A Bio-Signal Amplifier System with Very-Large Dynamic-Range

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Abstract- The recording of small signals such as body potentials requires high-gain amplification. In a high-gain system even small offset voltages pose a problem when they saturate the amplifier. Especially time-varying offset voltages (e.g. electrode drift) may lead to undesirable blank periods during recording. The system proposed in this work monitors the amplifier output voltage and resets the amplifier before it can leave its dynamic range. The feedback thus provided is not continuous and avoids the shortcomings of conventional filter and feedback approaches. A transistor level implementation of the system is described and simulated results are presented.

I. Introduction

The recording of very small signals from the human body using integrated circuits has become possible with the recent advances in technology. Typical applications include the recording of the electrical signal associated with heart, muscle or brain activity (ECG, EMG or EEG respectively) [1-5]. In modern recording systems, the analog input signals are converted into a digital representation to allow for easy storage and further processing. As the recorded signals are in the order of only a few millivolts or less, they require high-gain amplification to match the input requirement of the analog-to-digital converter (ADC). However, electrode offset voltages are present, which may be far larger than the signal amplitude, causing the amplifier to saturate [6]. Moreover, offset voltages due to the electrode-body interface tend to vary with time (electrode drift) and cause blank periods in the recording when the system temporarily saturates. Therefore, conventional systems selectively remove low-frequency signal content typically associated with drift by the means of electronic filtering before amplification. However, as very low-frequency filter cut-offs are required, these structures are space consuming and difficult to implement especially in a fully integrated system. Moreover, a-priori knowledge of the signal spectrum is needed to separate signal from drift. Several schemes exist to remove the low-frequency offset, which are discussed in Section II. These techniques are ultimately based on large time-constant integration and require special measures to recover quickly after disturbances, e.g. due to movement artifacts. The proposed approach avoids such blank periods as described in Section III. It is a low-power solution applied around the amplifier itself, rendering it suitable for any type of ADC. In addition, information about offset drift is preserved and the dynamic input range of the system is also greatly increased.

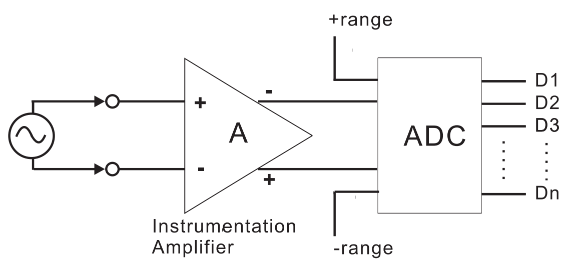

Figure 1. Diagram of a general bio-recording system.

II. System Description

Instrumentation amplifiers are used for biomedical signal acquisition, yielding high common-mode

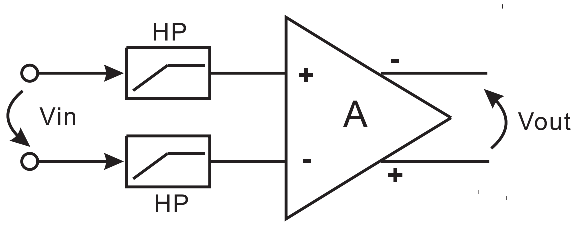

Figure 2. High-pass filters remove offset voltage before amplification.

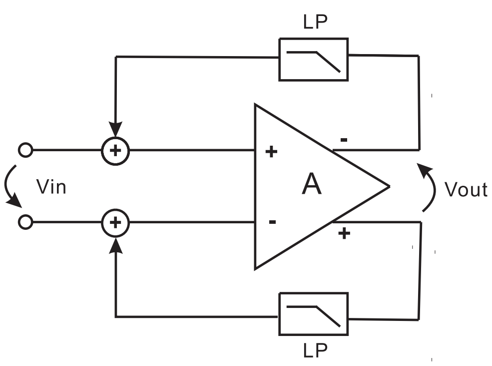

Figure 3. Feedback structure to remove low-frequency offsets.

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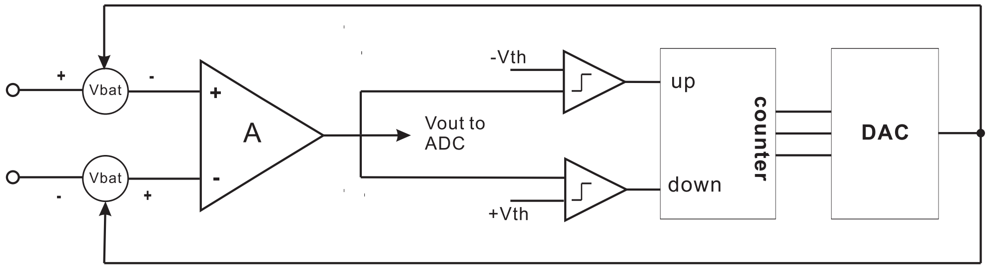

Figure 4. Block diagram of the proposed system to provide non-continuous discrete-level offset cancellation.

rejection with differential inputs, good linearity and a well defined gain A [6]. The amplifier delivers an output signal matched to the conversion range of the ADC as shown in Fig. 1. To avoid saturation of the amplifier, offset voltages at the input terminals must be removed. Offset removal can be achieved by placing high-pass filters in front of the amplifier as illustrated in Fig. 2. The filter is implemented either as a passive RC structure or as an active circuit [7]. The filter cut-off frequency is designed to be much smaller than the lowest signal frequency of interest. Typical medical signals exhibit signal content at relatively low frequencies (e.g. less than 0.5 Hz for the ECG), so that passive filter components become prohibitively large for an integrated solution. Active filters suffer from additional power consumption, which is undesirable in a low-power wearable or implantable recorder. Furthermore, their input range is limited by the input device. A common disadvantage of the input filter lies in the low filter cut-off frequency, which leads to a very long settling time of the filter output after any disturbance. Typical causes of disturbance are electrode movement and interference artifacts. During the settling phase the amplifier is saturated and no signal is recorded. To shorten the settling time, additional control circuitry is required which resets the filter. A different offset removal technique employs high-pass filters to generate an error signal, which is fed back to a summing node in front of the amplifier inputs to cancel the offset voltage. The block diagram of this arrangement is given in Fig. 3. The feedback loop is implemented either as an analog structure or in digital form, comprising the ADC and an additional digital-to-analog converter (DAC) to generate the feedback signal [5]. The feedback structure also relies on filtering to extract the error signal, resulting in the same shortcomings as the input filter, namely long settling time and the loss of signal information below the filter cut-off frequency.

The recording scheme proposed in this work avoids continuous filtering. Instead, constant offset compensation voltages are added at the amplifier input so that continuous recording over the full bandwidth down to very low frequencies becomes possible. The block diagram of the proposed system is detailed in Fig. 4. Its main component is a pair of floating voltage

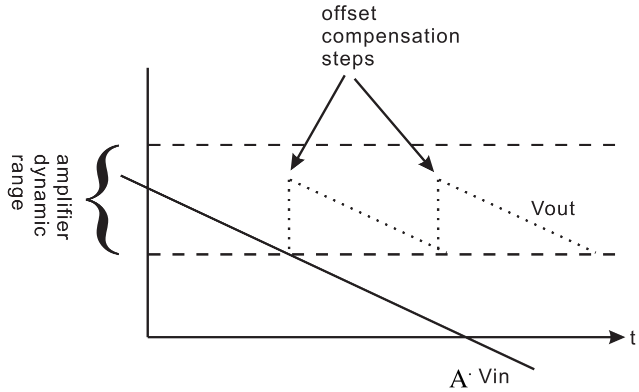

Figure 5. Amplifier input and output voltages in the proposed system (amplifier gain normalized to unity).

sources in the input leads of the amplifier. The voltages V_{bat} partially cancel the input electrode offset and thus prevent the amplifier from saturating. The output of the differential amplifier is compared to a minimum and a maximum threshold level $+/-V_{th}$ respectively. The levels define the maximum linear output swing of the amplifier. The magnitude of the thresholds is not critical as long as they are chosen within the amplifier dynamic range. As the amplifier output reaches $+/-V_{th}$, compensation voltage V_{bat} is altered to return the amplifier output to near zero. Note, that V_{bat} is increased or decreased by a fixed amount. Contrary to the conventional system, no feedback or filtering is involved to establish an exact output voltage at the zero level. The sole purpose of the compensation voltage is to ensure that the amplifier always works within its intended operating region; removal of any residual offset is not required. The increase or decrease of V_{bat} is controlled by the comparators connected to a counter as shown. The digital counter output controls the voltage sources as described in Section III. The amplifier output is graphed in Fig. 5 for an input voltage varying from zero to a large negative voltage, which in a conventional system would lead to saturation. It is observed that the output is reset to a level within the operating region as soon as the amplifier approaches the edge of its dynamic range. The resulting step in the output voltage is removed to restore the original signal using a simple post-processing routine. The processing is performed after conversion into the digital domain.

Therefore, it can be performed offline on the stored data. The original signal is reconstructed by realigning the signal V_{out} at the transition points to yield a constant slope across the reset point. If the amplifier was reset between digital data points $V_{out}(i)$ and $V_{out}(i+1)$ the following condition must be satisfied:

$$\frac{V_{out}(i+1)-V_{out}(i)}{\Delta t_s}=\frac{V_{out}(i)-V_{out}(i-1)}{\Delta t_s} \quad (1)$$

where Δt_s is the sample interval. The information on the occurrence of a transition point may be stored during recording. However, this is not required if the analog-to-digital conversion is performed with a high oversampling rate, as is typical for many medical applications. In these applications the occurrence of a reset step is found from the recorded data as follows. The height of the reset step is determined by the magnitude of the voltage source step ΔV_{bat} multiplied by amplifier gain A. The step is fast and occurs within a single sample interval. Thus, the slope l_r of the reset step is given by:

$$l_r=\frac{A\cdot\Delta V_{bat}}{\Delta t_s} \quad (2)$$

However, the maximum signal slope l_s depends on the highest frequency content f_{max} of the signal and its maximum amplitude V_{max}:

$$l_{s\_\max}=A\cdot 2\pi\cdot V_{\max}\cdot f_{\max} \quad (3)$$

If it is ensured that l_r is always larger than l_{s_max}, a reset step is unambiguously characterized by the occurrence of a slope larger than l_{s_max}. To ensure that (2) is always larger than (3), the ratio between f_{max} and the ADC sample frequency f_s must satisfy the following condition:

$$\frac{f_{\max}}{f_s}<\frac{\Delta V_{bat}}{2\pi\cdot V_{\max}}. \quad (4)$$

III. System Implementation and Simulation

The amplifier system given in Figure 4 is simulated on the transistor level using Cadence design software. The floating voltage sources are realized by the setup shown in Fig. 6. Transistor M2 is biased to operate in the ohmic region to provide a constant resistance between the terminals of the structure. Transistors M1 and M3 act as adjustable DC current sources, passing a small current I through transistor M2. As M2 provides high resistance, a small current is sufficient to generate the required voltage difference V_{bat} across the device. The drain ends of M1 and M3 provide high impedance, so that a floating source is realized. As the floating battery is connected to the high-impedance input terminal of the instrumentation amplifier, there is no significant signal current flow through M2. Consequently, signal distortion due to the inherent non-linear voltage-to-current relation of the MOS device is negligible in this application. Bias current I is generated by a weighted parallel combination of MOS current sources, which are selectively switched on or off by a digital signal. In this implementation, voltage V_{bat} can be set in steps of approximately 5mV. Notably the polarity of the floating source is fixed. Therefore, when reversal of the compensation voltage is required, instead of reversing the polarity of V_{bat}, the differential input leads are swapped over. This is achieved by cascading the floating sources with an MOS cross-switching matrix. Again, the transistors can be made small, as no signal current flows into the amplifier terminals. The amplifier is implemented using a current mode design consisting of a trans-impedance stage followed by a trans-resistance output stage [8]. It provides a differential signal gain of 200 over a bandwidth from DC to around 50kHz. The differential output range is +/-2V. As this amplifier design is representative for many recording input stages, it is chosen to evaluate the cancellation system on the transistor level. Note, that the proposed system does not depend on the amplifier characteristics, so that in general any other implementation can be used.

A voltage signal source is connected to the system input for simulation. The test signal is a 4mVp_p, 300Hz sine wave superimposed on a slow varying drift signal as shown in Fig. 7. The amplifier output voltage is plotted in the same figure. As expected, the voltage step caused by the reset action is visible on the output trace, occurring when the output voltage reaches the amplifier minimum output of -2V. To realign the signal around the reset transitions the digitized output

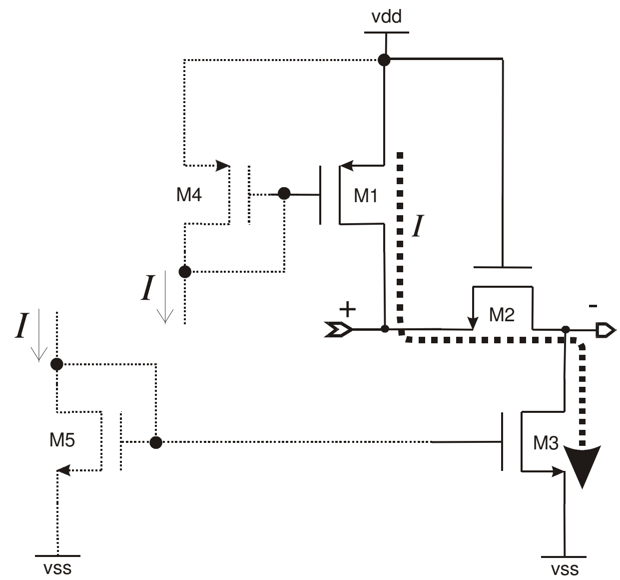

Figure 6. Transistor implementation of a floating battery with bias circuit.

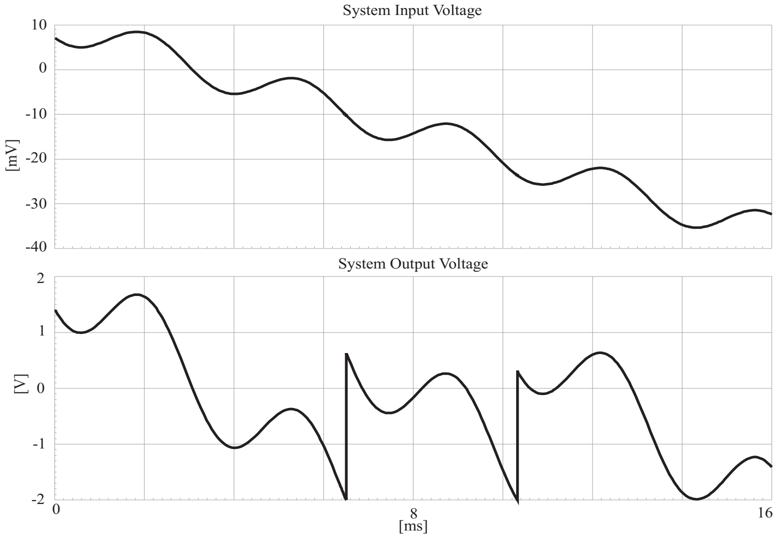

Figure 7. Input signal for simulation of the proposed system (top) and amplifier output voltage as passed to the ADC (bottom).

signal is processed by a post-processing routine as described in Section II using Matlab software. The resulting waveform is graphed in Fig. 8. The smallest recordable amplitude is determined by the ADC resolution, which remains unchanged by offset cancellation. Therefore, the larger recording range exhibited in Fig. 8 yields a significant increase in dynamic range. Furthermore, both, the 300Hz input signal as well as the offset drift is captured, preserving all low-frequency information.

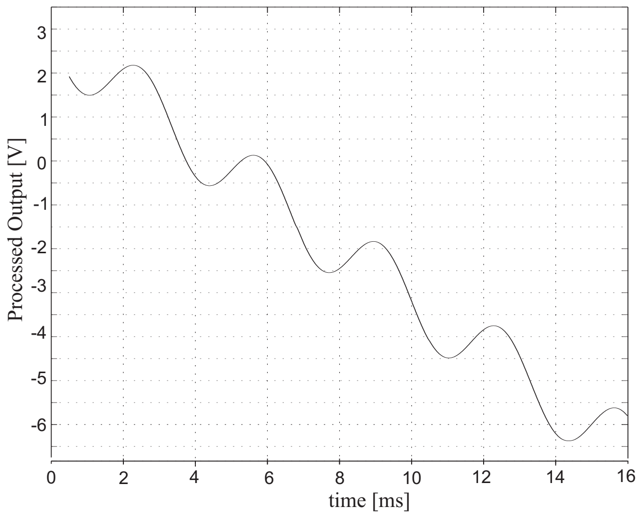

Figure 8. Output signal after reconstruction with the proposed post-processing algorithm.

IV. CONCLUSIONS

A system for the recording of small signals is proposed, which provides a very large dynamic range. Offset signals such as electrode drift are compensated for in discrete steps instead of the continuous removal performed in conventional approaches. Consequently, signal information down to very low frequencies is preserved and extended blank periods after signal disturbances are avoided. A small-size, low-power circuit implementation is presented, which is suitable for integration. A post-processing procedure is discussed, which reconstructs the original signal from the recorded data by detecting and re-aligning the sections in-between the reset points. Transistor level simulation results are presented which confirm the operation of the system.

V. REFERENCES

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