Threa-D Printing Tunable Bistable Mechanisms

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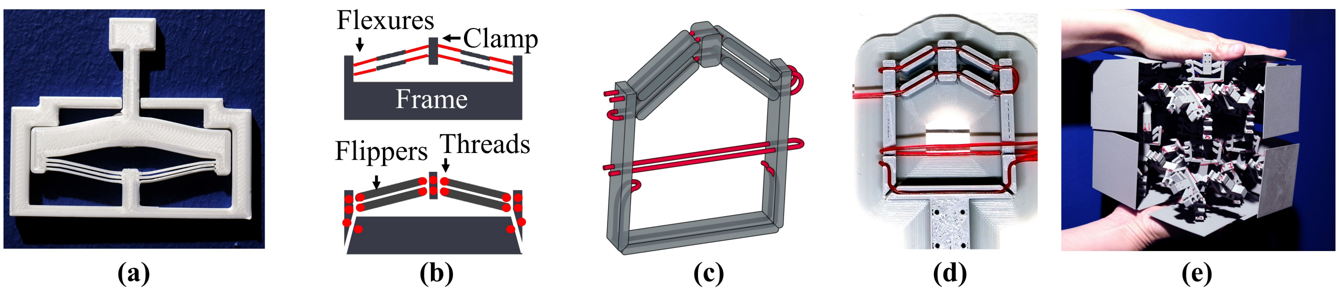

Figure 1: Mechanisms cannot be tailored easily, such as scaled-down (a) [Kuppens et al. 2020], when printed with commercially available machinery. We introduce a new approach (b)-(d) to fabricating tunable mechanisms using threads.

ABSTRACT

Nowadays, with 3D-printers becoming more accessible, hobbyists aim to create artifacts with integrated functional mechanisms. Many bistable mechanisms could be integrated into a variety of objects; however, adjusting their designs for different applications, when only low-cost hobbyist printers and commonly used filaments are available, is challenging. They include thin elements, which complicate their adoption and cannot be easily tuned post-fabrication. We adapt existing designs, using elastic threads and common filaments. Unlike the original design, the design we showcase is robust, can be adjusted for specific application requirements, and permits post-fabrication tuning.

CCS CONCEPTS

• **Human-centered computing** → Haptic devices; • **Applied computing** → Computer-aided manufacturing.

KEYWORDS

3D-printing, threads, tunable mechanisms, tactile devices, reconfigurable metamaterials

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1 INTRODUCTION

From the softness of a pillow (compliance) to the distinct on/off states of light switches (bistability), most objects are designed with a purpose in mind: to be functional for us. Bistability, in particular, is a property that enables the functionality of many common objects and, similar to other mechanical properties, can be perceived tactilely. It represents the ability to achieve two distinct stable positions.

In this work, we build upon existing compliant bistable mechanisms (Fig. 1(a)). Their functionality relies on flexible elements, namely flexures, which must often withstand significant stresses. Because of this, their fabrication is typically high-end, beyond the reach of most hobbyists, and tailored for specific applications [Raney et al. 2016; Zirbel et al. 2016]. When only low-cost machinery is available, they become fragile or non-functional. In the few cases where they have been successfully adapted [Gong et al. 2021; Ion et al. 2017], cannot be easily adjusted to different application requirements, and can rapidly degrade. As a result, these designs have not yet been widely adopted by non-experts. We are informed by existing mechanisms and post-fabrication tuning approaches [Florijn et al. 2014; Yang et al. 2022] to achieve accessible, quick, and affordable tuning, aiming to integrate functionality into artifacts:

- We construct low-cost robust adaptations of existing mechanisms that fulfill various motion requirements, using one as an example,
- we discuss size and stiffness requirements fulfillment, and
- we enrich the functionality by providing operations for post-fabrication tuning.

2 APPROACH

Motion Requirement: Different applications have different requirements, including motion. We select the appropriate mechanism from our dataset which covers a wide range of motions (Fig. 2, top row) based on the input application. For example, the mechanism in

Fig. 2(b) follows a linear motion where the output direction (dashed arrow) is parallel to the input direction (solid arrow). For complex tasks, such as: adjusting the number of stable positions (Fig. 3(i)), designing orthotropic meta-materials (Fig. 3(j)), or creating assemblies (Fig. 3(h)), we composite multiple mechanisms in grids and other formations. Next, we use as an example the design in Fig. 2(a).

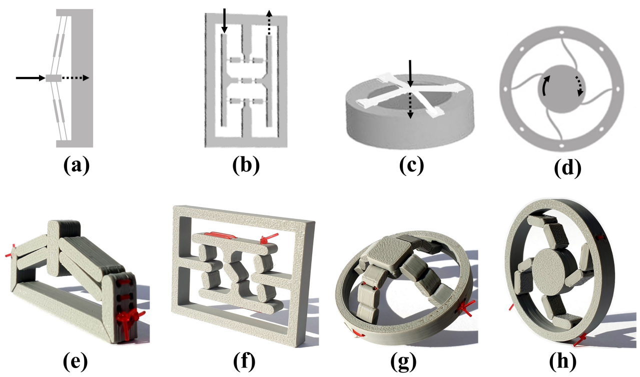

Figure 2: Top row: existing compliant mechanism dataset (figures from [Follador et al. 2015; Merkle et al. 2018; Pan et al. 2022; Zirbel et al. 2016]). Bottom row: adapted designs for accessible fabrication. Solid and dashed arrows indicate the input and output motion directions.

Background Material: This design is a well-known bistable form [Kuppens et al. 2020; Qiu et al. 2001]. It consists of two parallel rigid bars and thin compliant beams, i.e., flexures, arranged between them, and attached to a central clamp. The beams provide the compliance in otherwise stiff materials. When force is applied to its clamp, the beams deform, allowing the clamp to move between the stable states, passing through high-stress, unstable positions. Many parameters including: materials, beams geometry and topology, existence of the clamp, frame beams angle, influence the overall functionality, such as: stiffness, out-of-plane motion, number and placement of stable positions. This information along with our own experimentation inform the design process.

Robustness Requirement: To allow robustness using low-cost machinery, we manually adapt the existing designs by introducing compliance in the frame and by incorporating elastic threads (Fig. 2, bottom row). Threads provide flexibility and withstand high stress, replacing the flexures, while, the 3D-printed parts provide stiffness and rigidity under compression, restricting the threads. First, given a compliant design we identify the flexures. Next, we design the thread pieces and the 3D-printed parts (frame, flippers and clamp) (Fig. 1(b)). Neighboring pieces are connected to thread paths and pipes are carved in the 3D-printed parts (Fig. 1(c)). We replicate the thread paths in parallel planes, e.g., in Fig. 1(d) we manually insert and knot two thread paths. The materials and the printing parameters affect the mechanisms robustness.

Size-Stiffness Requirements: In our design, we notice that stiffness relates to the frame size and shape, the flipper frame angle, the flippers topology, and materials. For example, one way to adapt the stiffness, i.e., the force required to transition between the two stable positions, is to change the way we introduce the frame's compliance by modifying the shape. For smaller and medium stiffness flexures or threads can be used (Fig. 3(d), Fig. 1(d)), while for larger stiffness thicker frames (Fig. 3(c)) might be more appropriate. We fabricated the mechanism in sizes ranging from 1*cm* to 20*cm* (Fig. 3, top row).

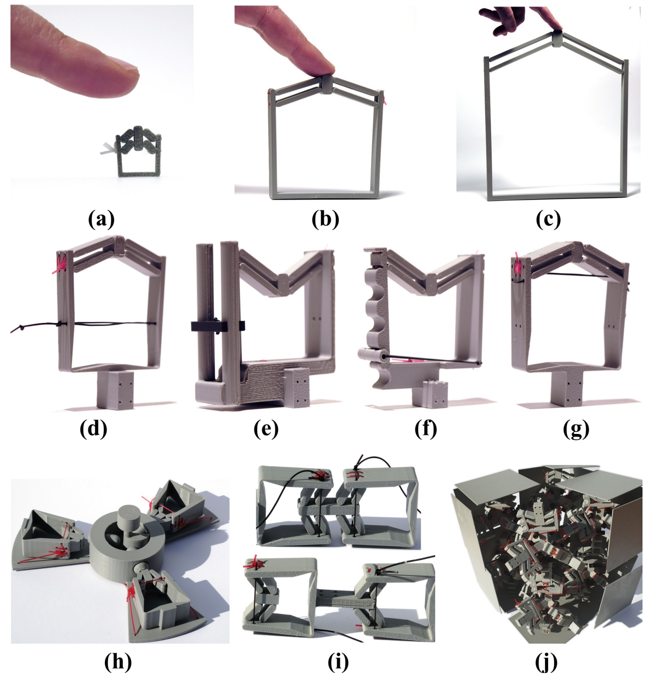

Figure 3: Mechanisms can: range from small (a) to large (c), allow functionality tuning, such as reset (g) and stiffness tuning using threads (d)(f) or rigid parts (e), form free-form assemblies (h), grids (i), or meta-material cells (j).

Tuning: Additionally, we provide approaches for quick post-fabrication stiffness tuning and resetting. The tuning approach, using tensioned elastic threads (black threads in Fig. 3(d),(f)) or sliding rigid blockers (black piece in Fig. 3(e)), affects the range of stiffness levels, whether the levels are discrete Fig. 3(f) or continuous Fig. 3(d), our tactile perception on the mechanism's smoothness, and its ability to be miniaturized. The force required for tuning can be dependent Fig. 3(d) or independent Fig. 3(e) of the enforced stiffness level, making the mechanism easier or harder to control. Finally, we introduce an extra path within the flippers (black thread path in Fig. 3(g)), effectively blocking one of the two bistable positions when tensed.

3 DISCUSSION

Our approach prioritizes accessibility rather than energy efficiency, unlike the original monolithic designs, which are well-known for their accuracy and absence of friction. We continue to work on exploring alternative tactile operations and functionalities, on synchronizing compositions' tuning and modularity, and on formalizing the design and fabrication process.

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