A Wireless System for Continuous In-mouth pH Monitoring

Daryl Ma*†, Christine Mason, Sara S. Ghoreishizadeh*†

*Dept. of Electrical & Electronic Eng., † Centre for Bio-Inspired Technology, Imperial College London, UK

Email: {dm2913, s.ghoreishizadeh14}@imperial.ac.uk, toothfary.mason@gmail.com

***Abstract*—A first prototype of a Smart Orthodontic Bracket (SOB) for continuous in-mouth pH monitoring is presented in this paper. The SOB system uses an Iridium Oxide (IrOx) pH sensor with 68.8 mV/pH measured sensitivity. It is powered through Near Field Communications (NFC) using a smartphone from a distance of 3.5 cm. The system resolves pH variations as small as 0.15 within a wide range of pH. The system is encapsulated in bio-compatible epoxy resin and successfully used to measure the pH in saliva.**

***Index Terms*—pH sensing, Near field communication, wireless system, Continuous measurement, wearable system**

I. Introduction

Saliva sampling is an emerging diagnostic technique used as a non-invasive alternative to blood sampling. It can identify health conditions such as diabetes, inflammation, infection, as well as hormonal perturbations [1], and has been increasingly used by dentists and clinicians as part of routine medical examinations. In particular, the baseline and variation of pH in saliva has been shown to be an indicator of dental health [2]. The baseline pH is within the narrow range of [7, 7.5] for a healthy person [3]. The pH levels drop (below 5) after drinking an acidic substance and reverts back to the baseline value after approximately one hour. A low baseline level (i.e. [5,7]) or lasting low pH episodes stimulate bacterial growth in the mouth and tooth decay. This could occur due to teeth enamel issues, or silent gastric reflux. Thus, continuous monitoring and balancing the pH of the mouth is essential to reduce bacteria causing tooth decay.

Current commercial options for wireless pH sensors consists of large glass pH sensors with inbuilt batteries which are cumbersome for wearable usage. Prior research includes the colorimetric detection of pH using a smartphone-based accessory [4]. Here, a test strip containing the user's saliva is inserted into an optical system integrated in a smartphone case. The pH of the saliva is then detected through the application of colour reagents. In [5] an iridium oxide (IrOx) pH sensor was used in tandem with a Resistor-Inductor-Capacitor (RLC) coil resonator. The pH variation alters the resonant frequency of the resonator. This is detected using an interrogator coil that transmits power to the device at 18 MHz.

In this work we present a small, wireless and wearable SOB that can be fitted in the mouth and continuously monitor the pH value of saliva with a high precision. The SOB allows frequent measurement using a smartphone as the reader. The measurement frequency and time depends on the reader and would most likely be performed an hour after eating, after having an acidic drink, or just after waking up.

In the next section the design rationale behind the choice of the pH sensor, energy harvesting and wireless communications are described. Experimental results validating the choices are presented in Section III. In Section IV the fabricated prototype and pH measurement results with saliva samples are presented, followed by the conclusion and future work.

II. System Design

The physical form of the SOB has to avoid interference with the user's jaw motion. Fig. 1 describes the envisaged placement of the SOB on a commonly used retainer.

The use of a retainer allows for the SOB to extend towards the side of the mouth in order to avoid the user's jaw motion. This method allows the greatest variety in terms of the device shape as compared to other dental equipments. The maximum device size is limited to $3{\times}3$ cm to ensure safety of the user when placed in the mouth.

The two key design choices are the pH sensing and the energy harvesting module. The component choices behind these two modules are detailed in this section.

A. pH Sensing

Glass electrodes, *Ion Sensitive field effect transistors* (ISFET), and IrOx electrodes are the most commonly used methods for pH sensing and are compared here based on their sizes and biocompatibility.

Although glass electrodes meet the biocompatibility condition, the smallest commercially available glass electrode is more than 10 cm long which is not suitable in this application. ISFETs [6] provide low-cost scalable sensing on unmodified CMOS technology. The ISFET are also passivated in silicon nitride which is bio-compatible. However, they are not yet commercially available and require long fabrication times.

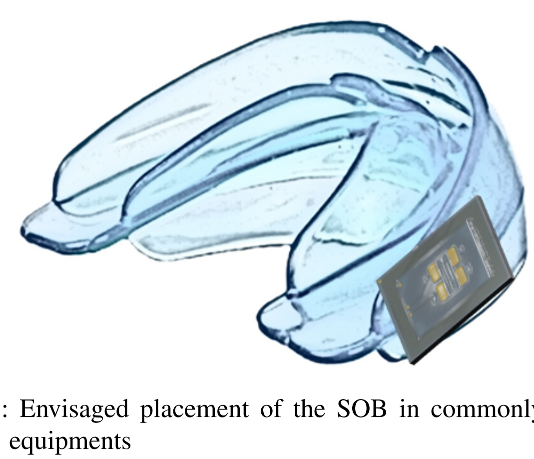

Fig. 1: Envisaged placement of the SOB in commonly used dental equipments

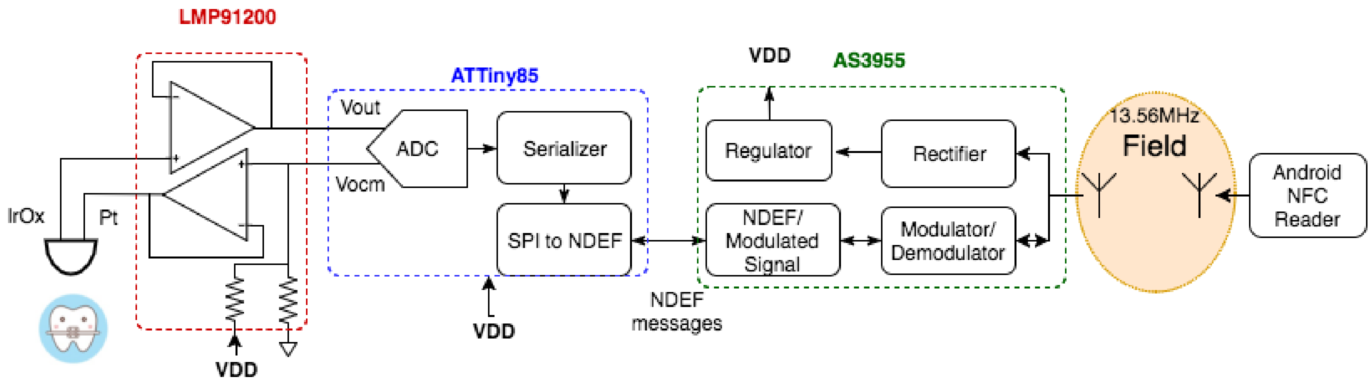

Fig. 2: The block diagram of the proposed pH-monitoring system

IrOx is a bio-compatible material used before in implantable applications [7] and chosen in this work due to its small form factor, bio-compatibility, ease of fabrication and relatively high sensitivity to pH.

B. Energy Harvesting

State-of-the-art physical energy harvesting options such as thermoelectric [8] [9] and motion harvesting [10] [11] [12] currently do not provide sufficient power for an embedded system. Inductive coupling is chosen due to the possibility of supplying more than 1 mW of power. In order to meet the industrial, scientific, and medical (ISM) radio band requirements, a 13.56 MHz-based inductive link is chosen. This opens the prospect of using NFC for communications. Commercial NFC ICs were compared, from which the AS3955 IC is chosen due to its small size, standard serial communication (I2C or SPI) and EEPROM which makes it capable of storing data to be read from any NFC-enabled device.

C. Implemented System

The block diagram of the proposed wireless system is shown in Fig. 2. An open circuit voltage measurement is performed between the IrOx electrode and a platinum wire as the reference electrode. Here a voltage of $V_{DD}/2$ is applied to the reference electrode through a buffer and the voltage at the IrOx electrode is read through a second buffer that does not allow any current flow into the sensor. This is done by the analog front-end IC (LMP91200 from TI) which is chosen for its low power consumption (165μW), as well as its internal potential divider that provided a reference voltage. This reduces the need for additional external resistors.

The output of the read out circuit is then fed into an ADC to be digitized. A voltage to pH conversion is then performed based on the measured linear characteristics of the pH sensor. This pH value is transmitted via NFC Forum Data Format (NDEF) through an SPI interface to the NFC IC. An ATTiny85 microcontroller is used for its low power consumption and its ability to be configured at SPI interfaces. The clock frequency of the microcontroller is set to a minimum (128 kHz) to minimize power consumption of the device.

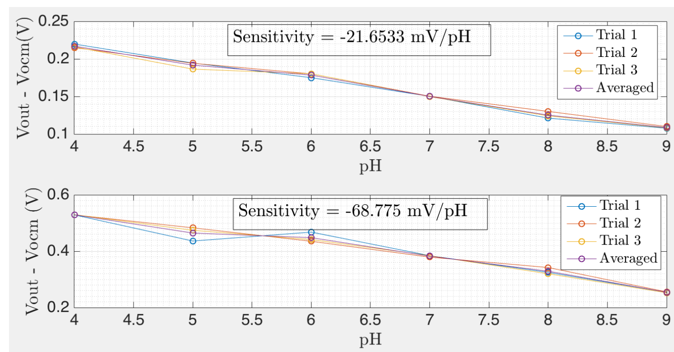

Fig. 3: pH measurement acquired with fabricated IrOx electrode and two different reference electrodes: Pt Wire(top) and Ag/Agcl (bottom)

The received NDEF messages at the NFC IC are then converted into a modulated signal (by the NFC Tag Logic available in the AS3955) and transmitted to the reader (i.e. the smartphone) via load modulation. The power management unit on the NFC IC consists of a rectifier and a voltage regulator that provide a stable 3.3 V supply voltage for the microcontroller and the analog front-end IC.

III. Experimental Results

A. IrOx pH sensor

The IrOx sensors were made by oxidizing Iridium wire (178 μm diameter, 99.9% purity from ADVENT RM) by immersion in a sulfuric acid solution (5%V/V from Sigma). To enable oxidation of Iridium, an Ag/AgCl reference electrode and a Platinum counter electrode were placed inside the solution and repetitive cyclic voltammetries between -0.2 and 1.2 V with 1.4 V/s scan rate were performed on the three electrodes (i.e. Ir wire as the working electrode) for 3 hours.

A calibration step was run to find the sensitivity of the fabricated IrOx electrodes using a standard Ag/AgCl reference electrode. The results are plotted in Fig. 3. The average sensitivity was found from three trials to be -68.775 mV/pH. However, as the standard reference electrodes are quite large,

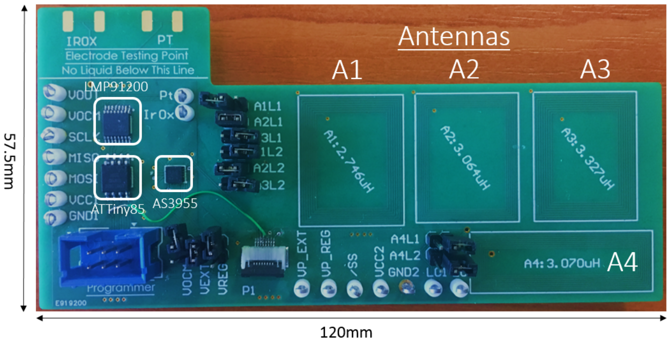

Fig. 4: The photograph of the fabricated test PCB with different antennas designed for testing

Antenna No.	Simulated (μH)	Measured (μH)	Max distance* (mm)	Supplied Power (mW)
A1	2.746	2.8	31	4.2
A2	3.064	3.1	35	6.3
A3	3.327	3.3	32	4.6
A4	3.070	2.8	–	–

*between antenna and phone case

TABLE I: Antenna Characterization results

a platinum wire reference electrode was used instead. The calibration was repeated with the use of a Pt wire which show the sensitivity has dropped to -21 mV/pH. This could be attributed to the higher internal resistance of the Ag/AgCl electrode [13].

B. Receiving antenna

An antenna with an inductance of 3.061μH is required to achieve resonance at 13.56 MHz with the internal capacitance of the NFC IC (45 pF). Inspired by the antenna design on the commercial NFC tag, four rectangular antennas with different geometries (i.e. diameter, wire thickness and spacing) were designed in order to find the optimal design that achieves a maximum output power when exposed to the electromagnetic field at 13.56 MHz. The inductance of each antenna, L_{ant} was first calculated by [14]:

$$L_{ant} = 2.34 \times \mu_0 \times N^2 \times \frac{\frac{d_{out}+d_{in}}{2}}{1 + 2.75(\frac{d_{out}-d_{in}}{d_{out}+d_{in}})} \tag{1}$$

where d_{in} and d_{out} are the inner and outer diameters of the rectangle and N is the number of turns. An on-line tool [15] was then used for fine tuning the gap size between the turns and the thickness of the wires as well as to ensure the accuracy of the calculations.

The antennas are fabricated on a PCB (See Fig. 4) and their inductances are measured using a RLC meter. The antennas are then tested together with the other components (NFC IC, microcontroller and the analog front-end) with a smartphone used at a controlled distance from it to power on the system. Measurements showed that antennas A1, A2 and A3 are capable of powering the device on, while antenna A4, which has a base ground plane, is unable to do so. The maximum distance in air beyond which the connection with the smartphone reader is lost is measured and listed in Table I along with the corresponding supplied power at that distance. Antenna A2 shows the ideal properties and is chosen in the final fabricated prototype.

TABLE II: System Performance and design summary

Parameter	value
Max distance	35 mm
pH sensitivity	-21.6 mV/pH
Min resolvable pH change	0.15
Encapsulated dimension	21.01x 26.43 x5.30 mm^3
base material	FR-4
encapsulation	Epoxy resin
Power consumption*	3.6 mW

* excluding NFC IC

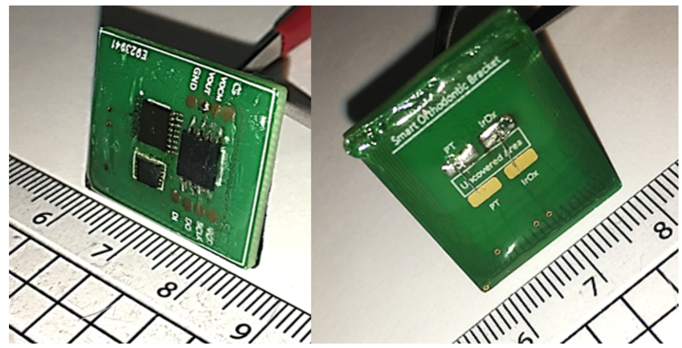

Fig. 5: Final Prototype encapsulated in biocompatible epoxy. Top side with components (left); and bottom side with antenna and IrOx electrode and Pt reference electrode.

IV. Fabricated Prototype

The fabricated device is shown in Fig. 5. It measures 2.1×2.6 cm (limited by the size of the antenna) and is fabricated (using a commercial PCB technology) on a FR-4 material, with a 1.55 mm thickness. The measured power consumption of the system from the generated V_{DD} is 3.6 mW.

The three ICs are soldered in the center on the top side of the PCB and the IrOx and Pt electrodes are placed at the bottom side together with the antenna. In order to place the device in a user's mouth, or in a liquid buffer for testing, the whole device, except the IrOx sensor and the Pt wire, is encapsulated in a biocompatible epoxy resin (EPO-TEK 301 from Epo-TEK) one side at a time and cured for 2 hours per side. The performance of the SOB is summarized in Table II. The minimum resolvable change for pH is calculated based on the use of Pt wire as the reference electrode and the 10-bit ADC on the microcontroller.

The encapsulated device is tested with human saliva in order to validate its performance. Different saliva samples are taken at approximately 10 second intervals after soda and an acidic meal is consumed. The smartphone was kept at a distance of 2 cm from the device. The pH was read on the smartphone

TABLE III: Comparison with state-of-the-art

Paper	pH Sensing	Continuous?	Power cons.	Size	Frequency	Max Distance	Bio. pack.*
[5]	IrOx	Yes	Inductive Coupling	4cm x 3cm	18MHz	18cm	No
[4]	Optical	No	Smartphone Battery	NA	–	NA	Yes
[16]	Micro pH Electrode	No	Wired Power Supply	NA	–	NA	Yes
This work	IrOx	Yes	Inductive Coupling	2.1x2.6cm	13.56 MHz	35mm	Yes

* Bio. pack.= Bio-compatible packaging

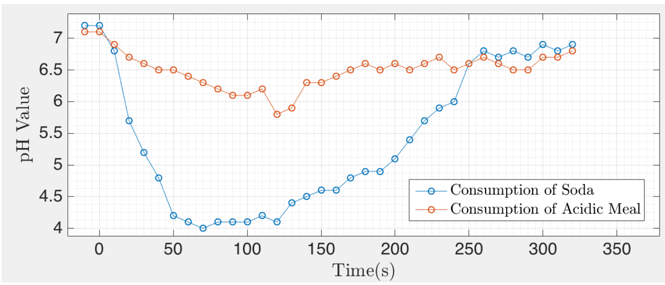

Fig. 6: The measured pH of saliva using the fabricated prototype, before and after consumption of Soda and meal

immediately. The results are presented in Fig. 6, showing a clear change in the pH in both scenarios.

The pH value of the mouth at -10 s indicates the pH value before consumption at 0 s. The pH rapidly decreases after the consumption of soda. This is due to the high acidity of the soda (pH=3) being detected. This acidity is then counteracted by the mouth producing more saliva, which brings the pH back up to near the rest state.

A less drastic change in the pH is observed after consumption of the meal. This is due to the meal being solid, which takes time to be broken down. Table III compares the proposed SOB prototype with state-of-the-art, showing that the presented system is the smallest wearable and wireless device that allows continuous pH sensing.

V. Conclusion and Future Work

A wireless embedded system is presented for continuous pH sensing in the mouth. The system uses standard NFC for power transmissions and data communication. It consumes 3.6 mW power provided and communicates to the smartphone up to a distance of 35 mm. The final prototype is encapsulated in biocompatible epoxy resin, is relatively small, and has been successfully used to measure the pH change of saliva after meal and drink consumption.

With the simple interface of a smartphone, monitoring and diagnostics could be done by individuals regularly, without the need for medical professionals. With wireless powering, maintenance requirements (i.e. battery recharge, replacement) are greatly reduced, making the SOB suitable for everyday usage. Ongoing work is focusing on developing a miniaturised SOB capable of sensing other metabolic analytes and bacterial infections.

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