Digitally Controlled Feedback for DC Offset Cancellation in a Wearable Multichannel EMG Platform

M. Tomasini, S. Benatti, F. Casamassima, B. Milosevic, S. Fateh, E. Farella and L. Benini

***Abstract*— Wearable systems capable to capture vital signs allow the development of advanced medical applications. One notable example is the use of surface electromyography (EMG) to gather muscle activation potentials, in principle an easy input for prosthesis control. However, the acquisition of such signals is affected by high variability and ground loop problems. Moreover, the input impedance influenced in time by motion and perspiration determines an offset, which can be orders of magnitude higher than the signal of interest. We propose a wearable device equipped with a digitally controlled Analog Front End (AFE) for biopotentials acquisition with zero-offset. The proposed AFE solution has an internal Digital to Analog Converter (DAC) used to adjust independently the reference of each channel removing any DC offset. The analog integrated circuit is coupled with a microcontroller, which periodically estimates the offset and implements a closed loop feedback on the analog part. The proposed approach was tested on EMG signals acquired from 4 subjects while performing different activities and shows that the system correctly acquires signals with no DC offset.**

I. INTRODUCTION

Recent technological advances and the application push from the consumer market have created a growing demand for wearable, low-cost and low-power devices with advanced bio-sensing capabilities. The processing of body-related potentials is becoming one of the main challenges in this field, leading towards efficient and unobtrusive applications. For this reason, the research on Analog-Front-Ends (AFEs) and on advanced energy efficient computing platforms is evolving both at silicon and at system level.

One of the most interesting biopotentials is the surface EMG signal that allows to detect the muscular activity of the human body [1]. EMG is widely adopted in human machine interaction applications, such as prosthesis control [2], even if it is affected by high variability and ground loop problems. For this reasons, in prosthetics and medical applications, where a high-quality signal is required, expansive analog sensors are adopted. Ottobock sensors [3] represent the commercial solution for EMG acquisition for high-end prosthetics, both in research and industrial applications. These sensors perform a full-analog signal conditioning based on a bandpass discrete filter, an instrumentation amplifier (IA) with a high gain stage and an offset cancellation feedback circuit that requires the use of a dedicated metal plate as the reference electrode for each sensor.

An alternative approach, mostly used at research level, is based on passive low-cost electrodes, which requires to place a common reference electrode on the user's body in a neutral position (e.g. on the elbow when collecting forearm signals). In this case, there is only one common reference, which is not adequate for all the channels. Each channel is therefore affected by an offset dependent on the input impedance and it is influenced by its position and the physical connection between the electrode and the skin. The input impedance changes every time we place the electrodes on the skin and it changes during an acquisition due to skin condition or electrode movement.

With the common reference approach, a digital signal processing stage is required to obtain a well conditioned, zero mean differential signal, suitable for further analysis. Nevertheless, a correct offset removal is not possible if the signal is unbalanced and near the saturation voltage of the input amplifier. In the case of saturation, a digital offset removal on the acquired signal via mean subtraction is not possible without a loss in the signal content.

The approach based on dedicated ASICs is becoming more promising for wearable biosignal acquisition platforms, principally for the reduction of costs and external components. The Texas Instrumets *ADS1299* and the Analog Devices *AD7194* are commercially available solutions, proposing AFEs with high CMRR, 24-bit resolution and a digital back-end suitable for integration with low power microcontrollers (MCUs). Nevertheless, the design of these components lacks flexibility because they are oriented to simplify the design of ECG systems with dedicated internal registers and circuits.

The literature of research on ASIC design is rich of inspiring solutions for EMG and other biopotential signal acquisitions [4], [5], [6]. These works are focused on performance optimization in terms of CMRR and ADC resolution or bandwidth, but they do not consider the DC offset removal necessary for the signal processing in prosthetics.

In fact, the offset due to input impedance and motion artifacts can be orders of magnitude higher than the biomedical signal being recorded. This tends to saturate a high gain IA causing losses of information content of the EMG signal. To overcome these problems, in [7] a pair of servo loops are used, combining a 16-element DAC and a fine analog feedback to remove DC offset up to ± 45 mV. An alternative approach is AC coupling performed at the input of the IA [8].

In this work, we propose a digitally controlled AFE solution for EMG signal acquisition with zero-offset. The

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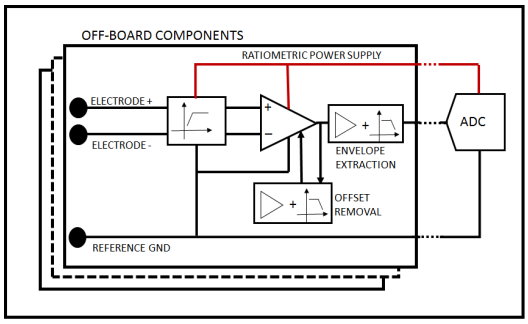

Fig. 1. Block diagram of the active sensors configuration.

proposed platform is based on Cerebro [9], a flexible AFE equipped with an internal DAC used to adjust the reference of each channel removing any DC offset. In our approach, we couple the AFE with a MCU, which initializes and triggers when necessary the estimation and removal of the offset. Each channel is independently analyzed and its offset is estimated and removed directly at the input using a binary-weighted 13-bit DAC. Its LSB is 75 µV so that the overall offset correction range is ±300 mV.

Based on the analysis of collected signals, we estimated the offset evolution in time and we developed smart offset update policies to ensure it is always correctly removed. For this purpose, we periodically check the characteristics of the signals, to ensure we perform the offset estimation and removal when no contractions affect the captured signal.

The proposed solution presents two significant improvements w.r.t. the SoA. Firstly, the proposed approach acquires a fully balanced and zero mean EMG signal, allowing to employ the full span of the ADC input while avoiding saturation and loss of signal content. Moreover, there is no need for a reference electrode for each channel, thus simplifying the system architecture, the AFE input stage and reducing the overall sensor area for a more scalable solution.

II. MATERIALS AND METHODS

A. System Description

A voluntary muscular contraction is caused by the membrane depolarization of the muscular fiber cell, which is activated by electrical stimuli from the central nervous system. The EMG signal is the superposition of the depolarization spikes during a muscular contraction. The currents and voltages involved in this phenomena are in the range of micro volts and micro amperes and for this reason the circuitry needed for signal acquisition and conditioning needs high quality components with a high CMRR.

The classical approach in active sensors is the use of 2 electrodes for the differential signal and a reference electrode for each sensor [3], as shown in Fig. 1. To detect the desired depolarization, the DC component is removed by a decoupling capacitor that allows to acquire the voltage change produced during the contraction. The AC component of the signal is the input of an IA in which the gain is set by a resistor net. In this solution, the offset compensation is based

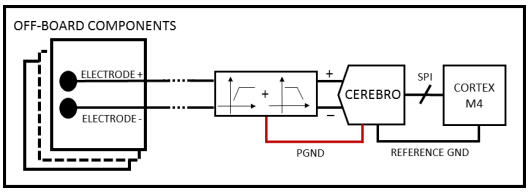

Fig. 2. Block diagram of the proposed solution.

on an integrator circuit which sets the averaged mean value of the IA output as its reference. Finally, the envelop extraction is made by another opamp with a low-pass configuration. This approach removes the DC offset of the signal, but it needs several off-board analog components and requires to distribute the power supply and the ground reference to this off-board circuitry to have a ratiometric measure. Furthermore, the system is not easily scalable because for each new input it requires to add all the compensation and conditioning circuitry.

The approach proposed in this work and illustrated in Fig. 2 significantly reduces the off-board components, limiting them to the 2 differential electrodes. Each channel has passive low and high pass filters mounted on the PCB board to decouple the input signal and reduce the low frequency noise. These filters are referred to the Patient Ground (PGND), a balanced voltage that can be set directly by the Cerebro ADC to modify the common mode voltage of the input. A significant improvement of the CMRR can be realized if a driven-right leg (DRL) is integrated on-chip to generate the patient ground [11]. The patient ground in the DRL circuit is derived from the common-mode voltage of the IA. Indeed, a DRL circuit is also used in practice to reduce the common-mode requirements of the IA.

A comparison of the biomedical data acquisition ASIC used in this work with other state-of-the-art AFE ASICs is shown in Table. I. One of the challenges for fully integrating the interface to a pair of electrodes is the DC offset due to input impedance and motion artifacts, which can be orders of magnitude higher than the biomedical signal being recorded and saturate the IA.

B. Offset Removal

An overview of Cerebro is depicted in Fig. 3(a). The ASIC allows to acquire eight analog channels simultaneously. While a separate AFE is implemented for each channel, as detailed in Fig. 3(b), the ADC is shared among the 8

TABLE I
COMPARISON WITH STATE-OF-THE-ART AFE ASICS.

	Yazicioglu [7]	Bohorquez [8]	Muller [10]	**Cerebro** [9]
Channels:	8	1	8	**8**
Offset comp.:	analog fine servo	AC coupling	comp. DAC	**comp. DAC**
IR-noise [μV_{rms}]:	0.59	3.4	3.6	**0.82**
Tol. offset [mV]:	±45	-	±50	± **300**

[a] 1-100Hz signal bandwidth

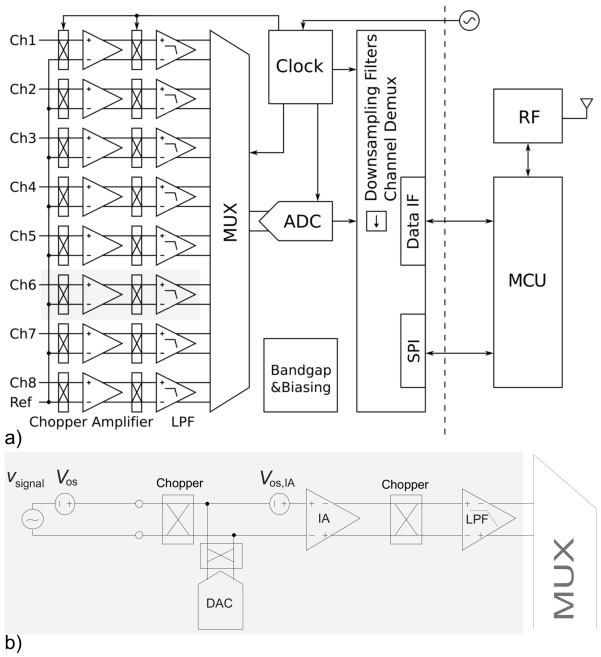

Fig. 3. Block diagram of a) Cerebro ASIC with b) a detailed illustration of one analog front-end channel.

available channels, which are sampled at 1 KHz. Prior to amplification, the signal offset is compensated with a current-steering DAC to prevent the IA from saturation. This DAC is regulated by a register and it is set by the MCU at run-time.

Chopping is used to suppress flicker-noise added by the IA. To avoid aliasing before sampling the analog signal, the modulated offset and flicker-noise are damped with an active low-pass filter with a corner frequency of $3.2kHz$. The gain of the AFE is dynamically adjustable by the MCU between $8\times$ to $2048\times$ to address signal amplitudes in different biomedical applications.

The closed loop feedback of the digital part on the analog represents an innovative approach in biopotential signal conditioning and it is the main contribution of this work. The algorithm to estimate and compensate the offset is executed in real time on the MCU. First, it checks if a contraction is in progress in the acquired EMG signal and eventually it waits until no contraction is detected. For this purpose, the standard deviation of the signal is computed and compared with a threshold.

The DC offset is estimated as the mean value of each channel and it is computed on windows of $0.25s$ (250 samples at $1KHz$ sampling rate). If the calculated value exceeds the resolution of the DAC, a proportional controller uses the AFE gain and ADC resolution to compute the number of DAC steps to apply to compensate the estimated offset. Since the DAC is not extremely precise and in the acquisition chain it is placed before the AFE, this approach is eventually repeated until the offset is within the DAC resolution. In our tests we needed a maximum of 3 iterations ($750ms$) to perform the correction. This technique can be applied to other biopotential acquisition scenarios, allowing an effective offset removal, simplifying the conditioning

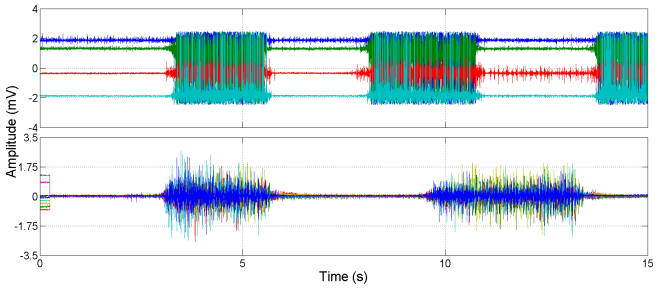

Fig. 4. EMG signal acquisition without (top) and with (bottom) offset compensation.

circuitry and reducing the number of on-body electrodes.

III. EXPERIMENTAL RESULTS

The proposed approach was developed and tested with EMG signals collected with eight differential pairs of disposable electrodes placed in a circular cuff on the forearm of four healthy subjects. The signals were sampled at $1KHz$ with a gain of 32. This data collection involving human subjects was approved by the Institutional Review Board.

Figure 4 shows a sample of raw acquired data with no compensation performed (top) and data acquired when applying the proposed offset compensation approach (bottom). In the first case, every channel has a different offset, which is not known a priori since it is affected by a number of factors such as electrodes location, skin humidity, and body potential. Moreover, a high offset can cause the saturation of the acquired signal. When the offset compensation is applied, it is instead possible to exploit the full span of the ADC avoiding saturation and the related loss of information.

The DAC implemented in Cerebro allows positive or negative fixed steps of $75\mu V$, regardless of the AFE gain. Thus, our compensation algorithm is able to reduce the offset within the $\pm 75\mu V$ range. Unfortunately, the signal offset is not stable in time, as can be seen in Fig. 5 where a longer acquisition is reported showing that some of the channels (the green one) derive in time. It is thus not sufficient to compensate the offset only at the beginning of each acquisition and we periodically check and remove it with the algorithm described above.

To evaluate the offset variations in time, we collected data from 4 subjects during different activities (walking, running, writing, working), with acquisitions of up to 30 min. From the analysis of the collected data we measured that in the

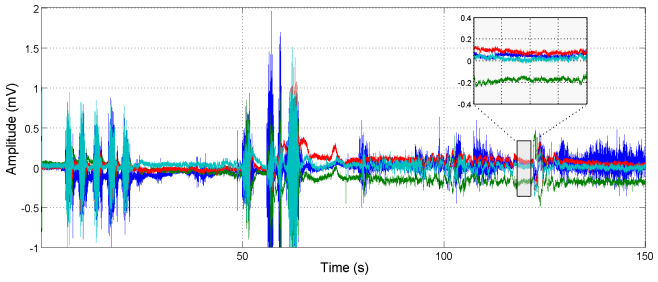

Fig. 5. Long time acquisition with offset compensation applied only during the initial phase.

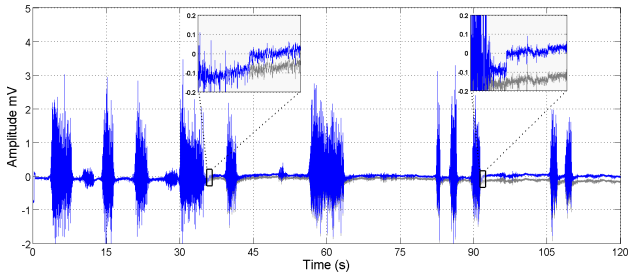

Fig. 6. Two channels acquiring the same EMG signal, one with only the initial compensation (gray) and one with periodic compensation (blue).

worst case scenario the offset of a channel exceeds $\pm 150\mu V$ (two times the DAC resolution) after 30 seconds. We thus decided to execute the offset compensation routine every $30s$.

It is crucial to perform the offset compensation only when no muscle contractions are in progress. We thus compute the standard deviation of the EMG signal and if it is higher than an empirically-set threshold, a muscle contraction is detected and the algorithm waits for its end to estimate the offset and to perform the compensation.

To evaluate the effects of periodic offset compensation, we connected two acquisition channels to the same pair of electrodes and collected again 10 minutes of signal from 4 users. In this case, on one channel the offset estimation and removal was applied only at the beginning, while on the second one we applied it periodically, every $30s$. One sample of this acquisition is shown in Fig. 6 where the periodically corrected channel is plotted in blue. It is possible to notice that at $30s$, when the compensation is triggered, a contraction is in progress and the algorithm waits for it to end to compensate the offset. At 60s there is no need to compensate the offset since the mean of the signal is within the DAC resolution of $75\mu V$ so the DAC settings are not modified. At $90s$ another contraction is in progress and the algorithm waits again to correctly compensate the offset.

Table II summarizes the overall performance of the proposed approach and shows the average offset on 10 minute acquisitions when no, initial and periodic compensation is applied. The initial and periodic approaches were applied to the same signal acquired connecting two channels on the same electrodes. The results show how the proposed periodic compensation reduces drastically the channel offset.

TABLE II

AVERAGE OFFSET WITH DIFFERENT ACQUISITION TECHNIQUES.

	No Comp. (mV)	**Initial Comp. (mV)**	**Periodic Comp. (mV)**
Subj. 1	1.62	0.29	0.05
Subj. 2	1.65	0.20	0.08
Subj. 3	1.33	0.26	0.08
Subj. 4	1.62	0.13	0.02
Mean	**1.56**	**0.22**	**0.06**

IV. CONCLUSION

In this work we presented an innovative approach for the acquisition of offset-free biopotentials signals. The proposed system is based on the Cerebro AFE and uses its internal DAC to correctly reference the signal to acquire and eliminate the need for an additional reference electrode for each differential input. It is interfaced with a low-power MCU, which is responsible to estimate the offset and to dynamically control the AFE settings in a closed digital-to-analogue loop.

The proposed system, suitable for wearable acquisition of biopotential signals, was tested with forearm EMG signals commonly used for hand gesture recognition and prosthesis control. We collected signals of up to 30 minutes from 4 healthy subjects while they were performing various everyday activities. From this analysis, we observed that the EMG signals exhibit a random initial offset, which changes in time during the acquisitions. Thus, we implemented an algorithm which periodically checks the offset of each channel only if no contraction is in progress and sets the Cerebro ADC to automatically compensate the estimated offset. The results show that our approach correctly removes the DC offset from the acquired signals and allows the development of flexible and scalable wearable devices.

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