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Harnessing Deep Learning of Point Clouds for Morphology Mimicking of Universal 3D Shape Morphing Devices

Shape-morphing devices, an emerging technology in soft robotics, have attracted significant attention due to their potential in applications such as human-machine interfaces, biomimetic robotics, haptic feedback, and tools for manipulating biological systems. These devices mimic the flexible, dynamic behavior of biological organisms, enabling programmable, controllable, and reversible transformations. This capability is highly desirable in fields such as augmented reality (AR), virtual reality (VR), and bioengineering. However, achieving precise 3D programmable shape morphing (PSM) is technically challenging because it requires controlling complex, often nonlinear, interactions within arrays of soft actuators to replicate target shapes accurately. Current control approaches struggle with the complexity of these systems, which limits their applicability in real-world settings.

To address this challenge, we propose Shape Morphing Net (SMNet), a machine learning-based solution that utilizes point cloud data to represent the deformation of shape-morphing devices. SMNet bridges the gap between the complex deformations of shape morphing devices and the high-dimensional control inputs needed to manipulate them. It allows for accurate, real-time reproduction of target shapes across multiple actuation mechanisms. Using finite element analysis (FEA) simulations to generate training data, SMNet leverages Kernel Point Convolution (KPConv) and PointNet++ architectures to map point cloud geometries to control input vectors.

The versatility of SMNet was tested on three types of 3D PSM devices with different actuation principles —ionic, thermal, and pneumatic actuators. In each case, SMNet demonstrated significant improvements in control precision, achieving accuracies as high as 97.68%, compared to 82.23% with traditional methods. This substantial improvement is a testament to the model's ability to handle the complex couplings inherent in 3D shape morphing.

We conducted a series of demonstrations to validate SMNet's performance, including replicating real-world shapes through 3D scanning and producing virtual shapes using Autodesk Maya software. The model successfully reproduced both simple and complex target shapes in the ionic and thermal actuators with high fidelity. However, the pneumatic mechanism, which involves greater actuator coupling, performed better on simpler shapes but struggled with more intricate geometries. We quantitatively evaluated the performance using Chamfer Distance, standard deviation, and Hausdorff Distance metrics, confirming SMNet's effectiveness in most cases.

In addition to its precision, SMNet's real-time capabilities are noteworthy, with prediction times under one second, making it suitable for dynamic, real-world applications. This breakthrough lays a foundation for further advancements in soft robotics, enabling the deployment of 3D shape morphing technologies in applications that require rapid, accurate, and versatile shape transformations, such as surgical tools, adaptive robotic skins, and custom-designed haptic devices.

Focus areas

Authors: Prof. CHORTOS, Alex (Purdue university); Mr SARKAR, Dhirodaatto (Purdue university); Mrs SUO, Jiaqi (Purdue university); WANG, Jue

Presenter: WANG, Jue