Shape optimization of robotically fabricated structures taking into account manufacturability constraints.

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Abstract

This study focuses on minimum compliance shape optimization of small-scale truss structures which are produced using freeform 3D printing. We developed a method to take into account the limitations of freeform 3D printing during the optimization process, to guarantee that the optimized designs are manufacturable, regardless of their possibly complex geometry.

The optimization problem is formulated as follows:

$$\begin{aligned} \min_{\mathbf{x}} : \quad & C(\mathbf{x}) \\ \text{s.t.} : \quad & g_j(\mathbf{x}, \theta(\mathbf{x})) \leq 0 \\ & \theta(\mathbf{x}) \equiv \arg\min_{\theta} \sum_j g_j(\mathbf{x}, \theta) \end{aligned}$$

C	Compliance
g_j	Fabrication constraints
$\mathbf{x}$	Geometric design variables
θ	Robotic fabrication variables

The optimization problem consists of two nested optimization loops. The external loop varies the design variables $\mathbf{x}$ in order to find the lowest possible compliance C, while satisfying the fabrication constraints. These constraints are represented by the functions g_j, obtaining a value of zero if no fabrication errors occur, and a positive non-zero value proportional to the severity of the error if an error occurs. An internal optimization loop searches the values of the robotic fabrication variables θ for which the sum of all fabrication constraints g_j is minimal. In order to reduce the computation time, the fabrication constraints g_j are evaluated in advance for all possible values of $\mathbf{x}$ and θ. This results in a manufacturability map that follows the concept of machinic morphospaces, as developed by Menges [1]. A machinic morphospace represents the set of all solutions that are manufacturable with a given machine.

PSO was used to perform a number of optimization runs of a simple test case, a truss consisting of six interconnected nodes, with the *xy*-position of the three support nodes as design variables. This showed that designs which were optimized considering fabrication constraints had a higher compliance than the designs optimized without such constraints. The production of a physical prototype confirmed that the theoretically manufacturable design could effectively be produced. We can conclude that adding fabrication constraints to the optimization problem indeed results in manufacturable designs, without the need for post-processing to solve manufacturability issues. It should however be noted that this problem with only six geometric variables already converges relatively slowly using a meta-heuristic optimization algorithm. For better performance, it would be advised to use gradient-based or hybrid algorithms.

References

[1] A. Menges, "Morphospaces of robotic fabrication", in *Rob|Arch 2012: Robotic Fabrication in Architecture, Art and Design*, Vienna, Austria, December 17-18, 2012, S. Brell-Çokcan, J. Braumann, Eds. Vienna: Springer Science & Business Media, 2013. pp. 28-47