# A 4-Degree-of-Freedom Origami Fingertip Haptic Device with Pneumatic Actuators

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***Abstract*—We present progress toward a 4-degree-of-freedom fingertip haptic device fabricated using origami manufacturing methods. The device can deliver normal, shear, and torsional haptic cues to the fingertip and is intended to be used in virtual reality applications for interacting with virtual objects. We present actuator requirements for this application and results towards achieving those requirements with pneumatic pouches and polyimide springs in our current design. Through this workshop, we aim to communicate performance requirements for such haptic devices and discuss smart-material based actuators that could be used in place of pneumatic pouches to eliminate the need for air supplies and pressure regulators, thus reducing device emcumbrance and improving user experience.**

## I. INTRODUCTION

Recent growth in commercial visual displays for Virtual Reality (VR) [1] has led to an iancreased interest in wearable haptic devices to provide immersive multi-modal sensory experiences [2]. These devices are used to transmit the force and tactile sensations of interacting with virtual objects within the VR environment. VR has applications in entertainment, social interaction, and training, and been shown to be particularly useful for training in tasks that require spatial and procedural memory as well as for the development of psycho-motor skills [3].

Although interacting with real-world objects involves both cutaneous (local tactile displacement and force) and kinesthetic (large-scale force across a joint) sensations, cutaneous feedback alone can create sensations that lead to perception of mechanical properties such as object mass, friction, and inertia [4, 5]. To this end, several 2-degree of-freedom (DOF) [6], 3-DOF [4, 7], 4-DOF [5, 8], and 6-DOF [9] cutaneous fingertip haptic devices have been developed in order to allow users to pick up and interact with virtual objects. In order for the device to be fully actuated and render forces and torques in all three directions, it must have 6-DOF. However, most researchers have focused on developing devices with fewer DOF, as increasing the number of DOF tends to dramatically increase the size and weight of the device [10].

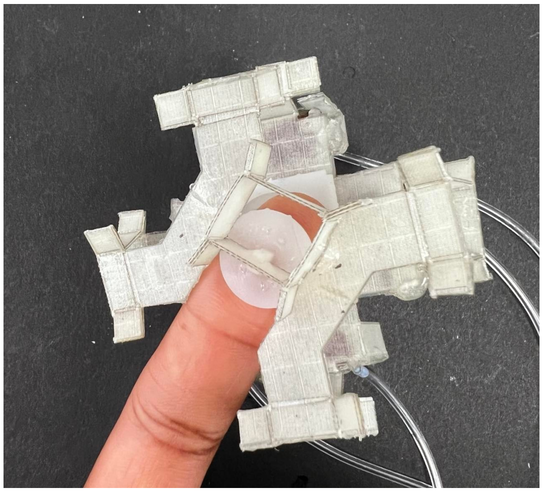

Fig. 1. 4-degree-of-freedom origami fingertip haptic device prototype.

Origami robots have been seen as a potential solution to these issues because they can provide a cost-effective and less effortful way to manufacture small, light-weight, kinematically complex robots. Origami robots are robots created using folding processes, often manufactured as a series of layered sheets laminated together into a folding robotic system. In many cases, these devices are fully self-contained robotic systems [11]. In addition to that, they often take advantage of relatively inexpensive and easily automated manufacturing techniques such as laser cutting and layer-by-layer lamination [8, 12]–[14]. Joints and kinematic linkages are built into the structure of the device during this layering process, and as a result one does not need to make and assemble these linkages individually, thus making these robots more compact and easier to manufacture. Consequently, such manufacturing techniques were used in our previous work to make a 4-DOF fingertip haptic device [8]. While this device takes advantage of origami manufacturing techniques to build a relatively compact 4-DOF mechanism, it is actuated by small DC motors screwed to the frame, which makes assembly quite difficult and adds significantly to the cost. Furthermore, after testing this device, we concluded that while it does transmit forces and torques to the fingertip in the desired directions, it needs greater force output for future user studies.

The focus of this work is to improve upon our original design [8] to build a more compact 4-DOF fingertip haptic device that has actuators integrated into its structure during the manufacturing process. This device should also be capable of transmitting forces and torques to the fingertip that are twice that of the original design. The current design, shown in Fig. 1 uses pneumatic pouches in order to achieve this performance. Ultimately, we aim to use this device in a human user study that investigates whether or not the twisting DOF on the fingertip improves a user's ability to perform certain tasks within a virtual environment.

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## II. DEVICE DESIGN

### A. Actuator Requirements

In our previous work [8], we developed a 4-DOF device that was capable of producing ±1.0 N, ±1.25 N, 1.6 N, and ±5 mNm about x, y, z, and $\theta$ axes. After testing the device, we decided we need to double these force/torque outputs in order to provide sufficiently compelling haptic feedback. The prior device also had an operating bandwidth of 9 Hz, which we aim to maintain in this iteration.

The requirements for the actuator depend on the geometry of the device as the total force output is related to joint torques by the device's Jacobian. However, given the size of the fingertip and the resultant range of dimensions for a fingertip device, an actuator at the joints would need to be capable of outputting torques between 25 mNm - 45 mNm depending on device dimensions and fit within a 1 $cm^3$ volume. Given the kinematics and desired workspace of the device, the actuators must also be bidirectional and be capable of moving each leg by 30°.

We considered a variety of actuators made from smart materials including shape memory alloys, piezoelectric actuators, electroactive polymers, and electrohydraulic transducers, but could not find any that meet these requirements. As such, we have decided to pursue pneumatic pouches as they are currently capable of meeting our requirements.

### B. Pouch Actuator Geometry and Manufacturing

Rotational pouch motors have been demonstrated to rotate hinge joints, like the ones seen in other origami robots [15]. These actuators consist of a pouch that is constrained on one face by the hinge joint and free to expand under pneumatic pressure on the opposing face. As the pouch inflates, one face of the pouch bends while the other remains flat, causing the joint to rotate. This is illustrated in Fig. 2a. This geometry is also what has been used for actuating hinge joints with electrohydraulic transducers [16, 17], where a pair of electrodes act as a pump at one end of the pouch, pushing fluid to the opposite end and rotating the hinge.

In order to reduce the size of our device and achieve bidirectional actuation, we have decided to use a different operating principle, where multiple pockets within the pouch push against each other as they are inflated, thus rotating the joint. The differences in those operating principles are illustrated in Fig. 2a. This is most similar to accordion-type pouch actuators like those in [18].

With the traditional pouch motor geometry, the hinge can only be rotated in one direction as rotating the hinge in the opposite direction would require stretching the antagonistic pouch. With this geometry, we can rotate the hinge in the opposing direction with minimal loading as the antagonistic accordion pouch folds flat. We investigated antagonistic pairs of pouches and pouch/spring combinations and have decided to use one pouch and an opposing spring as this allows us to reduce the total number of actuators. This actuation scheme is illustrated in Fig. 2b.

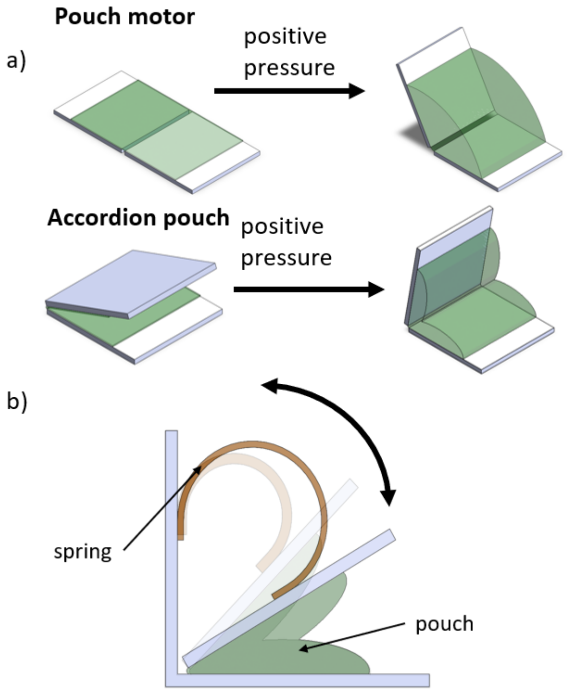

Fig. 2. **a)** Operating principle of pouch motors vs. our accordion pouch geometry. **b)** Pouch and antagonistic spring actuator geometry.

The pouches were manufactured through heat stamping. Two stamps were 3D printed on a Formlabs Form 3 SLA 3D Printer using a high temperature resistant material (Formlabs High Temperature V2). One stamp was heated to 360°F while two layers of TPU coated ripstop Nylon were attached to the other side of the stamp with polyimide tape. The end of the stamp with the fabric attached was then placed on top of the side that has been heated to 360 °F and held in place for 15 sec. The bonded fabric was then removed from the stamps and the pouch was cut out. A small piece of fishing wire was then inserted into the top of each pouch so that air can travel from one pocket to the other when it is inflated. A tube was then glued to the pouch inlet so that it can be connected to an air supply.

### C. Origami Structure

The origami structure of the device is built from layers of ripstop nylon fabric, adhesive, and fiberglass. The springs and pouches are then added as a final layer before the entire structure is folded into a fingertip haptic device. These layers are illustrated in Fig. 3.

Unlike several other origami robots [12]–[14], we use fabric for our hinge layer instead of polyimide (Kapton) so that if tears occur in the hinges after repeated use, they do not propagate across the entire hinge and break the device. An iron-on adhesive (Iron-on Adhesive Sheets Double-Sided Press-on Magic Patch Heat Melt Fabric Glue Sheet Permanent Fusible Adhesive Sheets, A4 Size, White outus) is first attached to the fabric using a heat press. This adhesive backed fabric is then

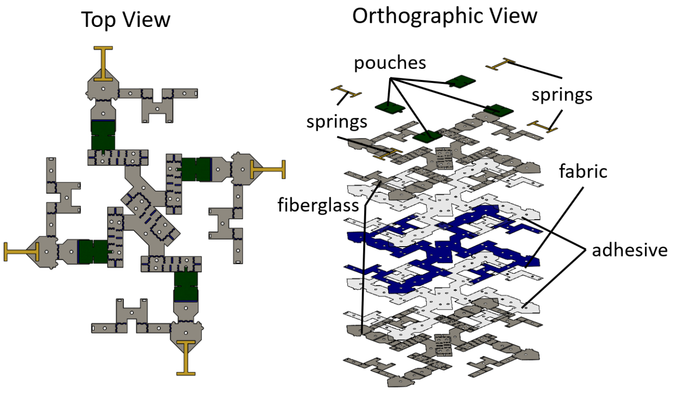

Fig. 3. Functional layers of the origami haptic device

laser cut into the shape of the device. The fiber glass layers are then placed on a 3D printed aligning jig and attached to the fabric in a few locations using a soldering iron. This entire stack is then fully laminated on the heat press. The pouches and springs are then glued to the structure and the entire device is then folded together.

## III. PRELIMINARY RESULTS AND FUTURE WORK

Using the kinematics from [8] and tests of the torque capability of a single pouch at a joint (max torque of approximately 30 mNm), the resulting device should theoretically be able to produce the desired force and torque outputs described in Section II-A. The device does move and produce forces in all four degrees of freedom, but the output is limited by unanticipated bending of the fiberglass and fabric composite structure.

In order to ready the device for our user study we need to continue iterating on the design to stiffen the overall structure. We also need to fully characterize the device and integrate sensing for feedback and control of the tactor. Finally we need to build up a virtual environment so that we can test the device and ensure it delivers adequate haptic feedback.

In terms of actuation technologies, we are planning to design electrohydraulic transducers with the same geometry as our current pneumatic pouches and see if they produce enough torque to meet our requirements. To date, we have not observed the use of electrohydraulic transducers with this geometry; given that other geometries have been close to meeting our torque and bandwidth requirements [19], we view this as a worthwhile endeavour. We also look forward to participating in the workshop and learning more about advancements in smart materials that may inform future actuator designs.

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