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COMBINING STRINGS AND FIBERS WITH ADDITIVE MANUFACTURING DESIGNS

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ABSTRACT

High tensile strength cables, low-resistance motor windings, and shape memory actuators are common examples of technical fibers used in robots and other electromechanical assemblies. Because properties like tensile strength, crystal structure, and polymer alignment depend strongly on processing history, these materials cannot be 3D printed with the same properties they have on the spool. Strings and fibers are inserted in mechanical parts at the end of the manufacturing process for these assemblies. When the fibers take complex paths, the installation is often done by hand. This activity can dominate the process time, increase its human labor and reduce its social sustainability [1].

This paper applies the non-traditional approach of machine embroidery to insert sheets of patterned fibers in layered additive manufacturing processes such as 3D printing and lamination. Fibers are aligned with features in laser-cut or printed parts without the manual labor of hand threading. We demonstrate that water-soluble stabilizer materials originally designed for textiles can hold hard mechanical parts in a machine embroidery hoop with enough strength and rigidity to withstand sewing through pre-existing holes in the part. Alignment to within 250 microns has been demonstrated with a sub- $300 consumer embroidery machine.

Case studies in this paper include a cable-driven mechanism, a soft-to-hard electronic connection, and an electromechanical sensor. Process-compatible and commercially available materials that can be embroidered include conductive threads, shrinking threads, water-soluble threads and high tensile strength fibers.

The biggest hurdle for a user interested in this automated fiber installation process is linking the existing design file with an embroidery machine file. There is a much larger user base for 2D and 3D computer-assisted design (CAD) software than for expensive and proprietary embroidery digitizing software. We take the route chosen by the laser cutter industry, where the user produces a CAD file in their preferred editor, and makes annotations that communicate where and how densely to stitch. Translation software scans the file for a particular line style and generates stitch coordinates along it. Development is done in Jupyter/iPython notebooks that allow end-users to inspect, understand, and modify the conversion code. The intent is for users of existing planar fabrication technology (whether laser, printed circuit board, or micro/nano) to apply this method to their own CAD files for a versatile and straightforward way to put advanced materials in their devices without adding manual labor. This general approach can solve a class of assembly problems relevant to underactuated tendon-driven robotics and other electromechanical systems, expanding the range of devices that can be put together using automation.

INTRODUCTION

A significant percentage of robotics manufacturing still consists of hand-routing fibers, wires, tubes, and tendons around mechanical parts, especially for soft and wearable robotic assistive devices. Manual installation of cables and elastic fibers is often the dominant activity in assembly videos for articulated 3D printed structures (Figure 1). Meanwhile, computer-controlled string handling machinery is moving onto the desktop in the form of computerized sewing machines, sergers and embroidery machines.

Most consumer sewing and embroidery machines connect two threads together, one coming from underneath and one from above the material. If parts are thin enough to fit in the space between the needle and bobbin (<1 cm), fibers are thin and strong enough to withstand machine stitching, and fiber paths can be described as plane curves in lists of x,y coordinates, consumer sewing equipment can automate the tedious fiber-installation process. For example, if the fibers in a 3D printed hand design can be brought to a 1cm thick plane in the design file, we can lay the fibers out and construct 3D parts around them. This "sandwich" concept organizes the strings into a layer that snaps in place within a part. Even though the strings start out in a plane, they can take non-planar paths after assembly if the layer can be folded during insertion into a larger part, or if the part itself can fold after completion. Fibers can also bring new functionality such as conductivity and elasticity. In this work, we apply an embroidery machine to install tensioning cables in a simple planar mechanism, and to create low-cost electromechanical devices by installing conductive thread in insulating parts.

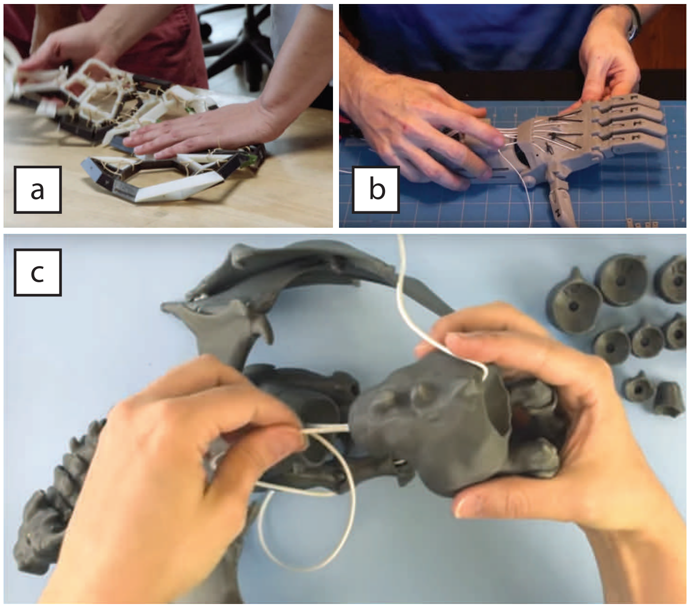

FIGURE 1 (a) Fold-flat bicycle helmet made from 3D printed parts connected by cables [2]. (b) Threading tendons and elastics into the e-Nable 3D printed raptor hand [3]. (c) Feeding elastic cables through an articulated 3D printed model [4].

FIBER INSTALLATION METHOD

We describe a fiber insertion technique that combines an embroidery machine with 3D printing and/or laser cutting in Figure 2. Parts are sandwiched between water-soluble films made of PVA (for example, *Vilene Plus* sticky self-adhesive stabilizer). The parts can be non-flat but should be less than 1 cm thick to clear the embroidery machine's sewing foot. After the stabilized parts are installed in an embroidery hoop, the needle is aligned to a pair of marks on the structure.

After alignment, the position of all features on the hoop is known with respect to the attachment fixture. By putting a hoop fixture at known position on the stage of a laser cutter or 3D printer, we can carry out further processing in alignment with the cables and previously constructed parts. The laser or 3D printing pattern is rotated and translated using the same offsets as the stitch pattern.

In Figure 2, water soluble thread (black) is used to temporarily hold the desired fiber (clear) in place during assembly. At the end, a layer with fiber and dual-sided alignment features is ready to snap into place in a larger assembly. Both the stabilizer and the water soluble thread are removed at the final step, after the fiber is locked in place within a 3D part.

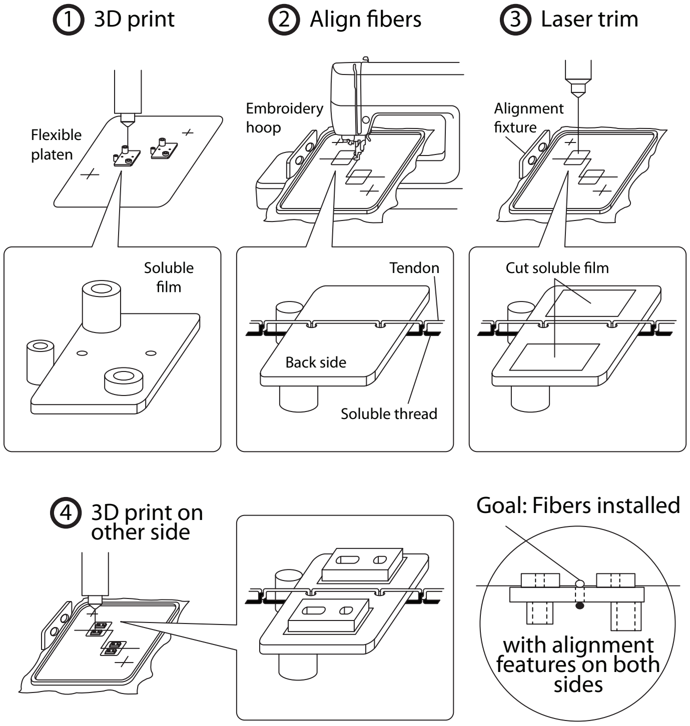

FIGURE 2 Process for using an embroidery machine (center column) to align fibers with 3D printed and laser-cut features. Printing starts on a water-soluble support film that holds parts in place during embroidery and subsequent processing.

Machine-sewable, commercially-available fibers can add several new functions to the part as listed in Table 1. The all-metal, high tensile strength, water-soluble and shrinking threads can be used as the top stitch (needle) thread, while all listed materials can be used as the bottom stitch (bobbin) thread.

Table 1: Machine-sewable commercially available fiber materials.

Thread Feature	Thread Name	Details
Conductive, metal coated	Bulk silver plated nylon	3 ply <100 ohm/cm. Manuf. by Shieldex
Conductive all-metal	Stainless thin conductive. Adafruit part # 640	2-ply stainless steel, 16 ohm/ft
High tensile strength	Kevlar	Sewable sizes have 14-30 lb breaking tension

Water soluble	Madeira Wash-A-Way, many others	Polyvinyl alcohol
Elastic	Gutermann Elastic Thread, others	Polyester-wrapped polyurethane
Shrinking	Chizimi	Polyester. 30% shorter when steamed
Fusible	Gutermann Fusible Thread	Polyester/polyamide melts when ironed
High temperature	Nomex	Chars at 315 C, doesn't melt
Solvent soluble	Danville 900 denier acetate floss	Used in fishing lures, dissolves in acetone

Materials are limited in diameter to less than 1 mm, comparable to sewing needle diameters in consumer machines. Table 2 lists the diameters of needle sizes 8-20 in mm.

Table 2: Needle diameters for consumer machines

Needle Size	Diameter (mm)	Notes
8	0.6	Very thin fabrics
10	0.7	Nylon
11	**0.75**	**Default***
12	0.8	Thin cotton
14	0.9	Regular cotton
16	1.0	Denim
18	1.1	Heavy denim
20	1.2	Heavy suiting

*Embroidery needle commonly shipped with machines

SOFTWARE

1. Layout Software

Because there is a larger engineering user base for machining and circuit board layout software than for embroidery software, we developed methods to create an embroidery file from a given Drawing Exchange Format (DXF) file produced by most CAD environments. The software finds the centers of all circles and puts a stitch coordinate there. Typically, the circles are listed in the DXF file in the order drawn by the engineer, so simply finding and connecting the holes in the order found in the file produces a disorderly stitch pattern. For example, when drawing an electrical contact pad with stitch holes for conductive thread, it is undesirable to stitch back and forth between adjacent pads more than once, because each linking thread must be cut to prevent shorting. However, the basic DXF file only lists feature locations and does not contain a description of the desired stitch tool path.

To convey this information, the designer draws a line denoting the stitch path in the same software used to produce the DXF file. This approach is similar to laser machining, where the user denotes laser dwell time and power with specific colors and fills in their native design environment. Our conversion software uses the path along with the hole coordinates to reorder the stitch coordinates in the desired sewing sequence. Given a list of x,y coordinates in mm, the software produces an .exp embroidery file. These files consist of byte pairs that encode the difference between successive x,y coordinates in 0.1 mm increments. Because the maximum stitch length in this encoding is 12.7 mm, the .exp files also provide codes for "jumps" which move the needle to an intermediate position, but do not stitch. Thread color changes are indicated in the file by a specific byte pair. Besides stitch data, most formats have a header section that specifies the number of stitches and the bounding box of the pattern, and they often contain a small 1-bit image of the pattern to display on the sewing machine's LCD screen. More about proprietary embroidery formats is available online [5].

2. Alignment Software

The low-cost consumer machine in this research project (Brother PE525 with a 4x4 inch embroidering area) does not offer direct alignment control beyond moving the needle in x,y in 0.5 mm increments, or rotating by 1 degree increments. Instead we use the sewing needle to locate a pair of alignment marks on the part. These alignment marks are typically a pair of laser-cut or 3D printed features 6 cm apart. The user loads a small design (3x3 cm or less in extent) and uses the machine's manual adjustments to move the needle over each alignment mark, lowering the needle to verify alignment. The Brother PE525 reports the current needle location to within 0.5 mm on its LCD screen. Users can often make a finer estimate by careful inspection. The user discards the small test file, and enters the measured coordinates (x_1, y_1) and (x_2, y_2) into software to generate a translated and rotated stitch file containing the actual pattern. For a design file with alignment marks drawn at ($-x_o$, 0) and ($+x_o$, 0), the alignment software generates a new .exp file with each *x,y* stitch coordinate transformed as follows:

$$\text{X\_Center} = (x_1 + x_2) / 2$$
$$\text{Y\_Center} = (y_1 + y_2) / 2$$
$$\text{Rotation\_Angle} = \tan^{-1}((y_2-y_1)/(x_2-x_1))$$

$$\theta = \tan^{-1}(y/x)$$
$$r = \sqrt{x^2 + y^2}$$
$$x_{new} = r\cos(\theta + \text{Rotation\_Angle}) + \text{X\_Center}$$
$$y_{new} = r\sin(\theta + \text{Rotation\_Angle}) + \text{Y\_Center}$$

where x_{new}, y_{new} are the positions of each stitch coordinate in the modified design file.

The software also adds jump stitches to move the needle from the origin to the start of the design file, in the case that the distance is greater than 12.7 mm. Careful inspection is warranted for any unintended stitches, because accidental contact is likely to hit a hard material and break the needle.

At run-time, some machines (including the Brother PE525) ignore bounding-box information in the file header and instead, automatically center the data. Because this would ruin the alignment of an off-centered pattern, the program avoids the auto- alignment problem by inserting a centered 9x9 cm bounding box in a second thread color that need not be stitched.

The modified file is loaded and stitched on the still-aligned part with no user-entered offset or rotation on the machine.

3. Format Conversion Software

The .exp format works with Bernina machines, but not the Brother PE525, which uses .pes format. Many file conversion software variants are available. We used the StitchBuddy program on iOS to convert files from .exp to .pes for this work.

RESULTS

Results consist of case studies for four types of designs: a folding structure that uses shrinking thread to maintain its shape, a soft-to-hard electrical connection between a wireless circuit and a sensor pad, an electromechanical switch, and a 3D printed cable-driven mechanism.

1. Folding design with shrinking thread

In this design, 1x1 cm tiles were hinged together with cotton sewing thread (red) as shown in Figure 3. Each tile could take one of two positions above the plane thanks to cutouts in the material; such structures can be "programmed" to make surfaces of elevation [6]. The tiles were also connected by shrinking thread (Chizimi, Table 1) in a specific arrangement above and below the material. The goal was to form the surface of elevation by folding the hinges, then use the shrinking thread to lock the structure in place.

For this application, the tiles could be 3D printed, machined or laser cut, as long as their relative alignment was maintained. We used laser cutting to make tiles from Mylar A (14 mil thick) and attached them to sticky, water-soluble Vilene Plus. To maintain alignment between neighboring tiles, the Mylar A was partially cut, then the sticky sheet was attached and the laser wrote a second pattern to finish separating the tiles without separating the stabilizer. Two x-shaped alignment marks were also cut into tiles 6 cm apart. After removal from the laser bed, an overlayer of water-soluble stabilizer on the back side helped hold the small tiles together.

The assembly was placed in an embroidery hoop (Figure 3a), the two thread patterns were aligned (Figure 3b) and stitched through holes laser-cut in each tile (Figure 3c) using a size 8 (0.6 mm diameter) needle. Chizimi shrinking thread was stitched using cotton bobbin thread, leaving shrinking thread on the top. Shrinking threads were applied to other locations on the back side by flipping and re-aligning the tile array, although it would also have been possible to swap the top and bobbin thread. The soluble stabilizer was dissolved. Finally, the structure was folded and exposed to steam from boiling water, causing the shrinking thread to pull tight at the inner 90-degree corners on both the front and back of the surface and stabilize the shape (Figure 3d).

For this design, the alignment error was 0.5 mm or less over a 5x5 cm area. Good alignment depends not only on the machine, but on using stabilizer materials that do not stretch or warp significantly over the embroidered area. Because needle diameters are in the 1mm range (Table 2), the minimum hole diameter was limited by needle clearance rather than by alignment accuracy.

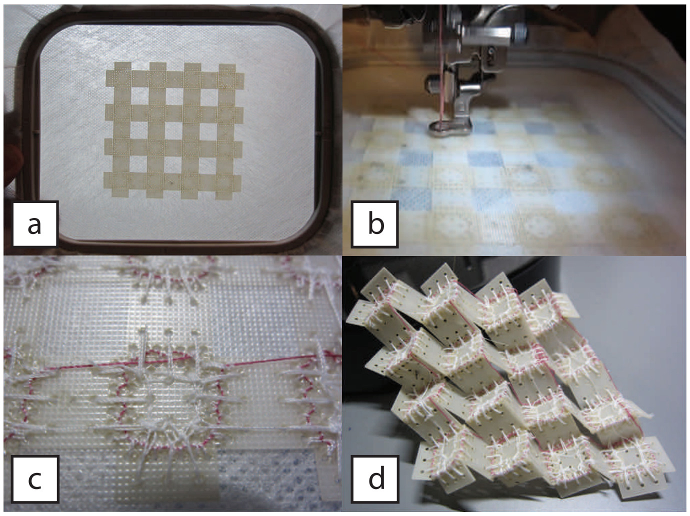

FIGURE 3: 1x1 cm plastic tiles (a) held in place in an embroidery hoop using water soluble stabilizer. (b) A machine embroidery pattern is rotated and aligned with the tiles. (c) Close-up of shrinking threads and ordinary sewing threads aligned with pre-cut holes. (d) After dissolving the stabilizer, the part is free to fold, with tiles held together by thread hinges. Steam shrinks threads tight to stabilize the shape.

2. Soft-to-hard electrical connection

In this case study, machine-embroidered threads were aligned to holes in a printed circuit board (PCB). The purpose of the embroidered PCB was to connect a Bluetooth module to a low-cost, large-area pressure sensor made by printing conductive ink (Bare Conductive, Inc) on a non-woven textile that was pleated to make electrical contact when a person or object pressed on it. This paper-like sensor could not be soldered, so conductive thread was chosen to make the connection. Machine-sewable conductive thread (silver plated nylon 117/17 2 ply, PlugandWear product PW018) was loaded as both the sewing and bobbin thread to make a soft-to-hard electrical connection between the circuit board and an underlying soft circuit.

The embroidered interface PCB was designed with "card edge" contacts, sliding into a card-edge connector (5650118-2, TE Connectivity AMP Connectors) on a small Bluetooth-equipped circuit board (LightBlue Bean, Punch Through Technologies) without adding any soldered connector components to the embroidered PCB. Keeping the PCB free of soldered components meant that it was inexpensive enough to be considered disposable, and also eliminated problems of the embroidery foot landing on uneven terrain. Using this design, the paper sensor circuit with embroidered board illustrated in Figure 4(a) could be unplugged and recycled when the sensor pad became dirty or worn out.

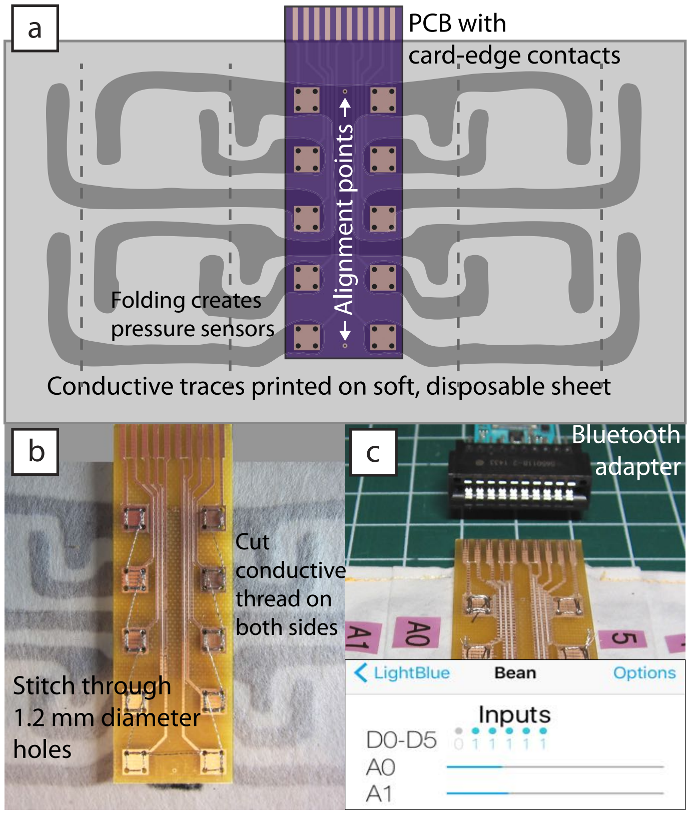

FIGURE 4 (a) A printed circuit board (PCB) with 4x4 mm contact pads is glued on to a soft printed sensor sheet in preparation for stitching with conductive thread (b) Aligned, stitched pattern with conductive thread on both sides. (c) The PCB joins the soft pad to a Bluetooth module via a card-edge connector for communication with a mobile phone (inset: app screen when switch 0 is pressed).

In this application, the PCB needed to be thick enough to properly interface with the card-edge connector. We used standard 1.6 mm thick FR-4 material that had a single-sided 1 oz/in^2 copper coating, and non-plated through holes.

Hitting the thick board would definitely break the #10 (0.7 mm diameter) sewing needle. The stitch pattern needed to be closely aligned to the 1.2 mm diameter circuit board holes. A circuit board has several options for alignment features. Silkscreen, metal traces, insulating solder mask, and drilled holes are typically available on the top surface. We decided to align the needle to a pair of drilled holes, because accurate alignment with other holes on the board is the most crucial for error-free stitching. The PCB was coarsely aligned with the paper pad using temporary spray adhesive, and the embroidery machine was aligned to holes illustrated in Figure 4(a).

To translate the PCB hole pattern to embroidery specifically for this simple board, DXF was an unnecessary detour. In nearly all printed circuit board design environments, the drill coordinates can be exported in Excellon format, giving a text-based list of x,y pairs that provide the source of stitching coordinates. Getting a comma-separated variable (csv) file to read in Excel can be done by finding/replacing the character X with an empty string, and Y with a comma. Because there were so few holes (40), and they were on a regular grid, a computer program was written to generate the stitch file.

To avoid short-circuiting neighboring traces, the conductive thread had to be cut between each circuit on both the front and back side, or it would carry a signal between pads (as can be seen in Figure 4b before trimming). This process could be automated with a more fully-featured embroidery machine that clips embroidery thread between colors—a common feature in mid-range machines. The measured electrical resistance between the card edge contact and the printed trace was an average of 450 Ω.

Figure 4(c) shows how the PCB plugged into the card edge connector and brought the signal to the Bluetooth module. The digital inputs on the processor were configured with a 10 kΩ pull up resistor. When a soft pad was pressed, the corresponding input was connected to ground over a ~1kΩ resistance, which was low enough to bring the voltage below the input-low threshold of the digital input and take its signal from 1 to 0, as shown for switch 0 in Figure 4(c).

In this application, conductive thread was used for both the mechanical and electrical connection. It would also be possible to create holes in the PCB specifically for insulating thread to attach the board securely to a surface, or to attach a PCB to a 3D printed part to add electronic functions.

3. Electromechanical switch

This design used conductive bobbin thread and insulating sewing thread to detect whether a laser-cut cantilever was above or below the surrounding material. The cantilever was at the center of a thin compressed beam. As the beam bent up or down, the cantilever deflected above or below the beam surface. A suspended conductive thread contacted a conductive thread on the cantilever only in one of the positions, as shown in Figure 5 (a) where a cantilever has pulled away from three suspended conductive threads and opened a circuit. The purpose was to read the state of bistable compressed beams in an actuator array, and convey each beam's orientation to a computer [7,8]. Because microcontrollers often have a much greater number of digital than analog inputs, and digital input reading takes less time and power than analog-to-digital conversion, a digital threshold-sensing switch was preferable to an analog sensor (for instance, a resistive bend sensor) in this application.

Here, making an aligned embroidery pattern was important so that the silver-plated nylon thread was applied to the center of the cantilever. However, the material (5 mil polyester) was soft and thin enough that even the #8 sewing needle could punch through, so pre-drilled sewing holes were not cut.

The beams were laser cut but were left attached to the polyester sheet at the ends; Figure 5 (c) shows the x-shaped alignment marks on the center beam that were used to align stitches on several samples. The beams were placed in a fixture that rotated their end points symmetrically. At a threshold angle determined by beam length [9,10], the beam snapped to the opposite orientation as shown in Figure 5 (b). When the beam was in the "up" position, the resistance across the switch was in the 20 Ω range. With the left side connected to ground and the right side to a digital input with 10 kΩ pull-up resistor, the input varied between 0 and 3.3 V; this voltage is shown in Figure 5(b) for 10 turns of the fixture.

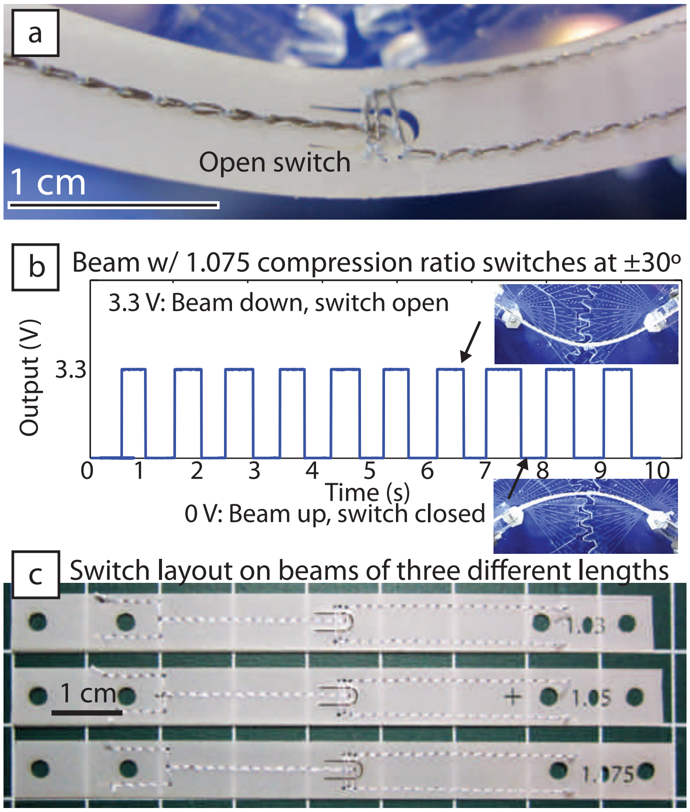

FIGURE 5 (a) Close-up view of cantilever deflecting downward and pulling conductive thread on the left away from overhanging conductive threads on the right. (b) Signals from switch in up and down positions. (c) Beams with stitched thread and lengths corresponding to three switching angle thresholds.

The method in Figure 5 could be extended to thicker 3D printed materials provided with stitch holes. Conductive threads could make contact when parts of the 3D structure touch-- possibly giving feedback on the relative positions of moving parts in an additively manufactured structure.

4. Cable-driven mechanism

In the final case study, the embroidery machine was used to route cables in a compliant 3D printed structure. This design used water-soluble bobbin thread to hold high tensile strength sewing thread within raceways in a thin, bendable plastic part. A pointer deflected in a direction depending on the relative tension in the two cables. A similar principle drives tendon-equipped robotic grippers [11].

Construction depended heavily on water-soluble stabilizer sheets. First, the design was 3D printed on a stabilizer sheet (Vilene Plus) by taping the sheet to a Makerbot Replicator printer bed sticky side up to promote adhesion of the deposited plastic. The structure and alignment marks were printed in polylactic acid (PLA) plastic. PLA and acrylonitrile butadiene styrene (ABS) are the most common types of plastic for consumer-grade fused deposition modeling (FDM) printers. PLA was chosen over ABS because laser-cutting of ABS releases hazardous fumes, and it may be necessary to laser-skim the stabilizer film or laser-cut threads around the 3D printed structure later on.

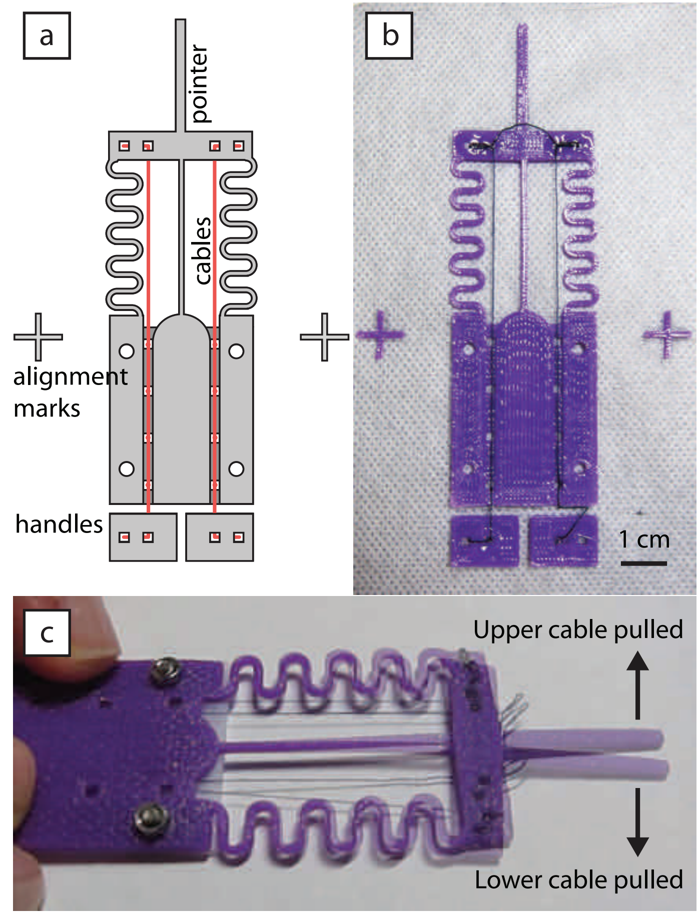

FIGURE 6 (a) Layout of cables in a 3D printed two-layer structure with alignment marks (b) Printed structure with attached cables on a water soluble sheet (c) 7mm vertical deflection of the pointer with ~1lb horizontal force on the cables.

Holes in the structure allowed the cable to make temporary attachment to the inside of the raceway using soluble bobbin thread from underneath the stabilizer sheet. This feature was not very important in the straight-channel design of Figure 6, but it would be crucial to keep cables seated in complex paths where thread tension would pull them in the direction of the needle during sewing. After printing and cable installation, we attached a cover using screws. The cables were then completely enclosed in the raceways. Because the cables needed to be anchored at the top bar and at the handles, we applied glue (E-

6000) to those points before removing the soluble materials in a 15 minute, 60 C water bath. The structure could then be deflected by pulling on either cable. Figure 6 (c) is a double exposure showing the end of the structure at the extent of motion as each cable was pulled.

DISCUSSION

The folding design in the first case study tested the limits of stitch spacing (1-2mm). Although the user can drive the machine in 100 micron increments, needle diameters in the 1 mm range put a practical limit on spacing. The soft-to-hard electrical connection method in the second case study showed how machine embroidery can help with the problem of economical multi-pin connectors for electronic textiles [12]. During the past few months, we further investigated the electromechanical switch in the third case study [13], finding that automated thread cutting and anchoring will increase the capability of this method. The 3D printed mechanism in the last case study came closest to the tendon installation process illustrated in Figure 2. Alignment features and multiple layers were accessible on the top side, and the structure could potentially be flipped to cut through parts of the stabilizer and print more alignment features on the back.

It would be most efficient to print or laser-cut on the sewn part without removing it from the hoop, in order to use its known alignment with respect to the hoop fixture after the sewing needle located the alignment marks. To do so, a fixture should be attached to the laser or 3D printer that matches one on the sewing machine [14]. In projects such as the 3D printed mechanism, the temporary soluble thread worked well except that it created the problem of lost anchor points. Stitching over anchor points with fusible thread (Table 1) as a patternable hot glue could keep fibers in place after soluble thread has been removed. For temperature-sensitive materials, stitching with a second layer of cotton thread could create a friction hold at the anchor points, trapping the underlying cable in place at the anchor.

Automated conversion to different machine formats (such as PES used for the Brother PE525) would have created a faster workflow in all four case studies. Since the specifications can change at any time. a non-proprietary open hardware platform would be preferable. The Embroidermodder project [15] aims to build for embroidery the open software environment similar to the one that exists for 3D printing. At this writing the PES specification is unstable but it is documented in the associated libembroidery C library. Other descriptions of the PES specification are available online [16,17,18].

CONCLUSIONS AND FUTURE WORK

We have described a design pipeline for integrating fibers and threads into parts that are described by a machining file. General design principles extracted from the four case studies were:

- Create widely-spaced alignment marks in the most dimensionally-stable layer of the machined object (for example, use holes in a PCB).
- In hard objects, the needle diameter (~0.8 mm) puts a lower limit on stitch spacing because closely-spaced holes weaken the material.
- When soluble thread is used for a temporary hold, consider how a second stitch pattern, glue or mechanical trapping will keep the tendons in place in the final product.

Two-way integration between the DXF file and stitch pattern will lead to a faster design process. When adding fibers to thick materials such as printed circuit boards or 3D printed parts, the designer must draw a hole for each stitch coordinate. Further development focuses on automatic placement of stitch holes in the part by combining the stitch tool path and a user-entered desired stitch spacing to draw holes. This pipeline takes a DXF file with user's annotations, outputs another modified DXF with stitch holes, and then generates the corresponding stitch file from the modified DXF.

Finally, fibers thicker than about 0.8 mm do not perform well on a consumer machine even as bobbin thread. However, thick fibers are needed for high-strength elastic cables. There are also materials such as fiber optics that are too stiff to be sewn, and coiled actuators [19,20] that would be damaged by taking paths through the plane of the fabric. In other work we are investigating the technique of machine couching, which uses sewable fibers to bind non-sewable fibers to the top surface of the material.

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