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EXPERIMENTAL AND NUMERICAL ANALYSIS OF LASER-CUT PNEUMATIC SOFT ROBOT STRUCTURES

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1. Introduction

Soft robotics has emerged as one of the most promising and rapidly evolving fields within robotics research. Unlike traditional rigid systems, soft robots are composed of highly compliant materials such as elastomers, allowing them to interact with their surroundings in more adaptable, safer, and biologically inspired ways [1]. Soft robotics also presents an opportunity to rethink actuation and control. Instead of relying on rigid mechanical linkages and electric motors, many soft robots utilize pneumatic actuators that mimic biological muscle behavior [2,3]. Combined with cost-effective fabrication techniques, like molding, 3D-printing, and laser cutting, these technologies make soft robotic systems increasingly accessible.

However, the highly nonlinear mechanical behavior of soft (rubberlike) materials coupled with complex fluid-structure interactions during pneumatic actuation presents significant challenges in design optimization. To address these, the optimal robot structure can be achieved through iterative finite element (FE) simulations.

This contribution presents the analysis of the mechanical behavior of laser-cut, pneumatically actuated soft robotic structures through experimental characterization and finite element simulations. By examining the mechanical response of different structural geometries and material compositions, the study contributes to a broader understanding of how soft robots can be used more effectively and widely in the future.

2. Robot layout, fabrication

For the analysis a PneuNet Bending Actuator was adopted based on the design description of the SoftRobotics Toolkit design library [3,4]. The soft robot structure (see Fig. 1.) consists of a series of channels and chambers inside an elastomer, which are inflated during pressurization and thus, creating the actuation. In this study, three base shapes (rectangle, triangle, ellipse) were manufactured, with two different line densities (high and low) for each shape.

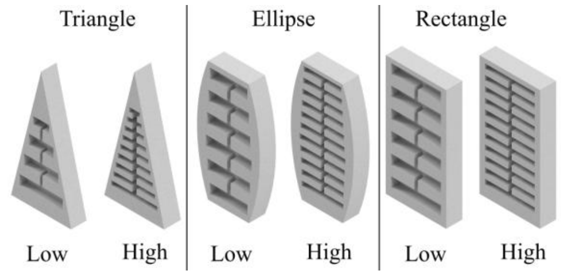

Fig. 1. Robot shapes with various line densities

The actuators were fabricated using laser-cut acrylic molds, for which an automated SVG shape generation tool was developed in Python to create the different actuator geometries with adjustable parameters. The bottom part of the actuator was cast from Elastosil M4601 material, while for the top (inflatable) part Ecoflex 00-30 and 00-50 two-component silicones were applied, thus altogether 12 robot variations were fabricated. After molding and degassing in a vacuum chamber, the specimens were cured in a drying oven. After that, the top and bottom parts of the soft robot structures were glued together using silicone adhesive.

3. Experimental investigation

The actuation of the soft robots was performed an Arduino-based pneumatic control board with pressure levels of $p = 35\,\text{kPa}$ and $p = 50\,\text{kPa}$ adjusted for Ecoflex 00-30 and 00-50, respectively. The deformation of the soft robots was analyzed with image processing methods using Motion Tracker Beta [5] software. As a result of the deformation analysis, the relation of the total bending angle $\theta(p)$, and the bending trajectory of the end point $\boldsymbol{\gamma}(p) = [x(p) \quad y(p)]^T$ was determined.

4. Material characterization

The material behavior of the Ecoflex and Elastosil materials can be described using Ogden's incompressible hyperelastic model, where the corresponding strain energy function is expressed using the Abaqus [6,7] formulation, as

$$U^{\text{Ogden}} = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2} \left(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3\right) \qquad (1)$$

where the corresponding material parameters μ_i and α_i were determined using experimental data, which were acquired from uniaxial tensile and compression using an Instron 3345 Single Column Testing System equipped with a 5kN load cell.

5. Finite element simulations

For the numerical simulation of the actuation process a full 3D FE model is built in Abaqus (version 2022) [7] using C3D8RH elements with hybrid formulation. The simulation was conducted in an automatic Python environment enabling the evaluation of various model parameters. The fluid-structure interaction of the chamber inflation was modelled using the Fluid Cavity Interaction approach with an incompressible gas model. During the inflation, the hyperelastic instability led to numerical convergence problems (i.e. the balloon-inflation problem [6]). To resolve this problem, the FE-simulations were performed using the arc-length method (RIKS analysis).

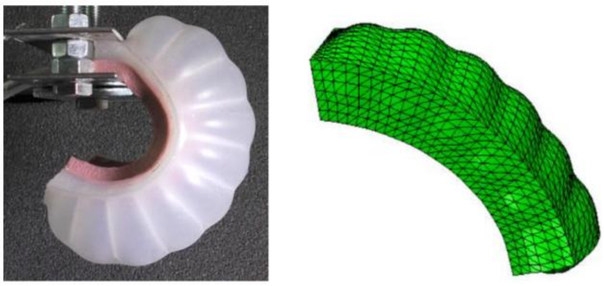

Fig. 2. Actuation (inflation) measurement and the finite element simulation of the soft robot actuation

6. Results

The comparison of the FE-simulation and the measurement results showed good agreement (see e.g. Fig. 3), indicating that the proposed material model and FE simulation approach are adequate for the analysis of such soft robot structures. Moreover, the results also revealed that both the robot shape and the line density significantly affect the maximal bending angle, and the end-point trajectory during actuation.

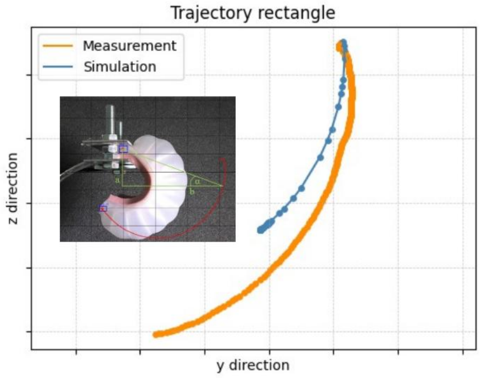

Fig. 3. The comparison of the image processing and simulation results of the end-point trajectory for a rectangular specimen with high line density made from Ecoflex 00-50 material

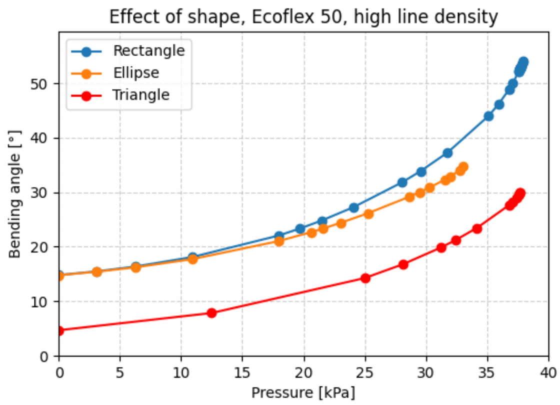

Fig. 4. The comparison of bending angles of the different robot shapes with high line density made from Ecoflex 00-50 material

Acknowledgments

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