Rapid Prototyping Dynamic Robotic Fibers for Tunable Movement

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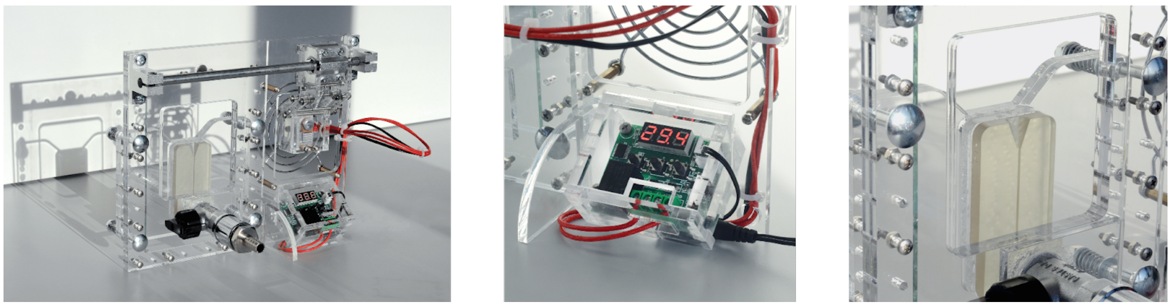

Figure 1: From left to right: vacuum fiber molding (VFM) machine, close-up of the thermostat, and close-up of the mold.

ABSTRACT

Liquid crystal elastomers (LCEs) are promising shape-changing actuators for soft robotics in human–computer interaction (HCI). Current LCE manufacturing processes, such as fiber-drawing, extrusion, and 3D printing, face limitations on form-giving and accessibility. We introduce a novel rapid-prototyping approach for thermo-responsive LCE fiber actuators based on vacuum molding extrusion. Our contributions are threefold, a) a vacuum fiber molding (VFM) machine, b) LCE actuators with customizable fiber shapes c) open-source hackability of the machine. We build and test the VFM machine to generate shape-changing movements from four fiber actuators (pincer, curl, ribbon, and hook), and we look at how these new morphologies bridge towards soft robotic device integration.

CCS CONCEPTS

• **Human-centered computing** → Interactive systems and tools.

KEYWORDS

Liquid Crystal Elastomers, Reversibility, Customization, Vacuum Molding Extrusion, Soft Robotics

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1 INTRODUCTION AND BACKGROUND

The demand for more nuanced, tangible approaches to interaction has inspired researchers to explore the potential for material actuators in HCI to provide high-resolution haptic and visual output with enhanced actuation speed for shape-changing interfaces (SCIs) and soft robotics [2]. Here, LCEs show promise as a stimuli-responsive material that can rapidly and reversibly change form when exposed to heat, light, or magnetism [5, 20], showcasing programmable, complex shape transformations.

Building on prior HCI work, mechanisms such as OmniFiber fluidic fiber actuators [1], ModiFiber, nylon thread actuators [4], and A-Line 3D-printed thermoplastic PLA structures [19] are line-based material systems with reversible actuation. While a range of shape-changing behaviors are observed (e.g., shrinking and twisting), LCE fibers offer the potential for more subtle, controlled, and programmable movements. Unlike other soft (e.g., pneumatics, hydraulics) [9, 23] and hard (e.g., electrical motor) actuating systems, the actuation is incorporated into the molecular structure [5], allowing the transition from static to dynamic states.

We introduce LCEs into the HCI design space in dynamic robotic fibers based on White and Broer's [20] thermal-actuation approach, where a drawn LCE fiber enables programmable and reversible shape-changing behaviors [21]. Our study examines how fiber shape affects actuation behavior. For example, LCEs can undergo complex shape changes based on programmed geometries and molecular orientations [8, 10, 14,]. Given that LCE geometry impacts actuation, fiber shapes could potentially enable tailored behaviors toward applications [5, 20].

Current approaches to manufacturing LCE fibers center on fiber-drawing, extrusion and 4D printing. While fiber-drawing [3, 15] is the conventional method and, more recently, extrusion of long fibers [16] is scalable, these techniques have limitations as the form can only be modified incrementally, restricting more diverse applications. To this end, we propose a novel fabrication approach based on vacuum molding extrusion. We build and demonstrate a

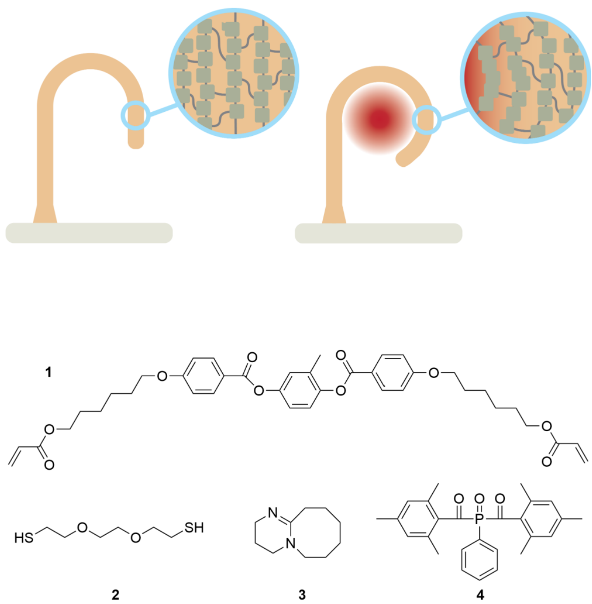

Figure 2: Top: LCE fiber in non-actuated state and actuated state. Local heating introduces a temperature gradient that disturbs the molecular order and produces macroscopic bending of the fiber. Prior chemical locking-in of the alignment allows the fiber to unbend upon removal of the heat source. Bottom: Molecular structure of materials used for oligomer fabrication (1) RM82, a commercial LCE solution, (2) DODT as a chain extension agent, (3) DBU as a catalyst, DCM as solvent, and (4) Irgacure-819 as a photoinitiator. (Image credits: Lio Huntjens).

vacuum fiber molding (VFM) machine through four fiber shapes (pincer, curl, ribbon, and hook) to assess form-giving and dynamic actuation qualities (Figure 1).

2 LCE FIBER ACTUATION PRINCIPLE

LCEs offer potential to the HCI community in performing complicated shape changes that are reversible, low-voltage, and programmable [21]. Here, LCEs combine the alignment of crystals with the mobility of liquids, forcing the material into the desired alignment [3]. This alignment can be chemically locked (i.e., crosslinked) and can be reversibly actuated via heat, light, or magnetism [5]. When drawn from small droplets, these LCEs take the form of fibers and exhibit a two-way-shape memory effect generated by a molecular-level structural change activated by heat, resulting in observable shape-changing behaviors. For example, locally heating the fiber causes molecules on the exposed side to contract, resulting in a bend (Figure 2).

Fiber-based LCEs can be manufactured by drop-casting oligomer solutions between glass slides, then gently separating the slides and drawing out the fibers prior to polymerizing them [3, 11]. To draw an LCE fiber, the viscosity of the oligomer or polymer melt needs to be lowered; this is done by heating the material. When heated,

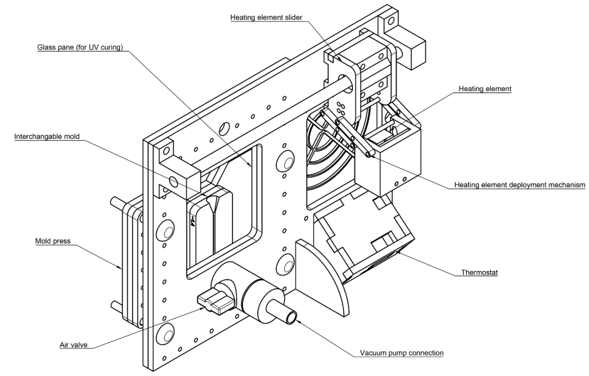

Figure 3: VFM machine schematic diagram

the molecules are in a disordered state, and the elongational flow from drawing the fiber causes the molecules to align parallel to the drawing direction. Polymerization under UV light triggers the crosslinking process, essentially "locking" the molecules in place [15] (Figure 2). This approach has limited control on LCE fiber properties. While minor changes in geometry (e.g., length and diameter) can be made, the fluid mechanics of the elongated flow produced by drawing the fibers results in the same form. Emerging approaches in LCE manufacturing, such as extrusion of long fibers (e.g., direct-ink-write printing), enable scalability [16] and are suited to applications such as artificial muscles and smart textiles [22] but limit the ability to manipulate fiber morphology. 3D printing, on the other hand, enables freedom in the morphology in design through complex geometries [10] by depositing and/or solidifying material [14]. However, manufacturing cycles can be lengthy, costly, and inaccessible, confining their use to advanced laboratories. We designed and constructed the VFM machine to produce moldable LCE fibers to meet this challenge. Through open-source hackability of the machine, the freedom to experiment and iterate with various forms can allow LCEs to be customized by researchers with different demands (e.g., designers, engineers, material scientists, and HCI researchers). We present this strategy for researchers to build and customize LCE fibers with off-the-shelf and easy-to-machine parts. [https://www.instructables.com/Vacuum-Fiber-Molding-VFM-Machine/]

3 VACUUM FIBER MOLDING (VFM) MACHINE

Three requirements from the fiber drawing process were addressed while designing the VFM machine:

1. The LCE mixture needs to be heated to lower the viscosity.
2. The force exerted on the material from the elongational flow caused by the material drawing directs the orientation of the molecules.
3. The material must be polymerized using UV light.

The VFM machine consists of several components: a plexiglass body, an air valve connected to a glass pane, a thermostat, a heating element, and a mold. The channels of the molds are aligned with a hole in the glass pane that connects to the air valve (Figures 1 and 3). Several molds are fabricated with shapes (pincer, curl, ribbon,

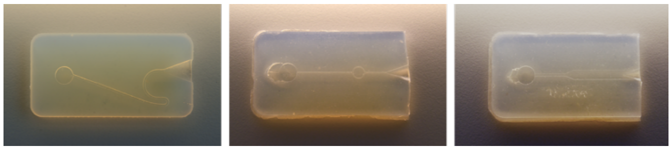

Figure 4: Fiber Silicone cast molds on an SLA-printed negative of the desired fiber shape.

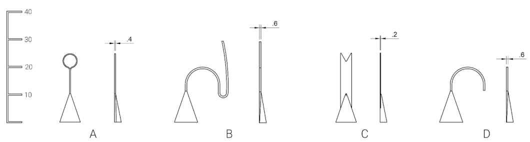

Figure 5: Fiber shapes: (a) pincer (b) curl (c) ribbon (d) hook.

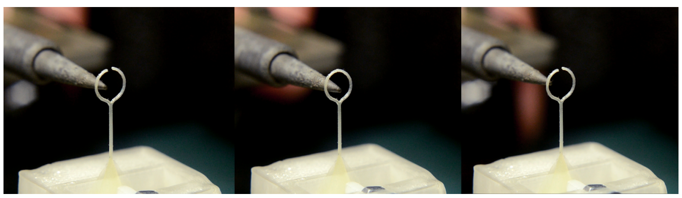

Figure 6: Pincer fiber in pinching motion.

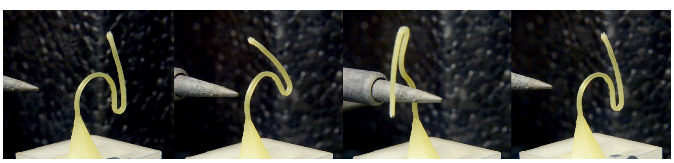

Figure 7: Curl fiber bending towards and over the heat source.

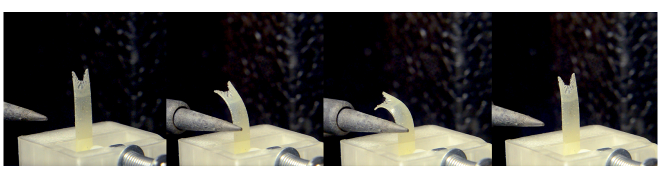

Figure 8: Ribbon fiber bending towards the heat source.

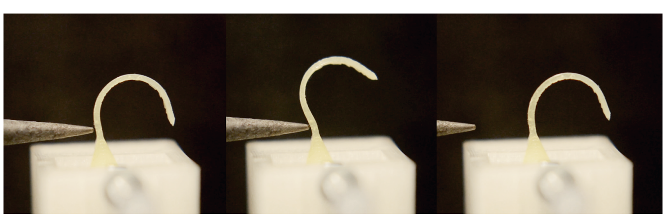

Figure 9: Hook fiber opening towards the heat source.

and hook) (Figure 4). The molds are created by casting silicone on a stereolithography (SLA) printed negative of the desired fiber shape.

Preparing a molded fiber using the VFM machine is done by completing the following steps: The mold is clamped against the glass pane of the VFM machine (Figure 3), and a vacuum pump is connected to the air valve. The oligomer is inserted in the mold funnel and heated to 85°C–90°C by sliding the heating element on the glass (approximately 2–5 min). This liquefies the oligomer, enabling the vacuum pump to pull the oligomer into the mold. When the oligomer has propagated into the channel of the mold, the vacuum pump is turned off, and the oligomer is cured under a UV lamp (15 min). Following removal from the mold, the fiber is post-baked in an oven (100°C for 15 min) to restore its molded shape.

4 ACTUATION DYNAMICS

To demonstrate the potential of the VFM machine, we fabricate four fiber shapes (pincer, curl, ribbon, and hook (Figure 5) and tested their deformation under heat to explore their morphologies.

Each fiber was exposed to localized heating in a setup designed to test actuation, consisting of an adjustable clamp to position the fiber, and a heating element on a linear axis that could be moved towards and from the fiber by turning a knob (200°C measured at the tip of the heating element with Seek thermal compact imaging camera). The actuation behavior varies depending on the time and location of the exposure to heat, where prolonged exposure increases the bending angle. Depending on geometry, fibers start to actuate at 60°C, but higher temperatures provide a faster response, enabling application-specific actuation. Finer structures (thin or flat dimensions, Figure 5; pincer or ribbon actuators, Figures 6 and 8) exhibit a faster response time when compared to hook and curl (Figures 7 and 9). Pincer opens within 3 seconds and recovers in the same period after cooling, exhibiting a "pinching" behavior. In contrast, progressive heating over time leads to a slower placement-displacement mechanism in both hook and curl actuators. Providing scope for compliant mechanism structures, e.g., twisting ties, clips and hooks. Similar to A-Line actuators [19], we also foresee how the temporal transformations of the fibers could be manipulated via control-system design [21] (e.g., programmable heating/cooling cycles). Although early tests in this paper offer movement insights, various heat sources and their location, such as resistive heating or infrared, may yield different tunable behaviors. A promising approach for future work, would be via integrated resistive heating in the LCE, enabling lower temperature activation [6].

5 DESIGN EXPLORATIONS

Early deformation testing demonstrate how customizable fiber shapes with tunable movements might enable tailored soft robotic device integration. Figure 10 shows pincer, a simple robotic actuator, using grasping actions to grab small, delicate items, such as a folded mylar sheet (7×7mm, 200 microns), demonstrating early-stage capabilities (e.g., to manipulate fragile objects or pick up products). Alternatively, fibers coupled with localized substrate resistive heating [7, 18] could allow for intricate integration into soft micro-structures for personalized human-interface devices [22],

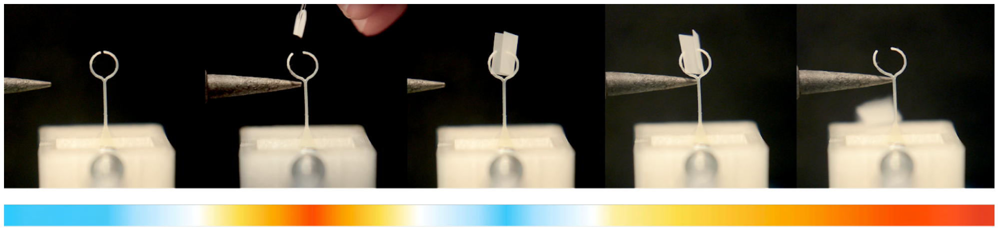

Figure 10: Pincer fiber opening in response to heat, gripping a piece of paper (mylar) upon cooling, and releasing the paper when heated again.

such as hair-like surface textures [12, 13] for simulated touch applications [17]. Finally, open-source hackability of the VFM can help researchers scale the technology (e.g., fabricating multiple fibers from a single mold).

6 CONCLUSION

This paper introduces the VFM for dynamic robotic fibers, a new rapid prototyping approach to generate customized LCE fibers for tunable movement. Our concept is demonstrated by four thermo-responsive LCE fiber actuators: pincer, curl, ribbon, and hook. We show how these creative morphologies can lead to novel actuation mechanisms in soft robotics, such as grippers or compliant mechanisms. We envision the VFM machine will extend the HCI's maker toolbox and decrease the barrier of entry for molecular-driven actuators for SCIs and soft robotic device integration.

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