Circuit2Yarn: From Planar Circuits to Electronic Yarns for Textile-Based Interactions

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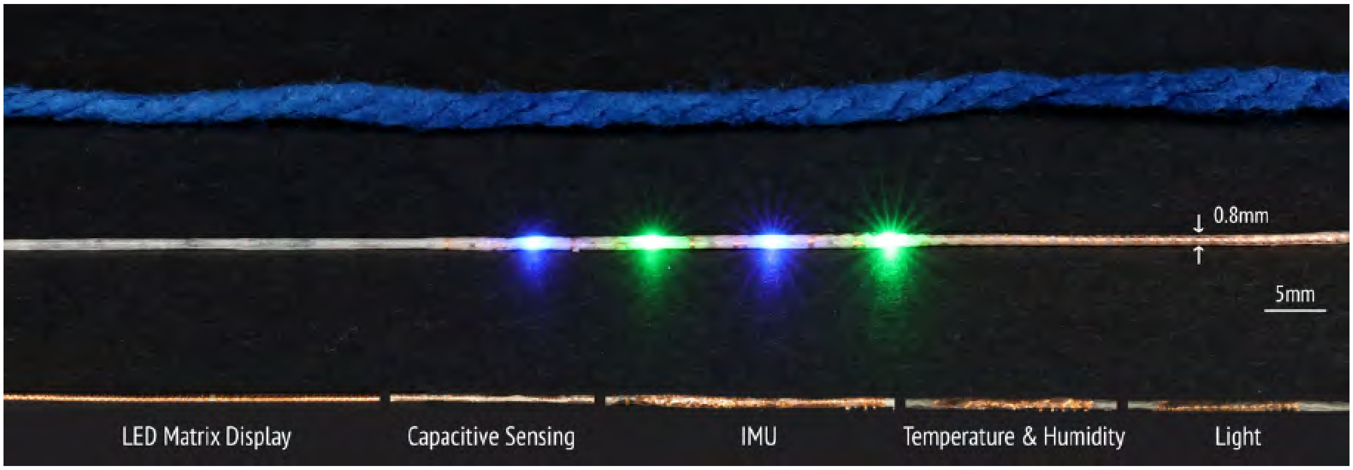

Figure 1: In this work, we introduce Circuit2Yarn, a fabrication pipeline that transforms flat flexible circuits into electronic yarns, enabling a wide range of computational functions, including light emission from LEDs and sensing of humidity, light, temperature, capacitance change, angular velocity, and acceleration. The LED yarn in the photograph has a 0.8 mm diameter, whereas the cotton yarn has a 3 mm diameter.

Abstract

Smart yarns hold the potential to transform everyday textiles into functional platforms, yet current methods remain constrained. These include conductive yarns, made from silver or stainless steel, which retain the feel of conventional yarns but offer limited functions, and PCB-based solutions, which add capability at the cost of bulk and rigidity. We present Circuit2Yarn, a fabrication framework that transforms planar printed circuits into flexible yarns by rolling copper-traced TPU films with soldered surface-mount components, preserving the capabilities of rigid electronics while producing yarn-like forms suitable for textile integration. We demonstrate yarns as small as 0.8 mm that integrate LEDs and sensors, including temperature, humidity, light, IMU, and capacitive sensing modules, enabling applications ranging from smart garments and interactive musical instruments to responsive tea bags. Characterization confirms durability under bending/stretching. By rolling planar circuits into yarns, Circuit2Yarn paves the way toward comfortable, multifunctional, and interactive textiles in everyday life.

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CCS Concepts

• **Human-centered computing → Interaction devices**; **Ubiquitous and mobile computing systems and tools**.

Keywords

electronic yarns, e-textiles, printed electronics, wearable computing, ubiquitous computing

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1 Introduction

In recent years, smart wearable devices—such as watches, wristbands, rings, and chest straps—have become increasingly popular. Yet, these accessories remain add-ons to a person’s attire rather than being seamlessly integrated into it. Textiles, on the other hand, offer a uniquely large and flexible surface area, making them well-suited for distributed sensing and actuation, in turn, informed interaction across the body.

Building on this advantage, a prominent research direction focuses on functional yarns and fibers as alternatives to centralized wearable devices [28]. Conductive yarns easily support basic forms of interaction, such as detecting touch, bending, and stretching by measuring electrical properties (e.g., resistance and capacitance). Further, when combined with machine learning techniques, simple conductive yarns enable more complex interactions, such as gestures, on-body locations, and activity recognition [30, 31, 57, 58]. Beyond conductive yarn, only a limited set of specialized variants exists, such as electroluminescent fibers for display [49], magnetic yarns [29], or pneumatic fibers for actuation [21]. Despite these advances, achieving comprehensive computational capabilities within fibers and textiles made with them remains an open challenge. Most of the functional yarns still fall far short of the rich diversity of electrical components available on conventional PCBs, leaving smart textiles restricted to relatively simple sensing and actuation modalities.

An alternative strategy for constructing smart textile products is to embed printed circuit boards (PCBs)—either rigid or flexible—directly into garments [15, 24]. This approach offers access to the full ecosystem of today’s electronic components, enabling more sophisticated functionality than yarn-based methods. Yet, PCBs are inherently constrained by their form factor: only a limited number can be comfortably integrated onto the body, and even flexible variants remain bulky and intrusive. Consequently, PCBs enhance functionality but compromise wearability, constraining the extent to which circuits can be integrated throughout clothing. Additionally, embedding electronics, such as PCBs, into garments centralizes them. This is a consequence of how PCBs are manufactured—optimized for compact and integrated circuits, yet typically rigid and localized. In contrast, the human body offers a vast surface area—about 1.5–2.0 m^2 for an average adult—that could support electronics in a distributed fashion [8]. Tapping into this space opens the possibility for large-scale integration of sensing, display, and computation directly on the body. Achieving this vision requires a platform that combines the versatility of PCB-based electronics with the softness, scalability, and comfort of textiles [59].

In this work, we present a fabrication method that produces yarns as functional electronic units—not only conductive or insulating, but capable of embedding highly functional distributed integrated circuits across textiles and, by extension, the human body. Our approach begins with planar printed circuits onto which off-the-shelf components are reliably soldered. These circuits are then rolled into thin, yarn-like form factors that can be seamlessly woven into fabrics, yielding electronic yarns that are compact, flexible, and highly functional. Unlike direct extrusion of functional fibers—where computational capability is limited by material and fabrication constraints—our method leverages mature PCB design and soldering processes before rolling, preserving the full richness of electronic components (e.g., LEDs, temperature and humidity sensors, light sensors, capacitive sensors, or IMU). This transformation enables textile-level flexibility and scalability, opening new opportunities for lightweight, comfortable smart wearables capable of supporting complex, interactive applications across the body. The thinnest electronic yarn diameter demonstrated in this work is 0.8 mm using 0402 components, with the methodology supporting further miniaturization through smaller component packages. It is worth highlighting that the rolling process substantially reduces circuit width. For example, a digital temperature and humidity sensor circuit shrinks from 13 mm to 2.5 mm (81% reduction) when it is rolled into a yarn, an IMU circuit from 15 mm to 3 mm (80% reduction), and an 8 × 8 LED matrix display circuit from 23 mm to 0.8 mm (96.5% reduction). This dramatic reduction enables compact integration of complex electronics directly into textile form factors.

The contribution of this work includes:

1. A low-cost, accessible framework for designing and fabricating electronic yarns that transform vinyl-cut copper traces and off-the-shelf components into thin, weavable forms, along with a comprehensive assembly methodology covering yarn-to-yarn connections, encapsulation, and circuit design strategies tailored to yarn geometries;
2. Demonstrations of functional electronic yarn primitives incorporating diverse components—including LEDs, temperature and humidity sensors, light sensors, capacitive sensors, and IMUs—within yarns as thin as 0.8 mm in diameter;
3. Technical evaluations of the electronic yarn performance under cyclic bending and stretching, and other electrical testing such as signal-to-noise ratio (SNR) measurements;
4. Application demonstrations that highlight the interaction potential enabled by Circuit2Yarn.

2 Related Work

2.1 Interactive Functional Yarn/Fiber Systems

Many smart textile applications have historically relied on conductive or resistive yarns, enabling sensing through mechanisms such as resistance changes or capacitive coupling [28, 38, 48]. Building on this, researchers have tried to add actuation components to smart textiles by using magnetic fibers, shape-memory alloys (SMAs), pneumatic channels, and polymer-based muscles [21, 22,

Table 1: Comparison of fabrication methods for electronic fibers and yarns across key design criteria.

Fabrication Method	Accessibility	Rapid Prototyping	Scalability	Routing Density	Dimension (mm)
Folded flexible PCB and thermo-drawing [11]	Low	✗	✓	Very high	1.35
Industrial flexible PCB as narrow strips [14]	High	✗	✓	Medium	1.3–1.5
Flexible circuit rolled into yarn (Ours)	High	✓	✗	High	0.8–2

29, 31]. While these functional yarns support useful interactions, including touch sensing [30], motion tracking [28], and pressure detection [54], they still remain limited to serve as conductors, resistors, capacitors, or pneumatic cylinders, constraining their interactive potential.

Recent advances illustrate how yarns might move beyond these basic roles. Electroluminescent fibers enable fabric-scale displays [43, 49], fiber batteries provide distributed energy storage [27], and energy-harvesting fibers generate power directly from movement or the environment [45]. While these developments bring functional yarns closer to more powerful modalities, their capabilities still fall short of commercial PCB-based counterparts—for example, electroluminescent fibers to today's LED matrices.

An alternative strategy has been to directly embed rigid or flexible PCBs directly into garments [15, 24]. This approach delivers computational richness and functionality well beyond what yarns alone can offer, but the planar geometry, centralized design, and rigidness of PCBs often compromise softness, flexibility, and durability. This tension underscores a central challenge for the future of smart textiles: achieving the functionality of PCBs while maintaining the drape and comfort of fabric. At the frontier, researchers have begun embedding microcontrollers directly into yarns using thermal drawing and braiding techniques, creating "fiber computers" that integrate sensing and processing within a single strand [11]. However, thermal drawing remains prohibitively complex—requiring specialized equipment, costly infrastructure, and wet-lab facilities—making it out of reach for most HCI researchers and designers. Most recently, another work FiberCircuits proposed an alternative that removes the wet-lab barrier by leveraging industrial flexible-PCB manufacturing to create fiber-like circuit strips at scale [14]. This method provides factory-grade precision, dense routing, and high reliability, making it well-suited for scalable production. Together, these advances point toward a future in which computational capability and textile wearability are no longer in conflict.

Compared with existing approaches, Circuit2Yarn adopts a new strategy that balances circuit complexity and fabrication accessibility. Instead of relying on thermal drawing or industrial PCB manufacturing, Circuit2Yarn converts a large, thin, 2D flexible circuit into a cylindrical yarn. While maintaining a comparable yarn diameter (e.g., 1–2 mm), Circuit2Yarn enables a great number of parallel routing traces/spaces within a millimeter-scale diameter. For instance, while FiberCircuits offers strong advantages in precision and scalability through industrial PCB fabrication, its layouts are also constrained by commercial process tolerances—limiting track density and routing flexibility (typically 1–2 mm wide, with around 4 parallel tracks). On the other hand, unlike the thermo-drawing process or the FiberCircuits' industrial process, Circuit2Yarn uses accessible desktop tools, allowing researchers to quickly build, test, and iterate yarn-like circuits within hours. To situate our approach within existing electronic fiber/yarn fabrication methods that fully support SMD components, we summarize representative techniques and their trade-offs in Table 1.

2.2 Printed Electronics for Interactive Devices

Our work builds on advances in printed electronics by transforming traditionally flat circuitry into functional yarns. Printed electronics has emerged as a powerful approach for fabricating interactive devices, offering low-cost, customizable, and scalable alternatives to conventional circuit manufacturing. Typically, these systems are printed in planar form, whether on rigid, flexible, or stretchable substrates [19, 55]. Early work demonstrated the feasibility of inkjet-printing conductive traces directly onto coated paper substrates using off-the-shelf desktop printers [20], enabling rapid prototyping of highly conductive silver circuits without the need for sintering or specialized equipment. This approach inspired a broad range of interactive applications, including customizable touch and pressure sensors [9, 12], flex and soil-moisture sensors [20, 47], antennas [42], interactive books [17], haptic and actuation systems [4, 18, 34], and large-scale interactive surfaces [1, 50]. Beyond paper, researchers have extended printed circuits to diverse substrates tailored for interaction. Stretchable PDMS elastomers have been used for on-skin touch sensing and electroluminescent displays [51, 52], while conformable tattoo paper has enabled multi-touch sensing directly on the body [16, 33]. Other methods such as screen printing, copper tape, and conductive sprays have broadened material choices to leather, ceramics, and stone, embedding circuits into unconventional surfaces [3, 35, 39, 40, 61]. Digital fabrication and transfer techniques have been explored to pattern and move conductive traces from temporary or flexible substrates onto three-dimensional or non-traditional surfaces [2, 10, 56]. Parallel advances in the materials science community have introduced new transfer and printing strategies [5, 7, 13, 25, 44], further expanding the design space for integrating electronics into interactive systems. While printed electronics are most often associated with flat, sheet-based devices, our approach leverages these techniques in a novel way by rolling printed circuitry into a yarn-like form. We directly fabricate functional yarns with unprecedented computational and interactive capabilities.

3 Circuit2Yarn Overview

Circuit2Yarn is a prototyping platform for yarn-like textile electronics, with a fabrication pipeline that starts with circuit design in common EDA tools, followed by cutting, assembly, rolling, and encapsulation to produce an electronic yarn that can be integrated

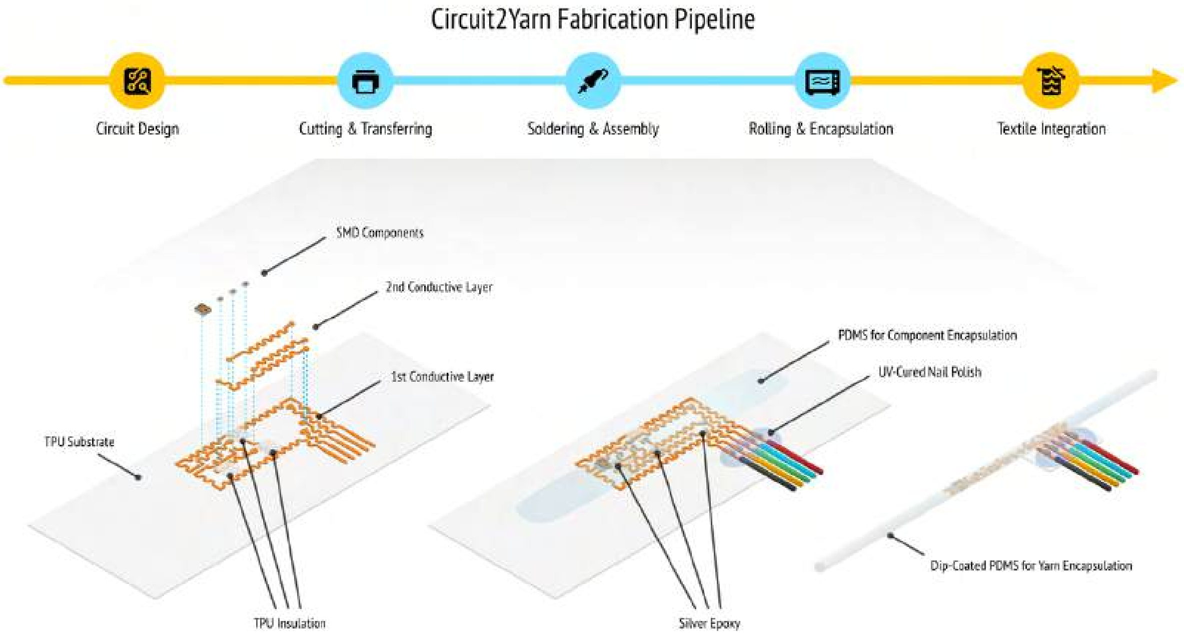


Figure 2: Overview of the Circuit2Yarn fabrication pipeline from flexible PCB design to functional electronic yarn using accessible equipment. Example shown: light sensor yarn.

into textiles. Each step is highly accessible by using desktop equipment such as a vinyl cutter, a soldering hot plate, and an oven. The entire road map is shown in Figure 2. The current pipeline addresses an important gap in the design workflow for prototyping yarn-like smart textiles. We aim to empower researchers and makers who often need to explore circuit architectures, sensing modalities, form factors, and interaction techniques at the yarn-scale during the early stages. Circuit2Yarn makes this early-stage exploration feasible within typical HCI labs or maker spaces. This accessibility also comes with a trade-off that the workflow is optimized for low-volume, iterative prototyping, not for high-throughput manufacturing. Producing dozens of identical yarns or long continuous lengths can cost substantial manual labor. Future automation—such as motorized rolling, or pick-and-place assembly—could extend the method toward more scalable production.

4 Circuit2Yarn Design Considerations

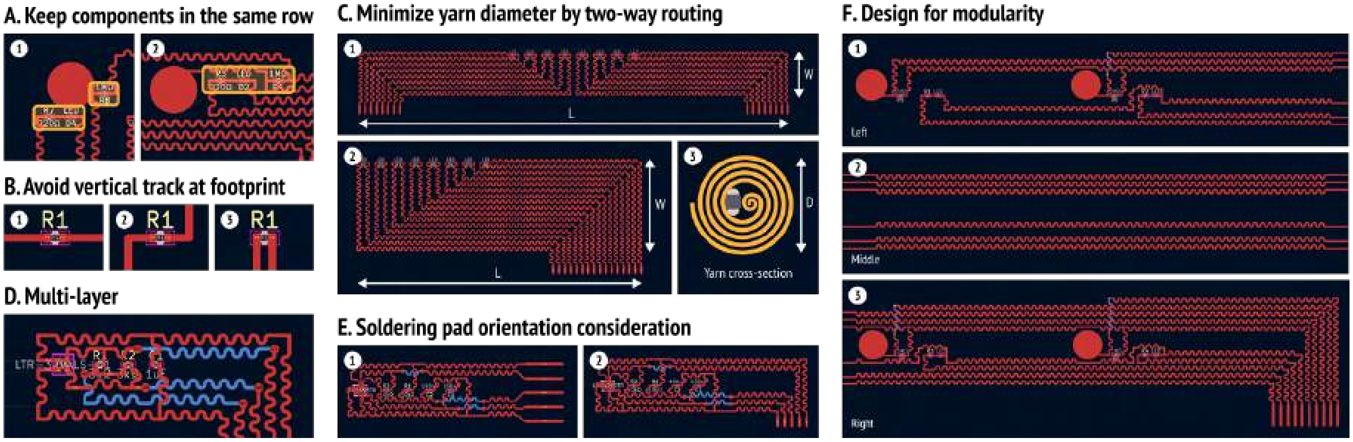
Incorporating complex circuit layouts and electronic components into a yarn form factor requires compressing a PCB layout—typically realized as a two-dimensional design—into a single dimension. In Circuit2Yarn, we create yarns by fabricating ultra-thin planar circuits in a long rectangular shape that can be rolled along the longitudinal axis into a 1-D structure. The process begins with a thin dielectric substrate, onto which a copper sheet is laminated. Undesired copper is then removed to form circuit traces in accordance with the EDA design. Next, electronic components are soldered onto the patterned sheet. Finally, the entire sheet is rolled along its longitudinal axis to complete the yarn that fully functions as a circuit board. In theory, this method allows us to realize arbitrary circuits in a yarn form factor. In practice, however, the design of such structures can be challenging. We discuss the challenges and corresponding design considerations in the rest of this section.

4.1 Minimizing Stress

The rolling process, central to our concept, can introduce extensive and uneven stresses across the planar assembly and its material layers. These stresses may lead to open circuits, from damage to copper traces or solder joints, or to short circuits, from unintended contact between conductors. Specifically, stress is caused by different fundamental reasons directly related to the architecture.

4.1.1 Embodied Stretchability. Firstly, differences in stretchability among the substrate, copper, solder, and components tend to separate these layers during rolling. To mitigate this issue, we recommend minimizing the thickness of each laminated layer. For Circuit2Yarn, we used a 65 µm TPU film with adhesive backing as the dielectric substrate and a 50 µm copper foil as the conductor. We also selected the smallest hand-solderable electronic components available, balancing fabrication accessibility with reduced rigid areas in the planar PCB design before rolling. Additionally, because copper traces are the weakest point of the assembly due to their narrow width, we recommend increasing their stretchability by using serpentine tracks instead of straight ones when routing the planar circuit.

4.1.2 Position of Rigid Feature. Another source of stress arises from uneven diameters, both during and after rolling. After rolling, rigid features such as components create thicker sections that concentrate stress at diameter transitions. During rolling, stress also develops when components are staggered along the longitudinal axis: as one component is rolled in, the diameter increases locally. The intervening material is forced to twist unevenly, creating local


A. Keep components in the same row

B. Avoid vertical track at footprint

C. Minimize yarn diameter by two-way routing

D. Multi-layer

E. Soldering pad orientation consideration

F. Design for modularity

Figure 3: Circuit design strategies to ensure planar circuits compactly rolled into cylindrical yarns while maintaining minimal diameter and robust functionality. (A) Position of rigid feature: distribute components along the longitudinal axis and align them along the transverse axis. (B) Route tracks that are immediately connected to solder pads along the longitudinal axis. (C) Minimize circuit width by distributing external connection points across both ends. (D) Multi-layer circuit should consider via size and minimize overlapping tracks. (E) Use transverse pads for external wire connection. (F) Use modular design for multi-yarn connected circuit.

stress. To mitigate these effects, planar designs should both distribute components evenly along the longitudinal axis and align them consistently along the transverse axis (Figure 3A.1 is not recommended; Figure 3A.2 is recommended). These practices help maintain a uniform diameter throughout the rolling process and reduce localized twisting and stress.

Beyond components, solder joints also introduce rigid regions. During reflow, solder tends to wick along adjacent copper traces, forming elongated stiff areas extending outward from the pad. When these traces are oriented along the transverse axis (Figure 3B.3), the cured solder creates a pronounced bump that sharply increases the local diameter. To minimize this effect, traces immediately connected to solder pads are recommended to be routed along the longitudinal axis (Figure 3B.1 and B.2) whenever possible.

4.1.3 *Circuit Width.*

A last major source of stress arises from local deformation when the rolled yarn is bent. Global bending stress induces differential strain across the circuit layers, with inner layers compressed and outer layers stretched. This strain mismatch can be mitigated by minimizing the number of layers, which in turn depends on reducing the circuit's width along the transverse axis. To interface each yarn with external circuitry, we allocate arrays of solder pads at either or both ends. Distributing these connection points across both ends, rather than concentrating them on one side, reduces the number of traces routed to a single end and thereby narrows the circuit, lowering bending-induced stress.

Figure 3C illustrates this effect: a circuit for eight individually controlled LEDs is shown with one-way routing (Figure 3C.2) and two-way routing (Figure 3C.1). Figure 3C.3 depicts a cross-section of the electronic yarn with diameter D, where the rolled distance (in yellow) corresponds to the planar film width W. The two-way routing design yields a thinner yarn by shortening the rolled distance.

4.2 Multi-Layer Circuit

Oftentimes, due to component footprints and circuit complexity, a single-layer design cannot be routed successfully. Conventionally, this is addressed using plated or riveted vias, which enable interlayer connections at designated locations. However, this method introduces bulky, rigid volumes into the structure, which is undesirable in the Circuit2Yarn architecture. To avoid this, we employ silver epoxy as a low-volume bonding agent to electrically connect corresponding via pads across two copper layers. To minimize epoxy overflow, the via pads on lower layers are designed slightly larger than their counterparts on upper layers, ensuring the epoxy bridges both pads reliably. In practice, we standardized pad sizes to 1.2 mm for upper-layer pads and 1.4 mm for lower-layer pads. Since no mechanical through-hole is required in this architecture, the via hole itself is omitted.

4.3 Beyond a Single Yarn

Depending on circuit complexity and component requirements, it is not always possible to encapsulate all functions within a single section of yarn, even with the strategies described above. In cases where multiple yarns are distributed across a larger textile area, physical signal-transmission channels are needed to enable communication between yarns or with external electronics. To support this, we designed wired connection outlets integrated into each yarn's circuit, providing solderable contact points that extend connectivity beyond a single section of yarn.

4.3.1 *External Cable Connection.*

As mentioned in Section 4.1.3, external cable connection pads can be placed at either or both ends of the circuit. After experimenting with pad orientations along both the longitudinal and transverse axes, we found that transverse pads perform more reliably.

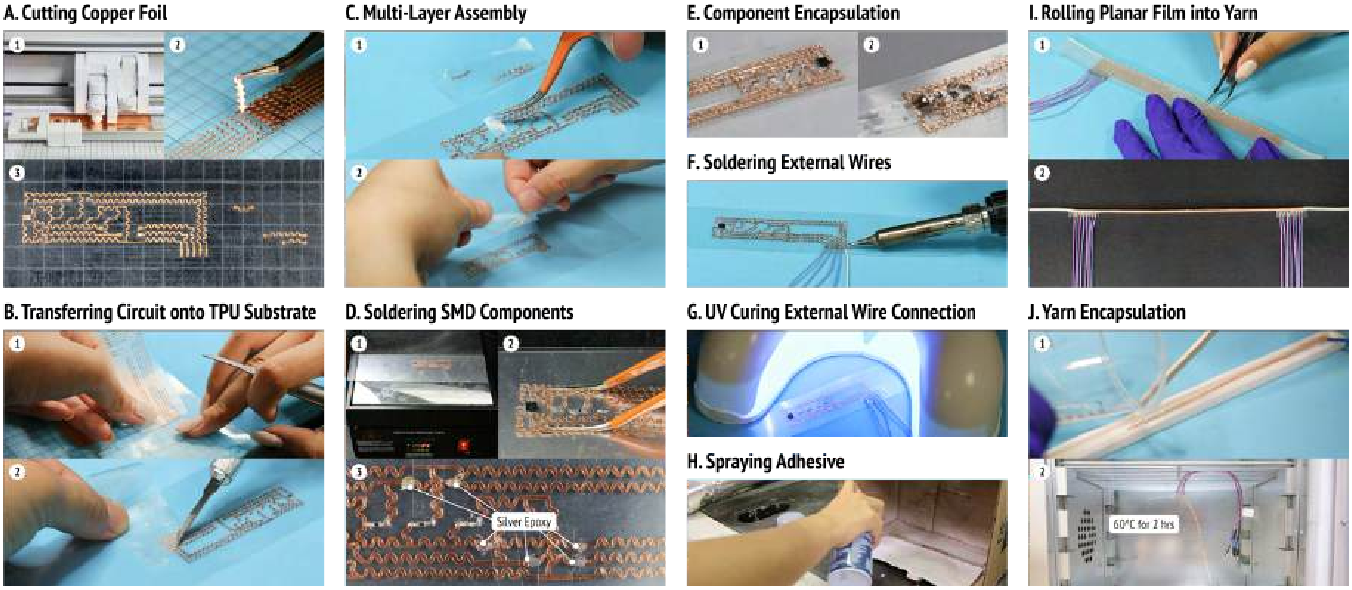


Figure 4: Fabrication steps of electronic yarn. (A–B) Circuit patterning and transfer: copper foil is cut with a vinyl cutter (A.1), excess copper peeled away (A.2–A.3), and the circuit transferred to TPU using a strong-grip sheet (B.1–B.2). (C–D) Layering and interconnections: multi-layer circuits are insulated with TPU films (C.1–C.2), components are soldered with low-temperature solder (D.1–D.2), and vias are connected using silver epoxy (D.3). (E–G) Component encapsulation and wiring: soldered components are coated with PDMS and oven-cured (E.1–E.2), external wires are attached and reinforced with UV-cured nail polish (F–G). (H–J) Yarn formation and final encapsulation: planar circuits are spray-coated with adhesive (H), rolled into cylindrical yarns (I.1–I.2), dip-coated in PDMS, and oven-cured at 60 °C for 2 hours (J.1–J.2).

Figure 3E compares two IMU circuit designs with external connection pads oriented longitudinally and transversely. In the longitudinal configuration (Figure 3E.1), multiple wires soldered in parallel near the circuit edge accumulate thickness at the soldering section when rolled, as their combined height is encapsulated together, generating local stress. This effect is further exacerbated by the additional encapsulation required at the solder joints.

By contrast, transverse pads (Figure 3E.2) avoid this cumulative thickness since the solder joints remain flat, and they can be directly replaced with FFC connectors for neat ribbon-cable packaging. In practice, we recommend transverse solder pad orientation for improved uniformity, reliability, and compatibility.

4.3.2 Extend Yarn Length. Yarn length is limited by the work area of the fabrication machine used to produce the pre-rolled planar circuit, in this case a vinyl cutter. To overcome this constraint, a modular approach is adopted at the circuit design stage: each planar module includes copper connection sections at its ends, allowing adjacent modules to be joined along the longitudinal axis.

As an example, Figure 3F shows a three-part design for a capacitive touch sensing yarn. The middle module (Figure 3F.2) is repeatable, enabling yarns of arbitrary length by inserting as many middle parts as needed. Short straight extensions of copper pads protrude beyond the substrate and overlap with corresponding pads on the next module, forming continuous conductive paths across modules. The detailed connection method is described in Section 5.1.2.

5 Fabrication Method

In this section, we describe the fabrication process of a single-strand electronic yarn and the method of integrating it into textiles.

5.1 Fabricating an Electronic Yarn

5.1.1 Create planar circuit pattern. We begin the process by cutting the copper trace pattern using a vinyl cutter. A thin copper foil with adhesive on one side is laminated on the cutting mat with its adhesive side facing down. The vinyl cutter then engraves the circuit geometry exported from the EDA design tool in vector format (Figure 4A.1). After cutting, the unwanted copper corresponding to isolation areas is peeled away with tweezers (Figure 4A.2–A.3), leaving the desired traces on the mat.

Next, a strong-grip transfer sheet is used to lift the patterned traces from the cutting mat and deposit them onto a TPU substrate (Figure 4B.1–B.2). We recommend transferring the traces immediately after cutting to minimize dust accumulation, which can compromise adhesion during transfer.

For multilayer designs, a thin TPU film is inserted between overlapping layers to prevent short circuits (Figure 4C.1). The upper-layer traces are cut using the same method as the lower layer and then transferred onto the existing stack. They are carefully aligned with the lower layer by matching the corresponding via pads on both copper layers (Figure 4C.2). Silver epoxy is applied across the vias pads and cured to form a reliable electrical connection (Figure 4D.3).

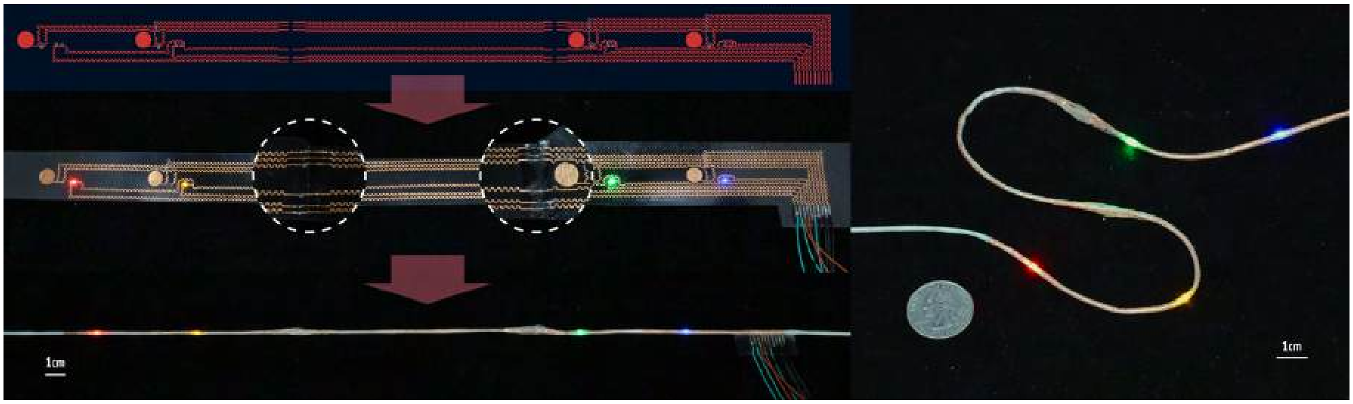


Figure 5: Demonstration of multi-yarn connection. A planar circuit for four capacitive sensing pads and four LEDs in three parts is connected, then rolled into a 60 cm electronic yarn.

5.1.2 Soldering and Assembly. To assemble electronic components, solder paste is applied to the pads (Figure 4D.1), and SMD components are placed accordingly. We use Sn42/Bi58 low-temperature solder paste to limit TPU deformation during reflow. The assembly is then reflowed on a heating plate. Slight warping of the TPU may occur during heating; in such cases, tweezers are used to hold the substrate flat against the plate (Figure 4D.2). External connection wires are soldered to the end pads of the circuit (Figure 4F) using a soldering iron. Because these joints are subject to greater mechanical stress than other solder points, they are reinforced with a thin coat of nail polish, UV-cured for approximately two minutes (Figure 4G) before further encapsulation. We apply a thin coat of polydimethylsiloxane (PDMS) over all soldered components that protects the assembly from damage caused by shear stress during rolling and subsequent textile manipulation. The coated PDMS can be oven-cured at 60 °C for 2 hours. This completes the manufacturing of a thin planar circuit.

Planar circuits for extra-long yarns can be connected by overlapping the copper connection sections at the ends of each module. Silver epoxy is applied across the corresponding copper pads and cured to establish conductive traces between modules. To ensure connection reliability and prevent short circuits, we apply a peelable nail-polish base gel over the joints after curing. Figure 5 illustrates this process: by joining three planar circuit modules at the flat stage, we created an extended electronic yarn integrating four capacitive sensing pads and four LEDs.

5.1.3 Rolling. Before rolling, a light layer of spray adhesive is applied to the circuit surface (Figure 4H) to aid the process. The film is then rolled tightly into a cylindrical yarn using tweezers, starting from one edge while applying consistent force (Figure 4I.1). The completed yarn is dip-coated in PDMS to seal the surface (Figure 4J.1) and cured at 60 °C for 2 hours (Figure 4J.2).

We also summarize the estimated durations for each fabrication step in Table 2. The numbers reflect the time required to fabricate a single electronic yarn with a digital light sensor. It is worth noting that simpler designs—such as a single-layer LED yarn—take less time, whereas more complex circuits like IMU yarns require more time due to greater circuit complexity and soldering difficulty. Although most steps are manual, an experienced maker can complete the full process with roughly one hour of hands-on work, plus four hours of PDMS curing across the two encapsulation stages.

5.2 Textile Integration

To bring multi-yarn networks into everyday use, we demonstrate that our electronic yarns can be seamlessly integrated into textiles, forming distributed computational networks on the body or in the environment. Like conventional yarns, our electronic yarns are compatible with many textile manipulation techniques. As shown in Figure 6, our electronic yarns can be hand-embroidered using the couching technique, hand-knitted directly into the fabric, and woven as wale yarns.

Figure 6: Demonstration of three textile integration techniques with electronic yarn. (a) Hand-embroidery. (b) Hand-knitting. (c) Weaving.

6 Primitive Electronic Yarn Architecture

To demonstrate the versatility of our fabrication framework, we developed a set of primitive yarn architectures that showcase both output and input capabilities. These primitives span from lightweight, componentless sensing modalities—such as capacitive touch—to more sophisticated, component-based integrations, including LEDs, digital light sensors, humidity and temperature sensors, and a 6-axis IMU (shown in Figure 7). Each primitive illustrates how planar circuits can be transformed into yarn-like form factors without sacrificing functionality, while maintaining softness, flexibility, and textile compatibility. Across these primitives, the resulting yarn diameter is primarily determined by circuit width and component

Table 2: Estimated fabrication time for each step in the Circuit2Yarn process. Times correspond to the pipeline shown in Figure 4 and reflect the fabrication of a digital light sensor yarn.

Step	Type	Estimated Time
A. Cutting Copper Foil	Vinyl cutter working time	~ 4 min (depends on circuit complexity)
B. Transferring Copper onto TPU Substrate	Manual	~ 18 min (depends on circuit complexity)
C. Multi-Layer Assembly	Manual	~ 10 min (depends on circuit complexity)
D. Soldering SMD Components	Manual	~ 10 min (depends on circuit complexity)
E. Component Encapsulation	PDMS oven curing time	2 hr
F. Soldering External Wires	Manual	~ 2 min
G. UV Curing External Wire Connection	UV curing time	2 min
H. Spraying Adhesive	Manual	~ 1 min
I. Rolling Planar Film into Yarn	Manual	~ 8 min
J. Yarn Encapsulation	PDMS oven curing time	2 hr
Total	–	~ 1 hr manual task + 4 hr PDMS curing

footprint. Smaller circuit width and smaller SMD packages will result in thinner yarns. For example, although the light-sensor yarn and IMU yarn share the same 15.17 mm circuit width, the light sensor's smaller package (2 × 2 × 0.7 mm) yields a thinner yarn diameter (1.36–2.12 mm) compared to the IMU yarn, whose larger package (2.5 × 3 × 0.83 mm) contributes to a wider diameter (1.06–3.38 mm). Likewise, while both the capacitive touch yarn and LED yarn use 0402-size components, their circuit widths differ substantially: 13.19 mm for the capacitive touch yarn versus just 3.88 mm for the LED yarn. This width difference directly translates to their diameters, with the capacitive touch yarn measuring 1.28–1.56 mm and the LED yarn achieving a much smaller 0.74–0.88 mm.

6.1 Component-Based Electronic Yarns

A key advantage of our approach is the ability to directly embed commercial electronic components into yarns, transforming them into multifunctional building blocks for smart textiles. Among the sensing modalities, **environmental perception/awareness input sensing** is particularly important for everyday interaction. We explored integrating the LTR-329ALS-01 digital light sensor into our electronic yarn, which provides both visible+infrared and infrared-only channels, enabling differential analysis of illumination. As shown on the right side of Figure 8, the yarn reliably distinguished between low (no overhead light), medium (overhead lighting), and high (direct flashlight) intensities. Similarly, the HDC2010 humidity and temperature sensor preserved its ability to capture both ambient conditions and subtle on-body changes, such as rises in temperature and humidity when touched, demonstrating that yarn encapsulation can maintain sensor precision while supporting applications in comfort tracking, on-body monitoring, and environmental awareness. Beyond environmental factors, **motion input sensing** plays the most central role in interactive textiles. Prior work has demonstrated the use of IMUs for applications such as motion tracking, body posture reconstruction, and medical monitoring [32, 37, 62]. However, these systems typically rely on IMUs mounted on planar PCBs, which constrain their placement on the body and limit the number of sensors that can be deployed. As a result, it remains challenging to achieve dense coverage and capture fine-grained three-dimensional deformations. We directly embedded the LSM6DSO 6-axis IMU, which integrates a 3-axis accelerometer and a 3-axis gyroscope, into the yarn. The IMU produced stable and accurate readings across a wide range of motion modalities, including rotations along the X, Y, and Z axes as well as vertical translations at varying speeds, which can enable activity recognition, gesture input, and motion-responsive interactions (as shown in Figure 8). In addition to sensing, **output** capabilities are also essential for communicating information through fabrics. To demonstrate this, we embedded 0402-size surface-mount LEDs onto copper traces and rolled the circuitry into the LED yarn. The resulting yarn retained a uniform cylindrical profile while allowing light emission through the encapsulation. Scaling this concept, multiple strands were woven in parallel to form an 8 × 8 LED matrix, creating a dynamic textile display suitable for notifications, indicators, and aesthetic expression.

6.2 Componentless Electronic Yarns

Beyond connecting external components, our electronic yarn itself can also function as a componentless sensor, enabling capacitive touch interactions. As shown in Figure 8, we integrated four capacitive pads along the yarn's length, each individually addressable to capture localized input. In this design, the TPU encapsulation acts as a dielectric layer between the pads and the user's skin, forming an additional capacitor. This configuration results in a two-plate capacitive structure where touch is detected indirectly through the yarn coating [4]. Capacitive measurements were performed using the CapacitiveSensor Library on an Arduino UNO with a 10 MΩ resistor in the sensing circuit.

Shown in Figure 8, we demonstrate three representative interaction modalities enabled by this setup. First, the system can differentiate the number of fingers simultaneously touching the yarn, with clear stepwise increases corresponding to the input of one, two, and three fingers. Second, by modulating the pressure on the yarn, the capacitance values reveal distinct stages from gentle to medium to hard presses. Third, sliding gestures can be detected with directional information by comparing signals across adjacent pads. With only two conductive pads, left-to-right and right-to-left swipes can be

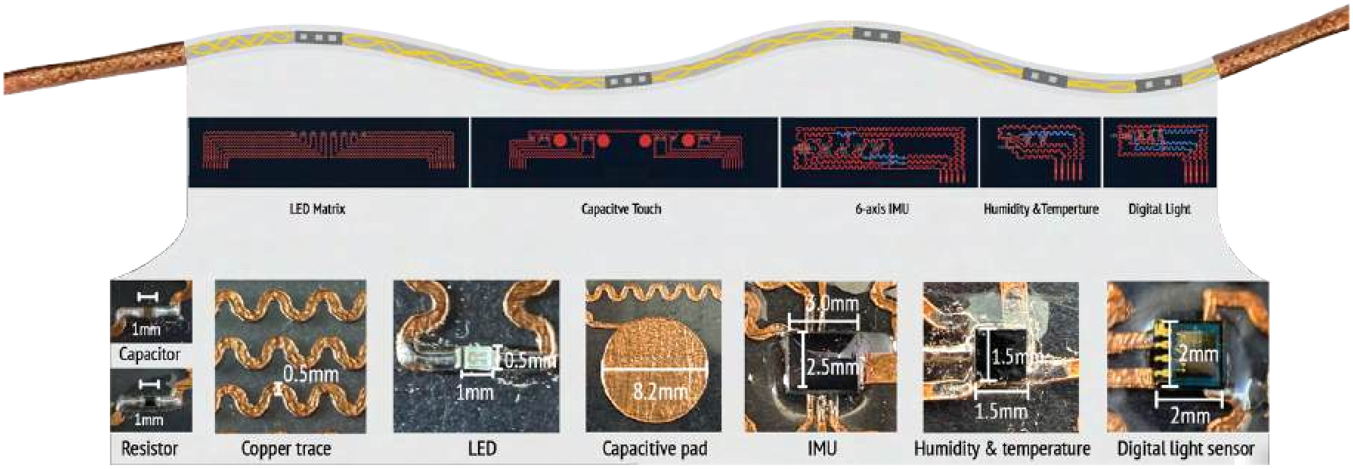


Figure 7: Overview of electronic yarn primitives. The yarn incorporates diverse functional modules, ranging from output capabilities such as an LED matrix to input modalities including componentless capacitive touch sensing, as well as component-based sensors like a 6-axis IMU, humidity and temperature sensing, and a digital light sensor.

easily distinguished, but the limited sensing range restricts their use as an input modality. When extending to multiple pads (e.g., four), interference among adjacent pads and copper traces makes the raw signals more ambiguous. To address this, we employed an SVM-based classifier with a sliding window of 100 samples (1 s) and a step size of 50 (50% overlap), achieving reliable binary classification of swipe direction. To quantitatively assess capacitive sensing performance, we also calculated the signal-to-noise ratio (SNR) as:

$$SNR_{dB} = 10log_{10}\left[(\frac{A_{signal}}{A_{noise}})^2\right]$$

where A is the root mean square amplitude of the signals calculated by

$$A_{signal/noise,RMS} = \sqrt{\frac{1}{n} \cdot \left(A_1^2 + A_2^2 + A_3^2 + \cdots + A_n^2\right)}$$

Based on this metric, the electronic yarn achieved an average of 13.27 dB across repeated trials. Together, these results highlight how electronic yarn can go beyond simple touch detection to support rich multidimensional input, offering new opportunities for interactive textile interfaces.

7 Evaluation and Testing

Understanding the electrical and mechanical performance limits of our electronic yarns is essential, particularly since they are designed to be integrated into everyday textiles for wearables. As noted earlier and widely reported in the literature [6], straight copper traces exhibit significantly poorer mechanical durability compared to serpentine designs, which we employ in this work.

We fabricated a testing yarn with a 9 cm serpentine copper trace and evaluated its electromechanical performance. As shown in Figure 9a, the yarn maintained stable resistance during both cyclic bending (2000 cycles, top) and incremental bending (bottom), where the two grippers of the tensile tester (Mark-10 F1505-IMT) were gradually moved toward each other. Because the yarn does not form a full circular arc in this setup, we report bending in terms of gripper displacement rather than bending radius; larger displacement corresponds to a sharper bend.

We then further examined the stretchability of the electronic yarn. As shown in Figure 9b, the resistance remained stable initially until a sharp increase indicated electrical failure, and the corresponding stress–strain curves show peak stresses at the failure point, marking mechanical rupture of the yarn. Across multiple samples, the yarn exhibited failure strains of 34%, 44% and 46%, with peak stresses of 1.3 MPa, 1.5 MPa and 1.3 MPa, respectively.

To evaluate environmental durability, we performed washing tests using a thermistor-integrated yarn. As shown in Figure 9c, the electrical resistance from the thermistor, which measures the ambient environment, remained stable over ten washing cycles (15 minutes per cycle) in a standard household washing machine. Across all experiments, we observed no issues with external wire connections, and the connections remained intact after repeated washing. Also, as shown in Figure 9d, the LED-integrated yarn remained fully functional while supporting a 50 g load and when tied into a tight knot, demonstrating mechanical robustness under practical handling conditions.

Finally, to evaluate fabrication consistency, we measured the diameters of 16 LED-integrated yarns. As shown in Figure 9e, the samples exhibit a narrow diameter distribution centered around 1.4–1.5 mm, indicating good uniformity and reliable repeatability in the fabrication process. Looking beyond handcrafted samples, the same factors that govern yarn diameter and mechanical uniformity—such as layer thickness and rolling tension—will similarly drive consistency at larger scales. These parameters can be standardized in batch workflows with pick-and-place assembly and motorized rolling. Our small-scale measurements indicate consistent material

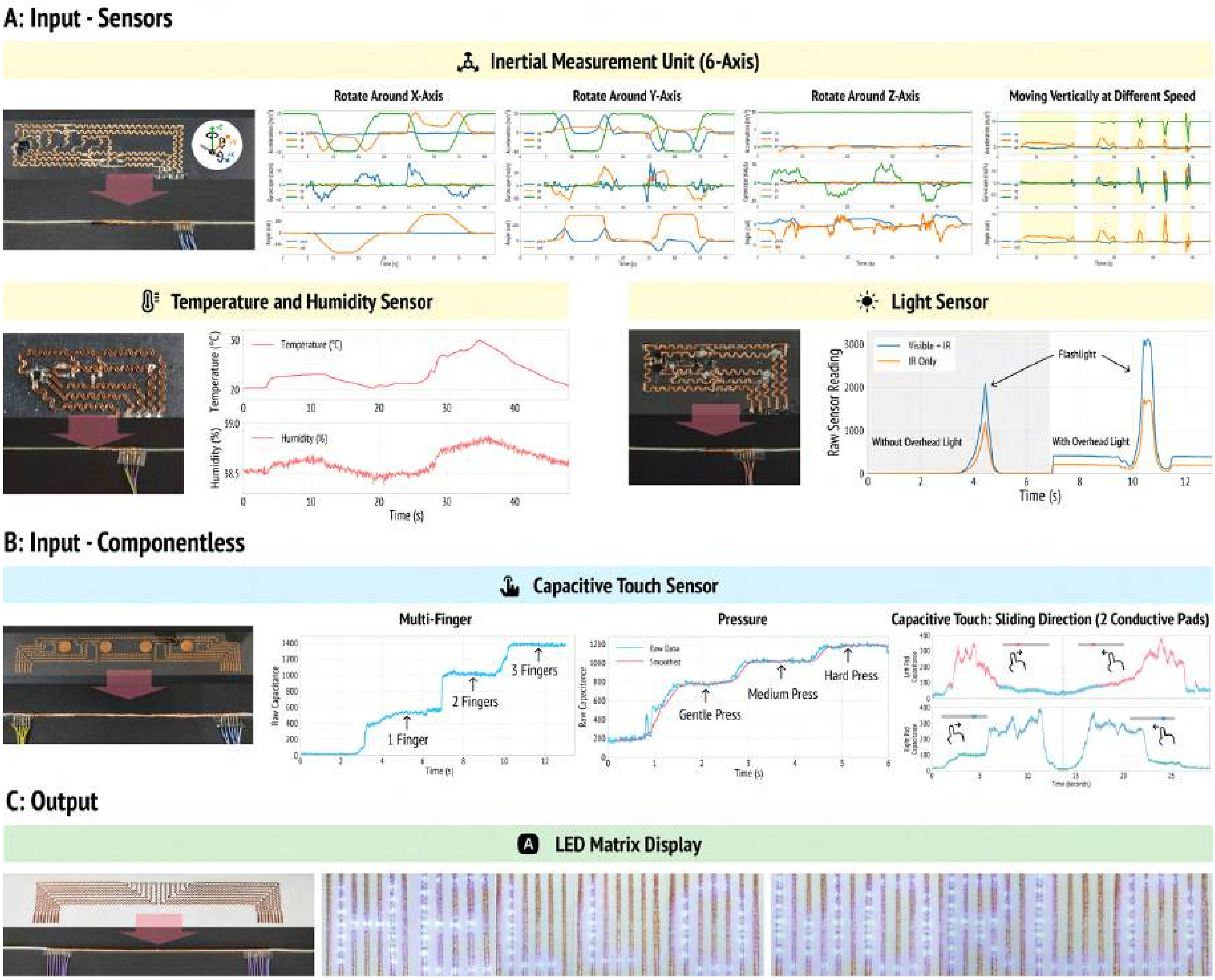


Figure 8: Electronic yarn primitives demonstrating diverse I/O capabilities. Our approach supports (a) Component-based input: examples include environmental sensors (temperature, humidity) and motion tracking (6-axis IMU). (b) Componentless input: capacitive sensing for touch, pressure, and gesture recognition. (c) Electronic output: visual feedback through integrated LEDs.

and geometric behavior, which can be preserved as the process moves toward future large-scale automated production.

8 Applications

To demonstrate the versatility of our electronic yarn, we showcase four scenarios that integrate sensing and display seamlessly into everyday interaction. These include a woven LED fabric display with motion-responsive visuals, a hoodie drawstring enhanced with machine learning for interactive control, a smart tea bag string that monitors water temperature, and a ukulele string that augments musical performance and learning. Table 3 presents the details of each electronic yarn used in our applications, including embedded components, physical dimensions, and circuit topology.

8.1 A Woven LED Fabric Display with Motion-Responsive Visuals

Woven fabric structures share strong parallels with pixel-based displays. Building on this analogy, we integrate electronic yarns as both sensing and display elements directly within the textile structure (Figure 10). In our prototype, 8 LED yarns are woven as weft yarns alongside conventional yarns, each containing 8 LEDs. Together they form an 8×8 matrix that produces pixel-like illumination across the woven surface. An additional IMU yarn, also woven as a weft, captures motion and orientation changes of the fabric patch (Figure 10d). Tilting the patch to the left, right, upward, or downward generates distinct light patterns (Figure 10c), enabling the textile to act as an embodied display of its own motion state. The

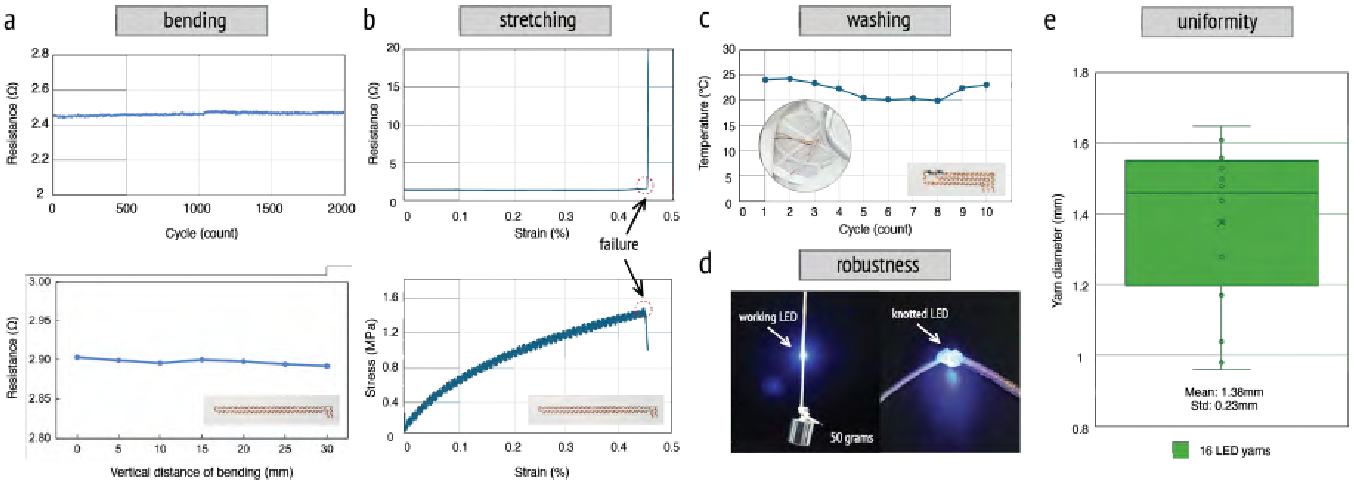


Figure 9: Evaluation of electronic yarn durability and robustness. (a) Resistance stability under repeated bending and increasing bending displacement.(b) Electrical and mechanical response under stretching, showing failure at 0.46 strain. (c) Washing test showing stable resistance after 10 full washing cycles. (d) Robustness demonstrations with functional LED operation under a 50g weight load and knotting. (e) Uniformity testing results for 16 LED yarns.

Application	Components in One Yarn	Min Diameter (mm)	Max Diameter (mm)	Parallel Tracks	Circuit Length (mm)	Circuit Width (mm)	Conductive Layers
Woven LED Display	0402 LED × 8	1.25	1.85	8	148.8	16.93	1
	IMU (LSM6DSOTR) × 1, 10kΩ 0402 resistor × 2, 100nF 0402 capacitor × 2	1.06	3.38	7	59.27	15.17	2
Hoodie Drawstring	10MΩ 0402 resistor × 4	1.24	1.71	9	149.01	17.64	1
Smart Tea Bag String	0603 thermistor (NCP18XQ681J03RB) × 1, 0402 LED × 4, 330Ω 0402 resistor × 4	1.38	1.81	8	121.04	15.88	1
Interactive Ukulele	10MΩ 0402 resistor × 3, 0402 LED × 3, 330Ω resistor × 3	1.57	2.11	11	160.94	35.98	1

Table 3: Specifications of applications, including the embedded components, the minimum and maximum yarn diameters, number of parallel tracks along the transverse axis, circuit length, circuit width, and number of conductive layers.

circuit designs and fabrication steps for both LED and IMU yarns are shown in Figure 10a–b, illustrating how sensing and actuation can be co-embedded within yarn geometries. Unlike approaches that mount LEDs and IMUs onto the textile surface, our method integrates them structurally into the weave, eliminating the need for surface modification. This structural integration underscores the potential for interactive woven interfaces, where fabric itself simultaneously serves as both input and output medium.

8.2 A Hoodie Drawstring as an Input Device

Cords and drawstrings provide natural and accessible interaction points in everyday garments, making them an attractive site for embedding input capabilities in interactive textiles [36, 41]. Hoodie drawstrings, in particular, are both familiar and intuitive, offering an ideal channel for unobtrusive sensing. Building on this opportunity, we developed a machine-learning-assisted electronic yarn that replaces a conventional drawstring with a capacitive, gesture-sensitive input device (Figure 11). The electronic drawstring integrates four distributed capacitive sensing pads (Figure 11a), enabling continuous detection of hand proximity and contact patterns along the yarn. Because the sensing mechanism relies on the spatial arrangement of pads and their deformation-dependent capacitance changes, different gestures naturally produce distinctive multi-channel signatures. The raw multi-channel signals (Figure 11c) visually highlight how different gestures deform the yarn and modulate pad-level capacitance in unique ways, independent of user-specific factors. To evaluate the electronic yarn's gesture recognition capability, we collected data from a single user at 100 Hz sampling frequency. A 1-second sliding window with 50% overlap was used as input to a support vector machine (SVM) classifier with default scikit-learn parameters. With an 80/20 random train/test split, the classifier achieved 100% accuracy for a five-gesture classification task, distinguishing out of reach, hover, tap, pinch, and grab (Figure 11b). Using the same scheme, a second classifier distinguished upward swipe, downward swipe, and idle with 100% accuracy. These results align with our t-SNE projections (Figure 11d-e), which show clear cluster separation. These gestures extend the expressive input vocabulary of the hoodie

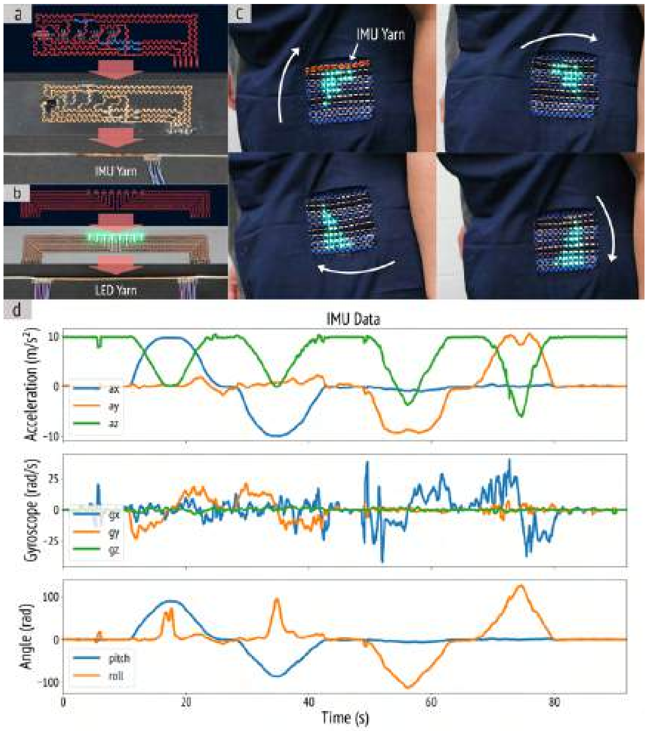


Figure 10: Woven LED fabric display with motion-responsive visuals. (a,b) Circuit design, fabrication, and rolling process of the IMU yarn and the 8 × 8 LED matrix. (c,d) Demonstration of the yarn-driven LED matrix responding to fabric orientation: tilting the fabric left, right, upward, or downward triggers corresponding directional light patterns based on IMU readings.

drawstring, transforming a commonplace garment feature into a versatile interactive interface. As a demonstration, we mapped gestures to media controls: sliding adjusts volume, while a pinch starts or stops playback (Figure 11d-e). This example illustrates how electronic yarns can augment familiar clothing elements into rich, contextually meaningful interaction channels.

8.3 A Smart Tea Bag String for Temperature Monitoring

Tea brewing is a daily activity, yet both temperature and steeping time are often difficult to control, and different types of tea require specific conditions. To enable more reliable brewing, we developed an electronic yarn that replaces the string of a conventional tea bag, transforming it into a situated, interactive guide for the brewing process (Figure 12). The smart tea bag string, fabricated with rolled electronic yarn, integrates a thermistor and 4 LEDs (Figure 12c). The thermistor continuously monitors water temperature, while the LEDs provide real-time visual feedback: blinking from bottom to top indicates that hotter water should be added; a breathing effect signals the start of steeping; and rapid blinking alerts the user when the tea is ready (Figure 12a). The temperature curve in Figure 12b confirms the successful monitoring of the relevant steeping range. By embedding sensing and actuation into a simple household object, this example illustrates how electronic yarns can unobtrusively enrich everyday routines with context-aware feedback, extending textile computing into applications beyond garments.

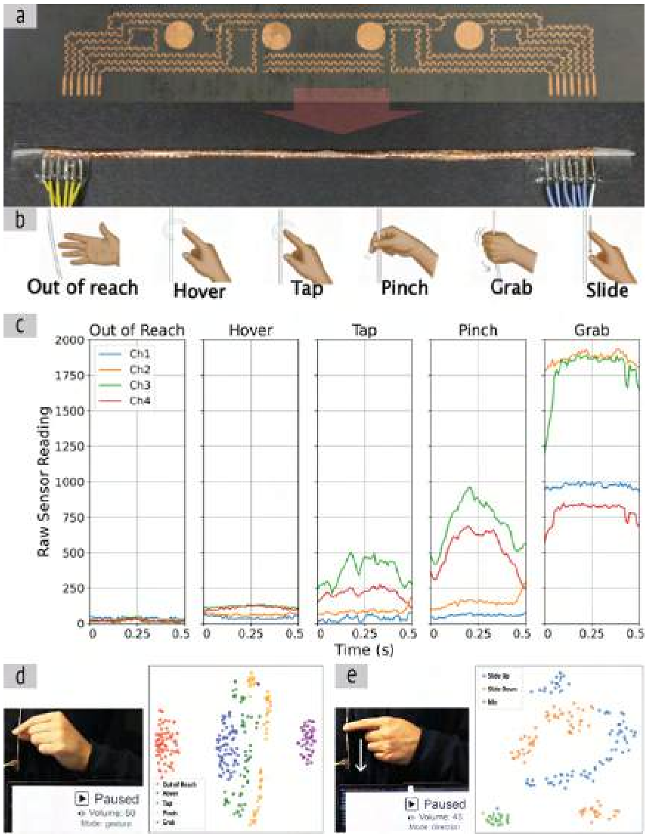


Figure 11: Hoodie drawstring as an input device. (a) Circuit design, fabrication, and rolling process of the four-pad capacitive sensing yarn. (b) Six gestures recognized by the system: out of reach, hover, tap, pinch, grab, and slide up/down. (c) Distinctive raw signals from the yarn: out of reach, hover, tap, pinch, grab. (d, e) Demonstrations of the machine-learning-assisted yarn used as a hoodie drawstring, enabling interactions such as adjusting volume by sliding and starting/stopping music by pinching, along with corresponding t-SNE visualization showing the separation of clusters corresponding to each gesture.

8.4 An Interactive Ukulele for Learning Finger Positions and Customized Performing

Many everyday objects take the form of strings, such as musical instruments. To explore this design space, we developed an interactive ukulele using our electronic yarns. The traditional strings were replaced with four electronic yarns, each embedded with three LEDs and three capacitive sensing pads (shown as Figure 12a,b). We designed two distinct modes for interaction. In interactive mode,

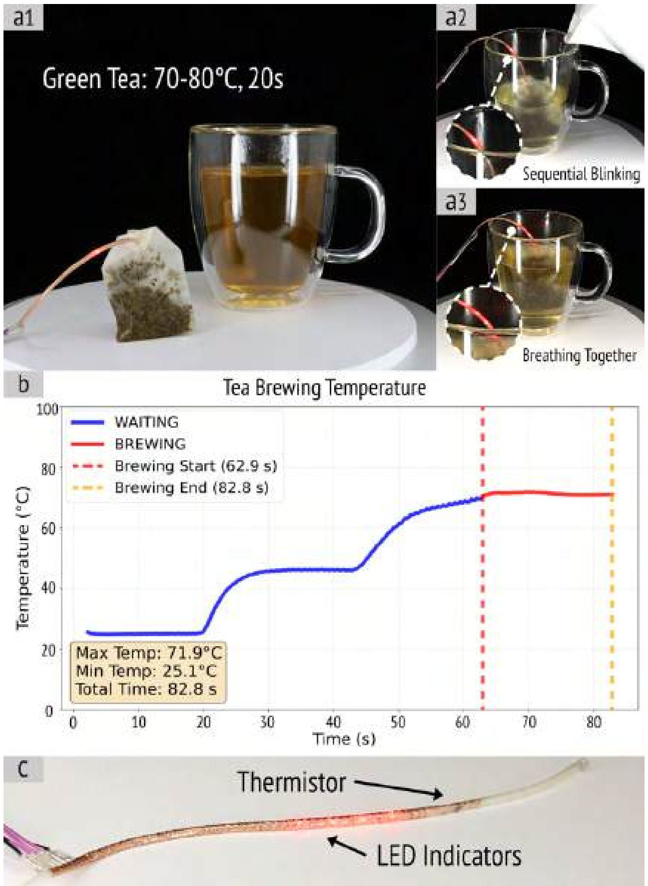


Figure 12: Smart tea bag string. (a1-a3) Demonstration of the yarn monitoring water temperature to ensure optimal brewing. LED patterns guide the user through different stages: sequential blinking indicates hotter water is needed, breathing signals the start of brewing, and fast breathing marks completion. (b) Temperature readings during brewing. (c) Overview for the smart tea bag yarn integrating four LEDs and one thermistor.

users can visualize the keys as they are played on the display. In teaching mode, the system guides beginners by automatically illuminating the correct finger positions along the strings, prompting users to follow the light cues to form the right chords.

9 Limitation and Future Work

9.1 Scalable Electronic Yarn Manufacturing

We selected vinyl cutting as our primary fabrication method due to its accessibility and suitability for rapid prototyping. However, the process presents several challenges that highlight opportunities for refinement. In particular, the peeling, transferring, and rolling steps remain highly manual and dependent on user expertise, where consistent, high-quality outcomes rely on careful handling to avoid delamination or circuit damage. To move beyond prototyping, automation will be critical. Existing industries provide useful parallels: textile manufacturing employs continuous processes such as spinning and braiding to produce kilometer-scale yarns, while the electronics industry leverages roll-to-roll fabrication for cost-efficient mass production of NFC tags and flexible LED strips. Inspired by these practices, we envision a pipeline that first mass-produces planar electronic sheets and subsequently transforms them into yarn form factors. Beyond reducing manual labor, achieving longer continuous lengths and higher throughput is critical for real-world deployment. Garments and large-area textile systems require meters of consistent circuitry—not short prototype segments—to support full-garment sensing, distributed interaction, and dense instrumentation.

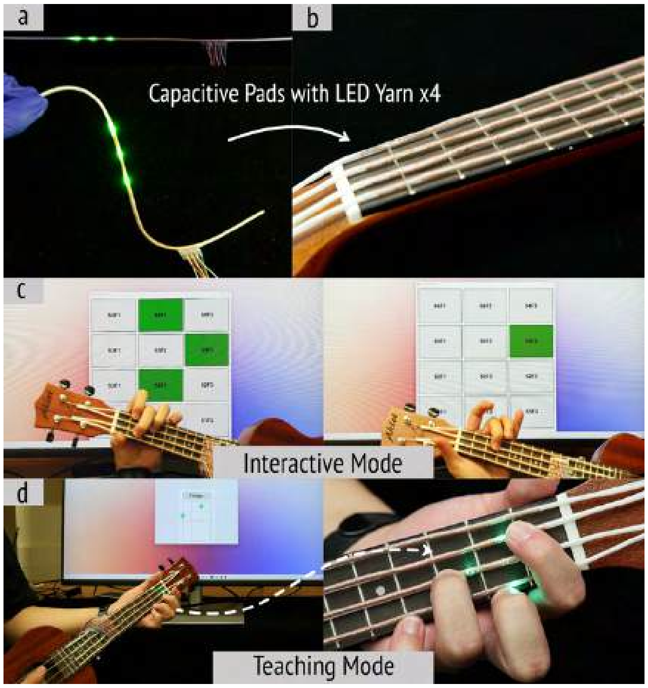


Figure 13: Interactive ukulele for learning finger positions and customized performing. (a) Electronic yarn string with integrated LEDs and capacitive sensing pads. (b) Integration of four electronic yarns into a ukulele, replacing the traditional strings. (c) Interactive mode: as the user strums, the playing position will be detected and recorded, and displayed to the user. (d) Teaching mode: LEDs illuminate the correct finger positions to guide users in forming chords.

9.2 Computing Integration

Another critical challenge, but less frequently addressed in prior work for wearable electronics, is the wire connection. Inevitably, yarns with embedded sensors must interface with a microcontroller and a power source, and more electronic yarns mean more wire connections. At present, this typically requires external hardware such as a commercial Arduino and jumper wires, which not only complicates the textile integration process but also undermines the comfort and wearability of textile-based systems. One possible solution, as demonstrated in prior research [53], is to directly print the microcontroller in flat alongside the rest of the circuit and roll it up into a microcontroller-embedded electronic yarn. Power delivery also remains another issue. While embedding ultra-small micro-batteries within the yarn is one option, an alternative is to develop self-powered yarns by leveraging emerging techniques such as safe-to-body transmission or energy-efficient inductive coils to wirelessly charge our electronic yarn, like how we charge our mobile devices nowadays [46].

9.3 Expanding Functionality

We demonstrate that even with our current approach, a wide range of sensors can already be integrated (e.g., IMUs, temperature/humidity sensors). More importantly, the method we introduced is highly expandable and can be applied to most of the printed flexible electronic systems. Beyond the modules already discussed—such as microcontrollers, batteries, and energy-harvesting coils—future opportunities include integrating wireless communication units (e.g., Bluetooth) or medical sensing components (e.g., PPG modules), further expanding the range of electronic yarns deployable in everyday textiles. In addition to conventional component-based integration, our approach offers unique advantages over other PCB-manufacturing-based electronic yarn fabrication (e.g., FiberCircuits [14]) by leveraging componentless approaches. Functional materials can be vinyl-cut or printed directly onto planar substrates before rolling. For instance, vinyl-cut carbon sheets can form strain gauges [23], magnetic inks can provide actuation [60], and biodegradable conductive inks such as PEDOT:PSS or hydrogel-based substrates can yield fully sustainable yarns tailored for environmental or biomedical applications [26]. Collectively, these directions outline a rich roadmap for developing versatile, functional, and scalable electronic yarns for the next generation of smart textiles.

10 Conclusion

In this paper, we presented Circuit2Yarn, a fabrication framework that transforms planar circuits into flexible electronic yarns, combining the functional diversity of PCB components with the comfort and wearability of everyday textiles. Our approach enables yarns thinner than 1 mm that integrate a wide variety of sensing and other functionalities, while remaining robust under bending and stretching. Through four application examples—including a woven IMU display, multimodal hoodie drawstring, smart tea bag string, and interactive ukulele string—we demonstrated how Circuit2Yarn opens new possibilities for embedding rich, distributed electronics into everyday garments and objects, advancing the vision of scalable and wearable interactive textiles.

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