ElectroMeter: The Practical Electrolyte Measurement System

ABSTRACT

Maintaining a healthy electrolyte balance is crucial for everyday well-being. Beyond enhancing overall quality of life, adequate electrolyte replenishment plays a pivotal role in mitigating the risk of serious health conditions such as hypertension and heart disease. It is unnecessarily difficult for users to compare options and determine the electrolyte content of many commercially available beverage options. Consumers must rely on manufacturer claims and cannot easily verify the electrolyte contents of beverages or compare their best options. This paper presents ElectroMeter, a novel end-to-end sensor system capable of measuring and ranking the electrolyte content of any beverage using non-intrusive and cost-effective hardware. This system incorporates innovative sensor hardware that interfaces with a companion application to measure the electrolyte content in liquids. Our solution empowers individuals to measure and verify the electrolyte content of liquids. ElectroMeter can accurately rank the electrolyte content of 13 commercially available beverages with various levels of electrolyte content in agreement with a Multimeter ground truth method.

1 INTRODUCTION

Electrolytes, such as potassium, calcium, and sodium, are minerals that become electrically charged when dissolved in water. These substances are acquired by consuming a variety of foods and beverages. Upon ingestion, electrolytes serve multiple crucial functions including regulating heart rhythm and blood pressure, maintaining proper hydration levels, supporting muscle and nerve function, and maintaining healthy bones. Electrolytes gradually deplete as they fulfill their roles within the body. Various factors contribute to this depletion, including the use of certain medications, episodes of nausea, profuse sweating, or medical conditions affecting the heart, liver, or kidneys. Insufficient fluid intake represents a prevalent cause of electrolyte depletion. [1, 2]

The ramifications of electrolyte depletion are severe and far-reaching. High blood pressure, also known as hypertension [3], is a symptom of electrolyte depletion that can lead to heart disease over time and is the leading cause of death in the USA. [4] According to data from the Center for Disease Control [5–7] and the US Department of Health and Human Services [8], 691,095 deaths were attributed to hypertension as the leading cause in 2021. Shockingly, 48.1% of the U.S. population, equating to approximately 119.9 million individuals, were recorded as having high blood pressure in the same year. Out of every four adults who have high blood pressure, only one has that condition under control. A comprehensive 12-year study [9] estimated that Americans spend a substantial sum, ranging from $131 to $198 billion annually, in efforts to mitigate the effects of high blood pressure. This condition can also result in arrhythmia, characterized by a rapid or irregular heart rate. Additional symptoms of electrolyte depletion include muscle cramps or weakness, confusion, irritability, headaches, and numbness or tingling in the limbs, toes, and fingers. [1, 2]

Replenishing electrolytes presents a challenge. The difficulty is exacerbated by the ambiguity surrounding the electrolyte content of numerous commercial beverages touted for their health benefits and electrolyte replenishment properties. The heart of the issue lies in the lack of consistency among these drinks, where the actual electrolyte levels may fluctuate. As a consequence, understanding the electrolyte levels in available commercially available beverage options becomes a tricky task. Consumers are left to navigate through manufacturers' claims, often resorting to guesswork to make informed purchasing decisions. There is a need for a practical solution that non-expert individuals can utilize to gauge the electrolyte levels of any liquid and compare the best options. Such a solution will enable users to make informed choices about beverages. A Multimeter [10, 11] can help with the manual calculation of the electrolytic conductance of liquids using voltage and current measurements; however, it is not easily accessible for untrained users since it requires manual calculations and unit conversions, as well as being prone to hardware faults such as blown fuses. It is not a feasible method of identifying the electrolyte contents of beverages for laypeople. This problem motivates our research question: **"How can we create a new sensor that facilitates user-friendly measurement and understanding of electrolyte levels among commercial beverages so that individuals can be more informed about their best options?"**

We introduce ElectroMeter, a sensor system designed for precise and user-friendly electrolyte measurement. The system is comprised of an innovative sensor and a user-friendly companion application. ElectroMeter removes the mystery behind electrolyte levels in beverages. The companion application interfaces with the sensor and can perform data collection and analysis on demand. We evaluate ElectroMeter's ability to measure electrolytes in 13 test liquids. The results indicate that our initial efforts have been successful. When compared to the widely accepted ground truth Multimeter method, all 13 liquids are correctly ranked. ElectroMeter can distinguish between liquids with varying electrolyte contents and is more user-friendly than the Multimeter method since it is not susceptible to catastrophic failures such as blown fuses which prevent measurement and require resources to fix. We also do not require the user to manually measure voltage and current to calculate resistance and conductance. Instead, we provide an automatic measurement using a smartphone application and an Electrolyte model. ElectroMeter's accessibility and unobtrusive design democratize electrolyte analysis and empower users across disciplines. Our hardware versatility enables integration into application-specific downstream designs.

Our system offers unique value since it is the first to introduce a practical electrolyte sensor system designed specifically for laypeople. To date, there has been no convenient or inconspicuous method available for continuously monitoring electrolyte levels on demand. In the absence of a system like ElectroMeter, consumers must rely on product labels and guesswork when preparing homemade electrolyte beverages or must conduct experiments themselves using Multimeters. Our innovation lies in providing a discreet sensor system with a wide range of application-specific downstream designs. The companion application to our hardware can be implemented on any operating system on any Bluetooth-enabled device. The materials required for implementing our solution are cost-effective, making our sensor accessible to users on a budget. We make the following contributions in this paper:

- Development of the ElectroMeter sensor, capable of measuring electrolyte content in solutions and wirelessly interfacing with a companion application analysis and interpretation. The sensor is unobtrusive, resilient to hardware faults associated with current methods such as blown fuses, and can be used by any layperson in a variety of contexts.
- Implementation of both hardware and software components of the sensor system, resulting in the creation of a functional prototype for electrolyte content measurement.
- Evaluation of the system through experiments with 13 test liquids including products from two popular energy drink brands, demonstrating that ElectroMeter can be used to distinguish between liquids of varying levels of electrolyte content and agrees with the rankings given by a well-accepted Multimeter ground truth method.
- Design of application-specific downstream sensors.

The remaining sections of this paper are organized as follows: Section 2 discusses the related works. Section 3 discusses the requirements and challenges of our solution. Section 4 overviews our system and discusses how it can be used to measure the electrolyte content of a liquid in a variety of applications. Section 5 details the technical design of our sensor system and suggests several downstream sensor designs that can meet the application-specific needs. Section 6 details how we model electrolyte content based on the sensor readings. We implement our solution in Section 7. We evaluate our solution in Section 8. We discuss the limitations in Section 9. We conclude and outline our future work in Section 10.

2 RELATED WORKS

Conductometrey [12, 13] and voltage [14] based approaches to electrolyte measurement are not new. These efforts model electrolyte content based on the voltage of the circuit in addition to the conductivity of the electrolyte solution. These works have demonstrated that a strong electrolyte presence increases the conductivity of a liquid solution. These research efforts are generally conducted by expert research teams and are less accessible to those outside the fields of physics and electrical engineering.

There are methods of measuring the conductivity of an electrolyte solution using a well-defined research method. [10, 11] However, these experiments take considerable and meticulous efforts to perform correctly. In these projects, voltage experiments are performed using an off-the-shelf multimeter connected with proprietary circuit components to measure the voltage of liquids. This method can allow an individual to see that electrolyte content and the conductance of a solution will vary between products such as sports beverages or juices. This method is not feasibly scalable and requires the user to build their own experimental sensor. These efforts do not propose a practical design for an unobtrusive and user-friendly system that can accurately measure electrolytes.

Sensor probes that can be dipped into liquids have been developed into commercial products such as the Vernier Go Direct Conductivity Probe [15] and the Extech EC500 Waterproof ExStik II pH/Conductivity Meter [16]; however, these products are not designed to seamlessly integrate into beverage containers or everyday products that humans would use. These solutions involve dipping a sensor into a beverage. These sensors utilize the coaxial cylinders technique in order to measure electrolyte content. [17]. We want to distinguish our solution from these works and provide a more human-centered solution. We desire a solution that can be integrated into everyday products such as water bottles.

Numerous research endeavors [18–35] build upon the techniques of conductometry and voltage analysis, while developing electrolyte sensors with a human-centered research perspective. These efforts primarily utilize sweat conductivity to gauge individual electrolyte levels. For instance, one proposed system [34] integrates an electrolyte sweat skin sensor into wearable glasses. While this research direction is valuable, it caters to specific applications that differ from our needs. Our focus lies in directly measuring the electrolyte content of solutions rather than analyzing the sweat of the individual consuming them.

We have not encountered any comprehensive solutions capable of measuring the electrolyte content of liquid solutions. The existing work concerned with electrolyte measurement is not replicated without diligent efforts. To our knowledge, our sensor system is the first to integrate both hardware and software effectively for user-friendly measurement of the electrolyte content of beverages in beverages. Without our solution, individuals are not easily able to measure and verify the electrolyte content of liquids. Given the absence of solutions meeting our needs, there's a need for us to develop a complete system capable of accurately measuring electrolyte content in solutions. The system needs to be accessible for any layperson to discreetly measure the electrolyte content of liquids and without being susceptible to catastrophic measurement-preventing faults such as blown fuses.

3 REQUIREMENTS & CHALLENGES

We have identified several system requirements that are necessary to accomplish our function of electrolyte measurement and interpretation. (1) Real-time measurement. We must design a system that can produce electrolyte analysis whenever the user connects our device to an electrolyte solution. (2) Unobtrusive & practical operation. We must create a sensor that is constructed from unobtrusive hardware, and which communicates using wireless technology. The technology should blend in seamlessly with everyday objects to avoid being conspicuous. (3) Actionable analysis. We must create a companion application with analysis features that allow the user to meaningfully interpret the electrolyte content in the solution. (4) Accurate and noise-resilient measurement. We must demonstrate accurate measurements of any liquid's electrolyte content and resilience to noise. (5) Safety. Our design must ensure that the beverage quality is not contaminated by electronic components.

We have identified several challenges in meeting these requirements. The first of which is making the sensor both practical and unobtrusive. Different sensor designs will be more appropriate for different applications. We need to produce thoughtful designs that solve real-world application-specific problems. The sensor needs to seamlessly integrate into a variety of everyday objects so that it is unobtrusive. We must propose a range of application-specific downstream sensor designs.

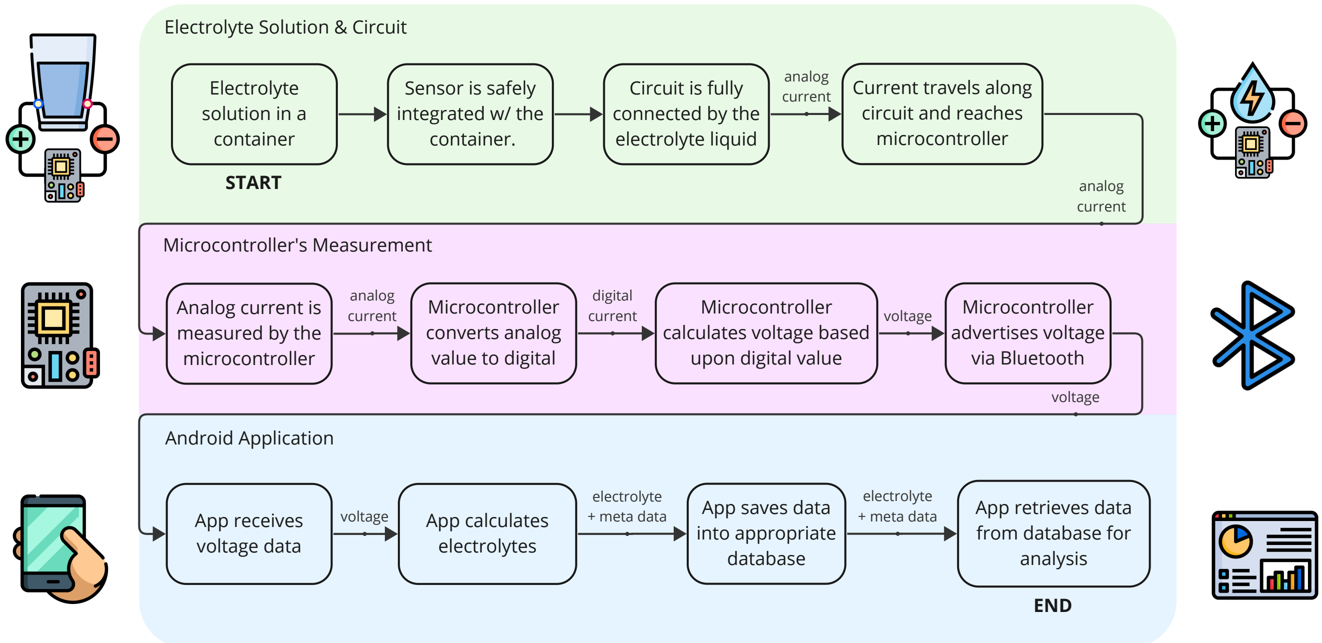

Figure 1: ElectroMeter System Overview.

Secondly, to develop a sensor that is resilient against interference from external factors, it is imperative to take into account various physical variables that may affect sensor readings. Factors such as the spacing between the prongs, the thickness of the prongs, the temperature conditions of the electrolyte solution, and the overall volume of the liquid container may influence the sensor's ability to deliver accurate readings. Ensuring the sensor's stability and reliability is paramount; unpredictable behavior is unacceptable. Addressing this challenge necessitates rigorous experimentation with our designed sensor across diverse environmental settings. It is crucial to analyze the outcomes of these experiments and incorporate appropriate strategies into our electrolyte measurement model to effectively mitigate potential issues.

Thirdly, we must determine what information to return to the user to achieve actionable analysis. The task of delivering pertinent data to diverse user categories is not a straightforward endeavor. It necessitates careful consideration of how best to convey the electrolyte composition of a mixture so that users can make informed and advantageous decisions for their application-specific needs. We must not only provide a number to the user. Instead, we must offer some common sense interpretation of the electrolyte content of a beverage. We should also provide some simple interpretation of the results to the user so that they can easily take some recommended action. Additionally, we must assess the merits of sharing both data collection and analysis outcomes, allowing users the option to transmit their data to secondary platforms for further examination or discussion. Multiple sensor users could collaborate to produce a community knowledge base.

4 SYSTEM OVERVIEW & APPLICATIONS

In this section, we first detail how ElectroMeter can produce measurements of an electrolyte solution. Secondly, we suggest a variety of applications for our design. The system overview is depicted in Figure 1 and operates as follows. (1) The electrolyte solution is contained in a container. (2) A sensor is seamlessly integrated into the liquid solution's container and has points of contact with the liquid. The battery is hidden and separated from the liquid and has no chance of contaminating the solution. (3) When the points of contact are submerged in the electrolyte solution, the circuit is completed and electrical current can flow along the circuit. (4) The analog current travels through the circuit and back to the microcontroller. (5) The microcontroller measures the analog current, (6) converts the analog current into a digital value, (7) and then calculates a voltage value. (8) The microcontroller transmits the voltage data wirelessly to (9) an Android application. (10) The application calculates the electrolyte value based on the voltage and (11) stores it in an appropriate database. (12) The app retrieves the stored data, providing analysis and interpretation.

The ElectroMeter sensor system meets the requirements for electrolyte measurement that we identified earlier. First, ElectroMeter provides real-time measurement and produces electrolyte analysis whenever the user connects our sensor to an electrolyte solution. Secondly, our system is unobtrusive and practical to use and is constructed from hardware components that can easily be integrated into a range of everyday products that will not cause inconvenience to use. The sensor hardware communicates using wireless technology, so there are no external data transfer cables required to tether our sensor to an external device. We design multiple practical downstream application-specific design variations of the sensor. Thirdly, an actionable analysis is offered by our system. The companion application contains analysis features that allow the user to understand the electrolyte content in the solution. Natural language interpretation is also shown to the user. Fourthly, ElectroMeter is accurate and resilient to noise as confirmed by our evaluation. We demonstrate that the sensor can accurately measure the electrolyte content of solutions and is not susceptible to noise. Our design is safe to use. Finally, our system is safe to use. Our application-specific downstream sensor designs ensure that the beverage quality is never affected by electronic components.

ElectroMeter can be useful in a range of application-specific problems, the most common being any person suffering from frequent electrolyte depletion can test healthy beverages they buy from local stores. This can allow them to choose the drinks that are most beneficial for their lifestyle. In addition, these individuals may want to make their drinks at home as part of their healthy lifestyle. These could include smoothies, protein shakes, or electrolyte-infused waters. Our system can help them build the best recipes without any guesswork. Sports organizations can establish and optimize the electrolyte content in beverages by measuring electrolytes. For instance, if a team needs a large quantity of electrolyte-infused liquid stored in an insulated beverage cooler, our sensor can indicate precisely when the electrolyte-to-liquid ratio is correct.

Health practitioners, such as nutritionists or dietitians, can utilize our sensor to add contextual data behind a person's electrolyte consumption over time. For instance, a practitioner could prescribe that an individual keep a log of the electrolyte contents of the drinks that they consumed in a particular week. Our system would easily allow this since we can save measurements over time to construct a timeline reflecting someone's electrolyte consumption. The health practitioner can then use this contextual information to help optimize hydration strategies and overall health outcomes. Clinical health institutions, such as hospitals or care centers, can use our sensor to monitor the condition and electrolyte content of certain high-value liquids, such as electrolyte replenishment solutions or even medicines. When kept in storage, these solutions can be monitored in their containers. If there is ever an issue with a stored high-value liquid, our system's software can alert the appropriate party so that action can be taken.

Food producers can use our sensor in order to quickly analyze the electrolyte contents of fruits in the field. For example, if there is a grocery store that is considering where to buy their next shipment of apples from. A producer could travel and measure the contents of a sample from a variety of supplier options and then choose the one that fits their desired electrolyte profile. This application can function as an augmentation to chemical food tests. [36]

5 SYSTEM DESIGN

In this section, we describe the hardware design. First, we discuss the motivating theoretical design behind our sensor. Secondly, we discuss the practical sensor design. Thirdly, we present application-specific downstream designs that demonstrate the real-world utility of our practical electrolyte sensor.

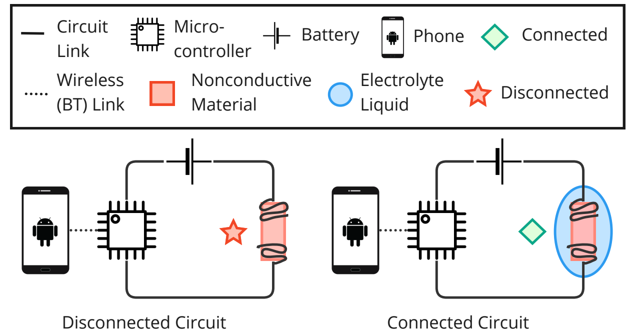

Figure 2: Theoretical Hardware Design.

5.1 Theoretical Electrolyte Sensor

Figure 2 shows the theoretical design that motivates our sensor. This theoretical design is inspired by Yaeger's award-winning science fair project [10, 11] and shows the intuition behind the practical sensor design we propose in the next section. Two circuit diagrams can be seen. Both diagrams include a battery, a microcontroller, circuit links, a piece of non-conductive material, and a phone. The difference between the diagrams is the presence of a conductive electrolyte solution. In both circuits, the current flows from the battery's positive terminal, across the circuit link, and reaches a piece of nonconductive material where there is a break in the circuit. At the other end of the nonconductive material, another circuit link travels back to the microcontroller. The microcontroller has a wireless Bluetooth link with a smartphone to send and receive data. The microcontroller is then attached to the negative terminal of the battery to complete the circuit.

Now that the basics of the circuits have been discussed, we can distinguish between the disconnected and the connected circuits. The left circuit in Figure 2 is disconnected. The disconnection points are where the circuit links end at either end of the nonconductive material (marked by the red star). This material could be any material that will not allow electrical current to flow across it. In this circuit, if the current flowing from the battery source measures 5 volts, the microcontroller will register a reading of 0 volts because there is no current flowing through the disconnected circuit. The right circuit in Figure 2 is fully connected. In contrast to the disconnected circuit, the nonconductive material is now immersed in an electrolyte liquid. This liquid, being conductive, should act as an "electrolyte bridge", facilitating electrical current flow between the two circuit link endpoints. The electrical current should encounter some resistance while traveling over the electrolyte bridge liquid. The microcontroller measures electrical current along the fully connected circuit within a range of 0V-5V, determined by the electrolyte solution's conductivity.

5.2 Practical Electrolyte Sensor

We have designed an electrolyte sensor that allows us to meet the requirements of our solution. The electrolyte sensor consists of two modules, the voltmeter module and the communications module. These two cohesive modules work together to accomplish the function of measuring electrolytes in a beverage. The sensor measures the voltage along the fully connected circuit and subsequently sends the measurement to a smartphone companion application. The application is then responsible for performing actionable analysis. We will examine each of these modules in detail. We will discuss the hardware components involved and how they work together in order to accomplish their task. First, we will detail the design of the voltmeter. Secondly, we will detail the wireless communications design.

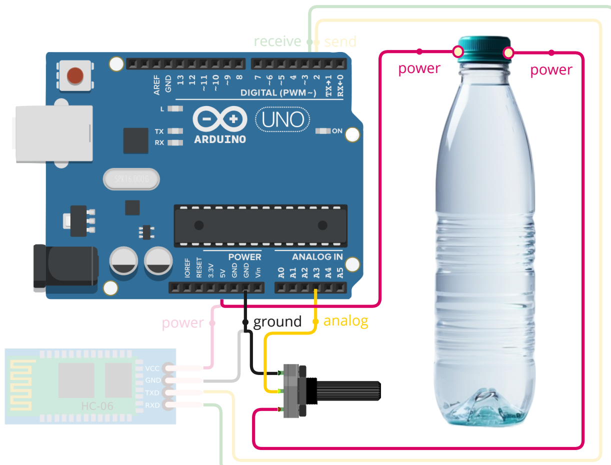

Figure 3: Voltmeter Circuit.

5.2.1 Voltmeter. The voltmeter itself is a simple design and can be seen in Figure 3. This voltmeter uses a voltage divider to read the voltage along our circuit. The microcontroller, the electrolyte bridge terminals, and the potentiometer are included. The components are connected by four wires and an electrolyte solution bridge. The components are not shown to scale. The battery power supply is not shown. The smartphone is also not shown.

The microcontroller, shown in Figure 4, first receives power from a battery and emits it from the 5V port on the microcontroller. The voltage of the current traveling along the wire from the microcontroller is 5V. We use the Arduino UNO microcontroller in our design; however, this could be substituted for a smaller microcontroller in future design iterations. The microcontroller has input and output ports for power, communications, and analog signal processing. It runs a program that can continuously collect data from the device.

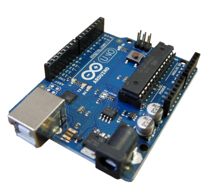

Figure 4: Arduino Uno.

Secondly, the circuit current reaches the first of the two electrolyte bridge terminals shown in Figure 5. An electrolyte bridge terminal is where the circuit ends, and there is a gap. This gap must be bridged in order for the circuit to be fully connected and for electrical current to flow. The connection point terminals are where the wire ends and the gap begins, irrespective of perspective. The electrolyte solution terminals are seamlessly integrated into an application-specific liquid container known as a “downstream design". In the example shown, we have embedded the electrolyte terminals into an application-specific downstream sensor design of a water bottle cap. The terminals are not connected by a wire and create a gap in the circuit. The current will not flow between the two terminals unless the circuit is fully connected. In a dry environment, this gap will prevent any current from traveling between the terminals. The “bridge" does not permit travel of current, unless a conductive solution replaces the air in between the bridge terminal points and completes the circuit between. The electrolyte solution acts as the bridge connection between the two electrolyte bridge terminals. Since electrolyte solutions are conductive, the current will travel from the first bridge terminal, along the electrolyte solution bridge, and reach the second bridge terminal. In this example, the water bottle would need to be turned upside down so that an electrolyte solution flows to the bottle cap. This can be replaced by any of the downstream designs discussed later.

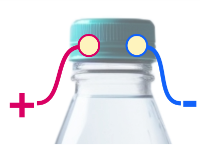

Figure 5: Electrolyte Bridge.

Thirdly, once the current has traveled along the electrolyte bridge, it reaches a B5K potentiometer variable resistor. This component acts as the voltage divider. This component is shown in Figure 6. The potentiometer looks like a volume control dial and can introduce a specific amount of resistance along a circuit. This component has three contacts: one is for receiving power, one is for grounding, and one is for sending an analog current value back to the microcontroller. An analog wire feeds into the A3 analog port of the microcontroller (any other port could be substituted). The potentiometer can add $0 - 5\,k\Omega$ of resistance. When more resistance is applied, more voltage will be read by the A3 pin. When less resistance is applied, less voltage will be read by the A3 pin. Our design keeps the potentiometer at the maximum $5\,k\Omega$ setting. The microcontroller has a program that is capable of converting the analog voltage value read by the A3 pin into a digital voltage measurement.

Figure 6: B5K Potentiometer.

Finally, the circuit is complete. Current has now traveled from a battery, along a wire, across an electrolyte bridge, and has reached a microcontroller. The microcontroller converted the analog current value into a digital value.

5.2.2 Communications. The communications module is responsible for handling the sensor data and is shown in Figure 7. Now that we have a digital value for the electrolyte-bridged circuit's voltage, we must do something with the information. This is where the communications module is needed. There is only one additional component needed for this module, with four additional wires.

In order to accomplish Bluetooth communications, we need a Bluetooth shield that can send and receive data. We use the HC-06 Bluetooth module, shown in Figure 8, to accomplish this function in our design. This module transmits the voltage from the microcontroller to whichever mobile device the user had installed our companion application to. In our design, we use a phone. We can advertise messages at whichever variable advertising rate we choose.

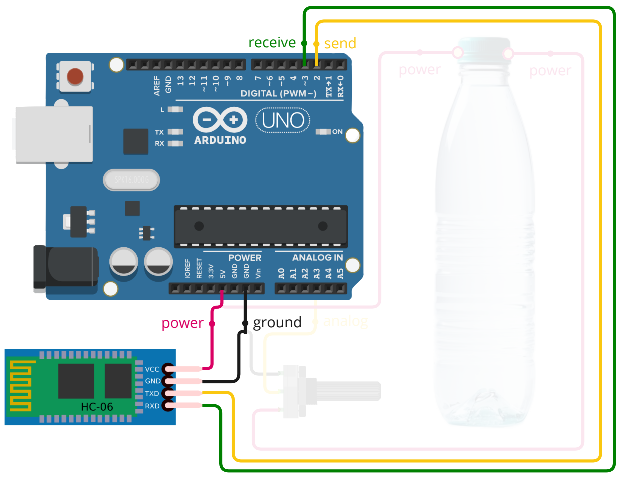

Figure 7: Communications Circuit.

The sampling rate is controlled by the microcontroller's software. The Bluetooth module receives 5V power from the microcontroller (the red connection) and is also grounded to the microcontroller (the black connection). There are connections to the receive and the send data ports on the microcontroller (shown in the green and gold connections).

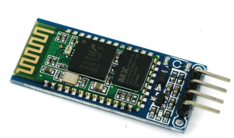

Figure 8: HC-06 Bluetooth Module.

This wireless communications module allows our sensor hardware to be compatible with any smartphone that has our companion application. The user does not need to buy specialized interface hardware to interact with our sensor and collect electrolyte readings. The companion application can be implemented on any operating system and can be made compatible with any common hardware that supports Bluetooth data connections. This makes adopting our sensor quite feasible for a wide range of users. In addition to compatibility, the wireless communications design ensures that we do not have to have a physical wire connection between the sensor hardware and the computing device that performs the analysis. Our design is practical for real-world applications and can be easily transported without being obtrusive.

5.3 Companion Mobile Application

We have designed a companion application that can receive and interpret the data from our practical electrolyte sensor, and provide actionable analysis to our users. This application is at an early version and can be improved in future research. There exists a simple suite of features supporting the function of electrolyte measurement, divided into a data collection and analysis screen. In the collection screen, shown in Figure 9, the user can (1) enter metadata about the current solution being measured, (2) record a new electrolyte reading, and (3) save the record into a database. In the example shown, we are measuring the electrolyte contents of the

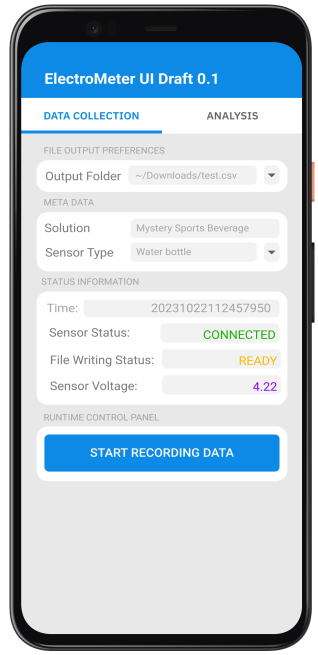

Figure 9: Data Collection Screen.

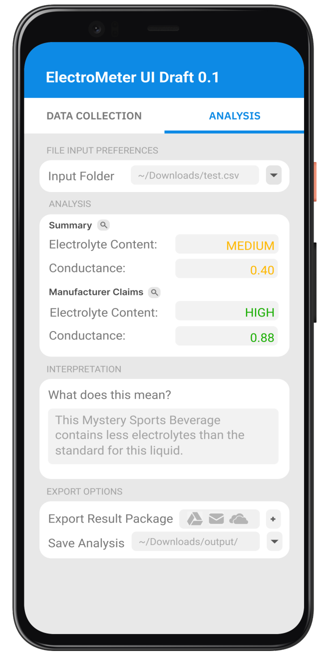

Figure 10: Analysis Screen.

"Mystery Sports Beverage" and are saving it into a test file. We can see that the sensor is connected and that the file writing status is ready. We can also see that the voltage value is 4.22 V. In the analysis fragment, shown in Figure 10, the user can (1) retrieve analysis for a measurement (2) retrieve an interpretation of the results, and (3) share their results to a community for further discussion or storage. In the example shown, we can see the summary of the electrolyte content from the "Mystery Sports Beverage". In this particular example, we see that this solution is supposed to have a high electrolyte content. At the bottom of the UI, there are options to share the analysis to a variety of destinations. The numbers and analysis used in this example are fictional.

6 FEATURES & MODEL

6.1 Feature Extraction

We extract the voltage measured across the electrolyte-bridged circuit to model electrolyte content. We utilize the technique of conductometry [12] which tells us that electrolytes reduce resistance due to their conductivity. As current travels across an electrolyte solution, it encounters some resistance. In our design, this resistance is encountered along the electrolyte solution bridge. The circuit wire, electrical components, and microcontroller do not introduce significant resistance. Higher electrolyte concentration leads to lower resistance and a voltage closer to 5 V. Conversely, lower electrolyte concentration increases resistance and lowers the voltage output. In a fully connected wire without any gaps, the voltmeter would register a measurement of 5 V since there would be no resistance impeding the current flow.

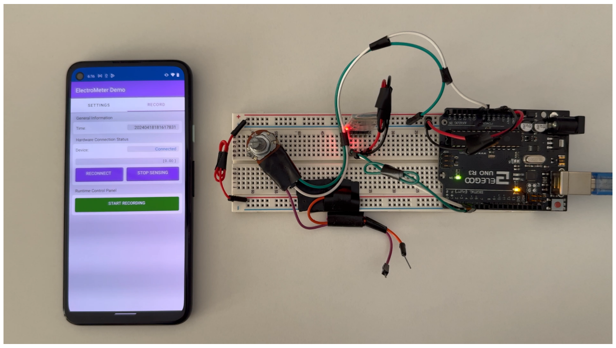

Figure 12: Functional Prototype.

6.2 Modeling Electrolyte Content

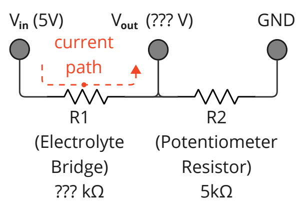

Figure 11: Voltage Divider.

We use a voltage divider equation to calculate the conductance of the electrolyte bridge liquid. The voltage divider circuit is shown in Figure 11. The current path is shown in red. We label the unknown resistance of the electrolyte solution as 'R_1'. This unknown resistance value is what we are trying to determine. Once we have the resistance value, we can then calculate the electrolytic conductivity of the liquid. The voltage measured by our voltmeter is labeled 'V_{out}' and is variable. The resistance of the potentiometer in our voltage divider circuit is labeled R_2 and has a constant value of 5 kΩ. V_{in} is the input voltage supplied by the USB A/B powered microcontroller to the circuit and has a constant value of $5V$. Since the current will flow along the path of least resistance, it will travel from V_{in}, across R_1, and then to V_{out}. We calculate R_1 using the following equation:

$$R_1 = \frac{V_{\text{in}} \cdot R_2 - V_{\text{out}} \cdot R_2}{V_{\text{out}}}$$

Low values of V_{out} result in higher resistance values for R_1. This means that a liquid resistor with low electrolyte content will have a higher resistance value and a lower V_{out}. If there is close to 0 V being detected by V_{out}, then either the terminals are not bridged, or some non-conductive liquid, such as distilled water, is being measured. Once the resistance of the electrolyte solution has been calculated in R_1, we can then calculate the conductance of the electrolyte solution, measured in Siemens (S). The conductance of the liquid is the inverse of the resistance:

$$Conductance(G) = \frac{1}{Resistance(R_1)}$$

The Siemens value of Conductance G will be small. We convert it to Microsiemens μS ($S * 10^6$) in order to get a value that is an appropriate range for electrolyte-infused beverages such as Gatorade and Powerade.

7 IMPLEMENTATION

We implemented our hardware design and developed a prototype that can measure the electrolyte content of a solution. Figure 12 shows the prototype hardware and the companion application. Future iterations can systematically refine the hardware design. This will require additional development efforts. We follow the circuit designs previously discussed in our design section. The only additional component we use in our implementation is the breadboard. We use a breadboard in our prototype so that we do not have to solder any connections. In future versions, this will be removed. We power the microcontroller via a type A/B USB cable. This will also be converted to a battery in the future.

The UNO contains a simple "sketch" (computer program) that measures and transmits the voltage along the electrolyte circuit at a variable sampling rate. The sketch has a file size of just 1 KB. We choose a 1 Hz sampling rate to start. This equates to one measurement per second. We do not need measurements at a high frequency. This rate can be adjusted as needed. The benefits of a lower sampling rate include extending the battery life of the hardware since fewer measurements and Bluetooth advertisements will be performed by the microcontroller, and fewer advertisements will be received by the paired mobile device. In the future, the UNO can also be substituted for one of a much smaller form factor and cost. This will more easily enable our implementation of the application-specific downstream sensor designs.

We implemented the companion application on Android OS running on A Google Pixel 4 device. We use just one activity with two fragments. Each fragment contains one of the app screens. This implementation allows the user to seamlessly swipe between screens and avoids using Android intents.

This prototype is fully functional and demonstrates that our sensor's design works. The hardware is connected to the application and displays the voltage along the circuit. The reading is 0.00V in this example since the electrolyte bridge terminals are disconnected and do not complete the circuit. We can measure different electrolyte solutions and receive a voltage reading for each of them. We can then analyze the readings to distinguish between liquids with high or low electrolyte content. The hardware cost of the functional prototype is $38.10. The UNO microcontroller [37] is the most expensive component at $27.60. The HC-06 Bluetooth module [38] and B5K resistor [39] can be found for $10 and $0.50 per unit.

8 EVALUATION

8.1 Settings

Figure 13: Drink Types.

We compare six electrolyte drink products across two brands of energy drinks that are popular in the United States. The drinks are shown in Figure 13. The first energy drink we will consider is Gatorade. We will use regular Gatorade, Gatorade Zero, and powdered Gatorade mix of both regular and Zero varieties. The second energy brand we will measure is Powerade. We will use both regular and zero varieties of the liquid energy drink. Powerade does not manufacture or sell powder in our area, so we do not complete a comparison for powdered Powerade. We will use distilled water as a control solution. The ingredients that are significant sources of electrolytes are summarized in Table 1 and were sourced from the manufacturers. sodium is abbreviated as Na, while potassium is abbreviated as K.

Drink Type	Na (mg)	K (mg)
Gatorade Powder Zero 200%	460	140
Powerade Zero	400	130
Powerade	400	130
Gatorade Powder 200%	300	100
Gatorade Powder Zero 100%	230	70
Gatorade Zero	270	80
Gatorade	270	80
Gatorade Powder Zero 50%	115	35
Gatorade Powder 100%	150	50
Gatorade Powder 50%	75	25
Gatorade Powder 13%	19.5	6.5
Gatorade Powder Zero 13%	29.9	70
Distilled Water Control	0	0

Table 1: Potassium (K) and Sodium (Na) by Drink.

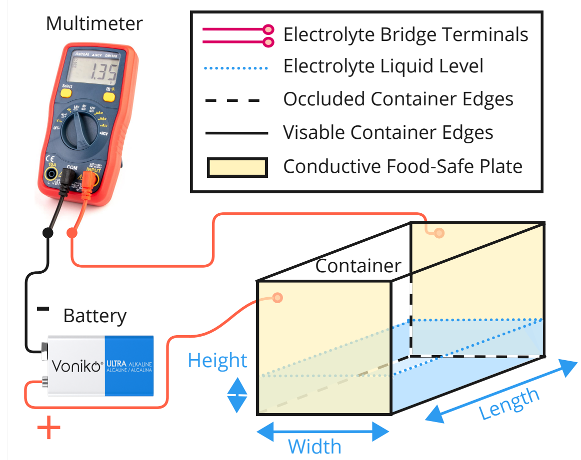

Figure 14: Experiment Testbed Diagram.

8.2 Multimeter as Ground Truth

We use the Multimeter method to obtain ground truth readings for the electrolyte content in various liquids. The voltage and current are measured in order to calculate conductance manually. We utilize an AstroAI DM130B Multimeter [40] and a Voniko 9 V battery [41] attached via a buckle connector. The container and electrolyte terminals used are identical to those used with the ElectroMeter. There are no changes in environmental factors between performing the ElectroMeter and Multimeter measurements.

In our evaluation, we employ a consistent test bed with well-defined characteristics. Since resistance is proportional to the distance between the probes and the area between them, we designed a new rectangular test bed with a precisely defined area. The experimental testbed is shown in Figure 14. The yellow shading represents the highly conductive material (e.g., aluminum or gold) to which the electrolyte terminals are connected. The dimensions of the rectangular test bed are 10 cm x 4.5 cm. When a quarter cup of liquid is poured into this container, the liquid height is 1.3 cm. The same container is used for all experiments. Since the container and terminals remain constant between the Multimeter and ElectroMeter methods, no environmental noise is introduced that could affect our results.

The experimental hardware cost is $27. There are two integrated fuses inside which may need to be replaced if the terminal bridge is connected without a resistance load, leading to additional costs. The Multimeter method and ElectroMeter method have a similar hardware cost within $10 of each other. Using the Multimeter is a simple and well-documented process [11]; however, the sensor suffers from a pain point that is not present within the ElectroMeter sensor system. When measuring current with the Multimeter, there is the potential to easily render the hardware incapable of measurement if there is no load within the circuit while the current is being measured. If the electrolyte bridge is somehow bypassed while measuring current and the bridge terminals become connected, the current reading ability of the Multimeter will be compromised. There must be a load in the Multimeter circuit when the 9 V battery is connected and the current is being read, or the fuse will blow. If the fuse blows, a replacement will be required. ElectroMeter does not have this pain point; the probes can touch each other without damaging the sensor hardware. This is a significant advantage of the ElectroMeter sensor method over the Multimeter method since our hardware does not have a fuse that will blow when a measurement is performed on a fully connected circuit. ElectroMeter is forgiving to users who do not have expertise.

8.2.1 *Mixing Powder Concentrations.*

Two products in our experiment require us to mix them ourselves. We must be precise with the brewing of these electrolyte concoctions so we can determine whether the results align with our intuition that a higher powder concentration will result in a higher electrolytic conductivity μS reading. We choose four concentrations of powder intensity: 13%, 50%, 100%, and 200%. These represent the various intensities that a consumer of these drinks may mix. We use a food scale to measure the ratio of distilled water to powder. This mixing method gives us confidence that these powder solutions are accurately mixed.

8.2.2 *Measurement Procedure.*

We first pour 0.25 cups of liquid into the test bed liquid container. Secondly, we use both ElectroMeter and the Multimeter to measure the conductivity of the liquid sequentially. The physical container and the liquid are not changed between measurements by the ElectroMeter and the Multimeter. We record data for 120 seconds using both methods. Thirdly, after finishing data collection, we empty and wash the container with distilled water so that there is no contamination between experiments. Finally, we proceed to the next liquid being tested. All the liquids measured are at room temperature in a room that is 70 degrees Celsius. The drinks being tested are fresh from the bottle and have not been exposed to the elements.

8.3 Results

The results show that both methods of measurement agree on the same ranking of electrolytic conductivity for all the 13 liquids that we tested. Our primary objective of accurately ranking the electrolyte levels in an array of commercially available liquids has been met. There is some discrepancy in the value of μS between

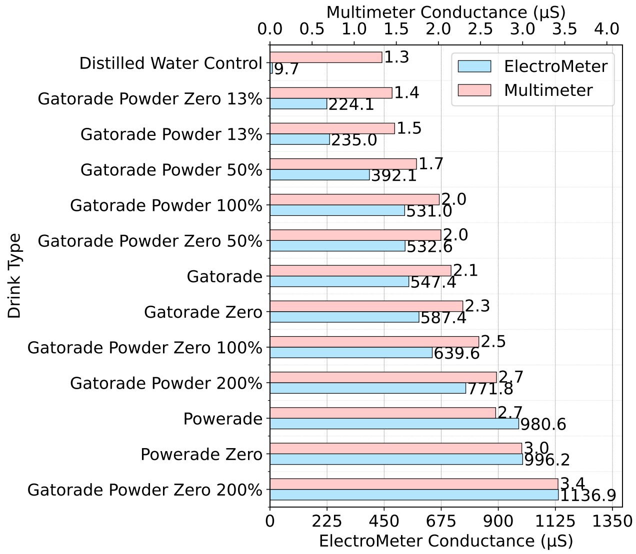

Figure 15: Conductivity by Drink Type.

methods; however, we can resolve this issue via calibration on scientific liquids with known µS conductivity levels in the future.

Figure 15 shows a summary of our results' rankings and µS conductivity measurements. The top x-axis shows the scale of the Multimeter ground truth conductivity readings, which are indicated by the pink bars in the plot for each drink type in the y-axis. The bottom x-axis shows the scale of the ElectroMeter conductivity readings, which are indicated by the blue bars. The plot bars from both the ground truth Multimeter and ElectroMeter conductance readings are synchronized at a maximum value (for Gatorade Powder Zero 200%) at 3.4 and 1136.9 µS respectively. ElectroMeter is able to correctly distinguish between the electrolyte levels in all of our test liquids. There is an agreement between ElectroMeter and the ground truth Multimeter for the ranking of all electrolyte drinks that we tested. The rankings of the liquids align with our intuition that higher concentrations of powder solutions (e.g., 200%) have a higher conductivity than lower-intensity concentrations of powder (e.g., 100% or 50%).

ElectroMeter may be more sensitive to small amounts of electrolytes being added to solutions than in the Multimeter method. There is a greater jump between ElectroMeter's readings for the distilled water control and the Gatorade Powder 13% mix concentrations than is observed with the Multimeter method. ElectroMeter had a reading of 9.7 µS for the control whereas the Multimeter had a reading of 1.3 µS. When considering the second lowest electrolyte concentrated solution, the 13% powder concentration mixes for both regular and Zero varieties of Gatorade are 2300% (9.7 vs. 224.1 µS) than that of distilled water, whereas the Multimeter method only shows an increase of 15% (1.3 vs. 1.5 µS). To investigate this further in the future, concentrations as low as 1% to 13% should also be tested. There may be a point at which one sensor emerges as the clear winner for its ability to distinguish extremely small concentrations of electrolyte content.

We can visualize the disagreement between the ElectroMeter and Multimeter methods by standardizing the scale between the two and then comparing the difference Δ for each drink type. In the results of our current experiment, we can use the liquid with the maximum conductance (Gatorade Powder Zero 200%) to calibrate our scale and set that value to a scaled 1.0 for both the ElectroMeter and the Multimeter methods. This scaling technique facilitates the calculation of relative disagreement between methods. After scaling all the values for both measurement methods, we calculate a difference Δ value for each drink type.

Figure 16 shows the scaled absolute Δ difference between both the ground truth Multimeter method and the ElectroMeter method. In this scenario, Gatorade Powder Zero 200% is serving as a calibration solution to find the maximum agreement value between the MultiMeter and ElectroMeter sensors. This plot highlights how there is the highest relative disagreement between methods on liquids with few electrolytes such as distilled water or only 13% concentration powdered mixes.

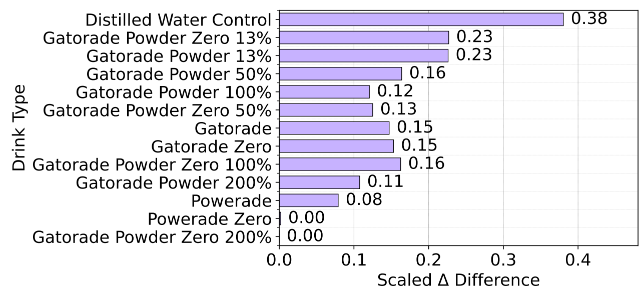

Figure 16: Scaled Δ Difference Between Methods.

8.3.1 *Case Study: Powerade vs. Gatorade Powder 200%.*

We perform a case study to investigate the greatest determining factor of electrolyte content. Interestingly, the 200% concentration of Gatorade powder had a lower conductivity than standard Powerade. This shows us that the concentration of drink mix may not be the greatest determining factor in the electrolyte content of a beverage. The greater determining factors may be the amount of common electrolytes such as potassium and sodium are present in the liquid.

To better understand the impact of electrolytes such as sodium and potassium on the readings from our sensor methods, we can perform a case study. sodium and potassium are two electrolytes that are commonly reported on the nutrition labels of commercially available sports drinks. We can determine the amount contained in each of the case study liquids by inspecting the nutrition labels. We can then compare the sodium and potassium levels for both Powerade and Gatorade powder Zero 200%. The nutrition information and the conductivity measurements are summarized in Table 2.

Drink Type	Na	K	ElectroMeter	Multimeter
Powerade	400 mg	130 mg	980.6 μS	2.7μS
Gatorade Powder 200%	300 mg	100 mg	771.8 μS	2.7 μS

Table 2: Electrolyte Ingredients and Conductance Case Study.

ElectroMeter was able to pick up on differences between conductivities that were not detected with the Multimeter method. This demonstrates the superiority of the ElectroMeter sensor over the Multimeter ground truth method in the ability to identify differences in electrolyte contents. The ingredient breakdown shows that the pre-mixed Powerade has a significantly higher sodium content of 400 mg in a standard serving, which is 133% of the electrolyte content in a 200% concentration of Gatorade powder (400 mg vs. 300 mg), or 266% of the regular 100% concentration of Gatorade powder. The pre-mixed Powerade also has 130% of the potassium content of Gatorade powder at a 200% concentration (130 mg vs. 100 mg). Despite the distinctly higher electrolyte levels in pre-mixed Powerade, the Multimeter records the same electrolytic conductivity value (2.7 μS) for both case study liquids with vastly different amounts of sodium and potassium between them. On the other hand, the ElectroMeter sensor method shows a large difference between the conductivity values of these two case study solutions (980.6 vs 771.8 μS). This difference aligns with our intuition that dramatically raising the sodium content of a beverage will also dramatically raise the electrolytic conductivity. This case study demonstrates that the ElectroMeter can offer increased utility over the Multimeter method if the user desires a method with the ability to distinguish between liquids with a higher amount of common electrolytes such as sodium and potassium. This superior utility is offered while also making user-experience improvements such as being resilient to blown fuses due to the electrolyte terminals touching.

9 DISCUSSION & FUTURE WORKS

Our current solution is not without its limitations. First, additional research must be conducted into the actionable analysis part of our system requirements. How effectively is our solution communicating meaningful information to a real person using it? To answer this question, we must perform a user study. We can use qualitative data to drive the development of our system.

Secondly, we have not sufficiently investigated whether our downstream sensors will work in practice. The development and testing of prototypes are required to ensure that our designs are not flawed. In particular, we must investigate designs such as the produce probe and the medicine bottle.

Thirdly, the current system's implementation is not sufficiently optimized. We have created a prototype version of our system and an experimental liquid container that accomplishes our initial goal of determining between high or low electrolyte contents in liquids while using the minimum resources and hardware required. This limitation will be addressed as we iteratively improve our designs and implementations. We can create well-optimized hardware and software that is both efficient and easy to use. None of these limitations threaten the validity of our system, since they can be addressed in future work. Our system provides value to those who seek to monitor the electrolyte content of liquids.

The exact μS accuracy of the conductivity readings for both the Multimeter and ElectroMeter must be investigated in future experiments. The precise measurement of electrolytic conductivity to the closest μS is not necessary for the scope of this paper, since we have accomplished our goal of correctly distinguishing between levels of electrolytes in commercially available liquids in agreement with the ground truth Multimeter method. Calibration solutions [42, 43] which have a known conductivity value, can be tested so that our model can be fine-tuned. This will ensure that we are giving the true conductivity values. Precise μS values are a secondary objective to providing the primary ability to distinguish between liquids with high or low electrolyte levels– an ability that ElectroMeter already has proven capable of as shown by a successful ranking.

Additional efforts must be dedicated to converting our μS into $\mu S/cm$ so that we can measure electrolyte content in a way that is meaningful to domain experts. The standard unit of electrolytic conductivity is Siemens per meter (S/m) according to the EPA. [44] This challenge can be overcome, thanks to our experimental test bed liquid container's design. We chose a rectangular-edged container with a well-defined area in between the conductive metal walls. We can feasibly convert μS into SI units $\mu S/cm$ for electrolytic conductivity by dividing our reading by the dimensions of the container. It is important to note that an additional ground truth sensor method must be acquired to attain a ground truth for $\mu S/cm$. A commercially available sensor such as the Vernier Go Direct Conductivity Probe [15] or the Extech EC500 Waterproof ExStik II pH/Conductivity Meter [16] should be appropriate for this purpose.

We also need to conduct a user study to assess people's thoughts about our solution, produce prototypes of the downstream sensors, and develop the analysis module to include more sophisticated features that facilitate actionable analysis. Customer discovery interviews will also help us develop useful application-specific downstream sensors.

10 CONCLUSION

We proposed ElectroMeter, a practical electrolyte sensor system that can measure and rank the electrolyte content of any beverage or solution using unobtrusive and user-friendly hardware. We evaluated the system's ability to measure and rank the electrolyte content of a variety of beverages. The results demonstrate that the ElectroMeter accurately determines the electrolyte content of beverages, producing rankings consistent with those generated by the well-established Multimeter ground truth method across all 13 beverages tested. ElectroMeter exhibits superior utility compared to the Multimeter for three reasons. First, it can distinguish small changes in electrolytes, such as potassium and sodium, which the Multimeter cannot. Secondly, ElectroMeter is more robust than a MultiMeter, as it is not damaged if the terminal bridges are directly linked, whereas the Multimeter's fuse blows under similar conditions, necessitating the costly and frustrating experience of replacing hardware components. Thirdly, ElectroMeter's electrolyte model automatically calculates conductance, whereas the MultiMeter method requires the user to manually calculate conductance based upon the current and voltage values. These three key advantages show that the ElectroMeter sensor is superior to the manual conductance calculation via the MultiMeter method. We have answered our research question by developing a user-friendly ElectroMeter sensor system capable of measuring electrolyte levels in commercial beverages, enabling users to make informed choices about their best options.

11 APPENDIX

11.1 Downstream Sensor Designs

We design several downstream sensors intended for application across various domains, spanning from healthcare to food production. The feasibility of these applications needs to be explored by creating prototypes. In each of these designs, we have opted to omit the microcontroller and other internal components. Instead, we focus on highlighting the points of contact between the circuit and the solution, represented by circular shapes. These points correspond to the electrolyte bridge terminals discussed earlier in Section 5.2.1, serving as crucial elements for interfacing with the solution. The end-users of these designs range from general user groups such as people with hypertension, athletes, or seniors to specialized user groups such as food producers or medical practitioners. These characters should all be interviewed in order to guide the development.

11.1.1 Water Bottle. The Bottle shown in Figure 17 is the first design aimed at consumers. For example, students, athletes, and senior populations. The need for these users is to monitor the quality of their hydration beverages for electrolyte replenishment. The solution for these users is to embed a sensor inside a cap that can measure the quality of any solution inside. This product will be safe to use. The battery will be separated from the container so that there is no risk of contaminating the beverage. When the bottle is upright, there will be no contact made between the sensor and the liquid. There will only be a measurement made if the bottle is turned upside down. This design means that the circuit components are minimally exposed to the liquid inside. This design could be used as an aid for practitioners in assessing the electrolyte consumption of patients over some time. In addition to manually logging beverage nutrition, our sensor can offer a supplementary source of data and help the practitioner develop an appropriate care plan for the patient.

Figure 17: Bottle.

11.1.2 Medicine Bottle. The medicine bottle equipped shown in Figure 18 could be used by hospitals and medical practitioners. These users need to monitor the state of concealed high-value liquids within medicine bottles. Our design for this medicine bottle incorporates embedded sensors, strategically positioned at various elevations within the bottle. Different elevations within the bottle may have different voltage levels, indicative of various properties and conditions of the liquid. By analyzing changes in voltage levels or other pertinent data, the system can flag instances where the liquid's integrity may have been compromised, signaling the need for further investigation or intervention. This approach to medication management may optimize operational efficiency within medical facilities. The feasibility of this design must be investigated.

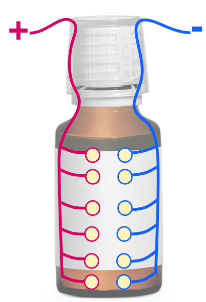

Figure 18: Medicine Bottle.

11.1.3 Insulated Beverage Cooler. Those who mix their electrolyte beverages with powder mixtures can also use our sensor. Our sensor-equipped solution offers convenience and precision in beverage preparation to fitness enthusiasts, athletes, or even sports teams and organizations. Consider the scenario of sports teams relying on Gatorade powder for hydration needs. The integration of our sensor into the cooler shown in Figure 19 allows users to achieve the optimal ratio of powder to water. The sensor guides users to attain the perfect balance, ensuring the resulting beverage tastes great and delivers the intended benefits. This design eliminates the guesswork and ensures consistency. Athletes can trust that their hydration needs are met optimally, enhancing performance and recovery. Moreover, organizations overseeing multiple teams or large-scale events can streamline beverage preparation processes, saving time and resources while guaranteeing quality.

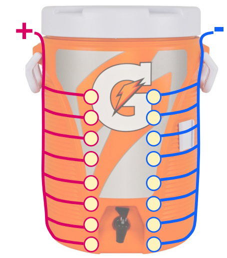

Figure 19: Insulated Beverage Cooler.

11.1.4 Produce Probe. The produce probe shown in Figure 20 is another downstream sensor tailored for food producers, a user group with unique needs. While less common than other user groups, their demand for quick quality assessment of fruits in field settings is significant. For instance, when deciding between trucks of apples, a food producer could benefit from a rapid sensor to discern the best quality. Equipping our sensor technology into a probe allows for swift electrolyte measurements directly within the fruit. Currently, sophisticated chemical tests can be performed to determine electrolyte contents in produce like citrus fruits. [36] Our probe doesn't aim to replace these tests but provides an additional tool for quick field measurements. This is a supplementary ability that can give a quick indication in a matter of minutes and can be performed by any person without particular expertise. Thorough investigation and validation are imperative to determine its feasibility.

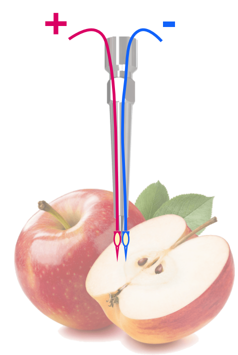

Figure 20: Produce Probe.

11.1.5 Blender. The electrolyte blender shown in Figure 21 is useful for general consumers and also food producers. It is common for individuals to make beverages at home for a range of purposes. In households, blending beverages has become a common practice for various purposes, including meal replacements. [45] Our innovative blender design caters to this trend by enabling users to create delicious and electrolyte-rich smoothies or shakes with ease.

Users will be able to store data from previous recipes, serving as a valuable resource for users in their quest to concoct new and improved health drinks. This design would not only enhance convenience but also foster creativity by allowing users to build upon their past experiences and experiment with different combinations of ingredients. Food producers can use this device effectively in the field by placing a sample of the prospective fruit supply inside the blender, processing it, and measuring the electrolyte content.

Figure 21: Portable Blender.

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