Designing and Fabricating Pneumatic Textures for Human-Robot Interaction

Yuhan Hu
Cornell University
Ithaca, US
yh758@cornell.edu

Guy Hoffman
Cornell University
Ithaca, US
hoffman@cornell.edu

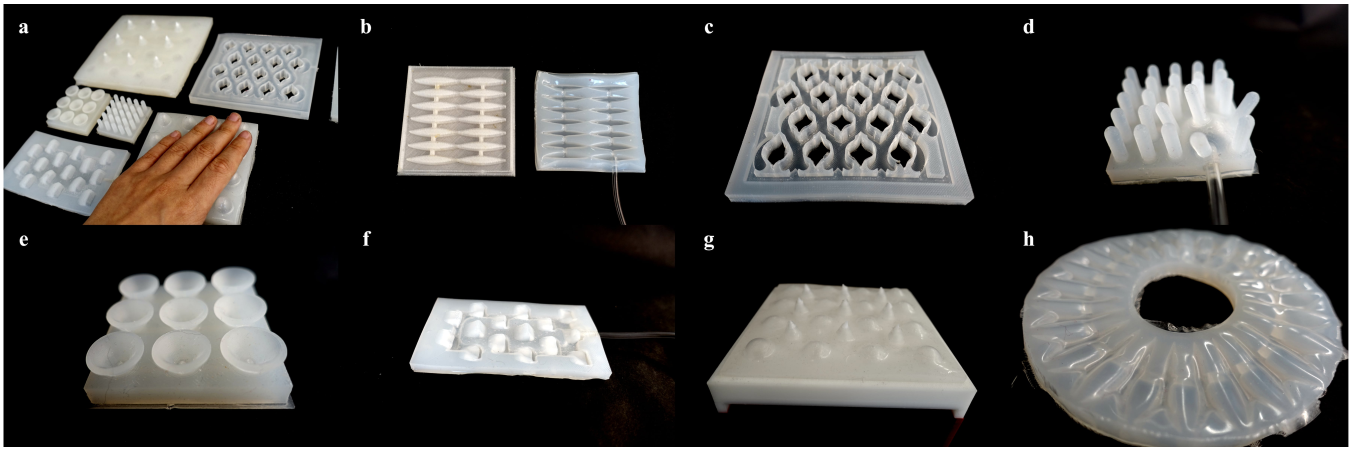

Figure 1: A collection of skin texture modules, including wrinkles (b), pores (c), tentacles (d), suction cups (e), scales (f), goosebumps and spikes (g), and circular wrinkles (h).

ABSTRACT

Inspired by biological systems that use skin textures to display emotions, we designed soft pneumatic textures for interactive robots to communicate their internal states visually and haptically. In this paper, we present our developmental process of creating new forms and behaviors of soft surface textures. A bio-inspired approach was used in ideating and prototyping texture patterns for natural communication. We discuss challenges we encountered when fabricating and actuating the textures, present potential solutions and compare different alternatives. We hope the documentation of our design and fabrication process can make the technology more accessible to researchers in human-robot interaction field, and serve as an inspiration for further research and development of pneumatic and expressive skin textures.

KEYWORDS

soft robot, skin, textures, human-robot interaction, haptics, bio-inspired design, pneumatics

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1 INTRODUCTION

In this paper, we discuss challenges and solutions of designing and integrating soft robotic skin with pneumatic textures. Inspired by biological systems displaying changes to their skin textures to reflect internal states, such as human goosebumps and cats' back fur raising, we developed an expressive channel for interactive robots in the form of texture change on a soft skin [7]. Our preliminary user study indicated that a robot's texture changes can be a promising channel for communicating specific emotions, such as excitement, anger, sleepiness and sadness, while users observe or touch the textures [5].

To integrate skin changes, we designed pneumatically actuated shape changing texture arrays, that deform in response to pressure changes inside fluidic chambers. We explored realistic and meaningful structures of such shape-changing texture units, and presented a texture vocabulary in [6] that generates different visual and haptic experiences.

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In this paper, we share our design approaches and some challenges we faced during the developmental process of soft textures. A bio-inspired approach is used to ideate new forms and behaviors of texture change, which are then modeled into mechanical design with different options of design parameters. To manufacture such textures, we discuss the challenges of fabricating surfaces with unique structures and present our solution of molding both internal chambers and external structures. Several limitations are discussed with potential alternatives mentioned. To actuate and control the textures, we compare two actuation systems, one with pneumatic pumps and one with powered syringes for their use in human-robot interaction contexts. Finally, we discuss additional challenges of integrating such soft textures on a social robot and generate communicative signals in different interaction scenarios. We hope the documentation of our process and discussion of challenges can make the technology more accessible to researches in human-robot interaction field for the exploration of future design of soft robot skin.

2 DESIGNING AND MODELING SOFT TEXTURES

Since skin texture change is still an under-explored area in soft robotics and human-robot interaction (HRI) research, the main challenge is to identify the design primitives and generate texture patterns that are meaningful and realizable for HRI scenarios.

We approach this with a bio-inspired design method, explore forms and shape-changing patterns of skin textures in biological systems. For example, a human furrowing the eyebrows generates dynamic wrinkle-like textures on his forehead, expressing states like confused and concentrated (fig. 2 a). To translate such behavior to robot skin design, we simulate the pattern to develop soft structures that can change between a flat surface to a furrow when adding a negative pressure (fig. 2 c). The strip-like air cavity forms a valley when being vacuumed, with several design parameters being iterated throughout the model generation process, including the width (w) and length (l) of the cavity, distance between two cavities (d), thickness of the top film (t) and the height of the cavity (h) (fig. 2 b). Such parameters were hand-tuned by iterative prototyping and testing to closely mimic wrinkle-like visual effect and haptic tension.

Parameters were experimented and intuitively decided following empirical experience on soft material mechanics. For example, a thinner top wall usually results in a higher deformation, thus a deeper valley when sucking out the air. However, this process has a slow iteration cycle and includes many arbitrary choices based on researchers' experience. Some software tools allow us to quickly test and predict with different design parameters and come up with an optimal solution before physically building the module. For example, Finite Element Analysis (FEA) can simulate motions of soft actuators such as bending and linear elongation, predict motion-force profile for a more efficient system [1, 9]. However, instead of optimizing efficiency or forces as most actuators do, our research focus on the users' haptic and visual experience with textured modules, which are hard to come with the simulation tools alone. Thus, we iterate our design through physical prototyping and user testing to get feedback on touch and visual effects, such as by feeling the tension or roughness of the skin with hand.

After design parameters are fixed for a specific texture pattern, we integrate them on a skin module. Texture distribution is defined by the shape of the robot surface, degree of freedom (DOF) for actuation, and the ideal function of the skin. In this example, the wrinkle textures can be arranged as a double-column parallel wrinkles on a rectangular module (fig. 2 c) or on a circular module with radial wrinkles (fig. 2 d) which was designed to fit under a mushroom robot's umbrella, simulating mushroom wrinkles. Air chambers connect all texture elements for uniform deformation. For skin modules with multiple control DOFs, networks of chambers can activate groups of textures separately.

3 FABRICATION

Aside from designing texture patterns and iterating design parameters for expressive skin structures, the mechanical realization of the skin is challenged by some limitations in the fabrication process. This section presents our fabrication approach and discusses some challenges we encountered during fabrication.

We use silicone elastomer (Ecoflex 00-30, Smooth-on, Inc) and an open-faced molding and casting process to fabricate the soft textures. Molding technique is commonly utilized in the fabrication of pneumatic soft robots [4, 8, 11]. However, none of them specifically present the molding process of skin textures with unique and non-flat surface shapes such as spikes and tentacles (see fig. 1 d, g). Our approach uses an assembled molding box to mold such texture modules. The mold box is composed of two elements, one for casting the inner air cavity and chambers (fig. 3 a, top), the other to mold the external structure of the skin surface (fig. 3 a, bottom). To enhance haptic experience, we embed rigid elements for some textures, such as embedding sharp, plastic tips when casting spike textures.

To elaborate the fabrication process, we capture the steps of fabricating a scale-like texture module in figure 3. Plastic mold components are 3D-printed using PLA and assembled to form a mold box (a). Haptic elements could be 3D-printed as well and embedded within the mold prior to casting (b). Then, we pour the mixed liquid silicone into the mold to cast the upper part of the skin (c). After the silicone is cured, we disassemble the mold box to take out the silicone (d). The bottom layer is fabricated with an inextensible film (paper) embedded (e). Finally the cured upper part is attached to the bottom layer to form a closed cavity (f), an air tube is added and sealed with silicone adhesive (Sil-Poxy, Smooth-on).

We encountered several challenges during the fabrication process. First, randomness is introduced in the manual fabrication steps. Tilted surfaces could be caused by uneven or tilted operation platform. Skin modules may have a variance of thickness due to the experimenter's error in eyeballing the filling level of silicone. Bubbles could be generated when pouring the liquid elastomer, and result in leakage and non-uniform deformation. Second, small and fine textures are hard to achieve. Liquid silicone may not fill in thin gaps (less than 1mm) due to surface tension and friction with the mold. Alternatively, a digital light processing 3D printer may allow for directly printing elastic materials [3], fabricate soft pneumatic textures of high precision, less randomness and with faster speed.

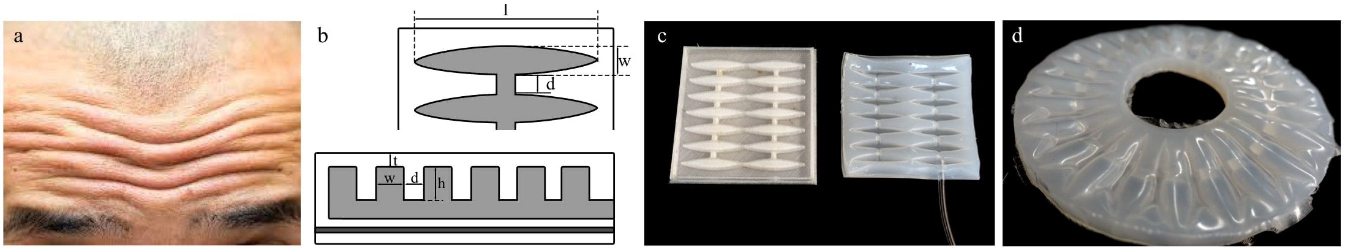

Figure 2: Inspired by dynamic wrinkles on human forehead expressing states like confusion or concentration (a), we model the mechanical design of wrinkle-like textures to generate similar expression. (b) depicts a top view (top) and a side view (bottom) of air cavities (gray) and elastomer body (white) with different design parameters. The mechanical patterns are adapted to form skin modules of different shapes, such as a rectangular skin with parallel wrinkles (c), or a circular mushroom-like skin with radial wrinkles (d).

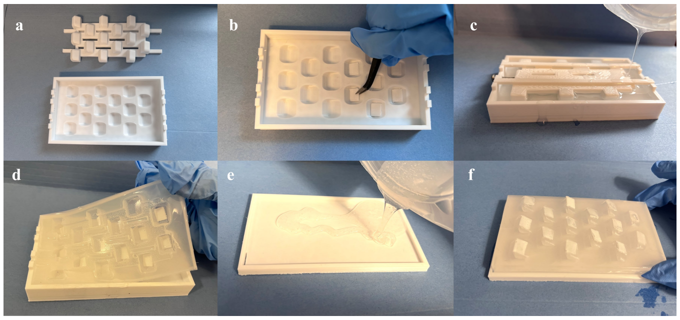

Figure 3: Fabrication process of a scale-like texture module: (a) 3D print mold components; (b) embed haptic elements; (c) pour liquid silicone into the box to cast the upper part of the skin; (d) detach the cured silicone from the mold, (e) cast the bottom part with an inextensible film, and finally (f) bond the two parts together with additional Ecoflex.

In addition, Ecoflex silicone does not form a tight bonding when gluing pieces of different materials, such as attaching the haptic component. Extra adhesive materials need to be applied in order to confine the elements to withstand users' touch.

4 CONTROLLING TEXTURE MODULES

To actuate and control the texture modules for use in human-robot interaction context, the system needs to have a fast response, low noise profile, and a self-contained size. We compared two powering systems for potential use: One method uses an air pump controlled with an array of solenoid valves and a pressure sensor for feedback [2]. We came across several challenges with this method: (1) The rotary pump and solenoid switches are noisy and distracting; (2) It is difficult to control the position precisely, and it is determined by the precision of the pressure sensor; (3) The system is inefficient because of the leakage and exhaust. (4) The skin may burst due to the failure of control or malfunction of sensors, such as when inflating too much air into the chamber. [7]

To overcome the above issues, we designed a second system, a power syringe actuated by a linear stepper motor [7]. This system has lower noise level, lower risk of burst by applying mechanical constraints, and precisely controlled deformation with prior calibration of skin and negligible leakage. However, the size of the powering system is proportionally scaled up by the volume of air chambers, and the control DOFs. It is difficult to achieve high frequency responses due to the limited speed of a stepper motor. Future work will look into more compact and easily controllable solutions, such as *FlowIO* [12]

5 INTEGRATING TEXTURE MODULES ON SOCIAL ROBOTS

Our goal is to integrate skin modules on social robots to enhance their communication capacity and expression effectiveness. Implementing skin textures on robot surfaces introduce several challenges and design considerations. First, our method only allows for the fabrication of a flat skin. Even though the skin module is bendable, it may not fit well with a robot surface of curvature and complex geometry. New fabrication methods need to be investigated for realizing curved skin modules. Second, the type of skin textures and placement needs to match a robot's form and character. For example, hair-like textures may only be placed on the back of a robot's head instead of on a face. It may not be appropriate to integrate suction cups on a humanoid robot skin, which may cause uncanny feelings [10].

Skin texture expression needs to be consistent with other communicative modalities of a robot to reduce confusion. Texture change serving as a form of involuntary expression in nature, usually communicate in a less noticeable and ambiguous fashion compared to other expressive channels such as facial expression, speech, and gestures. Thus, when designing a texture expression for an HRI application, designers and researchers should set reasonable expectation and consider use cases accordingly. For example, communication that requires accurate messages with low error tolerance may not be ideal. The ambiguity may lead to an open interpretation that varies for different people and interaction scenarios. Future research will compare and combine texture expression with other communicative modalities in human-robot interaction studies.

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