FiberCircuits: A Miniaturization Framework To Manufacture Fibers That Embed Integrated Circuits

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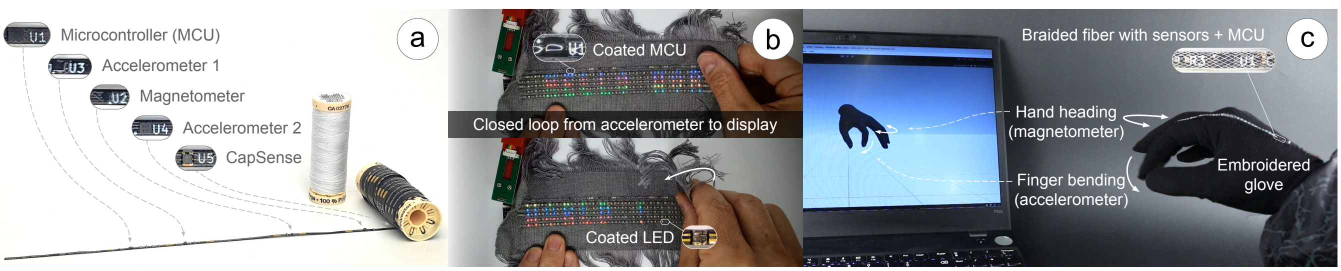

Figure 1: (a) The main FiberCircuit illustrated as a sewing thread with embedded processing and sensing (two accelerometers, a magnetometer, and capacitive sensor). (b) A woven sample with 250 LEDs scrolling "Hello World" at a speed controlled by the accelerometer. (c) A FiberCircuit embroidered on a glove to control a VR hand with touch, hand orientation and finger bending.

Abstract

While electronics miniaturization has propelled the evolution of technology from desktops to compact wearables, most devices are still rigid and bulky, often leading to abandonment. To enable interfaces that can truly disappear and seamlessly integrate into daily life, the next evolutionary leap will require further miniaturization to achieve full conformability. With FiberCircuits, we offer design and fabrication guidelines for the manufacturing of high-density circuits that are thin enough for full encapsulation within fibers. Our demonstrations include a 1.4 mm-wide ARM microcontroller with sensors as small as 0.9 mm-wide and arrays of 1 mm-wide addressable LEDs, which were woven into our interactive textiles. We provide example applications from fitness to VR, and propose a scalable fabrication process to enable large-scale deployment. To accelerate future research in HCI, we also made our platform Arduino-compatible, created custom libraries, and open-sourced all the materials. Finally, our technical characterizations demonstrate FiberCircuits' durability, thanks to its silicone encapsulation for waterproofness and braiding for robustness. From wearables to insertables or even implantables, we believe that by making miniature circuits accessible to researchers and beyond, FiberCircuits will open possibilities for new scalable interfaces that embody imperceptible computing.

CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**.

Keywords

HCI, Embedded Systems, Wearables, Miniaturization, eTextiles, Open Source, Rapid Prototyping, Scalable Manufacturing.

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1 Introduction

The evolution of computer interfaces has been deeply tied to the advances in electronics miniaturization—from room-sized computers, to today's small wearables. Many of the key revolutions in HCI (such as Ubiquitous Computing [74] and wearable computing [67]) were enabled by advances in electronics manufacturing and prototyping. These interface paradigms materialized thanks to the commodification of miniature electronic devices, suggesting that technology will continue to miniaturize further to "disappear and weave itself into the fabric of our everyday life" [74].

Existing platforms for electronics prototyping stop at the scale of handheld wearables. However, going to the millimeter scale would enable devices that could be integrated into people's lives. Fabricating these millimeter-scale fiber-like devices faces many technical challenges, and their integration needs to be as conformable as e-textiles, since comfort has been demonstrated as a fundamental factor in wearables adoption [4, 15]. To address this challenge, communities in HCI, Advanced Textiles Research, Electrical Engineering, and Computer Sciences have been joining forces to add intelligence and interactivity into textiles [25, 81]. In the long term, such miniaturization efforts could even democratize the development of implantable technologies for applications such as continuous health monitoring and beyond [2, 69].

In this paper, we pursue a technical exploration to lay out a platform that facilitates the prototyping of extremely thin circuits—so thin they can be encapsulated into fibers. Namely, we propose a platform with a set of practical prototyping guidelines for designing and fabricating these high density and thin PCBs. Our demonstrations include a 1.4mm-wide ARM microcontroller with sensors as small as 0.9mm-wide, and a 1 mm-wide strip of 50 addressable LEDs. Moreover, inspired by how the Arduino ecosystem revolutionized rapid prototyping, and how the LilyPad [6] extended this revolution to wearable devices, we designed FiberCircuits to be modular, open-source (software and hardware) and made the microcontroller compatible with Arduino to simplify fast prototyping.

Encapsulated in silicone for waterproofness and braided for durability, a mechanical evaluation shows that they can withstand 10,000 bending cycles with negligible effects. We illustrate possibilities with applications from safety to VR, and propose a scalable process to enable industrial textiles. By making ultra-thin circuits accessible, we open possibilities for wearable interfaces at unprecedented scales.

In summary, our proposed solution (illustrated in Figure 1) offers the following contributions:

- A design and manufacturing framework with:
  - Reviews of miniature ICs for processing and IOs.
  - Fabrication guidelines for high density Flex PCBs.
  - Encapsulation techniques and their evaluations.
- Open source hardware and software that enables the use of a miniature microcontroller with Arduino and custom libraries with examples for our input and output modalities.
- A set of user applications that demonstrate the potential of making interactive textiles with FiberCircuits.
- A roll-to-roll manufacturing process to enable affordable production of FiberCircuits for mainstream textiles.

2 Related Work

2.1 Functional Materials for Interactive Textiles

Embroidered capacitive sensing textiles were academically pioneered in the late 90's [57, 58]. They recently evolved thanks to commercially available conductive or resistive materials enabling more expressive affordances (proCover [38], Topographie Digitale [5]) and custom piezoresistive matrices [12, 68].

Thread-level research propelled sensing from 1D (ThreadSense [36]) and double-sided layouts (ZebraSense [78]) to 2D knits [50] and 3D mid-air sensing (TexYZ [1]).

Functionalization techniques such as in-situ polymerization (PolySense [24]), and piezoresistive coatings [48] increased sensing capabilities, and actuation was also explored through magnetic, SMA, pneumatic and polymer muscles [16, 31, 33, 49, 60].

Yet, textile-only solutions are limited, and functionalities such as magnetic-field and inertial sensing, or local processing are not easily implementable. The following section explores solutions and their trade-offs, which we also addressed with FiberCircuits.

2.2 Integrating Circuits onto Textiles

Adding discrete electronics extends functionality, but challenges comfort and durability. Rigid PCBs can augment wearables or textiles [17, 26, 63] but they can be obtrusive, limiting comfort. Flex PCBs were explored to sense bending [65] and for distributed sensing with processing [11, 35], but they remain surface-mounted and prone to snagging.

Knitted garments hosting stretchable PCBs [75, 76], sleeves with embedded IMUs [85], and custom glove circuits [53] improve draping, but planar boards and bulky inter-connects still limit the conformability potential of wearables [18, 70], which is too often leading to user abandonment[4, 15].

2.3 Advanced Fibers

Recent breakthroughs in materials science demonstrate that individual fibers can be endowed with sensing or output properties such as piezoelectric or electroluminescent fibers that form entire textile sensors or displays [8, 66]. They however rely on thermal–draw towers, vacuum deposition, or other advanced equipment that are costly, and process complexity blocking accessibility to most HCI or maker communities, while being limited in versatility.

Some implemented versatility by routed traces to externally processing [20, 87]. Other embed miniature integrated circuits directly into yarns [52] and "filament circuit" [34] techniques soldered single LEDs or low-memory MCUs onto FPCs (flexible PCBs). Embedded-IC yarns typically realise a single sensor, such as an IMU [39, 64], and must be custom-drawn for each function, hindering scalability. More recent "digital fibers" embed ICs inside thin enclosure similar to heat shrink, directly soldered on an I2C bus, but with a process that makes its mass manufacturability limited [43].

Summary. The literature highlights a research gap: scalable, multi-device fibers that use standard buses, affordable tooling, and accommodate accessible MCUs. Our FiberCircuits framework addresses this by miniaturising conventional flex-PCBs into yarn-scale strips with coating and braiding. By relying on globally available PCB fabrication instead of bespoke draw towers, we aim to participate in production-aware HCI research [22, 30, 86].

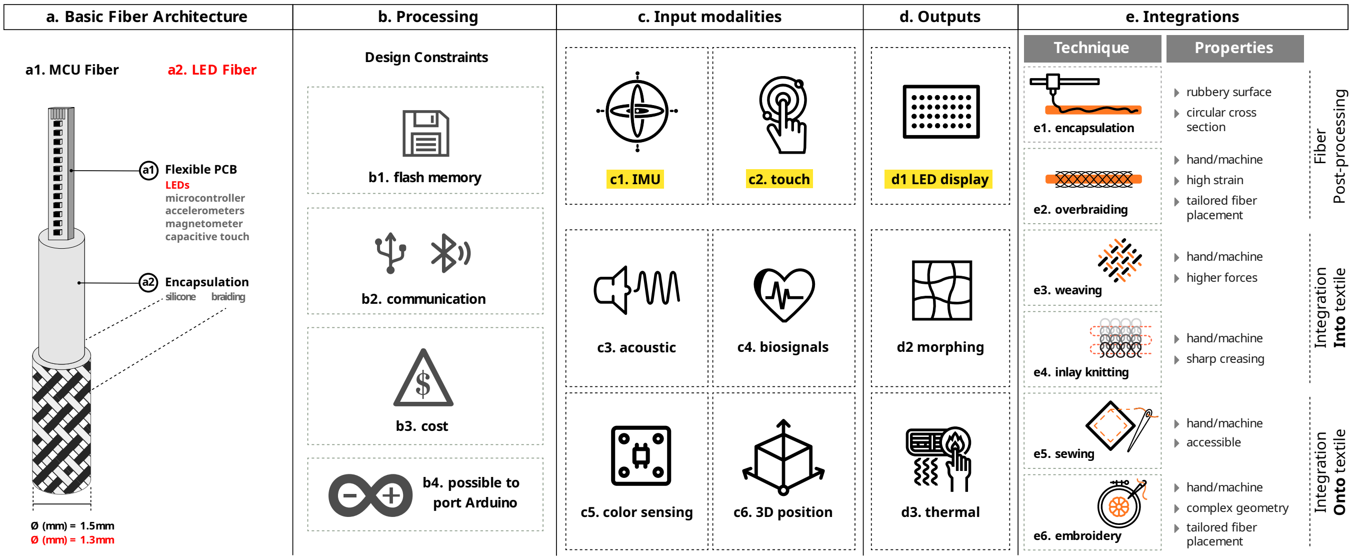

Figure 2: Design Space illustrating architectural structure, processing, I/O modalities, and integration techniques.

3 Framework

FiberCircuits can host processing, input and output modalities on a daisy-chained bus (MCUs with ICs for sensing, etc) and our design guidelines are made to allow adapting to future ICs. Beyond the hardware itself, the framework distills a repeatable decision-making process: component selection with tips for PCB layout, manufacturing, and encapsulation. By leveraging existing manufacturing techniques, we share everything needed to scale from fablabs to factories.[1] We next discuss key design considerations and detail the fabrication process (Figure 2).

3.1 Design Considerations

These flexible PCB fibers target diverse applications—from VR wearables to health monitoring—by integrating MCUs (figure 2b), input modalities (figure 2c), and output modalities (figure 2d) into fully interactive circuits. Because power is difficult to embed in a fiber, designers can rely on MXene-based [28] or organic energy storage fibers [3], or on small li-ion batteries that detach for washing (accessible examples: USB CR425 or CR322).

To simplify integration, fibers can be woven, knitted, or manually inserted into fabrics (figure 2e). The fiber diameter is limited by the MCU, leading to a 1.5mm profile. For flexible prototyping, each fiber is modular (dedicated to intelligence, sensing, or feedback) and these modules can be combined in numerous configurations to support many functionalities.

Technical design constraints include:

- Dimensions of the microcontroller (MCU): its width limits how thin the fiber can be.
- PCB factory capabilities: the distance between each MCU pads limits the manufacturer choice (and cost).
- Available sensors and feedback peripherals: there is a limited set of options that are smaller than the MCU.

[1]All the sources are available at: http://FiberCircuits.github.io

In addition to the design constraints mentioned, we can also optimize our design based on costs, efficiency, accuracy, and manufacturability.

To this end, we considered the following parameters:

Design Optimizations:

- Flex PCB bendability: an extra cost can be paid to ensure it withstands many bends
- Width of the copper layer: it impacts the flexibility, the conductance and the price
- More: see PCB design & fabrication sections

3.2 Process Inspiration

Light bulb started becoming obsolete when patents on LED filaments began to emerge [13, 14, 82]. They generally consist of 0.1mm LEDs on 1mm-wide FPCs [40], and silicone coating (see figure 3).

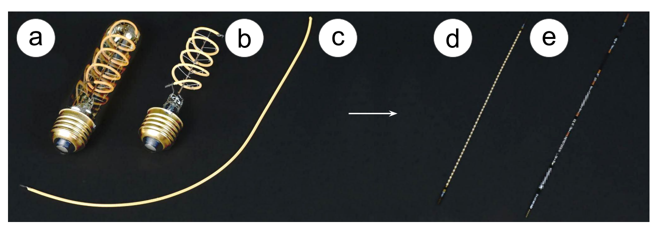

Figure 3: Fabrication process inspiration: (a) an LED filament bulb, (b) an open one, (c) its LED filament, made with an FPC and silicone, (d) our LED FiberCircuit made with a similar process, (e) our main FiberCircuit with MCU and Sensors.

The LED filaments process has been detailed in white papers [9], and manufacturers sometimes share their techniques [46, 47].

Not many factories produce these specialized FPCs, and they require a complex supply chain. However, the smartphone ecosystem made FPCs affordable and it can be leveraged.

Figure 4: FiberCircuits system summary: functional representation of the main fiber.

4 Embedded Processing

At the core of our design lies the microcontroller (MCU), which processes data and facilitates embedded communication with computers or smartphones, as well as sensors and feedback elements.

4.1 Comparison of Embedded Processors

To choose embedded processors suitable for integration into fibers, we searched for the smallest embedded processors currently available on electronic component suppliers, such as Digikey and LCSC[2]. We then compared the processors according to their sizes, storage, ADC availability, and ease of integration with the Arduino toolchain (see Figure 5).

Package Size: The smallest embedded processor option that we found is 1.4mm wide (Lattice Semi ICE40). We compared it to a number of embedded processor options with similar widths but will only discuss those that had significant differences according to our above mentioned criteria in the next section. Since our fibers are long, the length of the embedded processor is not an important design consideration.

Analog Inputs (ADC): For many wearables, different types of sensors, such as piezoresistive and capacitive sensors, are needed. To measure those signals, the embedded processor requires an ADC. The smallest processing option (ICE40) is an FPGA and does not provide an ADC peripheral. All other embedded processors on our list have ADCs. Thus, if the textile application requires these types of sensors, one of the other processors should be used.

Flash Memory: The MCUs we found have vastly different storage capability. Among the smallest options, the TI (MSPM0C1104) only has 16KB of flash, which is not sufficient for more applications. As a comparison, all the others have at least 32KB of flash (as does the Arduino UNO).

Communication: We also considered how the MCU can communicate with computers, and all of them can do serial communication. The DA14531 stood out as it embeds a Bluetooth radio, but as its memory is programmable only once (OTP), it makes it inconvenient for makers, and limited as research and development platform.

Software Accessibility: Another factor we considered is how well the microcontrollers integrate with the Arduino IDE. For instance, while the HC32L110 MCU is almost as small, it was much easier to port Arduino to our STM32 by adapting the STM32duino core, which is maintained by the open source community (see section 11.1 "Embedded Firmware").

Cost: The cheapest MCU is the HC32L110 and the most expensive is the MAX32660. The STM32, the MSPM0C1104, and the HC32L110 are in the "sub-dollar" range for 1000 units, they all qualify for scalable designs.

Power Consumption: Except for the ICE40, all the options are based on ARM Cortex cores, which are optimized for power-efficiency. Therefore, the STM32 emerges as an optimal balanced choice here.

4.2 Microcontroller Choice

Based on these criteria we chose the STM32. As a summary, the ICE40 does not have ADCs and the MSPM0C1104 does not have enough memory for most applications. The Huada is the cheapest, but its development environment is not ideal and our Arduino port with the stm32duino community makes it more technically accessible. The MAX32660 has a larger footprint, it lacks the Arduino community, and it is more expensive, but it is faster because of the M4 processor and has more memory so it might be suitable for applications that require heavier processing or large number of sensors. The DA14531 is wider than the STM32 and its OTP memory is not practical for development, but its Bluetooth capability is a great feature. As a reference, on top of being smaller, our STM32 has a faster MCU than the classic Arduino MCU (Atmega328: 16MHz VS 48MHz), and it also allows access to its software community.

5 Input Modalities

We surveyed available sensors with smaller widths than our MCU (1.4mm). In the next section, we discuss a few available options. Table 1 summarizes some inertial sensors that we considered, including our final choices (MEMSIC MMC5633NJL and MC3672 - see figures 6a and 6b).

[2]https://www.lcsc.com/

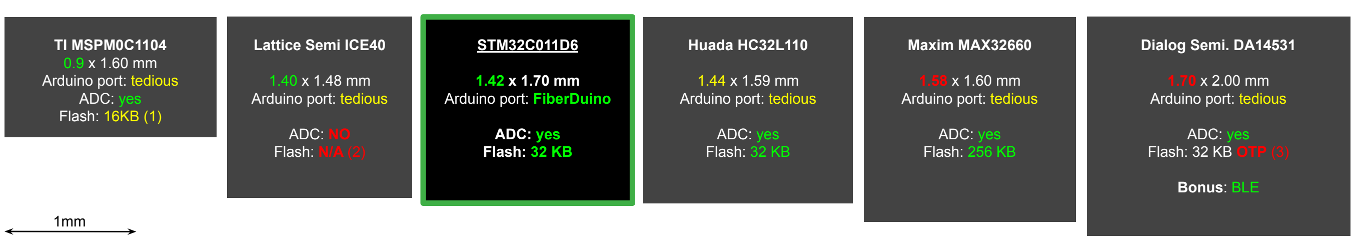

Figure 5: Processing options, proportionally scaled. Notes: (1) This flash size is too small for many applications. (2) The ICE40 has no flash memory. (3) The DA14531 only has a One-Time Programmable memory.

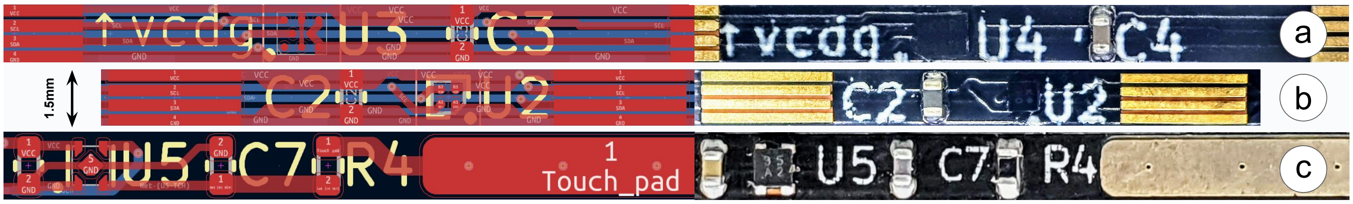

Figure 6: Layouts and FPCs of 3 sensing modules: (a) 1st accelerometer, (b) magnetometer, and (c) touch sensor.

5.1 Sensing Implemented in FiberCircuits

5.1.1 Motion and Orientation Tracking. **Accelerometers:** The smallest accelerometer available (MEMSIC MC3672) is 1.1mm wide (see figure 6a). However, its cost is not ideal for mass manufacturing (USD $3.4 for 100 units as of 2024) but cheaper options are compared here. Its width is smaller than our chosen microcontroller's (1.4mm) and thus does not increase the overall fiber diameter. Another option from MEMSIC (MC3635) is available at a lower price (USD $1.4) but has a wider footprint (1.6mm), which would increase the fiber's diameter. Finally, another good cost-size tradeoff is possible with the MEMSIC MXC4005XC (1.2mm at USD $0.8) but as a thermal accelerometer, it drifts with temperature variations, which can be a problem for wearables (from outdoor to indoor).

Magnetometers: The MEMSIC MMC5633NJL magnetometer is only 0.9mm wide (see figure 6b) and is available for USD$0.30 (for 100 units). The BOSCH BMM150 is 1.6mm wide, which is just above the space budget of this project, but it provides SPI capabilities, and it allows chaining a larger number of ICs than I2C. This feature can be advantageous for dense arrays, for example in 3D magnet localization used in magnetomicrometry [71].

5.1.2 Touch Sensing. We explored various methods to implement self-capacitive touch sensing, particularly focusing on strategies that balance simplicity, robustness, and noise immunity. These methods include leveraging the microcontroller's internal capacitive sensing capabilities, which involve charge-transfer or loading techniques, as well as employing dedicated ICs that mix signals to enhance sensitivity and interference resistance.

Using Microcontroller's Internal Capacitive Sensing: This solution only needs an MCU with an ADC, an electrode made of almost any conductive material, and a firmware library to implement the sensing mechanism[3]. This option was demonstrated to work in most cases, but it can be sensitive to noise if the electrode is far from the MCU, so we also implemented a more robust approach:

Using A Dedicated IC: Some ICs such as the PT2043AD4 (1.0mm wide - see figure 6c) by PinTeng [4] have practical features such as automatic calibration, but they also can be placed close to the electrode to get a better signal. They can then send a digitized version of the signal (as a binary information or over a communication bus such as I2C), which is more robust to interference.

5.2 Guidelines For Other Sensing Possibilities

5.2.1 Other Touch Sensing Options. **More Dedicated Capacitive Sensing ICs:** If a designer needs more capacitive sensing electrodes than the available pins, the Goodix GH6210 has a similar footprint (0.9mm wide) and has 3 capacitive sensing pins, allowing 6 sensing electrodes on one I2C bus (cost: USD$0.33 for 100 units).

Multiplexer Method: Increasing the number of capacitive sensing electrodes can also be achieved with special multiplexers such as the PI3A114-AZLEX by Diodes Inc (1.3mm wide, USD$1.06 for 100 units). As it is only for analog applications, the sensing range will not be improved, but this 4:1 bi-directional multiplexer can multiply the number of electrodes by four. For example, this can be useful to measure bending using the Sharc technique [65].

Resistive Touch Sensing: Connecting only 4 electrodes to resistive materials can achieve it thanks to ICs such as the Texas Instruments TSC2007IYZGR (1.5mm). The electrodes can be made of conductive thread, or sewn to our FiberCircuits.

5.2.2 Other Motion Sensing Options. **Gyroscopes:** Our applications did not need a high reactivity so the gyroscope was not mandatory. As there are no options below 2.5mm (and as the MCU is 1.5mm) we did not use any. For applications that need one and that have less miniaturization constraints, the smallest gyroscopes even integrate an accelerometer in the same package, example: ST Micro. LSM6DSM or Invensense ICM-42670-P. Gyroscopes tend to be power demanding, but these options only use 1.1mW and 0.9mW respectively.

[3]Example: https://github.com/arpruss/ADCTouchSensor

[4]http://pintengtech.com/product_detail.aspx?id=304

Table 1: Comparison of different inertial sensors by size.

Type	Company	Reference	Width	Pros	Cons
Magnetometer	MEMSIC	MMC5633NJL	0.9mm	smallest	slower than gyros (sufficient)
Accelerometer	MEMSIC	MC3672	1.1mm	smallest	expensive
Accelerometer	MEMSIC	MXC4005XC	1.2mm	cheap	thermal drift
Accelerometer	MEMSIC	MC3635	1.6mm	cheap	too wide
Gyroscope	ST Micro	LSM303AHTR	2.0mm	integrated accelerometer	too wide and power demanding

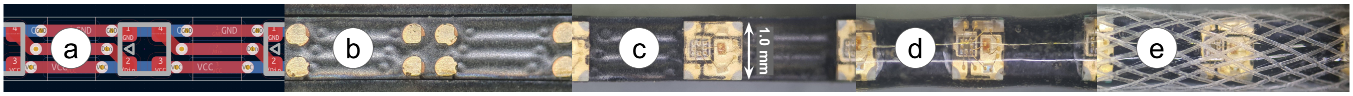

Figure 7: LED fiber module: each of the addressable LEDs only measures 1.0mm.

Barometers: Our applications did not need altitude sensing, and there are no options below 2.0mm (Example: TDK ICP-10101), but they might work for some applications that have less miniaturization constraints.

5.2.3 *Optical Sensing.* **Photosensors for 3D Positioning:** We found photosensors such as the Harvatek B17M1PD, which fits the fiber dimension constraint with its 1.3mm width. By combining it with a demodulating IC (Triad TS4231: 1.66mm wide) and open source 3d position sensing algorithms [23, 61], it can be used to create a high density position capture wearable.

Color Sensors: A color sensor such as Vishay VEML6040A (1.25mm) can also be used to detect gestures above it, but in a matrix structure, it can implement a flexible "camera".

5.2.4 *Acoustic Sensing.* **Microphones:** Wearable microphone arrays can be used to localize and focus on sound source, which can help people with hearing impairment for example. Small microphones such as the Zilltek ZTS6017 (1.4mm) can be used with analog inputs (ADCs). Small ADC extensions exist if the processing unit does not have its own, or not enough: for example, the Maxim MAX19777AZA (0.83mm) offers 2 analog inputs and transmits its data using the SPI protocol.

5.2.5 *Biosignals.* **PPG (PhotoPlethysmoGraphy) sensors:** We can also create sensors that combine several individual components. For example, PPG sensors can be made using photosensors like the B17M1PD (1.25mm), paired with LEDs such as the Harvatek B13V1IR (0.8mm), or LEDs emitting at comparable wavelengths (800 - 960 nm) [42]. These sensors are designed to measure blood oxygenation and heart rate.

EDA (Electro-Dermal Activity): EDA can be used to estimate stress [56] through sweat, which changes the electrical resistance of skin. This can be measured with a simple voltage divider (made with simple resistors) and an analog input connected to electrodes made in the PCB, using gold plating (affordable and commonly referred to as ENIG) to avoid oxidation. The electrodes can be smaller than our capacitive sensing electrode, as seen in off the shelf Empatica[5] smartwatches for example.

ECG (ElectroCardioGram) Sensors: ECG sensors can be used to detect heart dysfunction [72], and they have been demonstrated with textile electrodes [45], or with miniature flex PCBs down to 1mm [32]. Their signals can be measured with small low noise amplifiers such as the Maxscend MXD8921L (0.7mm).

6 Output Modalities

The tactile richness and ubiquitous nature of textiles have drawn the attention of HCI researchers as a potential interface for feedback mechanism. Consequently, several digital fabrication methods have emerged to incorporate functionality into conventional textiles, such as employing 3D printing to apply functional inks onto existing fabric sheets, or employing traditional fiber manufacturing techniques to extrude functional fibers that seamlessly integrate with textile production methods. In this section, we consider any output of the system as a feedback mechanism, such as a shape-changing, or LED display.

6.1 Feedback Implemented in FiberCircuits

LED fiber: We built a miniaturized addressable LED fiber consisting of 50 LEDs, to display information, or to be used as morphing actuator (see Guidelines below). Each LED is 1.0mm, the LED fiber is 1.3mm wide, and 180mm long, but can be chained with other fibers. It is common to find LED strips sold as 5 meter rolls, their flex PCBs are generally manufactured by panels measuring about 1 meter long, and the strips are soldered manually. This is an approach that we can adopt for medium size productions, but a roll-to-roll process is also possible for mass manufacturing (see the section 13 about scalability). As for industrial LED strips, our LED fibers might need a parallel power distribution after a certain length. If needed, the voltage drop can be compensated with higher voltage lines and regulators spread every few meters for example. Our LEDs use a "neopixel" type of protocol [7] with one data line only, allowing a chain topology. Figure 7 shows LEDs in these fibers, and Figure 10 shows the entire set of manufactured fibers in their panels, emerging from the assembly factory.

6.2 Guidelines For Other Feedback Possibilities

Shape Changing Interfaces: To demonstrate morphing capability, photoresponsive liquid crystal polymers (LCPs) can be used with our LED fibers [73]. These LCPs contract when they are exposed to a specific wavelength, and can be used as muscle fibers. They can be fabricated with direct deposition of the LCP resin onto the LED fibers, thereby creating a bilayer actuator. Different chemistries can be synthesized for this process to demonstrate a variable wavelength response of the bilayer actuators: LCP resin responsive to 470nm light (blue), or 365nm light (UV). Using a DIY direct ink write 3D printer specifically built for high viscosity oligomer extrusion [62], a 500 micron thick layer can be created. While printing, the shear aligned LCP can be exposed to 365nm UV light for cross-linking. Cross-linking adds extra mechanical connections between the elements to make them stronger and hold their shape better, especially when they are being printed. Cross-linking is a bit like adding glue while printing the material, making sure it stays strong and works as intended, without coming apart.

Electrostimulation for haptics: Electro-Muscle Stimulation (EMS) has been demonstrated in HCI from subtle tactile feedback [77] to powerful force feedback actuation [44]. More recently, it was demonstrated that higher frequency electro-stimulation (10kHz) allows using lower voltages (20V instead of more than 200V) [41].

[5]https://empatica.com

This can be achieved with small transistors such as the Onsemi NTNS2K1P021ZTCG (0.42mm wide), and can be chained using addressable current driver ICs such as the LC898229XI-MH by OnSemi (0.86mm wide) or BU64241GWZ-E2 by ROHM (0.77mm) which can also be used on our I2C bus. The necessary skin-contact electrode can be fabricated in a similar way to the EDA or ECG example in the sensing section (using gold plated PCB finish, or ENIG).

7 PCB Design

FiberCircuits schematics can be simple as the topology is limiting to chained devices, but the layout routing can be challenging due to the high pin density of parts such as the MCU. For advanced techniques on interfacing miniature FPCs, including connector options and prototyping methods, please refer to the appendix.

7.1 High Density Considerations

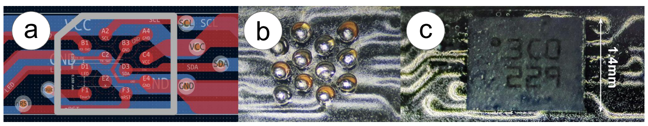

Figure 8: From layout routing to PCB and assembly: microscopic imprecision becomes visible with miniaturization.

Our chosen MCU has a 150µm distance between each of its solder pads (Figure 8), providing two routing options for the layout:

(1) 50µm Traces: these are not always accepted by common flex PCB manufacturers, but they can work with subcontractors for higher accuracies (see table 2).

(2) Via-in-Pad: it is generally advised against placing a via in a solder pad, as the solder might flow out during the PCB oven soldering process. However, adding conductive epoxy in the via holes avoids this problem. While it incurs a fixed additional cost, this expense is diluted when producing larger quantities.

7.2 PCB Design Method

Various scripting options exist, even in Javascript [51]. We chose KiCad, taking advantage of its layout section replication feature to customize dimensions and space between processing or IO cells. For example, the LED strip in figure 9 was designed using two steps:

- Design a Unit Cell Module: A single, repeatable section of the circuit that can be connected in a chained topology.
- Replicate the Cell: Using the Ctrl-T command, we programmatically copy-pasted the cell across the design. This feature is also found in other tools, typically referred to as repetitive "design blocks" in Altium or Eagle.

8 Fabrication

While custom flexible PCB manufacturing has become commoditized, miniaturizing them to insert them inside fiber in a scalable way presents unique challenges: mechanical robustness, miniaturization-related accuracy, and reliable textile integration remain underexplored and beyond established manufacturing norms. In the following, we present two complementary fabrication methods that we explored for making these flexible PCBs: (1) prototyping via fiber lasers, and (2) manufacturing with a factory.

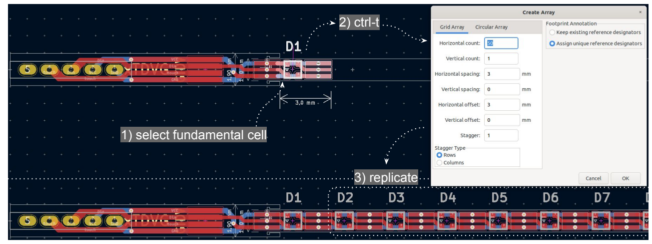

Figure 9: Generative PCB design with KiCad: from unit cell to functional array.

8.1 PCB Prototyping with Fiber Lasers

We prototyped the first FiberCircuits versions using fiber lasers (also called 'Q-switched' lasers). These lasers have been used in makerspaces [37, 80] for PCB prototyping as they can etch or cut metal, such as the copper tape that we used to prototype our FPCs. They are becoming accessible and they offer higher speed, delicacy, and resolutions (40µm for our latest model) than traditional PCB prototyping tools such as milling machines or vinyl cutters. We started prototyping our FPCs on a Trotec 100 (hybrid fiber laser), which used to cost about $40k. This machine uses a CNC system and it is not the fastest nor the most accurate approach. We then acquired a JPT MOPA for about $5k[6] but similar machines can be purchased for less than $1k[7] depending on the desired speed. These fiber lasers achieve their precision by using galvo-controlled mirrors to rapidly and accurately steer the laser beam.

8.2 PCB Manufacturing

The prototyping phase allowed improving and validating the design, to then get it manufactured by PCB factories. We compared a dozen of options and summarized here relevant parameters about four manufacturers that could work with our constraints:

Table 2: Limitations of flex PCB manufacturer candidates

	iSource Asia	PCB Way	JLC PCB
Track spacing (mm)	0.05	0.06	0.08
Via with ring (mm)	0.15	0.35	0.40

Trace Resolution: Since the focus here is on miniaturization, we used minimum trace width as the main criteria to choose a manufacturer. Table 2 summarizes the resolutions offered by the different manufacturers, it shows that iSource Asia was the best option at 0.05mm. We thus used their service for the fiber circuits presented in this paper.

Manufacturing parameters: We provided our manufacturers with the following parameters for fabrication. For the base material of the flexible PCB, we requested adhesiveless Polyimide, which allows for more flexibility than what is normally used (the cost difference is about 15%). For the board thickness, we requested the thinnest option, which is 0.09mm. For the copper layer width,

[6]US Fiber Laser distributor example: https://lasersonly.com
[7]We tested one made by X-Photonics: https://xinghanlaser.com

we used 0.5oz, which is sufficient for our low-current applications. For the surface finish, we requested ENIG, which is important for the WLCSP / BGA parts we use, to avoid oxidation of the solder pads. For the stiffener, we requested to use Polyimide, which is the thinnest available but still helps to secure the BGA pad's solder while keeping some flexibility. Finally, we let the manufacturer design the panels for optimal parameters (see figure 10):

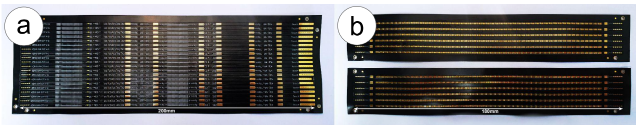

Figure 10: Flex PCB panels assembled by a factory: (a) the main FiberCircuits with MCU and sensors, (b) the LED fibers.

Testing: The assembly can introduce failures such as bridges between solder pads. For small quantities (e.g. less than 20 units), it is not necessary to provide functional test procedures to factories. When the quantity and cost become significant, a test jig (or instructions to build and program one) can be sent to the factory. These test jigs should be simple and fast to use. If the board has an MCU, it seems important for the test jig to attempt to program it, maybe install a bootloader, and quickly test the other components. If the board has I2C sensors, a simple ping message can be sent to each of them to check that they respond, and if everything works, a green LED can be activated on the test jig. If the test fails, an engineer can attempt to re-solder the parts that failed the test.

Mechanical Characterization: We used adhesiveless Polyimide for our PCB to be bendable as many times as possible, and evaluated: (1) cyclic bending endurance and (2) breaking tensile strength.

For (1) we mounted a 5 cm FPC sample on a custom motorized stage and imposed 10 k bend–relax cycles around a 5 mm radius, representative of stresses experienced when folded inside cloths. The resistance of a 200 mm copper trace was logged (see fig 11a). Up to 4 k cycles, the resistance remained stable, and reached 4.6 Ω after 10 k cycles, versus an initial 3.2 Ω. Despite this rise, the conductor stayed fully functional. Linear extrapolation of the post-4 k trend suggests an additional 30 Ω per subsequent 10 k cycles, most likely caused by cumulative micro-fracturing that, while not creating failures, could introduce voltage drops in very long yarns.

For (2) we subjected a 30 mm section (1.3 mm × 0.6 mm cross-section) to uniaxial tension on an Instron 4411 (Fig. 11b). The sample elongated 1.8 mm before failing at 6 N, roughly the force exerted by a 0.5 L water bottle, confirming that the polyimide–copper FPC can endure typical garment-level pulls without tearing.

Collectively, the bending and tensile data verify that the manufactured PCB fibers tolerate 10 000 tight-radius bends and everyday tensile loads while maintaining conductivity, satisfying the mechanical demands of integration into woven or knitted wearables.

9 Enclosure Techniques

After PCB fabrication, the next step is to protect the resulting flexible PCB with a coating that acts as a waterproof enclosure for the electronics, protecting them from mechanical stress, and making them ready for textile integration.

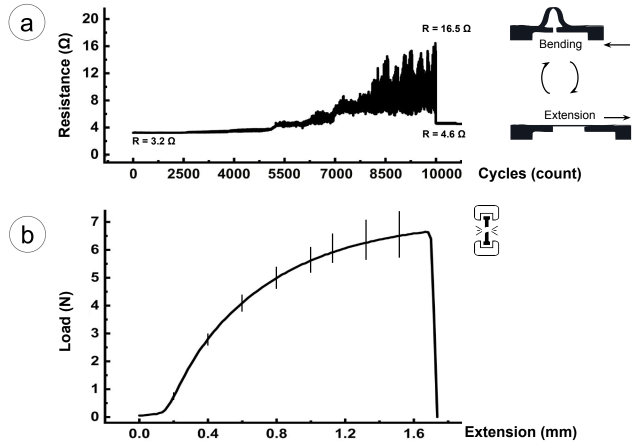

Figure 11: Mechanical Characterization: (a) stable performance under 4K bending cycles; (b) tensile strength of 6N with an elongation of 1.8 mm.

We explored two different types of coating methods, which are each most suitable for a specific textile integration method (see next section).

Braided encapsulation: The simplest and fastest option is to use braided tubing such as Flexo PET by Techflex. For fast prototyping the flex PCB fiber can be inserted manually, then the braiding can be burnt at the ends and secured with heat shrink (see figure 12a). However, it can also be consistently produced in large-scale manufacturing processes with various densities. Higher densities can increase the width of the final fiber, and can protect the electronics better (see figure 12b).

Silicone coating: In order to enhance the mechanical robustness of the FPC, it was coated with a 200-micron layer of PDMS (polydimethylsiloxane). PDMS is a transparent silicone-based polymer with excellent optical, electrical, and mechanical properties widely used in soft electronics. As a coating material, PDMS offers a layer that is both flexible and electrically insulating from e.g. moisture and dust. Figure 13 illustrates our coating results, and the appendix figure 26 shows more about the manual curing process.

Mechanical Characterization of coating benefit: In order to evaluate the added protection provided by different types of coatings, LED strips of the Fiber circuits were subjected to another cyclic 5-mm bending test. The tests were performed on three categories: non-coated, silicone-coated, and braided LED strips. A bare, non-coated LED strip was able to sustain up to 800 bending cycles before showing signs of degradation, such as LEDs beginning to turn off completely. On the other hand, the silicone-coated LED strip demonstrated a significantly enhanced performance, enduring about 2000 cycles prior to degradation. Finally, the over-braided LED strip surpassed both, withstanding approximately 5000 cycles before degradation. A typical usage scenario for wearable devices would incorporate a device bent twice daily, worn, and taken off, totaling approximately 1200 cycles per year. The silicone and braided coatings would meet the minimum durability requirements for an approximate life span of 2 years for such devices.

Figure 12: Braided encapsulation: (a) our main FiberCircuit, (b) zoom to illustrate two braiding density options.

Washability: Following the 40-cycle e-textile protocol of Zaman [83], 12 FiberCircuits were machine-washed (30 min, express cycle) inside a sock: 6 PDMS-only (including 3 inside woven samples) and 6 PDMS with braiding (3 woven too). PDMS-only samples showed damages after the 2nd cycle, and failed by the 3rd. All braided samples remained electrically and mechanically intact after 40 cycles. Resistance stayed within 3–6 Ω (for the measurements, connector oxidation was removed with flux). We performed destructive inspections to look for leaks and internal oxidation, but did not find any. Finally, low density woven samples did not significantly improve PDMS coating protection.

Overall, braided silicon encapsulations seem sufficient for outer garments such as the Google-Levi's jacket [59] as they are infrequently washed.

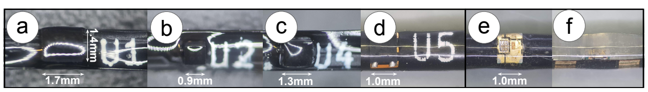

Figure 13: PDMS coating results: microscope images of the integrated circuits of the main FiberCircuit (a: MCU, b: Magnetometer, c: 2nd Accelerometer, d: CapSense IC), and the LED fiber (e: top view, and f: profile view).

10 Textile Integration

Since textiles can be augmented in various ways, from embroidering to knitting or weaving, we explored different integration approaches to illustrate a wide range of textile applications. The FiberCircuits were connected manually, and some details about the connectors are developed in the appendix A.2. Manual integration can be replaced by traditional textile processes FiberCircuits are produced by kilometers (as seen in the section 13 about scalability).

Embroidery: We integrated FiberCircuits into a glove via a digital embroidery machine made by Tajima (see fig. 14).

The digital design and integration process not only allows for tailored fixation of the FiberCircuits but also facilitates the precise placement of additional conductive patches to extend the touch-sensing area as needed. The fabrication of the full-sized glove with integrated FiberCircuits consists of 4 steps. Firstly, we used silver plated polyamide thread (Madeira HC40) at the desired location, which serves as an expanded sensing area to the touch sensitive electrode. Subsequently, we executed zig-zag embroideries, which function to secure the FiberCircuits onto a separate Spandex fabric. These traces can be applied either before or after the FiberCircuits placement, offering flexibility in the manufacturing process. Then, we aligned the two fabric components and proceeded to embroider the glove's outline seams. To complete the assembly, we trimmed any excess fabric and flipped the glove inside out so that it generates an enclosed full-sized glove with conductive patches and the fixation of FiberCircuits on the outside of the glove. The full integration process is done in 20 minutes.

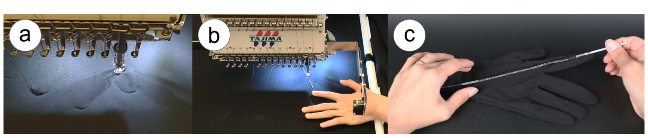

Figure 14: Integration via digital machine embroidery: (a) A spandex glove was designed digitally and subsequently embroidered by an automated machine with zig-zag fixation. Such integration can either be done (b) during the embroidery process or (c) through manual insertion afterward.

Knitting: The knitted beanie in figure 15 was generated via a double-bed digital knitting machine made by Shima Seiki (SWG091N2). The cuff of the beanie features alternating front and back stitches, which is known as the structure of ribs. These stitches serve as fixation for the FiberCircuits. As they are integrated into wearables in a post-knitting procedure, this integration remains universally compatible with all knitted fabrics. It introduces no alterations to the knitting process, thereby offering extensive freedom for customization and design possibilities.

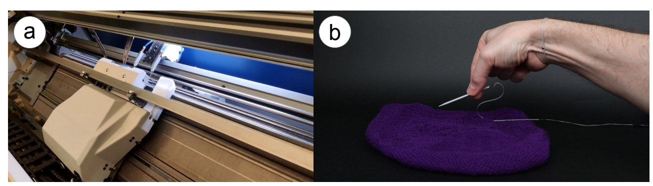

Figure 15: Integration via digital machine knitting: (a) The beanie was digitally designed and fabricated via an industrial-scale digital knitting machine. (b) FiberCircuits was integrated with the knitted beanie via manual insertion.

Weaving: Weaving involves the interlacing of warp and weft threads to create a fabric; woven structures are determined by variations in the interlacing of the warp and weft. Plain weave is the most fundamental woven structure, where each weft thread consistently passes over and under one warp thread, leading to a versatile, durable, balanced textile.

Hand-woven on a 16-harness loom, the following application demonstrates how FiberCircuits can be seamlessly integrated into a plain woven structure. The presented wrist band (see figure 16) was created with black cotton thread as a warp and weft, while the FiberCircuits represent a supplemental weft where electronic implementation can take place when the form is taken off the loom.

Overall, this application demonstrates craft compatibility and a potential for the seamless integration of FiberCircuits into textile, but not industrially yet. This speaks to the potential of future work that leverages textile knowledge and the placement of FiberCircuits to create new tangible interactions.

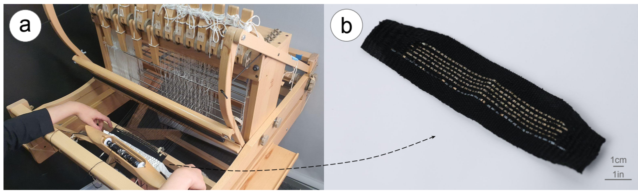

Figure 16: Weaving integration: (a) during the weaving process as a supplemental weft. (b) A woven wristband with seamlessly integrated FiberCircuits.

11 Software

11.1 Embedded Firmware

11.1.1 Arduino Port. To enable simple and fast development, we modified the Arduino IDE to work with FiberCircuits. The Arduino SDK modification is explained below, and we outline the steps required to develop code for FiberCircuit applications.

Porting an STM32 to Arduino using the STM32duino core
We chose a specific STM32 model that has limited memory but is the smallest in size. It is not the best trade-off for some applications, but there are slightly bigger ones with more memory (example: STM32C071FB: 4x more flash but 1.6mm instead of 1.4). Also, some new STM32 variations will appear eventually, so to be future-proof, we share the process to port Arduino to new MCUs. This step is detailed on our github, and an example made by Lady Ada (Adafruit) can be found here:
https://github.com/stm32duino/Arduino_Core_STM32/pull/701

As a summary, here are the files that we had to create or modify:

- *cmake/boards_db.cmake*
- *variants/STM32C0xx/<CORE_NAME>/boards_entry.txt*
- *variants/STM32C0xx/<CORE_NAME>/ldscript.ld*
- *variants/STM32C0xx/<CORE_NAME>/variant_generic.cpp*

Once the custom core was validated, the modifications were pushed, and a pull request was created. We worked with the Arduino community to add this core to the Arduino IDE, which is now officially integrated and maintained by the STM32duino team.

Using a custom Arduino core
Like other Arduino-compatible boards such as Teensy or NodeMCU, our firmware requires two steps: (1) install the STM32duino core, and (2) select it in the "Boards" menu. Detailed instructions are available in the official STM32duino repository:
https://github.com/stm32duino/Arduino_Core_STM32

11.1.2 Libraries for I/O modalities. We developed libraries for our input and modalities, which users can add to their Arduino library subfolder and import into their code. For customization, the files can be directly integrated into the working environment, as we did in some cases seen below.

Memory optimization: 32KB of flash memory is standard in the classic Arduino, but it is sometimes insufficient when we use too many device drivers. For our IMU application example, using software capsense, accelerometer, and magnetometer drivers would normally overflow the flash. To solve this, we applied a few optimizations detailed in our repository, along with techniques to debug memory issues.

Accelerometer: Before committing to our final choice, we developed a custom Arduino library to test the MXC4005XC, but after evaluating the thermal drift, we decided to use the MC3672, a more expensive but more stable and smaller version of this device. Both the libraries are open source and instructions on how to use our optimized versions are available in our repository.

Magnetometer and Capacitive Touch Sensing: These drivers were already available, but we had to optimize them, so we incorporated our versions in our repository.

11.2 Visualization Interface

For our applications, we share visualizations made with OpenFrameworks, Blender and Unity, available in our repository. Section 12 illustrates and explains their use in more detail.

12 Applications

To show FiberCircuits' potential, we built the following applications, each highlighting a distinct capability:

12.1 VR Glove: Sensing Touch and Orientation

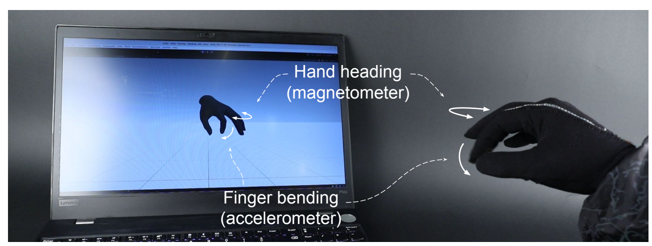

Figure 17: VR application: a glove augmented by our sensing FiberCircuit controls a hand model in virtual reality.

We built a glove that can track the user's index finger orientation and detect touch to control VR systems, but also music, or other real time systems. To measure orientation and bending of a finger, we created a custom Inertial Measurement Unit (IMU) with two accelerometers and a magnetometer. One of the accelerometers measures how much a finger segment is bent, while the other measures the inclination of the hand. The magnetometer and accelerometers communicate on the I2C lines and the capacitive sensing is on a GPIO. The magnetometer measures the heading of the finger as a compass would. We used the embroidery as an extra encapsulation and attachment onto the glove, then to add conductive thread at the fingertip to extend the CapSense electrode, and to fabricate the glove seam at the same time. Fig. 17 shows a visualization of accelerometer, magnetometer, and capacitive sensing data.

12.2 Interactive Beanie with LED Display and Accelerometer Input

Figure 18: Hands-free turn signals for cyclists - made with an LED fiber controlled by the MCU and the accelerometer.

Our knitted beanie was designed to further explore the integration of FiberCircuits across fibers with LEDs in a daisy chain topology controlled by the fiber with the MCU and the accelerometer. Once placed on the head, this combo enables detecting when the head is tilted (Figure 18-a and 18-c) and turns LEDs on accordingly. For safety, the LEDs were placed to be visible even under a helmet (tested with POC Myelin). A programmable hysteresis can ensure that the LEDs stay off when the head is straight (Figure 18-b).

12.3 Interactive Display with Accelerometer

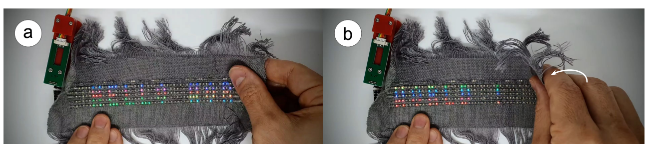

Figure 19: Closed-loop demo. with LED fibers controlled by the accelerometer: the matrix displays "HELLO WORLD !" and shifts the text faster when we tilt the sensor.

We developed an interactive wristband prototype that integrates multiple FiberCircuits: a sensing and processing fiber, along with five LED fibers woven together to form an LED matrix display. It shows the ability to weave multiple FiberCircuits into textile, and demonstrates a closed-loop system as sensors data processing controls the display. The wristband uses an accelerometer to measure orientation: when tilted (Figure 19-b), the accelerometer output increases the animation speed. The wristband can be used as a fitness trackers: its sensors and display allow it to monitor movement and display step counts for example. Moreover, the magnetometer provides orientation, helping runners get back on course if they got disoriented. This application underscores the versatility of FiberCircuits for wearable devices that seamlessly integrate sensing, processing, and display capabilities within a textile medium.

12.4 Speculative Applications

The speculative scenarios in figure 20 spotlight FiberCircuits' potential beyond current prototypes: electro-stimulation haptics enable eyes-free control on body-worn devices (a, b, h), augmented pillows and speakers augmenting media interactions (e, f), and haptic warnings [55] in spacesuits (h, i); while bio-signal sensing enriches personal health (c, d) and integrated impact detection strengthens extravehicular safety (g), charting a rich roadmap for future textiles from earth to space.

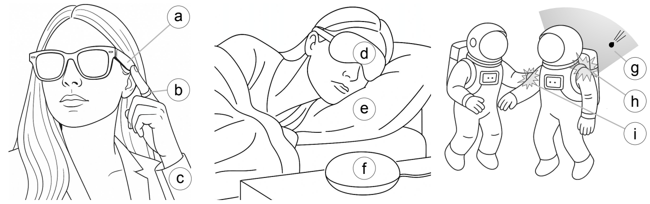

Figure 20: Speculative applications in *Wearables* (a: augmented eye-wear, b: smart ring, c: health tracker), *Ambient Intelligence* (d: smart sleep mask, e: augmented pillow, f: smart speaker), and *Responsive Spacesuits* (g: impact detection, h: haptic warning, i: human touch feedback).

13 Scalable Manufacturing Speculations

For affordability and adoption, scaling fiber circuit production is essential, as textile factories need long fiber spools.

Most FPCs are made on panels under one meter. For instance, LED strip reels are usually soldered by hand, meter by meter. Extreme cost optimizations as for NFC tags use continuous processes such as roll-to-roll production. They unwind flexible material from a feed roll, go through steps like etching, printing, bonding, and coating, then rewind onto a take-up roll.

For yarn fabrication, similar continuous processes are employed, including spinning, and braiding. Spinning involves twisting fibers together to create yarn or thread. And braiding involves intertwining multiple strands to create yarns, laces or ropes.

Drawing from these industries, we propose a hybrid approach for kilometers of FiberCircuits (see figure 21), considering speed and precision limitations.

13.1 Interconnects synthesis

In roll-to-roll fabrication of flexible ciruits, conductive traces can be created using various methods such as screen printing conductive inks, inkjet printing, or etching copper-clad films after a photolithography process [10, 19, 29].

We propose using a fiber laser with galvanometer, offering high speed and precision at low setup cost. In our tests, the best results were achieved on FPCs with 9 µm copper layers (Dupont 0.25oz/ft^2). It yielded clean 40 µm laser traces, suitable for our 150 µm solder pads. Engraving a 20 mm x 20 mm PCB took about 1 second ; extrapolating to 1 meter, this would take 3.8 seconds, though most lasers handle only up to 300 x 300 mm. Using two lasers on the same 1-meter panel allows 2 km/hour processing. Also, multiple fibers can be engraved in parallel on a wide copper roll (e.g., 180 mm from MSE Supplies), enabling panels of 100 fibers simultaneously.

If needed, multilayer PCBs are also possible by replicating the laser stage (21-1). The bottom layer can be etched by the first laser, and additional layers are added at subsequent stages. Vias can be laser-drilled and then filled with solder paste or conductive glue. Alignment can be achieved using pre-punched holes along the edges to fit onto guide pins. Polyimide is a good substrate as it tolerates soldering temperatures, but stretchable PCBs can be made with TPU (e.g., Dupont TE-11c), though they require conductive adhesives due to lower heat tolerance.

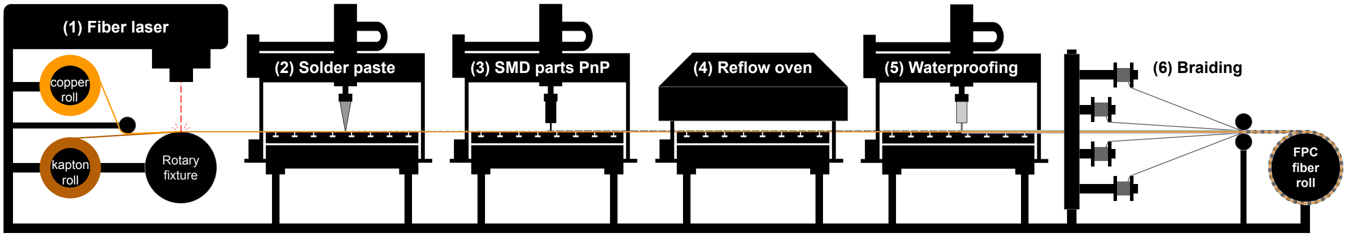

Figure 21: Six steps to continuously fabricate FiberCircuits in a roll-to-roll process.

13.2 Solder Paste Deposition

There are several ways to assemble SMDs, solder paste stenciling being the most common, conductive glues can also be applied by a CNC syringe pump. Stencil-based solder paste deposition is faster, and cheaper, but requires a reflow oven (see figure 21-4). Operating at about 1 m/s with 180 mm-wide rolls, stencil machines can process around 100 fibers in parallel, reaching a rate of 360 km/hour. This high throughput becomes useful during the reflow stage. Some conductive glues, such as Ablestik 2030sc, offer fast, low-temperature curing and can be used with flexible substrates like TPU. However, glue deposition cannot be done in parallel and is far more expensive than solder paste. For advanced miniaturization with bare dies, methods like flip-chip assembly or wire bonding are options, but they usually suit higher volumes due to higher setup costs.

13.3 Pick and Place

Precise CNC machines can rapidly populate FPCs with ICs. High-speed systems like the Yamaha YSM40-R can handle up to 200K parts per hour, and with 85 parts per meter of fiber; production can reach around 2.3 km per hour. This sequential process can be accelerated by duplicating the manipulator or entire machine. For massively parallel assembly of extremely miniaturized parts (e.g., micro LEDs), fluidic self-assembly can achieve yields over 99% [54] by using surface tension and component shape for self-alignment. For further miniaturization, optical tweezers pick-and-place uses highly focused laser beams to position nanoscale components [84].

13.4 Oven

When solder paste is used, two reflow stages are required. They include a 150°C (302°F) preheat and a 250°C (482°F) peak, totaling about 3 minutes. Using rolls that process 100 FiberCircuits in parallel through a 1-meter oven can achieve about 2 km per hour. To maintain the peak temperature in the last third of the oven, the roll shifts by 0.3-meter increments. Fast-curing conductive adhesives (e.g., Loctite Ablestik 2030sc) need just 1.5 minutes at 110°C (230°F). This can double the production rate, though deposition is slower.

13.5 Waterproofing

In our tests, we used silicone and TPU filament for 3D printing. TPU can be deposited by (multiple) nozzles, or it can be injection molded. At a production line speed of 0.3 meter per min, both methods are feasible. Fast-curing silicones (e.g., Ecoflex 00-35 FAST, SS-3007EF) can be syringe-deposited at a similar rate, but this must happen before the oven stage for curing.

13.6 Fiber Texture Finalization

Parallelization requires mechanical separation into 100-fiber reels, achieved with simple knives. Over-braiding or spinning can provide a more textile-like feel, but nonwoven-textile deposition techniques (electro-spinning or foam spray) are also scalable.

13.7 Throughput and Optimizations

As in processor architecture optimization for high frequency computation, a pipeline approach can be used by parallelizing some stages. For example, the laser stage seemed to be the slowest here. A more powerful laser might speed the fabrication up, and using more lasers for more parallel processing will accelerate the overall production pipeline.

Scalability conclusion: with a minimal redundancy, we estimate that this FiberCircuits production line can run at about 2 km per hour. The set of machines needed for this continuous fabrication would cost from USD 12K to 52K, and the materials would cost about 10K to 50K per kilometer. In comparison to roll-to-roll lithography, exemplified by the LR2RC1500 platform, the process demonstrates approximately fivefold greater cost-efficiency and achieves operational speeds that are five times faster.

14 Discussion

14.1 Challenges summary and solutions

Miniaturization of Components: The size of the microcontroller is a limiting factor for how thin the fiber can be. The smallest option (1.4 mm wide) has dimensions that dictate the fiber's thickness, defining our trade-off between functionality and compactness.
Manufacturing Precision: The high density of solder pads and traces requires precision in PCB design and fabrication. This includes managing trace spacing (as small as 50 µm), avoiding soldering bridges, and keeping vias as distant as possible from each other to avoid creating mechanical weaknesses.
Mechanical Robustness: The fibers must withstand repeated bending or stretching without degrading functionality. Mechanical failures such as microfractures can be delayed thanks to encapsulations. It can also protect from moisture, but it affects the fiber's diameter.
Scalability: Mass-producing these fiber circuits at scale involves challenges such as continuous roll-to-roll manufacturing. Current panel-based PCB manufacturing processes are limited to smaller dimensions, and roll-to-roll processes require precision and speed optimization to meet industrial needs.

14.2 Limitations

A significant concern arises from the challenge of recycling such specialized fibers, underscoring the necessity for continued exploration into sustainable disposal and recycling solutions to mitigate environmental impacts. A more integrated connection and integration pipeline could expand the design possibilities and unlock further potential for FiberCircuits in real-world applications. Additionally, the size constraints inherent to FiberCircuits impose limitations on the number of output or communication pins that can be seamlessly integrated, particularly in applications demanding extensive connectivity. Finally, the power dissipation problem was not in the scope of this work, but it remains a vital area for future research to optimize energy efficiency and manage thermal loads in compact systems.

14.3 Future work

In the medium term, we plan to extend FiberCircuits for more modalities, including integrating energy harvesting components such as photovoltaic cells, in combination with fiber batteries [21, 79]. More widely available options include miniature LiPo cells for smart rings or earbuds (even on mainstream platform such as Aliexpress), USB-chargeable CR425/CR322 "pin-batteries", and mass-produced and customizable curved batteries[8], or even flexible batteries[9], but there are great online guidelines to create soft battery holders[10]. However, the effectiveness of each modality depends on the energy source available to this small form factor, underscoring the need for efficient energy management. Each FiberCircuit consumes energy comparable to typical activity monitors like Fitbits, making this challenge manageable. Another key step will be to incorporate wireless communication using miniature Bluetooth ICs such as the InPlay IN100-W (1.1 mm wide). This addition will enhance FiberCircuits' versatility, enabling wireless connectivity and transforming them into a comprehensive platform.

Scaling FiberCircuits to large-scale architectural and industrial textiles could also further enable responsive wearables and dynamic environments that seamlessly integrate technology into daily life. Additionally, we plan to use FiberCircuits for pervasive data collection and analysis of daily human activities, enabling unobtrusive data gathering to yield valuable insights into behavior and support intelligent systems to assist people in myriad ways. As alluded to in the speculative application section, we also aim to explore new form factors, integrating sensors and MCUs into wearables beyond textiles, such as rings or eye-wear but also earrings or implants. These options offer new ways to implement continuous health monitoring, addressing conditions such as sleep apnea. Finally, in the long term, extreme miniaturization could enable the direct fabrication of complex integrated circuits on fiber [27].

15 Conclusion

The FiberCircuits project presents a novel framework for miniaturizing flexible printed circuit boards to enable their seamless integration into fibers and textiles. By reviewing available electronic components and flexible PCB design and manufacturing techniques, this work demonstrates how to create mm-thick interactive fibers with processing and I/O modalities. The sample applications we have built with FiberCircuits, from a VR glove to an interactive wristband, showcase the potential for ubiquitous computing applications where electronics disappear into the textiles we wear. Through open-sourcing the hardware, firmware, software libraries, and documentation, this work aims to make the creation of e-textiles more accessible, while keeping them mass manufacturable. FiberCircuits contributes both a practical toolkit for makers and researchers as well as a roadmap for further miniaturization and integration of circuits into fibers, paving the way for a future where electronics are an intrinsic part of our clothing.

[8] e.g. https://grepow.com/shaped-battery

[9] e.g. https://tycorun.com/blogs/news/flexible-battery

[10] e.g. https://kobakant.at/DIY/?p=6284, https://kobakant.at/DIY/?p=4432

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A Extra PCB Design techniques: Interfacing Miniature Flexible Circuits

A.1 Module Pins

Our microcontroller fiber module (STM32C011D6 microcontroller) provides 4 main pins for I2C (3V, GND, Clock, Data), with a 5th optional pin used for capacitive touch sensing in our 1st application.

I2C allows chaining up to 128 devices (sensing or feedback devices), since it uses a 7-bit address to identify devices in the chain that should get the message. This makes it more scalable, since we are limited in the width of the fiber and can not create an arbitrary number of GPIO lines.

To support the potential I/O modules not communicating via I2C we added a GPIO pin. In the Applications section, we show how we use it for touch sensing, and then to control addressable LEDs. Moreover, if we do not decide to use the I2C bus, its clock and data lines can be used for any other purpose (e.g., LED control, ADC, etc).

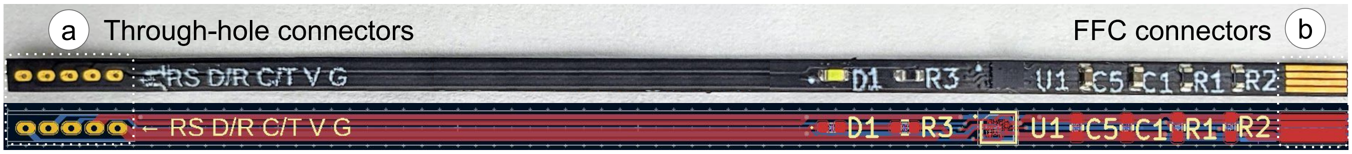

Figure 22: MCU module pinout: (a) THT pins to program or communicate with the MCU; (b) FFC pins used for I2C.

A.2 Connectors

To enable modularity, we added redundant and complementary connector types to the end of each fiber that are trade-offs between ease of reconfiguration and strength of connection.

Through-Hole Connectors: Soldering is the simplest way (fig 23-b), but other approaches can be used:

Pogo pins: Pogo pins are spring-loaded connectors that provide a quick connection. They are commonly used as battery or charger connectors, but are also the industry standard for test jigs. They can now be purchased in mainstream shops such as Amazon[11].

Z-tape: To connect two fibers, it is possible to use a piece of tape that conducts vertically only. It allows both fibers to make a connection at the connector pads without creating cross talk. Its anisotropy comes from its sparse conductive particles embedded in glue (see fig. 23-c & 24). This tape is common in high density display connector industries, but here it mostly makes it easy to add or remove connectors if a user needs to reconfigure fiber segments.

Connector Pads: We also implemented the Flat Flexible Cable (FFC) format at the ends of each fiber module (see figure 24). They can be used with off-the-shelf connectors, or with interlocked mechanisms to improve alignment for soldering or z-tape connection with the same fibers.

Interlocked Connection: We propose a connector that improves alignment by interlocking the ends of two LED fiber modules. The FFC pads are 200-300μm wide, so the alignment helps avoid undesired connections with the neighboring pad. This connector can also be easily disconnected and reconnected, allowing for fast reconfiguration of fiber modules without the need to de-solder and re-solder the connection.

Soldering: Users can also solder two fibers by pre-tinning each pad, aligning them using the interlock, and either using a hot air gun or a classic soldering iron.

Z-tape: As for through-hole connectors, z-tape can be used for simpler disconnection and reconnection.

[11] Example: https://www.amazon.com/gp/product/B09MGXHV54

B Further PCB Prototyping with Fiber Lasers

PCB Material: For most PCB designs, prototypes can be made from basic copper tape and Kapton tape. But when prototyping for high density designs such as our MCU PCB, the 40μm laser trace becomes noticeable vs the 150μm width of the MCU pads. In some cases, the laser might leave some microscopic metal hair, creating undesired electrical connections. Luckily, the accuracy of the results can be improved with a thinner copper layer. For example, some Dupont flex PCBs have a 9μm copper layer (vs 35μm in general). Otherwise a slow laser scan on the areas that need cuts can partially etch the copper layer and make it thinner.

Cutting VS Etching the traces: The laser can be used to either etch areas where there should be no conductivity, or to trace thin cuts around these areas. Since etching is slower than cutting along

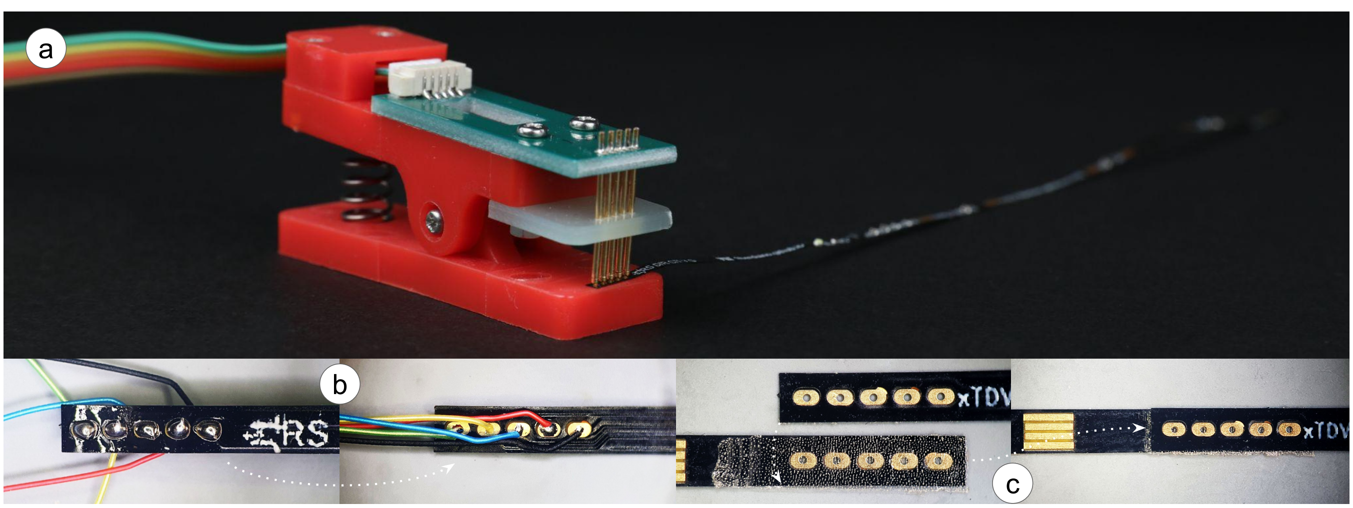

Figure 23: Through-hole connection options: (a) pogo-pins, (b) soldering, and (c) z-tape.

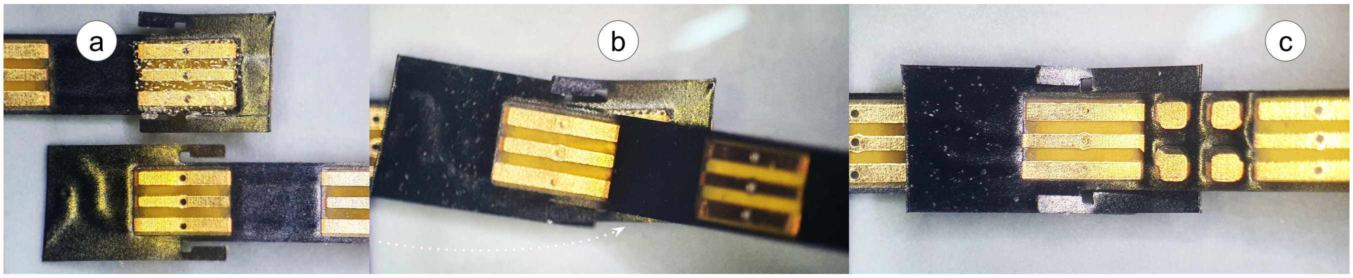

Figure 24: FFC connection using z-tape: (a) preparing the connectors and z-tape placement, (b) initiating the interlocked connection, and (c) connectors secured.

contours, solely lasing the contours can greatly accelerate prototyping. In our experience, this acceleration can go up to a factor of 10x, but it depends on the designs. However, only lasing the contours will increase the risk of short circuiting when the flexible PCB is bent, since the non-conductive separations are smaller.

Trace Resolution: The resolution or the circuit traces depends on the machine. Our best results were with the JPT fiber laser, achieving a 40μm cut and 40μm trace width, which is sufficient even for the MCU layout, our most challenging design. The lasing area has a size of 300mm x 300mm, which is bigger than any of our fiber modules. Our longest fibers measure 200mm, but as our MCU only measures 1.4mm, our entire MCU prototype board measured about 5mm x 5mm (see fig 22). Since this laser uses a Galvo system (Galvanometer), it also has a faster fabrication speed, i.e., our most complex fiber circuit takes about 5 seconds to fabricate on the JPT. Some prototyping illustrations are available in figure 25.

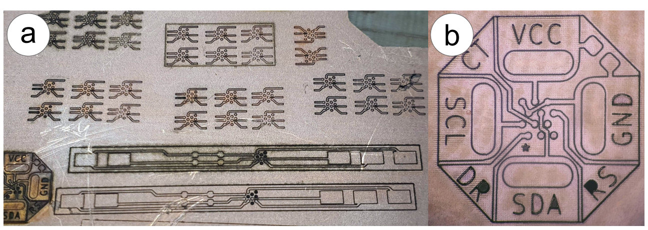

Figure 25: Lasing PCBs for quick prototyping, from 1st tests (a) to fully functional PCB ready to be assembled (b)

We also explored the use of a Trotec fiber laser which uses a CNC system with 1,000 ppi theoretical precision instead of a galvanic mirror. The best etching precision we obtained was about 120μm trace width and 100μm cut width, which was sufficient to create our LED fiber modules, but not sufficient to create our most complex fiber designs, the MCU module. When attempting higher resolution cuts, we encountered PCB etching "hair" problems due to the limited software options available for the CNC control. However, the Trotec has a laser bed size of 300mm x 600mm, and could also be used to create flexible PCB boards for long fibers without the need to connect them.

Laser Cutting the Solder Mask: These lasers can also be used to create solder masks for the circuits, which avoid solder paste that may spread onto undesired areas. To create the solder mask, we applied masking tape to the top of the copper tape and etched it directly in situ. The solder pads image can be extracted from the gerber files of the PCB.

Laser Cutting Stencils: Stencils can also be made with these lasers, using the same file extraction method used for the solder mask. PCB stencils are not necessary if the used parts have solder balls, which is the case for our WLCSP parts (the MCU and the sensors).

C Silicone coating

We used the Sylgard 184 silicone elastomer kit with a ratio of 10 (base):1 (curing agent). It was thoroughly mixed and degassed before manually coating with a cotton swab. Then, it was left in the oven at 80°C for 1 hour to cure completely. In order to ensure uniform coating across the length of the fiber as much as possible, the fiber was vertically clamped during the coating and curing process, as seen in figure 26:

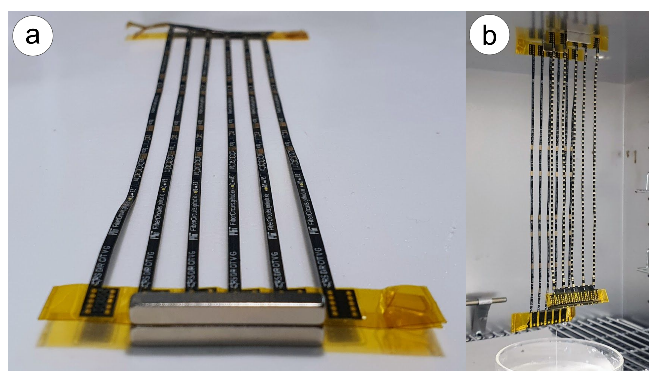

Figure 26: Silicone curing: (a) preparing the fibers, and (b) attaching them with magnets in the oven.

D Acronyms

- ADC: Analog-to-Digital Converter
- BGA: Ball Grid Array
- CNC: Computer Numerical Control
- EDA: Electro-Dermal Activity
- ECG: Electro-Cardio Gram
- EMS: Electro-Muscle Stimulation
- ENIG: Electroless Nickel Immersion Gold
- FFC: Flat Flexible Cable
- FPC: Flexible Printed Circuit
- GPIO: General-Purpose Input/Output
- HCI: Human-Computer Interaction
- I2C: Inter-Integrated Circuit bus
- IC: Integrated Circuit
- IMU: Inertial Measurement Unit
- LED: Light-Emitting Diode
- LCP: Liquid Crystal Polymer
- MCU: Microcontroller Unit
- PCB: Printed Circuit Board
- PDMS: Poly-Di-Methyl-Siloxane
- PPG: Photo-Plethysmo Graphy
- SPI: Serial Peripheral Interface
- TPU: Thermoplastic Poly-Urethane
- UV: Ultraviolet
- VR: Virtual Reality
- WLCSP: Wafer-Level Chip-Scale Package