Design optimization for direct 4D printing

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ABSTRACT

4D printing has emerged as a family of methods that enable fabrication of 3D structures, which can transform into new shapes when subjected to environmental stimuli such as temperature, light, or humidity. Attractive features of 4D printing are the potential to realize a complex 3D structures by self-assembly from low-dimensional printed structures, offering significant advantages of saving both raw materials and manufacturing time, as well as new programmed functionality.

In this talk, we introduce the "direct 4D printing" method, which is based on multi-material 3D printing of active composite materials [1]. Using inkjet 3D printing, we manufacture laminate structures from a polymer material and an elastomer, the latter being programmed with a compressive stress during the printing process. When heated, the stiff glassy polymer softens, resulting in release of the stress in the elastomer, and causing the structure to actively deform into a new, permanent 3D configuration.

To model and predict the deformation behaviour of direct 4D printed structures, we formulate a nonlinear thermomechanical model, which is validated experimentally [2]. To be able to fully exploit the design and fabrication freedom offered by direct 4D printing, we develop computational methods and tools that allow us to optimize the design of structures in terms of shape and material distributions for tailored active deformation and programmable self-assembly behaviour:

a) First, we present a design optimization approach based on the nonlinear, geometrically exact 3D beam model with laminate cross-sections [2]. The cross-section parameters of complex beam structures, i.e., diameter and layered material distribution of polymer and elastomer, are tailored for desired large deformation behaviour, including complex bending and twisting effects.
b) Furthermore, we also present a nonlinear topology optimization method, which is based on the level set approach with the extended finite element method (LS-XFEM), combined with the density method to describe the polymer/elastomer material phases [3].

The capabilities of both computational design optimization methods are validated and demonstrated by fabrication of physical artefacts, highlighting the potential for increased functionality with material and time savings through 4D printing.

REFERENCES

[1] Z Ding, C Yuan, X Peng, T Wang, HJ Qi, ML Dunn: "Direct 4D printing via active composite materials". *Science Advances* 3 (4), e1602890 (2017)

[2] Z Ding, O Weeger, HJ Qi, ML Dunn: "4D rods: 3D structures via programmable 1D composite rods". *Materials & Design* 137, 256-265 (2018)

[3] MJ Geiss, N Boddeti, O Weeger, K Maute, ML Dunn: "Combined Level-Set-XFEM-Density Topology Optimization of 4D Printed Structures undergoing Large Deformation". *ASME Journal of Mechanical Design,* in press (2019)