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Wireless, reconfigurable electrochemical measurement platform for wearable applications

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***Abstract*— Wearable devices have become transformative tools in healthcare and fitness, providing valuable insights into an individual's health and fitness. Recent advances in electrochemical front-end integrated circuits have expanded the horizons for wearable technology, enabling the incorporation of electrochemical testing in small, power efficient wearables devices. This paper presents a reconfigurable platform tailored for use in a wearable context, offering a versatile transducer interface and electronic configuration suitable for a diverse range of analytes and applications. The platform is based on a custom electrochemical shield with two analog front-end integrated circuits (AD5941), miniaturized IoT board (XIAO ESP32C3) and optional I2C extension boards for physiological measurements. Future endeavors will focus on enhancing accuracy and integration into clothing.**

Keywords—real-time monitoring, wearable devices, system integrations, sweat sensing, laser-induced graphene, sensors

I. INTRODUCTION

Sweat sensing in wearable applications represents a cutting-edge advancement in the realm of personalized health monitoring. This technology leverages biosensors to detect various biomarkers in sweat, such as electrolytes, metabolites, and proteins, providing real-time data on an individual's physiological state. Unlike traditional methods that often require invasive procedures like blood tests, sweat sensing offers a non-invasive, continuous, and convenient alternative. Current research activities under investigation include sweat sensing wearable devices such as smartwatches [1], patches [2], [3], and clothing [4], allowing users to monitor hydration levels, stress, glucose, and even detect early signs of illnesses [5], [6], presenting the potential for such systems to be routinely used in a wide range of applications, including performance assessment, chronic conditions monitoring and more.

Wearable devices offer numerous advantages in health and fitness monitoring in comparison with benchtop solutions. Wearable sensors can track data over extended periods of time and provide continuous monitoring, allowing for the detection of trends and patterns that might be missed with solely periodic measurements. To allow for a range of electrochemical metrics as wearable potentiostat solutions have been presented, including TinyStat [7] and We-VoltamoStat [8]. The recent launch of commercially available Sensit Wearable [9] is another example of an increasing interest in area of wearable electrochemical sensing.

However, when considering health and performance monitoring, a holistic approach is preferable to measuring sweat biomarkers in isolation. Physiological parameters cannot only improve accuracy of analyte measurements, but also improve detection of target conditions, for example, monitoring heart rate in combination with lactate levels in sweat can provide better assessment of the physiological load on an athlete [10]. With the current advances in electronics, it is possible to design miniaturized reconfigurable multi-parameter systems. The platform described in this article allows for reconfigurable configuration that supports not only a variety of electrochemical measurement but also allows to include physiological measurements such as skin temperature, heart rate or motion activity.

The integration of multiple sensor modalities enhances the platform's applicability in both medical and sport contexts. It enables personalized training regimens, optimizes recovery strategies, and helps in preventing injuries by detecting signs of overexertion or dehydration early on. Additionally, prolonged, nonobtrusive monitoring of chronic conditions, medicine intake and advanced healthcare diagnostics that account for physical activity of an individual can be realised using such platforms.

With the growing popularity of wearables, the environmental impact and sustainability of systems under development is also becoming a critical consideration in design methodology. Researchers are increasingly focusing on the use of eco-friendly materials, specifically considering the relatively short life of biochemical sensors. One such sustainable material which can be used as a transducer in such applications is laser induced graphene. Laser-induced graphene (LIG) represents a cutting-edge category of three-dimensional porous carbon nanomaterials [11]. This innovative material is fabricated through direct laser writing on select polymer substrates in ambient conditions. Compared to other fabrication techniques, such as lithography and printing, this offers several advantages, including high spatial resolution, non-contact operation, easy scalability, high efficiency, low power consumption, low cost and environmental friendliness [12], [13], [14]. This trend highlights its substantial potential in routine monitoring of chemical biomarkers during everyday activities using wearables devices.

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The presented platform supports a variety of biochemical sensors, including LIG-based sensors on variety of substrates, to ensure sustainable use and minimize environmental impact, particularly when deployed as a wearable device for extended periods. Platform's reconfigurability and adaptability offers a development solution in continuous monitoring of sweat biomarkers such as ions, glucose and lactate in combination with physiological measurement to enhance health and fitness assessment.

II. System Design

The proposed system design developed to meet the needs of wearable sweat sensing (Fig. 1) includes an IoT module and an associated daughter card (shield) designed around an electrochemical front-end (EFE) integrated circuit (IC), which provides a reconfigurable solution for a range of electrochemical techniques (chronoamperometry (CA), cyclic voltammetry etc.) allowing for measurement of a variety of biomarkers such sweat electrolytes, glucose or lactate concentration. Moreover, the platform allows for additional physiological measurements to be taken due to its modular design, and the ability to add expansion boards as needed. A variety of I2C connected sensors can be used to monitor skin temperature, heart rate, blood oxygenation, motion and other parameters.

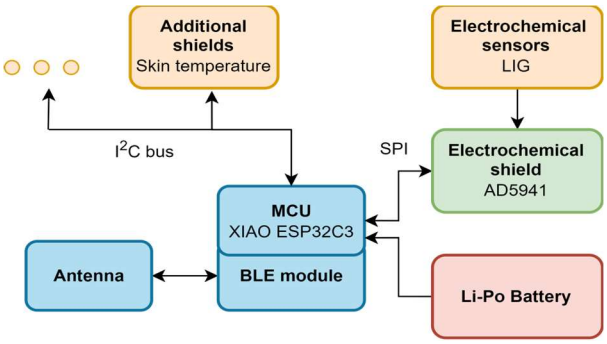


Fig. 1. Block diagram of the proposed device.

1) Electrochemical front-end

Currently, the trend towards miniaturization and the widespread adoption of wearable devices for glucose monitoring has encouraged manufacturers to develop ICs with specialized functions such as electrochemical interfaces. One of the recent products incorporating this functionality is the AD5940/41 from Analog Devices [15], a high-precision, ultra-low-power analog front-end integrated circuit.

This IC is engineered to stimulate and measure the current, voltage, or impedance response of sensors, with a particular focus on providing accurate analysis of electrochemical cells. A programmable switch matrix links the sensor to the internal analog excitation and measurement blocks allowing flexible device configuration. Due to ultra-low power, low noise and support for various types of electrochemical techniques (potentiometry, amperometry, voltammetry, and impedance spectroscopy), this AD5941 was chosen as the foundation for the electrochemical sensor interface for the presented platform.

The sweat sensing system which was developed contains two AD5941 AFE IC s allowing for simultaneous testing of multiple analytes. The card edge connector (Fig. 2), featuring six open contacts and a total of twelve usable contacts, along with a series of jumpers, enables the device to be used with sensors containing either one or two working electrodes. Additionally, it allows for independent open circuit potentiometry measurements.

2) Microcontroller unit

Similar to FreiStat [16], the proposed platform is comprised of a base board and an electrochemical interface shield board to allow for fast prototyping and reconfigurability. However, as the platform is intended for wearable applications, a small footprint is crucial as well as potential to include multi-analyte sensing. To address this, a low-cost (5USD) IoT mini development board XIAO ESP32C3 from Seed Studio [17] was used as the base board. The XIAO ESP32C3 is based on the Espressif ESP32-C3 WiFi/Bluetooth (low-energy) dual-mode chip, with the 32-bit RISC-V CPU, which includes a floating-point unit for 32-bit single-precision arithmetic. The board provides 400KB of SRAM and 4MB of on-board flash memory as well as a lithium battery management chip. The 21 x 17.5mm, single sided, surface mounting PCB design allows for combination with our custom developed shield (60x35mm) containing AFEs (Fig. 2). Additionally, the external antenna of the XIAO module offers the potential for future development, enabling it to be replaced with a textile-based antenna for seamless integration into clothing.

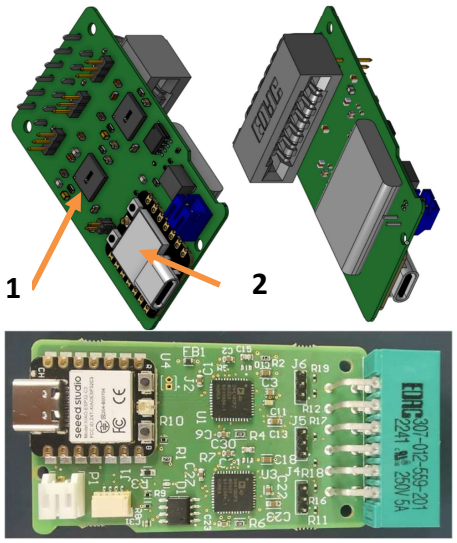


Fig. 2. Electrochemical shield (1), IoT base board XIAOESP32C3 (2).

B. Firmware and Software

For the firmware development Arduino IDE 2.2.1 was used. Firmware is based on examples from Analog Devices [18] for electrochemical measurements. Freistat framework [19] was referenced to port the code to XIAO ESP32C3. A graphical user interface was developed using MATLAB for for real-time signal pre-processing and data.

Different approaches exist to reduce noise in electrochemical measurements, including analog filtration,

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shielding and others [20], however considering the intended application of the proposed platform and respective size constraints, software signal smoothing was chosen over hardware options that require additional components to be mounted on the shield PCB. From the variety of approaches available for signal smoothing, a moving average was elected as one of the more simple techniques (compatible with typically resource constrained edge based wearable sensors) which does not significantly distort signal shape [21] and allows for displaying data in close to real-time.

C. Biochemical Sensors

The suggested sensors for the described system are 3-4 electrode LIG sensors (Fig. 3) consisting of a one or two working electrodes, a counter electrode, and a reference electrode fabricated using the direct laser-writing technique.

The sensors are intended to be used with a rigid substrate (Fig. 4, 1 - green) allowing for its use with card edge connector. Additionally, a microfluidic sweat collection skin interface (Fig. 4, 2 - orange) can be positioned over the sensor to prevent direct contact with the skin and ensure efficient sweat collection. The suggested options for device positioning are shown in Fig. 5.

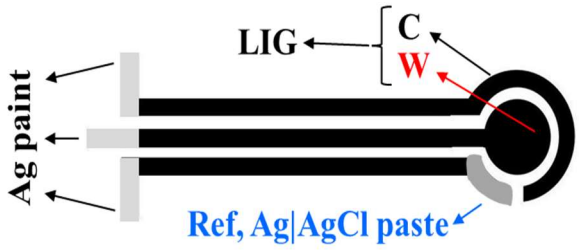


Fig. 3. Schematic design of a LIG sensor.

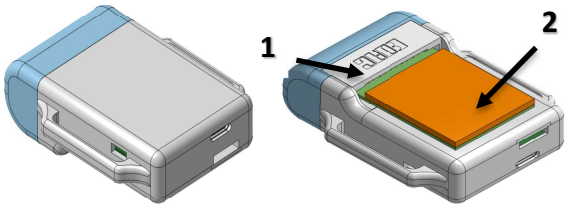


Fig. 4. Measurement platform outlook: enclosure, biochemical sensor (1), microfluidic interface (2).



Fig. 5. Device placement options: back & upper arm.

D. Graphical User Interface for Data Aquisition

A PC app (Fig. 6) was developed to provide a sensor data interface designed to communicate wirelessly with the device via BLE. The app allows users to choose desired tests, configure measurement settings, visualize measurements in real time and export recorded data.

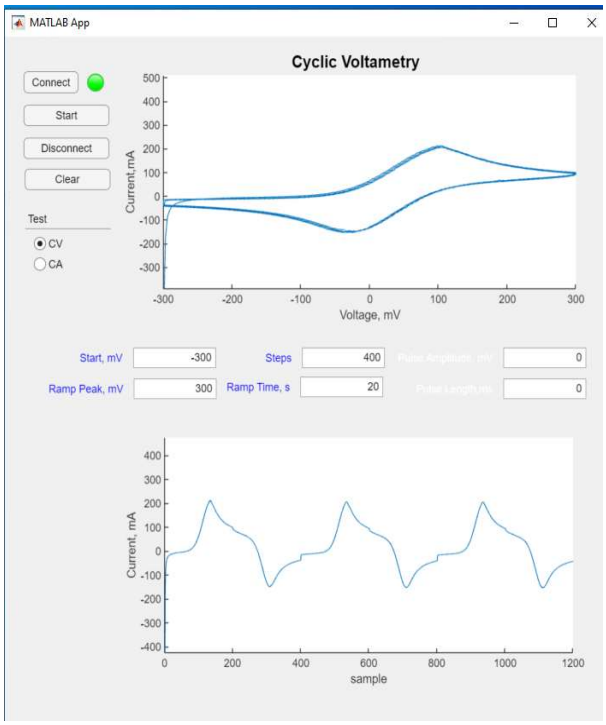


Fig. 6. User interface GUI. Typical CVs of the LIG sensor in aqueous solution containing 5 mM $Fe(CN)_6^{3-}$ and 0.1M KCl(top). Plot of current versus time (bottom).

III. System Validation

To validate the proposed solution, tests were conducted using the Autolab potentiostat PGSTAT204 (Metrohm, Utrecht, Netherlands) as a gold standard. CA measurements were performed on the same LIG sensor in a flow injection analysis (FIA) system with a three-electrode setup.

Firstly, the accuracy of the applied potential of the prototype was assessed by applying a range of potentials (+300 to –300 mV vs. Ag|AgCl, 0.1 M KCl) and recording the current response from successive injections of an aqueous solution of a standard electrochemical probe (1 mM potassium ferricyanide) in FIA system. The sampling rate of response was 10 Hz. For comparison, the same experiment was performed with the gold standard system.

Current peaks were extrapolated, mean and standard deviation values of the peaks were calculated for each potential. Fig. 7 shows the results, where the curves obtained from both devices exhibit similar trends, with a correlation of 0.99. Additionally, Mean Percentage Error (MPE) was calculated to further compare the systems' current responses, yielding MPE values of 0.99, 11.68, 3.58, and 6.04 % for potentials of -1, -100, -200, and -300 mV, respectively.

To further evaluate performance, FIA traces of ferricyanide were recorded across a concentration range of 1 to 5 mM for both the prototype and the gold standard system, using an applied potential of –200 mV vs. Ag|AgCl (0.1 M KCl). Note that each concentration injected three times into the FIA system and current recorded at a 10 Hz sampling rate. Figs. 8 presents the results, with a correlation of 0.99, indicating consistent trends between the two

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systems. Additionally, MPE values of 3.72, 4.55, 2.99, 3.43, and 1.91 were obtained for concentrations of 1, 2, 3, 4, and 5 mM, respectively. The results demonstrate no significant difference between the prototype and the gold standard, indicating comparable accuracy and reliability.

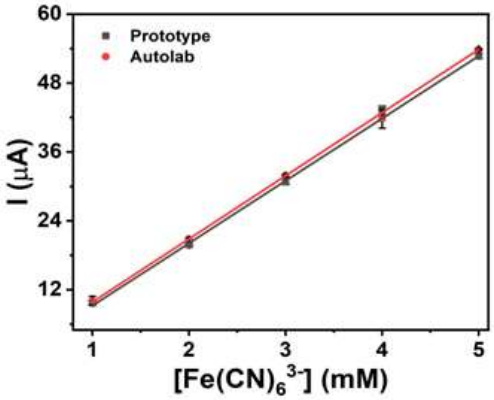


Fig. 8. Mean and standard deviation values for both the prototype and Autolab - Same potential with different concentrations.

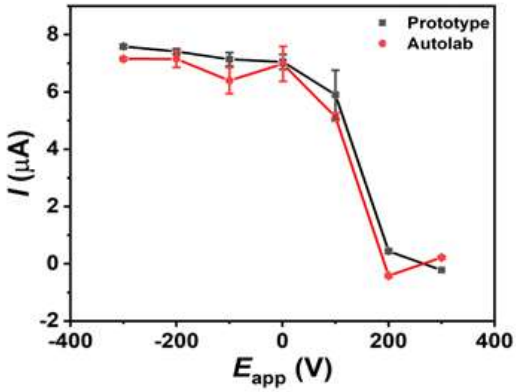


Fig. 7. Mean and standard deviation values for both the prototype and Autolab - Different potentials with the same concentration.

IV. Conclusion and Outlook

This work demonstrates a wearable wireless platform for monitoring sweat biomarkers and physiological parameters such as skin temperature or motion. The platform is potentially useful for a variety of applications, including use in the development of novel sweat sensors, research on athletes' performance, load and fatigue, as well as in health applications. Future work includes further device development into integrated into clothing platform, testing in artificial sweat, improving accuracy with pH and temperature measurements, optimization of a microfluidic interface for sweat collection, as well as conducting trials with athletes to assess functionality and accuracy in field applications. These trials will evaluate the system's performance during real scenario activities, focusing on sensor accuracy, data reliability, user comfort, and impact on athletic performance. Real-world testing will provide valuable insights into the device's practicality, usability, and potential to enhance health monitoring and performance optimization in sports settings.

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