Biohybrid Devices: Prototyping Interactive Devices with Growable Materials

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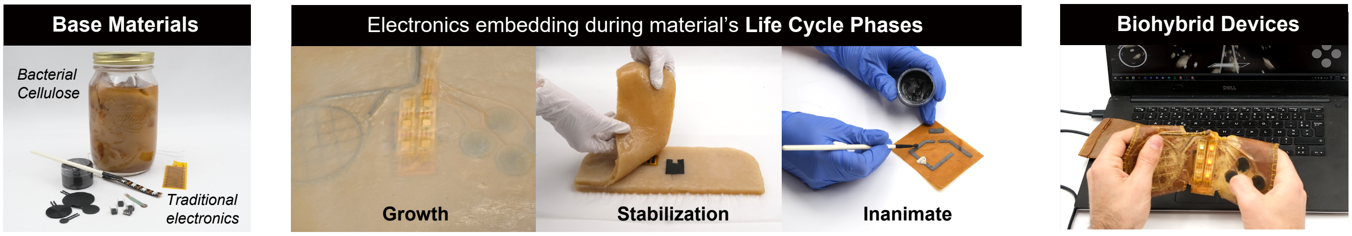

Figure 1: We combine Bacterial Cellulose with traditional electronics to create *Biohybrid Devices*. We identify three phases to embed electronics, based on the material's life cycle: Growth, Stabilization, and Inanimate. The embedding techniques allow to grow functional input and output devices.

ABSTRACT

Living bio-materials are increasingly used in HCI for fabricating objects by growing. However, how to integrate electronics to make these objects interactive still needs to be clarified. This paper presents an exploration of the fabrication design space of Biohybrid Interactive Devices, a class of interactive devices fabricated by merging electronic components and living organisms. From the exploration of this space using bacterial cellulose, we outline a fabrication framework centered on the biomaterials' life cycle phases. We introduce a set of novel fabrication techniques for embedding conductive elements, sensors, and output components through biological (e.g. bio-fabrication and bio-assembling) and digital processes. We demonstrate the combinatory aspect of the framework by realizing three tangible, wearable, and shape-changing interfaces. Finally, we discuss the sustainability of our approach, its limitations, and the implications for bio-hybrid systems in HCI.

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1 INTRODUCTION

The HCI community has pivoted towards making use of the natural growth or reproduction processes of living organisms for fabrication. As an emergent and promising material practice, Growing Design [15] employs fermentation, biomineralization or cellular division as a form of bio-fabrication. Growing materials is a compelling, novel addition to the fabrication of DIY Materials [7], allowing designers to engage with the material at different steps

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of the growth cycle. In contrast to bioplastics obtained from processed plant or animal parts, "growing" fabrication involves living organisms such as bacteria, fungi, or plants. *Growing* as fabrication process opens up a unique space of opportunities where makers can leverage, for instance, the material's ability to self-reproduce and compost to boost sustainability [10] or make use of bioassembly to create seamless connections. Yet, the integration of interactive elements (e.g., electronics) during the growth process to enhance interactivity remains under-explored.

We envision *Biohybrid Devices* as interactive devices that integrate conventional electronic components with bio-based materials produced by living organisms. Our primary research question is to investigate how such Biohybrid Devices can be created with Bacterial Cellulose (BC). BC is a bio-based polymeric material that is produced through fermentation by a Symbiotic Culture of Bacteria and Yeast (SCOBY) – most commonly found in the home production of Kombucha tea. It has a set of desirable properties that make it particularly well-suited: fabricating with BC is accessible and can produce objects of high durability, versatility, and mechanical flexibility.

So far, Bacterial Cellulose has mainly been used to fabricate passive objects [47, 63, 66]. Only very few works exemplified how the material can be blended with electronics to create interactive artifacts [10, 57]. This is highly challenging, as the growth medium required by a living SCOBY is acidic and moist, which tends to corrode electronic components. In consequence, fabrication techniques and materials for Biohybrid Devices using BC need to be carefully attuned to the needs of the involved living organism. To the best of our knowledge, no systematic exploration of the design space encompassing the integration of BC with electronics and conductive materials has been presented to date. In consequence, designers and makers are forced to revert to "trial-and-error" when attempting to integrate electronics with BC.

With this work, we contribute a framework for fabricating Biohybrid Devices by combining conventional electronics with biofabrication through a living material. The framework identifies three distinct phases of the material's life cycle to support designers and makers in leveraging the growth process of BC to embed electronics. For each life cycle phase, we contribute novel fabrication techniques for embedding conductive elements, sensors, and output components through bio-fabrication, bio-assembling and assembling. During the **Growth** phase, bioassembly enables the seamless integration of electronics where the organic material "grows around" and encapsulates each component. We contribute insights on material and chemical compatibility. The **Stabilization** phase enables a range of additive fabrication techniques that we carefully adapted to leverage BC's unique characteristics. We contribute wet layering, delamination, and imbuing with conductive particles as novel, BC-specific fabrication techniques along with insights on mechanical properties and conductivity. In the **Inanimate** phase, subtractive fabrication techniques become available. We provide insights on laser cutting, carbonization, engraving, and folding and contribute a novel technique for creating BC-based PCBs by filling laser engraved traces with graphite-doped conductive paste. The fabrication techniques have been designed to be accessible to a wide audience of makers, designers and electronics enthusiasts. They can be used in a DIY environment (e.g., fablab), with only simple tooling and commercially available materials required.

To validate this framework and demonstrate the significance of the proposed fabrication techniques for HCI, we demonstrate a set of fully functional Biohybrid Devices that showcase different inputs and outputs, including flexible deformation sensors, planar and curved multi-touch sensors, ambient humidity sensors, visual displays and mechanical actuators. We finally discuss the sustainability of our proposed approach, its limitations, and the implications for bio-hybrid systems in HCI.

In summary, this work contributes:

- a framework supporting the fabrication of Biohybrid Devices by leveraging the life-cycle of BC as a living material,
- a set of novel fabrication techniques for embedding conductive elements, sensors, and output components through bio-fabrication and bio-assembly that are attuned to the unique characteristics of BC in each phase of the life-cycle,
- insights on material characteristics, compatibility and performance based on comprehensive technical experiments, and
- a set of example applications showcasing the design opportunities for input and output-capable Biohybrid Devices for tangible, wearable and shape-changing interfaces.

2 BACKGROUND & RELATED WORK

2.1 From Sustainable Prototyping towards Growing Devices

While existing encapsulation fabrication techniques rely on additive manufacturing or silicone/epoxy encapsulation [52], biological-technological hybrids take advantage of the biological functions of a living entity [49] or its properties [42] to create functional interactive devices that expand the interaction design space and promote sustainability.

Researchers developing interactive devices tackle notions of environmental sustainability [8, 51] and sustainable prototyping [77]. The use of materials that are both bio-based and bio-degradable, allows implementing a sustainable prototyping life cycle by replacing petroleum-based materials (3D printing, PCB manufacturing) and metal and alloy-based materials. They also aim for environmentally harmless end-of-life of prototypes [6, 45]. The DIY BIO Community [21] gathers research labs, community science labs, hacker labs and amateur biologists who engage in biological research to create accessible innovation [4, 5, 12], biohacking [54] or bioart [23] outside of traditional lab setting.

A fully sustainable interactive prototype is yet challenging to create, although attempts have been made to explore new materials as base substrates, and fabrication processes that avoid the production of new materials via material re-use [24, 43, 80] or upcycle [17, 20, 41]. Among the new materials, several alternatives show potential for DIY fabrication. Alginate has been successfully used to create interactive devices substrates [42, 44] or combined with clay to create a new manually deformable prototyping substrate [11]. Gelatin has also been explored for the fabrication of hydrogels in soft robotic skins [34]. While those two methods involve pre-processed raw materials and require cooking, some bio-based materials can be grown from basic nutriments.

Growing Design and growable objects is an emerging interdisciplinary material practice that consists in replacing synthetic materials and classical fabrication processes with products from biological processes. An increasing number of designers explore growable materials for product design in DIY setups. This practice has been used to grow sheets of materials [47], objects [19, 22], or complex structures [82]. Going beyond small scale, the production of Growable Bio-Materials is already reaching industrial scales [22, 60].

Transforming these materials into objects, however, requires a change of mindset and design process [16]. Karana et al. [39] introduce Material Driven Design (MDD), a framework that places materials as the motor of the design process and empowers designers to easily "design experiences with and for a material" [40, 58].

Two growing prototyping materials have been particularly explored in the context of digital fabrication: mycelium and bacterial cellulose. Mycelium-based materials have been used as prototyping enclosures, breadboards and to enclose other passive prototype elements [29, 45, 75, 76, 81]. However, while mycelium allows to create 3D structures, the fabrication process is based on molding and the robustness of the forms created depends on the other materials composing the substrate, the mycelium acting only as a catalyzer. Dried Bacterial cellulose (BC) is close to leather, and its chemical, mechanical and physical properties uphold higher opportunities for HCI. Advances in Material Science have shown that the use of BC as substrate is relevant for wearable health applications such as heart rate monitoring and temperature sensing [86], biomimetic actuators for soft robotics [35], and more [37].

2.2 Bio-based Electronics Sensors and Circuits

Several materials and fabrication techniques have been proposed in Material Science to create bio-based electronic sensors and circuits.

Conductive metals have been used to create circuits. On top of bio-based substrates, gold coatings [50] ensure a high conductivity while carbon-based coating allows for pseudo piezoresisitive effect. Within the material, silver nanowires can be mixed with alginate [48] to create on-skin sensors or magnesium with Gelatin to create sensors in soft robotics [30]. These metallic alloys are often not suitable for creating circuits in DIY context.

Carbon-based conductors (Carbon Black, Activated charcoal, graphite) have the advantage of being bio-degradable and can also be mixed with other bio-based elements (wax [83], cellulose [36] or alginate [42]). The carbon material formulations can be done in a DIY setup, creating materials with a conductivity ranging from approx. 34 $\Omega/\square$ for conductive alginate sheets to >1.8M $\Omega/\square$ for gelatin conductive sheets. Thus Carbon is a good candidate to create capacitive or resistive, flexible and stretchable circuits.

2.3 Bio-based Electronic Fabrication

Several fabrication processes have been presented to implement bio-based electronics. Solution-based processing techniques, inkjet printing of conductive ink [28] or electroless plating [86] are precise methods that allow to create complex circuits or sensors in 2D. Fused deposition modeling printers have been used to print conductive gelatin hydrogels [34]. These approaches require a high degree of expertise and specific equipment to democratize these methods in DIY prototyping are very limited. Hand painting, drawing [9] or stencil [42] layering of metal-based or carbon-based pastes are suitable to create conductive traces or sensors. ReClaym [11] takes a manual approach, where the graphite-based clay is manually formed to create a capacitive touch sensor.

Preliminary attempt on mixing bacterial cellulose with of-the-shelve electronics [10, 53, 57] demonstrate early stages of integrating electronics within the BC film. However, these methods do not exploit the potentialities of biofilms such as growing or functionalizing the material - not just an insulating film.

Existing works demonstrate an increasing interest in using biomaterials combined with electronics. Only recent works cover the entanglement of electronics within Growing materials, and the possibilities for HCI and fabrication stages need to be clarified to accrue maximum benefit.

2.4 Understanding Bacterial Cellulose (BC)

While prototyping interactive devices with Bacterial Cellulose (BC) in a DIY setup does not require advanced knowledge in biology or chemistry, understanding the material is required to grasp the origin of its properties as functionalities.

The BC biofilm is created by a cascade of sugar-based metabolic processes that occur during the fermentation of Kombucha tea (called Growing Medium- GM), in which a symbiotic culture of bacteria and yeast (SCOBY) is inserted via a piece of BC biofilm from another culture, commonly called *mother SCOBY*. Kombucha and SCOBY's microbiological composition varies according to the strain's origin, substrates, and production conditions. The main biological processes involved here [18, 79] are led by the yeasts, that hydrolyze sucrose into glucose and fructose, and the Gluconoacetobacter Xylinus family bacteria that synthesize glucose and fructose into cellulose. As Gluconoacetobacter requires oxygen for its growth and activity the cellulose is produced using aerobic method. During these processes, the pH of the medium drops gradually from 5.0 down to 2.3 after 15 days of fermentation becoming corrosive and/or oxidant for metallic materials, including the recipient, etc. The biofilm can be extracted from the growing medium and can either be inserted as SCOBY in another culture, therefore, allowing indefinite multiplication of the material, or be cleaned and stabilized (i.e. the culture is killed by sterilization and/or drying).

Overall this material is easy to reproduce in a DIY setup and once dried provides a substrate robust enough for various uses.

3 FABRICATION FRAMEWORK

We propose the term *Biohybrid Devices* to describe the use of bio-assembling and digital fabrication to create interactive devices composed from bio-fabricated ingredients and conventional electronic components (e.g. conductive materials and off-the-shelf electronics). In this section, we present a conceptual framework supporting the fabrication of Biohybrid Devices. It proposes to conceptually structure this novel space following three life-cycle phases of living materials during which the designer can intervene. This framework forms the conceptual basis for the fabrication techniques that we will present further below.

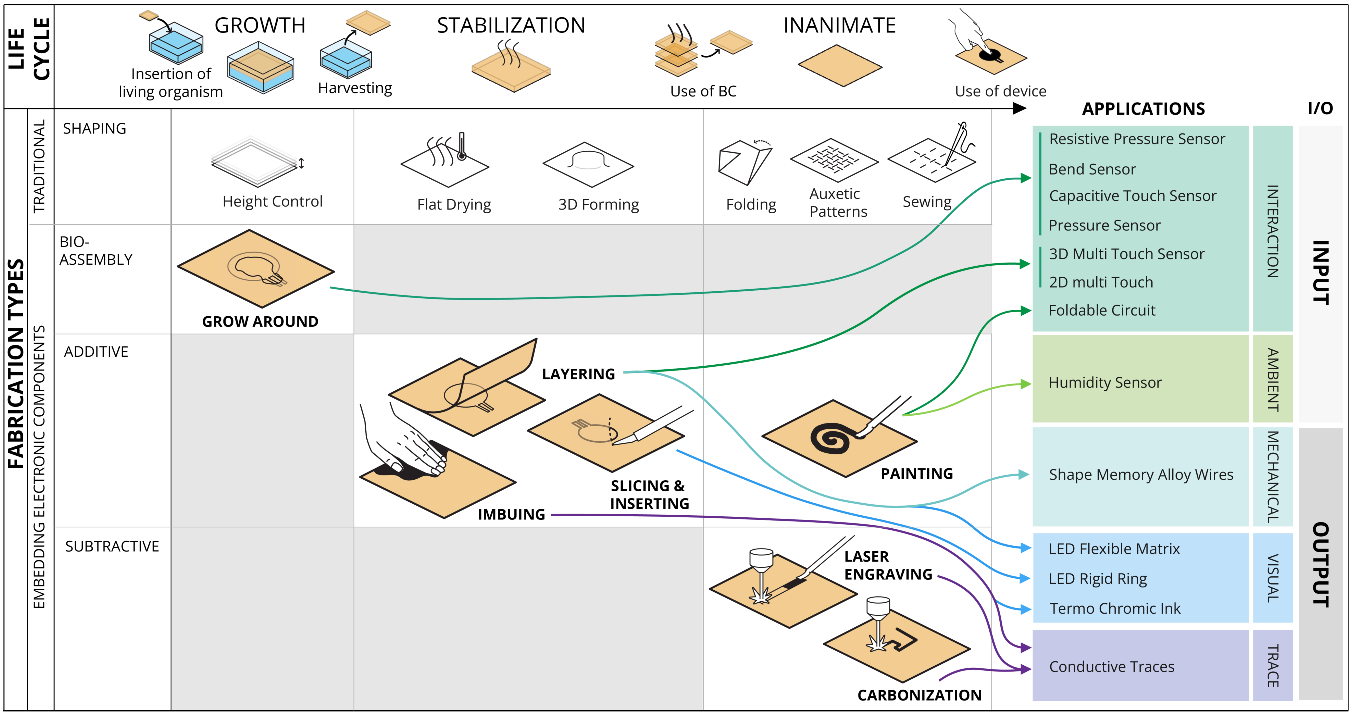


Figure 2: Design Space of Biohybrid Devices, organized by life cycle phases and fabrication types. In pink, the three phases (Growth, Stabilization, Inanimate) of the material life cycle from Bacterial Cellulose. In brown are the techniques introduced to embed electronics (*Grow Around* , *Layering* , *Imbuing* , *Slicing & Inserting* , *Laser Engraving & Filling* , *Carbonization*). In black and white are the traditional techniques for transforming the material that are compatible with BC. We linked our 13 application samples to show how they relate to the technique.

3.1 Methodology

Intervening in collaboration with a growing process presents a shift in our understanding of the traditional fabrication process and requires an exploratory design methodology [59]. We focus our exploration on the opportunities that can arise from collaboration with non-DNA-altered living organisms. We base our approach on Value Sensitive Design and Post-Antropocenic Design [13, 27] whose shared goal is to iteratively integrate ethical and environmental considerations into the design process based on a tripartite methodology comprised of conceptual, empirical, and technical investigations. Therefore, we relied on a mix of functional interactive design, based on cross-referencing the interdisciplinary literature review, and hands-on experimentation, to gather knowledge on the material properties and opportunities.

During 12 months (3 months of exploration, 6 of building techniques and 3 of production) we iterated between phases of fabrication, crafting and discussion about the results. These sprints were performed with the authors of the papers during workshop sessions. The rhythm was dictated by the growth of the bacterial cellulose cultures. It followed a cycle of 1 day of ideation and culture, a 7-14 days waiting time during growth and 3-7 days of prototyping, analysis and discussion. In total, we have grown a total of over 170 cultures. We ideated on the possible functionalities, and interactive possibilities and designed a series of prototypes that guided the creation of a conceptual design space. The design space was derived progressively as a framework to reflect and make sense of the diversity of potential fabrication techniques with growing material and in particular BC. The design space stabilized after 5 versions when it provided us with a framework to reflect on the explored and underexplored spaces of the fabrication process which we illustrate through three main case studies.

This alternation created knowledge by combining systematic research and intuition derived from physical prototyping, during the creation of functional biohybrid devices with BC. Our research process is thus in line with the *research through design* (RtD) and *research for design* (RfT) criteria from [31, 88]: our approach is inventive (no previous exploration), relevant (three case study demonstrate it), extensible (the design space provides a first framework) and rigorous (all our RtD is documented). The knowledge gained in this RtD is threefold: 1) defining a novel fabrication approach by merging electronic components and living organisms. 2) formalizing the first design space, 3) presenting new fabrication techniques relative to this approach. All three provide building blocks for future HCI researchers towards more sustainable devices.

3.2 Fabrication Framework of Biohybrid Devices

Designing biohybrid devices requires taking into consideration the full life cycle of the material. With traditional prototyping materials, the fabrication process is dictated by the desired design and mechanical properties of the artifact. Going back and forth between different processes at various stages of prototyping is possible. In contrast, with living entities, there is only one timeline possible for a culture. Hence the material life cycle has a direct impact on the design possibilities. Despite these restrictions, this timeline offers multiple opportunities. We observed and identified three different phases, during each of which the designer can intervene: 1) **Growth**, 2) **Stabilization**, 3) **Inanimate**. Each of these phases offers multiple opportunities for fabrication techniques to embed electronics and make interactive device prototyping.

Growth The growing phase of a biomaterial is a time period in which, through biofabrication and bioassembling, the living entities consume the raw nutrients present in their Growing Medium (GM), multiply, evolve and create macro-scale structures. In section 4 we describe one technique (*Grow Around*), that allows to enclose electronic components in BC during the growing process.

Stabilization Once the growing material reaches the desired finished aspect (thickness, shape, color etc.), it can be harvested and stabilized. During this phase, the living organisms are eliminated and different treatments can be applied to change the aspect (dyeing, texturing, shaping), modify the mechanical properties or to extend the material’s lifespan (waterproofing). We identify three techniques during Stabilization to embed electronic components in BC (*Layering*, *Imbuing*, *Slicing & Inserting*) describe in section 5.

Inanimate The inanimate phase starts when the living entities involved in the growth of the material are dead and therefore the material can be considered as biologically stable. At this stage, the material is considered a fabrication substrate. In this phase, we identify one additive technique (*Painting*) and two subtractive techniques (*Laser Engraving & Filling*, *Carbonization*) that allow to create conductive circuits on BC and described in section section 6.

Despite the unidirectional timeline of a culture, life-cycle loops can be performed between different cultures, i.e., an inanimate biofilm can be reinserted in the growing phase or the stabilization phase of another culture, enlarging fabrication opportunities.

We constructed a design space (Figure 2) of Biohybrid Devices. This design space is defined around two dimensions: the life-cycle of the material (horizontal axis) and the type of fabrication: Bio Assembly, Additive, Subtractive, and Shaping (vertical axis).

This design space provides a structure to conceptually relate and situate the seven fabrication techniques we identify. These techniques allow to 1) grow bacterial cellulose around electronic components (*Grow Around*), 2) insert electronic components inside bacterial cellulose (*Layering*, *Slicing & Inserting*, *Imbuing*), 3) engrave (*Laser Engraving & Filling*, *Carbonization*) or paint (*Painting*) electronic circuits on top of bacterial cellulose. To explore the space, we inserted a variety of Input and Output electronic components (listed on top of the shades of green to purple in Figure 2). These include a variety of inputs (Capacitive sensor, Bend Sensor, Pressure Sensor, Multitouch Sensor, and Temperature sensor) and outputs (Shape Memory Alloy, LED, LED Matrix and Termo Chromic Ink).

3.3 Opportunities for HCI

The living and biological aspect of BC complements established additive and subtractive fabrication techniques with new opportunities.

New prototyping materials suitable for soft interactive device fabrication have emerged recently (e.g. tattoo paper, metalized textiles or synthetic polymers). However, despite their outstanding performance, most of them are challenging to recycle or bio-degrade. In contrast, BC is infinitely renewable and biodegradable, therefore it is a sustainable alternative material for prototyping with similar mechanical properties.

Compared to other biomaterials explored in HCI such as bioplastics and mycelium, BC offers a range of benefits. BC has a longer lifespan and higher stability over time than bioplastics, which are often sensitive to heat, moisture and air quality [9, 42]. In contrast to mycelium [29, 75, 76, 81], BC does not require a substrate (such as grains, fibers, etc.) and thus can produce more flexible (e.g., bendable, soft and thin) and manufacturable (e.g., sewable) results. BC is also highly accessible because it is easy to obtain, non-toxic and safe to work in simple DIY environments (e.g., a kitchen). Lastly, due to its natural defense, BC is less prone to contamination than mycelium or bioplastics (during growth or drying). Therefore it’s easier to deploy as it doesn’t require complex set-ups.

While past works embed electronics in BC during the stabilization, this exploration emphasizes how the embedding can be performed at several life stages and highlights how natural processes such as bio-assembling, used in the “Grow Around” technique, can allow embedding of electronics without creating an assembly of layers and with fewer assembling steps. Scaling up the process for large surfaces only requires additional space, without significant extra effort from the designer. Our work contributes therefore novel techniques for designing at multiple lifecycle stages and scales.

The design space illustrated through Figure Figure 2 synthesizes all the traditional and embedding techniques, classifies them in four types (shaping, bio-assembling, additive, subtractive) and organizes them based on the life-cycle phase where they can be performed. The life-cycle order illustrated through the mono-directional arrow and the gray sections remind the designer of the order in which these fabrication techniques can be performed. For each embedding technique, we provide concrete application samples for input and output ranging from interaction to ambient sensing, mechanical shape-change, visual display and conductive traces creation.

In the following three main sections, we explore each life-cycle phase and present fabrication techniques that can be used separately or used as building blocks and combined to achieve more complex biohybrid devices. In the remainder of this section, we illustrate how these techniques can be used and combined to prototype interactive devices for tangible, wearable and shape-changing interfaces.

3.4 Application 1: Shoulder responsive accessory

Inspired by prior works on e-textiles and shape-changing interfaces [3, 85], we built a physiological-responsive shoulder accessory that changes its shape through electromechanical actuation to display biological signals (e.g. stress) the wearer expresses in social contexts. The shoulder accessory demonstrates how BC is

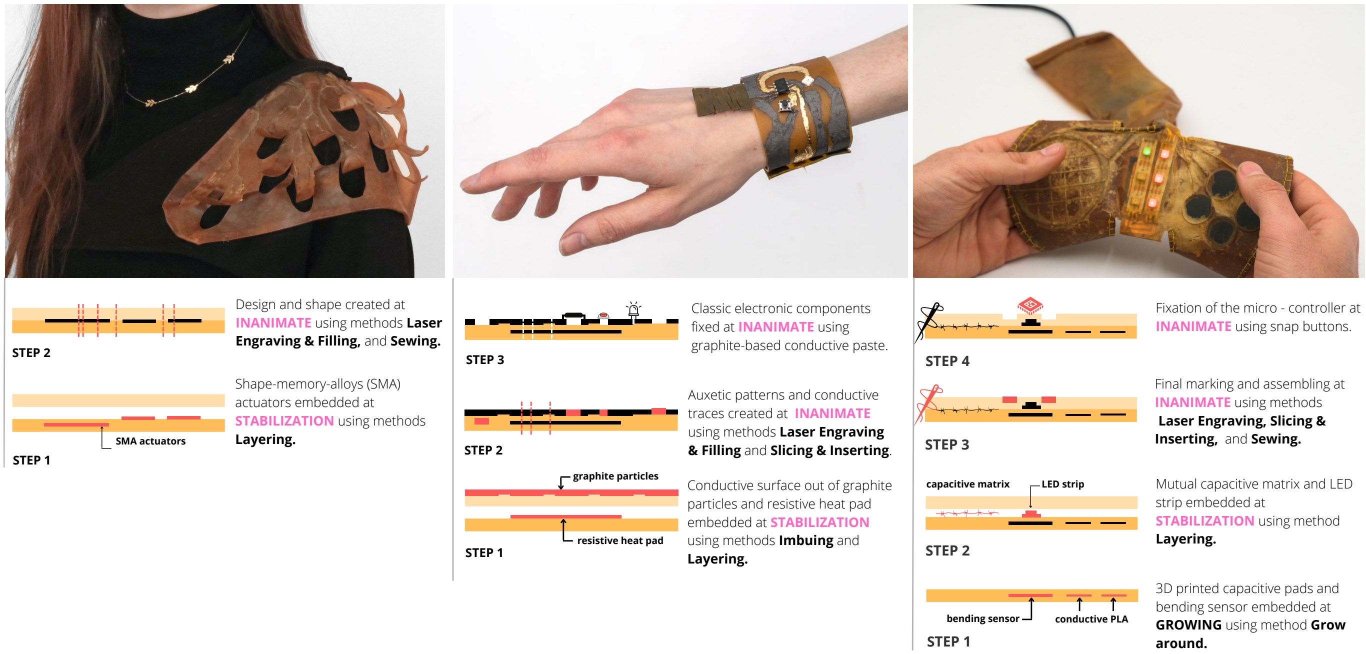


Figure 3: Example applications fabricated with our techniques: a shape-changing wearable accessory (left), a wearable interactive bracelet (center), and a deformable game controller (right). The fabrication steps and used techniques are visually summarized. Please refer to sections 4–6 for a detailed description of the fabrication techniques. ©Madalina Nicolae & Vivien Roussel

strong yet flexible, allowing seamless embedding of actuators at the drying stage. The overview of the fabrication steps and techniques we have combined in its fabrication is shown on Figure 3 left.

The device features 12 shape memory alloy actuators (SMA Flexinol Muscle Wire 0.01") that are triggered based on readings of a galvanic-skin-response (GSR) sensor through an Arduino Leonardo. When the wearer experiences a high level of anxiety or stress, 12 tiles of BC actuated by SMA rise, thus changing the accessory's shape to display the wearer's discomfort state. The SMA wires are encapsulated during drying between two biofilms used as support, then the shapes are cut as the designer wishes.

3.5 Application 2: Wearable Bracelet

Inspired by LASEC [32] and Silicone Devices [52] fabrication techniques, we built an interactive bracelet that changes its visual appearance (color) by sensing an auxetic strip stretch. The bracelet demonstrates input-output and user interaction and can be considered as a sustainable alternative of these work's applications. It aligns with existing work on soft wearable devices [46] and demonstrates how it can replicate interactive sustainable accessories [10, 53, 76]. The prototype is shown in Figure 3 center. This device consists of a mix of electronic components, conductive BC, conductive textile, heating materials, heat-reactive particles and auxetic patterns. When the user pulls on the auxetic patterned sensor, the LED displays the stretch force and the bracelet tightens accordingly the region B. A push-button is used to release the bracelet. We used an Attiny85 as Microcontroller, a NeoPixel LED and a SMA wire embedded in the BC film. The fabrication relies on a BC biofilm covered in conductive particles as base support. Electronics placed during growth to ensure higher mechanical stability while surface electronic components can be easily replaced.

3.6 Application 3: Game controller

Our third application is a two-handed flexible game controller, representative of the widely investigated class of tangible interfaces. The controller takes inspiration from alternative DIY controllers [69]. It demonstrates the embedding of advanced input sensors and illustrates how fabrication techniques from all 3 life cycle phases can be combined. The user can fit both hands in the side pockets of the controller, similar to mitten gloves. The device can be used to control a game interface, the left multi-touch matrix is used as a joystick to control the direction of the movement, the bending sensor to control the acceleration, and the right capacitive buttons to trigger actions.

This interface associates electrical components embedding with artisanal fabrication techniques (sewing). The Arduino Nano controller is connected to a Mutual Capacitance controller [71] on the left side. Its matrix is made of embedded conductive yarn. The capacitive buttons are made of 3D-printed conductive PLA pads. Three LEDS display the state of the interface while three others display device status-related information.

To create this device, the BC biofilm has been grown to serve both as plastic encasing equivalent and electronic support. It has been grown over-sized on a flat surface and shaped using traditional craft (cutting, sewing) once dried.

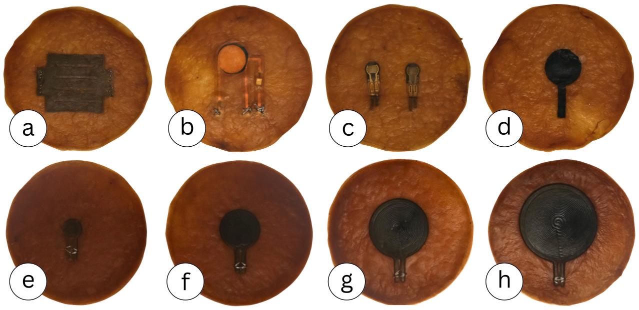


Figure 4: Passive inputs embedded by bioassembling: a) textile-based stretch sensor, b) DIY piezo-resistive pressure sensor with LED visual output, c) off-the-shelf pressure sensors, d) carbon black-doped wax touchpad and e-h) conductive PLA touchpads (⌀5mm, ⌀15mm, ⌀30mm, ⌀50mm). ©Madalina Nicolae & Vivien Roussel

4 GROWING PHASE

The growing phase of the BC fosters all the biological processes leading to the creation of the biofilm, i.e., biofabrication and bioassembling. This section presents how these processes can be leveraged to seamlessly encase electronic components within a single layer of BC biofilm. We start by reviewing key properties of traditional BC material growth, before detailing on the fabrication technique for embedding electronics.

4.1 Traditional DIY Material growth

The growing phase of Bacterial Cellulose (BC) starts a few hours after the inoculation phase. First, the cellulose fibrils are assembled in the growing medium at a microscopic scale until the surface is covered with a macroscopic translucent thin layer of BC with a gel consistency. Bacterias on the medium-air interface keep producing and assembling homogeneously fibrils of cellulose at the surface. As a result, the film becomes off-white, opaque and thicker. The growing process takes between 7 and 20 days, the peak production of BC being reached after 18 days [2].

The GM is prepared based on previous literature [2] using an optimized formulation and off-the-shelf available products (Tea: English Breakfast Carrefour, Sugar: Brown Sugar Blonvilliers, Vinegar: Organic Carrefour Bio). For 1L of GM we infuse 3g of tea in 0.8L of boiling water for 20min. After removing the tea, 100g of brown sugar are added and stirred until complete dissolution. The mix is let to cool to about 30°C, then 100g of white vinegar and 100g of grounded mother SCOBY are added. For our exploration, we selected three strains are acquired from different sources and considered the growth speed and homogeneity of the biofilm as the main selection criteria. We used the same mother (and siblings) for all our cultures. Rectangular, transparent polycarbonate gastronomic recipients with surfaces between 429,3 cm^2 (GN1/4) and 1722,5 cm^2 (GN1/1) and a depth of 6.5cm are used as culture containers to have a clear sight of the cultures while ensuring compatibility with their acidity. To eliminate the risk of contamination while allowing air exchange, the containers are covered with cling film in which we cut several perforations covered with microporous tape. During growth, the cultures are placed in a indoor culture tent at a temperature controlled between 24 and 25°C .

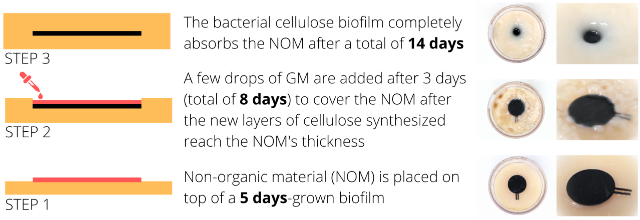
4.2 Techniques for Embedding Electronics

Grow Around. This technique consists of placing active components (non-organic materials (NOM)) on top of the growing material and let them be "absorbed". This technique takes advantage of the bio-assembling of the growing phase to embed electronics. Compared to additive manufacturing, this technique allows embedding without creating assemblies, the electronics being embedded within the material itself (i.e. the BC is not a carrier substrate). We insert the NOM after the biofilm becomes opaque (i.e. approx 5 days) and continue the culture for another 10 days. As it grows, new layers form first around the NOM and then above, thus naturally embedding it in the BC biofilm over time. To facilitate the embedding, when the layers formed around the NOM reach its thickness, a few drops of growing medium from the current culture are collected with a syringe beneath the biofilm and placed on top of the NOM. This allows to create a "bridge" and fastens the growth of cover layers. The amount of growth medium required is proportional to the surface that needs to be covered (e.g. < 5 ml in all following examples.

We use this technique to build a set of five prototypes presented in Figure 4 a - e. They measure an average diameter of 8cm and feature conductive materials or sensors with an average thickness<1.5mm. Using an Arduino Uno board, we measure their characteristics at approx. 20°C with approx. 40% humidity.

Deformation Sensor. We built this sensor using a 30*30mm piece of conductive textile (EeonTex COM-14112) connected through 30mm two parallel electrode wires sewn on the sides. The sensor has a resistivity of 590kΩ that varies between avg. 1.03MΩ and 1.62MΩ when bent parallel to the electrodes with an SNR of 66.0dB.

DIY Pressure Sensor. The sensor is fabricated using a pressure-sensitive material (Velostat) and two copper electrodes enclosed in Polyimide film. An LED is added to visualize the pressure. The connections to the board are realized via sewn snap buttons. With a thickness <0.5mm we can measure a change of resistance in the range 0.6KΩ to 2.2KΩ with an SNR of 54.1dB.



The bacterial cellulose biofilm completely absorbs the NOM after a total of **14 days**

A few drops of GM are added after 3 days (total of **8 days**) to cover the NOM after the new layers of cellulose synthesized reach the NOM's thickness

Non-organic material (NOM) is placed on top of a **5 days**-grown biofilm

Figure 5: Non-organic materials (NOM) can be embedded in 3 steps by taking advantage of bioassembling. We illustrate this here with a large conductive pad (⌀3cm) that was 3D-printed using Protopasta carbon-based conductive PLA filament. ©Madalina Nicolae & Vivien Roussel

Pressure Sensor. The electronics feature a commercially-available FSR sensor with a sensitivity range of 20g to 2kg connected to the board via simple soldering. With a thickness of 0.4mm we can measure a change of resistance in the range of 0.9KΩ to 15.4KΩ with and SNR of 73.5dB.

3D printed Capacitive Touch Sensor. We embedded a ⌀15mm circular pad (1mm thickness) 3D printed using ProtoPasta Electrically Conductive Composite PLA to offer touch sensing within the material. As the pads are rather rigid, this can be used for touch sensing without additional support as used in the game controller. The SNR value was calculated at 42.7dB.

Deformable Capacitive Touch Sensor. The sensor uses as active area a ⌀18mm circular pad made out of a carbon black-doped beeswax sheet containing 10% Vulcan XC 72R Carbon Black. While PLA is quite stiff, the carbon-doped wax can be slightly deformed and therefore has a smaller impact on the flexibility of the sensor. We obtained SNR of 44.8dB.

This technique limits the risk of damaging the electronic components by the acidity of the GM, as the components are not submerged for long periods of time. Also, as it is not necessary to manually interfere with the biofilm (e.g. as opposed to *Slicing & Inserting*), we limit the risk of contamination with other bacteria or fungi.

4.3 Additional Findings

Material Compatibility. Not all non-organic materials are compatible for embedding during the growing phase. Some materials may alter the synthesis of biofabricated ingredients or the bio-assembling, kill the culture or, on the contrary, be damaged (e.g. through oxidation, corrosion etc.) by the growth conditions. Therefore, we tested the compatibility of 8 frequently used conductive materials used in prototyping. The results are summarized in Table 1. While Figure 4 presents the compatible and successful test results, Figure 6 illustrates the failed tests. The the GM's acidity (measured PH at approx. 5.5 at inoculation and under 3.5 for most cultures after 7 days) oxidizes copper within a few hours. The toxic molecules released by the tin welding wire induce a color change noticeable after approx. 3 days and the culture stops growing. The antimicrobial properties of silver kill the culture, a 2mm groove being noticeable after approx. 3 days appears below and around the silver coated fibers.

Size of embedded NOM. During this phase, we observed that the size of the embedded material has a substantial influence: the larger the surface is, the more difficult is for the bacteria to cover it. We successfully tested the *Grow Around* technique on circular pads with diameters of ⌀5mm, ⌀15mm, ⌀30mm and ⌀50mm (Fig. 4 e - h).

5 STABILIZATION PHASE

Once the BC film has reached the desired finished aspect during the growing phase (thickness, color, shape), the BC biofilm needs to be stabilized. In this case, the bacterial growing process needs to be terminated. The main process used for the stabilization of BC biofilm is water evaporation. BC contains a high content of liquid when removed from the medium. We exploit this phenomenon to stick together different layers of BC, and thus encase between the BC layers electronic components, or to imbue different particles between the cellulose fibers of outer layers to coat BC biofilm with functional particles.

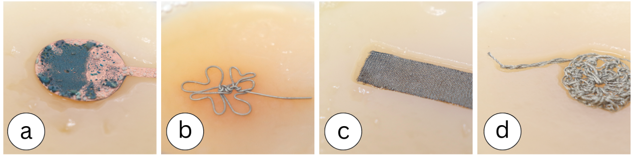


Figure 6: Copper, tin and silver are not compatible, resulting in a) oxidation on copper, and culture death under and around the non-organic materials for b) welding tin wire, c) silver wire with anti-oxidant treatment S2103FX-100G and d) Adafruit knit silver conductive fabric 1167. ©Madalina Nicolae & Vivien Roussel

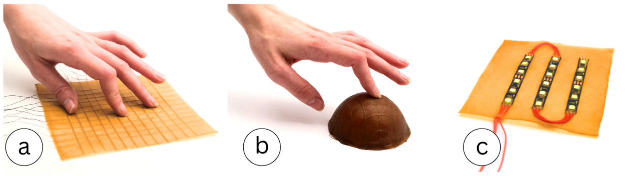


Figure 7: Multi-touch organic surface out of BC (a) planar and (b) hemispheric, and (c) visualization surface using flexible Neopixel matrix. ©Madalina Nicolae & Vivien Roussel

5.1 Traditional DIY Material drying

The drying process has an impact on the mechanical structure (e.g. porosity, water absorption capacity) of the BC film. Room drying and hot pressing are proven to be the most suitable to conserve both BC's tensile strength and Young modulus, followed by hot air drying that only conserves the Young modulus [84, 87]. Hot-pressing reduces the drying time to a few hours compared to 5 to 15 days for room drying, but it involves heavy and expensive machines and can damage components embedded in the BC. To foster accessibility while ensuring an even and controlled drying, we focus on room drying and air-hot drying methods. Therefore, we build a box enclosure that features a ventilator and filters (HEPA and carbon), to stack and room dry several BC films simultaneously. The enclosure has a temperature that varies between 19 and 23°C and a constant airflow which allows to dry a BC film between 3 to 7 days while limiting the risk of contamination. For air-hot drying, we use a kitchen-grade convective oven (Sage Smart Oven™ Pro) at 80°C that allows to dry the biofilms within 4h for thin films and 12h for thick films.

We harvest the biofilms when they reach 3–6 mm thickness (8–10 days growth) to develop prototypes that need thin films, and 7–10mm (10–15 days) for thicker films. Each biofilm is first placed in a bath of water and dish soap for 3 to 4 hours, then washed and rinsed to be cleaned of residues. The films are dried

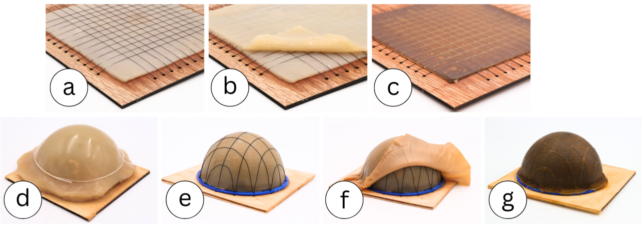


Figure 8: Embedding of DATASTRETCH 1468-SI Elastic conductive yarn in planar (top) and non-planar (bottom) geometries. Top: (a) first layer and conductive yarn, (b) final assembly before drying and (c) after drying. Bottom : (d) first layer before partial drying, (e) first layer partialy dried and conductive yarn, (f) final assembly before dring and (g) after complete drying. ©Madalina Nicolae & Vivien Roussel

either on a plane surface (planar drying) or on a volumic object (forming). For planar drying, we place the cleaned biofilms on waterproof medium-density fibreboards (MDFs). They ensure an even drying and force the shrinking in the thickness direction. As high flexibility and elasticity are desired for this type of applications, room drying is recommended. When the BC is dried on a textured surface, fine topology or complex patterns can be obtained [53, 64, 78]. For forming 3D objects, an oversized BC film is layered on top of a volumic object (e.g. a 3D printed form) and hand shaped to fit its topology. Room drying is compatible, but air-hot drying is recommended as it allows to better preserve the volume of thick films. The films are hand-shaped regularly (every 1h for air-hot and every day for room drying) to eliminate all air bubbles that may appear between the BC film and the wooden board or the 3D object. Once dry, the edges are cleaned with a sharp blade.

5.2 Techniques for Embedding Electronics

While shrinkage and water evaporation are usually limitations of bio-materials, we take advantage of this natural phenomenon as it allows for different embedding techniques.

Layering is a technique that consists of positioning electronic components between two different biofilms of wet BC. This technique takes advantage of the stickiness of two biofilms and their binding during drying. In the case of planar applications, the embedding is done in three steps (Fig.8 a-c). First, a thin biofilm is fixed on a flat wooden surface, then the electronic components are placed at the desired position and a second biofilm is placed on top. Finally, the assembly undergoes planar room drying. For non-planar applications, the embedding is done in four steps (Fig.8 d-g). First, the biofilm is layered on a lubricated form and undergoes air-hot forming until the layer reduces its thickness by approx. 60% (still humid). Next, the conductive elements are placed into position and the second biofilm is placed on top and the assembly undergoes again air-hot forming until the assembly is dry.

We built three prototypes to explore this technique and demonstrate input and output capabilities.

Planar and hemispherical multi-touch sensor. Inspired by multi-touch touch interactive surfaces present in literature [71], we use this technique to create two multi-touch organic surfaces based on mutual capacitance sensing, one planar and one hemispheric (Fig. 7 a and b). Both matrices are created by embedding Datastretch 1468-SI Elastic conductive yarn between two biofilms using planar room-dring and forming.

LED Matrix. The embedding capabilities of bacterial cellulose can be used also used to stabilize the shape of electronic components. In this example, we use bacterial cellulose as structuring material to create a 3*6 visualization matrix out of a three-segment LED strip (Fig. 7 c).

Imbuing is another technique that consists of imbuing functional particles in the external layers of the BC by hand friction. This technique takes advantage of the stickiness of wet BC biofilms. Different particles such as carbon black, graphite, or thermochromic pigments are spread by hand on the biofilm until all surface is covered by a uniform layer (Fig. 9 a and b). Exposed to hand friction, the particles penetrate between the superficial cellulose fibers and remain trapped or stick to the surface after the biofilm is dried.

We test this method with three types of carbon particles to create large conductive surfaces: graphite[1], carbon black[2] and activated charcoal[3]. While the first two types provide positive results, activated charcoal does not stick to the biofilm, resulting in cracking and particles falling off the biofilm.

For each graphite and Carbon Black imbued biofilm, we create 3 samples of 80 mm long and 10 mm, 5 mm, 3 mm, and 2 mm width traces and measure their surface conductivity using an Arduino Uno: 2 times 10 measures separated by a 10 s delay for each sample. While Carbon Black does not seem to stick well to the BC substrate after drying, graphite shows a resistivity down to 1.48k Ω/□ and 414 Ω/□ for 5mm and respectively 10mm wide traces (Tab. 2).

Our results show that the smaller the conductive traces' width, the higher the standard deviation. As the traces are thin and no binding agent is used, small cracks significantly impact the conductivity. Therefore, the smallest trace width that we can create by *Imbuing* is 3mm wide.

Pocket slicing This technique consists of embedding electronics in the material by creating a cavity via angular slicing, and inserting electronic components before drying (Fig. 9 c and d). The size of the cavity depends on the film's thickness and the size of the blade. We consider this technique as a "retouch" technique that can be used complementary to *Grow Around* for small elements that were not included in the initial design. We use this technique to embed a 6.7mm thick ⌀44.5mm Adafruit Neopixel ring in a 10mm thick biofilm (Fig. 9 c and d). Air-hot drying method is used to finish the embedding.

5.3 Additional Findings

Compatibility of the drying process. The choice of drying process depends on the materials embedded, as not all of them can withstand the air-hot drying or hot press temperatures (e.g. polyester-coated wires or Velostat-based sensors).

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[1] Prographite Micro-graphite avg. particle size 10 micron
[2] Vulcan XC R Carbon Black
[3] Gewürzland

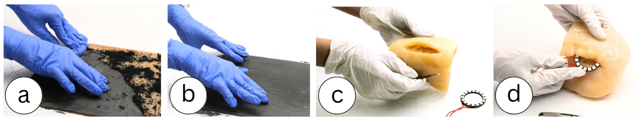

Figure 9: Creation of conductive surface via Imbuing: a) Spreading the particles by hand friction until b) the surface is completely covered. Insertion of electronic components via Pocket slicing by c) creating a cavity in the biofilm using a blade and d) sliding in. ©Madalina Nicolae & Vivien Roussel

Damages by types of embedded electronics. Depending on the type of electronics embedded, the BC film can be damaged during the stabilization or afterward. During the stabilization, if the assembly contains a large impermeable surface (i.e. flex sensor in the game controller or heating circuit in the bracelet) the lower biofilm gets damaged when air-hot dried, becoming bleached and brittle. Therefore we recommend and use room drying, and flip the assembly every day. If the assembly is compatible, air-hot drying can be used partially until the assembly is almost dry and later combined with room drying until completely dry. After the stabilization, the BC can be damaged during manipulation if the electronics comprise sharp edges/angles or if the embedded electronics contain heatable elements. To avoid long exposure to heat, we recommend and use intermittent signals to power applications such as the SMAs in the *Shoulder responsive accessory* or the heatable pad in the *Wearable Bracelet.*)

6 INANIMATE PHASE

When the BC film is stabilized, it becomes an inanimate traditional fabrication material. We use the inanimate BC biofilm as **substrate** to create conductive traces and surfaces.

6.1 Traditional DIY Material Processing

When dried and treated, BC biofilms look and feel similar to leather (also called "bacterial leather"). Attaching pieces together by gluing, sewing and patching are compatible with traditional practices imported from textile manufacturing [46]. Additionally, pleating and cutting auxetic patterns can be used to create volumic[53] or stretchable [65] artifacts via hand-cutting, laser cutting and laser engraving. Keeping in mind BC's water absorption ability, a waterproofing treatment [70] can be applied every year or 6 months to protect the material against ambient humidity and mold.

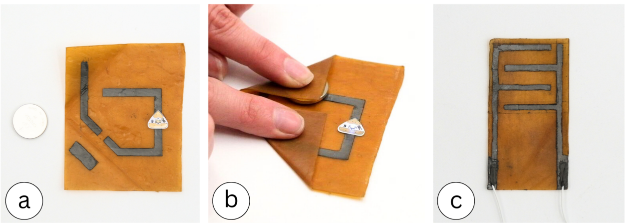

Figure 10: Folding circuit stencil-painted on BC substrate and ambient humidity sensor made of BC. ©Madalina Nicolae & Vivien Roussel

6.2 Techniques for Embedding Electronics

We present several techniques for creating conductive traces or attaching classic electronic components to inanimate BC biofilms:

Carbonization of the material consists of creating patterns through laser engraving and using the generated carbon as conductor. It has already been used on various organic materials, such as wood [38] or mycelium [45].

We use this method to create conductive traces on bacterial cellulose using a ARKETYPE Jade 1290 CO2 120W laser. To achieve carbonization, we use reduced lens air blow to keep the carbon particles on the surface. We tested the power/speed ratio first, by setting the speed to 100mm/s and variating the power from 12W to 20W and then by setting the power to 12W and variating the speed from 100mm/s to 10mm/s 11. Our power/speed ratio tests showed that speed is the main factor contributing to carbonization and conductive traces start appearing at 20mm/s and below. Using 12W at 10mm/s we carbonize 80mm long, 2mm, 3mm, 5mm and 10mm wide traces. While traces <5mm do not seem conductive, we obtain a resistance of 27.5k Ω/□ and 3.21k Ω/□ for respectively 5mm and 10mm traces.

Figure 11: Carbonization tests: a) master sample with power/speed ratios, b) 12W 10mm/s ablation on simple BC sample and c) 12W 10mm/s ablation on the graphite-imbued sample. ©Madalina Nicolae & Vivien Roussel

Painting and Stencil Painting consist of creating conductive traces or surfaces on top of the BC surface using conductive pastes or inks using transfer printing [10], a paintbrush or scrapping over a stencil. We use this technique to create an *ambient humidity sensor* (Fig. 10 a) that takes advantage of the water absorption ability of BC to measure natural environment variations with a sustainable and biodegradable sensor. We stencil paint two electrodes on an inanimate biofilm using a conductive paste composed of bio-based CléoBio Cléopatre starch-based glue with 40% graphite (Prographite Micro-graphite avg. particle size 10 micron) [42] to which we attach two wires. We test the variations of our sensor using an Arduino Uno by placing it in the same environment as a DHT22 Arduino module. We increase the environment's humidity using a CONOPU Ultrasonic Air humidifier. We take measures every two minutes until the humidity reaches saturation. We measured a resistance difference from avg. 215k Ω (sd. 14k Ω) to avg. 2M Ω (sd. 80k Ω) for respectively 28% and 100% humidity.

Laser engraving & Filling technique consists of engraving patterns on the inanimate BC film, to create a porous dented surface and therefore increase adhesion force, and then fill them in with conductive pastes. This improves the stability of the conductive pastes to deformation of the substrate such as bending.

We test the conductivity of six pastes that use bio-based starch glue as binder for several conductive particles using an Arduino

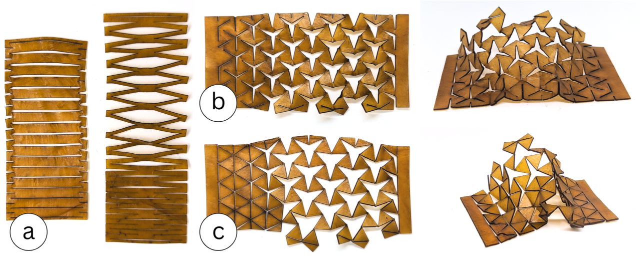

Figure 12: Three examples of auxetic patterns (created by laser-cutting BC inert biofilm in original and extended states. ©Madalina Nicolae & Vivien Roussel

Uno and the same measuring method as for imbued traces. Our results detailed in Table 2 show that our 40% graphite-based conductive paste allows the creation of stable conductive traces down to 2mm width. We measure surface resistance variation of 2.51k Ω/□ for 2mm traces down to 39 Ω/□ for 10mm wide traces. Using this formulation we create a *foldable led switch* bacterial cellulose analogy of the Chibitronics DIY Switch circuit [61] (Fig. 10). The circuit has 5mm wide traces, is powered by a 3.7V coin battery and features a Chibitronics LED powered by a folding switch.

6.3 Additional findings

Laser can create structure damage. When exposed to the high energy of the laser beam, the water contained in BC films with high water content boils and evaporates, leading to an apparent "melting" of the biofilm as mentioned by Bell et al. [10]. In this process, the structure of the fibers can be altered as the boiling would happen inside the material destroying the cellulose fibrils.

Ink compatibility. Although appealing for high conductivity circuits, conductive inks that need high-temperature sintering such as silver-based inks, should be avoided, as exposing the BC film to high temperatures for too long can make it brittle. Instead, we successfully created highly conductive traces using *Laser Engraving & Filling* with gold foils that we use for signal pins on the Wearable bracelet (Fig. 3 center).

Hysteresis of auxetic patterns. We created three samples of auxetic patterns (Fig. 12) derived from literature [32]. While the BC biofilm is easy to deform using these patterns, it does not retract to its original shape without human intervention. Therefore, we report that the creation of auxetic actuators via *Imbuing* or *Painting and Stencil Painting* and laser cutting is rather difficult.

7 DISCUSSION AND CONCLUSION

In this paper, we presented biohybrid devices as a new class of interactive devices that combine electronic components and living organisms. Following an exploratory design methodology, we illustrate this class of devices with BC. We created 14 simple electronic embedded devices that exemplify seven fabrication techniques (*Grow Around* , *Layering* , *Imbuing* , *Slicing & Inserting* , *Laser Engraving & Filling* , *Carbonization*, *Painting*). In combination, they demonstrate potential for the fabrication of fully functional interactive applications. Making use of BC as a growing and living organism, we contribute three concrete examples: a Shoulder responsive accessory, a Wearable Bracelet, and a Game controller.

Our application examples demonstrate that it is possible to embed conventional electronic components within growable materials produced by a living organism (BC). We contribute and exemplify seven different fabrication techniques that are possible using common DIY set-ups and enable a range of HCI applications. In summary, this contributes towards lowering the entry barrier for sustainable prototyping and sheds light on new avenues for research, design and making.

7.1 Design Space Generalizability and Extension

We presented a design space structured around three main phases (Grow, Stabilization, Inanimate) in which we can intervene to embed electronics in a living organism. This design space has been generative enough to identify seven nonexclusive and combinatory techniques. However, our exploration is not exhaustive, and multiple techniques at every dimension and materials remain to be discovered.

Each living organism might provide specific cycles that could extend the framework in future research. While the life cycle dimension of the design space is limited to the Bacterial cellulose's life cycle, it provides a first structure that is generic enough to be extended in future research with other bio-materials by substituting or adding phases. There is a range of growing materials available that serve as substrates for biohybrid devices, including mycelium [29, 75], plants [56, 67], silk worms [55] and others. For instance, mycelium enables techniques that can be used before the Growth phase [29] such as mixing electronic components at the inoculation phase, and before the colonization. This opens up additional opportunities. It is also possible to create conductive composite material by trapping gold particles at a nano scale [68, 73]. However, despite showing high potential, these processes are currently out of the scope of a DIY fabrication setup.

7.2 Constraints and Limitations of BC for HCI

Translation of low-level parameters into design considerations can be rather challenging without understanding in depth the material and biological processes involved. The parameters we used during growth are optimized to maximize the yield of BC. They can be tuned to change the material's properties (structure, thickness, color).Unless the micro-organisms DNA is altered, an intense intervention of the designer to control or to stimulate the micro-organisms can result in the compromise of the symbiosis (one species multiplies faster than the others breaking the metabolic cascade) or the organism's agency or integrity (mutations or death of the culture). Details on our experience interpreting the visual and structural well-being of the culture are included in the appendix. Similar to animal leather processes (tanning, coating, etc.), the BC stability and durability are impacted by the treatments applied during the stabilization. BC artifacts can degrade within a few days [10] or, under appropriate conservation conditions, can reach a lifespan of a few years. Non-treated BC thermally degrades on average at approx. 300 °C [72], which is above the heat produced by most embedded electronic components, including low-temperature SMA wires. However, the impact on the BC film varies depending on the water content. Although the SMA's wire temperature did not impact the BC, we experienced localized damages around the connections between the electrical wire and the SMA wire on very hydrated films.

7.3 Ethical Considerations when Working with Biohybrid Devices and the Challenges of Prototyping Through Slow Manufacturing

Although humans have been manufacturing goods by means of living organisms for millennia, the utilization of living bio-materials in electronic manufacturing poses ethical challenges. Therefore, we could question the limits of transforming living organisms into a commodity for creating new information devices. While developing future research involving non-human living organisms, we need to consider 1) concerns relative to the non(human) consent [74]), 2) concerns raised by practitioners when experimenting at the *stabilization* where the bacterias are terminated. Even though terminating nano-scale organisms (such as bacteria) seems to be accepted in the community, there is a need to define and explicate an agreed-upon limit. Yet, criteria are so far unclear: might this be based on organisms' ease of access, scale, or level of consciousness? Future research should critically question the presumed superiority of symbiosis over extractivism [1]. While symbiosis with living organisms receives praise as an alternative approach to avoid the exploitation of natural resources, long-term consequences need to be weighed up: what is the impact of living organisms replacing electronic substrates?

In this paper, we propose Biohybrid Devices as a new realistic perspective for prototyping interactive devices that can be applicable today in a DIY setup. Our framework allows designers to create interactive systems using Nature's natural development processes and provides an alternative approach to existing design and production processes.

These works are in line with slow technology [33] and care-based fabrication. Our alternative approach to manufacturing prioritizes taking time to create interactive products, which contrasts with fast prototyping which emphasizes speed and optimization. Furthermore, the designer's actions (care) impact the final material, but the organism's natural growth and development ultimately produce the material.

Research on *biohybrid interactive devices* is just at its beginning. Learning from the life cycle phases and properties of new materials might allow to discover novel strategies for embedding electronics. We hope that this work inspires the interdisciplinary community of designers, makers, DIY enthusiasts, biologists and engineers to embrace the opportunities inherent to fabricating with growable materials, to contribute to a future of hybrid functional devices which offer new types of interactive experiences, novel forms of engaging with making, and more sustainable alternatives to today's interactive devices.

7.4 Opportunities for Recycling and Re-use

With Biohybrid Devices, we demonstrate that integrating and embedding electronics into living bio-material can be achieved in a DIY setup. The contributions presented in this work focus on how to create this kind of devices. We combined seven fabrication techniques through three application examples. They demonstrate a sustainable way of fabricating electronic devices where polymer and silicon -carbon dioxide-intensive materials are replaced by living, growable and compostable organisms with low carbon emissions. However, so-far they do not extend towards a circular economy model. Our approach envision electronic components that can be retrieved in a few days or weeks once the prototype's substrate is decomposed [10, 14]. However, complete considerations regarding the full life-cycle assessment analysis of the BC still need to be explored [26]. As a new fabrication paradigm, Biohybrid Devices opens up new opportunities for research to find new knowledge on techniques for every usage cycle of the objects, including repair, reuse, remake, and recycling. Future work in this area may explore the techniques to repair Biohybrid Devices in case of dysfunction of embedded electronics or techniques to disassemble or dissolve the biomaterial for extracting and retrieving the electronic components.

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APPENDIX - SUPPLEMENTAL MATERIAL

Compatibility during growing phase

Materials	Possible I/O	Result
Copper	Capacitive Touch	Oxidation
Tin	Capacitive Touch	Death
Silver Anti-Oxidant Wire S2103FX-100G	Capacitive Touch	Death
Conductive Protopasta PLA filament	Capacitive Touch	Success
Polyimide film & Velostat	Pressure piezo-resistive	Success
EeonTex COM-14112	Stretch	Success
Adafruit Knit Silver Conductive Fabric 1167	Stretch	Death
Off-the shelf FSR	Pressure	Success
Carbon-doped wax	Capacitive Touch	Success

Table 1: Compatibility of common prototyping materials with growth embedding process described in Figure 5.

Conductivity of different traces created at Stabilization and Inanimate phases

Type	Characteristics	Resistance (Ω/□)			
		2mm	3mm	5mm	10mm
Imbue	100% GR	43.49K	5.72k	1.48k	414
DIY Paste	40% GR	2.51k	0.56k	229	39
Carboniz.	P12/S10	na	na	27.15k	2.31k
Barepaint	na% CB GR	6.33k	na	na	4.96k

Table 2: Most relevant values of conductivity of traces created by *Imbuing* with graphite, *Laser Engraving & Fill* with graphite-based DIY paste, *Carbonization* and commercially available conductive paste as reference.

Interpreting visual and structural well-being of the culture

Although micro-organisms can communicate their well-being visually or structurally, one needs to understand the biological processes involved to be able to interpret these signals and transform them into design considerations. For clarification, the Figure 13 sums-up the main metabolic processes involved in the production of BC film.

1. Stage 1 (Gray): Yeasts hydrolyze sucrose into glucose and fructose via invertase, and sucrose into ethanol via glycolysis.
2. Stage 2 (Yellow): Acetic Acid Bacteria (Acetobacter) oxidate glucose to produce gluconic acid, and ethanol to produce acetic acid.
3. Stage 3 (Orange): Gluconoacetobacter Xylinus also known as Acetobacter Xylinum (A. Xylinum) synthesizes glucose and fructose into cellulose in two stages : (1) production of glucan chains and (2) crystallization of the cellulose.

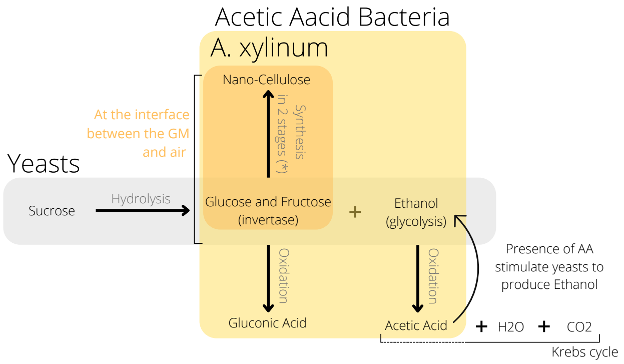

Figure 13: Metabolic process of the synthesis of Bacterial Cellulose.

The metabolic activity of growable materials is directly impacted by environmental factors such as the quality of the ingredients fed, temperature, pH and CO2% [25, 62]. These factors influence the mechanical properties, look and feel of the final biofilm, and produce variations of color, thickness, and texture [18, 79]. From our experience, we can report the following :

- temperatures above 27.5°C caused a fast fermentation which resulted in an irregular surface due to the gas produced and trapped beneath the film.
- a film texture similar to creme brulee or Havarti cheese translates in a high mechanical fragility.
- a fast drop in the pH in the beginning of the culture (pH 2.5 after 3 days) caused by the over-development of the yeasts resulted in a dark troubled growing medium and a very thin biofilm.