Data Driven Inverse Kinematics of Soft Robots created using Geometrical Constraints ensuring Safe Manufacturing

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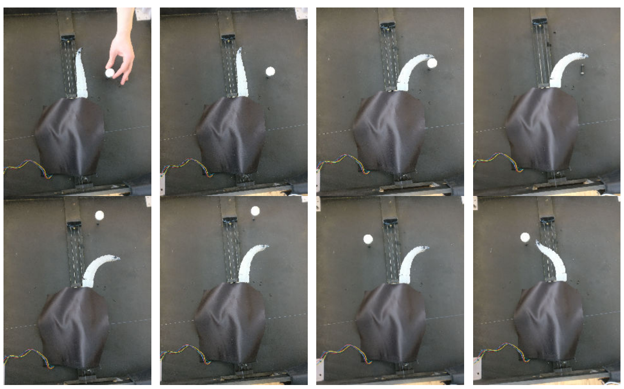

Fig. 1. Successful manufacturing of a cable driven soft silicone robot is a manual trial and error process to determine a safe geometric shape that will not break the robot when extracted from its mold. The figure illustrates a prototype that took us one attempt to get right with geometrical design constraints.

***Abstract*—We present an empirical derived geometric feasibility model for manufacturing of cable driven soft silicone robots using a single cast molding process. Through structured experiments and observations, we inductively designed a mathematical model based on direct geometric measurements of a boundary representation of a soft robot design. Further, we demonstrate how the feasibility testing is incorporated into modeling with constructive solid geometry (CSG) operations to verify design before 3D printing molds for casting soft robots. The simplicity of geometric - position-based- constraints for a design verification model provides us with a finite dimensional parameter space linked to a low number of CSG parameters. Future work may exploit our low-number parametric position-based approach in combination with position-based dynamics to yield fast simulations for exploring the design space prior to manufacturing**

***Index Terms*—Soft Robotics, Inverse Kinematics, Geometric Constraints**

I. Introduction

Robots are playing an ever-growing role in modern society, due to their ability to perform a variety of tasks more accurately, less expensive and faster than humans. The majority of these robots are *rigid-bodied* robots made of either aluminum or steel, which makes them robust, reliable and able to work in hazardous conditions unsuitable for humans. However, using these robots present several issues that makes it desirable to investigate the usage of less rigid materials. Unlike their rigid counter-parts, soft robots are often designed to mimic biology, with common sources for inspiration including octopi [1], geckos [2] or parts of the human body [3]. This provides the robots with a natural versatility to variable tasks, which is difficult to produce in rigid robots.

Conventional robots are often quite expensive, which makes them difficult to acquire for an average consumer. The unit-cost of soft robots is very low and manufacturing is 'kitchen table level' as evidenced by the Soft Robotics Toolkit grabbers [4]. Hence, it is quite affordable to test new ideas or replace a whole robot if it is broken. Given that everybody can make such robots and everybody can afford creating them, then the real challenge to enable this to become more than a gimmick or toy is to be able to efficiently design functional robots that work in the real world.

II. Methodology

The first step towards creating usable soft robots is to increase the efficiency of the manufacturing process. With the advent of affordable consumer-level 3D-printers, rapid production of casting molds has become more feasible than ever. However, as of now, starting to use 3D printing for mold creation of soft silicone robots is a manual trial and error process of refining a design idea by manufacturing a real mold and testing the design by casting and finally observing the real robot. Observe in Figure 2 examples of robots that failed due to poor design choices. Through structured experiments and observations, we inductively designed a mathematical model based on direct geometric measurements of a boundary representation of a soft robot design which we have used to demonstrate how the feasibility testing can verify designs before 3D printing molds for casting soft robots. The simplicity of geometric - position-based - constraints for a design verification model provides us with a finite dimensional parameter space linked to a low number of shape parameters.

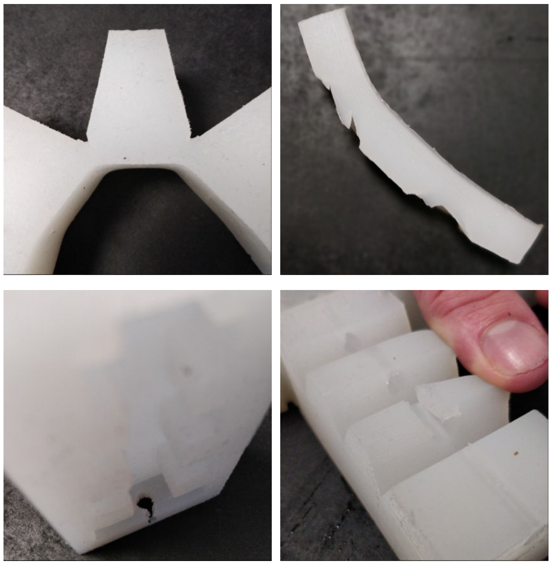

Fig. 2. Robots that have ruptures due to too thin structures, poor cable shielding placements, or too sharp features.

Figure 2 shows how rupture and other manufacturing failures are observed. To lower the risk of the manufacturing process failing, we formulate geometric constraints on the thickness and curvature of the robot shape - the thickness constraint, for example, can be formulated as: For a robot $\mathcal{S}$, where $S \in \mathbb{R}^3$ is a closed connected set and p is a point, we define the restricted surface neighborhood $\mathcal{N}_\delta$ at $\mathbf{p}$ to be any point $\mathbf{q} \in \mathcal{S}$ that lies inside the thickness cone $\mathcal{T}_\delta(\mathbf{p})$ and where a continuous path to $\mathbf{p}$ exists strictly inside $\mathcal{T}_\delta(\mathbf{p})$. The restricted robot surface at $\mathbf{p}$ is then simply $\mathcal{S}_\delta(\mathbf{p}) \equiv \mathcal{S}/\mathcal{N}_\delta(\mathbf{p})$. We can now state our novel thickness constraints formally as

$$\forall \mathbf{p} \in \mathcal{S}, \quad \mathcal{T}_\delta(\mathbf{p}) \cap \mathcal{S}_\delta(\mathbf{p}) = \emptyset \tag{1}$$

This definition states that the robot is too thin if only a "backside" surface part intersect the thickness cone. The reason is that any surface connected directly to $\mathbf{p}$ will always intersect with the thickness cone.

Another issue of soft robots is that it is difficult to predict how they will behave during actuation. This is due to the soft robots being under-actuated systems, which means that they have more degrees of freedom than actuators. We therefore want to be able to predict the shape of a soft robot for a given set of control parameters, as this allows us to solve the inverse problem: finding an optimal set of control parameters needed to achieve a given deformation. This means that we are able to overcome the reality gap, and as shown in [5] we gain performance and naive parallelism from using local instead of global models.

The usage of accessible and in-expensive depth sensors provides us with agile and low-cost method for both validation of designs simultaneously with providing us with direct methods for acquiring data for constitutive models. Figure 3 shows our robot finger suspended in the CUBE environment during a training session.

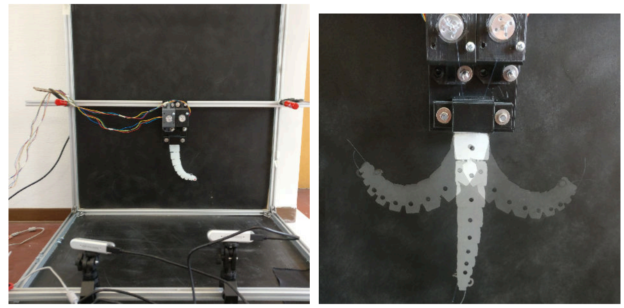

Fig. 3. One of the robots manufactured in the first try, suspended in the CUBE environment during training of an inverse kinematics model.

Observe in Figure 4 some examples of robots created in one try using our geometric constraint model.

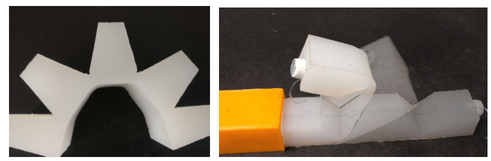

Fig. 4. Robots created using our geometric constraint model.

III. Conclusion and Future Work

We present a new novel model for verification of cable driven soft silicone robots. Our model includes four elements, cast extraction, thickness constraints, curvature constraints, cable shielding constraints.Further we presented an efficient numerical approach to measure thickness with the added benefit of providing design feedback to correct too thin structures. We presented insight on making good shelving for cable shielding as well as empirically derived thresholds that so far have guaranteed safe designs of our robots.

Future work may exploit our low-number parametric position-based approach in combination with position-based dynamics to yield fast simulations for exploring the design space prior to manufacturing. The data driven inverse kinematics model would then allow us to validate our simulations, further bridging the gap between reality and simulations.

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