue is made of thermoplastic polymer (TPE), which can stretch significantly (300% under 2.4 MPa) and revert to the original shape. The material's internal arrangement is based on a cellular pattern that is employed to create a self-supporting structure and can be fabricated by a robotic arm. By using robotic additive manufacturing that deposits fused material using a Stäubli TX200 6-axis robotic arm, the chaise longue was produced within 30 hours. A demonstration movie of the fabrication process is available online (Bier, H., Hidding, A., Wang, Q., Teuffel, P., & Senatore, 2017). The process is based on Design-to-Robotic-Production (D2RP) techniques developed at Delft University of Technology (TUD) (Bier, Liu Cheng, Mostafavi, Anton, & Bodea, 2018; Bier, 2018; Bier, Mostafavi, Anton, & Bodea, 2017) for additive and subtractive manufacturing. It is unique due to the integration of functional, structural, material and production requirements in design.

Design Process

The design process described in this section has been developed during a research project carried out in 2017 through support of 4TU Federation (Wang, Senatore, Teuffel, Hidding, & Bier, 2018).

The chaise longue is designed to accommodate an average human body either sitting or lying. A virtual human body model has been used to define the boundary geometry of the chaise. The desired shape-change from sitting to lying has been achieved by tuning the stiffness through strategic material deposition. This approach is not commonly used in additive manufacturing because material is usually uniformly deposited. The main requirement is for the chaise longue to be self- supporting. In addition, it should be 3D-printed without any supporting material.

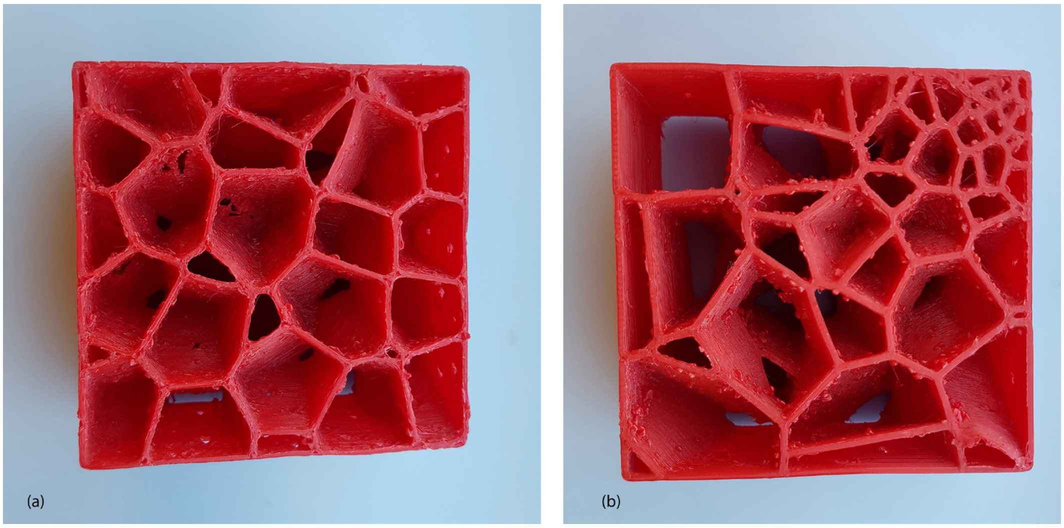

FIGURE 2 Uniform density distribution (a) and transition from small to large cells (b).

The cellular pattern is made of units, of which dimensions are varied to obtain variable stiffness properties. Several patterns have been tested to characterise deformation behaviour and fabrication feasibility. The aim is to obtain a large deformation of the back support when a user lies against it as shown in Fig. 1 (b) yet maintain structural integrity. To achieve this required deformation behaviour, cells are differentiated by varying their size distribution along specific directions as shown in Fig. 2 (b) as well as the cell height in the out-of-plane direction. The combination of these geometrical variations results in relatively well-defined directional stiffness properties of the assembly, which has been employed to obtain the required functional behaviour of the chaise longue.

Variable stiffness properties though geometry and material deposition

Material deposition is driven by stress: material density is increased where high stress areas occur whereas porosity is increased where low stress areas occur. The external load is modelled as a distributed load equivalent to the average human weight (80 kg), sitting or lying on the chaise longue. As a result of the structural analysis, the principal stresses are derived. The lines indicate tension (red) and compression (blue) stresses.

Fig. 3 (a) shows a detail of the chaise including the corresponding stress lines. The stress lines are subdivided to be converted into a point cloud by extracting points along their segments. The point cloud density is related to the stress intensity and thus more points are distributed in highly stressed area. These points are used to generate a Voronoi pattern (Fig. 3 b). The position of the points determines the position and sizes of the cells, as well as the angles of the cell walls. When the points are packed more densely, the 3D cells become smaller, since the cell size is influenced by the positions of neighbouring points. Therefore, size and density distribution of the cells can be controlled by adjusting the placement of these points. This way the cells are set to be smaller in highly stressed area increasing material density though their walls (Fig. 3 c). Fig. 3 (d) shows a detail of the 3D-printed cells.

Regarding the back support of the chaise, the combination and transition between high- and low-density areas ensure enough resistance to counteract bending and torsion caused by the weight of the user, while allowing for large deformations to fulfil functional requirements. The cell shapes and sizes, as well as the overall shape of the geometry can be adapted to individual requirements. For example, depending on the user's weight, the cell densities can be adjusted to match individual needs. This process has been implemented through parametric modelling using Rhinoceros 3D and its built-in visual programming environment Grasshopper with the structural analysis plug-in Karamba.

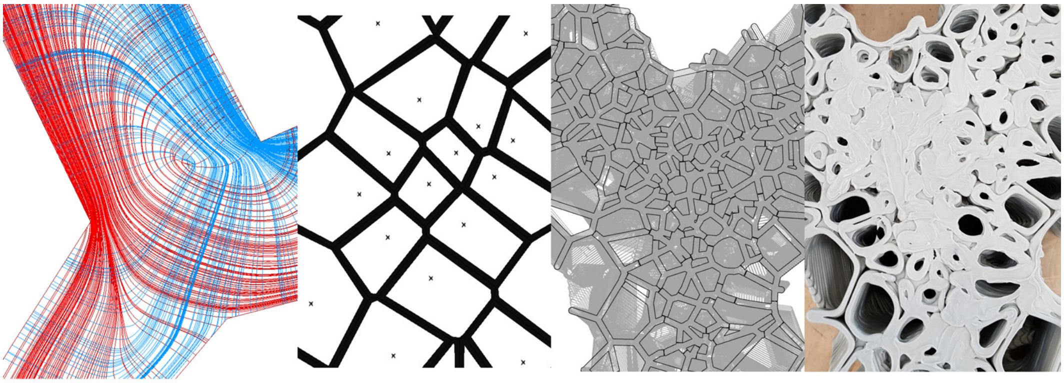
(a) (b) (c) (d)

FIGURE 3 Stress analysis detail (a), subdivision pattern (b), cell face section (c), cell face section printed (d).

Robotic Production

Cell Size and Thickness

The cell walls consist of two layers in order to increase stability during material deposition. Thermoplastic polymer (TPE) remains malleable after extrusion and therefore deforms significantly when unsupported. These material characteristics prevented the use of wireframe structures, as implemented in the work of Martínez [6]. For this reason, a cellular approach via continuous self- supporting material deposition has been developed.

The angles of the Voronoi cell walls are also controlled by strategic placement of the cell centres. These points are placed in a configuration so that all cell walls are oriented between -45Ð and 45Ð in relation to the printing bed to avoid the need for any additional supporting material during material deposition.

Conversion of the cellular pattern into robotic toolpaths is a process that starts by intersecting the assembly though planes as shown in Fig. 4. The intersection results into a series of polylines, specifically one polyline for each cell (Fig. 4 a). Since it is more efficient to deposit material via continuous tool paths, an algorithm has been developed to join the individual polylines into one continuous line (Fig. 4 b). By using this algorithm, which is based on an implementation of the traveling salesman algorithm, fabrication time decreased by 90% through minimisation of the printer head travel time between material deposition.

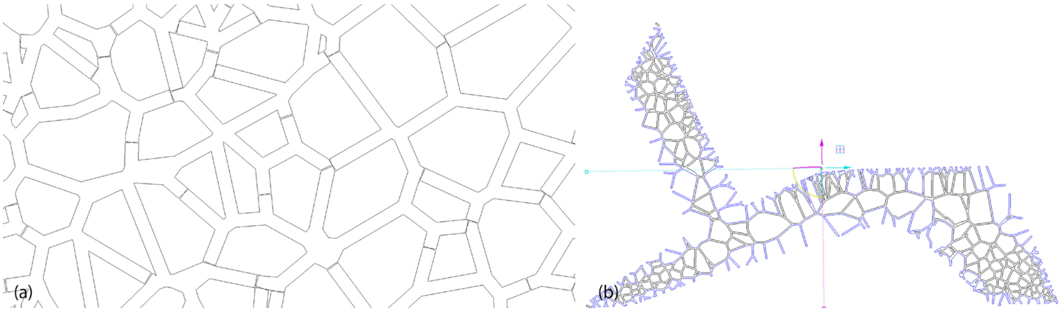

FIGURE 4 Conversion of cellular geometry (a) into robotic toolpaths (b).

Polylines to G-code

The X, Y, and Z coordinates of the control points of the polylines are converted into G-code using a proprietary algorithm. The link between the cellular pattern, their control points, and the resulting G-code ensure satisfactory control over the production process which was completed without any manual intervention.

Conclusion

The Design-to-Robotic-Production (D2RP) process presented in this paper is unique in the way it links computational design with robotic production. Along with traditional design tasks, this process involves the design and optimisation of material distribution layout to achieve desired functionalities. This approach introduces an adaptive behaviour that allows for customisation as well as improved performances (e.g. increased comfort for the chaise longue case study). It furthermore reduces material waste by depositing self-supporting material only where structurally required, while speed of material deposition is increased because of the proposed optimised robotic path.

This D2RP process has potential for developing other types of products including civil engineering scale structures and components. Future work will investigate scaling effects by modelling and testing larger scale prototypes. Furthermore, the potential of stiffness control to improve comfort and durability of industrial design products by cushioning and damping will be explored.

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