Soft Pneumatic Actuator Design using Differentiable Simulation

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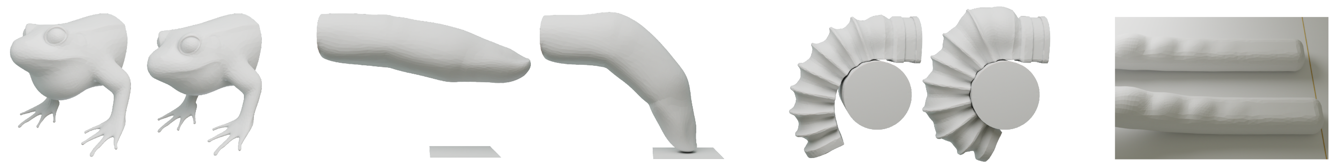

Figure 1: Shape optimization of a pressure cavity. We optimize the interior cavity of pressurized chambers to reach prescribed shapes (Frog, Finger, Gripper), displacements (Worm), and contact forces (Gripper). These results are then fabricated and tested experimentally to validate the efficacy of our pipeline.

ABSTRACT

We propose a computational design pipeline for pneumatically-actuated soft robots interacting with their environment through contact. We optimize the shape of the robot with a shape optimization approach, using a physically-accurate high-order finite element model for the forward simulation. Our approach enables fine-grained control over both deformation and contact forces by optimizing the shape of internal cavities, which we exploit to design pneumatically-actuated robots that can assume user-prescribed poses, or apply user-controlled forces. We demonstrate the efficacy of our method on two artistic and two functional examples.

CCS CONCEPTS

• **Computing methodologies → Modeling and simulation**; **Shape modeling**; **Simulation evaluation**.

KEYWORDS

Differentiable Simulation, Finite Element Method, Shape Optimization, Pneumatic Actuator, Soft Robotics

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1 INTRODUCTION

Pneumatic chambers embedded in soft materials is the predominant method to build soft robots that can reliably grasp fragile objects, locomote in challenging, obstacle-rich environments, or take on a desired shape if in- and deflated. Yet, it remains challenging to design soft pneumatic actuators that fulfill a set of artistic and functional requirements, especially if frictional contact is considered during the design phase.

In this work, we propose a differentiable simulation for shape optimization of soft robots that interact with the environment and satisfy a set of user-prescribed geometric and mechanical requirements. We extend the recently proposed differentiable incremental potential formulation to support pneumatic actuation and show that high-order finite element simulation with a Mooney-Rivlin material can faithfully capture large deformations of pneumatically-actuated soft robots.

We define a contact-aware objective that promotes high traction forces between a robot and an object, which is a common scenario in optimal actuator design for soft manipulation. We show that traction forces are too expensive to compute in optimizations, as they are only accurate if a dense mesh is used for simulation. We propose instead to use gradients of the contact potential as a proxy, as they are less sensitive to discretization.

The resulting inverse problem is computationally challenging to solve due to the sheer size of the problem (each iteration requires several forward simulations, which take up to tens of minutes) and the large number of local minima. We use a cascading optimization approach, together with a hierarchical shape parameterization with linear blend skinning subspaces, to tackle this optimization problem,