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Portable Multipurpose Bio-signal Acquisition and Wireless Streaming Device for Wearables

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***Abstract*—Physical indicators are directly related with health and fitness of human body. By employing real-time e-health monitoring systems for acquiring, and analyzing bio-signals by measurements such as electrocardiogram (ECG) and electromyography (EMG), it is possible to extract information to achieve better health-care in terms of observation, diagnosis, and treatment. However, those systems are limited in acquiring and sending data at high rates, are not energy efficient, or, are restricted in terms of portability due to large size and weight. In this paper, a compact portable bio-signal acquisition device for wearables has been designed and implemented. The developed hardware is capable of acquiring and reliably sending the data wirelessly at a high transfer rate in real-time while keeping the overall energy consumption low. Finally, the signal acquisition performance of the device has been evaluated for both ECG and EMG at 8 channel 24 bit resolution/channel 500 samples/s configuration. Measurement of energy consumption has been conducted using professional tool and it is found that the device can continuously work for up to 13.6 hours with a 3.7V 1700 mAh battery. In addition, the device has been used in an IoT-based system as an example of possible integration.**

***Keywords*— Bio-signal, Bio-potential, Acquisition, Wireless, Portable, Wearable, IoT**

I. Introduction

Bio-signals, bio-potentials or bio-electrical signals are electrical potentials captured between two points in living cells and are widely employed in biomedical monitoring, psychological studies and human-computer interaction (HCI) related applications. With Ag/AgCl electrodes, bio-signals can be easily gathered from the skin surface. Abundant information can be obtained from different measurements involving bio-potentials, for example, electrocardiogram (ECG) for heart monitoring, electromyogram (EMG) for muscle activity monitoring, electroretinogram (EOG) for eye movement measurement, and electroencephalogram (EEG) for detecting brain activities [1]. The way of transforming physical activities to interpretable electrical information not only lets us know ourselves better, but also enables use of advanced signal processing with computers intelligently [2, 3].

In bio-signal pattern recognition applications, multiple channels of bio-signal measurement are required in clinical and human computer interaction (HCI) fields, for example, monitoring of high density muscle and its motor units in neurophysiology [4], emotion recognition from multiple facial muscles [5], hand gesture recognition with multiple channel EMG measurement from arm [3] and sleep analysis with EEG [6]. As related applications are getting more and more close to everyday life, the need of portable or wearable multi-channel bio-signal acquisition device for easier mobility is highlighted. With the development and popularity of wireless communication technology, portable or wearable devices can be easily connected to smart phone, or smart gateway [7, 8], so as to merge into Internet of Things (IoT) for remote monitoring and control.

There are several challenges in the design of wearable multi-channel bio-signal acquisition device, and they are summarized as follows: i) Energy efficiency- As bio-signals are weak electrical signals and are susceptible to environmental interference, power supply from battery is always preferable in device design. However, this brings the issue of battery life, where energy efficiency of the overall device needs to be carefully considered. ii) High data transmission rate- In case of real time bio-signals monitoring, streaming the measured data is required for continuous monitoring and analysis. Meanwhile, although sample rate requirement varies among types of bio-signals, it should be at least 200 samples per second for each channel [9] according to Nyquist Shannon sampling theorem. iii) Compact size- Unlike single channel bio-signal measurement, multi-channel measurement needs dense electrode placement for exquisite monitoring (e.g. facial muscle activities and motor unit activities) or dispersive electrode placement to measure multiple types of bio-signals (e.g. both ECG and leg EMG in kinesiology). However, for both cases, a centralized data acquisition device is required with a compact size for digitization and transmission of data from all channels. iv) Noise- bio-signals are weak analog signals in the range of micro-volts or milli-volts captured from skin surface. These tend to be contaminated by noise from surroundings such as power line interference, and thus noise on device should be minimized.

In this paper, the design and implementation of an 8 channel bio-signal acquisition device reaching a balanced trade-off between reasonable energy efficiency and data transmission rate has been presented. It is battery powered with Bluetooth wireless data transmission making it easier to communicate with mobile devices and any other device with available Bluetooth receiver. The device has been miniaturized for integration

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TABLE I
OSCILLATOR FREQUENCY AND BAUD RATE SELECTION

Oscillator frequency	8.0000 MHz			**14.7456 MHz**			16.0000 MHz			HC-05
Baud Rate (bps)	UBRR (hex)	Actual Baud Rate	Error Rate	UBRR (hex)	Actual Baud Rate	Error Rate	UBRR (hex)	Actual Baud Rate	Error Rate	Bluetooth (supported?)
230.4k	1	250k	8.5%	3	230.4k	0.0%	3	250k	8.5%	✓
250k	1	250k	0.0%	3	230.4k	-7.8%	3	250k	0.0%	
460.8k	0	500k	8.5%	1	460.8k	0.0%	1	500k	8.5%	✓
500k	0	500k	0.0%	1	460.8k	-7.8%	1	500k	0.0%	
921.6k	0	500k	-45.7%	0	**921.6k**	**0.0%**	0	500k	8.5%	✓
1M	0	500k	-50%	0	921.6k	-7.8%	0	500k	0.0%	
Max	500 kbps			921.6 kbps			1 Mbps			

into dedicated wearable applications. Based on the design, a prototype has been presented and validated. Furthermore, it is tested in a potential IoT application scenario. In summary, our main contributions in this paper are as follows:

- Proposing a design solution of multi-purpose wearable/portable multi-channel bio-signal acquisition device with balanced high streaming data rate and energy efficiency
- Implementing and validating the proposed design as a compact device along with performance evaluation
- Demonstrating an IoT-based complete system implementation from the signal acquisition node all the way to the cloud and user interface

The rest of the paper has been organised as follows: Section II presents related work and motivation for this work, Section III clarifies the device design requirements and discusses respective solutions accordingly, Section IV presents the implemented prototype based on the design, Section V evaluates bio-signal acquisition functionality and energy consumption and illustrates the results from tests conducted with the prototype, Section VI reflects design-time issues and findings, and finally, VII concludes the paper and provides possibility about future work.

II. MOTIVATION

In our previous work, the method of identifying facial expressions from facial sEMG was discussed in [10] and was presented in [11], together with an IoT-based remote monitoring system. The system had three architectural layers-sensor device layer, gateway-in-fog layer and cloud layer. Multi-channel facial sEMG were processed in cloud, then transmitted to remote end user and finally visualized in a browser. The hardware setup composed of separate functional devices including an Arduino Uno R3 board along with the ADS1299 evaluation board, all together which was bulky to carry, higher energy consuming and required mandatory wired USB connection to computer.

The existing open source devices and products in the market for multi-channel sEMG acquisition are either big in size, use wired mode data transfer or cannot reach adequate wireless data transmission rate. For example, Olimex ECG/EMG shield [12] which is stack-able with single channel and MySignals HW [13] need to work with a separate controller like Arduino Uno and send data through USB cable. Moreover, the energy efficiency is not considered properly when combining several separate devices together. Comparatively, OpenBCI Cyton Board [14] designed for brain computer interface development is better in terms of size and data resolution for denser channel sEMG, whose core is ADS1299 [15]. However, its wireless data transmission through Bluetooth LE (Low Energy) may cause issues when data rate is higher than 9600 bps. Regarding wireless bio-signal acquisition products such as Trigno™ Mobile [16] and BioNomadix [17], usually each transceiver only support 1 to 2 channel(s) acquisition and need dedicated receiver. Therefore, we came up with a concise, widely compatible device design for real time multi-channel wireless bio-signal acquisition and monitoring.

The ADS1299 [15] from Texas Instruments (TI) provides low noise bio-signal measurement with low energy consumption and flexible configurations such as, but not limited to, lead-off detection for input connection checking and patient reference drive to counter common-mode interference in measurement. Due to the impressive performance of ADS1299, the design in this paper is centered around it.

III. DEVICE DESIGN

To make useful interpretation of a bio-signal, several parameters such as number of acquisition channels, channel resolution, sampling rate, communication latency, error-free data transfer, host compatibility, configurable options and energy efficiency have been considered.

The brief target specification of the proposed device is as follows:

- 8 channels
- 24 bit resolution
- 250-1000 samples/s
- Low noise
- Wireless and wired communication (Selectable)
- Compact
- Energy-efficient

Fulfilling these requirements brings several challenges. Firstly, the high resolution data imposes the need of integrity and reliability in communication between the device and the host. The acquired data should arrive at the receiving end in proper interpretable format without any corruption. As the device is meant for prolonged usage, it must sustain the continuous data rate without any stall. The communication latency should also be low enough to ensure real-time monitoring and to prevent data from getting lost or arriving out of order. Secondly, communication mode should meet the specification and provide wider compatibility while keeping the infrastructural and energy requirements to a minimum. For example, Wi-Fi requires an access point and uses considerable amount of energy relative to Bluetooth. Other alternatives such as the nRF and Zigbee wireless technology improves energy efficiency but the need for matched receiving ends limits the compatibility with devices such as computers and portable smart devices. For these reasons, Bluetotoh has been chosen for communication. Besides, use of low power variant of integrated circuits for control and measuring further reduces energy consumption. Thirdly, to use the device along with multi-disciplinary wearable sensors, it has to be compact and portable. When reducing size, inter-component interference becomes an issue. By incorporating appropriate high accuracy components, proper placement, shielding, separate power supply, multi-stage filtering and filling of unused spaces on the printed circuit board with ground, the effects caused by noise can be reduced.

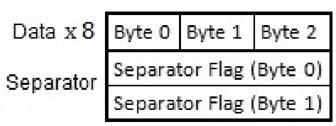

Fig. 1. Communication packet contains 24 bytes of data (3-bytes/channel, for 8 channel) and 2 bytes separator

When acquiring bio-signals, the device continuously transfers measurement data. Although other lower data rates are possible, for ensuring capability of the device, the upper bounds of the specification have been considered when calculating communication requirements. As shown in Figure 1, to ensure data integrity and distinguishing samples, a 2 byte separator- carriage return (CR, 0x0D) and line feed (LF, 0x0A) are used at the end of each set of 8-channel data.

Data /channelsecond = (24 bit 1000 samples) = 24 kb

Data /8.channels.second = (24 kb 8 channels) = 192 kb

For 1000 samples, this adds (16 bits * 1000 samples) = 16 kb resulting in total transferable data of (192 kb + 16 kb) = 208 kb. The host software checks for separator flag and extracts channel data accordingly. A built-in communication test function in the firmware can generate pre-defined set of numbers randomly and send it over Bluetooth so the receiving software can compare and detect any possible error. During several tests ranging from 30 minutes to 4 hours and the device configured as 24-bit resolution, 8 channel, 500 samples/s, the data transfer error within 10 meters (Bluetooth class 2) was found to be 0%

IV. Device Implementation

The functional architecture of the device along with related reasoning for component selection and the developed prototype is presented as follows.

A. Device Architecture

Hierarchical blocks of the proposed design shown in Figure 2 can be divided into four categories- power supply, control, measurement and communication which are described next.

1) Power Supply: The power supply block consists of the battery, the 5V voltage step up/down converter, 3.3V voltage regulation, and 3.3V low-noise voltage regulation unit. Coupling capacitors are used at each stage to filter ripple noise. An LED indicates power on mode. The device can be powered from 2.5V to 18V, making it possible to run it on two AA or AAA sized 1.5V alkaline batteries. For the prototype, a rechargeable 3.7V 1700 mAh Lithium-ion battery has been chosen because of its smooth discharge rate and compact size.

The 5V step-up/down block, similar to S10V4F5 from Pololu, converts battery input to a regulated 5V output at 400 mA output current, 70-80% efficiency and 4% accuracy. This powers the analog part the measurement block and the 3.3 volt regulation circuit. For the 3.3V regulation, an LDO voltage regulator L1117 has been chosen due to its high quality regulation and low output ripple. This block supplies power to the low-noise 3.3 volt voltage regulation, main controller and the communication block. At the next step is a 3.3 volt low-noise voltage regulation circuit. ECG and specially EMG signals are very small in amplitude, they are prone to noise. To reduce noise and to quantize signal from the probes more accurately, a very low-dropout, low-noise, ultra-low quiescent current regulator LP5907 has been chosen. The input is taken from previous 3.3V regulator and the output is fed exclusively to the digital part of the measurement block.

2) Controller: For the controller, to ensure portability and to use as low power as possible to save limited battery power, the 8-bit micro-controller ATmega8L from ATMEL has been chosen which features stable, low voltage operation at 3.3V. Alternatively, an ATmega328P can be used to implement very low-power modes and more flash program memory for the firmware to accommodate more features. Acting as the master, the controller reads bio-signal data from the measurement block via SPI, and then depending on wired or wireless configuration, sends it to external device or Bluetooth module, respectively via 3.3V TTL compatible UART. Besides, it is possible to change device configuration options such as sampling rate, delay and packet separator at run-time from the host. 3 LED lights are driven to indicate different working states such as initialization, active, idle and error.

3) Measurement: The most important block of this device is the measurement. It contains the highly configurable, multipurpose ADS1299 from TI. It can be configured on-the-fly during initialization process for acquiring EEG, ECG or EMG signal. It is capable of reading data from 8 different channels simultaneously at maximum 16k samples per second at 24 bit resolution per channel. It requires both 3.3V and 5V simultaneously as power supply. For signal acquisition, it boasts 8 positive, 8 negative inputs, one bias, and one reference input pins. In addition, it can work in two different modes- the common reference mode and differential signal mode. In common reference mode, all the channels are measured with

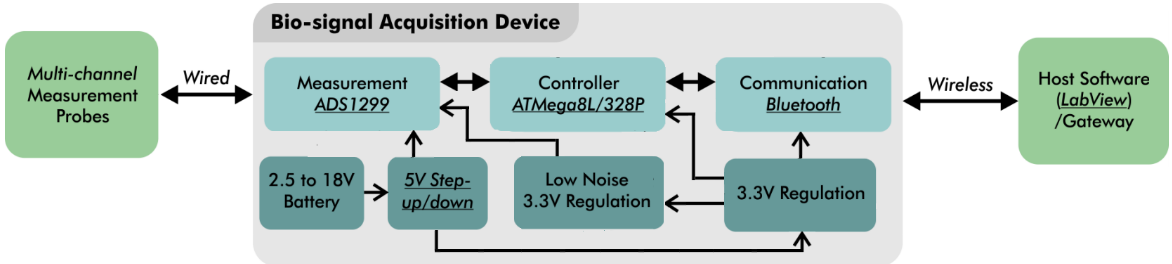

Fig. 2. The device architecture

respect to the indicated reference signal. In contrast, in the differential mode, a set of two signals are compared with each other for measurement. Furthermore, an ultra-low noise operational amplifier has been used to amplify the reference signal.

4) Communication: The communication block links the device with the host software on a computer or gateway for transferring data. The popular HC-05 UART to Bluetooth 2.0 with EDR module is chosen to use the serial port profile (SPP). Configured as a slave, it runs at 921.6 kbps in 8 data bits, no parity, and 1 stop bit (8N1) UART mode. Using 14.7456 MHz clock and UBRR register value of 0 ensures that the micro-controller can communicate with the Bluetooth module at 0% UART error (Shown in Table I). While other non-standard baud rates such as 500 kbps could be used, that would make the device incompatible with legacy standard. Besides, by running at high baud rate, bit transitional energy consumption is also reduced due to the fact that average pulse width is smaller.

B. Device Prototype

The developed prototype shown in Figure 3 is compact and has a footprint of 57mm x 38mm. It has a switch, 5 indicator LED lights, a user configurable 4-pin jumper and 3 different sized connector headers. Briefly pressing the switch resets the board, the program initializes and enters into standby mode. The red LED *POWER* indicates power on mode and a blue LED *BT* blinks once each 2 seconds or twice per second indicating Bluetooth connected or disconnected state. Besides, 3 customizable LEDs labeled *LED1*, *LED2* and *LED3* indicate various status accordingly. The jumper can be used for three functions- to program the Bluetooth module, to connect the board using Bluetooth, or to connect the board using wired UART. The wired option is very important and useful in special conditions where wireless transmission can affect sensitive medical devices such as a pacemaker. For operation, a 2-pin and an 18-pin connectors are used to connect the battery and the bio-signal measurement probes. In addition, a 6-pin connector is used to connect the board to an in-system programmer to upload firmware.

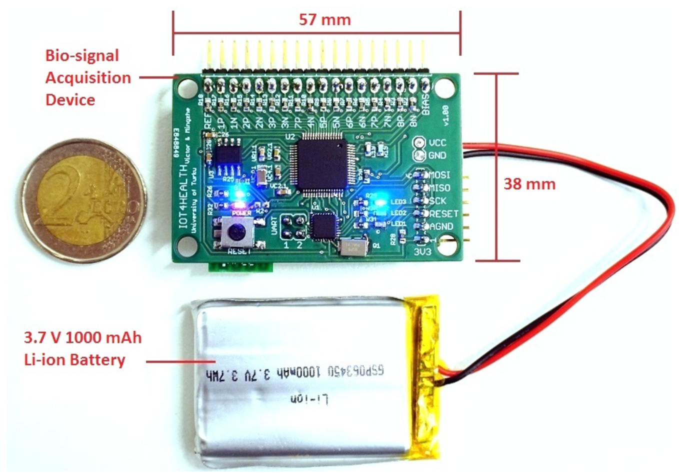

Fig. 3. Prototype of the proposed device

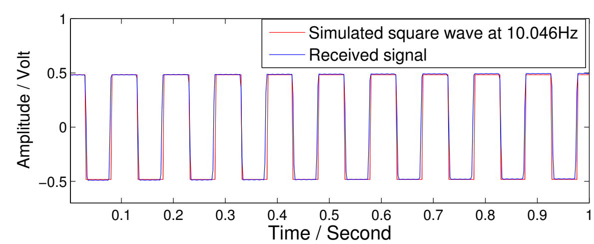

Fig. 4. Comparison of simulated square wave and actual signal acquired by the device

V. Experimental Setup and Results

To demonstrate the functional correctness of the device according to design specification, it was configured to acquire 8 channel sEMG signal with 24 bit resolution at 500 samples/s per channel. The host was configured to communicate with the device over Bluetooth at 921.6 kbps, and the amount of data transmitted each second was 112 kb. Furthermore, the device was used in a IoT-based configuration to demonstrate integrability.

A. Data Visualization

The response of the acquisition system due to input signal was first checked with 10 Hz square wave at minimum possible amplitude from a function generator. The output of function generator was connected to channel 1 of the device, of which the gain was programmed as 1 to avoid ADC saturation. On the host, the measured signal data obtained through Bluetooth receiver was saved and compared with a simulated square

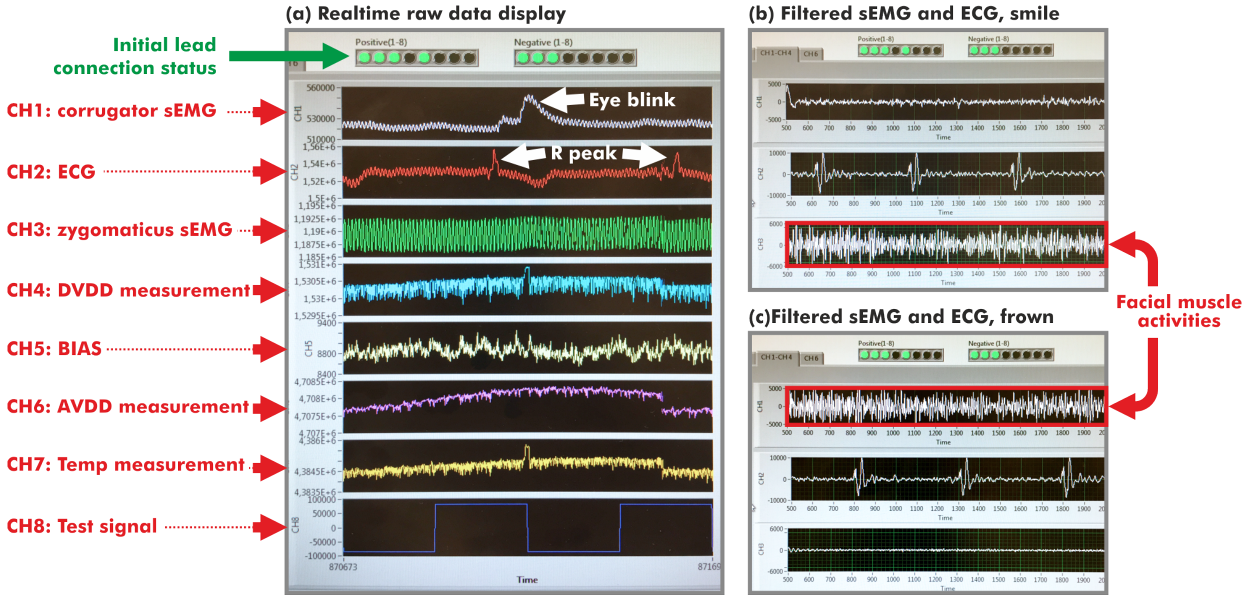

Fig. 5. Waveforms of raw and processed data

wave in Matlab, as shown in Figure 4 which resulted in a very high correlation with a factor of 0.943.

To further validate the functionality of the device and to check the quality of acquired bio-signal with lead wires and electrodes, tests were conducted with two lead ECG and facial sEMG from Corrugator Supercilii and Zygomaticus major. Received by desktop through a USB to Bluetooth dongle, real-time measurement data were presented in our customized LabVIEW based software, as shown in Figure 5. All 8 channels were utilized during measurement, where the first three channels were for differential bio-signal measurement, channel 4 and 6 for power supply voltage measurement, channel 5 for bias signal measurement from patient body as the drive, channel 7 for monitoring the temperature on chip, and channel 8 for showing a 1 Hz square wave. All channels were set with a sample rate of 500 Hz and the input gain of bio-signal acquisition was programmed as 24. Besides viewing data waveforms, the lead(test probe) connection status for each channel could also be checked while in lead-off detection (idle) mode from green-colored Boolean indicators at the top. The electrodes were first placed and the lead connection status indicators in Figure 5 (a) shows the initial lead connection conditions before getting into measurement (active) state. It can be seen that the inputs of channel 1 to channel 3 and the positive input of Channel 5 were detected to have valid contact with the skin surface. Low frequency eye blink sign from Corrugator sEMG and ECG waveform can be easily seen from real-time raw data plot.

To eliminate noise due to 50 Hz power-line and its harmonics, notch filters were applied on every 2000 samples while processing signal data. The filtered bio-signal signal data from first three channels while demonstrating two different expressions are presented in Figure 5 (b) and (c). Zygomaticus major muscle activity during smile expression and Corrugator supercilii muscle activity during frown expression can be clearly differentiated from the baseline.

TABLE II
POWER CONSUMPTION OF THE HEALTH MONITORING DEVICE

Mode	Voltage supply (V)	Average power (mW)
Idle	4.2	218.57
Idle	3.7	219.63
Idle	3	226.7
Active	4.2	451.3
Active	3.7	464.53
Active	3.0	481.27

B. Device Power Consumption

In order to provide a profound view of power consumption of the device, different specifications (i.e. idle and active modes, or different voltage supplies) are applied during measurements. A specific configuration of the device was applied in individual measurements and was carried out for 2 hours with a professional power measurement tool [18]. The power consumption of the device is shown in Table. II.

Table II indicates that when increasing the supplied voltage, the average power consumption of the device decreases. One of the main reasons causing this is the booster circuit boosting any input voltage into 5V power supply in the device. The use of the booster circuit is justified in section VI. The results show that the device can work up to 13.6 hours with a single 3.7V 1700 mAg lithium-ion battery.

C. Integration with IoT-based system

For setting up an IoT-based system, the device was connected to a gateway which supports Bluetooth and Internet connection. It was built upon a Raspberry Pi equipped with 1.2 Ghz quad-core processor and 1 GB RAM [19]. For managing hardware and performing the gateway's task efficiently and conveniently, Linux operating system was used. For cloud, a Linode cloud featuring 4 GB RAM, 2 CPU cores and 48 GB SSD plus 3 TB storage [20] was used. The web server was run at the cloud and the web page was pre-processed for presenting data. End-users could access the page via a web browser as shown in Figure 6.

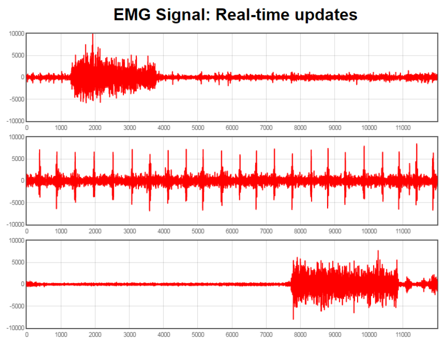

Fig. 6. Web interface showing real-time bio-signal from device via cloud

VI. Discussion

While developing and testing, several issues have been faced. As the typical compact rechargeable battery voltage ranges from 3V to 4.3V and over time it slowly decreases and gets lower than the minimum required voltage for proper regulation, a step up/down converter has been used to maintain 5V at output irrespective of the voltage level within the stated input range. While the actual energy consumption of the micro-controller and ADS1299 is very low, due to variable efficiency of the converter at different supply level, the overall energy consumption increases and can be significantly reduced by using a higher, constant efficiency converter.

For the communication, a baud rate higher than the theoretical requirement has been selected. Popular low-cost Bluetooth modules cannot sustainably transfer data via SPP profile at high baud rates. Testing at 1000 samples/s in wired mode worked perfectly, however, the HC-05 and additionally an RN-42 Bluetooth modules resulted in transmission jitter. Due to same reason, Bluetooth LE module is also not suitable. Although the proposed design can work at 1000 samples/s by inserting delay between data packets, but that reduces the actual sample rate by about 10% and hence 500 samples/s has been used for detailed testing. With the use of high-end Bluetooth module, the device can operate flawlessly at 1000 samples/s.

VII. Conclusion and Future Work

In this paper, a micro-controller based multi-purpose bio-signal acquisition device has been designed and implemented. The device is highly configurable, wireless, energy efficient and compact in size. The prototype of the device has been used in a sEMG signal measurement scenario to test the design features while operating in a wireless and battery-powered setup. The acquired 8-channel, 24-bit, 500 samples/second data in raw and processed forms have been illustrated and discussed. Also, the current consumption while the device was in different states of operation- measurement (active) and lead-off detection (idle) has been measured and presented. Furthermore, it has been connected to a IoT-based setup and the web interface with real-time updating of bio-signal data has been shown. The device can be setup in multiple configuration to include it in a wide range of applications. In future, we plan to further miniaturize in order to integrate the design within wearable devices. Besides, the device can work up to 13.6 hours with one 3.7V 1700 mAh Li-ion battery. However, we will look deeper into the energy efficiency of the device so that it can work for longer period before needing to replace or recharge supply source.

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