SoRoCAD: A Design Tool for the Building Blocks of Pneumatic Soft Robotics

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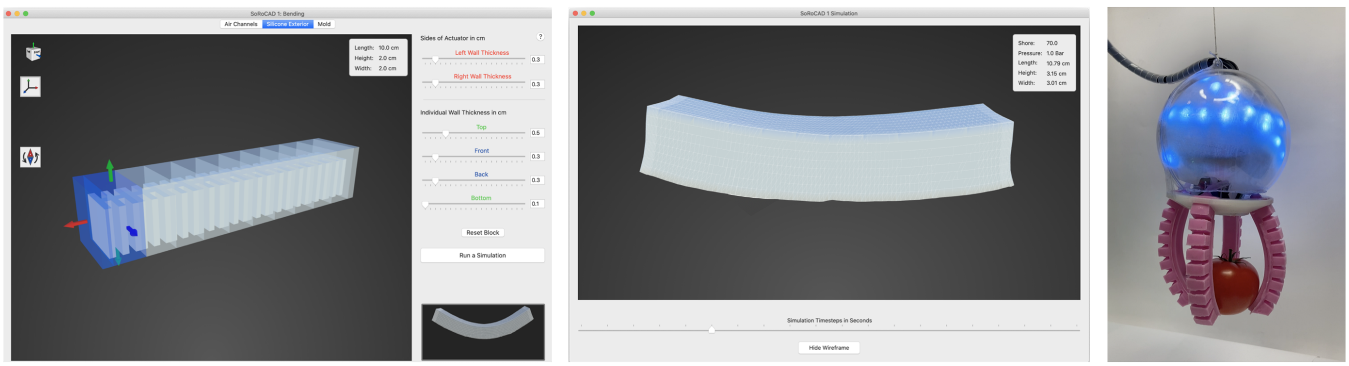

Figure 1: *SoRoCAD* is a tool that simplifies creating pneumatic soft robots. It encodes soft robotics design expertise by exposing meaningful design parameters, and eliminates the need for most prototyping iterations by simulating the resulting actuation in the design step. The left image shows the design of a soft bending actuator, which is reviewed in the simulation to check its behavior (middle image). The right image shows a soft robot in which four segmented bending actuators are combined to function as a gripper.

ABSTRACT

Soft robotics uses soft, flexible materials and elastic actuation mechanisms to create systems that are more adaptable and tolerant to unknown environments, and safer for human-machine interaction, than rigid robots. Pneumatic soft robots can be fabricated using more affordable materials compared to traditional robots and make use of technologies such as 3D printing, making them an attractive choice for research and DIY projects. However, their design is still highly unintuitive, and at up to two days, design iterations can take prohibitively long: The behavior of, e.g., a pneumatic silicone gripper only becomes apparent after designing and 3D printing its mold, casting, curing, assembling, and testing it. We introduce *SoRoCAD*, a design tool supporting a Maker-friendly soft robotics design and fabrication pipeline that incorporates simulating the final actuation into the design process.

CCS CONCEPTS

• **Human-centered computing → User interface toolkits**.

KEYWORDS

Soft Robotics, Fabrication, Simulation, User Empowerment, CAD Design

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1 INTRODUCTION

Soft robotics is the subset of robotics that focuses on technologies that more closely mimic the physical characteristics of living organisms [2]. Soft robots afford fluid movement and are robust under physical stress [10]. This provides them with increased adaptability and flexibility for interacting with their environment [3], and enables various tasks that cannot be accomplished by rigid robots [20].

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Compared to traditional robots, soft robots can be built using more affordable materials and technologies such as 3D printing, making them attractive for personal fabrication, whether in research labs or DIY projects. To create flexible shapes, silicone rubber is commonly used, although other inflatable or shape-changing materials like Shape Memory Alloys (SMAs) are also suitable [4, 19, 21, 23]. Actuation uses techniques such as air (pneumatics), liquids (hydraulics) or embedded threads. Of these, pneumatics are easier to use in practice than hydraulics since there is no need to protect the electronics from water or deal with messy leaks.

A pneumatic soft robot consists of one or more pneumatic actuators. Each of these in turn consists of basic actuator building blocks, such as actuated cuboids. In principle, fabricating these actuators only involves three steps: First, design parameters of the external and internal geometry, such as wall thicknesses, that define the behavior of the actuator are selected in CAD. Next, a suitable mold for the actuator is 3D printed. Finally, a silicone rubber cast is created using the printed mold. However, this process is an open loop: The entire design needs to be fabricated and assembled before you can test whether the soft robot moves as intended. Depending on printers and silicone used, this can easily take two days, and offers no way to verify actuator behavior beforehand. The resulting trial-and-error process can be frustrating, especially for beginners [15]. This fact is exacerbated by the complex dependencies of the movement of an actuator on its external and internal geometry. Developing a feel for how parameters like wall thickness, height, etc. affect actuation and movement is an arduous learning task.

For rigid mechanical movement, a variety of mechanical construction sets such as LEGO[1] or Meccano[2] have long existed to help users understand and design systems, but the pool of creatable shapes with such rigid physical kits is limited. Therefore, for prototyping soft robotics, we aim for digital design support, and introduce *SoRoCAD*, a tool that supports designing soft robots by encoding design expertise for soft robotics. It contains a pipeline for designing soft robot actuators, and supports previewing their behavior by simulating the final actuation during the design phase. This simulation drastically reduces the trial-and-error process when building soft robots, since the user can test whether the actuator moves as intended without having to physically build it each time. While professional CAD tools such as Autodesk Fusion 360[3] also integrate simulation features, these tools are missing a dedicated workflow and UI designed specifically to support the simple simulation and fabrication of soft robotics actuators. Thus, our contributions in this paper are:

- an overview of Maker-friendly design parameters that are essential for soft robotics design, and their effects;
- the *SoRoCAD* tool for soft robotics design that exposes these parameters in its UI, and that supports previewing the behavior of actuators before fabrication.

2 RELATED WORK

In recent years, soft robots have become popular due to their advantages such as their adaptability to the environment and suitability for human-machine interactions. In HCI, they fall into the research field of Shape-Changing Interfaces. In this field, Material Science is of crucial importance, and its influence in this area of HCI has been growing. Qamar et al. [17] provide a recent review of shape-changing interfaces in HCI, and of how shape changing techniques have evolved. They categorise the type of shape change into mechanisms such as rollable, foldable, and inflatable. For each of these, researchers have developed a variety of designs for soft, flexible, shape-changing robots.

2.1 Designing and Fabricating Soft Robots

Creating a soft robot poses several challenges, starting with a good concept of its internal actuation network, irrespective of whether it uses air, water, or threads. Several projects have developed fabrication processes for one particular type of soft robot each. These include hardware kits like InflatiBits [13], which lets children experience and learn about the construction of pneumatic actuated robots in a playful manner, or various materials such as thermoplastic fabric in Printflatables [18] to fabricate large and functional pneumatic objects.

Siloseam [15] presents a whole pipeline that improves and streamlines the time-intensive mold–cast–cure pipeline of silicone actuators. It supports fabricating inflatable silicone bladders in almost any shape via custom air channels, in three steps: Preparing a vector graphics outline of the bladder, importing it into the design tool and adding air channels, and extruding the resulting vector graphic using Fusion 360 to create the mold. While SiloSeam allows almost any shape for the air chamber, the only movement supported is inflation. Defining other movements like bending or elongation is not supported, reducing the complexity of shape design but limiting the output and movement options. Siloseam's workflow has recently been extended to prototype wearable haptic interfaces as well. [7] MorpheesPlug [12] is a toolkit for creating shape-changing interfaces that is integrated into Fusion 360. The toolkit provides design parameters six standardized widgets the user can define and also includes a hardware platform to actuate the fabricated widgets. In their evalutation users wished for a simulation feature to better understand the behaviour of the widgets. Ma et al. [14] developed a method that automatically calculates the interior air channel design to actuate a given 3D object movement. However, their focus is on the algorithm calculating the 3D-printable model, and not on helping users develop an understanding of the design parameters.

It is important to understand how the movement can be influenced, and what types of movements a soft robot can perform [11]. Basic 'finger actuators' are in the shape of a cuboid and are used frequently for bending and gripping tasks [20]. Combining these basic actuators can create complex movements. By combining five cuboid actuators each being able to elongate, Sheperd at al. [19] fabricated a small robot with four legs that is able to crawl and undulate to move forwards. Finger actuators have also been investigated by comparing four different soft robotic grippers and testing their characteristics of force and gripping to understand for what materials they are most suitable [10].

Including other materials in addition to silicone rubber in soft robots opens up more opportunities. For example, PneUI [23] presents

[1]https://www.lego.com
[2]https://www.meccano.com
[3]https://www.autodesk.com/products/fusion-360/overview

Parameters		Effect
$w_{top} > w_{bottom}$		Actuator bends upward
$w_{top} < w_{bottom}$		Actuator bends downward
$w_{top} = w_{bottom}$		Causes actuator to extend or inflate without bending
Small $n_{chambers}$		Results in concentration of pressure; can lead to bursting due to excessive pressure
Large $n_{chambers}$		Evenly distributes pressure, smooth deformation when positioned at regular intervals
Small	$h_{channel}/(w_{top} + w_{bottom})$	Increases stability, but decreases flexibility, i.e., the ability to bend or extend
Large	$w_{side}/l_{channel}$	
Small	$w_{chamber}/s_{chambers}$	
Large	$h_{channel}/(w_{top} + w_{bottom})$	Lowers resistance to extension and bending
Small	$w_{side}/l_{channel}$	
Large	$w_{chamber}/s_{chambers}$	

Table 1: Design parameters of soft robot actuators and their effects assuming that an actuator is made of a homogeneous material, without reinforcement in the walls, and involving symmetry properties: top, bottom, side and air chamber wall thickness ($w_{top}, w_{bottom}, w_{side}, w_{chamber}$), air channel height and length ($h_{channel}, l_{channel}$), number of air chambers ($n_{chamber}$), spacing between the air chambers ($s_{chambers}$)

several pneumatic actuated soft robots made from composite materials. The authors evaluate how using pre-programmed structures help to design and control the angle and direction of shape changes.

2.2 Application Areas

The various gripping and shape-changing features of pneumatic soft robots enable a wide range of wearable applications in HCI. Several wearables projects use them as haptic interfaces. For example, the PneuHaptic [9] wristband creates haptic cues by increasing and decreasing air pressure inside its pneumatic networks of silicone actuators. These cues were found to be missed by the user more frequently in active movements. Scarfy, an interactive scarf [22], and ShapeTex, a shape-changing fabric [6], integrate actuation into textiles and fabrics in order to, e.g., adapt the wearer's look to their emotion or intent. ShapeTex and PneuHaptic are each limited to one type of motion: ShapeTex can bend according to the ShapeTex pattern, and PneuHaptic inflates air channels into round bumps.

As these examples illustrate, designing and fabricating soft robots can employ a variety of techniques depending on the purpose of the robot: For example, it may need to support a specific actuation type, or sense user input.

However, all the approaches presented require the designer to complete the entire design–fabricate–test pipeline to verify if their robot behaves as intended. This takes significant time and has the potential for frustration if observed behavior does not reflect design intent. To complicate things further, it may remain unclear to the designer if their design or their fabrication is at fault.

The key concept underlying SoRoCAD, therefore, is to (a) encode design knowledge by identifying the right parameters for soft robotics design that can be abstracted into a user interface for the designer to manipulate, and (b) to provide, at design time, a *simulation* of the resulting actuation that takes these design parameters into account and applies the right manipulations (such as a certain air pressure) to the model to mimic intended use. Such a design tool should reduce the need for iterative fabrication, cutting down on design cycles and times.

3 BACKGROUND & PARAMETERS

We focus on supporting the design of pneumatically actuated soft robots due to their advantages explained above. These soft robots consist of a pneumatic network of elastomeric *air channels* to distribute air pressure. Pressure changes in this network result in motion [16]. Both shape and movement of these soft robots are defined by the exterior and interior of the actuator(s) they consist of. The interior design of each actuator determines the air distribution inside it.

To achieve movement, the pneumatic network of embedded elastomeric air channels with defined shapes is connected to an air pressure source, distributing the air inside each actuator. The exterior layout therefore includes parameters for the thickness of each actuator wall. This wall thickness has a strong influence on the direction in which an actuator moves, making it a key design parameter. Air always flows in the direction of least resistance, bulging the walls with the least resistance outwards. Consequently, under the assumption that an actuator is made of a homogeneous material, without reinforcement in the walls, and involves symmetry properties, an actuator will bend towards its thicker wall [5]. Gohlke et al. [8] present some essential technical parameters for designing silicone soft robots, such as air pressure, material stiffness (Shore value), air channel thickness, and their effects. They do not, however, report on varying wall thickness to achieve different deformations, and do not state the effect of these parameters on the movement direction.

3.1 Fabrication Process

Creating a silicone soft robot actuator happens in two phases: the design phase, which provides the design for the molds, and the fabrication phase, in which molds are created and the actuator cast from them. This fabrication phase in turn consists of three steps. In the first step, a mold for the silicone rubber needs to be printed. The mold must be robust enough to use for casting, and is often made from PLA or PVA. The second step is casting: The 3D-printed mold is filled with silicone, and then needs to cure. The time depends on the silicone used. The third step depends on the mold

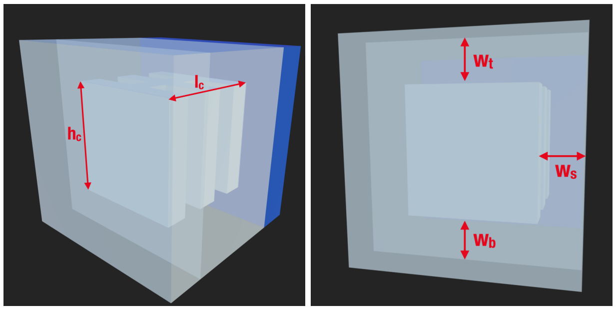

Figure 2: Design parameters of soft robot actuators: air channel height ($h_{channel}$), air channel length ($l_{channel}$), top wall thickness (w_{top}), side wall thickness (w_{side}), bottom wall thickness (w_{bottom})

material. Soluble printing material, like the PVA used in Siloseam [15], functions as a placeholder for the air channel inside the soft robot, and is dissolved to form the air channel. With non-soluble material, the mold is split into two halves, and the two resulting cured casts are glued together with uncured silicone afterwards.

3.2 Parameter Study

To better understand how design parameters influence actuator movement, and to identify parameters that could be exposed to the designer in a UI, we first conducted a technical evaluation. We took Gohlke et al.'s findings [8] as a starting point. Their overview, however, is not exhaustive. We therefore tested several air channel designs, observing how air is distributed and which channel design leads to what movement. We also investigated what parameters, such as the number of air chambers in the air channel, chamber height, or wall thickness, are the most important to consider when building a soft silicone actuator (Fig. 2). To investigate these parameters, we started with a simple zigzag air channel design. We varied these parameters over eighteen design cycles, and recorded the effects. The results are summarized in Table 1, and helped us to develop a database of air channel types and identify appropriate design parameters for *SoRoCAD*.

4 SOROCAD

Based on these results, we created *SoRoCAD* (Soft Robotics CAD), a 3D design environment for soft robotics. Initially, *SoRoCAD* supports fast iterative design of soft pneumatic finger actuators, a common choice in soft robotics, by using single cuboid building blocks. How a pneumatic actuator's geometry governs its movement is not trivial, and designing it from scratch without prior knowledge is challenging. It is difficult to know what shapes actuators usually have, and how material and geometry parameters such as wall thickness and air chamber height influence their movement. To simulate how an actuator will move once fabricated, *SoRoCAD* uses the open-source *Simulation Open Framework Architecture (SOFA)*[4], which is widely used for physics-based simulation in research, prototyping, and development. We also use the *SOFT ROBOTS Plugin for SOFA*[5], which combines mechanical modeling of soft robot elements with real-time direct/inverse FEM (finite element method) solvers.

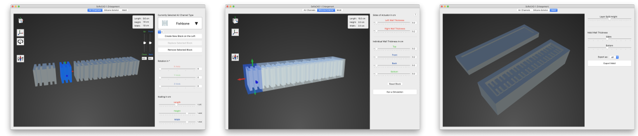

Figure 3: In *SoRoCAD*, the designer starts by building the pneumatic network (left), before defining the exterior geometry such as wall thicknesses (middle), and finally exporting the automatically generated mold.

4.1 Design Process in *SoRoCAD*

SoRoCAD is designed to fit the two-phase design process described earlier in section 3.1. In the design phase, the user first defines the interior and exterior geometry, then views the mold needed to cast the actuator (Fig. 3). The design parameters *SoRoCAD* exposes are those that we identified in our study. The following sections will explain each step of the design phase. For orientation, Fig. 5 presents the full design and fabrication process of a soft robot using *SoRoCAD*.

4.1.1 Air channels. When starting a soft robot design from scratch, the user first defines the interior air channels to provide space for the air to be pumped into. Fig. 3 (left) shows the pneumatic network of air channels inside a silicone soft robot actuator. The air channels distribute the air inside, pushing out those parts of the soft robot with the least resistance. Most soft robots contain a single air channel that is repeated several times, like a skeleton (Fig. 3). This basic element can have various shapes; we investigated six of these in our parameter study. The user designs the air channels using single basic elements as building blocks. They can assemble these building blocks one by one to configure the pneumatic air channel network for the actuator. For each air channel building block, they can choose its individual size and shape, e.g., a fishbone or a snake.

4.1.2 Silicone Exterior. In the second step, the user defines the exterior geometry, by setting the thickness of the walls enclosing the air channels (Fig. 3, middle). As a starting point, *SoRoCAD* generates a default exterior block around each air channel block, which the user can then adjust individually. The relations between wall thicknesses are key to define the motion of the actuator. Therefore, every time the user changes an exterior wall thickness, small 5-second animated GIFs provide an instant preview of the resulting change in behavior (Fig. 4e). This helps the user understand how the design parameters influence actuator movement. The primary feature during exterior design is simulating the movement of the designed soft robot actuator. Clicking the *Run Simulation* button opens a dialog asking for Shore values and air pressures to start rendering the simulation (Fig. 4d). The Shore value influences actuator movement since it defines the stiffness of the silicone; smaller Shore values correspond to more flexible silicone in its cured state. The user can manually step through the time steps of the simulation (Fig. 4g).

[4]https://github.com/sofa-framework/sofa/

[5]https://project.inria.fr/softrobot/

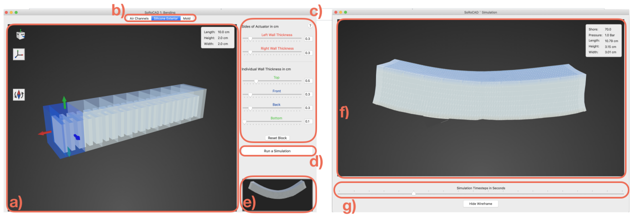

Figure 4: Left: Interface of *SoRoCAD* during exterior geometry design: a) the viewport on the left showing the actuator (viewport control is possible); b) the three steps in the design pipeline (Air Channel, Exterior, and Mold); c) sliders and text fields to control parameters that define the actuator; d) Run Simulation button; e) simulation preview (GIFs). / Right: Simulation window: f) viewport showing the simulation of the actuator; g) the user can step through the simulation using a timeline slider.

SoRoCAD does not provide any information about the internal volume of the actuators in their unactuated and fully-actuated states yet, but the user can define the air pressure value when starting a simulation. To compare different alternatives, the user can also open several soft robot designs and start a simulation window for each design in parallel.

4.1.3 Mold. For fabrication, *SoRoCAD* provides a 3D-printed mold to cast the silicone rubber actuator. When the user switches to the mold generation step, a functioning mold consisting of two joinable halves is generated automatically. The user can export those as 3D-printable files (in stl. and obj. format). These exported files can be opened and processed with other CAD applications. The user can adjust the split point if necessary to ensure that the silicone casts can be uncased easily, without material being stuck in the molds.

4.1.4 Actuator Templates. Since starting out to design a pneumatic soft robot is not trivial, *SoRoCAD* provides templates for basic motions like inflation, bending, and elongation. Choosing a template will skip the interior air channel design, since the template already provides this. The user starts in the exterior geometry design; she can adjust the actuators in the template to her desired dimensions, or use them as a starting point to design other custom actuators.

4.2 Software Implementation

SoRoCAD requires a Mac running macOS Mojave 10.14 or higher. The SoRoCAD project uses Xcode storyboarding for designing the user interface. I.e., SoRoCAD uses a Model-View-Controller pattern where all the Views have a corresponding Controller file. Regarding system resources, for easy repetitive shape designs the simulation process only needs less than ten seconds to be completed.

4.2.1 Installation Process. Setting up the SoRoCAD software on a macOS system requires pulling the git and opening it with Xcode. While the SoRoCAD software itself works by simply starting the Xcode project, a run script needs to be executed to deploy the simulation feature using SOFA when starting SoRoCAD the first time. Therefore, compiling and starting the software the first time requires around 2–3 hours. The run script is integrated in the Xcode project and therefore the user does not need external help to execute it.

4.2.2 Implementation Challenges. The biggest challenge while developing SoRoCAD was integrating the simulation using SOFA. As mentioned, to deploy the simulation, a run script was implemented, because the SOFA tool needs several plugins to be installed such as the Soft Robotics plugin and the CGAL plugin. The There Soft Robotics website offers a pre-compiled binary, but this binary does not include the CGAL plugin that we need to transform the surface mesh that SoRoCAD generates into volumetric meshes that SOFA requires for simulation. Therefore, when installing the software the run script needs to build the SOFA tool with both of these plugins embedded when developing SoRoCAD by creating the run script. Other challenges we encountered were mostly related to a reasonable UI design. Developing the tool to its current state took approximately ten months.

4.2.3 Technical Evaluation of Simulation Accuracy. A technical evaluation that provides correlation of simulation and fabricated actuators is important. The tool gives a preview of the direction of the actuator and of what the real movement will look like using the simulation feature, e.g., is it going to be a bending motion, or just inflation. Our tool provides the same dimensions in design and the fabricated actuators. We tested if simulation and real behavior are consistent for different movement types, including bending, s-shape, and inflation and found that the behavior match the simulation *SoRoCAD* provides. The accuracy of exact angles matching in the simulation and reality needs to be investigated in the future.

5 RECOMMENDATIONS FOR FUTURE EVALUATION

Initial impressions from informal user observations and interviews, which had to be conducted remotely due to the pandemic, have supported our hopes that *SoRoCAD* can enable novice users to rapidly design simple soft robots that move as intended, by providing features that allow them to explore, test, and understand how to design soft robots. In more formal user studies, we intend to seek validated answers to the following questions around the usage of *SoRoCAD*:

Can novices design functional soft robotic actuators using *SoRoCAD*? Users should be able to design specified soft robotics actuators using *SoRoCAD* without getting frustrated by trial-and-error. The fast turnaround time of the simulation may help greatly.

Can *SoRoCAD* help novices understand the design factors affecting actuator movement? Soft robot design is highly unintuitive, especially for novice users. Without knowing how design parameters relate to each other, and how material choices and air pressure impact behavior, building a soft robot usually requires resorting to finding templates and other resources online. Our simulation should improve this, by enabling quick exploration and iterative testing.

How does *SoRoCAD* support knowledge transfer, i.e., allow novices to debug and customize their designs? *SoRoCAD* should help users think about further aspects that are not directly needed to design the shapes at hand. This should enable novices with no knowledge of pneumatic soft robotics to explore, design,

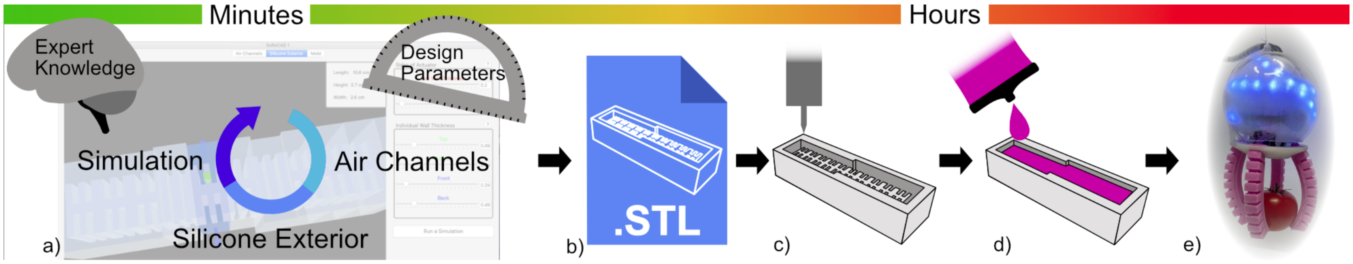

Figure 5: Overview of the design and fabrication process using *SoRoCAD*. a) The design tool encodes expert knowledge in the form of design parameters from our technical evaluation that are exposed to the designer in the UI. In an iterative design and simulation cycle, she defines interior (air channels) and exterior geometry, and checks the resulting behavior in the simulation. These iterations take only minutes each. b) For the verified design, 3D mold files are exported, c) 3D-printed, and d) the actuators are cast from the molds. e) The finished actuators can be assembled to build soft robots, such as a gripper.

and debug functional soft robots, and should support rapid prototyping and iterative testing. Our goal is that the visibility and language of the interface allow users to discover the design factors affecting their actuators, and inspire novel creations.

6 LIMITATIONS & FUTURE WORK

Several UI and design workflow improvements were suggested in our informal tests which we added. These included an orientation guide to track the axis, an option to change the complete size of the actuator in the exterior geometry design, the option to let the user decide at which side the air channel blocks are created, other terms for naming the walls, the selection of multiple block elements to change parameters simultaneously, and a copy/paste function.

There are several milestones we would like to tackle additionally for future versions of *SoRoCAD*. At the moment, the design pool *SoRoCAD* offers is limited to rectangular cuboid shapes. While these are the common building blocks of more complex actuators, the inability to have actuator shapes such as spheres can restrict the application areas of the resulting actuators. It also limits the range of possible movements and shapes. Therefore, as a first milestone we want to support other shapes than cuboid rectangles and more complex shapes. This also would require testing to derive the correct value ranges to expose in the UI. Since fabricating more complex shapes with different air channel blocks or different orientations of air channels is rather complex, the mold generation algorithm inside *SoRoCAD* would need to be extended ([1] provides potential starting points for this). This milestone is rather complex and will be tackled after all other milestones. Architecturally, *SoRoCAD* supports designing more complex shapes, and the SOFA library provides simulation data for testing limits like actuators bursting or breaking.

As a second milestone, we also aim to add the ability to combine several actuators in one design to create more elaborate soft robots. Research on how these actuators can be connected meaningfully, possibly using connection functions like those in LEGO kits, still needs to be conducted. This extension would increase the pool of shapes *SoRoCAD* can support. At the moment, *SoRoCAD* robots can create output in form of force or touch, applied to a user or any other object, by using pneumotactile feedback [8]. As a third milestone, we plan to extend this functionality with input modalities, for example by providing a way to integrate touch sensors. *SoRoCAD* could then support simulating the dependencies of sensors and actuators, such as a certain force triggering a 50 degree bending angle. This could lead to programmable structures, inspired by the approach described in PneUI [23]. We envision those structures to be changeable and not purely pre-programmed.

7 CONCLUSION

We presented *SoRoCAD*, a CAD tool that contains a beginner-friendly pipeline to design the building blocks of pneumatic soft robotics actuators. Using simulation, *SoRoCAD* enables users to preview actuator movement behavior during design, eliminating much of the trial-and-error loop of traditional soft robotics fabrication. First informal user tests support our expectations of *SoRoCAD* helping novice users understand the influence of design parameters on the movement behavior of their soft robot. In the future, we aim to further study the effects of *SoRoCAD* on novice users, and to refine the functionalities of the tool to enable the construction of more complex shapes, while keeping design features like affordable materials and technologies. *SoRoCAD* is available as open source (https://hci.rwth-aachen.de/sorocad), and we hope that it helps inspire a new generation of soft robotics designers.

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