HYFAR: A Textile Soft Actuator for Haptic Clothing Interfaces

Jose Barreiros
Cornell University
jab879@cornell.edu

Tianshu Liu
Reality Labs Research, Meta
tianshu.liu@fb.com

Maurizio Chiaramonte
Reality Labs Research, Meta
mchiaram@fb.com

Kristy Jost
Reality Labs Research, Meta
kjost@fb.com

Yigit Menguc
Reality Labs Research, Meta
softrobot@fb.com

Nicholas Colonnese
Reality Labs Research, Meta
ncolonnese@fb.com

Priyanshu Agarwal
Reality Labs Research, Meta
pagarwal18@fb.com

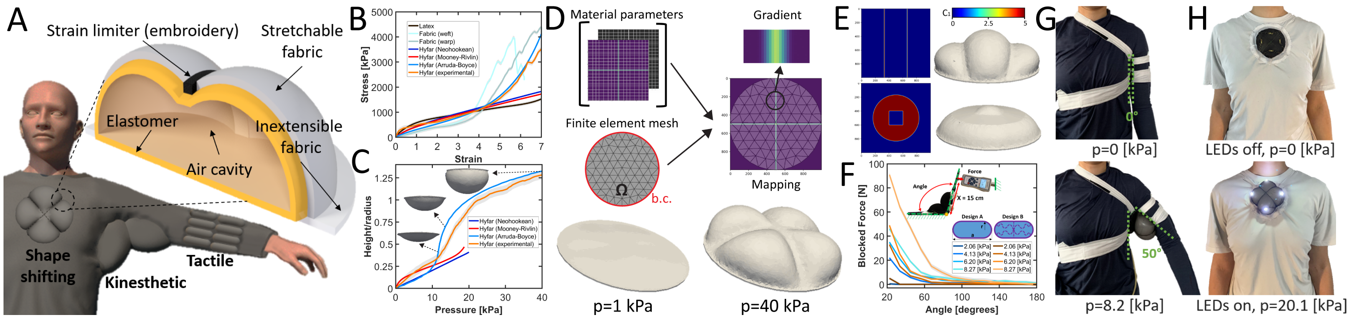

Figure 1: A) HYFAR for haptic clothing interfaces. B) Uniaxial tensile test of HYFAR, its constitutive materials, and finite element (FE) simulation. C) Experimental data and simulation of the inflation of a circular actuator. D) Mapping of material parameter matrices to the FE mesh for an actuator embroidered with a cross-pattern (c.p.), and simulation results. E) Simulation of HYFAR with various embroidered patterns inflated at 40 kPa. F) Blocked force versus bending angle for stadium-shaped HYFARs integrated in a unidirectional joint. Upper-body functional garments integrated with HYFAR G) (Design B) for kinesthetic haptic feedback, and with H) circular actuator (r=4.5 cm; c.p. and four LEDs) for showcasing shape shifting behavior.

CCS CONCEPTS

- **Human-centered computing → Haptic devices**.

KEYWORDS

Interaction, haptics, AR/VR, soft robotics

ACM Reference Format:
Jose Barreiros, Tianshu Liu, Maurizio Chiaramonte, Kristy Jost, Yigit Menguc, Nicholas Colonnese, and Priyanshu Agarwal. 2022. HYFAR: A Textile Soft Actuator for Haptic Clothing Interfaces. In *Proceedings of August 08–11, 2022 (SIGGRAPH '22).* ACM, New York, NY, USA, 2 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

Haptic feedback is important in augmented and virtual reality (AR/VR) because it closes the loop of touch sensation and provides physical realism to what is being rendered in the virtual world [3]. In this context, clothing is an appealing substrate for haptic interfaces because it is in direct contact with the user's skin and provides a large space for delivering haptic feedback. Most haptic garments are based on rigid devices (e.g. electromagnetic vibrotactors) which tamper the softness of clothing and increase encumbrance for the user. Fluidic elastomeric actuators are interesting because they are soft, can be molded in a variety of shapes, and manufactured at scale [4]. We introduce a HYperelastic FAbric-Reinforced (HYFAR) soft actuator that is pneumatically powered and suitable for haptic clothing. It can render high forces, hyperinflate, be manufactured from textiles, and thanks to the local programming of the active membrane, render low encumbrance to the user and inflate into diverse shapes. We present the manufacturing process to program the local material properties of the membrane to achieve custom inflation by reinforcing a fabric-elastomer composite using embroidery. Furthermore, we present the modeling method that simulates the behavior of inflated, multi-material, hyperelastic membranes. Finally, we develop functional garments with HYFAR to demonstrate shape shifting behaviors and render kinesthetic haptic feedback at the shoulder abduction-adduction joint of the user.

2 SYSTEM DESIGN AND FABRICATION

The HYFAR actuator has two components: 1) an active membrane, which inflates against the user's body and 2) a passive inextensible membrane that serves as a backing for 1. These components create an airtight bladder that can be integrated on a piece of clothing (Fig. 1A). The active membrane (~ 635 um) is a composite made of a hyperelastic material (i.e., an elastomer) and a stretchable fabric, which can be embroidered with an inextensible thread to allow for

---

SIGGRAPH '22, Vancouver, BC, Canada,

ACM ISBN 978-x-xxxx-xxxx-x/YY/MM...$15.00
https://doi.org/XXXXXXX.XXXXXXX

custom shape and force profiles. We manufactured HYFAR with a combination of embroidery, stencil printing, and heat pressing (Fig. 2A). Digital embroidery is interesting because of its rich design space that includes patterns such as single, filling, linear and zigzag stitches, etc. We developed HYFAR actuators (r = 1.5 cm) with various embroidered patterns including strain-limiting regions for custom inflation. We achieved diverse inflatable shapes including non-symmetrical and directional inflation (2B1), and semi-flat structures even when pressurized (Fig. 2B2, inner circular region).

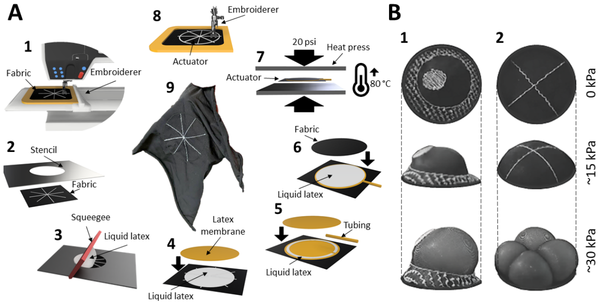

Figure 2: A) Fabrication process for HYFAR actuators. B) Example of HYFAR actuators inflated from 0 - 30 kPA.

3 MODELING AND SIMULATION

Inflation of HYFAR membrane can be expressed as a minimization problem over a domain $\Omega \subset R^3$ as described in the Finite Element (FE) theory [1]. This problem can be summarized as finding the displacement field u: $\Omega \to R^3$ that minimizes the total Helmholtz free energy Π in the admissible function space H that satisfies boundary conditions ($b.c.$; Fig. 1D):

$$min_{u \in H} \Pi, \Pi = \int_{\Omega} \psi(u)dx - PV \tag{1}$$

where $\psi()$ is the Helmholtz free energy density function, u is the displacement field, V is the volume enclosed by deformed and undeformed configuration, and P is the uniform force per unit deformed area applied by pressurized air on the inner surface of the membrane. The stress-strain relationship of a hyperelastic material derives from its strain energy density function ψ. We explore three models of hyperelastic materials: Neohookean, Mooney-Rivlin, and Arruda-Boyce, and implemented our simulation using a partial differential equation solver (FEniCS [2]). In our implementation, we seek a solution for the variational equation:

$$L(u;h) = \frac{d\Pi(u + \epsilon h)}{d\epsilon}|_{\epsilon=0}, \forall h \in H \tag{2}$$

and used lower-upper decomposition (LU) to solve the variational problem at each step for increasing pressures ($p_{i-1} + \Delta p$), where Δp is initially defined by the user and adaptively decreased to ensure convergence. We validated our simulation by comparing it to experimental data for a tensile test (Fig. 1B) and inflation of a circular non-embroidered specimen (Fig. 1C; r = 1.5 cm). The results showed that the Arruda-Boyce material model can best fit the experimental data with a mean absolute error (MAE) of 0.17 kPa and root mean squared error (RMSE) of 0.22 kPa for tensile test over the ranges of 0 - 700% strain; and MAE = 0.13 cm/cm, RMSE = 0.15 cm/cm for an inflation pressure range of 0 - 40 kPa.

To represent a multi-material membrane, we map the elements of Ω to cells of material matrices with values corresponding to the parameters of the material locally. We consider an example circular actuator (r = 1.5 cm) with an embroidered cross pattern and an inflation pressure ranging from 0-40 kPa (Fig. 1D). Parameter matrices (e.g. C_1, N for Arruda-Boyce) consist of two materials: hyperelastic and inextensible part of the HYFAR membrane, which were fitted from tensile test data. A Gaussian filter was applied to the parameter matrices to smooth the transition between materials. Using the aforementioned method, we simulated a set of membranes with various embroidered patterns (Fig. 1E).

4 HYFAR HAPTIC CLOTHING INTERFACES

We designed two upper body functional garments demonstrating kinesthetic haptic feedback (Prototype 1, P1; Fig. 1G) and shape shifting capabilities (Prototype 2, P2; Fig. 1H). For P1, we fabricated two versions of a stadium-shaped (a=20 cm, r=4.75 cm) HYFAR actuator without embroidered patterns (Design A) and with a serpentine-like pattern (Design B). Both designs were tested for blocked force and bending angle in a unidirectional joint (human shoulder abduction-adduction joint) at inflation pressures ($0 < p < 8.27$ kPa). The results (Fig. 1F) show that both designs are capable of exerting increasing blocking force with incremental pressures; Design A can exert forces from 0-45 N, and Design B from 0-92 N at the aforementioned pressure range. Design B was integrated in a haptic shirt (Fig. 1G) and tested in a human subject with pressures from 0-8.2 kPa. At maximum pressure, the actuator caused a bending angle of 50 deg. and an estimated blocking force of ~38 N (Fig. 1F) on the shoulder joint. P2 showcases shape shifting capabilities and local inextensible areas that can be used to incorporate rigid components (e.g., electronics). This actuator includes an embroidered cross pattern and four LEDs located on the embroidered islands with conductive thread stitched in a serpentine-like pattern serving as electrical connection to an external power supply.

5 DISCUSSION

We presented a new class of soft actuators for haptic clothing interfaces. Our actuator is textile based, lightweight (~ 0.13 g/cm^2), can exert large forces (up to ~ 92 N in kinesthetic configuration), and can be easily integrated in garments using standard manufacturing methods. In addition, we developed a model to simulate the actuators based on FE method that can be expanded to other inflatables consisting of dissimilar materials and used to explore different geometries and actuation modalities. In the future, functional garments based on HYFAR can allow for realistic whole-body interactions in virtual reality that increase the believability and realism of simulated medical procedures, gaming, and training in AR/VR.

REFERENCES

[1] Matthews, Davies, Hitchings, and Soutis. 2000. Finite Element Modelling of Composite Materials and Structures. https://doi.org/10.1533/9781855738928.2.39
[2] The FEniCS Project. 2015. v1.5. (2015). https://doi.org/10.11588/ans.2015.100.20553
[3] Sodhi, Poupyrev, Glisson, and Israr. 2013. AIREAL: Interactive Tactile Experiences in Free Air. In *ACM SIGGRAPH 2013*. https://doi.org/10.1145/2461912.2462007
[4] Sonar and Paik. 2016. Soft Pneumatic Actuator Skin with Piezoelectric Sensors for Vibrotactile Feedback. https://doi.org/10.3389/frobt.2015.00038