Power Generation for Wearable Electronics: Designing Electrochemical Storage on Fabrics

Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Bachelors of Science in the Department of Electrical and Computer Engineering of The Ohio State University

By

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Abstract

We report a new class of textiles with electrochemical functions which, when moistened by a conductive liquid (saline solution, sweat, wound fluid, etc.), generate DC voltage and current levels capable of powering wearable electronics on the go. Contrary to previously reported power generation techniques, the proposed fabrics are fully flexible, feel and behave like regular clothing, do not include any rigid components, and provide DC power via moistening by readily available liquids. Our approach is inspired by the commercially available Procellera® wound dressing, and entails printed battery cells that are composed of silver and zinc electrodes deposited onto a fabric to generate power in the microwatt range. Proof-of-concept results using the Procellera® dressing show feasibility and reproducibility. Scalable DC power may also be achieved by connecting multiple battery cells in series via flexible and conductive E-threads. Indeed, a series connection of two Procellera® dressings was demonstrated to boost the generated voltage from 0.9 V to 1.2 V. Notably, this in-series printed battery arrangement was further shown to successfully power a digital thermometer using 0.5 M NaCl solution (mimicking human sweat) as the electrolyte. Furthermore, customized fabric creation, which optimizes the Procellera® dressing for power generation, is discussed. Overall, the proposed technology is expected to be of utmost significance for healthcare, sports, military, and consumer applications, among others.

Acknowledgments

The author would like to acknowledge the work and efforts of all the members of Dr. Kiourti's Wearable and Implantable Technologies (WIT) laboratory and Dr. Co's Electrochemistry laboratory, without whom the work would not have been possible. Additionally, special acknowledgement is given to Mr. Wesley Thio, a close researcher collaborator with the author on the project detailed in this Thesis.

Vita

Mr. Ramandeep S. Vilkhu is currently an undergraduate student at The Ohio State University, Columbus OH, studying Electrical and Computer Engineering. He will receive a B.S. degree in Electrical and Computer Engineering in spring 2018 with a focus in computer engineering and signals processing. His previous work experience includes a software engineering internship at Cisco Systems Inc. in San Jose, CA and a hardware engineering internship at Northrop Grumman Corp. in Baltimore, MD. Additionally, since 2016, he has been a research assistant under Dr. Asimina Kiourti in the ElectroScience Laboratory.

Notable Accomplishments

Patents:

P. Ghatak, A. Kiourti, C. Sen, S. Steiner, and R. Vilkhu, "Power Harvesting from Fabric Electrochemistry", 2017. (provisional patent)

Publications and Papers:

R. Vilkhu, W. Thio, P. Das Ghatak, A. Co, C.K. Sen, and A. Kiourti, "Power Generation for Wearable Electronics: Designing Electrochemical Storage on Fabrics," 2018 IEEE Access. (Submitted)

Conferences/Symposia:

R. Vilkhu, W. Chen, B. DeLong, A. Kiourti, "Towards Batteryless Wearables and Implants," 2018 ACES Conference, Denver CO, April 26 – April 28, 2018.

R. Vilkhu, C. O'Connor, W. Thio, P. Das Ghatak, A. Co, A. Kiourti, "Scalable Power Generation for Wearable Electronics Using Fabric Electrochemistry," 2018 USNC-URSI National Radio Science Meeting, Boulder CO, Jan. 4 – Jan. 7, 2018.

R. Vilkhu, B. DeLong, P. Das Ghatak, S. Mathew-Steiner, C.K. Sen, and A. Kiourti, "Power Harvesting for Wearable Electronics Using Fabric Electrochemistry," 2017 IEEE International Symposium on Antennas and Propagation, San Diego, CA, Jul. 09 – Jul. 15, 2017.

R. Vilkhu, P. Das Ghatak, S. Mathew, C. Sen, and A. Kiourti, "Powering of Wearable Sensors via Fabric Electrochemistry," 10th Annual T2C Regenerative Medicine and Wound Care Conference, The Ohio State University, Mar. 9-11, 2017.

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TechHub Student Project Grant (https://goo.gl/MTKXSC), November 2017

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R. Vilkhu, C. O'Connor, W. Thio, P.D. Ghatak, A. Co, C.K. Sen, and A. Kiourti, "A New Method of Power Generation for Wearable Electronics Using Fabric Electrochemistry," OSU Fall Undergraduate Research Forum, Sept. 14, 2017.

R. Vilkhu, C. O'Connor, W. Thio, P.D. Ghatak, A. Co, C.K. Sen, and A. Kiourti, "A New Method of Power Generation for Wearable Electronics Using Fabric Electrochemistry," Consortium on EM and RF (CERF) Annual Meeting, Aug. 1, 2017.

R. Vilkhu, P. Das Ghatak, S. Mathew-Steiner, C.K. Sen, and A. Kiourti, "Powering of Wearable Sensors via Fabric Electrochemistry," 2017 OSU Materials Week, Columbus, OH, May. 09–12, 2017. [**won Top Poster Award**]

R. Vilkhu and A. Kiourti, "Powering of Wearable Sensors via Fabric Electrochemistry," Denman Undergraduate Research Forum, Columbus, OH, Mar. 28, 2017.

Fields of Study

Major Field: Electrical and Computer Engineering

Minor Field: Economics

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Chapter 1. Introduction

Wearable electronics are becoming increasingly popular for consumer, sports, and healthcare applications [1]-[3]. In fact, the International Data Corporation (IDC) predicts shipment of over 240 million wearable devices (smart watches, bracelets, socks, shirts, etc.) by 2021 [4]. As is well known, one of the biggest challenges associated with these wearable devices relates to the way of powering them [5]-[6]. Conventional batteries are typically employed, but they are bulky and rigid, and, thus, obtrusive for wearable applications.

Alternate power-generating technologies are recently being explored, but they exhibit several drawbacks. For example, solar energy harvesters occupy large surfaces, require bulky/rigid energy-collecting panels, and only collect energy at certain times of the day [7]. Another popular method, namely Radio-Frequency (RF) power harvesting, requires an RF source within close proximity of the wearer, exhibits low efficiency, and requires bulky/rigid circuitry to perform the AC-to-DC conversion [8]. Wearable biomechanical energy harvesting technologies have also been reported [9]-[10]. These harvesters capture energy from human motion (foot strike, limb motion, or joint motion) and typically rely on nano-triboelectric [11] or piezoelectric [12] actuation, converting naturally available mechanical energy to electrical energy directly. Nevertheless, these

solutions still require bulky components that inhibit the flexibility of the wearables they power. Finally, a commercial product known as BrightVolt has been recently been reported as being the thinnest battery pack to target medical and wearable applications [28]. However, the BrightVolt battery still uses Lithium, which is an inherently reactive, toxic element not ideal for on-body wear. In addition, the battery is not fully flexible for seamless integration with wearables.

In this work, we introduce a new path to unobtrusively powering wearable electronics by integrating electrochemical functions onto textiles [13]. This proposed method involves printing silver- and zinc-based electrodes (cathodes and anodes) on fabrics to generate DC power when moistened by a conductive liquid (saline solution, sweat, wound fluid, etc.), see Fig. 1.1 [14]-[16]. The conductive liquid serves as an electrolyte, enabling ion flow between the anode and cathode. Flexible inter-connections between several of the printed battery cells allow one to connect them in series or parallel to achieve desired voltages and current, per the application requirements. Such inter-connections may be ubiquitously realized on the fabric via conductive E-threads [17], [18]. To our knowledge, this is the first time that fully-flexible batteries are implemented directly on fabric and activated via readily available bodily fluids (saline solution, sweat, wound fluid, etc.). Example applications include T-shirts and leggings that power up sensors while the wearer is exercising and sweating (accelerometers, gyroscopes, heart rate sensors, etc.) [19], epidermal pads that trigger an alarm when the underlying wound

opens up [20]-[21], or smart diapers that assist in toilet training for kids with autism [22]-[23].

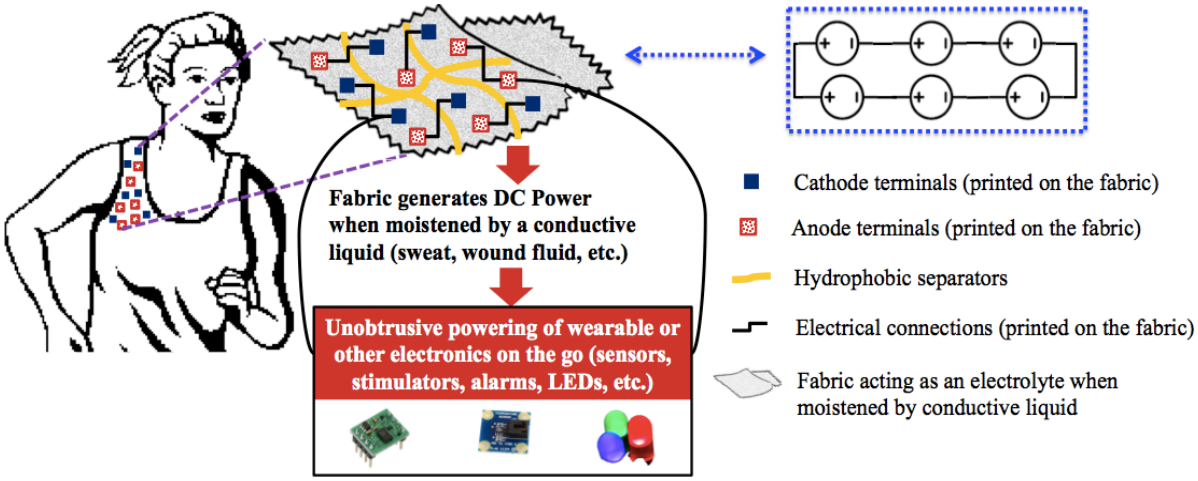

Figure 1.1: Overview of proposed flexible power generation system.

Influence and Inspiration from Procellera Wound Dressing

To provide some background to the project, the team developed the idea of power generation on fabrics while studying the electrical nature of the Procellera® wound healing dressing (shown in Fig. 1.2) , sold by Vomaris Innovations Incorporated [14], [27]. Professor Asimina Kiourti's electrical engineering team was contacted in order to study and classify the electrical nature of the wound healing dressing—attempting to further understand its wound healing abilities. The electrical engineering team was able to successfully characterize the power generated by the Procellera dressing as a DC power, leading to discussions whether the dressing could not only improve wound healing but also power wearable sensors. However, the Procellera® fabric was designed and optimized as a wound healing dressing; therefore, it was extremely difficult to

experimentally connect the fabric to low-power sensors. As a result of the Procellera® findings, the team set out to design a custom made electrically active fabric—optimized for power generation. The majority of this Thesis will outline the pioneering work conducted with the Procellera® to explore the feasibility of implementing a flexible power source, with a section at the end detailing continuing, collaborative work being done to create a custom fabric to replace Procellera®.

Figure 1.2: Procellera® wound healing dressing.

The rest of the Thesis is organized as follows. Chapter 2 describes the operating principle. Chapter 3 presents the results and lessons-learned from the Procellera® dressing proof-of-concept study. Chapter 4 discusses fabrication of these electrochemical-storage-integrated fabrics. Chapter 5 details current results from customized printed battery cells. Chapter 6 details research thrusts to be focused on in the future. The Thesis concludes in Chapter 7.

Chapter 2. Operation Principle

The operation principle of the proposed fabric with integrated electrochemical functions is summarized in Fig. 2.1. The main element of this approach is a printed battery cell (see Fig. 2.1(a)) that is composed of two electrodes deposited onto a fabric. Inspired by our previous work [14]-[16], the electrode materials used to realize the anode and cathode are selected as zinc (Zn) and silver oxide (Ag_2O), respectively. When the electrochemical fabric comes into contact with an ionic conducting liquid, the latter acts as an electrolyte. This means that the Ag_2O cathode will undergo a reduction process, while the Zn anode will be oxidized. In turn, ionic current will flow through the electrolyte to balance the charges at the anode and cathode. The circuit will close when flexible conductive E-threads [17], [18] (marked as "electrical connections" in Fig. 2.1) are used to connect a sensor or other device to the battery's electrodes. In this particular case, electrons will flow through the E-threads, serving as current collectors for the DC power to be utilized. The aforementioned oxidation-reduction process is outlined in (1) and (2) for an example case where NaOH is used as the electrolyte. That is, DC voltage and current can be generated just by getting the electrochemical fabric moistened via an ionically conducting liquid (saline solution, sweat, wound fluid, etc.).

$$Ag_2O + H_2O + 2e^- \rightarrow 2\,Ag + 2\,OH^- \quad (1)$$

$$Zn + 2\,OH^- \rightarrow ZnO + H_2O + 2e^- \quad (2)$$

Incorporating engineering concepts into the design of the printed battery cells can boost/scale the generated DC power levels depending on the application. For example, a voltage boost can be achieved by connecting two or more of the printed battery cells in series. An illustration of this principle is shown in Fig. 2.1(b). Such connections among different battery cells may be implemented via flexible and conductive inter-connects, such as conductive E-threads [17], [18] and/or inks [24].

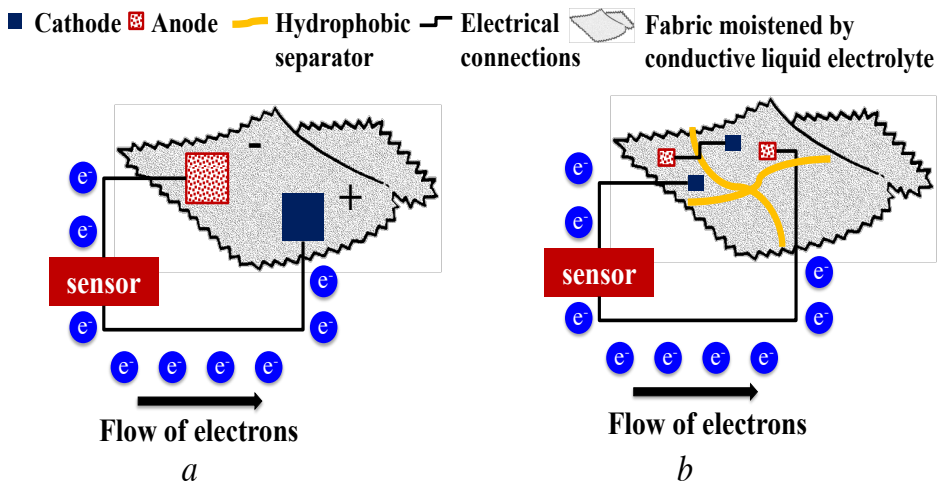

Figure 2.1: Operation principle of the proposed electrochemical fabrics with power generation capabilities: (a) Realization of a single printed battery cell. (b) Example series connection of two printed battery cells aiming to boost the generated voltage.

Chapter 3. Procellera® Proof-of-Concept Results

3.1. Initial Electrical Characterization

As discussed in Chapter 1, preliminary experimentation and analysis of the electrical behavior of the Procellera® wound dressing served as inspiration for the work presented in this Thesis. The Procellera® dressing consists of micro metallic deposits of silver and zinc on a fabric, which generate micro-currents in the presence of a conductive fluid (shown in Fig. 3.1). This generated micro-current is then shown to significantly improve the rate of wound healing, specifically improving the rate of cell migration and re-epithelization in a uniform manner underneath the fabric [14],[15].

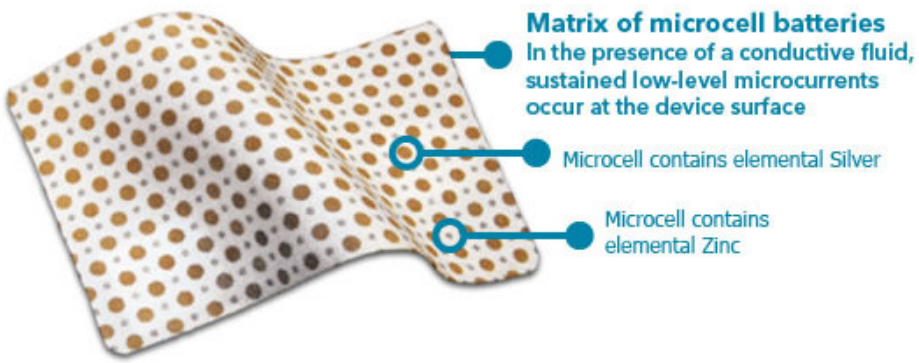

Figure 3.1: Working principle of Procellera® wound dressing [27].

Initially, the team was tasked with determining how much power is produced by the electrically-active wound dressing and whether that produced power was AC power

or DC power. In order to determine the type of power produced by the Procellera® dressing, a Fast Fourier Transform (FFT) was taken, as shown in Fig. 3.2. The steady-state FFT results show that the dominant frequency component of an active Procellera® wound dressing (moistened by a saline solution) arise at 0 Hz, with random noise at higher frequencies. Therefore, the Procellera® wound dressing was experimentally shown to produce DC power. Next, voltage and current measurements were taken to measure the DC power from a single Procellera® dressing. Voltage measurements recorded when the positive (silver) and negative (zinc) dots of the moistened Procellera® pad were connected to a voltmeter are shown in Fig. 3.3. The observed DC voltage measured from the Procellera® electrochemical dressing was approximately 0.9V. A peak current of ~40 µA, as shown in Fig. 3.4, was observed when the moistened pad was connected in series to a current meter. Remarkably, even these voltage/current levels measured from a proof-of-concept pad are high enough to produce several microwatts of power, enough to power a wide range of low-power electronic sensors.

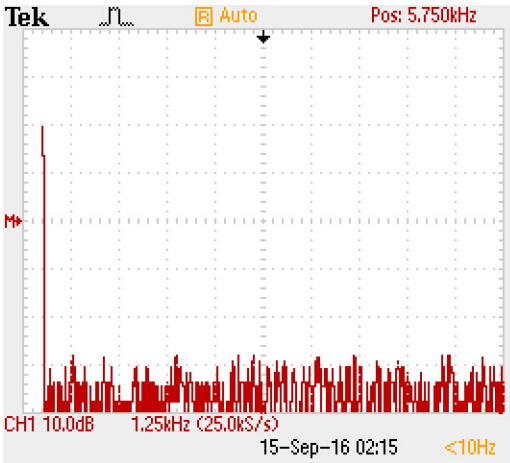

Figure 3.2: Steady-state FFT response of Procellera® wound dressing.

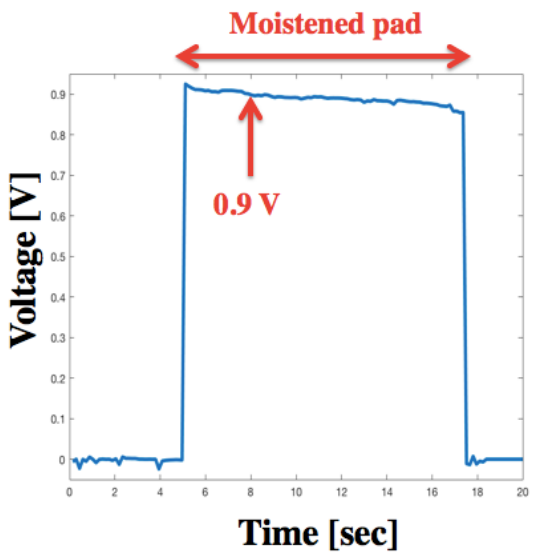

Figure 3.3: Generated open DC voltage across one pair of zinc and silver electrodes on the Procellera® dressing.

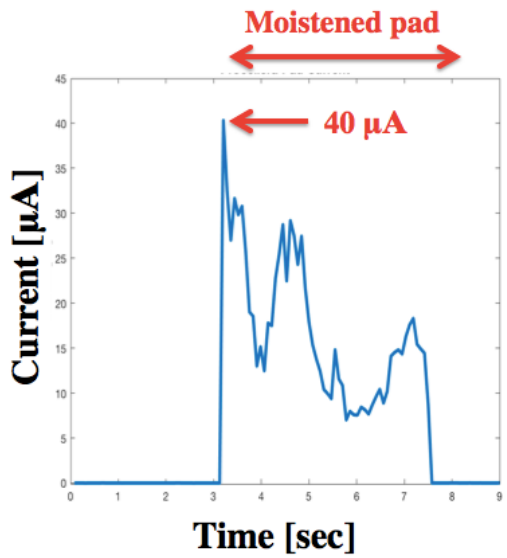

Figure 3.4: Generated closed circuit current across one pair of zinc and silver electrodes on the Procellera® dressing.

3.2. Using Procellera® for Sensing Applications

The data presented up to this point was primarily taken to electrically characterize the Procellera® wound dressing in an attempt to better understand its wound healing behavior [14]. However, after realization that the fabric is capable of producing microwatts of power in a completely unobtrusive, flexible fashion, Dr. Kiourti's WIT lab started to explore using the Procellera® fabric as a power source for low-power, wearable electronics. Fig. 3.5 outlines the initial proposed concept of using electrochemically active fabrics such as Procellera® in wearable sensing applications.

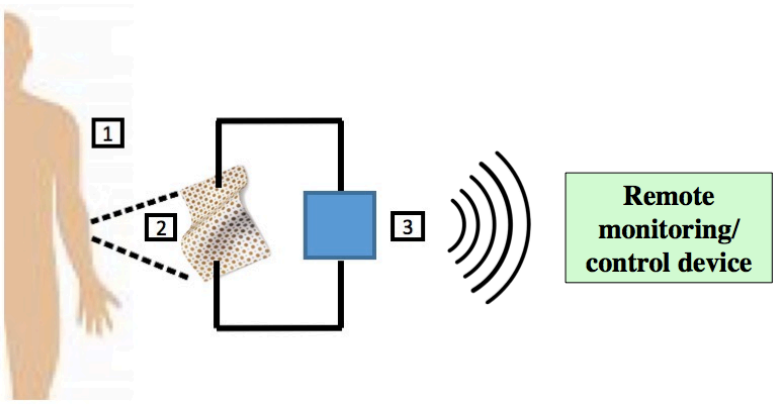

Figure 3.5: Proposed concept of power generation from an epidermal electrochemical dressing (2) dampened by a bodily exudate (1). Generated DC power levels in the order of a few microwatts can be used to power on-body electronics (3).

To experiment with the concept presented in Fig. 3.5, a batteryless 'wound sensor' was subsequently demonstrated that was powered via fabric electrochemistry to detect the presence of an underlying open wound. As shown in Fig. 3.5, for this particular 'wound sensor', the Procellera® electrochemical dressing (2) was used to actively

‘monitor’ the skin surface (1). In case an underlying wound opens, the resulting exudate acts as an electrolyte for the electrochemical fabric, causing it to generate static voltage. In turn, this voltage is used to activate an indicator/alarm unit (3), and/or wirelessly transmit this information to a remote monitoring/control device. For this proof-of-concept experiment, a diode was used in place of the alarm unit, and a saline solution (100 mL water and 5 mL salt) was use to emulate the wound exudate. When the electrochemical dressing came in contact with the saline solution, a static voltage was detected across the diode terminals; therefore, this ‘high’ voltage represented the ‘open wound state’ (see Fig. 3.6).

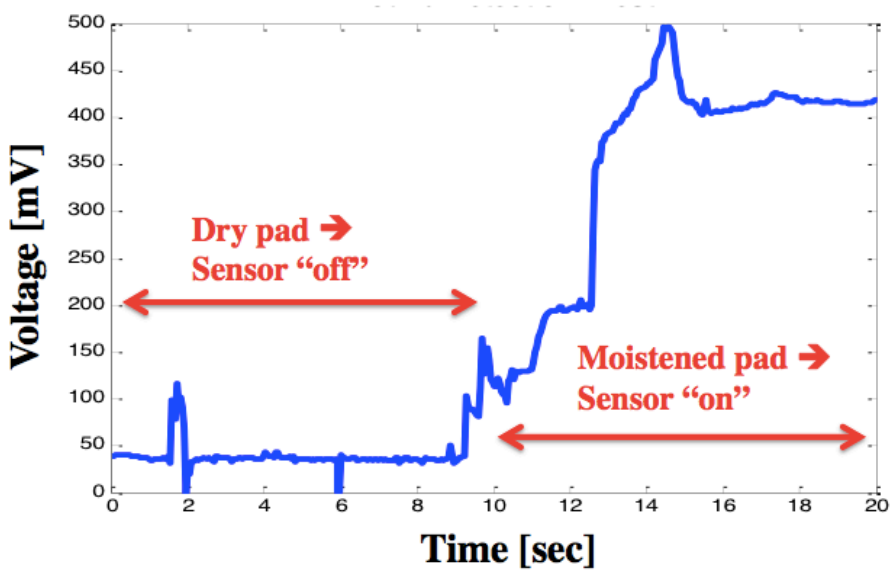

Figure 3.6: Demonstration of powering a sensor that detects open wounds underneath its surface.

3.3. Scaling the Power Generated from Procellera®

Despite the success of the wound detection sensor, it was observed that the Procellera® dressing did not produce enough voltage to consistently supply enough power to a high resistance load. This drop in voltage can be seen in Fig. 3.6 where the addition of a simple diode dropped the open-circuit voltage of the Procellera® dressing from 0.9 V to an observed 0.5 V across the diode. For practical sensing applications, the Procellera® power source will be put in systems with much larger load resistances than that of a simple diode; therefore, the team was tasked with finding a way to boost the voltage produced by the Procellera® dressing to make it a feasible power source. After experimentation, it was determined that a simple series connection of multiple Procellera® dressings resulted in the desired voltage boost.

To serve our purposes, individual Ag_2O and Zn dot pairs on the Procellera® dressing, which correlated to the proposed 'printed' battery cells (outlined in Chapter 2), were electrically isolated from each other using insulating tape adhered to each of the two dressings. Series connection between the two 'printed' battery cells was achieved via conductive E-threads threads [17]. These threads consisted of 332 silver-coated polymer filaments that were twisted into a single thread having an overall diameter of ~0.5 mm and a DC resistance of ~0.5 Ω/ft. Fig. 3.7 demonstrates how a voltage boost can be achieved by connecting two Procellera 'printed' battery cells in series. As illustrated, ~0.9 V generated via a single cell was boosted to ~1.2 V when two cells were connected in series. The reason why the voltage was not linearly boosted (doubled in this case) is

due to the high impedance of the Procellera® 'printed' battery cell (measured to be 1.2 MΩ), which was comparable to the internal impedance of the voltmeter. The steady-state open current flowing through an ammeter connected in series to the Procellera dressings was in the range of ~10-11 μA.

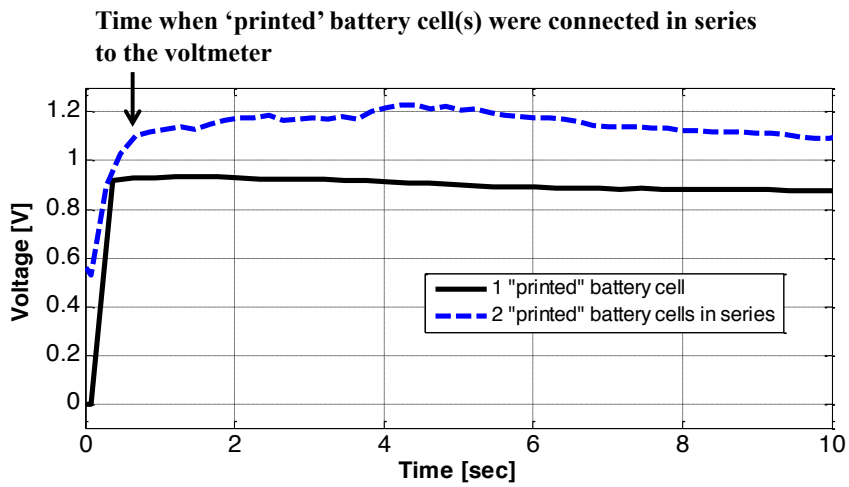

Figure 3.7: Demonstration of a voltage boost when connecting two electrically isolated 'printed' battery cells on the Procellera® dressing in series.

3.4. Powering a Digital Thermometer with Procellera®

With the advancements in voltage scalability from the Procellera® electrochemical dressing discussed in Chapter 3.3, the power boost enabled integration of additional low-power sensors. As shown in Fig. 3.8, a digital thermometer's display was shown to turn 'on' (flickering) when attached to a series connection of two silver/zinc-based 'printed' battery cells moistened by a saline solution. To our knowledge, this was

the first time that electrochemically active fabrics were used as a power source for low-power electronics.

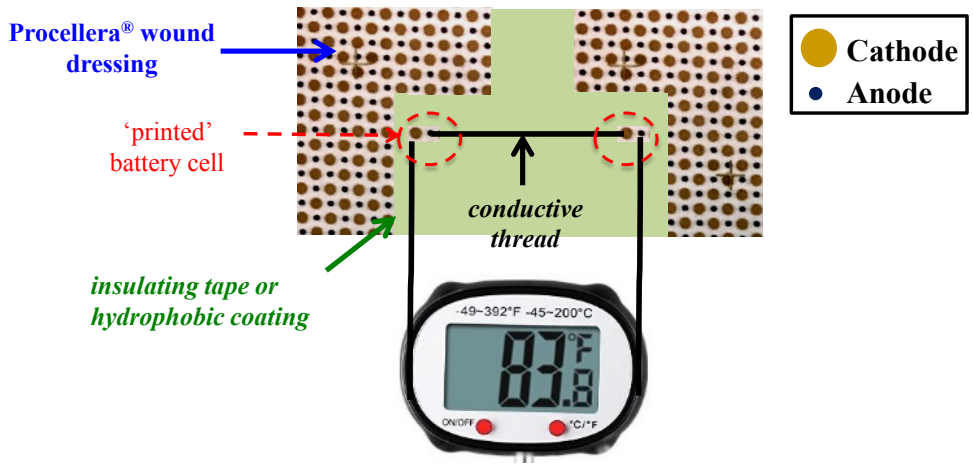

Figure 3.8: Procellera® results: Series connection of two 'printed' battery cells causing a digital thermometer screen to flicker.

Overall, while these initial results from the Procellera® pad were critical in realizing the possibility of having a flexible power generation source, however, Procellera® was optimized to be a wound healing fabric—not a power source. Therefore, the team branched out from the Procellera® wound healing fabrics and started exploring creation of a custom designed Ag/Zn printed battery cell. This research into the design of a custom printed battery cell that can be deposited onto fabrics—optimized for power generation—is discussed throughout the rest of the Thesis.

Chapter 4. Electrochemical Fabric Fabrication

4.1. Fabrication of a Single Battery Cell

In order to create a conductive paste that can adhere onto a polyester fabric, a standardized method for making battery electrode slurry is employed (outlined in Appendix A) [25]. First, the powdered form of the electrode (Zn or Ag_2O) is crushed to fine powders using a mortar and pestle. Then, a binder such as polyvinylidene fluoride (PVDF) in an n-methyl-2-pyrrolidone (NMP) solvent is added to the powder to form an ink that can be screen-printed, hand-printed or printed using an inkjet printer. In this work, a typical ratio of 90 wt.% active materials and 10 wt.% PVDF is experimentally determined to provide maximum conductivity while still allowing the electrodes to adhere to the fabric. The desired ink viscosity is tuned by adding and removing the NMP solvent. For screen- or hand-printed electrodes, the ideal ink attains a paste-like viscosity.

The Zn and Ag_2O inks are deposited onto a medical-grade polyester fabric via hand-printing or screen-printing. Medical-grade polyester fabrics are used in order to provide maximum bio-absorbability (absorb on-body sweat), however most conventional clothing fabrics (cotton, silk, and linen) can be potentially used instead. Once the electrode inks are deposited, the cloth is dried at 100 ^{o}C for one hour. The dry weight of

the Zn electrode was standardized to 30 mg (90 wt.%) and up to 300 mg for Ag_2O (90 wt.%). The standardized dry mass of the metal slurries was chosen to provide sufficient battery capacity to power a sensor for several hours using Zn as the limiting reactant. This procedure creates circular deposits with a diameter of approximately 0.50 cm for the Zn (anode) and Ag_2O (cathode) onto a 1.5 cm × 4.0 cm fabric cutout. This proof-of-concept diameter of the anode and cathode was chosen so as to allow the battery cell to fit onto the defined fabric cutout while also enabling hand-stitching of E-threads across the deposits to serve as current collectors. In this particular case, flexible Cu/Ni E-threads of 0.075mm diameter [26] are selected for electrical probing. Fig. 4.1 shows a completed, flexible printed battery cell on a polyester fabric.

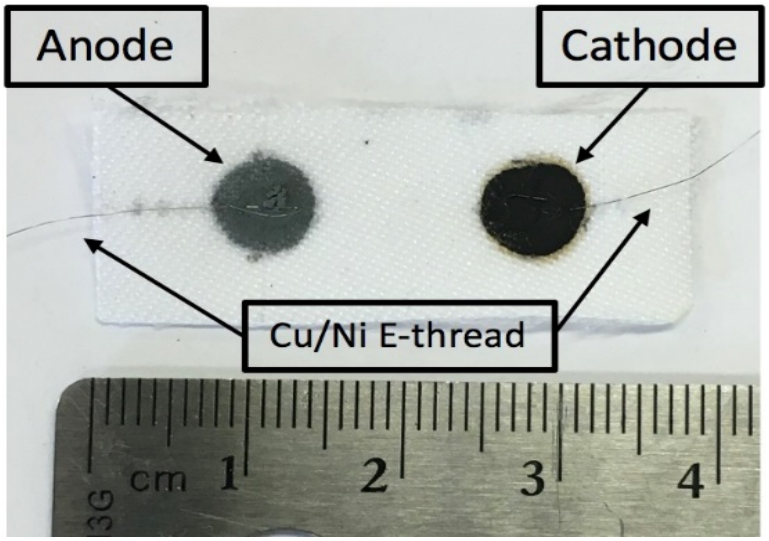

Figure 4.1: Printed battery cell consisting of Silver Oxide (cathode) and Zinc (anode) deposited onto a flexible fabric. (Photo taken while collaborating with Wesley Thio)

4.2. Fabrication of Inter-Connected Battery Cells

To allow for DC power scalability, multiple printed battery cells can be inter-connected in series or parallel, or combinations thereof depending on the desired current and voltage output. For example, a voltage boost can be achieved by connecting two or more of the printed battery cells in series. To do so, flexible electrically conducting threads can be stitched into the polyester fabric in order to electrically measure and utilize the energy stored in these battery cells. As an example, Fig. 4.2 shows the physical representation of two printed battery cells in a series arrangement. In this particular case, two battery cells were printed on two separate pieces of polyester fabric, and flexible Cu/Ni E-thread was used to stitch/connect these cells for maximum electrical contact. Each of the cells were, eventually, moistened separately. Alternatively, instead of physically separating the two cells, hydrophobic sprays (or other means of physical separation) could be employed between adjacent battery cells to avoid detrimental short circuits. Expectedly, similar techniques can be pursued to wire the printed battery cells in a parallel arrangement, per the application requirements.

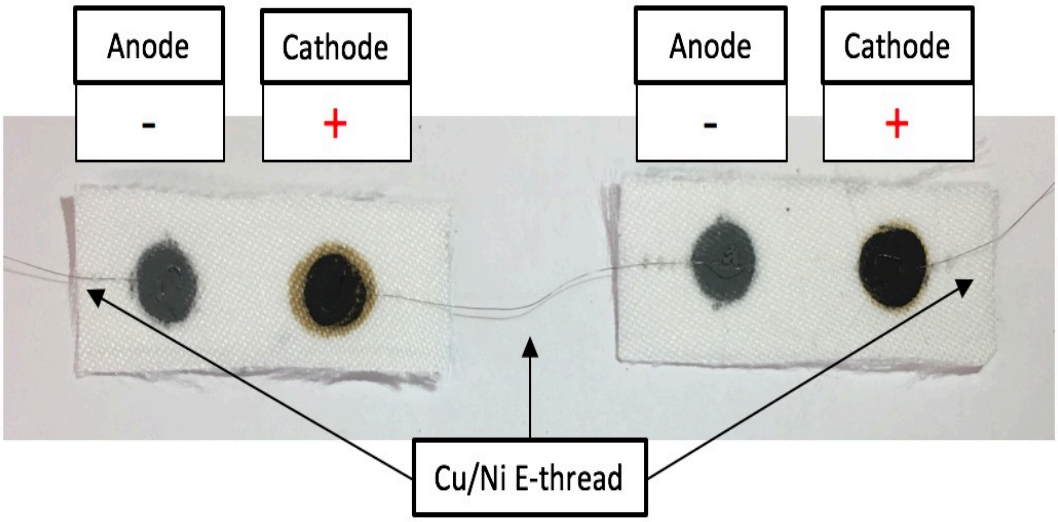

Figure 4.2: Two printed battery cells consisting of silver oxide (cathode) and zinc (anode) wired in series using Cu/Ni E-thread. (Photo taken while collaborating with Wesley Thio)

Chapter 5. Customized Fabric Measurement Results

5.1. Power Generation from a Single Battery Cell

The power generation capabilities of our in-house fabricated electrochemical fabrics, made in close collaboration with Dr. Co's Electrochemistry Lab, were measured using standard electrochemistry techniques. To obtain the discharge characteristic of the printed battery cells, galvanostatic measurements (constant cell discharge) were performed that helped evaluate the voltage performance and capacity available.

As a proof-of-concept, a conventional electrolyte for an alkaline Ag_2O/Zn battery, 10 M NaOH, was used to establish the discharge characteristics of the batteries printed on fabrics. A constant discharge current of 100 μA was applied to a single pair of anode and cathode while the voltage of the cell was measured. The results show that the customized printed battery cells are capable of producing upwards of 80 μW for several hours [29].

5.2. Power Scalability

Table I shows the voltage boost achieved by connecting multiple printed battery cells in a series arrangement (see Fig. 4.2). As shown, a single cell in 10 M NaOH generates 1.46 V, whereas the voltage is boosted to 2.54 V when two cells are connected in series, and to 2.85 V when three cells are connected in series. Similar voltage scaling is observed when using DPBS buffer (mimicking wound fluid) and 0.5 M saline solution (mimicking human sweat) as the electrolyte. Since DPBS and saline are weaker electrolytes compared to 10 M NaOH, lower voltage levels are generated by the printed battery cell.

As seen, and contrary to conventional batteries, the voltage boost from the batteries printed on fabrics is not linear. This non-linearity is due to the high built-in impedance associated with the printed battery cell. To better understand this non-linearity, Fig. 5.1 shows an equivalent circuit model for two printed battery cells connected in series, while (3) shows how to calculate a potential voltage boost when the battery cells are connected to a sensor.

$$V_{sensor} = 2V_b \frac{Z_{sensor}}{2Z_b + Z_{sensor}} \tag{3}$$

Here, V_b is the voltage generated by each of the printed battery cells, Z_b is their built-in impedance, and Z_{sensor} is the impedance of a sensor device to be powered via the

proposed configuration. For a conventional battery, Z_b is orders of magnitude less than Z_{sensor}, so the Z_b term in (3) is negligible and linear voltage scaling occurs. However, the built-in impedance of the printed battery cell is not negligible compared to a typical sensor impedance (e.g., Z_{sensor} = 120 kΩ for the digital thermometer to be employed in Chapter 5.3); therefore, non-linear voltage scaling occurs. This high value for Z_b is attributed to a range of factors, ranging from the exact geometry of the metal deposits on the fabric to possible impurities in the metals used to make the metal slurries.

Table 1: Scalability results.

Number of 'printed' battery cells in series	0.5 M NACL SALINE SOLUTION	DPBS BUFFER SOLUTION	10 M NAOH SOLUTION
1	0.96 V	0.97 V	1.46 V
2	1.52 V	1.76 V	2.54 V
3	2.07 V	2.41 V	2.85 V

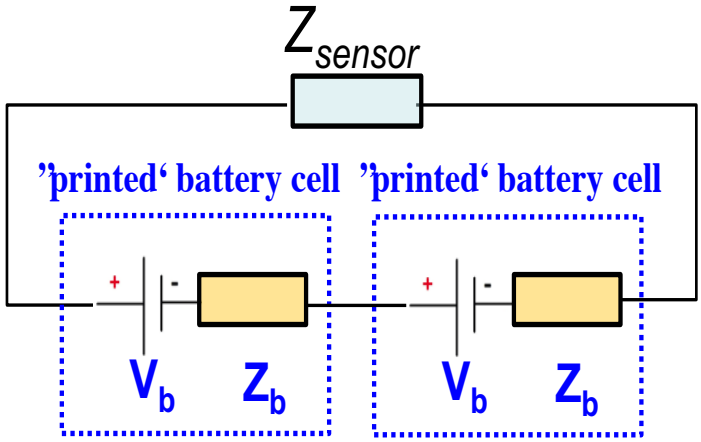

Figure 5.1: Equivalent circuit model for two printed battery cells in series arrangement.

5.3. Proof-of-Concept Demonstration: Powering a Thermometer

A proof-of-concept experiment was performed to demonstrate powering of a digital thermometer using the proposed printed batteries on fabrics. To do so, an Anpro thermometer was employed. The minimum operational voltage and current requirements for this device were measured to be 1.5 V and 12.5 μA, respectively. Under these conditions, the impedance of the thermometer was calculated to be 120 kΩ. According to Table I, the voltage level produced by a single printed battery cell was not enough to consistently power on the sensor. Hence, two printed battery cells wired in a series arrangement were used to meet the sensor power requirements.

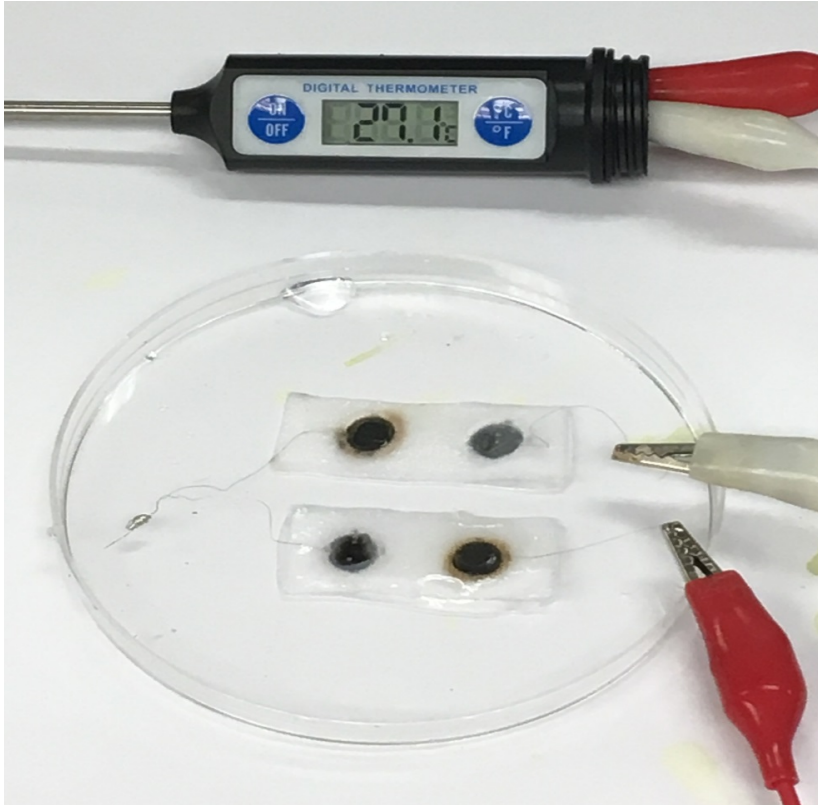

Figure 5.2: Two printed Zn/Ag_2O battery cells deposited onto a flexible fabric, wired in series using thin Cu/Ni E-thread and soaked in 10M NaOH, powering a digital thermometer. (Photo taken while collaborating with Wesley Thio)

Our proof-of-concept experimental set-up is shown in Fig. 5.2. Specifically, the employed printed battery cells were fabricated based on the process described in Chapter 4.2, connected via conductive E-threads as shown in Fig. 4.2, and further moistened by: a) a conventional 10 M NaOH solution, b) a buffer solution (mimicking human body fluid) and c) a saline solution (mimicking human sweat). In all three cases, and as shown in Fig. 5.2, the power levels were high enough to successfully power the digital thermometer.

Chapter 6. Future Research Thrusts

6.1. Operation under Biological Conditions

The majority of the results presented throughout this thesis were taken for a printed battery cell in an ideal 10 M NaOH electrolyte. The 10 M NaOH ideal electrolyte was chosen because it is consistent with the electrolyte used in similar Ag/Zn electrochemical cells used for hearing aids. However, as outlined in Chapter 1 and Chapter 2, a key novel function of our flexible power generation source is operation under biological conditions. In particular, this implies consistent power generation when readily available bodily electrolytes (sweat, wound fluid, etc.) are used as the electrolyte for the printed battery cell. While this concept of using biological electrolytes is slightly explored throughout this thesis (see Table 1) and tested in our proof-of-concept demonstration, consistent plots detailing the power discharge of a printed battery cell in a biological electrolyte were not observed. In fact, Fig. 6.1 shows the results of measuring the power discharge of a printed battery cell in biological electrolytes (data taken and plotted by Wesley Thio). The observed discharge plot was inconsistent, with noticeable fluctuations in the observed voltage over time. This large variance in voltage is likely due to secondary redox reactions taking place with the complex, biological electrolytes and the Ag/Zn printed battery cell system. Therefore, future work must be done in order

to fully understand the functioning of the printed battery cell system under biological conditions in order to ensure consistent power generation.

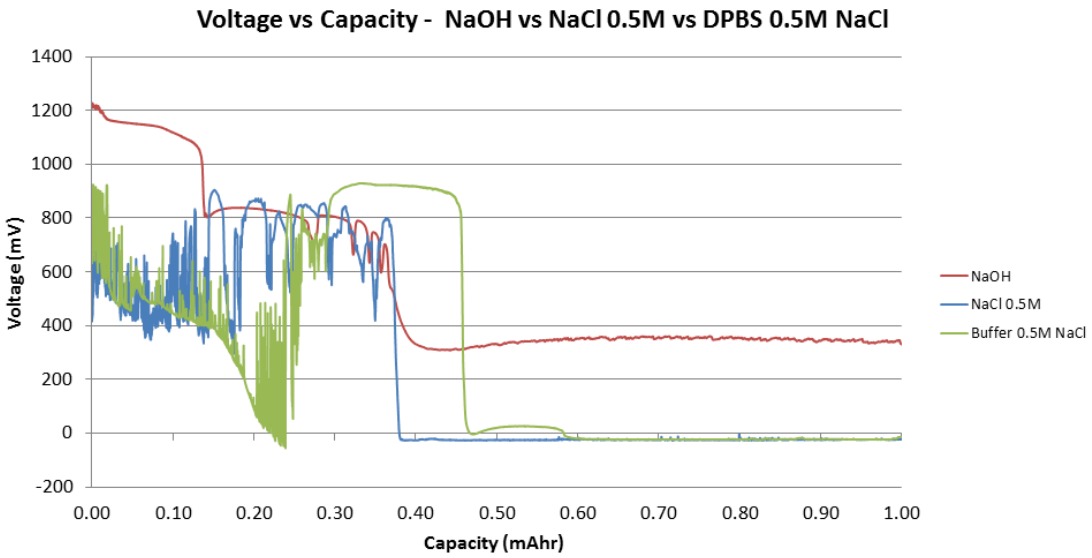

Figure 6.1: Power discharge curves comparing ideal electrolyte versus biological electrolytes (buffer and saline). (Data gathered and plotted by Wesley Thio)

6.2. Optimize Manufacturing

The second envisioned research thrust relates to the way in which the printed battery cells are manufactured. Currently, as described in Chapter 4, the printed battery cells are manufactured by hand, a very tedious and inaccurate process. While the geometry and mass of the printed battery cells are standardized, due to the process being done by hand, it is nearly impossible to get a smooth/even distribution of the metallic slurry on the surface. So, occasionally, the manufactured cells end up with a non-uniform distribution of the slurry material on one of the printed battery cell ends—leading to a non-circular anode/cathode post drying in an oven, as shown in Fig. 6.2.

In general, manufacturing is a reoccurring problem because slight variances in the construction and geometry of the printed battery cell can lead to drastic effects on the internal impedance of the battery cell. The internal impedance characteristics of the printed battery cells is outlined briefly in Chapter 5; however, formal experimental analysis is required to fully determine how the geometry of the battery cell impacts its impedance.

In order to solve potential problems arising due to inconsistent printed battery cell manufacturing, as well as reduce the variance in constructing battery cells to fully characterize the internal impedance, a customized ink-jet printer might be used. The ink cartridge of the printer can be customized to hold various metallic slurries and the printer head can be fine-tuned in order to consistently deposit the material onto fabrics. Furthermore, the ink-jet printer will allow the team to experiment various metallic slurries in order to rapidly test the redox reaction capabilities of other cathode/anode pairs.

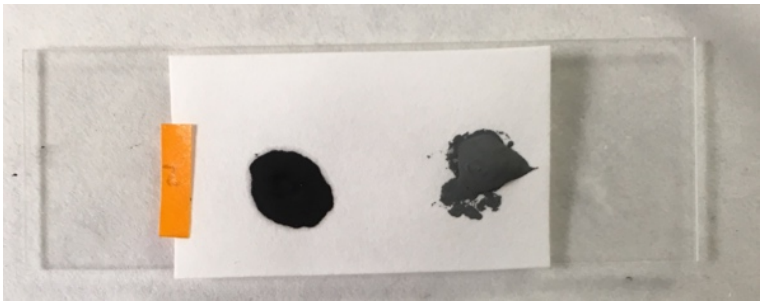

Figure 6.2: Manufacturing difficulties of the printed battery cells due to human error. (Photo taken by Wesley Thio)

6.3. Medical Dosing

The third envisioned research thrust is inspired by the medical research described in [14]-[16], related to electroceutical uses of the printed battery cells. The inspiration for this project, Procellera, as described in Chapter 3 was the utilization of charged fabrics to speed up wound healing. In fact, research completed at Dr. Chandan Sen's lab at The Ohio State University shows that charged fabrics have a potential to kill viruses and bacteria otherwise immune to conventional pharmaceutical techniques. In particular, this research thrust leverages the scalable nature of the printed battery cells in order to provide an "electrical dose" for electroceutical treatment. Currently, the purpose of the work described in this thesis is to generate power, however the electroceutical nature of the solution can be exploited in the future for more medically relevant projects.

6.4. Further Integration with Wearable Electronics

Finally, the prototype printed battery cells were used in order to power a low-power thermometer, as seen in Chapter 5. Future research thrusts aim to expand this proof-of-concept demonstration and integrate the printed battery cells with a wide array of wearable sensors. As a starting point, the team has identified Battery Assisted Passive (BAP) RFID tags as a first step towards wearable integration. Specifically, the current problem with integrating the designed battery cells with wearable electronics is that the wireless communication modules on the wearable electronics draw too much power—typically in the milliwatts range. However, even the customized printed battery cell only

produces power in the microwatt range [29]. Hence, BAP RFID's have been targeted because they rely on a RFID reader in order to supply the power for wireless communication, but the printed battery cells can still be effectively used to power any sensors attached to the BAP RFID.

Furthermore, robust integration with wearable antenna modules is envisioned for the near future. The Wearable and Implantable Technologies (WIT) lab at The Ohio State University has had success in creating textile antennas that seamlessly integrate onto a fabric. The end goal is to have the printed battery cells and textile antennas lie on the same fabric plane—creating the first truly unobtrusive, wireless wearable solution. Fig. 6.3 shows two printed battery cells wired in series and attached to a sample textile antenna. This demonstration is to just show the two solutions integrated on the same fabric plane, and future work must be done to actually integrate their functionalities.

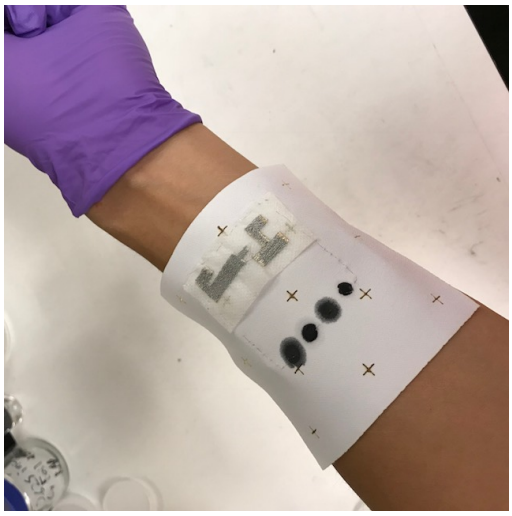

Figure 6.3: Potential integration of printed battery cell with textile antenna. (Photo taken by Wesley Thio)

Chapter 7. Conclusion

We introduced a novel method for powering wearable electronics by integrating electrochemical storage onto fabrics. Contrary to conventional powering techniques (batteries, RF power harvesting, etc.), the designed method leverages conductive liquids readily available on the body (sweat, wound fluid, etc.), and is fully flexible, behaving like regular clothing. Proof-of-concept results with the Procellera® wound dressing indicate the feasibility of having creating electrochemical storage on fabrics and using it to power sensors. Furthermore, in-house customized printed battery cells demonstrated sustained power generation capable of powering low-power electronics for sustained periods of time [29]. Importantly, multiple of these printed battery cells can be inter-connected to scale the DC power, hence, allowing flexibility in meeting various application/sensor requirements. As an example, a series combination of two Procellera® fabrics was shown to successfully result in a voltage boost—a similar combination of the in-house fabricated fabrics was also shown to produce a voltage boost.

Scalable DC power up to the mW range and for long periods of time is envisioned for the future, to be realized via optimization of the associated materials, pattern design, internal impedance characteristics, and inter-connections. Overall, this novel technology

is expected to be vital for unobtrusively powering electronics in military, sports, and emergency operations, among others.

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Appendix A

Slurry Procedure

Procedure for preparing Ag_2O and Zn slurry (90% wt.)

1. Add 0.4 grams Polyvinylidene fluoride (PVDF) powder to a 100 mL beaker.

2. Add 3.3 grams of N-Methyl-2-pyrrolidone (NMP) to the beaker and slowly stir. The NMP solution acts as an organic solvent for the PVDF binder because the PVDF will not dissolve in water.

3. Fully mix the solution until the PVDF is completely dissolved in the NMP.

4. Add 3.6 grams of the desired metal (Ag_2O or Zn).

5. Mix the solution until a paste-like viscosity is reached and store in a sealed container.

Glossary

Relevant Acronyms

1. WIT: Wearable and Implantable Technologies
2. RF: Radio-Frequency
3. AC: Alternating Current
4. DC: Direct Current
5. FFT: Fast-Fourier-Transform
6. PVDF: Polyvinylidene Fluoride
7. NMP: n-methyl-2-pyrrolidone
8. DPBS: Dulbecco's Phosphate-Buffered Saline
9. BAP: Battery Assisted Passive
10. RFID: Radio-Frequency Identification