Design and Evaluation of a Mobile Sensing Platform for Water Conductivity

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***Abstract*—Electrical conductivity (EC) is one of the many water quality parameters that provides an indication of total ionic contaminants in water. This is traditionally measured with either lab-based equipment or battery-powered portable meters. These tools are expensive and require expertise to use, hindering their widespread adoption. We aim to address this challenge based on a custom-made electrode and processing unit that can be plugged into a smartphone via the USB port. In this paper, we present the design, development and evaluation of our mobile sensing system that is low cost (<35 USD), easy-to-use (SUS score of 89.3) and accurate. Our initial testing suggests that the sensor is able to measure EC with $<3\%$ root mean squared percentage error compared to a lab-based instrument. We believe our approach will empower a large group of people to contribute to water quality measurements.**

***Keywords*—Citizen Science; Eletrochemical Sensor; Mobile Sensing; Water Quality**

I. INTRODUCTION

Contamination of freshwater sources is a growing concern, especially with the increasing population and urbanisation [1]. Washout of air pollutants, road surface contaminants, household chemicals and [2] industrial activities [3] contribute to the declining water quality in urban areas. In rural settings, agricultural runoff is a major contributor to water pollution [4]. Therefore, it has become vital to analyse and monitor the quality of these sources in the interest of public health.

Sensing at scale (frequent sampling in terms of locations and across periods) is still an open problem due to lack of skilled workforce, high cost and unavailability of specialised technology. Several ongoing works [5, 6] aim to sense various water quality indicators such as pH and conductivity. These prototypes are expensive, bulky and require expertise making it hard to use them at scale. We investigate the challenge of designing an easy-to-deploy, low cost sensor to measure the total ionic contaminants with sufficiently high accuracy.

Our approach includes a plug-and-play sensor and a companion mobile app. The sensor is based on the Electrical Conductivity (EC) of water. Although EC alone is not sufficient to assess the quality of a water source, the trend of electrical conductivity over time can help detect discernible changes in pollutant load [7, 8].

We tested the accuracy of our sensor with various ionic contaminants found in natural water and benchmarked that with industry-grade lab-based analysers. Based on our initial testing, we found that our sensor achieves a 2.51% root mean squared percentage error (RMSPE) on a set of freshwater samples while remaining under 100 USD in total manufacturing cost. We have also developed a smartphone app with cloud data storage to complement the sensor. The app was evaluated for its usability and received a score of 89.3 on the System Usability Scale (SUS) [9]. With this we confirm that our approach results in an easy-to-use and affordable sensor that can be used without specialised training. This could enable the general public to generate significant data with good coverage, as identified by Njue et al. [10].

In summary, our contributions include:

- Technical details of the development of a portable, low-cost, and scalable water conductivity sensor and evaluation of its performance.
- Development and evaluation of a user-friendly smartphone app and a cloud platform for data collection and visualisation.

Figure 1 illustrates the proposed solution consisting of three systems (1. Measurement system (Sensor), 2. Data processing system (Smartphone), and 3. Data storage system (Cloud service)).

Measurement system consists of a planar electrode connected to a custom measurement circuit. These two components are described in detail in section III. The data processing system (smartphone) improves the sensor readings by utilising smartphone's processing and location capabilities. These augmented readings are then stored in a cloud service (central data storage system).

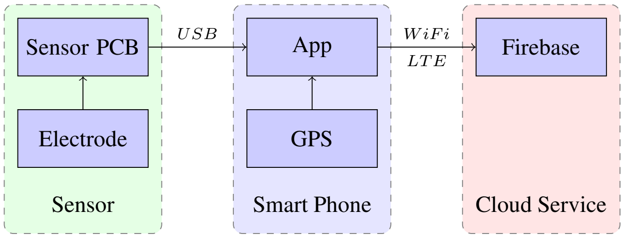

Fig. 1: System architecture

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II. Related Work

A. Water quality & sensing

The approaches to sensing electrical conductivity range from hobbyist's do-it-yourself sensor to high end laboratory instruments. At one end, methods such as use of a multimeter to measure the DC resistance and calculate the conductivity [11], or Arduino microcontroller board in place of the multimeter in a similar approach [12] are relatively low cost and easy to set up. However, the accuracy is low. On the other end of the spectrum, laboratory grade instruments such as ion chromatography, Orion[13], or professional portable meters such as CA 10141 [14] achieve a higher accuracy and repeatability at a higher cost, but require expert training.

B. IoT in water sensing

Work has been done on developing a water conductivity sensor that communicates using wireless protocols for long distance data collection [15]. Other research, [16], [17] include additional water quality parameters such as turbidity, temperature and pH. A wide range of connectivity options have been explored in the prior work in sensing water quality, starting from low power long range protocols such as Zigbee [15], [17], [18], to general purpose protocols such as GPRS [16].

The ubiquity of the modern smartphone makes it a reasonable choice as a computing device that would complement a portable sensor. A well designed app can present a user friendly interface and leverage the communication and location capabilities of the smartphone.

III. Development of the Sensor

A. Electrodes

Electrical conductivity between two electrodes in a solution can be approximated by 1) where d and A represents the separation and area of the electrodes, while R_{BULK} represents the bulk resistance of the solution ([19]).

$$Conductivity(\sigma) = \frac{1}{R_{BULK}}\frac{d}{A} = \kappa\frac{1}{R_{BULK}} \tag{1}$$

κ values can be obtained for the planar interdigital electrodes using (2)([19]). a is the ratio between thickness and spacing of digits of the electrode.

$$\kappa = \frac{\epsilon_0\epsilon_r}{C} = \frac{1}{(N-1)L}\frac{2K[cos(\frac{\pi}{2}\frac{1}{a+1})]}{K[sin(\frac{\pi}{2}\frac{1}{a+1})]} \tag{2}$$

The reusable electrodes are manufactured using inexpensive Printed Circuit Board technology, consisting of thin gold plated copper on an FR4 substrate (Figure 2).

B. Sensor PCB

The measurement system is designed around Analog Devices AD5933 2-port impedance converter chip (Figure 3 B) configured for a 2 kHz output. The analog front end of AD5933 is complemented by two amplifiers (Figure 3 A) acting as buffers to manage input and output impedance.

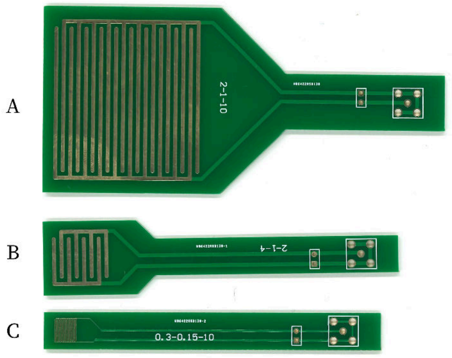

Fig. 2: Custom-made Electrodes of 3 sizes.

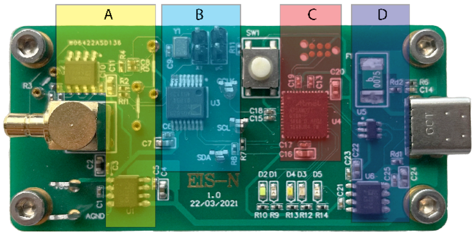

Fig. 3: Sensor PCB. A - Analog frontend with two amplifiers, B - AD5933 impedance converter, C - ATSAMD21G18 microcontroller, D - Power management and input protection

A Microchip ATSAMD21G18 microcontroller (Figure 3 C) functions as the main controller for the sensor. It communicates with the impedance converter through an I^2C bus and transmits the data to the mobile device over a USB connection using the USB-CDC protocol. Also, the sensor is powered by smartphone through the USB-C port and carries a self-resetting fuse and Electrostatic Discharge (ESD) protection diodes (Figure 3 D) to protect both the sensor and mobile device from power-related incidents.

IV. Evaluation of the Sensor Performance

A. Effect of electrode size

The sensor reports the impedance measured as a complex number. This can be converted to Electrical Conductivity using

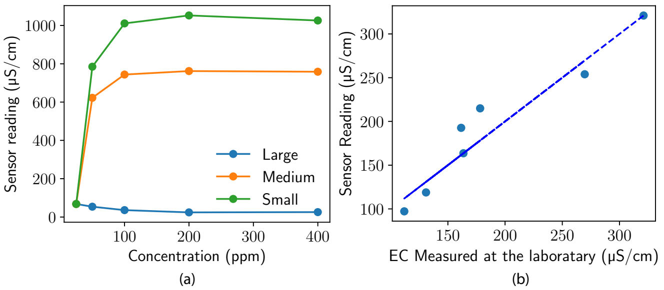

Fig. 4: Conductivity readings from the sensor (a) Effect of electrode size (b) Calibrated sensor output vs laboratory measurement for real world water samples

the equation (3) and cell constant(κ) derived in (2).

$$EC = \kappa / \sqrt{Real^2 + Imaginary^2} \tag{3}$$

The first stage of the evaluation was to compare the effectiveness of different electrode sizes. Three electrodes rated Large, Medium and Small were compared with a series of $\mathrm{NH_4Cl}$ solutions ranging from 25-400ppm. From the results shown in (Figure 4(a), it is apparent the smallest electrode offers the best measurement range before saturation.

B. *Sensor Performance*

Seven samples were collected from water streams covering urban and suburban parks, stormwater drains, treated wastewater drains and rural farmlands. Each sample was separated into two parts. One part was measured for electrical conductivity at the laboratory using a *Thermo Scientific*™*Eutech CON 450* and the other was measured using our sensor.

The final sensor reading was calculated following a two-point calibration. These figures were compared against the reading from the *Thermo Scientific*™ instrument, and the RMSPE was found to be 2.51%, as shown in Figure 4(b).

V. MOBILE SENSING PLATFORM

A. *Development of the platform*

The main requirements for the smartphone application were identified as

1) Ease of use
2) Geotagging sensor reading using localization features of the phone
3) Visualising and publishing data to a central database

The USB connected sensor is powered by the smartphone battery and sends the data to the app through the same connection. The data processing happens on the app, using the powerful smartphone processor. The backend data storage system is built on Google Cloud Firestore, known for its offline synchronisation capabilities and excellent scalability.

B. *Workflow*

The user connects the sensor to the smartphone using a USB cable (Figure 5a), which will trigger the mobile app to open and display a live feed of the conductivity readings (Figure 5b). The user can then capture the reading and opt to save it to the database (Figure 5c). In this step, the user is presented with a list of *sampling locations* in the vicinity. The user can select the location of the current reading (Figure 5d) or add a new *sampling location*. As the last step, the user will click 'Save', and the application will ensure the reading gets uploaded to the clour service. In order to get a comprehensive picture of spatial or temporal trends of conductivity, the user has the option of navigating to the location list view (Figure 5d) or the map view (Figure 5e).

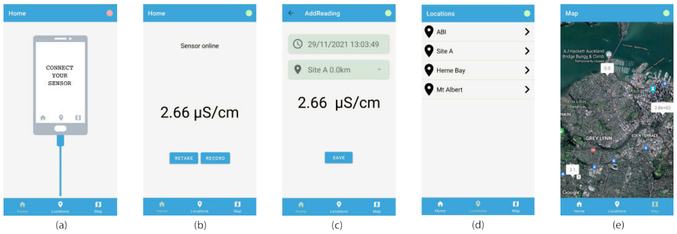

Fig. 5: Screenshots from the smartphone app. (a) Homescreen (b) Live data from the sensor. (c) Recording screen with time and location selection. (d) List of all the sampling locations. (e) Map displaying most recent data.

VI. USABILITY EVALUATION

The mobile app was distributed to 12 participants. Eight of the participants had prior experience with field data collection work. The participants were given a sensor with a similar operation and a document outlining instructions for the evaluation along with instruction videos for the sensor and the mobile app. Finally, they were asked to complete a questionnaire on the System Usability Scale (SUS)[9].

The SUS score had a mean of 89.3 and a standard deviation of 7.62, implying the mobile app had a high usability.

VII. LIMITATIONS AND FUTURE WORK

The sensor evaluation with real world samples has been limited to a narrow EC range of $100-400\mu S/cm$. This covers the lower conductivity range for most freshwater streams, and it would be ideal if the sensor was tested for higher conductivity values as well.

The electrodes were not tested for durability. However the gold-plated electrode is in contact with the sample only for a short duration ensuring longevity. Even if the electrodes degrade, they are inexpensive and easily replaced.

The sensor will not communicate with iPhones due to manufacturer restrictions. This can be overcome by enrolling in the Apple MFI program or by including wireless communication capabilities.

In addition to EC, measuring the concentration of individual ions can be beneficial, especially since agriculture can introduce specific ions to the water [20]. Our preliminary work with high-frequency impedance spectroscopy indicates that ion-selective electrodes or optical spectroscopic methods may be more effective.

VIII. CONCLUSION

The mobile sensor we introduced in the paper was able to produce results within a 3% range compared to a lab-based instrument. The associated mobile app was found to be easy to use through a user study. This ease of use empowers the general public to participate in data collection, leading the way to citizen science. The cost of the overall system was kept low by leveraging the features of smartphones. Future work could take the direction of improving the sensing accuracy and identifying specific ions.

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