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# Wireless connection of bioimpedance measurement circuits based-on AD5933: a state of the art

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**Abstract.** This contribution describes the state of the art in bioimpedance measurements through development boards to build portable devices that perform in-situ measurements and potential technological opportunities to separate the AD5933 integrated circuit from a PC. The presented research is based on prototypes developed with the aim of achieving portability with the AD5933 integrated circuit and it includes different wireless connection methods and a varied software design for the acquisition, visualization and storage of data obtained from biological systems. As a result, this work describes twenty articles that perform wireless connectivity using different microprocessors for different applications. These references seek to explore technological trends, deficiencies, and opportunities for future development projects in telemedicine.

## 1. Introduction

There are diverse electrical bioimpedance applications in the medical, agrarian and food industries [1]; such as the electrical impedance tomography (EIT) [2], the study of cardiovascular parameters [3], the differentiation of frozen food [4] and plantations facing climate changes [5], among others [6]. Commercial devices such as the NIM 1000 (Megger, UK) meter [7], Battery Impedance Meter BT4560 (HIOKI, Japan) [8] and Solartron 1260A (Solartron Metrology Ltd, England) [9] are used to measure electrical properties in biological systems. However, they have a high cost (tens of thousands of dollars), and there are no portable versions. On the other hand, evaluation boards available in the market can measure electrochemical impedances with certain limitations, and they need to be operated by trained users. Still, its cost is much more affordable for researchers and students from countries where electronics are not manufactured. We are especially interested in the evaluation boards based on the integrated system AD5933 (Analog Devices, AD, USA) [10]: EVAL-AD5933EBZ (AD, USA) [11] and PmodIA (Digilent®, USA) [12]; both with AD5933 capabilities, including taking bipolar measurements. Table 1 summarizes the characteristics of each of these boards. In the biomedical field, there is a strong trend towards portability in equipment that measures physiological parameters, such as multiparameter monitors, ultrasound equipment, pacemakers, blood glucose meters, or even surgical systems. Therefore, our interest is to generate a low-cost device that establishes wireless communication between the bioimpedance measurement stage and the Graphical User Interface (GUI) stage. Hence, in the present contribution, we decided to review the state of the art in the



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implementations of development boards that use the AD5933 to take electrical bioimpedance measurements wirelessly for subsequent applications in telemedicine.

**Table 1.** Comparison between AD5933/EVAL-AD5933EBZ/PmodIA [10–12]

Characteristics	AD5933	EVAL-AD5933EBZ	PmodIA
Broadband without external clock	5-100 kHz	5-100 kHz	5 -100 kHz
Measured impedance range	1 k $\Omega$ to 10 M $\Omega$	100 $\Omega$ to 10 M $\Omega$	10 $\Omega$ and 100k $\Omega$ <sup><math>\Delta</math></sup>
Internal Clock	16.776 MHz	16.776 MHz	16.776 MHz
External Clock	Optional	16.776MHz <sup><math>\diamond</math></sup>	Optional
Communication	I2C	I2C/USB	I2C
Voltage regulator	No	ADP3303	ADP150
ROM	No	Yes	No
GUI	No	Yes <sup><math>\triangleright</math></sup>	No
FeedBack Resistor (RFB) pins	Yes	Yes	No
Microcontroller	No	CY7C68013-56LFC	No

<sup>$\Delta$</sup>  With two fixed RFB values [10], constraining the external measurement to these values.

<sup>$\diamond$</sup> Capable to use another external clock to increase its broadband.  <sup>$\triangleright$</sup> For Windows.

## 2. Methodology

The bibliographic review was based on the web search engine “Google scholar” using the following combinations of terms: “AD5933+Portable”, “AD5933+Evaluation Board+Raspberry”, “AD5933 + Arduino”, “AD5933 + Raspberry”, “Bioimpedance + AD5933 + Arduino”, “Bioimpedance + AD5933+Portable”, “PmodIA + Raspberry”, “PmodIA + another microprocessor”, “AD5933EBZ + Raspberry”, and “AD5933EBZ + Arduino”. The review was limited to papers in English. We focused on the above mentioned impedance meters in combination with Arduino (ARD) and Raspberry (RSP), because these microprocessors are low-cost, commonly used, and recommended by the same manufacturers [12]. However, results with other microprocessors were not excluded. The search returned 1383 results, including papers with non-wireless connectivity between the user interface and control stages, and the AD5933 measurement stage. It also included articles that did not provide details or descriptions about how to carry out the wireless connectivity between the mentioned stages. The articles with these characteristics were discarded since they were no longer of our interest, and there were a total of 26 documents left, including conference papers, journal papers, undergraduate thesis, and postgraduate thesis. Finally, these 26 papers included similar versions by the same authors, therefore 20 papers were chosen without repeating any author among them.

## 3. Results

This section presents the results divided according to AD5933, EVAL-AD5933, or PmodIA in combination with a microprocessor, specifically ATmega328P, ATmega32U4, RSP, or others. In all of the cases, the communication is established with the I2C protocol, regardless of the measuring or control system used. The portable prototypes published in the reviewed articles have an Analog Front End (AFE) circuit that allows for the conditioning and treatment of the measured signal and the setting of the amplitude range in the impedance values to be measured [13–32]. Additionally, it was found that the GUI stage is applied in different modes: smartphones or personal computers with an app, and the communication can be made via Bluetooth [13, 16, 17, 21, 23, 26, 29], radio frequency [25, 30, 32], wireless WiFi networks

[14, 15, 18, 20, 22, 24, 27, 28, 31] or mobile data networks [19]. No results were found under the following combinations of search terms: PmodIA + Raspberry, PmodIA + another microprocessor, AD5933EBZ+Raspberry, and AD5933EBZ+Arduino. All the papers found were published between 2006 and 2019, and the last review access was on May 2021.

### 3.1. AD5933+Arduino

ARD is an open-source electronics platform that is wired to AD9533 and it connects wirelessly to the GUI. Specifications are provided below. The biomedical applications found are described in this paragraph. The development of a protein detector for point-of-care testing, developed by Zhang et al., is applied by electrochemical impedance spectroscopy. The device uses the GUI stage in a smartphone through an app especially designed to allow the user to configure each measurement according to their needs. The measurement stage (“hand-held detector”, as authors name it) uses ARD Uno and it connects to a smartphone via Bluetooth with an additional module. The results are presented in Cole-Cole and Bode diagrams [13]. Pothof et al. research phenomena in intracerebral tissue; they developed a 1024-channel impedance spectroscopy system. The results were broadcasted through 19 transmission wires on a HDMI that also provides the supply voltage. The results are saved in an ARD Yun microcontroller that communicates with AD5933 using the I2C protocol. Moreover, the network obtains remote access through a Wi-Fi connection; additionally, multiplexers and demultiplexers switch to different unknown impedances. The GUI is designed for personal computers only [14]. Afsarimanesh et al. present a portable device to detect bone loss through the evaluation of variations in the level of CTx-I in serum, using the AD5933 to monitor the impedance variation with different CTx-I concentrations. The ARD Uno Wi-Fi microcontroller obtains the data, and the ADG849 (AD, USA) is used to switch the RFB between calibration (fixed resistance of 2.1k $\Omega$ ) or measurement mode, via firmware. The collected data are sent to the Thingspeak platform, a free ARD-compatible, and IoT cloud-based server that can be accessed from any location. The information obtained is an indicator for osteoporosis diagnosis [15]. In [16], the authors implemented a portable sensor for the measurement of bacteria preconcentration in microfluidics based on an impedance detection system; the system communicates with an Android smartphone, which remotely controls the ARD Uno microcontroller through a Bluetooth module (Seeed SLD63030P). The ARD generates the commands for the AD5933 according to the input parameters set up by the user in the smartphone. The GUI offers the visualization of results in a Cole-Cole diagram and a calibration curve between the resistance and concentration values. An application for the measurement of dehydration in infants was developed by Agcayazi et al. based on a portable device that is placed on the leg and uses two electrodes; the AD5933 is connected through an RFDuino (RFD22301) that sends the acquired data to a mobile application, via a Bluetooth antenna. This application verifies the connection between modules, collects acquired data and charts it with the AD5933. The dehydration values generated from the bioimpedance measurements are displayed numerically and plotted into a dehydration time curve. The data validation is performed by comparing the measurements with the AD5933EBZ [17]. Environmental applications have been found, and they are detailed in this paragraph. Simic et al. developed a remote device to measure temperature, relative humidity, volatile organic compounds, and pH level in water, using impedance as a variable in the measurement of the last parameter; wireless communication is performed using a Wi-Fi module with ARD Uno. Then, through Message Queue Telemetry Transport (MQTT) protocol, the data are received on an IoT interface where it can be visualized and saved for further analysis [18]. Carminati et al. present a water quality monitor by placing sensors in the internal parts with cells and films developed by themselves. The device has an AFE for the AD5933, and it is composed of two ADA4891 (AD, USA), an ADG604 (AD, USA), and an RFB fixed in 20k $\Omega$ ; it measures the conductivity applying a 100kHz sinusoidal signal. The ARD Mega used integrates

the control and processing of the measurement stages of the conductivity (from impedance), pH, and temperature. In addition, the central system application monitors the presence of dirt layers in the pipe flange cells to improve and supervise the drinking water distribution network [19]. Alahi et al. developed a smart system to detect nitrate in the soil; the authors created an adapted cell used by the AD5933 to obtain soil impedance data. The ARD Uno Wi-Fi connects to the IoT server and sends the average nitrate concentration through a Dragino LoRa shield to link the measure stage with the cloud, as it enables long-range data sending. The cloud server is Thingspeak, and the development was validated by a HioKi IM 3536 LCRmeter (China) [20]. The group led by Zhang developed a portable biosensor platform to detect 2,4,6-trinitrotoluene (TNT) with monitoring by spectroscopy of impedance with screen-printed electrodes. The GUI and measurement stages communicate via a Bluetooth module (HC-06 shield); they are controlled by an app that allows users to receive and visualize the data in real time, and to set the impedance measurement parameters. The authors do not detail the ARD model used [21]. Alemayehu et al. implemented the real-time monitorization of oil in a high-power electrical transformer. The ARD MKR Wi-Fi 1010 is used for wireless communication via Wi-Fi 802.11n protocol, and the input data for the AD5933 was programmed with C++; the frequency sweep ranges from 10 kHz to 98 kHz with a step size of 1 kHz (the frequency range from 10 kHz to 50kHz is of special interest). Once measurement data are obtained in the PC, they are stored in an open-source IoT platform called “thingier.io” that allows to store, display, analyze and share the acquired data, thus reception and plotting in real-time is possible. The impedance values correlation and the oil quality condition are obtained by immersing the electrodes in two types of samples: new, clean oil and used oil [22].

### 3.2. AD5933 + Raspberry

The developed system is called Z-RPI [23] and it performs cardiography by electrocardiography (ECG) and by impedance cardiography (ICG); for the first application an ADAS1000 (AD, USA) is used, and for the second one, the AD5933 is used. The system is coordinated by a RSP Pi3 and powered entirely by lithium batteries. It contains an implemented AFE that allows a tetrapolar electrode application and an impedance measurement range between  $0\Omega$  and  $1k\Omega$ , making it compatible with nutrition applications of segmental and full-body electrical impedance measurements. This system automatically calibrates the AD5933 using an ADG774 switch (AD, USA) with a bioimpedance similar to the one present in the human thorax, with a circuit made up of a resistor ( $150\Omega$  0.1%) in series with a capacitor (10nF 1%), and both of them in parallel with a resistor ( $150\Omega$  0.1%). The device is controlled from the RSP by a touch-screen and, in turn, has wireless connectivity via Bluetooth to a personal computer. The measurements are stored on a micro-SD card included in RSP and they are sent to the PC via Bluetooth. It is worth noting that the RSP model can also communicate wirelessly via a Wi-Fi module. Jasinski and his team implemented a sensor module for gas concentration measurement. They used an ATmega8 microprocessor (Microchip Technology, USA) in I2C communication with the AD5933; it has an AFE composed of an LMP91000 (TI, USA), with a three-pole measurement configuration. In addition, the ATmega8 communicates with a supervision module that processes and collects measurement data; this module is a RSP Pi powered by Linux, which connects to a Mysql database, allowing the user to control and visualize the available data over the Internet. Finally, the prototype was calibrated with different NH<sub>3</sub> concentrations [24].

### 3.3. AD5933 + Other microcontrollers

The wireless communication was done in another system using an nRF24E1 microprocessor (NordicSemi, Norway) with a personal computer. The nRF24E1 communicates via I2C with the AD5933, it transmits the information via RF to a system connected to the PC, and performs RS232 communication with the GUI developed from Windows XP for calibration, control,

storage, visualization, and measurements [25]. Al-Ali et al. developed a prototype coordinated by the ATmega3288 (ATMEL) that communicates via I2C with the AD5933 and via Bluetooth using the HC-05 module with a PC, which also has a data storage module for Micro-SD memory cards. Once the data are sent wirelessly to the PC, it is processed with Matlab®. The AFE consists of a multiplexer (ADG849), two operational amplifiers (AD8605), and a fixed RFB at 20 k $\Omega$ . Passive components of different values perform the calibration of the prototype. Finally, it takes measurements on apples that are compared with the measurements obtained with a commercial device, such as PSM3750 impedance analyzer (Newton 4th LTD, UK) fitted with an IAI fixture (Impedance Analysis Interface) (4th LTD, 2005) [26]. A contribution in [27] presented a comparison between bioimpedance meters: AD5933EBZ, Bodycomp-MF (AKERN company, Italy), Quantum II (JBL company, USA), and the AD5933; for the last one, a prototype was developed based on the AT91SAM7256 microcontroller (Atmel, USA) with a matrix keyboard, an LCD (RX240160A- FHW), and a module for data storage in SD memory cards. This device is portable and integrates the measurement and GUI stages in the same module. The AFE is made up of an AD820 (AD, USA) but there are no details on the calibration RFB values. Using a BeagleBone Blackboard (BBB TI, USA), Seoakchan Yoo presented an impedance spectroscopy system that uses four electrodes. The BBB is used to control the AD5933 and provide an external clock signal; it has a Wi-Fi Dongle to offer wireless communication with a web server accessed via a smartphone. The development has a GUI from a mobile application allowing the calibration of the AD5933, as well as the acquisition, storage and charting of data. The AFE is made up of an INA826 (TI, USA), an AD8608 (AD, USA), an AD8220 (AD, USA), and resistors of different values for multiple calibration RFB values [28].

### 3.4. AD5933EBZ + Other microcontrollers

In [30], a design of an impedance sensor based on the AD5933EBZ (Review A, older design is used) and the ATmega128L microcontroller is presented; the wireless connection is performed through a 2.4 GHz XBee module and an XBee base station, the measurements are made with piezoelectric transducers controlling the voltage and current applied to them. Furthermore, this device provides wired data communication via an RS-232 port on a PC to process the results. Finally, this development is applied to monitor the interrogation of structural health. Sairin et al. developed a device to detect different concentrations of lard as a palm oil adulterant. It comprises a Maker Uno, an AD5933EBZ, a Bluetooth module, and a mobile application that receives the data for analysis; the app was developed by Android Studio to be used in smartphones, and the frequency and impedance measurements are saved in a CSV file. The acquisition of measurements from the AD5933EBZ is carried out with an Interdigitated electrode (designed and manufactured at the Universiti Putra Malaysia), and its calibration is performed with a 4.7 k $\Omega$  resistor [29].

### 3.5. PmodIA + Arduino

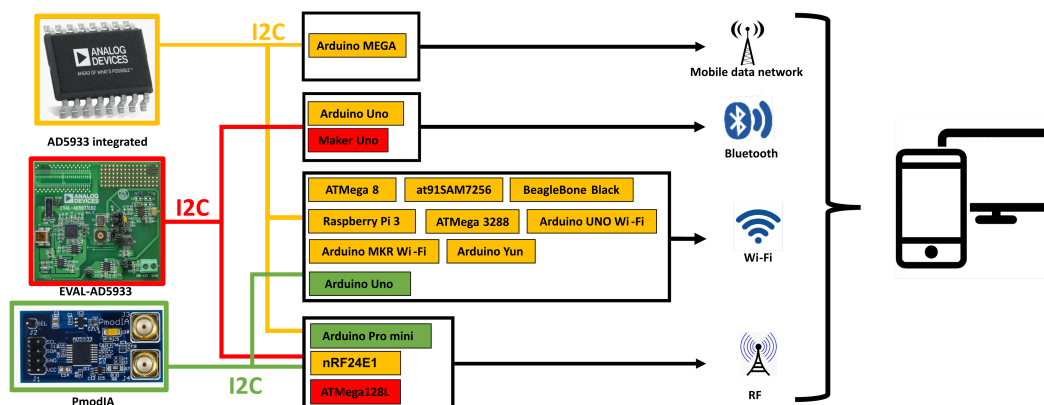
Zet et al. designed a plants monitoring system at home by measuring the following parameters: air and soil humidity, ambient temperature, and amount of light. This system uses bioimpedance measurements to quantify soil moisture; the frequency range used for the analysis ranges from 1 kHz to 100 kHz. The control system is an ARD Uno using the ESP12 mini-board; it communicates through wireless Wi-Fi. It has a module incorporated into the ARD, with a server to an interactive platform where the obtained results are visualized. The above mentioned server is based on the MQTT communication protocol. This system allows for the visualization of results but not the modification of the measurement parameters. The information from the sensors is stored in a local database of a RSP Pi; thus, monitoring the plants according to their species and characteristics is achieved [31]. AboBakrs et al. developed a system that can receive data either wired from a USB port or wirelessly based on HC-11, a radio frequency module; the

data are sent and received in the range of 433.4-473.0 MHz. The microcontroller used is the ARD Pro mini, and it is responsible for communicating with the PmodIA and the PC interface to program the initial parameters and receive measurements. On the other hand, it has an energy storage device for wireless applications that gives it an autonomy of 3 months. The focus given by this author is for applications in the field of agriculture to measure impedance changes in vegetables based on their growth. The device measurements were validated and compared with those obtained with the Potentiostat SP-150 (BioLogic, France) [32].

**Table 2.** Comparison between working ranges of the different developed systems.

Author	Measured range[ $\Omega$ ]	Frequency bandwidth [Hz]	Applied voltage	Comm.	Microcontroller
Zhang	-*	10 to 10k	200 mV	Bluetooth	ATmega328P
Pothof	1 k-2M	500 to 100 k	26 mV	Wi-Fi	ATmega32U4
Afsarimanesh	-*	-*	-*	Wi-Fi	ATmega4809
Jiang	-*	2 k to 100k	-*	Bluetooth	ATmega328P
Agcayazi	-*	1 k to 100 k	-*	Bluetooth	-*
Simic	-*	-*	-*	Wi-Fi	ATmega328P
Carminati	33 -100	-*	100 mV	GSM	ATmega2560
Alahi	-*	10 to 100 k	-*	Wi-Fi	ATmega4809
Zhang	100 k-1M	10 k to 100 k	200mV	Bluetooth	-*
Alemayehu	.*	10 k to 98 k	-*	Wi-Fi	SAMD21 Cortex®
Hafid	0 -1k	1 k to 550 k	58 mV	Bluetooth	Raspberry Pi3
Jasinki	-*	-*	-*	Wi-Fi	Atmega 8
Majer	0-500 k	10 k to 100 k	1.5 to 3V	RF	nRF24E1
Abdulwadood	10 - 100 k	5 to 100 k	-*	Bluetooth	Atmega3288
Walków	-*	10 k to 90 k	-*	Wi-Fi	at91SAM7256
Yoo, S.	100 -10k	20 to 100 k	-*	Wi-Fi	BBB
Sairin	-*	5 k to 100 k	-*	Bluetooth	ATmega328P
Mascarenas	-*	10 k to 100 k	-*	RF	ATmega128L
Zet	-*	100 to 100 k	-*	Wi-Fi	ATmega328P
AboBakr	10 - 100 k	5 to 100 k	-*	RF	ATmega328

Comm.-Communication, ARD-Arduino, -\*No information reported.



**Figure 1.** Schematic view summarizing the current state of the art technology.

#### 4. Discussion

As shown in the obtained results, several microprocessors allow the connection with the different presentations of the AD5933 for its control and consequent impedance measurement, among which ARD and RSP stand out. However, there is no concrete evidence of the reason for the choice of each microcontroller other than the final application to be given to the device. Among the other microprocessors, there are several benefits to be highlighted: the ATMega8 [24] allows placing multiple analyzers in the same bus, and they can be controlled separately or simultaneously; both the ATmega128L and the BBB have a built-in 8MHz oscillator which allows them to generate an external clock signal for the AD5933, offering greater thermal stability [30]. Another worth noticing finding is that, in its official website, the manufacturer of the PmodIA board (Digilent ®, USA) for the connection via I2C protocol with ARD and RSP has published a guide for the physical connection along with scripts to be applied in “plug and play” mode [12]. However, these scripts do not permit the correct use of the PmodIA and impedance measurements cannot be performed with this information. As mentioned above, we are not interested in the wired connection between the measurement and GUI stages. However, several applications were found that could be adapted to a wireless device, such as an imaging system based on EIT [33], a system for noninvasive blood glucose monitoring [34], a multipurpose bioimpedance meter [35], an impedance plethysmograph [36], and a device for impedance in electroluminescent structures [37], among others. Al-Ali et al. offer clear evidence, with images, that they have fully developed the impedance measuring device with the ATMega328p microcontroller without using a Development Kit containing the integrated microprocessor with various I/O, and peripherals, among other electronic elements. This fact cannot be guaranteed in the rest of the cases, where authors use microprocessors different from ARD, RSP, or BBB. In Table. 2 a comparison between the developed systems is included. Figure 1 shows a schematic view that summarizes the possible connections reported by different authors.

#### 5. Conclusion

AD5933, AD5933EBZ and PmodIA have inherently the same frequency spectrum of measurement if an external clock is not applied (an available option), for this reason, it is very important that the microprocessor used for control can provide a clock signal to expand the bandwidth of the EIS [13, 14, 16, 17, 23, 25, 26, 28, 31, 32]. In the shown works, the lowest cost microprocessor used is the ARD Uno Maker, and the most commonly used is the ARD Uno [13, 14, 18, 21, 31]. On the other hand, the ARD Yun and nRF24E1 (Nordic) are now obsolete. The communication between AD5933 and the two Evaluation Boards with the controlling microprocessor is done through the I2C protocol. However, no author provides the I2C communication protocol script (“open sources”). The present review work lays the basis for the wireless applications of the AD5933 in its various presentations, determined by the microcontroller that manages it and the existing applications, frequency spectrum of the applied signal, and dynamic range of impedance measurements.

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