Low-Cost, Wireless Bioelectric Signal Acquisition and Classification Platform

Eric J Earley\textsuperscript{1,2,3,4}, Nathaly Sánchez Chan\textsuperscript{1,2}, Autumn Naber\textsuperscript{2}, Enzo Mastinu\textsuperscript{1,2,5}, Minh T N Truong\textsuperscript{1,6}, and Max Ortiz-Catalan\textsuperscript{1,2,7,8}

\textsuperscript{1}Center for Bionics & Pain Research
\textsuperscript{2}Department of Electrical Engineering, Chalmers University of Technology
\textsuperscript{3}Bone Anchored Limb Research Group, University of Colorado
\textsuperscript{4}Department of Orthopedics, University of Colorado School of Medicine
\textsuperscript{5}BioRobotics Institute, Scuola Superiore Sant’Anna
\textsuperscript{6}MoveAbility Lab, KTH Royal Institute of Technology
\textsuperscript{7}Bionics Institute
\textsuperscript{8}University of Melbourne

January 18, 2024
Low-Cost, Wireless Bioelectric Signal Acquisition and Classification Platform

Eric J. Earley1,2,3,4, Member, IEEE, Nathaly Sánchez Chan1,2, Autumn Naber2, Enzo Mastinu1,2,5, Minh T.N. Truong1,6, and Max Ortiz-Catalan1,2,7,8, Senior Member, IEEE

1Center for Bionics & Pain Research, Mölndal, Sweden
2Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden
3Bone Anchored Limb Research Group, University of Colorado, Aurora, CO, USA
4Department of Orthopedics, University of Colorado School of Medicine, Aurora, CO, USA
5BioRobotics Institute, Scuola Superiore Sant’Anna, Pisa, Italy
6MoveAbility Lab, KTH Royal Institute of Technology, Stockholm, Sweden
7Bionics Institute, Melbourne, Australia
8University of Melbourne, Melbourne, Australia

Corresponding author: Max Ortiz-Catalan (e-mail: maxortizc@outlook.com).

E.J. Earley and N. Sánchez Chan share first authorship. This work was supported by the Promobilia Foundation, the IngaBritt and Arne Lundbergs Foundation, and the Swedish Research Council (Vetenskapsrådet).

ABSTRACT Bioelectric signal classification is a flourishing area of biomedical research, however conducting this research in a clinical setting can be difficult to achieve. The lack of inexpensive acquisition hardware can limit researchers from collecting and working with real-time data. Furthermore, hardware requiring direct connection to a computer can impose restrictions on typically mobile clinical settings for data collection. Here, we present an open-source ADS1299-based bioelectric signal acquisition system with wireless capability suitable for mobile data collection in clinical settings. This system is based on the ADS_BP and BioPatRec, both open-source bioelectric signal acquisition hardware and MATLAB-based pattern recognition software, respectively. We provide 3D-printable housing enabling the hardware to be worn by users during experiments and demonstrate the suitability of this platform for real-time signal acquisition and classification. In conjunction, these developments provide a unified hardware-software platform for a cost of around $150 USD. This device can enable researchers and clinicians to record bioelectric signals from able-bodied or motor-impaired individuals in laboratory or clinical settings, and to perform offline or real-time intent classification for the control of robotic and virtual devices.

INDEX TERMS bioelectric signal, data acquisition, EMG, open source, pattern recognition

I. INTRODUCTION Skin-surface electromyography (sEMG) systems have been drawing attention within the biomedical field in the past decade. The reason behind this focus is the desire to enhance prosthetic functionality as well as contribute towards research in rehabilitation technologies [1]. These systems are typically divided into two sections: data acquisition and data processing. On one hand, data acquisition measures the sEMG representative of active muscle contractions. And on the other hand, data processing primarily aims to denoise the acquired sEMG signals and to perform analyses such as pattern recognition, which in turn can be used to control rehabilitation devices such as prostheses [2].

The acquisition process is performed using a device that collects the electrical activity from the muscles with the help of skin-surface electrodes. The signals acquired from the electrodes are in the order of millivolts with a frequency that ranges between 0.01 to 500 hertz [3, 4]. Given the millivolts range of amplitude, the sEMG signals are highly sensitive to different sources of noise like motion artifacts or electromagnetic radiation [5]. Therefore, sEMG systems need to carefully eliminate unwanted noise while maintaining the essential information the signal carries. Several low-cost solutions for bioelectric signal acquisition have been proposed [3, 4, 6-12], however these solutions often do not consider clinical applicability.

Data processing is also a critical step for working with bioelectric signals and can vary widely depending on the application. For work related to the control of rehabilitation devices, data processing typically comprises treatment of the raw signals, extraction of time- or frequency-domain features,
and application of pattern recognition algorithms to decode the executed movement correlated with the sampled signals. Some of the aforementioned devices can perform raw signal treatment via hardware and firmware filtering [3, 4, 6, 11, 12], but custom software must typically be written to complete subsequent signal classification.

The system described in this paper is a complete bioelectrical acquisition platform comprising hardware, namely the ADS_BP, and its respective software, namely BioPatRec. The ADS_BP acquires sEMG signals (or other bioelectric signals including electrocardiography (ECG) and electroencephalography (EEG)) and streams them wirelessly via Wi-Fi to a connected computer running BioPatRec [13, 14]. BioPatRec, originally intended for researching intuitive control of prosthetic devices, is an open-source MATLAB-based platform which provides a variety of algorithms for bioelectric pattern recognition and robot control. BioPatRec provides tools for signal recording, labelling and storing, signal treatment and pre-processing, feature extraction and classification, and evaluation as well as a virtual reality environments for controlling virtual limbs. These tools can be customized and operated via a Graphical User Interface (GUI).

II. METHODS

A. HARDWARE DESCRIPTION

The first version of the ADS_BP was released in 2017 by Mastinu et al. addressing the need for an open-source and low-cost bioelectric signal acquisition device [14]. Since then, the device has evolved with improvements in communication, firmware, and enclosure. The latest version of the device includes a Wi-Fi module to facilitate wireless transmission of the digitalized data to the test computer. Changes were also made to the software for full compatibility with the ADS_BP. The assembled ADS_BP is shown in Fig. 1, and descriptions of the individual components are provided in the following sections.

1) ADS_BP BOARD

A detailed summary of the ADS_BP and MCU boards is provided in [14]. Briefly, the main ADS_BP board comprises an ADS1299 analog front-end (Texas Instruments, USA) installed on a PCB designed using DipTrace (Novarm, Ukraine). An opto-isolated USB port is included for a wired but safe computer interface. Jumpers are provided to expand the number of acquisition channels via daisy-chaining additional boards over the Serial Peripheral Interface (SPI). In the present configuration proposed herein, an updated ADS_BP board is mounted above the MCU board, which itself is mounted above a new COMM_B board.

The ADS_BP board has an optional isolated USB port to communicate with a computer instead of the COMM_B board. In the current paper, the components are left unpopulated. The ADS_BP boards are also designed to allow daisy-chaining of multiple units based on the selector jumpers. The current scope involves only one unit.

2) MCU BOARD

The Tiva LaunchPad (Texas Instruments, Dallas, USA) was selected as the MCU platform for the ADS_BP. It is based on the ARM Cortex-M4 core which runs up to 80 MHz and features 256 kB of internal flash memory and 32 kB of SRAM. The Tiva LaunchPad board comes in a low-cost and stackable format, allowing the ADS_BP access to power lines, general-purpose inputs/outputs (GPIOs), and peripherals.

3) COMM_BP BOARD

The COMM_BP Board consists entirely of a Zentri AMW136 Wi-Fi module (Silicon Labs, Austin, USA), breakout pins for communication and power, and appropriate grounding to minimize electrical interference. The AMW136 module features a maximum baud of 5.25 Mbps and contains an 802.11b/g/n transceiver, a built-in antenna, Universal Asynchronous Receiver/Transmitter (UART) modules, and a Cortex M4 processor for control.

0Ω resistors are used to connect or disconnect either the SPI or UART interfaces depending on communication mode used for interacting with the ADS_BP board and TIVA board. In the current paper, we connect the UART traces to connect the TIVA to the computer system and leave the SPI traces disconnected to allow the TIVA to control the ADS_BP board.

FIGURE 1. The ADS_BP device comprises the ADS_BP board, Tiva LaunchPad, and COMM_BP board.

The ADS_BP board offers three ways for referencing the analog front-end to the body of the user for optimal bioelectrical signal recordings. The reference electrode can be shorted to the ADS_BP system ground node, or to an op-amp buffered and shielded version of the ground node, and additionally, to a dedicated bias driver circuit. The ADS1299 offers the possibility to improve noise-rejection by using a built-in amplifier and an external RC net to drive the user’s bias voltage similarly to a classic Driven-Right-Leg circuit [15]. These options are made available on the ADS_BP via two jumper resistors, R_REF_GND and R_REF_SHD, for selecting the physical reference electrode connection, and a BIASINV pin (the inverting input pin of the driven amplifier) for a bias driving optional electrode. Note that the bias driving circuitry must be enabled via firmware by setting the dedicated configuration registers. Components R1-R16 and C1-C16 are used to condition incoming bio-signals for receiving with the ADS1299 chip.
directly. A developer could program the microcontroller on the AMW136 module to communicate directly with the ADS_BP, in which case the TIVA would be unnecessary. However, this is beyond the current scope.

The RESET_N pin on the AMW136 is not externally driven, so the C5 capacitor is used to bypass noise to prevent unintended resets.

The COMM_BP board operates best when there are no traces or conductors near the antenna. The antenna sticks out from the main PCB and should not be impeded by the circuit boards in the proposed system, but looping wires and other conductors should be kept away from that end of the unit during operation.

4) ADS_BP FIRMWARE
After powering up, the Tiva MCU goes through the initialization stage to prepare the ADS_BP system for signal acquisition and to receive commands from the computer interface. This initialization stage includes, in brief, GPIOs and peripherals initialization to enable communication with the ADS1299 and the AMW136, via SPI and via UART respectively. After the communication interfaces are established, the ADS1299 is configured to the default mode (8 channels; 1kHz sampling frequency; externally applied reference on GND; amplification factor of 1). Direct Memory Access (DMA) is enabled and used for receiving/transmitting messages via UART to reduce the burden on the microcontroller main tasks and ultimately the communication latency. After initialization, the device is ready to decode and execute commands from the computer interface. The device operation loop constitutes waiting for messages, processing any received command, executing and acknowledging such commands, and acquiring and transmitting ADS1299 samples (if sample streaming is enabled). A GPIO Interrupt Service Routine is configured for handling processes related to acquiring ADS1299 samples, filtering the acquired signals, and preparing the data for transmission to BioPatRec or any other computer interface on a connected device.

5) BIOPATREC SOFTWARE
The ADS_BP has been designed to work in concert with the open-source biosignal pattern recognition software, BioPatRec [13]. Briefly, BioPatRec is a modular platform implemented in MATLAB (Mathworks, USA) designed to perform signal acquisition, preprocessing including frequency and spatial filtering and signal segmentation, extraction of time- and frequency-domain features, pattern recognition via linear and nonlinear classification, and real-time control and evaluation. It is intended as a unifying platform with which researchers in different fields may benchmark their algorithms, which may only entail one of the aforementioned steps, and determine their impact on prosthetic control. BioPatRec comprises modular structure arrays which can be updated or replaced without affecting prior or subsequent processes, as shown in Fig. 2 above.

Since its initial release in 2013, BioPatRec has seen five released versions. Communication with data acquisition hardware in these earlier versions was accomplished via a Session-Based Interface (SBI) paradigm, with additional support for Serial Computer Interface (SCI) routines for communication with microcontrollers. The most recent modifications presented herein include support for direct wireless communication with the ADS_BP via Transmission Control Protocol/Internet Protocol (TCP/IP) routines. Specifically, there are four possible commands from BioPatRec for controlling the ADS_BP device, each identified by a unique opcode.

- **TEST CONNECTION** (opcode 1), used to check if the connection with BioPatRec is established and requires the device to respond with an acknowledgement message (ACK).
- **START STREAMING** (opcode 2), used to start sample acquisition. For this purpose, the microcontroller enables the Read Continuous Mode in the ADS1299, enables the NDRDY GPIO interrupt, and prepares the transmission packages. It is noted that, during streaming mode, the status LED will be on, indicating that the device is acquiring EMG samples.
- **STOP STREAMING** (opcode 3), used to stop sample acquisition. Consequently, the microcontroller disables the Read Continuous Mode, disables the NDRDY GPIO interrupt, resets the buffers, and turns off the status LED.
• SET ADS_BP (opcode 4), used to configure the ADS1299 analog front-end by setting up the sampling frequency, setting up the amplification factor and, optionally for testing purposes, enabling/disabling the internal oscillator.

The ADS_BP is always expected to acknowledge any received command.

6) HOUSING

ADS_BP housing was designed using Fusion 360 (Autodesk, San Francisco, USA) with a minimum wall thickness of 2mm and inside dimensions of 68x60x43 mm. The housing is designed to firmly hold the ADS_BP assembly and to offer good accessibility, as shown in Fig. 3(a). To facilitate use and portability while recording bioelectric signals, a point of lanyard and the use of a standard USB power bank were added. To hold the power bank to the case, there are two additional cutouts in the case and cover allowing a Velcro or other strap to pass through.

Fig. 3(b) shows a cross-section emphasizing the snap fit design holding the lid securely to the case without the need for additional components. (c) Supports were added to provide a secure platform on which the ADS_BP rests in the housing. The hole in the bottom surface aids the removal of the PCB from the case.

- 3D-printed housing was designed to store and protect the ADS_BP during research and clinical use. (a) The housing features openings for the signal electrodes (left), reference electrode (back), and power (right). A USB power bank can be suspended from the front face of the housing, and the entire assembly can be worn or suspended using a lanyard. (b) A snap fit design holds the lid securely to the case without the need for additional components. (c) Supports were added to provide a secure platform on which the ADS_BP rests in the housing. The hole in the bottom surface aids the removal of the PCB from the case.

The ADS_BP components include:

- Power bank and USB cable costs are not included in the cost estimate. Detailed component and cost breakdowns are provided in the Bills of Materials available as supplemental materials. The PCB printing costs provided are an upper estimate, as unit costs will be dependent on quantity and source – PCBWay quoted $1 USD per board and Eurocircuits quoted $11 USD per board when ordering 10.

In addition to the per-board components listed below, the AMW136 Wi-Fi module on the COMM_BP board requires an AMW136-E03 development board ($59.00, Digi-Key) for configuration. It should also be noted that End of Life for the AMW136 Wi-Fi module went into effect on 21 December, 2021; parts stocks are still available for purchase at the time of writing, and replacement parts are available from the manufacturer (WGM160PX22KGA3, Silicon Labs, Austin, USA).

- Flash Forge Dreamer 3D printer (Zhejiang Flashforge 3D Technology Co, Jinhua, China) using 18 meters of polylactic acid (PLA) filament with a 0.00124 g/mm³ density and 1.75 mm diameter, for a total weight of 53g. Printer settings focused on balancing material savings with stable print quality; hexagonal infills were used after the fifth solid print layer. Other manufacturing techniques may be more appropriate when producing larger quantities of cases, but this is beyond the scope of the present manuscript.

B. BILL OF MATERIALS SUMMARY

An inventory of the finalized components is provided below. Power bank and USB cable costs are not included in the cost estimate. Detailed component and cost breakdowns are provided in the Bills of Materials available as supplemental materials. The PCB printing costs provided are an upper estimate, as unit costs will be dependent on quantity and source – PCBWay quoted $1 USD per board and Eurocircuits quoted $11 USD per board when ordering 10.

In addition to the per-board components listed below, the AMW136 Wi-Fi module on the COMM_BP board requires an AMW136-E03 development board ($59.00, Digi-Key) for configuration. It should also be noted that End of Life for the AMW136 Wi-Fi module went into effect on 21 December, 2021; parts stocks are still available for purchase at the time of writing, and replacement parts are available from the manufacturer (WGM160PX22KGA3, Silicon Labs, Austin, USA).

Emphasizing the need for secure housing for the PCB, supports were added in each corner of the inner base of the case. In this way, the PCB is centered and secure in the horizontal plane. A hole was created on the bottom surface to push the circuit board out of the case, as shown in Fig. 3(c).

The housing shown in this manuscript was prototyped using a Flash Forge Dreamer 3D printer (Zhejiang Flashforge 3D Technology Co, Jinhua, China) using 18 meters of polylactic acid (PLA) filament with a 0.00124 g/mm³ density and 1.75 mm diameter, for a total weight of 53g. Printer settings focused on balancing material savings with stable print quality; hexagonal infills were used after the fifth solid print layer. Other manufacturing techniques may be more appropriate when producing larger quantities of cases, but this is beyond the scope of the present manuscript.

<table>
<thead>
<tr>
<th>Component</th>
<th>Total Cost [USD]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADS_BP PCB</td>
<td>$11.00</td>
<td>Eurocircuits'</td>
</tr>
<tr>
<td>COMM_BP PCB</td>
<td>$11.00</td>
<td>Eurocircuits'</td>
</tr>
<tr>
<td>ADS_BP Components</td>
<td>$85.44</td>
<td>Digi-Key</td>
</tr>
<tr>
<td>COMM_BP Components</td>
<td>$25.37</td>
<td>Digi-Key</td>
</tr>
<tr>
<td>Tiva Launchpad</td>
<td>$16.99</td>
<td>Texas Instruments</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td><strong>$149.80</strong></td>
<td></td>
</tr>
</tbody>
</table>

*PCB costs provided are an upper estimate as unit costs are dependent on quantity and source.
Enabled

placement of surface electrodes [17]. Signal quality can be maximized by using recommended measured SNR of the ADS_BP ranged between 19 and 27 dB grid.

no physical connection between the subject and the power

voltage battery pack and wireless communication, resulting in

data were

AFEs. sEMG signals were sent to BioPatRec via wired

ADS_BP was analyzed and compared between different

in previous work by Mastinu et al., the performance of the

III. RESULTS

In previous work by Mastinu et al., the performance of the ADS_BP was analyzed and compared between different AFEs. sEMG signals were sent to BioPatRec via wired communication with a USB connection [14, 16]. Data were recorded from eight different people with full mobility of their arms, who were asked to perform 10 hand and wrist movements. Sample EMG recorded from the ADS_BP are displayed in both time and frequency domains in Fig. 4. The measured SNR of the ADS_BP ranged between 19 and 27 dB [14]. Signal quality can be maximized by using recommended placement of surface electrodes [17].

Additional validation focused on the performance of the system while using Wi-Fi to send the acquired signals from the ADS_BP to BioPatRec. For this validation, the number of communication errors were counted during a 60-second recording session. Preliminary testing of the ADS_BP revealed factors which could significantly affect the number of communication errors, including the type of power supply used and the network settings of the test computer [18]. Computers usually scan through different wireless networks aiming for the best possible access to the internet. This feature, called wireless auto-scanning, is typically enabled by default. Since the ADS_BP does not have internet access, a computer will continue scanning for other networks even while connected to the ADS_BP. Because of this scanning process, communication between the ADS_BP and the computer experiences a greater frequency of errors (Fig. 5).

The Wilcoxon rank-sum test was used to statistically compare the medians of error distributions between the two auto-scanning settings. Our results confirmed that disabling wireless auto-scanning yielded fewer communication errors (median [quartiles]: 6 [2,9]) than when wireless auto-scanning was enabled (8 [5,12]; \( p < 0.001 \)). Although wireless auto-scanning did tend to result in more communication errors, completely disabling the feature may bring its own challenges. The computer may need to forget all previous wireless networks, meaning it loses the option to easily switch between networks.

Another variable influencing the communication error onset is orientation between the ADS_BP and the test computer. Since the COMM_BP board has an antenna built into the PCB, certain orientations have a higher probability of communication errors. The ADS_BP orientations tested in this validation are shown in Fig. 6. Following those orientations, the right side corresponds to the power supply port (as also shown in Fig. 3(a)). Test results shown in Fig. 6 demonstrate that by placing the ADS_BP with the right side facing the computer tends to generate more communication errors than other orientations.

The Wilcoxon rank-sum test was similarly used to statistically compare the medians of error distributions between the four orientations; Holm-Bonferroni corrections were used to adjust for family-wise error rate. The results showed significantly more communication errors occurred when the test computer was located towards the Right side of the ADS_BP (median [quantiles]: 11 [7,14]), compared to all other orientations (\( p < 0.005 \)). Additionally, we found no significant differences (\( p > 0.312 \)) in communication errors between the Back (6 [4.75,8]), Front (7 [4,9]), and Left orientations (4 [1.5,7]). Furthermore, the minimum number of measured errors was also higher with the power supply port (Right) facing the computer, which also suggests a higher likelihood of experiencing more errors in this orientation.

It is therefore not recommended to orient the ADS_BP with the power supply connector facing the test computer, when possible.

IV. DISCUSSIONS

The field of biomedical engineering can be prohibitively expensive and difficult for early-career researchers and researchers in economically disadvantaged regions to enter. This has the potential to weaken the overall quality of the output within the field by promoting homogeneity in research centers and topics, and an omission of research focused on the needs of disadvantaged areas from the overall body of literature. A healthy body of research is one in which a diverse range of researchers can participate, which in turn necessitates adequate access to critical equipment.
The ADS_BP and BioPatRec are designed to provide researchers of all backgrounds with an inexpensive platform for research related to bioelectrical signal acquisition and classification. Examples include the control of prosthetic devices using EMG signals and brain-computer interfacing using EEG signals. Additionally, these serve as a benchmarking platform through which signal processing and classification algorithms can be tested using comparable hardware, ensuring a level playing field for comparisons.

Enabling wireless communication on the ADS_BP represents an important advancement in terms of safety and clinical utility. First and foremost, wireless communication ensures electrical isolation from the power grid, which was not the case when the device was connected to the PC via a wired connection. This provides an additional layer of safety for the subject. Second, wireless communication allows for a broader range of data collection scenarios, notably walking. This opens the door for researchers interested in fields such as gait rehabilitation for stroke [19] and gait prediction for prosthetic legs [20].

Despite the advantages of the added wireless communication, it is not without its drawbacks. Dropped data packets are an unavoidable complication of wireless communication. Knowing this, we investigated several ways to minimize these errors. Disabling wireless autoscanning and ensuring the ADS_BP is oriented such that the computer is not to the right of the device is shown to significantly reduce these communication errors. While the former can easily be set up on the test computer, the orientation requirement may be more difficult depending on the task. For seated tasks, the computer can simply be placed in a static location relative to the ADS_BP to ensure optimal communication. However, for walking tasks, researchers may decide to only collect data while users are walking in one direction, and omitting data while the user walks in the other direction when more communication errors are expected. Regardless of the methods used to minimize communication errors, it should be noted that some instances of missing data are to be expected. Such missing data may be estimated using data modeling postprocessing techniques [21, 22], however this is beyond the scope of the present work.

V. CONCLUSION
Here, we present recent work for a complete bioelectrical acquisition platform. In contrast to other open-source bioelectrical signal acquisition devices, the ADS_BP hardware interfaces inherently with the BioPatRec software to allow for out-of-the-box acquisition-to-output signal classification. The low cost of the ADS_BP hardware makes for an accessible benchmarking platform which lowers the bar to conducting research in the field of biomedical engineering, allowing for bioelectric signal recording in laboratory and clinical settings, as well as offline and real-time intent classification, all for a cost of approximately $150 USD per device.

SUPPLEMENTARY MATERIALS
All source files for the ADS_BP and BioPatRec can be found in the following repository on the Open Science Framework: https://osf.io/k5yut/

A user guide describing in detail the assembly and set-up procedures for the ADS_BP can be found in the Supplementary Materials for this manuscript.

ACKNOWLEDGMENT
We would like to acknowledge and thank the participants in this study for their time and effort.

REFERENCES


