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Salivary Impedance-Based Glucose Sensing: A Hardware-Assisted Approach and Performance Evaluation

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Presenta: **VICENTE IVÁN RUIZ GARCÍA**

Directores **MARTÍN ALONSO SINSEL DUARTE, ESTEBAN MARTÍNEZ
GUERRERO**

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Vicente Ruiz-García

Departamento de Electrónica, Sistemas e Informática

Instituto Tecnológico de Estudios Superiores de Occidente

Tlaquepaque, Jalisco, México
vicente.ruiz@iteso.mx

Esteban Martínez-Guerrero

Departamento de Electrónica, Sistemas e Informática

Instituto Tecnológico de Estudios Superiores de Occidente

Tlaquepaque, Jalisco, México
margres@iteso.mx

Martín Sinsal-Duarte

Departamento de Electrónica, Sistemas e Informática

Instituto Tecnológico de Estudios Superiores de Occidente

Tlaquepaque, Jalisco, México
msinsald@iteso.mx

Abstract— Non-invasive glucose monitoring faces significant reliability hurdles due to electrode polarization and low-amplitude signal interference in salivary sensing. This paper presents an integrated mixed-signal platform using the ADuCM350 system-on-chip to evaluate the feasibility of salivary bio-impedance analysis for glucose estimation. The methodology implements an isolated 4-wire Kelvin technique and hardware-accelerated DFT processing to mitigate contact impedance and systematic errors. While the system demonstrated high accuracy in characterizing Randles equivalent circuits, preliminary measurements with hydrogen peroxide (H_2O_2) solutions revealed significant challenges in electrochemical stability and signal-to-noise ratios. These results provide critical insights into the limitations of current portable architectures and highlight the need for further optimization in electrode-analyte interface stability for reliable non-invasive diagnostics.

Keywords— Bioimpedance, ADuCM350, digital signal processing (DSP), non-invasive sensing.

I. INTRODUCTION

The global prevalence of diabetes has risen significantly over recent decades, driven largely by increased consumption of added sugars and sedentary lifestyles. Accurate glucose monitoring is essential for disease management, and the current clinical standard relies on blood-based measurements, typically obtained via finger-prick blood draws or venous sampling. These methods offer high accuracy and reliability, but they cause patient discomfort, require repeated painful pricks, and involve a tedious process [1].

Non-invasive blood glucose monitoring has emerged as a critical field of research to overcome the limitations and patient discomfort associated with traditional invasive methods. However, these alternative methods face significant challenges, primarily individual variability and insufficient measurement reliability, which have prevented universal clinical approval [2].

Building upon the research by Sánchez-Hernández et al. [3], in which the 'Strong Follower' topology was validated for quantifying ultralow salivary currents (1–15 μA), this work aims to develop a robust non-invasive glucose monitoring solution

using the ADuCM350 system-on-chip, based on a saliva byproduct, (H_2O_2).

The remainder of this paper is organized as follows: Section II describes the methodology, detailing the isolated 4-wire Kelvin technique, the integration of the ADuCM350 analog front-end, and the digital signal processing framework. Section III presents the experimental validation and results, including the characterization of Randles circuits and the analysis of hydrogen peroxide solutions to validate the system's accuracy. Finally, Section IV provides the conclusions and outlines future work.

II. METHODOLOGY

The experimental procedure is organized into three sequential stages: hardware setup using the ADuCM350 with 4-wire Kelvin sensing; digital signal processing via DFT and median filtering; impedance characterization across test circuits (resistors, capacitors and Randles model circuit), ferri/ferrocyanide, and hydrogen peroxide solutions.

A. Kelvin (4-wire) connection

The ADuCM350 system employs a 4-wire Kelvin measurement technique to ensure high precision in bio-impedance acquisition, as shown in “Fig. 1”. This configuration is specifically designed to mitigate systematic errors caused by electrode polarization and contact impedance, which are common challenges in body-worn sensors. The 2 ADC channels are explained in more detail below [4]:

- **Current Channel:** The excitation signal, generated by the internal DAC, is propagated through the sample via the AFE8 and AFE1 terminals. Capacitors C_ISO1 and C_ISO2 are placed in series to block DC current, ensuring patient safety and preventing electrode polarization.
- **Voltage Channel:** To measure the voltage drop across the unknown impedance Z_{unknown} , two high-impedance sensing lines are connected to an external instrumentation amplifier. This path uses DC-blocking capacitors C_ISO3 and C_ISO4 to eliminate

half-cell potential interference, maintaining the maximum dynamic range for the analog-to-digital converter.

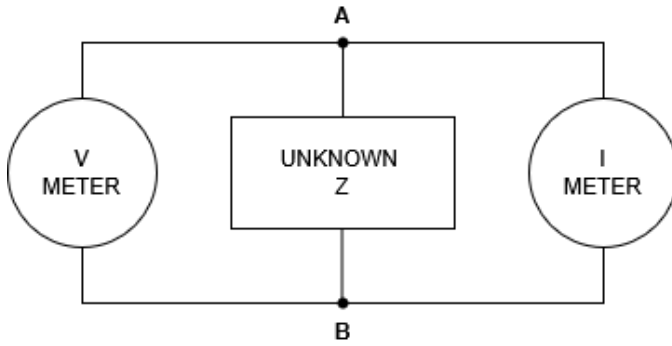


Fig. 1. Basic 4-wire Topology.

B. ADuCM350 Analog Front End (AFE)

The ADuCM350 serves as an integrated mixed-signal metering solution, providing an ultra-low-power environment for complex biosignal acquisition. A flow diagram is shown in “Fig. 2”.

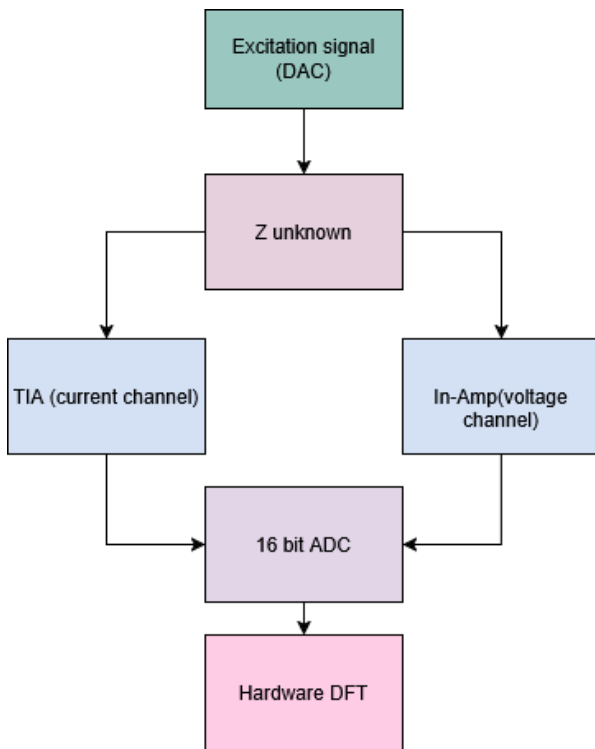


Fig. 2. Analog Front End Flow Diagram.

The key functional modules of the AFE are described below [4]:

- Transimpedance Amplifier (TIA): The AFE includes a TIA that converts the current flowing through the sample I_{TIA} into a measurable voltage. In the current implementation, the resistor is set to 1000 ohms to balance signal-to-noise ratio (SNR) and gain requirements.

- Instrumentation Amplifier (In-Amp): An external AD8226 In-Amp is integrated into the front end to perform high-precision differential voltage measurements. Its gain G is determined by an external resistor, which in this design is set to 120 kohms.
- DAC and ADC: The system utilizes a 12-bit DAC for precision waveform generation (e.g., sine waves with a customizable V_{peak}) and a 16-bit ADC operating at 160 kSPS to digitize the resulting current and voltage signals.

C. Signal Processing in ADuCM350

Hydrogen peroxide solutions and impedance signals processing are managed by an ARM Cortex-M3 processor supported by a dedicated hardware accelerator. The hardware modules and software components used for this task are presented below [4]:

- Discrete Fourier Transform (DFT): The hardware accelerator performs a single-frequency DFT on the captured buffers. This allows the extraction of complex results (real and imaginary parts) for both the current and voltage channels. From these, the system calculates the impedance magnitude and phase using the relationship between voltage and current.
- Fixed-Point Arithmetic: To maintain high computational precision without floating-point overhead, the software implements fixed-point numbers using $q15_t$ and $q31_t$ formats. Results are stored in a custom $fixed32_t$ union, utilizing 28 integer bits and 4 fractional bits (28.4 format) to keep track of decimal positions during transmission and MATLAB analysis.
- Median filter: A median filter was implemented to reduce signal noise and improve measurement precision by suppressing spurious outliers without distorting relevant features.

D. Impedance Measurements

The impedance measurement procedure was carried out in four stages. First, impedance measurements were performed using a test circuit composed of carbon resistors and ceramic capacitors to validate the experimental setup. Second, a Randles circuit, as shown in “Fig. 3”, was employed to obtain both Bode and Nyquist plots, establishing a baseline for electrochemical impedance behavior. Third, impedance spectroscopy was conducted using a 5 mM potassium ferri/ferrocyanide solution in 1M KCl, with the setup shown in “Fig. 4”. Finally, measurements were performed on hydrogen peroxide (H_2O_2) solutions at five different concentrations ranging from 1 to 5 mM to establish the correlation between the measured current and analyte concentration.

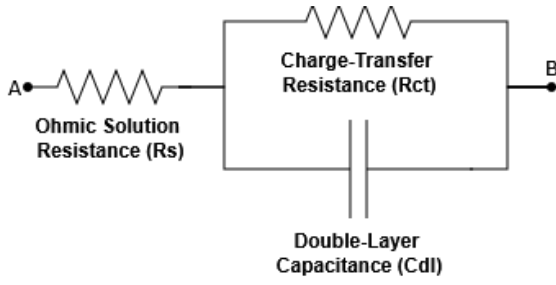


Fig. 3. Schematic diagram of Randles Equivalent Circuit.

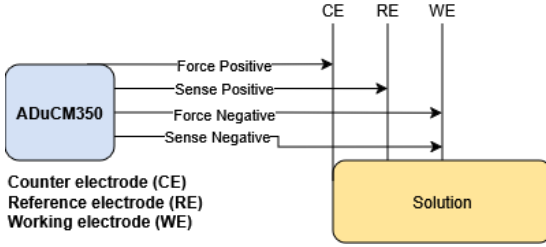


Fig. 4. Experimental Setup of the Solution Electrodes.

E. Glucose Estimation

The estimation of glucose levels is based on the indirect measurement of hydrogen peroxide, a byproduct of glucose oxidation. Previous research has established a direct electrochemical correlation where the concentration of H_2O_2 is linearly proportional to the Faradaic current [3]. In this work, the ADuCM350 board measures salivary bioimpedance to estimate the current and construct a calibration curve between those variables.

III. RESULTS AND VALIDATION

A. Randles Circuit Measurements

Resistors and capacitors were configured to emulate a theoretical Randles circuit model, representing solution resistance (R_s), charge transfer resistance (R_{ct}), and double-layer capacitance (C_{dl}). These circuits were measured using the ADuCM350 board across a defined frequency sweep and compared with its theoretical values as shown in “Fig. 5” and “Fig. 6”.

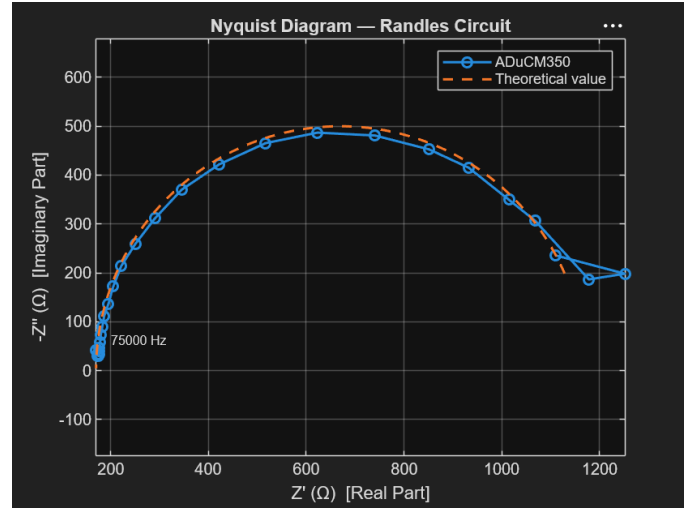


Fig. 5. Simple Randles Circuit Nyquist Diagram.

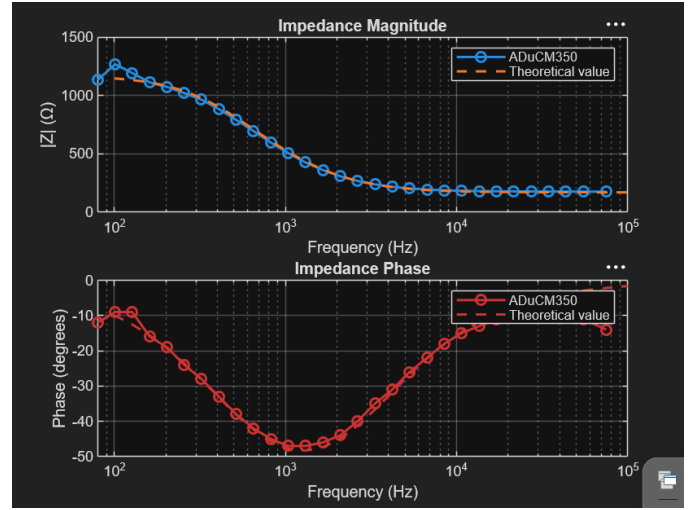


Fig. 6. Simple Randles Circuit Bode Diagram.

B. Potassium ferri/ferrocyanide (5 mM) in 1 M KCl

Following passive component validation, a standard 5 mM potassium ferri/ferrocyanide $K_3[Fe(CN)_6]/K_4[Fe(CN)_6]$ redox probe in 1 M potassium chloride (KCl) was characterized. To benchmark the portable ADuCM350 board, measurements were cross-validated with a laboratory-grade CS310 commercial potentiostat under identical ambient conditions as shown in “Fig. 7” and “Fig. 8”.

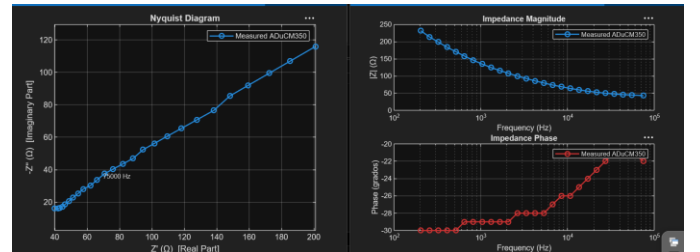


Fig. 7. Potassium Ferri/Ferrocyanide Solution Nyquist and Bode Diagram using ADuCM350 Board

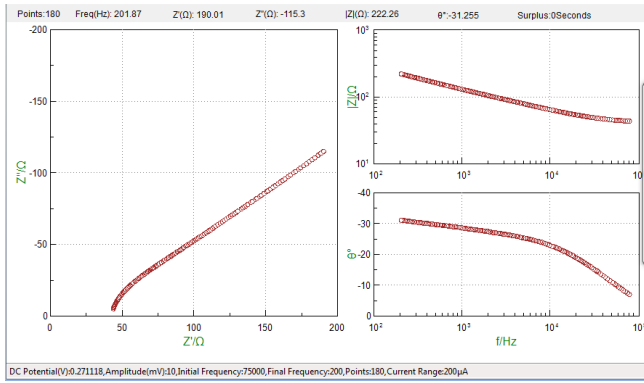


Fig. 8. Potassium Ferri/Ferrocyanide Solution Nyquist and Bode Diagram Using CS310

C. Hydrogen Peroxide

As a final validation stage toward biochemical sensing, 5 hydrogen peroxide (H_2O_2) solutions were evaluated. Impedance sweeps were performed using both the CS310 workstation and the ADuCM350 board to track interface variations, as shown in “Fig. 9” and “Fig. 10”.

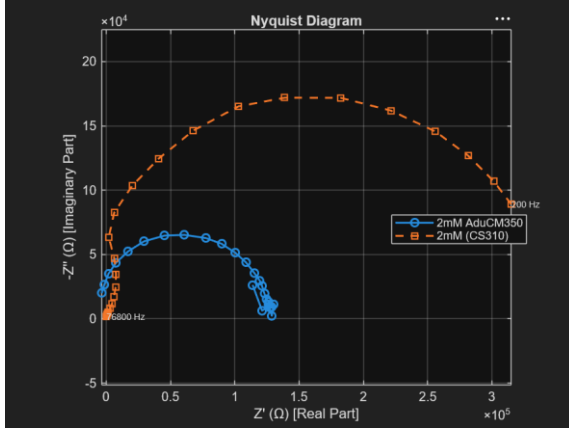


Fig. 9. Hydrogen Peroxide Solution Nyquist Diagram using ADuCM350 Board and CS310 Potentiostat.

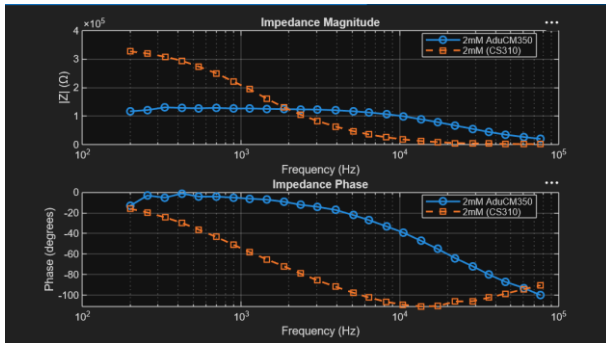


Fig. 10. Hydrogen Peroxide Solution Bode Diagram using ADuCM350 Board and CS310 Potentiostat.

The evaluation of five (H_2O_2) concentrations revealed inconsistent measurements when using the ADuCM350 platform, in contrast to the CS310 commercial potentiostat, which produced stable and repeatable readings. This discrepancy is attributed to fundamental limitations of the ADuCM350 in measuring high-impedance electrochemical systems. As noted in a technical discussion on the manufacturer's support forum, the ADuCM350 struggles with the very low currents associated with high-impedance measurements due to inherent offset errors, gain errors, and susceptibility to system noise. Consequently, the observed variance reflects the architectural constraints of the measurement platform rather than the electrochemical behavior of the analyte-electrode interface [5].

IV. CONCLUSIONS AND FUTURE WORK

This work successfully demonstrated the development of a portable salivary bio-impedance platform utilizing the ADuCM350 board and an isolated 4-wire Kelvin technique. The system proved effective for characterizing Randles equivalent circuits and potassium ferri/ferrocyanide solutions, showing a strong correlation with laboratory-grade electrochemical workstations.

To overcome the inconsistencies observed in H_2O_2 measurements, future efforts should concentrate on a redesigned platform that follows the ADuCM350 manufacturer's guidance for high-impedance electrochemical sensing, including optimized PCB layout, reduced leakage currents, and robust power filtering.

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