Development of Urine Conductivity Sensing System for Measurement and Data Collection

Roozbeh Falah Ramezani[1(✉)], Abdul Hadi Nograles[2], Wen-Yaw Chung[1], Jennifer Dela Cruz[2], Kuan-Hua Li[1], Chean-Yeh Cheng[3], and Vincent Tsai[4]

[1] Department of Electronic Engineering, Chung Yuan Christian University, Chung-Li, Taiwan, ROC
s3153079@gmail.com
[2] Department of Electronics Engineering, Mapua University, Muralla St., Manila, Philippines
[3] Department of Chemistry, Chung Yuan Christian University, Chung-Li, Taiwan, ROC
[4] Ten-Chen Medical Group, Chung-Li, Taiwan, ROC

Abstract. This paper presents the design of an analog front-end of an electrochemical conductivity sensor. This forms part of a multi-parameter sensing device for use in the detection and diagnosis of urolithiasis in its preliminary stages. The proposed conductivity bio-sensor is used for measuring the concentration of total dissolved salts in urine. It will be combined with FET-based potentiometric sensors for measuring Ca^{2+} and pH, and an amperometric sensor for measuring uric acid into an integrated lab-on-a-chip point-of-care device.

Furthermore, measured data are collected and stored in a database for future use in an AI (Artificial Intelligence) diagnosis system. Such a multi-parameter approach caters for a more effective stone-risk indexing.

The conductivity sensor readout circuit works on the principle of electrochemical impedance spectroscopy. The sample under test (urine) is subjected to a constant sinusoidal current which causes it to develop a potential difference. The sample interface is via four-point gold coated flat electrodes. The true RMS (root mean square) value of current and voltage is measured and impedance magnitude is calculated by dividing voltage to current.

Measurement is iterated for several frequencies in the range between 1.5 kHz and 3.3 kHz. The frequency is selected from prime numbers to avoid harmonics distortion.

The proposed system has been tested in an on-board platform and the results of the measurement are correlated to a commercial conductivity meter device. The developed conductivity sensor and its readout circuitry have potential usage in point-of-care test device for urolithiasis prognosis and screening.

Keywords: Conductometry · Conductivity meter · Electrochemical impedance spectrometry · Urine studies · Urolithiasis · Point-of-Care · Conductivity sensor

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1 Introduction

Diagnosis of Urolithiasis (kidney-stone formation) in early stage by testing urine sample using multi-sensor platform is presented in [1]. Improving the accuracy of measured parameters, collection and storing such data contributes to more efficient stone-risk indexing. Multi-frequency bio-impedance measurement is a disruptive technology as it is both non-destructive and relatively simpler to implement especially in portable or point-of-care based systems. This paper presents a novel system for measuring and storing the data of urine sample conductivity. A design of multi-frequency bio-impedance spectroscopy system is presented in [2]. The system is combination of front-end analog signal conditioning circuit and FPGA as digital back-end. The frequency range between 10 kHz and 250 kHz is used in their system. In [3] multi-frequency range between 3 kHz and 1 MHz and mono-frequency of 50 kHz is used for measuring the whole-body and thoracic bio-impedance. A Design of bio-impedance spectrometer for early detection of pressure ulcer with frequency range between 10 Hz and 1 MHz is presented in [4]. Multi-frequency electrical impedance is used for skin cancer identification [5] using 31 logarithmically distributed frequencies between 1 and 1000 kHz. For the circuit interface to the sample under test, a two-point probe setup was used in [5] which makes the implementation simpler whenever the impedance of the sample is larger than that of the electrode's equivalent impedance. However, a four-point probe setup is suggested to have a more accurate reading that is unaffected by electrode impedances as suggested in [1–4].

The block diagram of system presented in this paper is shown in Fig. 1:

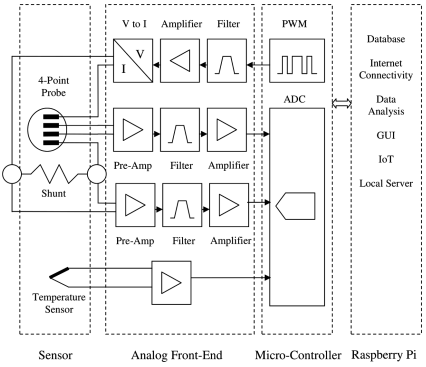


Fig. 1. Conductometric sensor system

Four-point probe forms the urine sample sensor. The desired PWM frequency generated by micro-controller passes through a band-pass filter. The filter outputs a sinusoidal wave that is coupled to an amplifier. Then, the voltage signal is converted to a constant current and fed to the outer probe of the sensor. Such current passes through the urine sample and creates a voltage proportional to its resistance measured between the inner probes. Resistance is function of conductivity and geometry of the sensor.

The voltage signal will pass through pre-amplifier block formed by a high CMRR (Common Mode Rejection Ratio) instrumentation amplifier (IA). The output of the IA passes through a band-pass filter. The succeeding block is a signal conditioning amplifier which brings the signal to the level of ADC (Analog to Digital Converter) input. The microcontroller uses the ADC measured value for calculating the amplitude of impedance of the sample.

In addition, the micro-controller communicates with a Raspberry Pi single-board computer through SPI (Serial Port Interface). Raspberry Pi acts as local server that keeps the database, analysis the data, provides internet connectivity. It also acts as GUI (Graphic User Interface) for overall system.

2 Methodology

Our preliminary tests of several samples include KCl, NaCl solution and urine shows decrease of impedance against increase of frequency that agrees with the results in [1] and [2]. Thus the simplified equivalent circuit shown in Fig. 2 is used for total impedance of sample. Conductivity of sample is measured by the system while eliminating the effect of parasitic capacitance.

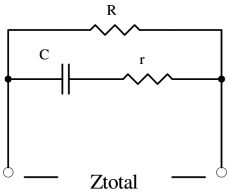


Fig. 2. Electrical equivalent circuit of the sample

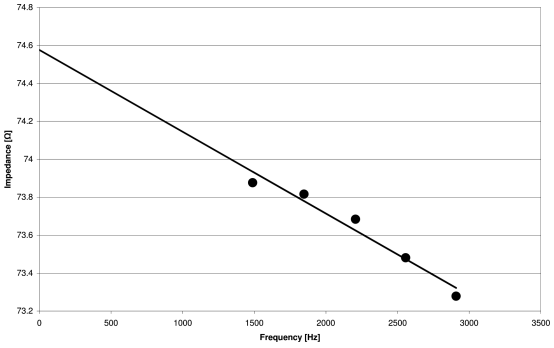


Fig. 3. Impedance of 0.1 M KCL solution at various frequencies

The system measures the impedance in several frequencies and the linear regression line of the impedance in different frequencies is calculated. The Y-intercept of the linear regression (at zero frequency) is the sample resistance as shown in Fig. 3 Conductance is obtained by inversing the resistance, and after multiplying it by the cell constant, the conductivity is calculated.

3 Measurement Range

The conductivity results from 20 urine sample test of three volunteers were taken. In order to find the range the samples are taken randomly during the day. Our test results in Table 1 show the urine conductivity range between 3.13 mS/cm and 19.20 mS/cm. The study of 2000 urine sample presented in [6] shows the urine conductivity range between 1.1 mS/cm and 33.9 mS/cm. Our system is designed to operate in range between 0.1 mS/Cm and 50 mS/cm.

Table 1. Urine sample conductivity

Urine Sample	Conductivity [mS/Cm]	Remark
1	10.18	
2	12.48	
3	10.56	
4	14.10	
5	14.38	
6	13.08	
7	16.74	
8	19.20	Max.
9	15.68	
10	13.31	
11	11.43	
12	8.84	
13	13.78	
14	14.21	
15	7.42	
16	3.13	Min.
17	18.74	
18	8.42	
19	13.14	
20	11.49	

4 Sensor

A gold coated PCB is used as four-point probe that forms sensor for this system. The four-point probe is selected due to its higher accuracy compare to two-point probe. Two-point probes are suitable for measurement of high-impedance and low-conductance samples since the error is negligible. In low-impedance high conductance samples the separation between current feeding and voltage reading circuits of four-point probe reduces error in measurement. Measuring the impedance of the sample between two inner connections is desired. The voltage of inner connectors is measured while current is fed through outer connectors to the all sensing parts. Although sensors could be designed with any arbitrary shape and geometry in this paper only the bar-shape and circular sensors and their cell constant is presented.

4.1 Bar-Shape Sensor

Electrical equivalent circuit of bar-shape conductivity sensor is shown in Fig. 4:

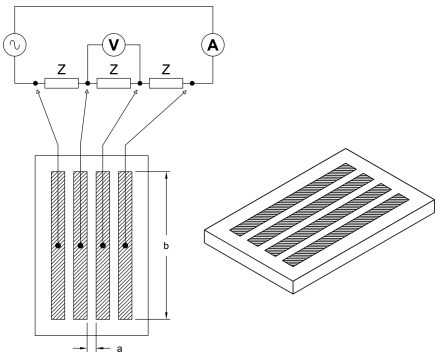


Fig. 4. Bar-shape conductivity sensor

Resistance of sensing section of bar-shape sensor is calculated using (1):

$$R = \rho \frac{a}{bt} \tag{1}$$

R is the resistance in Ω, ρ is the resistivity in Ω-m, a is the sensing part width in m, b is sensing part length in m and t is combined thickness of copper and its gold coating in m.

4.2 Circular Sensor

The electric field in the corner edges of bar-shape sensor is not uniform and caused error in measurement. Circular conductivity sensor shown in Fig. 5 eliminates such error by creating uniform electrical field in whole sensing area.

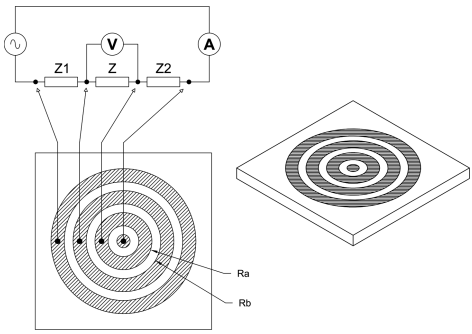


Fig. 5. Circular conductivity sensor

Resistance of sensing part in circular sensor is calculated using (2):

$$R = \frac{\rho}{2\pi t} \ln \frac{R_b}{R_a} \tag{2}$$

R is the resistance in Ω, ρ is the resistivity in Ω-m, R_a is the sensing part inner circle radius in m, R_b is sensing part outer circle radius in m and t is combined thickness of copper and its gold coating in m.

5 Analog Front End

The analog front end of the system consists of four signal conditioning sections. The first section converts receiving digital PWM signal from microcontroller to sinusoidal constant current. The second section receives the input signal from sensor voltage probes. It will be sent to microcontroller ADC input after amplification and filtering. The third section is similar to second section except receives its input signal from shunt resistor in series with sensor current feed circuit. The fourth section is amplifier and low pass filter for the temperature sensor that will be connected to another microcontroller ADC channel.

6 Digital Back End

Digital back end of the system is a 32-bit Cortex-M0 + ARM microcontroller. It has 8-channel 12-bit SAR ADC with conversion rate up to 1 Msps. The sinusoidal signal from analog front end is fed through ADC after gain and offset adjustment. The ADC input signal voltage level should remain between 0 and 3.3 V that dictates DC offset of 1.75 V with maximum amplitude of 1.75 V for sinusoidal signal. The sampling rate is adjusted to 250Ksps which provide more than 64 samples per cycle for the highest frequency of 3.3 kHz. The samples from ADC then fed through fast digital IIR high-pass filter for removing the DC offset. True RMS values of both sinusoidal signals are calculated by firmware in microcontroller.

In addition, base PWM signal with desired frequency is made using microcontroller timer and connected to analog front end through GPIO.

Furthermore, the temperature sensor DC signal is measured by microcontroller and used for temperature compensation.

Microcontroller performs the calibration process and store the measured value. Communication with single board computer is maintained through SPI.

7 Database and Connectivity

A Raspberry Pi single board computer acts as the gateway of the system. Thanks to its Linux operating system several applications could be run on Raspberry Pi simultaneously.

Serial Port Interface (SPI) is used for low level communication with microcontroller. Calibration commands, adjustments, measurement data and other specific data will be exchanged between microcontroller and Raspberry Pi.

MySql is used as database server. The data are stored in two separate databases for security reason. One secure database with limited access holds patient information. It links to the other database through an ID record. The test results database keeps patient ID, gender and the birthday year info of each patient along with urine test results, test time and date and general condition of patient at the time of test.

Apache 2 html server is used as local server, while combined with PHP it provides GUI for the overall system.

Connection to internet through Wifi or Ethernet converts the whole system to an IoT device that allows storage of data on cloud or access to the system via secure internet connection.

8 Conclusions

Preliminary test results from KCl solution shows improvement in reliability and accuracy of conductivity measurement. Such multi-frequency measurement system combined with data collection and storing system will provide essential point of care solution for diagnosis of kidney-stone in early stages.

Most of existing commercial conductivity meter are using two-point probe as sensor. In addition measurement is performed in single or few frequencies only. Result is considered valid if the difference between such measurements is less than predefined error.

This paper presents utilizing of four-point circular probe which has significant contribution to improve the accuracy of overall system. Furthermore, the system is using innovative approach of multiple impedance measurement in different frequencies and calculates the conductivity at zero frequency. Direct measurement at zero-frequency is not possible due to electrolysis of sample.

The novel concept that presented in this paper will be implemented on a single chip in future.

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Conflict of Interest. The authors declare that they have no conflict of interest.

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