Strategies for mechanical metamaterial design

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Summary

Making their initial appearances in the field of optics, acoustics and electromagnetism, metamaterials [1–3] are carefully engineered macro-, micro- and nanoscale materials, whose physics is governed by their architecture - often consisting of periodically arranged specially designed unit cells. The central concept of design-determined material properties has led to the discovery of several non-trivial materials with unique functionalities such as negative refraction index. Mechanical metamaterials [4–19] - a more recent branch of metamaterials - further extend this principal idea to design soft deformable materials with extreme mechanical responses as well as advanced functionalities such as programmability in mechanical response [20], tunable control of response parameters [13], shape-transformable materials [16, 37].

On a structural level, the properties featured by a majority of mechanical metamaterials can be ascribed to the finite number of soft internal degrees-of-freedom that allow the system to deform via preprogrammed frustration-free, low-energy deformation pathways in the configuration space [37]. As it so happens, often it becomes possible to represent these low-energy deformation modes in an ideal fashion through a mechanism consisting of rigid geometrical units connected together either by soft slender connector joints (3D) or by ideal pin-joints (2D) [18, 38–41]. Conversely, these mechanisms also serve as an intuitive starting point to initiate and adapt the design of mechanical metamaterials to requirements. Traditional design methods mainly comprise of trial and testing, and can only well handle simple design tasks, not to mention that the suggested designs can be periodic and non-generic. In order to solve complex design problems, computer algorithm based inverse strategies provide state-of-the-art solutions [43–51]. One way in which they can be utilized is by framing the material design problem as an optimization problem, where we optimize the values of parameters that control the design -

design variables - in order to meet the desired target response. Such 'inverse' material design frameworks offer two other main advantages: *(i)* automating the process by facilitating to optimize the material design for more than one target property, and *(ii)* discovering many near-perfect solutions that fit the target criteria reasonably well, thus enlarging the design space [35].

In this thesis, we present novel inverse strategies to design 2D mechanical metamaterials, whose zero-energy deformations can be modeled by one degree-of-freedom mechanisms consisting of pin-jointed polygons. We demonstrate that, by optimizing the characteristic trajectory of these mechanisms, one can design generic metamaterials that exhibit complex programmable mechanics, atypical zero-energy deformations and shape-transformable behavior.

Chapter 2 – In the second chapter of this thesis, we start off by discussing a physical approach aimed to qualitatively model the four different mechanical regimes observed for a laterally confined quasi-2D biholar sheet [20], by a one degree-of-freedom spring-coupled mechanism consisting of pin-jointed rectangles - *soft mechanism.* Once confirming its capability to do so, we show that the experimentally observed mechanical regimes can also be retrieved geometrically. Based on the geometrical analysis, and as the most pertinent result of the chapter, we suggest an inverse strategy to rationally design mechanical metamaterials for several different confinement controlled responses. The main essence is that different types of equilibria, that unfold as the control parameter (horizontal confinement in this case) is varied, can be manipulated by the trajectory of the underlying mechanism. We modify our soft mechanism by coupling its hinges with torsional springs and observe some of the qualitative agreements with [70] in terms of how the critical values of horizontal strains that separate the mechanical regimes alter as the thickness of the hole-connector beams is increased. Finally, we use the soft mechanism to understand the case where the neighboring holes in the biholar sheet approach to be equi-sized, and mathematically show that at this limiting point, the four mechanism regimes emerge from the unfolding of an imperfect pitchfork bifurcation.

Chapter 3 – In the third chapter, we begin by asking the question which generic systems of specially designed pin-joint quadrilaterals can form perfect or approximate mechanisms. We do this with the ultimate purpose of designing generic yet flexible 2D mechanical metamaterials based on these mechanisms, which feature an extremely low-energy deformation mode, while ordinarily one would expect them to be rigid. We demonstrate that the problem can be answered by searching for optimal design of a *precursor* one degree-of-freedom mechanism such that it meets a specific target curve that characterizes the internal deformation. We tackle this problem inversely, formulating it as an optimization problem, and in a nutshell, optimize for the design variables in order to match the prescribed target curve. We utilize a search algorithm inspired from the food-searching capability of bird flocks - *Particle Swarm Optimization (PSO)* [60, 90, 91] to carry out the optimization task. We show that the hyperparameter setting of PSO plays a critical role in influencing the solution quality, solution distribution type and the local or global search behavior of the swarm. PSO discovers a plethora of designs that render high quality approximate mechanisms, when structurally one would guess them to be rigid. We prove that for the good-quality solutions, it is highly likely that PSO gets trapped in deep local minima, while this is not true for the poor-quality solutions. Finally based on these mechanisms, we fabricate unit cells of soft mode exhibiting metamaterials, via 3D printing and suggest a method to tile these unit cells into regular tessellations, while preserving the original soft mode.

Chapter 4 – In the fourth chapter, we put to test a crucial feature of any automated inverse material design framework, which is to be able to optimize for not just one but multiple target properties. Specifically, by optimizing for different target curves of the *precursor* mechanism, we aim to: *(i)* statistically correlate the performance of our model versus the general complexity of the input target curves, and *(ii)* on top of these computer-designed mechanisms, fabricate bi-stable and tri-stable unit cells and some tilings comprising of them that exhibit multi-stable behavior. Doing this, we establish novel examples of 2D shape-transforming mechanical metamaterials.