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Rhapso: 自動將纖維材料嵌入 3D 打印以增強互動性

Rhapso: Automatically Embedding Fiber Materials into 3D Prints

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摘要

我們提出了 Rhapso，一種在打印過程中將多種連續纖維材料嵌入 3D 物體的 3D 列印系統。這種方法使得低成本熱塑性 3D 列印可以直接整合拉伸強度、光傳輸、導電性和熱產生等特性。這些功能性物體可以具有複雜的驅動、自我組裝和感測能力，且幾乎不需要手動干預。為了實現這一點，我們改造了一台低成本的熱熔融層積（FFF）3D 列印機，在列印床上方添加掛有纖維線卷機構的齒輪環，並由一步進馬達控制齒輪環。除了硬體之外，我們還提供了分析軟體，用於精確的纖維放置，生成用於控制列印印機操作的 G 代碼。為了展示我們系統的多功能性，我們展示了幾個應用，展示了其廣泛的設計潛力。此外，我們提供了全面的文檔和開放設計，使他人能夠複製我們的系統並探索其可能性。

關鍵字：製造、積層製造、纖維、多種材料、G 代碼

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Abstract

We introduce Rhapso, a 3D printing system designed to embed a diverse range of continuous fiber materials within 3D objects during the printing process. This approach enables integrating properties like tensile strength, light transmission, electrical conductivity, and heat generation directly into low-cost thermoplastic 3D prints. These functional objects can have intricate actuation, self-assembly, and sensing capabilities with little to no manual intervention. To achieve this, we modify a low-cost Fused Filament Fabrication (FFF) 3D printer, adding a stepper motor-controlled fiber spool mechanism on a gear ring above the print bed. In addition to hardware, we provide parsing software for precise fiber placement, which generates G-code for printer operation. To illustrate the versatility of our system, we present applications that showcase its extensive design potential. Additionally, we offer comprehensive documentation and open designs, empowering others to replicate our system and explore its possibilities.

Keywords: fabrication, additive manufacturing, fiber, multi-material, G-code

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Chapter 1 Introduction

1.1 Introduction

Personal fabrication technologies such as 3D printers offer the possibility to create entirely custom objects on demand. While 3D printing has not yet reached the ease of use of inkjet printer technology, it is not unusual to find 3D printers in schools, offices, and private homes. Despite the technology's accessibility, it remains difficult to fabricate objects with functionality beyond their form. fused-filament fabrication (FFF) printers, today's popular low-cost machines, print by melting and extruding thermoplastic filament, meaning the possible functionalities of the resulting objects are limited to those that can be implemented with thermoplastic.

To overcome the material limitations of FFF printing, companies and researchers have developed composite thermoplastics that enable properties such as conductivity [78], magnetism [79], or stretchability [39]. Such composite materials have the advantage that they can be directly used with typical FFF-printer extruders; however, they are also limited by the necessity of being compatible with the FFF melt-and-extrude process.

To overcome this limitation, researchers have begun exploring the possibilities of incorporating *non-extrudable* materials into printed objects. In contrast to embedding dis-

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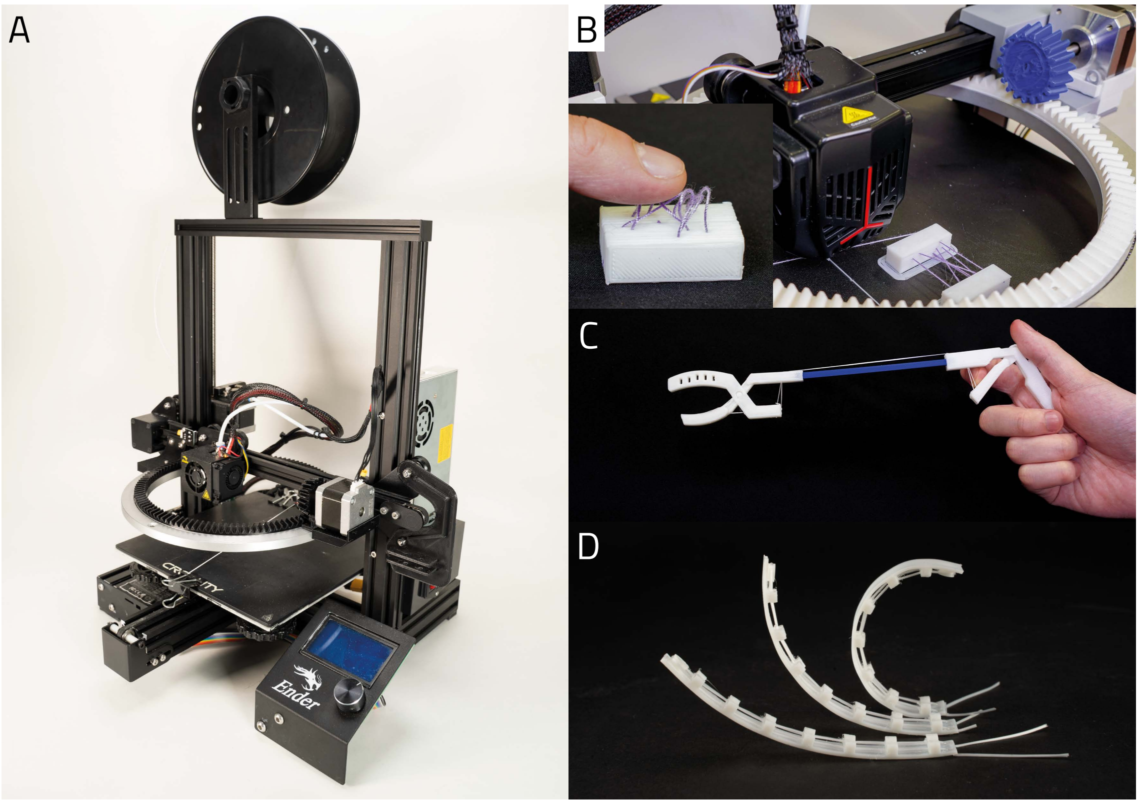

Figure 1.1: Rhapso allows embedding various types of fibers into 3D prints to enable quick fabrication of multifunctional objects. A) Rhapso hardware made by modifying a consumer grade 3D printer. An added fiber spool is moved along the attached ring. B-D) Objects created by Rhapso. B) Hairy object. A cotton fiber is embedded between two cuboids and creates hairy texture. C) Grabber. The white cotton thread transfers users' pinch to the extended grabber. D) Test of tension control system. The same 3D design can result different shapes by controlling the tension of the elastic fiber during print.

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crete *components* [7] such as bolts, magnets, or microcontrollers, these efforts augment the printed plastic with a second homogeneous material such as fabric [73], wire [64], or magnetophoretic liquid [102]. To date, however, these efforts have been limited by requiring the user to manually embed the material, necessitating a heavily modified or entirely custom 3D printer, or addressing a narrow range of functionality with only a single material.

In this paper, we present Rhapso, a system for automatically incorporating non-extrudable fiber-like materials into objects during the 3D printing process. Such materials, while affordable, accessible, and easy to work with, offer an incredibly wide variety of useful properties. Typical threads, strings, and yarns are extremely durable and flexible and have been used to create actuators [83]; elastic fibers can store energy, resist change, or—coupled with conductive thread—create sensors [94]; optical fibers can transmit light [98] and sense touch [85]; and copper wires offer 10^9 times the conductivity of typical conductive thermoplastic filament [68]. Rhapso enables such materials to be laid out inside 3D printed objects, imparting new functionalities via the fiber's properties and its interaction with the printed structure.

To begin to uncover the potential of embedding fiber in printed objects, we created a design space. We first survey existing aesthetic, functional, and material properties of fibers that exist pre-print and could be of interest for interaction. We describe during-print requirements for attaching printed structures and fibers together or leaving the fiber free, including the need to control position, tension, fixation, and arrangement of the fiber. Finally, we discuss the concept of thread as a signal-bearing substrate within printed objects for interactive purposes.

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To enable exploration of the design space, we present Rhapso, a 3D-printing system that embeds a continuous fiber into objects as they are printed. Rhapso—named for a Greek goddess associated with organizing the thread of a person's life—consists of a high-level architecture and abstract algorithms for embedding a fiber in a user-specified path through the printed object, as well as two concrete instantiations suitable for consumer-level 3D printers. The first, which automatically embeds fiber, is based on simple modifications to a low-cost 3D printer. We add a geared ring parallel to the print bed and level with the currently printing layer. Fiber stretches in a straight line from a ring-mounted spool to an anchor point on the bed or object. To embed the fiber, the ring rotates to position it across a new anchor point, where the extruder prints over and affixes it. This process can repeat multiple times in a single layer and over multiple layers.The second implementation requires no printer modification; instead, the user takes the place of the ring to reposition the fiber when and as prompted, allowing for quick and easy experimentation. The systems use identical algorithms to print the object and route fiber on the user-specified path.

Finally, we show the interaction potential of 3D printing with fiber via ten examples illustrating a subset of the design space. We also provide open-source code and 3D design files to enable others to replicate our work.

To summarize, the main contributions of our work are:

- a design space describing the interactive potential of fibers in 3D prints;
- a high-level architecture and abstract algorithms for embedding fiber in a user-specified path through a 3D-printed object;

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- an open source hardware and software system for low-cost 3D printers that enables embedding different types of fiber-like materials; and
- example applications demonstrating the interaction potential of combining fibers with 3D printing.

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Chapter 2 Related Works

Researchers have expanded the functionalities of 3D printed objects by exploring new printing techniques and materials as well as adding functional materials during and after printing process. These functional materials include fiber-like materials, though the design space has not in general been explored nor has a generic automated solution been proposed.

2.1 Fiber-like materials in 3D printing

Fiber-like materials (variously referred to in related work as “line materials”, “fibers”, “fiber”, and “fibrous materials”), as noted, offer a wide variety of desirable characteristics, and Rhapso is far from the first to capitalise on them. Shape-change is a popular application [59], with explorations in using shape-memory alloys (SMAs) [57, 63], and tensionable cables [104]. Variable haptics is another area with multiple explorations, seeing fibers used to create texture [31] and modulate stiffness [62], or generate heat [11]. Naturally, sensing is a third explored area, with conductive fiber being used to connect modules [14, 34], measure stretching [94], and create inductors and similar sensors [20, 66]. PunchPrint designs printed objects for later fiber embedding and EscapeLoom for later weaving, with the goal of supporting crafters [8, 9]. Non-fibrous metal wires have also

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been explored as components that can be wrapped to create electromagnets [64] or enable poseable objects through manual wire threading [84]. In terms of characterization, the effects of fiber inclusions in 3D printed objects have been measured with respect to their mechanical [3, 71], electrical [66], and thermal [5] properties. These works each explore a single type of fiber-like material, and for the most part do not offer automated solutions. Our work unites their explorations.

2.1.1 Automated solutions for embedding fibers

Automated solutions to embed fiber-like materials have been explored in different 3D printing systems in multiple contexts. For example, some embed wires [13, 30, 38] as electronic components, or carbon fiber [4, 33] as a structural or electrical component. Others embed various materials in printed concrete [47, 54] as a reinforcement method, or develop custom filaments (or filament-creating machines) with fiber-like cores for conductivity [105] or structural stability [70, 103]. While these solutions all include machines capable of depositing the needed fibers alongside other geometry, they each focus on a specific fiber/application context and lack flexibility.

Stalin et al. propose an automated device that can embed fiber-like material into 3D models created with a silicone printer, and explore their influence on shape-change rigidity and local heating, as well as their use as electronics [80, 81]. This is conceptually similar to our work, but we focus on a system for modifying low-cost, generic FFF printers instead of a special-purpose silicone printer. Stiltner et al.'s method for including fibers as joint actuators in polyjetted models [82] similarly explores possibilities and demonstrates deformable interactive devices, but requires manual fiber embedding during layer pauses and an expensive machine.

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2.2 Fabrics and 3D printing

Fabric, a dense mesh of fibers, is also of interest to HCI and other researchers as a desirable embedded material thanks to its flexible properties that complement hard thermoplastics. Rivera et al. [73] and FabriClick [21] embed fabric into 3D printed objects to leverage its rich interactive capabilities, and CurveUps [25] and Koch et al. [41] embed pre-stretched fabric with precise printed components to enact shapechange. Fiber offers fundamentally different opportunities from full fabric sheets; instead of being a plane, it is a line that can be woven through space in varying configurations. Rivera et al. also explored including individual fibers as actuators for their fabric-embedded objects (similar to our robot finger example); Rhapso expands the opportunities of fiber-like material embedding, and automates the bespoke, manual embedding process used for that example object. Others have built custom machines that 3D print out of cut-and-layered fabric sheets [65], felted yarn strands [29], spooled yarn or fiber [45], or hydrogel added into existing fabric materials [72], thus creating fully-soft objects in a 3D printer-like manner. These last works create unique, soft objects, but cannot take advantage of the blending of hard and soft materials that Rhapso explores.

Others examine not just how to integrate fabric into 3D printing processes, but rather how to print fabric-like materials directly from common thermoplastics. Commercially, this was most famously explored by n-e-r-v-o-u-s systems in their Kinematics project [60], which created small, rigid, linked units that flowed like a textile. In research, DefeXtiles uses a single printed material (PLA) to create both flexible and rigid components by fabricating a novel metamaterial structure [15], while Takahashi et al. [86] and Li et al. [46] explore weaving-like techniques.

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2.2.1 Other uses of fabrics and fibers in HCI

Many other explorations of fibers and fabrics in HCI go beyond embedding them in 3D prints, including developing novel fabric– or fiber-like materials and structures that behave like actuators [17, 37, 58], sensors [49, 67], or both [2, 50, 55, 61]. Compilers and design software for knitting and textiles is also a popular area of research [2, 18, 53]. A future version of Rhapso could integrate some of these novel fiber-like materials, but our exploration is largely orthogonal to this body of work.

2.3 Multimaterial processes and non-printable materials

Multimaterial printing processes and processes that allow integrating several machines into the manufacture of a single object [22, 51] offer many opportunities for embedding interactivity. But the fact remains that, while 3D printers and related techniques offer many different material possibilities, there are still many classes of material and objects which cannot be printed—or even "faked" with clever metamaterial designs—by consumer-grade machines. Thus, others have explored embedding non-printable materials during and after 3D printing to achieve interactivity goals. Aside from fabric, discussed above, these investigations in HCI examine embedded electronics like IMUs [28], cameras [75], or as integrated bricks [19, 44]. More generally, everyday objects can be embedded into prints to enhance their capabilities as in Medley [6], or just to make printing faster [95]. Rhapso focuses on fiber-like materials, but we take inspiration from the use cases described in these works and the general concept of adopting existing materials' properties for use in 3D printed objects.

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Chapter 3 Design Space of Printing with Fiber

Combining non-printable materials with fabricated objects can add desirable characteristics not possible to achieve with printable material alone; Rhapso accomplishes this by interleaving fibers into 3D printed objects. Here, we loosely define *fibers* as continuous fiber-like materials. To understand and organize the opportunities for fiber embedding, we developed a design space Figure 3.1.

As a practical matter, our design space assumes an extrusion-based thermoplastic printing process—i.e., FFF—as this is the printer type we use for our implementation (**??**). We organize by the three stages of the fabrication process: *fiber properties (pre-print)*, *fiber/print assembly actions (during print)*, and *signal and force transmission (post-print)*. Design choices made in each stage have cascading effects on later stages; e.g., choice of fiber material in the first stage can impact adhesion between fiber and printed object during the second. We conclude with an exploration of design patterns resulting from combinations of design space elements.

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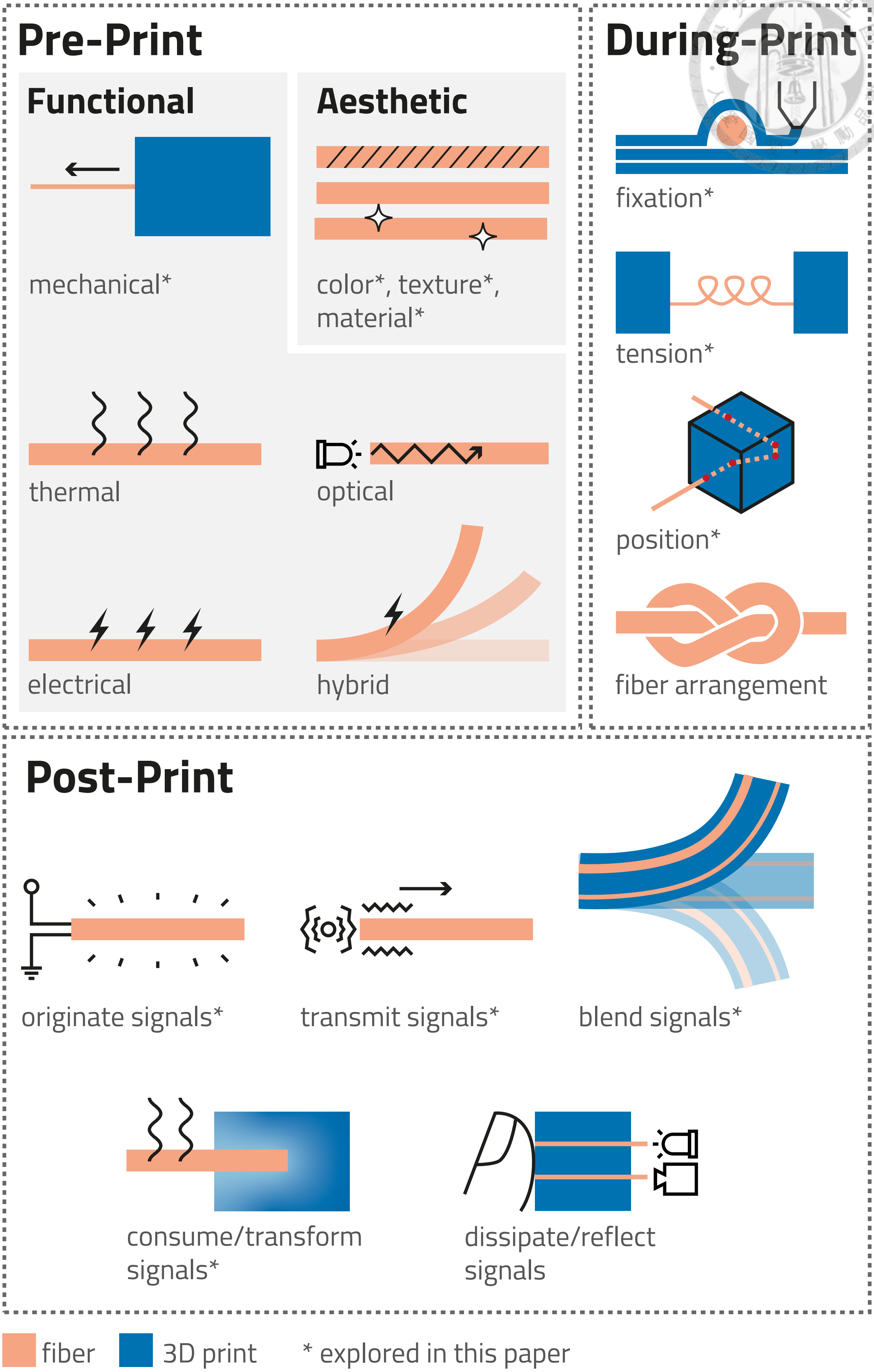

Figure 3.1: The design space of working with fiber embedded in printed objects.

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3.1 Pre-Print: fiber properties

The quantity of available fiber-like materials is vast, with thousands of general- and special-purpose fibers, cables, fibers, and wires for sale, and properties are as varied as fibers themselves. We briefly survey aspects of fiber properties that we explored and discuss some of their potential uses for interaction.

3.1.1 Aesthetic properties

Including non-thermoplastic material offers an opportunity to vary object aesthetics in both texture and colour. Common sewing thread is available in hundreds of colors, with textures ranging from smooth to hairy. Metallic materials such as wire, or textile fiber that incorporates metal—such as conductive fiber—can be shiny. Optical fibers may emit light only at the ends or all along their lengths.

3.1.2 Functional properties

Beyond aesthetics, fibers offer various functional properties, which we conceptualize in terms of their ability to transmit or distribute energy or signals. Specific base properties of various fiber types enable them to work with mechanical, thermal, electrical, and optical signals.

Mechanical Properties. The varying mechanical properties of fibers—including thickness, flexibility, strength, elasticity, slipperiness/friction, and more—suggest various interactive uses. In combination with 3D-printed structures that affix, tension, or constrain fiber relative to the printed object, they can give objects a wide range of capabilities.

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Inelastic fibers can enable cable-drive actuation [15, 74] or constrain the shapes of inflatable or flexible objects [80], while embedding strong fibers could strengthen prints [103]. Many fibers—e.g., textile-based—are extremely flexible and can withstand an essentially unlimited amount of bending [74].

Thermal properties. Fibers possess diverse thermal properties. In general, textile– or plastic-based fibers insulate thermally while metallic materials transmit and diffuse heat and can feel cool to the touch [43]; resistors like nichrome actively increase in temperature with electrical current. Interactivity is possible by combining these fibers with printed thermochromic polymers [11, 36, 69] or low-melting-temperature materials or metamaterials [23, 40].

Electrical properties. Multiple electrically-conductive fibers are available, like wire and conductive thread. Although 3D printable conductive thermoplastics exist, issues such as low conductivity [27, 79] and sensitivity to printing parameters [1] can make them difficult to work with. Embedding conductive fibers could enable simpler fabrication of objects capable of wireless power transmission [64] and sensing interaction [32, 78], or containing complex electronic circuits [91, 96].

Optical properties. Fiber optics offer unique properties for object enhancement. End-emitting fibers can provide an object with point light displays or touch sensing [99] while side-emitting fibers glow along their lengths, offering aesthetic design possibilities [89]. Optical fibers with Bragg gratings can richly detect strain over long distances, offering fine-grained sensing [85].

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Hybrid properties. As noted in Related Work, researchers are actively creating fiber-like materials with hybrid properties for sensing and actuation [16, 37]. We did not explore such fibers, but consider them as generic combinations of the above properties.

3.2 During-print: fiber/print assembly actions

To leverage the properties and opportunities of fibers, they must physically interface with the fabricated object. We focus on the design space with respect to FFF 3D printers, discussing fixation of fiber and printed object, tension between them, 3D placement, and fiber topology—how the fiber is arranged.

3.2.1 Fixation

The fundamental interaction between fiber and printed structure is fixation, or how they are attached. A fiber can be permanently or temporarily affixed, and fixation points can occur at one or multiple locations along the fiber's length and one or more locations within the printed object.

The method of fixation depends on the interaction between the fiber's properties (Section 3.1) and those of the printed material. Such interactions are complex and difficult to predict [26], but experimentally we have observed several potential fixation mechanisms. For some fiber types, *adhesion* is possible, where the thermoplastic seeps into the fiber material (as with loose or "hairy" cotton fiber) or partially melts the fiber (as with TPU fiber), forming a strong bond. When adhesion is poor, multiple lines of plastic laid down perpendicular to the fiber can *clamp* it into place between the object's layers. Some fibers (like nylon fishing line) will not adhere at all; in such cases, *winding* the fiber around a

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printed internal post followed by clamping can be effective. Printed hooks and clips can also be used, for less-permanent fixation.

3.2.2 Tension

Closely related to the attachment between a fiber and an object is the *tension* of the fiber between attachment points: as-printed fiber tension controls the fiber's behaviour post-print. Tension relates to mechanical properties: a fiber under tension can be strummed or more easily cut or snapped, while a loose fiber droops. With elastic fiber materials, a fiber can be extended under tension beyond its natural length and its tendency to contract can be used post-print to implement, for example, self-assembly.

3.2.3 Position

For full flexibility in adding fiber to printed objects, we must be able to position the fiber at various points in 3D space. This includes *in-plane* and *out-of-plane* positioning. Thanks to the planar nature of the typical FFF 3D printing process, in-plane direction changes can be achieved by printing guiding or affixing paths or points in an object, with the fiber strung through or between them. The fiber can then be sealed into position in the layer.

Out-of-plane fiber pathing can be more difficult for machines of this design. In the easy case, a fiber affixed at layer N_i can be brought upwards for further fixation in layers $N_{i+1}, N_{i+2}, \ldots$. The other direction is more difficult: it requires special design care to attach to layer N_{i-j}. This is conceptually related to either tension (e.g., drooping the thread to send it downwards), wrapping (e.g., using the object itself as a guidepost [45]),

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or having print-head access to a specific location despite existing structure (e.g., to print thread and anchors in an area of shallow slope [56]).

3.2.4 Fiber arrangement

Fibers afford various modifications to how they are arranged with respect to themselves or other fibers; for example, two ends can be attached to form a loop, or fibers can be twisted together to form thicker strands. Certain properties (e.g., aesthetic, optical, mechanical) may be more sensitive to topological modification than others (e.g., electrical, thermal).

Fibers with free ends can have their topologies modified after printing, but fixing a fiber's ends also fixes its topology. Fiber topologies can also be modified by *cutting*, creating two fibers where previously there was one, and can be achieved in some cases by the fabricating machine (for example, by using the printer's hotend to sever some types of fibers). Networks of fibers, similar to circuit networks and in star or tree topologies [76], can be created through a combination of fiber arrangements.

3.3 Post-print: signal & force transmission and interaction

Much literature on 3D-printed interactivity involves routing signals and forces between fabricated objects and external sensors and actuators. This is frequently achieved by printing two materials with differing properties—for example, conductivity [24, 78], flexibility [39, 92], or optical transmissivity [99]—or by incorporating empty cavities [87, 90]

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or air tubes [77, 88, 92] in single-material objects. Embedding fibers into printed objects enables signal routing in accordance with the fiber's properties (Section 3.1) while sidestepping typical issues with printable material (e.g., poor conductivity [79]) and print processes (e.g., layer-line-induced turbulence [77]) and still routing signals deep within an object.

Fiber materials can originate, transmit, blend, dissipate, reflect, consume, transform, or stop signals in concert with user interaction and printed structures. These interactions have been explored in prior work that uses fibers to generate heat [11], measure touch location [101], or transform user pulling force from linear to rotary [15]. In mechanical systems, this can mean using fiber for pushing and pulling, or using its elasticity or friction to change dynamics as compared to rigid components. Fiber arrangement also has a role to play, as fibers joined in a network can (often) transmit signals between each other.

Perhaps the most interesting aspect of working with two distinct materials with distinct material properties is that they can be selectively affixed during printing to enable either conjoint or separate signal transmission post-fabrication.

3.3.1 Originate signals

Fibers, particularly active ones like electroluminescent [76], electrothermal [12], or hybrid fibers [16], can originate signals within an object. This added energy allows interactions at other positions along the fiber.

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3.3.2 Transmit signals

Fibers can carry signals from one point in an object to another; for example, a fiber pulled by a user carries that force all the way to where the fiber is fixed to the object [52], or an optical fiber will carry light between its ends [98].

3.3.3 Blend signals

By modifying fibers' topology or by stacking multiple fibers, signals can be blended. For example, fiber art projects stack multiple fibers in various colours on top of each other, and the resulting visible appearance at a given point is a blend of all the fiber colours overlapping at or near that point [35]. By linking several fibers with a single printed body, a user can pull them to create a force vector which is the sum of their applied forces [97].

3.3.4 Consume/transform signals

Structural interactions and geometry can enable fiber/object pairs to transform signals from one form into another. For instance, linearly pulling a fiber through a set of printed joints can create a curling finger tendon [73], or routing an electrothermal fiber beneath a thermochromic polymer transforms electricity to visible color change [12].

3.3.5 Dissipate/reflect signals

Interactively changing fiber tension or bringing a printed piece or other object into contact more or less with a fiber can dissipate or reflect signals; which can be measured by in the time [101] or frequency domains [85], using e.g., thresholding [100].

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Chapter 4 Rhapso

In order to explore the design space of printing with embedded fibers, we created Rhapso. Rhapso's goal is to automatically embed a single continuous fiber into 3D-printed objects during FFF printing, a process which presents multiple challenges.

Fiber cannot be dispensed in the same way as thermoplastic filament. While 3D printers typically grip and push filament with motorized rollers, this approach causes many fibers to tangle and clump. Additionally, most fiber material is incompatible with the FFF printing process, which relies on the ability of thermoplastic filament to melt, adhere to previously-extruded filament, and then quickly solidify.

These challenges require a non-extrusion-based system for fiber printing. To instantiate the during-print fiber/object assembly actions enumerated in the design space (fixation, tension, and topology; see Section 3.2), a fiber-embedding printer must support three primitive operations:

1. *Position fiber:* The printer must be able to place the fiber in the desired 3D location and orientation with respect to the object.

2. *Avoid fiber:* To allow the fiber to freely move in some location, or to print parts of the model not involving fiber, the printer must be able to extrude plastic without intersecting the fiber, to avoid fixing the fiber in place.

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3. *Print over fiber:* To attach the fiber to the model in order to gain the desired functionality, or to allow the fiber to make directional changes within the model, the printer must be able to extrude plastic on top of the fiber to fix it in place.

In the following sections, we present a high-level overview of Rhapso's system architecture and how it uses the primitive operations to solve the challenges of incorporating fiber into the FFF printing process. We then detail implementations that instantiate Rhapso's architecture in a low-cost consumer-level printer.

4.1 Abstract system architecture

To facilitate various future concrete implementations of the Rhapso concept, we first present an abstract overview of basic requirements, representations, and processes involved in embedding fiber into a model during the print process, along with resultant limitations.

4.1.1 Requirements and representations

Our abstract architecture for Rhapso makes a few assumptions about the physical implementation. First, we assume the printing device works via the typical FFF process of creating a 3D object by building it one 2D layer at a time, with each layer containing a set of lines of thermoplastic extruded by a print head that moves in 2D within the layer. Second, we assume a fiber delivery mechanism, or carrier, that can maintain the fiber within the plane of the currently printing layer, in a straight line between where the fiber is anchored and the carrier. For maximum flexibility, we assume the carrier is located outside of the print volume.

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To implement the three primitive operations (*position*, *avoid*, and *print over*), Rhapso needs to know about the object to be printed, and how the fiber should be incorporated into the object.

In the abstract, Rhapso represents each object layer as an ordered list of 2D line segments, each signifying a move of the print head that extrudes plastic.

The path of the fiber within the object is represented as an ordered list of 3D points, or *anchors*, at which the fiber should be fixed inside the completed object. The arrangement of fiber is subject to the constraint that the print head cannot pass through already-printed material, and thus once a layer is complete and the printer has moved to the next-higher layer, it is not usually possible to return to a previous layer to lay down further plastic. This limitation affects how fibers can be routed through an object: they can be arranged in many ways within a layer, and can transition from a completed layer to a higher one, but they cannot return to a layer printed earlier; thus, anchor points must be monotonically increasing in the `Z`-axis.

4.1.2 Basic routing

Given object and fiber geometry, Rhapso determines how to route fiber through the object. This operation involves *positioning* the fiber to either be *printed over* by or *avoid* lines of extrusion. Because FFF 3D printers sequentially extrude one line at a time, the routing process involves determining how, when, and where to position the fiber.

The routing algorithm, sketched in Algorithm 1, works on one layer of the to-be-printed object at time. As input, it takes two ordered lists: `Layer`, 2D line segments comprising the printed geometry of that layer, and `Anchors2D`, 2D points within the layer

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through which the fiber should pass. Except for the first anchor in the list—the location at which the fiber is currently fixed, and which may be on the print bed—all points within `Anchors2D` must lie on at least one of the segments from `Layer`. This requirement ensures that the fiber path within the printed object matches the path specified by `Anchors2D`.

The algorithm produces an ordered list of operations `Ops`, alternating between *fiber rotations* and *print operations*. A *fiber rotation* is a rotation of the fiber around an anchor point, and a *print operation* is a group of one or more line segments representing extruded plastic.

In some cases, such as printing non-anchoring segments of a layer (Algorithm 1:24), the path of the fiber from the current anchor point to the carrier may intersect geometry that should *not* fix the fiber in place. To print these segments, the *avoid* operation is used to prevent undesired attachment, by rotating the fiber to prevent its being fixed.

Executing the operations `Ops` on a printer produces the input `Layer` with the fiber embedded in it according to the locations in `Anchors2D`.

4.1.3 Pre-routing setup

The basic routing algorithm given above describes the rough procedure, but is missing a number of important details. Those specific to a particular implementation will be discussed in Chapter 5; here we briefly sketch several implementation-independent procedures which work to prepare a 3D model and fiber path for routing. The 3D model consists of an ordered list of layers in 3D $\texttt{Layers3D} = [\texttt{Layer}_0, \texttt{Layer}_1, \ldots, \texttt{Layer}_N]$, and the fiber path is specified as an ordered list of anchor points `Anchors3D` in 3D coordinates.

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Algorithm 1 ROUTELAYER(Layer, Anchors2D)

Input: Layer, a list of 2D line segments representing the geometry that will be printed for a given layer
Anchors2D, an ordered list of points through with the fiber should pass, where each fixation point $A_i \in$ Anchors2D lies on at least one segment of Layer. The fiber should be fixed at A_0.

Output: Ops, an ordered list of fiber moves and line segments to print.

MARK all segments in Layer as UNPRINTED
Ops ← [ ]   #Initialize Ops to empty

ROTATE(A_O, A_T)→
    Append to Ops a command to rotate the fiber
    about A_O so it crosses A_T

PRINT(G)→
    Add segments in G to Ops
    MARK all segments in G as PRINTED

for each A_i in Anchors2D:
    #Fiber is fixed at A_i ; now rotate it to cross over A_{i+1} Fig.4.1e
    ROTATE(A_i, A_{i+1})   Fig.4.1f
    G_{fix} ← UNPRINTED segments in Layer
        which intersect A_{i+1}

    #Print over fiber to fix it at A_{i+1}
    PRINT(G_{fix})   Fig.4.1g

    #Find geometry that will print over fiber between points; we will print that next.
    $\overline{S_i}$ ← line segment between A_i and A_{i+1}
    G_{isec} ← segments from Layer intersecting $\overline{S_i}$

    #But don't print geometry that will print over future fiber segments!
    for each (A_{i+1}, A_{i+2}) in Anchors2D:
        $\overline{S_{i+1}}$ ← line segment between A_{i+1} and A_{i+2}
        G_{future} ← segments from G_{isec} intersecting
            segment $\overline{S_{i+1}}$
        Remove G_{future} from G_{isec}

    #Now print segments that cross only $\overline{S_i}$, not any future fiber segments
    PRINT(G_{isec})   Fig.4.1h

PRINT(all UNPRINTED segments in Layer)   Fig.4.1l

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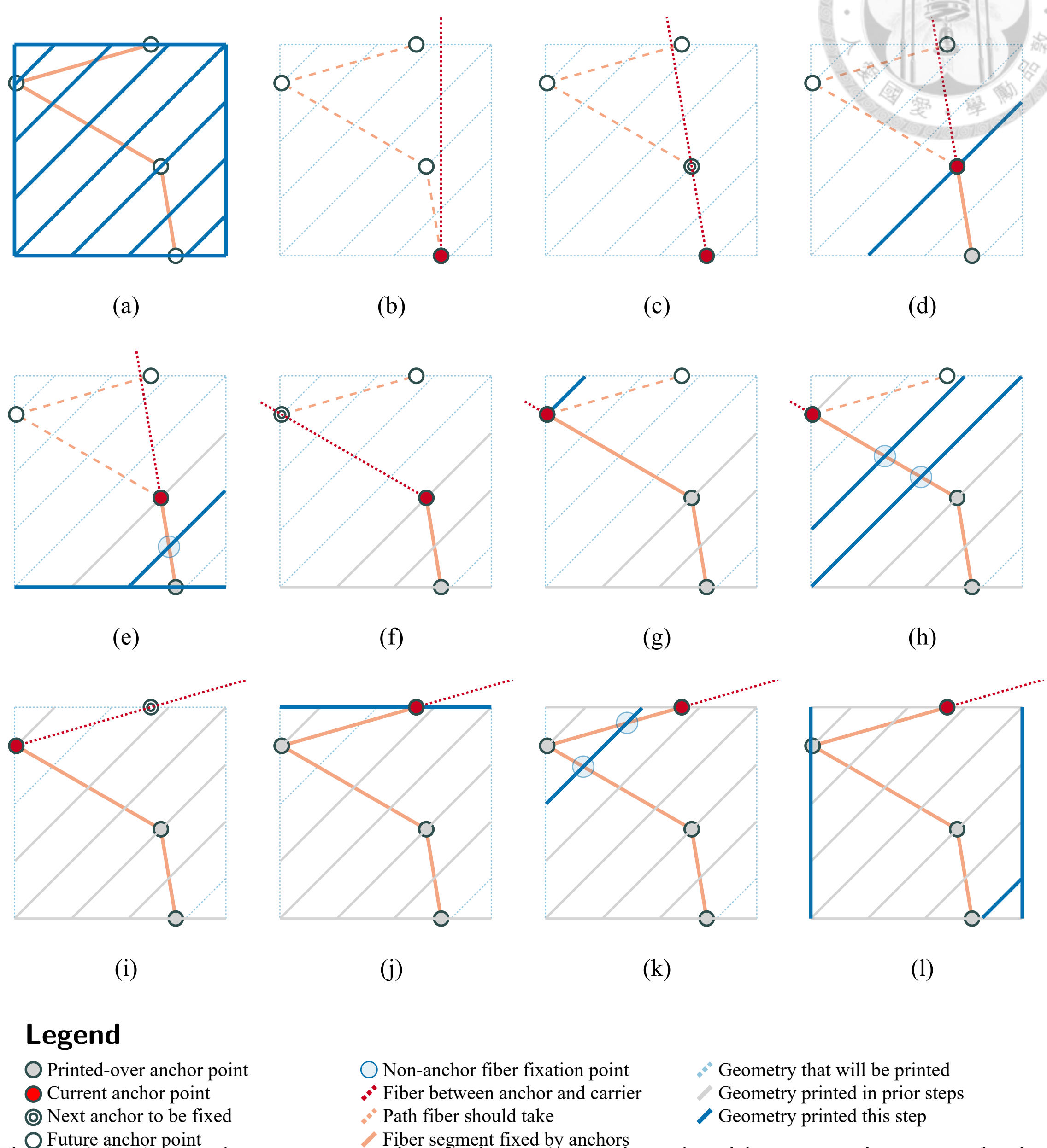

Figure 4.1: A step-by-step example of Rhapso's routing algorithm operating on a single layer of an object. (a) A preview of the finished layer. (b) The initial state of the layer and fiber. (c) The fiber rotates to cross the next anchor point. (d) The fiber is anchored via a *print over* operation. (e) Geometry which does not interfere with the fiber's upcoming paths is printed, including further fixations. (f) The fiber rotates to cross the next anchor point. (g) The fiber is anchored via a *print over* operation. (h) Geometry which does not interfere with the fiber's upcoming paths is printed, including further fixations. Note the line of geometry closest to the anchor point which, if printed at this stage, would prevent the fiber being fixed by that line. (i) The fiber rotates to cross the next anchor point. (j) The fiber is anchored via a *print over* operation. (k) Now the line of geometry can be printed over both segments of fiber it crosses. (l) All remaining unprinted geometry is printed.

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Multiple layers: While the basic algorithm detailed in Section 4.1.2 routes fiber in 2D, we want to allow fiber to routed through the object in all three dimensions. We want to transform `Anchors3D` into a list $[\texttt{Anchors2D}_i, \texttt{Anchors2D}_{i+1}, \ldots, \texttt{Anchors2D}_M]$, where $i \ldots M$ correspond to the layers through which fiber passes. First, we ensure all anchors are *on* a layer, not between layers, by "snapping" their `Z`-coordinate to the nearest layer boundary (Figure 4.2b).

It may be the case that multiple layers separate two subsequent anchors, so that some layers have fiber passing through them. RouteLayer must still be used on these layers in order to prevent the fiber from interfering with the printing process. We thus generate new anchors for these cases by finding every length of fiber between two anchors not on the same layer, and making new anchors where the fiber intersects the intervening layers (Figure 4.2c).

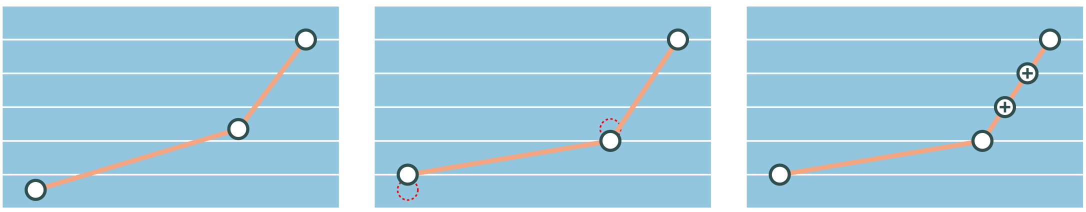

Figure 4.2: Layer/anchor snapping process. (a) Cross-sectional view of input anchor points ○ and fiber path ⁄, against layers ■ (layer thickness exaggerated). (b) Anchor points snapped to the nearest layer boundary. (c) New anchor points added where fiber crosses layers without anchor points defined.

Anchor/layer alignment: RouteLayer requires that the points in `Anchors2D` be aligned to segments of printed geometry represented in `Layer`. Without this requirement, an anchor not located on a printed segment will effectively "move" to a nearby intersection of fiber with printed plastic, a potentially large distance from the desired anchor point.

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Rhapso thus “snaps” each anchor to a point on a printed segment that is closest to that anchor point.

Splitting geometry: After adjusting anchor points, it may be the case that a longer segment of printed geometry contains more than one anchor point. If those anchors are non-sequential, then printing that segment to fix the fiber at the first anchor will prevent fixing at the second anchor. To avoid this problem, we split such segments into parts between the anchors.

4.1.4 Complete routing procedure

For clarity, we have described the processes involved in routing fiber through a model out-of-order. From start to end, the full implementation-independent procedure is as follows:

1. Input is a 3D model as `Layers3D` and a fiber path as a set of anchors `Anchors3D`, where the first anchor A_0 is fixed outside the model (i.e., to the print bed).
2. Snap each anchor in `Anchors3D` to a layer boundary.
3. For each layer through which fiber would pass without a defined anchor, insert a new anchor at the layer boundary.
4. Snap the anchors on each layer to the nearest printed geometry.
5. Split printed segments containing multiple anchors.
6. Execute $\textsc{RouteLayer}(\texttt{Layer}_\texttt{i}, \texttt{Anchors2D}_\texttt{i})$ for each $\texttt{Layer}_i$ that contains anchors $\texttt{Anchors2D}_i$.

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Chapter 5 Implementations

Having described the general theory of Rhapso's operation, we now detail two instantiations of the model. Our first implementation, which automatically embeds fiber, consists of a physical printer (Section 5.1) which enables *positioning*. The second implementation (Section 5.3) uses a guided, manual approach to work on an unmodified printer, with the user taking the place of the automated embedding hardware. Both share software based on the Rhapso algorithms (Section 5.2) to implement *avoiding* and *printing over*.

5.1 Hardware

We implemented Rhapso by modifying a Creality Ender-3 Pro, a low-cost, small-size, consumer-grade 3D printer. The printer is configured in a typical Cartesian setup where the build plate (220×220 mm) moves along the Y axis and the printer head moves within the XZ planes (maximum Z of 250 mm). We replaced the stock motherboard in the printer with a BIGTREETECH SKR V1.4 Turbo control board, which supports five independent motors in contrast to the stock Ender-3's four.

To enable the *position fiber* primitive operation, we mount a fiber carrier to the bottom of a two-part movable ring[1] attached to the printer (Figure 5.1) The outer portion of the

[1] An aluminum turntable bearing, or "Lazy Susan"

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ring is fixed to the X axis, while the inner part of the ring can rotate freely through 360°. A 3D-printed gear mounted to the top of the inner ring meshes with a gear attached to a motor, mapped in firmware (Marlin 2.1.0) to a rotational fourth axis `A`, allowing the printer to control the fiber carrier's position by rotating the ring.

The carrier itself contains a spool of fiber with a spring-based tensioning mechanism. To keep the fiber in the plane of the layer being printed, it exits the carrier level with the opening of the printer's nozzle. In our current design, the spool and tensioning spring are adapted from a standard retractable lanyard; this spool can hold about 10 m of .25 mm-diameter sewing fiber, or about 2 m of .7 mm-diameter elastic fiber, although our current design is constrained by the maximum extension of the spring to about 65 cm. In addition to this spring-based spooling mechanism, we also designed an active spool tensioning system, illustrated in **??**.

Rhapso's fiber-routing algorithm (Section 4.1.2) assumes the fiber forms a straight line between its current anchor point and the fiber carrier. To form the first anchor, we attach the fiber to the print bed via a clip. Further anchors are created during the printing process via the *print over* operation. By controlling the positions of the ring (`A` axis) and the bed (`Y` axis), the fiber can be made to cross over any point within the printer's build area.

The ring is mounted on the printer so that its diameter (197 mm) along the `X` axis is aligned to allow the print head (57 mm wide) the maximum amount of travel; even so, the usable travel of the print head in `X` is reduced from 220 mm to 110 mm (we must avoid collision of the ring with the print head as well as the belt fixation points on its underside). The `Y` and `Z` axes maintain their full 220 mm travel.

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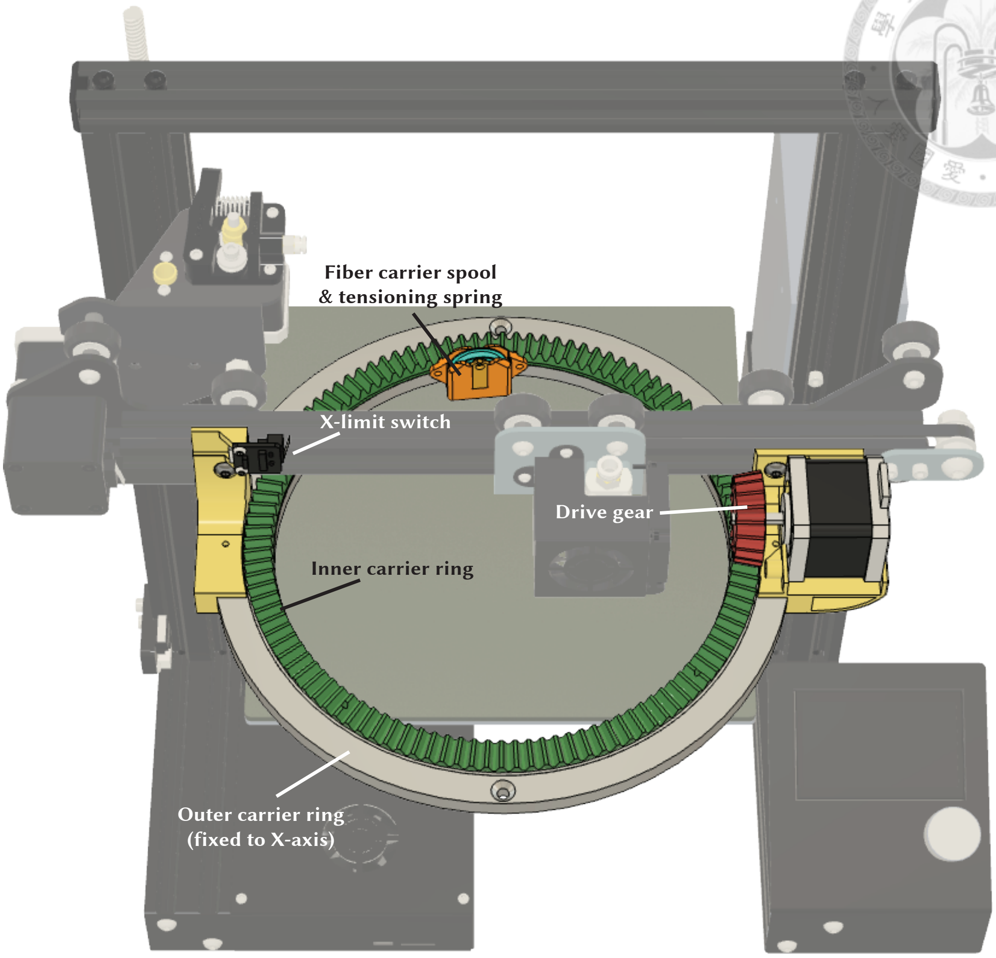

Figure 5.1: Detail view of Rhapso implementation.

5.2 Software

Using Rhapso to print an object with embedded fiber involves several steps:

1. **Design:** The user designs the object to be printed, and specifies anchor points where the fiber will be affixed to the object.

2. **Slicing:** As is standard for FFF printing, the 3D model must be sliced and transformed into G-code instructions for the printer.

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3. **Adding fiber-embedding instructions:** Rhapso's routing implementation post-processes the G-code output from the slicer, adding ring-movement instructions to position the fiber in order to produce the desired output.

4. **Printing:** The printer uses the processed G-code to simultaneously print the model and embed the fiber.

5.2.1 Design

Rhapso's routing algorithm (Section 4.1.2) requires a list of 3D model-space coordinates indicating where fiber anchor points should be located relative to printed geometry and in what order the fiber should pass through them. We use Autodesk Fusion to specify anchor points. The user designs or imports a model as usual, then models the fiber path as a series of connected line segments in 3D. Rhapso uses the Fusion API to export the path vertices, and the user exports the model itself via the standard Fusion interface. Currently, we do not detect errors or enforce design constraints such as requiring the fiber path to increase monotonically along the `Z` axis. Figure 5.2 shows a model and fiber path in Fusion.

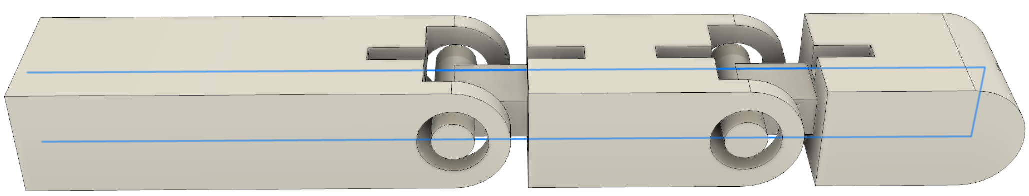

Figure 5.2: An example of a Rhapso design in Autodesk Fusion, with the fiber path drawn as a 3D sketch line (blue).

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5.2.2 Slicing

In FFF 3D printing, slicing is the process of transforming the mathematically defined 3D model into instructions for the 3D printer to execute [48]. We conducted our experiments using Ultimaker Cura[2] version 5.3, but Rhapso is not dependent on a particular slicer.

Slicers enable end-user manipulation of many printing parameters which can affect print speed and quality. Several of these parameters are important to adjust with the Rhapso fiber-embedding process in mind:

- **Bed size:** The slicer needs to know how the bed size is restricted by the fiber-carrier ring to avoid collisions between the print head and ring.
- **Printing temperature:** Recommended printing temperatures vary dramatically for different filament types and manufacturers; suggested temperatures for polylactic acid filament (PLA) range from 195–230° C, while polycaprolactone (PCL) filaments can be printed at temperatures as low as 60° C. Designers must consider compatability of the chosen fiber material with the print temperature; for example, low-cost optical fibers are typically made of acrylic with a melting point of 70° C.
- **Print speed:** Higher print speeds are desirable as they shorten print time; however, depending on the strength of the fiber and the force exerted by the tensioning mechanism, high acceleration of the print bed for `Y` axis moves could cause the fiber to snap.
- **Infill type and density:** Infill settings influence print speed, amount of material used, and object strength. When a fiber path is designed to pass through the interior of an

[2] https://ultimaker.com/software/ultimaker-cura/

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object, the routing algorithm snaps anchor points to the nearest printed geometry. The maximum possible distance an anchor could be moved is influenced by the type and density of infill.

Once slicing is completed, the generated G-code is then passed to the Rhapso routing program, which post-processes it to generate instructions for embedding the fiber.

5.2.3 Fiber-routing implementation

Our implementation of the Rhapso routing procedure accepts a G-code file as input, modifies it according to the routing algorithm, and outputs a new G-code file that can be used to print the fiber-embedded model without manual intervention. While our software follows the algorithms laid out in Section 4.1.2, there are a number of implementation-specific details which must be accounted for.

To make calculations of how to move the carrier ring, our system needs to know details of the physical hardware, including the location of the ring relative to the printer gantry, the ring size, and the location of the initial anchor point on the bed.

We transform the G-code output from the slicer into a list of line segments in 3D, allowing us to more easily perform operations such as finding intersections between fiber and print geometry. This transformation also enables manipulating printing order within a layer. Slicing software optimizes in-layer print order for factors like speed or surface appearance. In some cases, we must disrupt this ordering to enable proper fiber routing.

As an example, we have reproduced Figure 4.1h with added annotations in Figure 5.3b. The lines labeled 1–3 are printed in sequence by the original G-code from the

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slicer (Figure 5.3a). If line 3 is printed, it will fix the fiber at location **P**, but will also cross location **Q**, where the fiber has not yet moved. Thus, we first rotate and fix the fiber before printing line 3 (Figure 5.3d), which necessitates reordering the G-code (Figure 5.3c).

Because the center of rotation for each fiber segment will typically be different than the ring's center, additional calculation is required to determine what ring rotation will yield the desired fiber rotation. We find where a ray from the current anchor to the next anchor intersects with the ring, then determine the angle of the intersection relative to the ring center.

5.2.4 Printing

When all layers have been processed, Rhapso generates the final G-code. This step is dependent on the specific printer setup. In particular, for printers with an XZ-head configuration (like our Ender-3-based system, see Section 5.1), where `Y` axis movement occurs via a moving bed, each line of output G-code is augmented with a ring-movement instruction that keeps the fiber angle constant as the bed moves. For every line containing a `Y` move, we calculate the amount the ring must rotate to keep the fiber at the same angle (Figure 5.4), and modify the G-code to add a corresponding `A` axis rotation.

5.3 Manual printing implementation

Our second implementation of Rhapso uses the same concepts as the first, but does not require adding a carrier ring to the printer. Instead, we take a *hybrid-fabrication* approach [10], where the user takes the place of the ring, moving and tensioning the fiber when prompted.

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While this fully manual approach lacks the benefits of automation, it offers wider accessibility of Rhapso, as no hardware beyond a FFF 3D printer is required. Leaving fiber manipulation in human hands also provides opportunities to work with fibers that cannot easily be mounted on the carrier spool due to thickness, bend radius, or fragility. The tradeoff is the loss of automation and consequent tedious fiber manipulation work.

The software implementation of the manual printing process uses nearly the same code as the automatic process, but replaces ring movement commands with `M601` pause commands. We also print numbered guide-lines to indicate where the fiber should be moved to at each step. Figure 5.5 shows an example of the manual embedding process; the total fabrication time, including moving and securing the fiber, was about 10 minutes.

5.4 Implementation discussion

In this section we discuss some specific considerations and details of using our Rhapso implementations to embed fiber.

5.4.1 Fabrication-related material considerations

Some fiber properties may necessitate design modifications, extra machine configuration, or special care during and after fabrication. Specifically, some thermal and mechanical properties can interact with the printing process itself: if fiber is not flexible enough, it cannot be bent around an arbitrary corner radius. If fiber is too fragile, it will not sustain tensile forces during fabrication or interaction. Different fibers and their coatings may adhere to different degrees to printed material, or might absorb plastic between their component strands. Unintentional contact with the printer's heated parts may melt

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or burn vulnerable fibers, and require special methods for affixing them to the printed object without damage. Our software offers configuration parameters for changing printer behavior when the hotend and a fiber cross, but experimentation is required to discover the specific values for each fiber type.

5.4.2 Fiber-fixing techniques

For "normal" fibers not requiring specific considerations, several approaches can be used to fix the fiber, or prevent its fixation.

First anchor. Rhapso's architecture requires that the fiber always be under tension; there is currently no way to manipulate free-hanging fiber. Thus, as a manual first step, the user must secure the loose end of the fiber to the print bed and inform the router of its location. We designed a small, reusable anchor that clamps to the edge of the print bed to capture multiple sizes of fiber (Figure 5.6).

Off-object anchors. Some designs are more easily printed if the fiber is not wholly contained in the object; in these cases, sacrificial objects can be designed to provide anchors external to the main object. Off-object anchors can be *fixing*, where the fiber is captured through the normal *print-over* process, or *wrap-around*, where fiber is tensioned against, but not captured by, the anchor.

The puppets shown in Section 6.1 use wrap-around anchor objects to provide extra tension and to allow the fiber to be cut; the hook in Section 6.9 uses a wrap-around anchor to lengthen the fiber between two objects; and the pop-up mechanism in Section 6.5 uses a *fixing* external anchor to provide a fixation point to withstand the tensioned elastic fiber.

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In-object anchoring. At times, the *print over* operation by itself does not provide sufficient adhesion to fix a fiber at an anchor point; for example, large fiber rotations at an anchor can overcome the inter-layer adhesion of the plastic and cause the fiber to detach. We developed a technique for printing a `Z`-axis-oriented “blob” to provide extra anchoring strength, illustrated in Figure 5.7.

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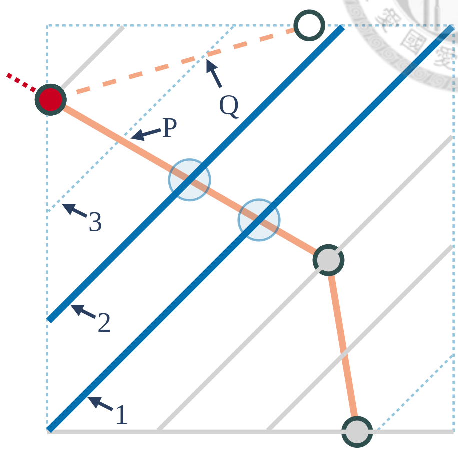
```
;Extrusion line 1
G0 X33.719 Y33.719
G1 X10.279 Y10.279 E4.2423

;Extrusion line 2
G0 X10.279 Y16.643
G1 X27.355 Y33.719 E5.04551

;Extrusion line 3
G0 X20.991 Y33.719
G1 X10.279 Y23.007 E5.54936
```



(a) (b)

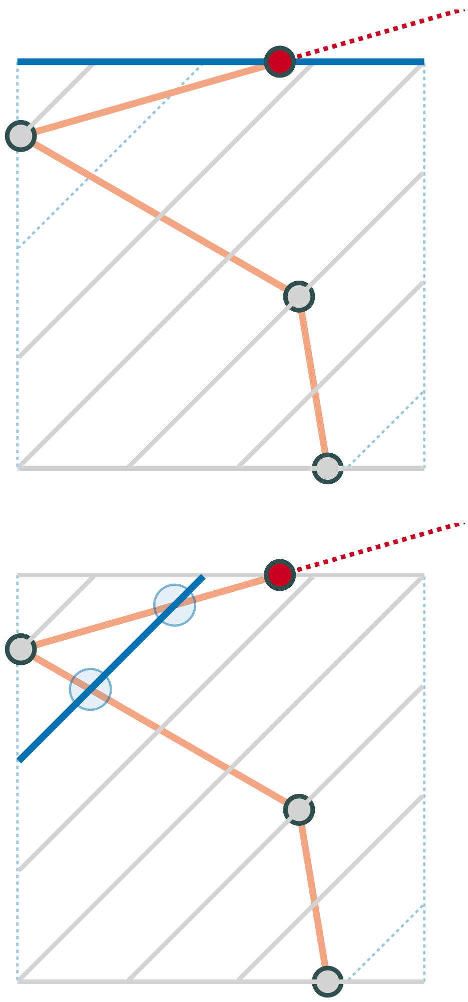
```
;Extrusion line 1
G0 X33.719 Y33.719
G1 X10.279 Y10.279 E1.0254

;Extrusion line 2
G0 X10.279 Y16.643
G1 X27.355 Y33.719 E1.9058

;Relative rotation to cross
;  next anchor
G0 A-134

;Print top line
G0 X33.8 Y33.8
G1 X10.2 Y33.8 E2.69069

;Extrusion line 3
G0 X20.991 Y33.719
G1 X10.279 Y23.007 E3.19454
```



(c) (d)

Figure 5.3: (a) G-code from slicer that would print lines 1–3 of (b) in order. (c) G-code modified by Rhapso to print lines 1 and 2 (b), rotate the fiber and fix it at the anchor (d, top), then print line 3 (d, bottom).

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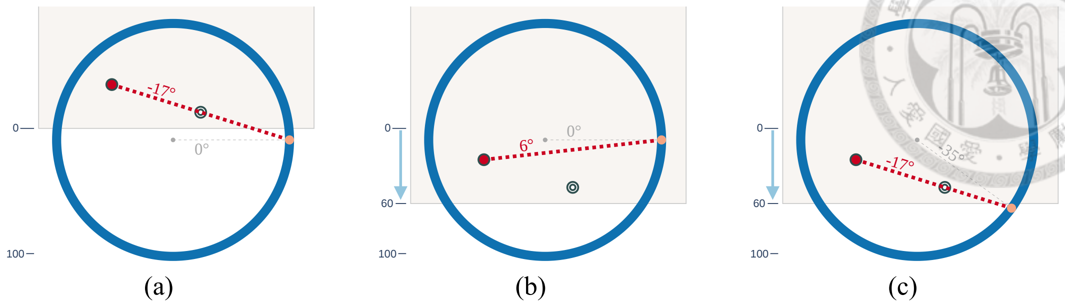
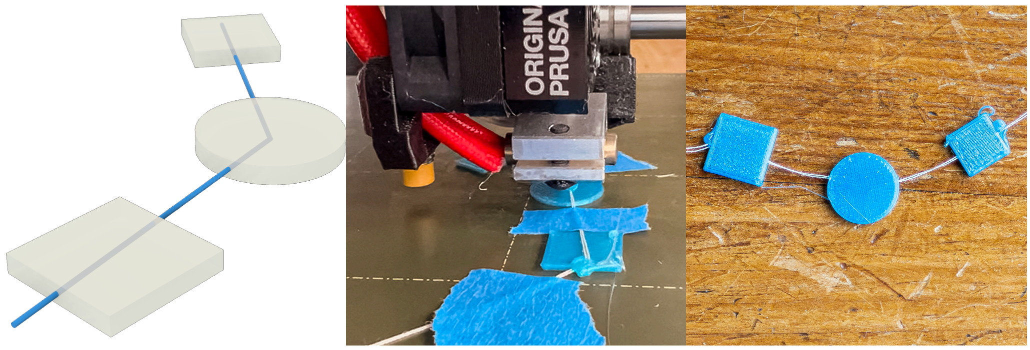


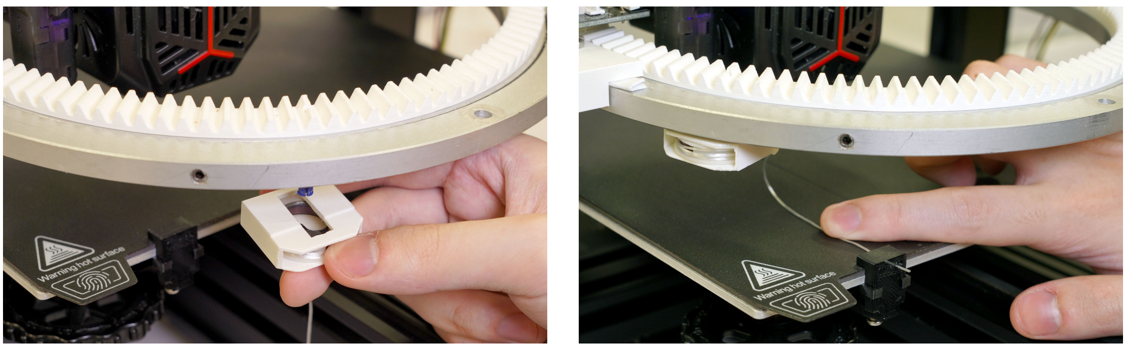
Legend: Printer bed Fiber carrier ring Fiber carrier Fiber anchor Next fiber anchor Fiber Ring angle

Figure 5.4: On printers with an `XZ`-head configuration, the print bed moves relative to the ring, changing the fiber angle. (a) The initial printer state, viewed top-down. (b) If the bed moves and the ring does not, the fiber angle changes. (c) Rhapso synchronizes ring moves to bed moves to keep a constant fiber angle.



(a) (b) (c)

Figure 5.5: (a) A design for embedding cotton string via the manual printing process. (b) Using tape to secure the string; an anchor has just been printed via the "blob" technique, Section 5.4.2. (c) The resulting beaded string.



(a) (b)

Figure 5.6: (a) We attach a fiber spool with a rotational spring inside to the ring. (b) Our bed anchor attaches one end of the fiber to a consistent location on the print bed.

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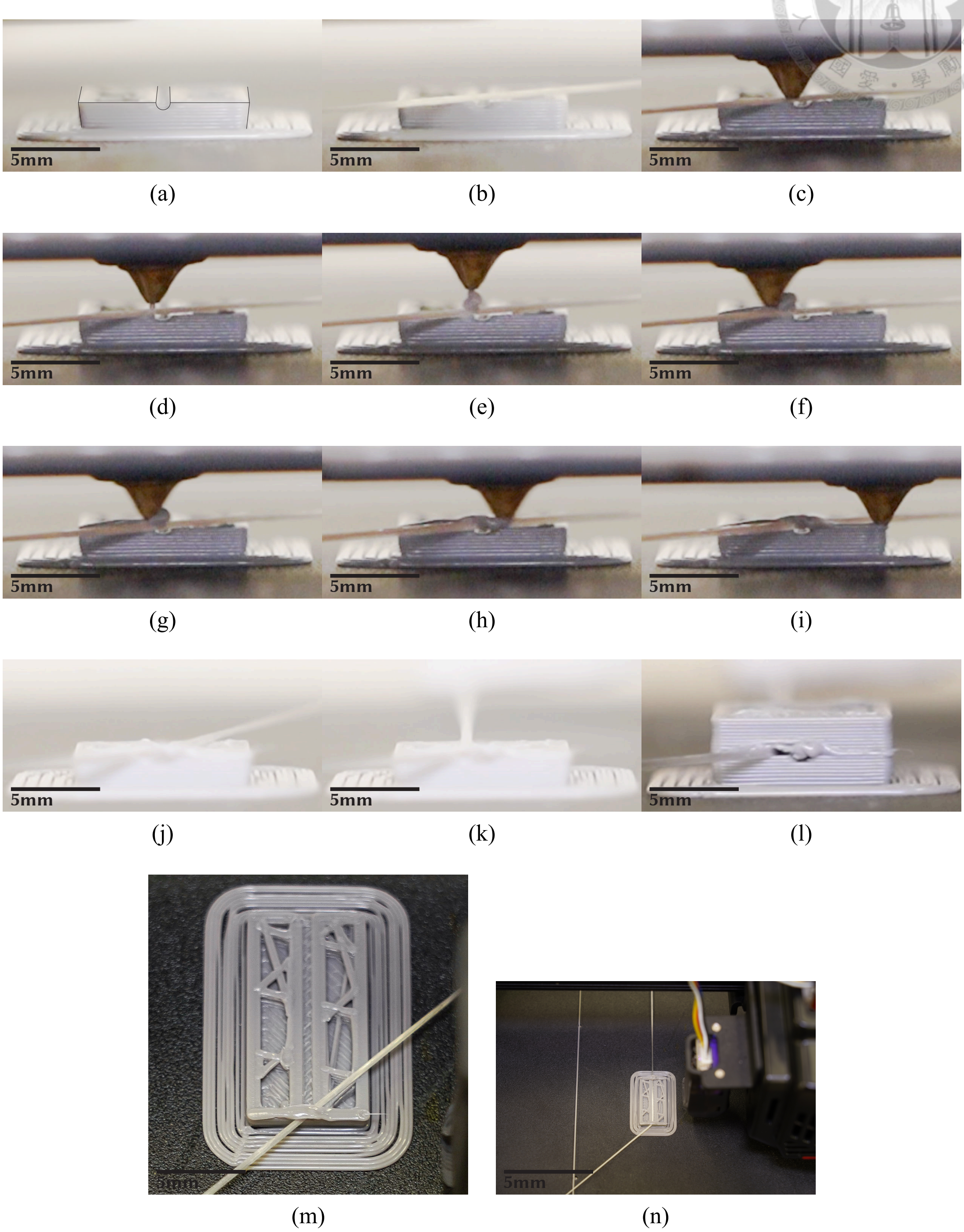

Figure 5.7: Stronger anchoring procedure. (a) A “half pipe” as tall as the fiber and twice as wide is designed into the object to help capture the fiber (lines overlaid for clarity). (b) The ring rotates so the fiber crosses the anchor point. We print a “blob” of filament out-of-plane (c)–(e) which the printer then spreads over the fiber (f)–(i). After a brief cooling period, the ring rotates the fiber to the next anchor point (j), (k) (top view (l), (m)). When the object is finished (l) the fiber is securely attached.

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Chapter 6 Applications

We now present a selection of applications built using our implementations of Rhapso, illustrating the breadth of possibility offered by fiber embedding. All of these examples were printed in-place on our prototype printers.

6.1 Articulated puppets

We created two articulated puppets. The first, modeled after a popular cartoon character (Figure 6.1), demonstrates transforming translational signals into rotary motion. Pulling the embedded cotton thread causes the puppet to lift its arms, while releasing the thread allows gravity to return the arms to a lowered position. We used an off-object wrap-around anchor to enable us to clip the thread (Figure 6.1c); routing the thread directly between the two arms in the object's interior would have prevented their moving.

The second puppet (Figure 6.2) also uses elastic thread as a signal transmitter. To ensure the right amount of stretch, the elastic fiber was embedded under full tension during printing using an extra, off-object wrap-around anchor (Figure 6.2c). When removed from the print bed, the extra anchor was discarded and the fiber relaxed. When the lever is pressed, the robot stands straight and the fiber is tensed; when released, the fiber and robot relax.

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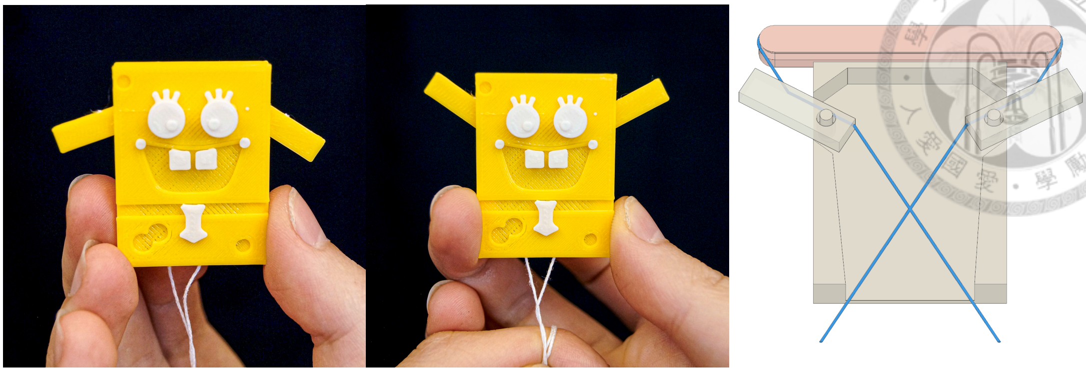
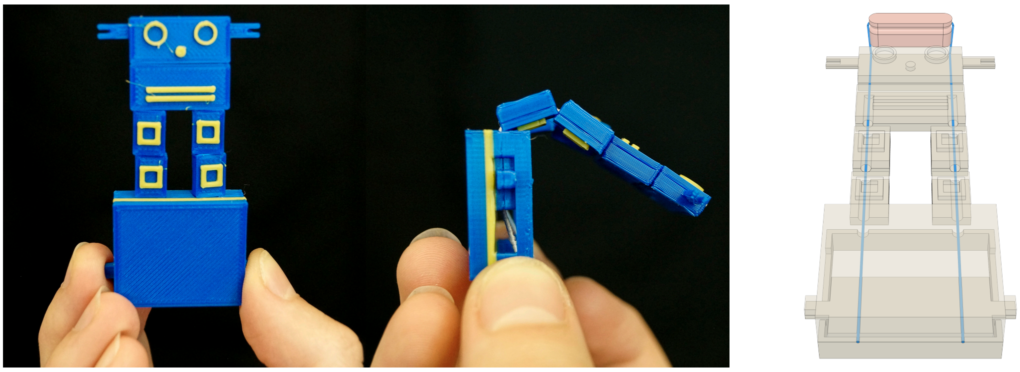


(a) (b) (c)

Figure 6.1: Articulated cartoon puppet with embedded cotton thread (a) slack and (b) pulled. (c) Interior thread route.



(a) (b) (c)

Figure 6.2: Robot puppet with embedded pre-tensioned elastic fiber. (a) Base pulled down to keep fiber tensed. (b) Base released to allow fiber to relax. (c) Fiber route through robot.

6.2 Abacus

We created a simple abacus inspired by the Japanese Soroban[1] (Figure 6.3) that features decoupling of fiber and printed object signals through objects printed along a cotton thread without fixation. The fiber is fixed to the frame at both ends, and the beads are printed around it with 2mm tubes; they can slide freely while the fiber and frame remain in-place.

[1] https://en.wikipedia.org/wiki/Soroban

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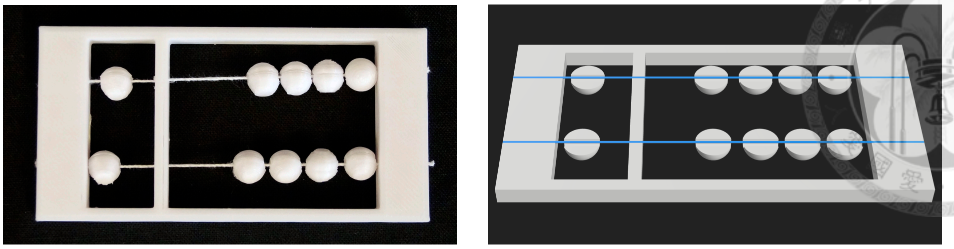
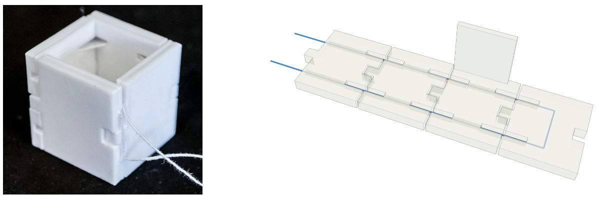


(a) (b)

Figure 6.3: (a) Abacus printed with free-sliding beads. (b) Cutaway view of embedded fiber design.

6.3 Pull-to-assemble box

Conversely, this decoupling can enable the fiber to move relative to the object: we used this in combination with fiber hinges that transmit forces around corners to create a box which is printed flat but can be quickly assembled into 3D. The box (see Figure 6.4) uses interlocking tabs for alignment and cutaways where the edges meet so that the tension on the thread causes each pair of edges to fold to 90°.



(a) (b)

Figure 6.4: (a) Box printed flat, assembled by pulling threads. (b) Transparent view showing internal thread routing.

6.4 Self-assembling boxes

Embedded, signal-originating fiber presents opportunities for objects which can self-assemble. Similar to the pull-to-assemble box, we created several boxes using elastic fiber printed under tension which fold up into closed shapes when removed from the printer

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(Figure 6.5); the blend signals concept combines their force to overcome the weight of the print. To ensure sufficient tension, we used an off-object anchor to keep the thread pulled to its full extent (Figure 6.6).

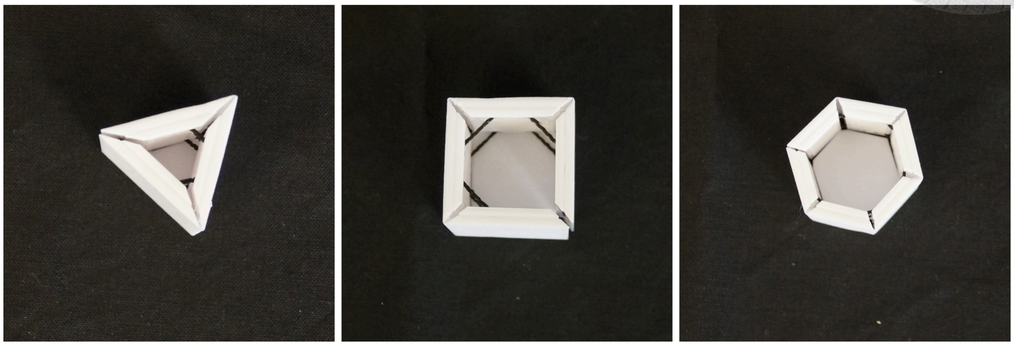

Figure 6.5: Self-assembling boxes with elastic fiber at various angles 30 degrees (left), 45 degrees (middle) and 60 degrees (right)

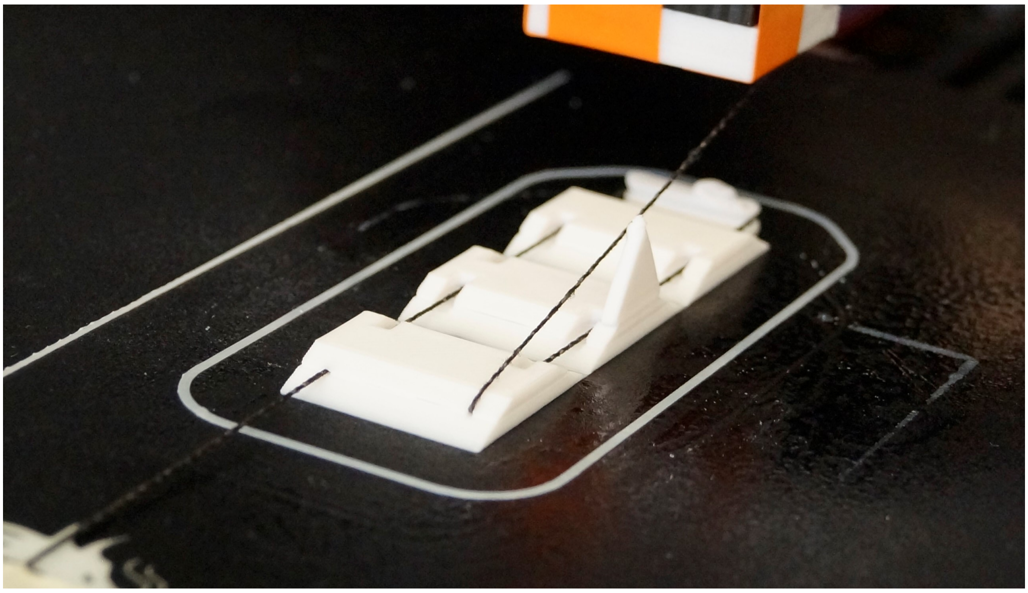

Figure 6.6: Self-assembling box on the build plate

6.5 Tensioned Pop-Up Mechanism

We printed a two-part scissor mechanism—similar to that used in some keyboards for haptic feedback—which includes tensioned elastic thread as a signal originator. When the device is removed from the print bed, it pops up to a 3D configuration and can be repeatedly pressed while popping back up.

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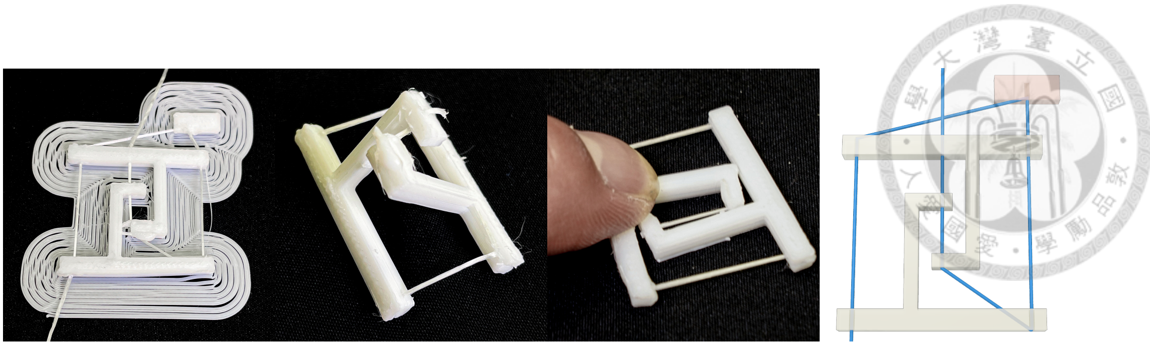
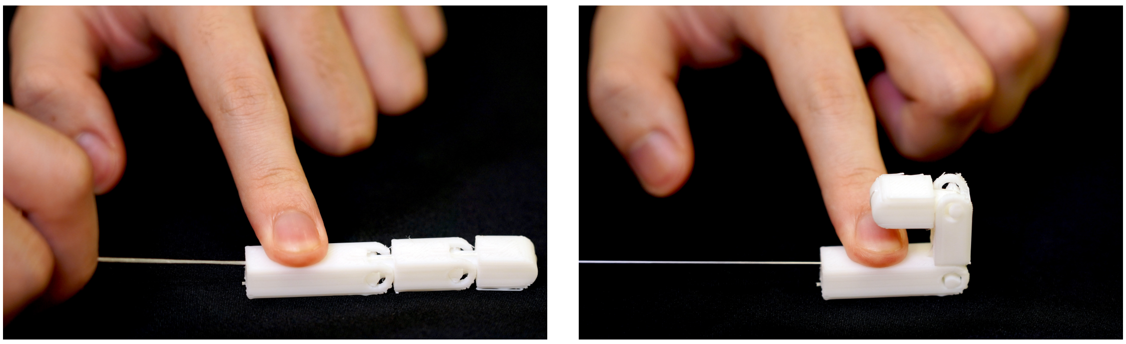


(a) (b) (c) (d)

Figure 6.7: (a) A pop-up mechanism printed flat while the thread is in tension. (b) The mechanism contracts and stands on its own after removing the brim. (c) The structure works like the scissor mechanism in keyboards. (d) The design of the fiber path; note the off-object anchor (pink).

6.6 Robot finger

Combining embedded fiber and motion transfer, we designed a robot finger which contains two horizontal elastic fibers. It curls when the upper fiber is pulled and transmits its force and straightens when it is released, as the tension of the lower fiber signal originator pulls it down. In this way, its position is a blend of user input and printed tension.



(a) (b)

Figure 6.8: (a) A printed robot finger relaxing and (b) contracting.

6.7 Grabber

We printed a reach-extending "grabber" device which uses elastic fiber to transmit force from a user's pinch to a distant pincer mechanism. This object was printed with two

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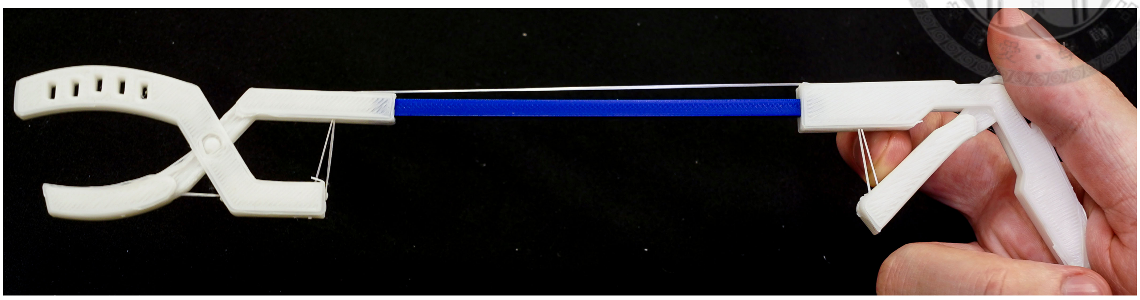
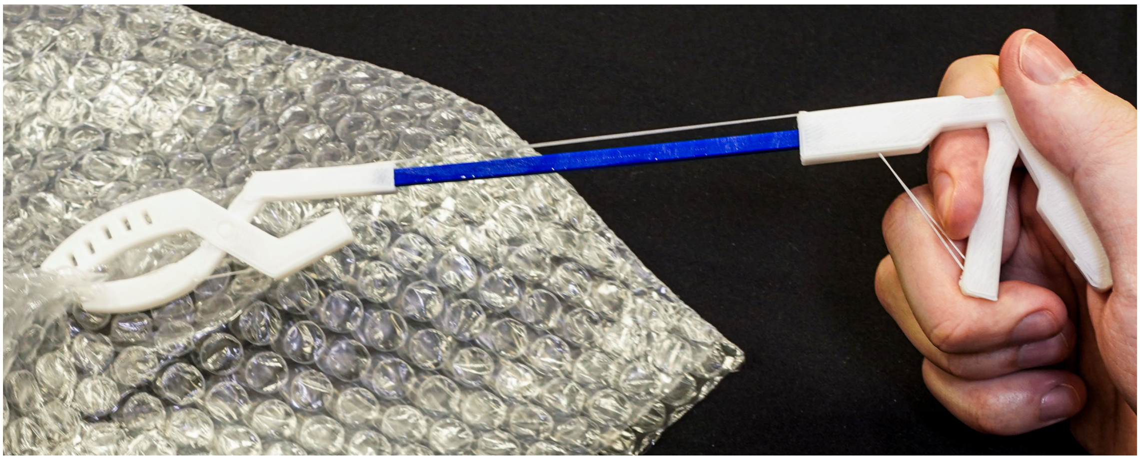
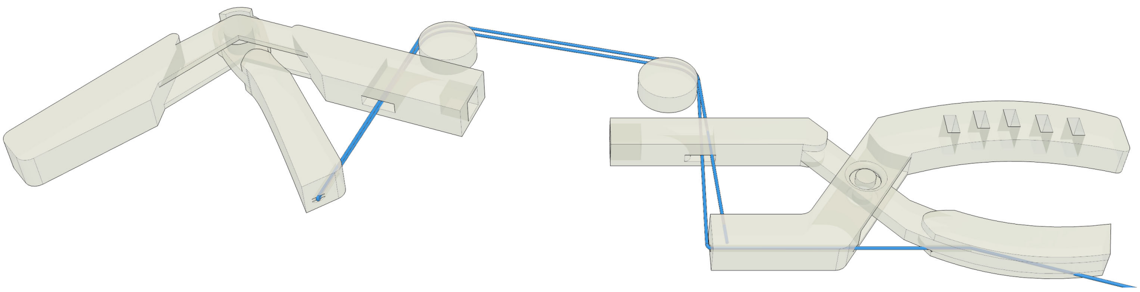
separated plastic parts connected by the fiber, such that the fiber also acts as a measurement tool to help the user insert a stick of the correct length during final assembly.



(a)



(b)



(c)

Figure 6.9: Our grabber device was printed as two plastic parts connected by thread and which, after printing, are rigidly connected using an inserted stick.

6.8 Fiber "hair"

Fiber can enter and exit a single object multiple times, in a single plane or across multiple planes. We used this technique with cotton thread to generate loose, multi-plane

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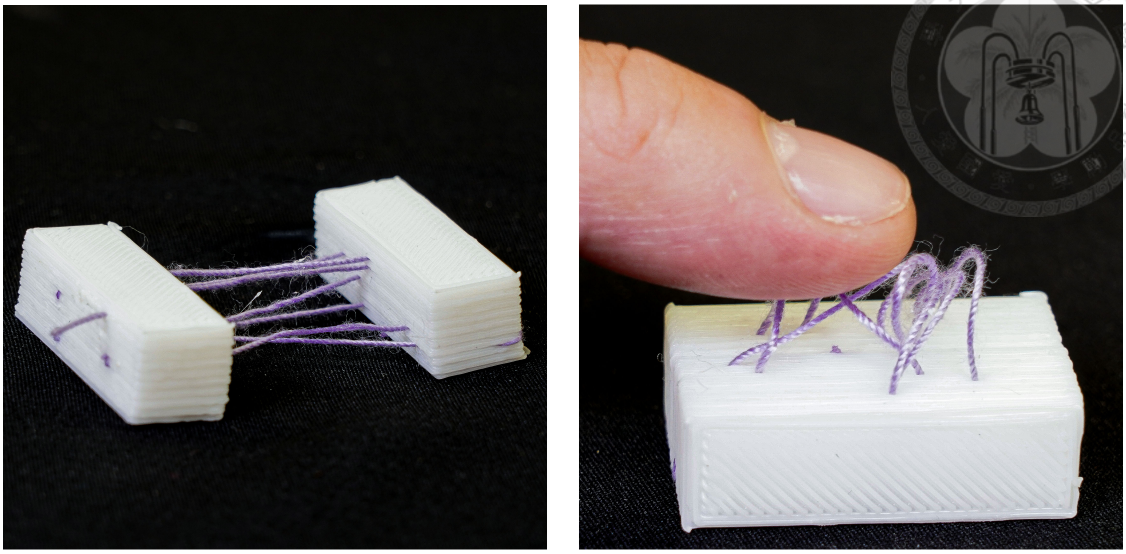

(a) (b)

Figure 6.10: (a) The fiber enter and exit a on object multiple times and across multiple layers. (b) The object can fold to perform hair-like texture.

loops which give a hair-like texture to the printed object (compare to 3D-Printed Hair [42]). These loops can also be cut post-print.

6.9 Extended hook

Fiber is not bound to print bed size in the same manner as extruded thermoplastic, as explored previously by Rivera et al. [73]. Here, we fabricated a two-part over-door hook with connecting fibers that stretch longer than the print-bed (Figure 6.11) by adding a sacrificial spool for thread winding during the print.

6.10 Design patterns

During the course of exploring the applications presented above, we recognized a number of recurring patterns in our fiber-embedded designs. Here we briefly discuss these patterns and how they might be generalized for use in further designs.

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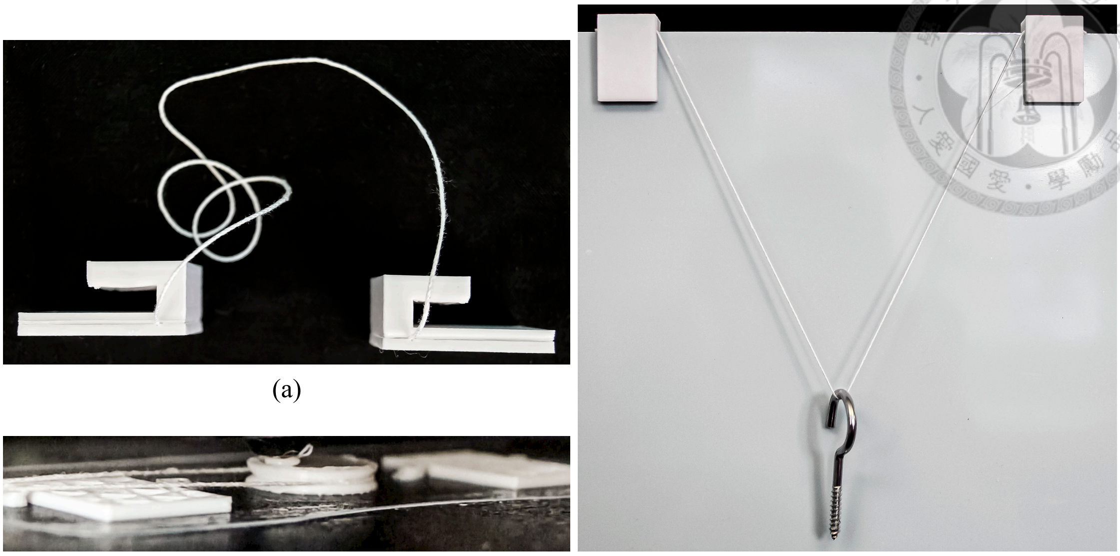

(a) (b) (c)

Figure 6.11: Embedded fiber can enable fabricating objects larger than the printer' build volume. (a) A hook printed to hang from a door (c) can be created by wrapping extra fiber around a temporary structure on the print bed (b).

6.10.1 Slide-guides

Fiber selectively left free to move allows printing objects with tubes through which fiber freely passes, creating a "guide" along which an object slides like a bead on a string. Conversely, guiding structures can be printed around non-fixed fibers to enable the *fiber* to slide. This pattern appears in the *abacus* (Section 6.2) and *pull-to-assemble box* (Section 6.3) applications.

6.10.2 Mechanical motion transfer

Push- and pull-cable mechanisms are commonly used to transfer power between locations. Examples include Bowden cables used in bicycle braking systems and robots [93]. Using guiding tubes, fiber can be pulled from one location to create actuated motion in another part of the object. Our *grabber* and *robot finger* applications (Sections 6.6 and 6.7) illustrate this pattern.

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The motion-transfer effect can be multiplied using *fiber arrangement* techniques to achieve *blending of signals*; by attaching a single user-facing fiber to multiple object-interfacing threads, motion can be transferred to several locations, directions, or planes.

6.10.3 Hinges

In contrast to common printed thermoplastics, many common fibers have a nearly unlimited ability to bend without weakening. One or more strands of fiber affixed between two parts of an object can form strong and flexible hinges, allowing movement or assembly by concentrating bending force in the most flexible part of an object. The *pull-to-assemble* box (Section 6.3) uses fiber hinges, allowing it to be assembled and disassembled many times.

6.10.4 Elastic "springs"

Spring-like behavior can be created by using elastic fiber with inelastic thermoplastic. Tensioning the fiber before fixing it in place creates stored energy that can be released for self-assembly, while un-tensioned elastic fiber can resist displacement of a moving part and return it to its original position. Several of our applications use pre-tensioned elastic fiber: the *self-assembling box*, the *pop-up mechanism*, the *robot finger*, and the *grabber* (Sections 6.4–6.7).

6.10.5 Extending objects

Due to printer size constraints, some larger objects can be difficult to fabricate via typical methods. In some cases, fiber can replace portions of models that do not need to be

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composed of rigid plastic, enabling the creation of objects larger than the print bed. Our *extended hook* example (Section 6.9) used fiber to lengthen the reach of a hook; while the *grabber* (Section 6.7) needs a solid strut in between its two components, the connecting fiber must be continuous.

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Chapter 7 Conclusion

We presented Rhapso, a software and hardware system to automatically embed fiber materials in FFF prints for enabling richer interactions and capabilities in low-cost 3D objects. Rhapso and its open source implementation invite HCI researchers and hobbyist makers to explore the advantages of multi-material fabrication and go beyond purely thermoplastic-based FFF prints. Rhapso solves several algorithmic challenges in fiber-based printing, and provides a platform from which we explored several points in the design space of fiber-embedding: taking into consideration pre-print fiber properties, during-print fiber-object structures, and post-print interactive capabilities. We also shared several example objects which highlight both novel interactions made possible by automated fiber embedding and our system's ability to replicate previously hand-made interactive objects.

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