Sensitive bacteria: E-skin based on bacterial cellulose

Krieger Maximilian
Saarland University
Germany
makr00005@stud.uni-saarland.de

Schiffmann Tobias
Saarland University
Germany
s8ttschi@stud.uni-saarland.de

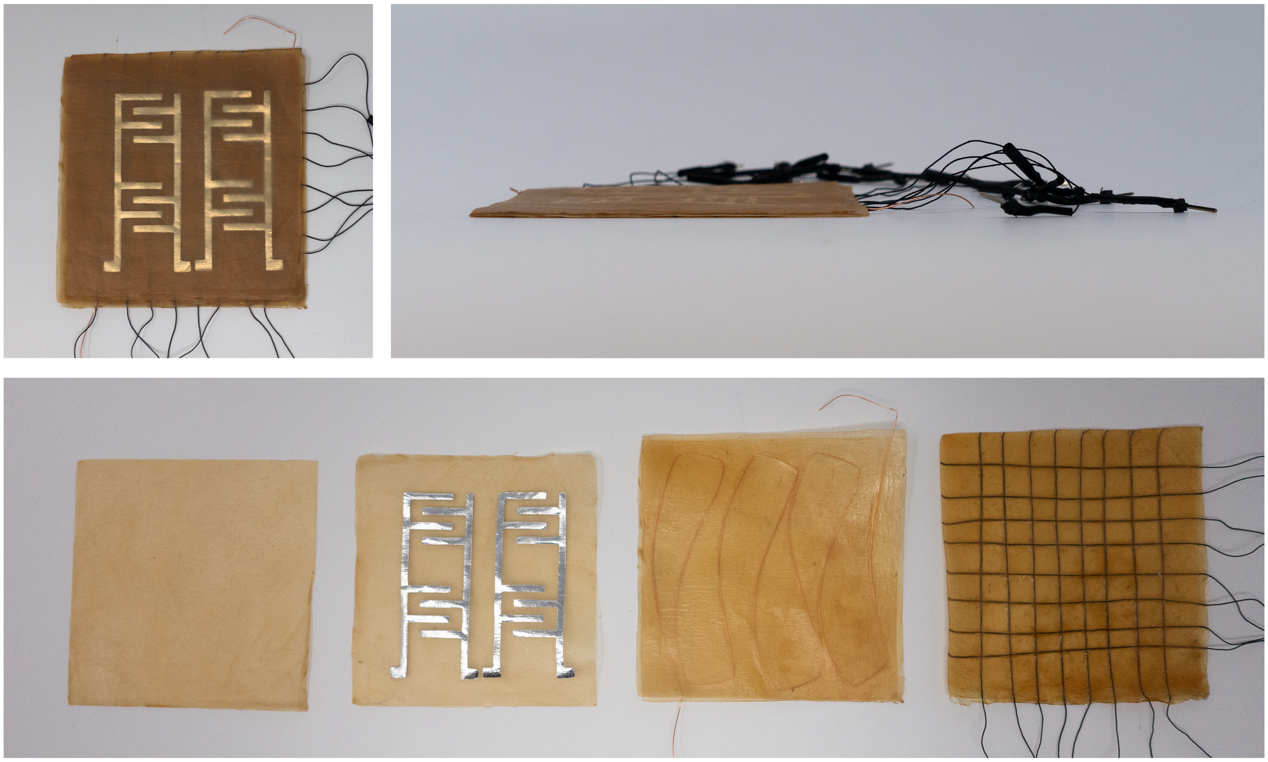

Figure 1. E-skin and individual layers.

Abstract

E-skin finds use in different devices and interfaces, as properties like flexibility and sensitivity are highly beneficial and applicable in various fields, such as Human-Computer Interaction (HCI), wearable electronics [1], and robotics [2]. However, does e-skin often face challenges in terms of durability, self-healing capabilities and sustainability. Sustainable materials offer an alternative providing physical advantages in addressing these challenges. In this context, we therefore explore how the inherent characteristic of biomaterials, such as bacterial cellulose, can be utilized for the development of e-skin, as it has shown promising results in biohybrid devices and artifacts [3], [4]. We demonstrate the design and use of bacterial cellulose as e-skin by multilayer assembly, sensor development, and sensor integration into the material.

CCS Concepts: • **Human-centered computing → Interaction devices**.

Keywords: bacterial cellulose, e-skin, human computer interaction, interactive systems

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1 Introduction

E-skin is an advanced interactive device designed to replicate the sensory and self-healing functions of human skin. Consequently does its development often impose significant importance for advanced robotics [2], enhancing accessibility [1], and driving innovation in research and development. In addition, do many fields like HCI strongly depend on non-sustainable materials, e.g. plastics, for prototyping and further development steps. Therefore, is the combined pursuit of sustainability with the advancement of e-skin technology an intersection of topics with great need for increased research.

Fabrication and development steps for e-skin and similar interfaces do require materials with specific physical properties to achieve desired outcomes. This constraint limits the range of usable materials and complicates the challenge of balancing e-skin properties like durability and sensitivity. This often results in the use of non-sustainable materials like silicone or plastics.

We explore an approach based on bacterial cellulose, also known as vegan leather, to provide a prototype embodying our vision of what e-skin can be, what materials it can be made of, and where it could be applied. Bacterial cellulose being a form of vegan leather and leather being essentially torn-off skin makes the material quite similar to actual skin. Furthermore, besides this fact, are the physical properties of bacterial cellulose ideally suited for such application case; as those include flexibility, great mechanical strength, high heat and water erosion resistance [5], and easy reproduction. Consequently, by utilizing a sustainable material we aim to demonstrate the potential of eco-friendly e-skin in various interactive systems but also contribute to the research of e-skin in a greater scheme and exposure for sustainable materials in the fields of HCI and similar.

2 Related Work

As our work is based on existing knowledge about bacterial cellulose and e-skin, we want to further elaborate on the information with high importance to us.

2.1 Bio-digital interactive artifacts

Results from previous work [3] confirm that bacterial cellulose is a viable material for the development of bio-hybrid systems. Further use cases and fabrication techniques have been explored in more recent studies, such as [4], expanding the potential applications of bacterial cellulose and establishing a fundamental approach for the development of bio-hybrid devices. Combined with knowledge in regards of physical properties of bacterial cellulose [5] does this promise the opportunity to use this material for the development of e-skin. As those properties allow us to explore a new approach in e-skin development with hopes of resolving existing challenges. Considering aesthetics, as skin is something that is mostly exposed, and the use of bacterial cellulose for more than the creation of interactive devices does [6] demonstrate how such living material can be fabricated to be worn.

2.2 E-skin advancements

Furthermore is the sole development significant to various fields, since e-skin and similar, as shown by [1], [2], does contribute towards the advancement of many different domains, often changing the way we interact with systems or devices. Either by enhancement of capabilities, providing safety or creation of novel interactions and interpretations of known systems. This contribution by e-skin development does not exclude the integration of bio-materials into the development process [7]. Drawing inspiration from the concept of living skin in robotics, we propose a way to integrate bacterial cellulose into the development of e-skin.

2.3 Sensor development

Consequently, for the development of e-skin that meets both aesthetics and functionality, similar as one would expect from real skin, is the need for sensors that allow such functionality crucial and under constraint. The constraint to be exact is the physical form factor in which the sensors need to be developed to retain fundamental properties of e-skin. Therefore we use concepts as shown in [8] and [9], to fabricate small form factor sensors.

3 Idea

3.1 Design Concept

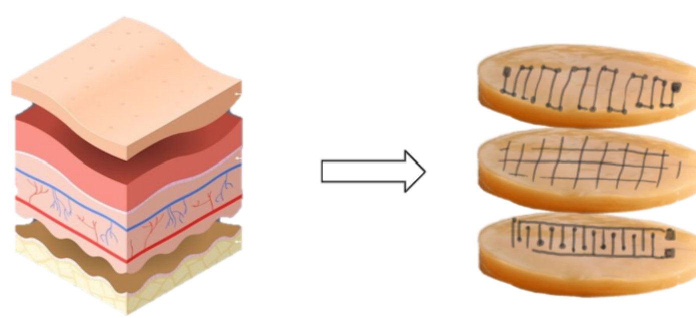

Figure 2. From human skin to e-skin

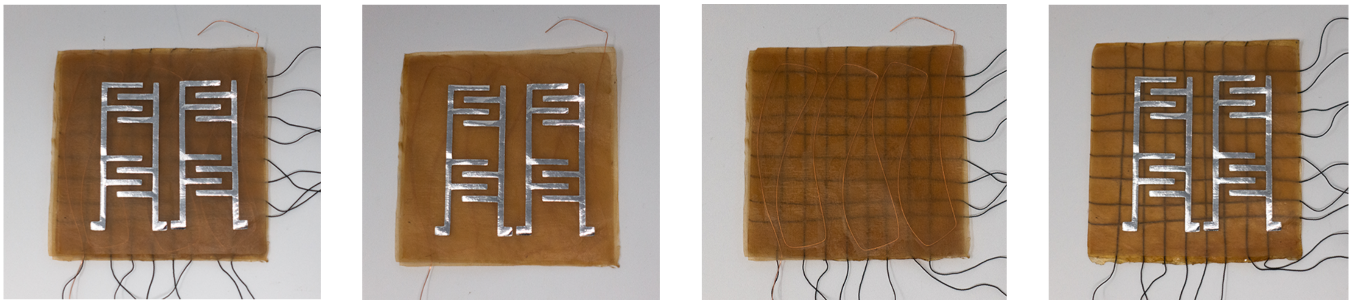

Figure 3. 1. Touch matrix, temperature sensor and humidity sensor 2. Temperature sensor and humidity sensor 3. Touch matrix and temperature sensor 4. Touch matrix and humidity sensor.

E-Skin can be designed and fabricated in various ways, from different materials used to initial divergent inspirations. For example does [2] rely on silicon as a substrate in their design and implements a novel event based approach for sensing. For our prototype, we chose to take direct inspiration from nature, the human skin. Observing the human skin does reveal the fact that it is composed of individual layers with each layer serving another purpose or functionality. We applied this observation to our own design, deciding to utilize multiple individual layers to mimic, to some extent, the anatomy of real human skin (Fig. 2).

Each layer should only inherit one of the three sensor types: touch/pressure, temperature, or humidity. This approach led to the idea of skin segments. A skin segment, in the context of our work, does describe any arbitrary constellation of individual skin layers (Fig. 3). Furthermore do we demand that every fabricated layer is as thin as possible, to fit our desired form factor and to keep aesthetics high.

3.2 Opportunities

This approach of e-skin fabrication does allow for fast and simple prototyping of single sensors or layers as they can be tested individually, being independent from other elements. In addition does this mean that our approach allows us to avoid unnecessary materials if they are simply not needed and reduce computing power, which does contribute positively towards sustainability. Even further than that, do we assure that with this approach integrated components are easily retrievable after the e-skin is worn down.

3.3 Implementation

3.3.1 Growing the bacterial cellulose. As mentioned in section 3.1, we require our e-skin to meet a small form factor in terms of height. This means growing the substrate, bacterial cellulose, was a crucial step during fabrication. Growth information provided by [10] influenced the decision on ingredients and the amount of ingredients used.

Figure 4. From top left to lower right: 1. Preparing sugar, water and tea 2. Adding SCOBY 3. After 1 week of growth (side view) 4. After 1 week of growth (top view) 5. Comparison between dried and fresh kombucha sheet 6. Hand under dried kombucha sheet.

- 2400g of water
- 300g of sugar
- 300g of vinegar
- 300g of a symbiotic culture of bacteria and yeasts (SCOBY)

Furthermore, we decided on a growth time of one week, since during our prototyping this time frame gave the most promising results in terms of durable but yet thin sheets of a height smaller than 1mm (Fig 4).

3.3.2 Touch/pressure matrix. As most touch/pressure matrices consist of multiple layers combining various materials with either dielectric, piezo-/resistive or conductive properties they tend to enlarge fast regarding height or either reduce their flexibility (Fig. 5). Consequently, this meant we had to search for other options which minimize material usage. We decided on utilizing an approach demonstrated by [9]. This approach consists of two main elements, the "Muca Breakout" board, which is essentially a hardware interface for multi touch sensing based on mutual capacitance, and a special conductive electrically insulated yarn also developed by Muca (Fig. 6).

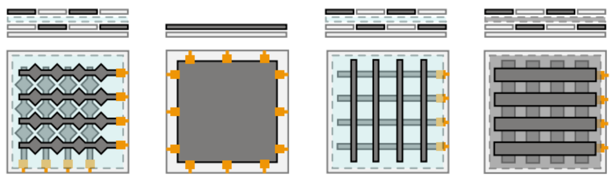

Figure 5. Various touch/pressure matrix designs.

Figure 6. "Muca Breakout" and conductive yarn.

The matrix fabrication process itself incorporated steps of matrix design and matrix fabrication. The matrix design was done by laser cutting a matrix fabrication board made of wood, while the matrix fabrication consisted of layering wet kombucha sheets and conductive yarn on top of each other (Fig. 7).

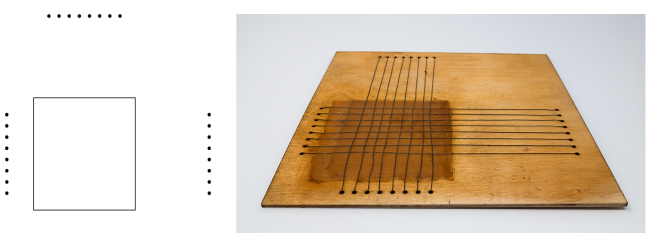

Figure 7. 70mm x 70mm mutual capacitance touch matrix. Conductive yarn is sandwiched between two kombucha sheets.

The resulting matrix is therefore made of a height of smaller than 1mm and a total size of 70mm x 70mm, while keeping total material cost as low as possible.

3.3.3 Temperature sensor. Taking inspiration from existing literature [8] we create a temperature sensor that uses the electrical resistivity of conductive metals, including materials like aluminum foil, silver ink or copper wire to sense change in temperature. Testing direct ink-jet printing of electrode patterns using silver ink, as demonstrated by [5], we noticed that our available Espon WF-2010 printer was not able to print continuous patterns onto the material (Fig. 8). Consequently resulting in an insufficient sensor.

Furthermore, did our DIY environment not allow the usage of aluminum or copper foil. As our design is based on the electrical resistivity of conductive metals are the temperature coefficients of resistance (TCR) and base resistance at approximately room temperature crucial for success. This can be explained by taking a look at the following table:

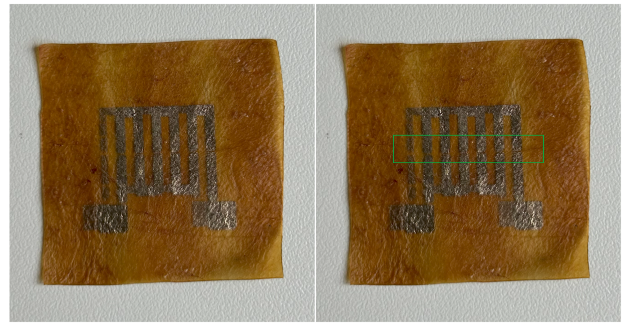

Figure 8. 1. Printed temperature sensor 2. Highlighted disconnected electrodes.

temperature (celsius)	copper (Ω)	copper (Ω)
20	0,2	1
21	0,200786	1,00393
22	0,201572	1,00786
23	0,202358	1,01179
24	0,203144	1,01572
25	0,20393	1,01965
26	0,204716	1,02358
27	0,205502	1,02751
28	0,206288	1,03144
29	0,207074	1,03537
30	0,20786	1,0393
31	0,208646	1,04323
32	0,209432	1,04716
33	0,210218	1,05109
34	0,211004	1,05502
35	0,21179	1,05895
36	0,212576	1,06288
37	0,213362	1,06681
38	0,214148	1,07074
39	0,214934	1,07467
40	0,21572	1,0786
41	0,216506	1,08253
42	0,217292	1,08646
43	0,218078	1,09039
44	0,218864	1,09432
45	0,21965	1,09825
46	0,220436	1,10218
47	0,221222	1,10611
48	0,222008	1,11004
49	0,222794	1,11397
50	0,22358	1,1179
	0,02358	0,1179

Figure 9. TCR for copper: 0.393%. Last row difference between resistance at 20 and 50 degree Celsius.

Since the TCR acts percentage wise per degree Celsius, does a higher base resistance at a given room temperature (here 20°C) result in stronger changes. Our copper and aluminum foil electrode patterns did not exceed a base resistance of 0.5 Ω. Consequently, we decided on using copper wire to fabricate electrodes as they had a base resistance of approximately 1.5 Ω, when tested with a Fluke high precision multimeter. The fabrication of the sensor utilized a 3D printed board to form the copper wire electrode (Fig. 10), an Analog to Digital Converter (ADC) with 16 Bit resolution and a Wheatstone bridge (Fig. 11, Fig. 12). The ADC and Wheatstone bridge supported our Arduino Mega 2560 Rev3 detecting small changes in resistance with changing temperature by measuring voltage.

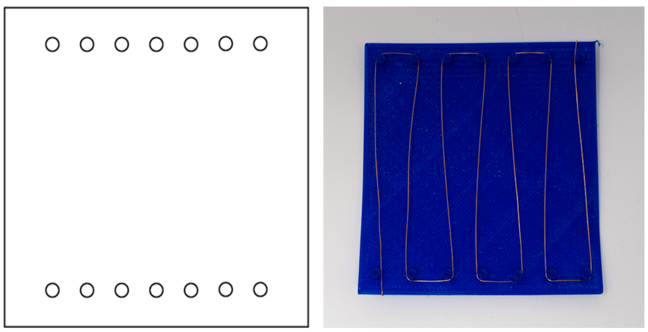

Figure 10. 1. 3D printed board design 2. Board and electrode.

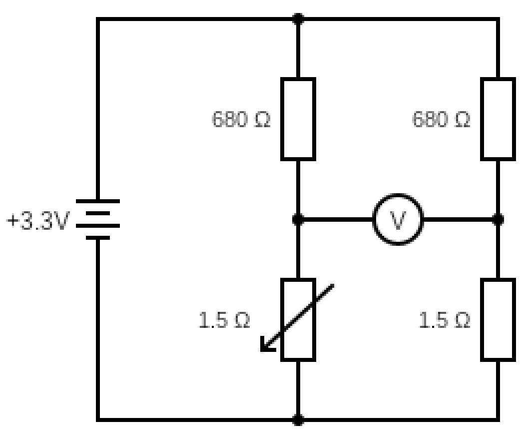

Figure 11. Wheatstone bridge circuit design.

3.3.4 Humidity sensor. Talking about properties of different metals, we decided on using aluminum foil to fabricate the humidity sensor. Previous testing involved usage of a conductive bio-paste [11] consisting of graphite, starch glue

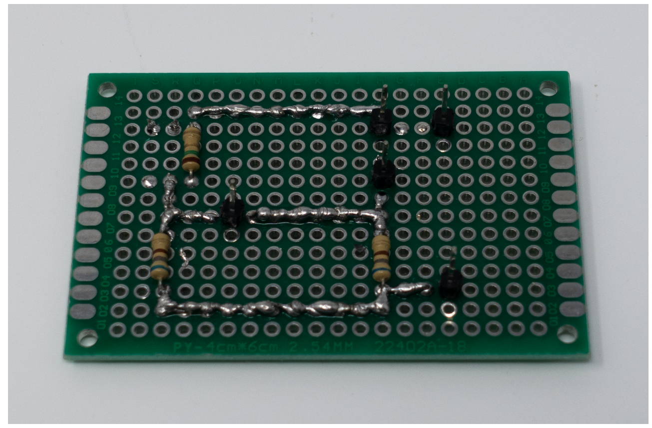

Figure 12. Wheatstone bridge.

and essential oils. This initial method proved fast to be insufficient for our desired result, since deformation of the skin, e. g. by consecutive bending, caused tears inside the material and therefore loss of conductance across sections of the electrode.

Aluminum foil did not only solve this issue, but also has the property of having an oxide layer which prevents it from corroding, e. g. rust build up when exposed to water. The fabrication process involved the Brother ScanNCut CM750 plotter cutter, to create electrode tattoos from aluminum foil.

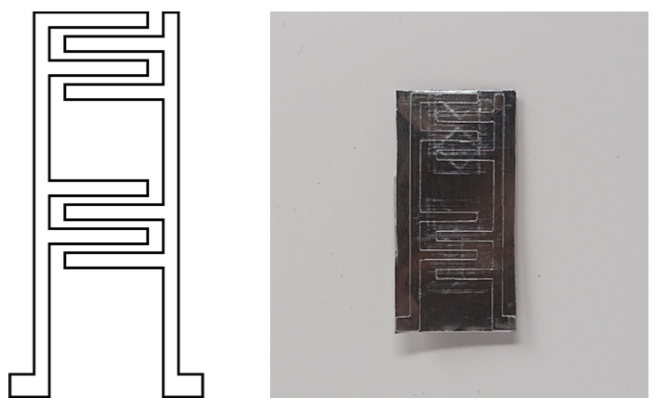

Figure 13. 1. Pattern design 25mm x 50mm 2. Aluminum foil electrode tattoo.

The design, as depicted in Fig. 13, features two "F"-shaped electrodes that initially form an open circuit. In this state does the sensor display high resistance. Exposing the electrodes to humidity, e.g. exhaled human breath, causes the circuit eventually to close, resulting in a change of resistance. To measure this change in resistance we did utilize an voltage divider circuit (Fig. 15, Fig. 16) in combination with our Arduino Mega 2560 Rev3.

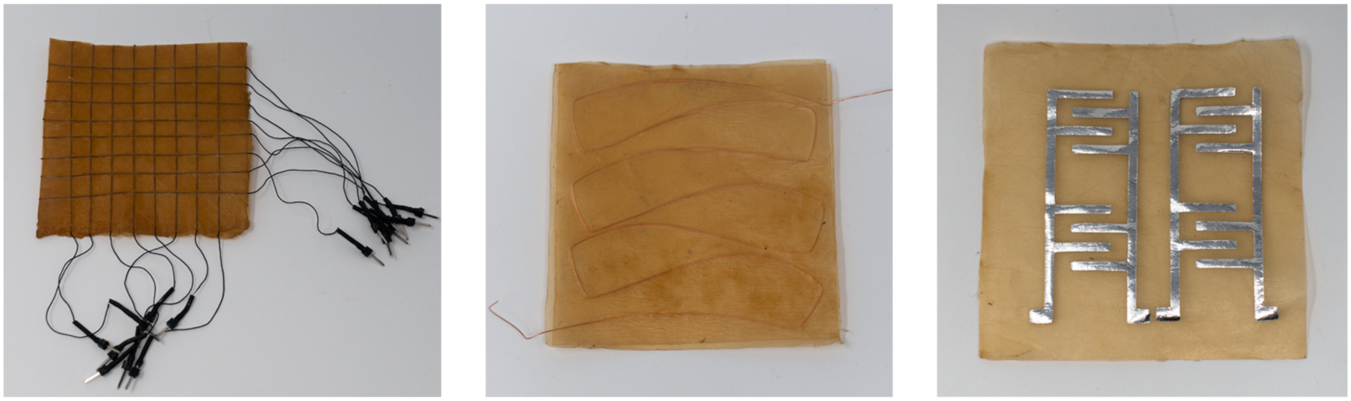

Figure 14. 1. Touch matrix 2. Temperature sensor 3. Humidity sensor (all 70mm x 70mm).

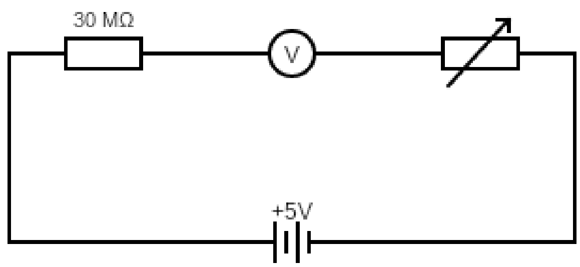

Figure 15. Voltage divider circuit design.

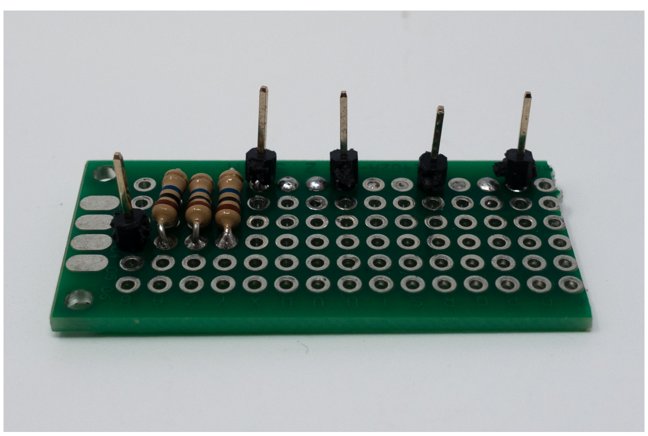

Figure 16. Voltage divider.

3.3.5 Combining kombucha sheets with sensors. The final e-skin prototyping step consists of embedding the electrodes into or onto the grown kombucha sheets. We therefore decided on a uniform form factor of 70mm x 70mm, as this allows us to easier fabricate a skin segment holding all three different sensor types. The touch matrix does not need any further fabrication steps to be finished once it dried, since during the initial fabrication we sandwiched the electrodes between two sheets. However before embedding the temperature sensors copper electrodes between two kombucha sheets it is necessary to insulate the electrodes. This is important, since kombucha is acidic and therefore imposes the risk of corroding the copper, and can be done by using an electronics isolation spray. Once between two sheets the sensor can be left to dry. Contrasting to the temperature sensor is it possible to simply put the humidity sensors electrode tattoos onto an already dry sheet of kombucha. Covering the humidity electrodes with another kombucha sheet does not create any risks of corroding (further elaboration in Sec. 3.4). Furthermore, fabricating a skin segment asks to combine individual layers. This can be achieved by moisturizing the layers and stacking them on top of each other and therefore again letting them dry (Fig. 17, Fig. 18).

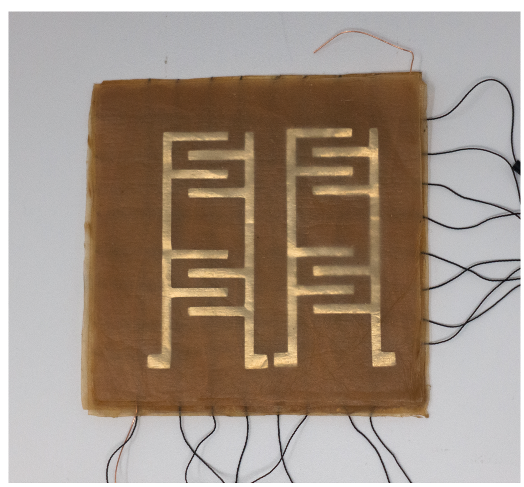

Figure 17. Full skin segment consisting of three layers (70mm x 70mm, thickness 1mm).

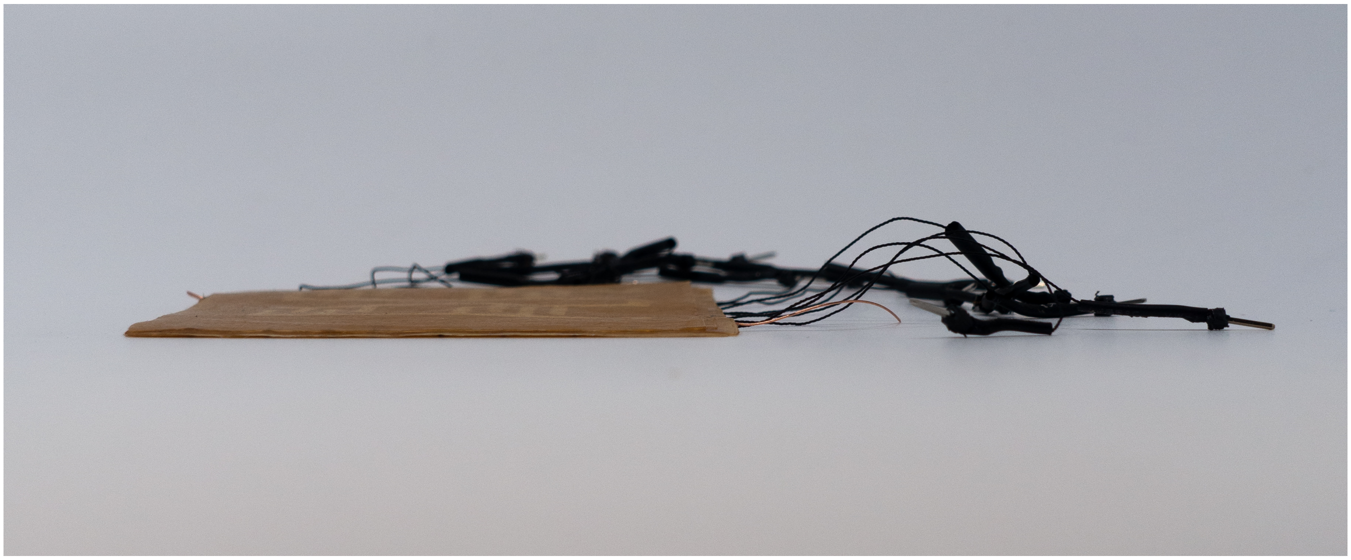

Figure 18. Full skin segment consisting of three layers side view (70mm x 70mm, thickness 1mm).

3.4 Evaluation and testing

Our testing included an compatibility test between aluminum foil and SCOBY. We put therefore a piece of aluminum foil into a glass containing SCOBY. This setup was left untouched for 2 days and resulted in no decay. Consequently, does this mean aluminum foil is a material that can be used in combination with kombucha.

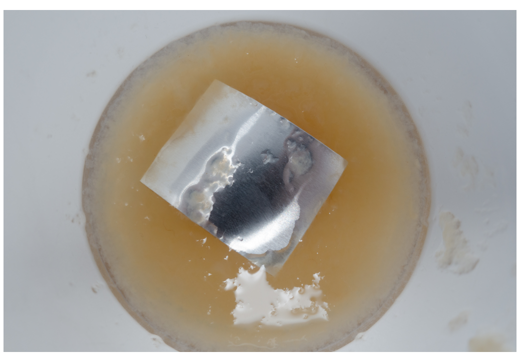

Figure 19. Compatibility test setup after 2 days.

Further testing involved evaluating the sensor performance. Specifically, the touch matrix was assessed by calculating the Signal to Noise Ratio (SNR). The SNR calculation was based on four 1-minute long recordings of raw values. During two of the recordings, no touch was applied, while in the other two recordings, touch was applied by a stable object. The SNR was calculated using the following formula:

$$\text{SNR (dB)} = 10 \times \log_{10}\left(\frac{\left(\frac{1}{N}\sum_{i=1}^{N} S_i^2\right)}{\left(\frac{1}{M}\sum_{i=1}^{M} N_i^2\right)}\right)$$

Using the collected data, we achieved an SNR value of 13.4 dB, classifying the sensor's performance as moderate. This issue can be attributed to multiple factors, such as loose connections and other potential interference's, which require further investigation.

The evaluation of the temperature sensor consisted of two tests, during which raw values were recorded. The sensor was gradually heated up to 80°C using a heat plate. The

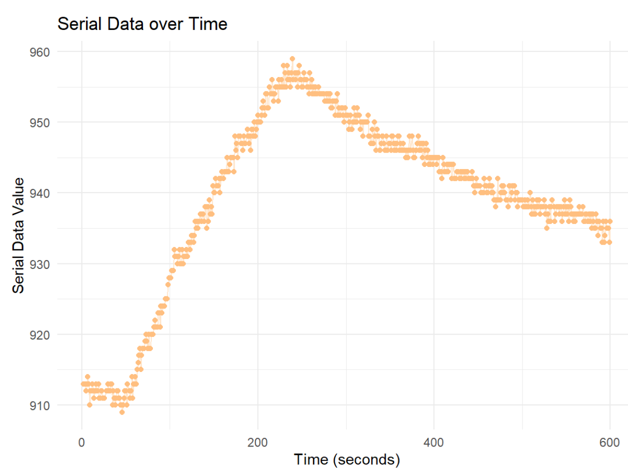

Figure 20. Peak temperature 80°C at 4 minutes

above plot (Fig. 20) illustrates how the sensor detects gradual heating and cooling in a linear manner. As a result we can confidently conclude that the sensor behaves as expected, as the Temperature Coefficient of Resistance (TCR) of metals changes their resistance proportionally with each degree Celsius. Further testing involved a lighter to expose heat quickly to the temperature sensor for a short period of time.

The sensors reaction to quick heat appliance is displayed in the following plot (Fig. 21)

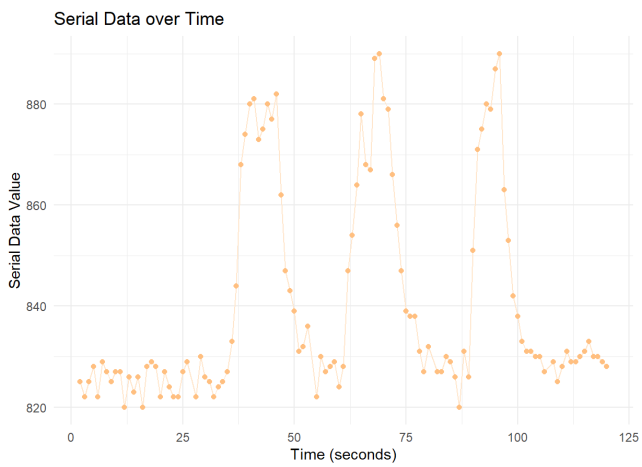

Figure 21. Heat appliance using a lighter.

This demonstrates successfully fast reaction to heat appliance.

The humidity sensors evaluation was conducted similarly. Recording raw sensor values while exposing the sensor multiple times to humidity, here human breath, for a short period of time (Fig. 22).

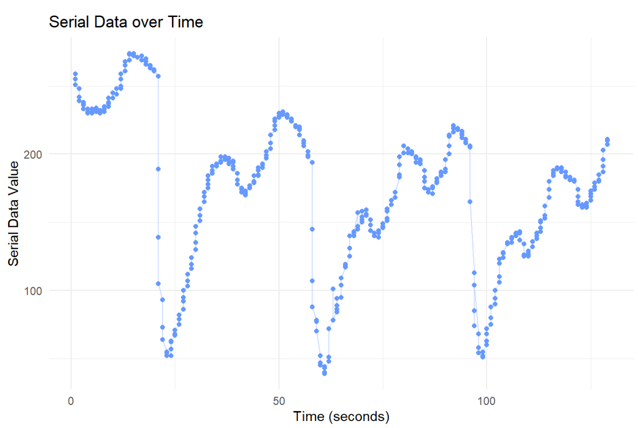

Figure 22. Humidity sensor exposed to human breath.

Examining this plot reveals how the sensor responds quickly and effectively to changes in humidity.

Concluding we can say that performed tests demonstrate promising capabilities, making the fabrication techniques and the use of bacterial cellulose a viable option for sustainable e-skin development.

3.5 Use Cases

3.5.1 Interaction with animatronics at amusement parks. Amusement parks, like Universal Studios and Disneyland, have shown increased use of animatronics in recent years. This trend can be mostly attributed to the fact that it gives people visiting those parks the chance to see their favorite fictional characters move in real life, creating a special experience. Contradictory to the experience itself, it is rarely possible to get close to or even interact directly with such animatronics, thus often remaining a purely visual experience since there is a risk of getting harmed, e.g., by unexpected movements. We see e-skin, based on bacterial cellulose, as an opportunity to bridge this gap and allow direct interaction with animatronics.

Besides enhancing capabilities of such animatronics and allowing new ways of interaction with such, does our e-skin development approach allow it to be used in harsh environments. This can be attributed to already named physical properties of our used substrate, bacterial cellulose([5]). Consequently, this means easy repair if damaged and general longevity (Fig. 23, Fig. 24).

Figure 23. Snake animatronic with e-skin applied.

Figure 24

3.5.2 In general. Besides our proposed use case, we do see in addition opportunities for further usage in broader fields like HCI, e. g. as an on body input device, or even for advanced robotics, e. g. sustainable prototyping.

4 Limitations and Conclusion

4.1 Limitations

Since we utilize bacterial cellulose as the substrate for our e-skin development approach, it is important to mention that it is a living material. This means the material degrades and changes over time, e. g. by molding or even drying out and therefore losing some physical properties like flexibility along side this process. Consequently, it is of significant importance to take care of the material over longer periods of time.

Furthermore, are skin segments currently not universally applicable, as they need adjustments depending on the use case and structure applied to. E-skin fabricated for specific system, e.g. snake animatronics Fig. 24 cant be easily transferred to other systems with different dimensions.

4.2 Conclusion

Sensitive bacteria, as we call our e-skin prototype, is a novel approach for e-skin development with promising results regarding its capabilities. The usage of bacterial cellulose is itself still a topic that needs more research. We therefore hope that our work does add positively towards new insights on what can be made from the material and helps to grow awareness that sustainable solutions exists with beneficial properties. Further work is still to be done, e. g. exploration of better sensor development approaches in combination with bacterial cellulose or more sophisticated testing.

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