Closed-Loop Design of Programmable Liquid Crystal Polymer Surfaces through Automated Photoalignment and Machine Learning

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Liquid crystal polymer (LCP) coatings enable programmable surface morphing through spatially controlled molecular alignment, offering opportunities for adaptive optics, soft robotics, tuneable interfaces, and bioinspired materials. However, realizing complex surface morphologies remains challenging because existing photoalignment methods often require manual generation of exposure patterns and are generally limited to specific classes of director-field configurations. Moreover, the inverse problem of determining the alignment required to achieve a desired three-dimensional surface has remained largely unexplored. Here, we present a closed-loop computational and experimental framework for the design of programmable LCP surfaces. We first establish the relationship between fundamental director distortions and the resulting out-of-plane deformation, revealing how local splay- and bend-dominated regions govern surface curvature. Building on this understanding, we develop a generalized computational workflow that automatically converts arbitrary analytical descriptions of director fields into the binary mask sequences required for digital micromirror device (DMD)-based photoalignment, eliminating manual mask design and substantially expanding the accessible alignment design space. Using this platform, we fabricate a diverse range of complex alignment patterns that produce programmable surface topographies. The resulting dataset of paired alignment fields and surface profiles is then used to train a machine-learning model that solves the inverse design problem by predicting the required director field from a target surface height map. The model accurately reconstructs alignment patterns for previously unseen morphologies, enabling rapid design of experimentally realizable LCP surfaces. This integrated framework establishes a general strategy for programmable surface engineering by unifying physical understanding, automated fabrication, and inverse computational design.