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ActiveThree advertorial

BioSemi introduces the ActiveThree biopotential measurement system for scientific research in the field of electrophysiology. The new system is the third iteration of the successful line of BioSemi active electrodes systems. In this white paper, we explain the reasons for developing a new system, and we highlight the improvements and advantages with respect to the previous systems.

All BioSemi systems use the same basic setup with active electrodes: preamplifier integrated in the electrode, a compact battery powered AD-box, and data transfer to the acquisition computer via a single optical fiber. This setup offers optimal reduction of interference and maximal subject safety. In 2000, BioSemi introduced the ActiveOne, the first commercially available biopotential measurement system with active electrodes. In 2002, this system was succeeded by the 24–bit ActiveTwo, which became the de facto standard workhorse for electrophysiological research with more than 2000 systems in use leading to over 10,000 scientific publications:
https://scholar.google.com/scholar?hl=en&q=biosemi
However, recent advances in semiconductor and battery technology offered opportunities to develop a significantly improved successor.

A first important upgrade is a change of Analog-to-Digital Converter (ADC) technology, which offers a cleaner frequency spectrum. A second change is the use of novel low-voltage components, allowing the AD-box to run on half the supply voltage when compared to its predecessors. As a result, a much smaller battery could be used, leading to decreased size and weight. The setup of the auxiliary sensors (response switches, respiration, temperature, etc.) was completely revised. Finally, the CMS/DRL circuitry was redesigned for improved interference suppression. The sum of these changes offers improved signal quality coupled with much easier handling and operation of the hardware and software.

Below, the new features of the ActiveThree are explained in detail

1. New ADC technology

Analog to Digital Converters are mainly based on two different technologies: Successive Approximation Register (SAR) and delta-sigma. SAR converters work by comparing the analog input signal with a bank of resistors or capacitors, with each of the component values double the value of the previous one in the bank. Delta-sigma converters are basically oversampling 1 bit converters. The analog input signal is converted to a high frequency bitstream (serial stream of ones and zeros) and this bitstream is converted to a multibit output word by a digital decimation filter. To reduce the rate of required oversampling, the bitstream is converted back to an analog signal and subtracted from the input signal (a process called “noise shaping”).

Even from the very simplified description above, it wil be clear that SAR converters need precise fabrication of analog sections (the resistor or capacitor banks) whereas delta-sigma converters rely on fast precise clock signals. In integrated electronics, it is easier and cheaper to fabricate circuitry with fast precise timing, than to fabricate accurate component values for analog circuits. That’s of course why digital circuitry have replaced analog in the past decades.

The introduction of delta-sigma ADCs in the late 1990s meant a breakthrough. At the time, the dynamic range of SAR converters remained limited to 16 bit (approx. 90 dB). With the delta-sigma topology it became possible to make low-cost 24-bit ADCs with a much larger dynamic range of more than 110 dB. For biopotential measurement systems this was a major step forward, because DC amplifiers could replace the AC amplifiers that were required with 16-bit converters. The cumbersome high-pass filters that were needed with 16-bit converters to cancel the electrodes offset voltages could be eliminated. BioSemi quickly applied this new development in ADC technology with the introduction of the ActiveTwo system in 2002, while all competitors followed in the years thereafter. The result is that we now see a situation where all manufacturers of biopotential measurement systems basically employ the same circuit setup: a DC amplifier followed by a 24-bit delta-sigma analog to digital converter. Differences between the manufacturers are found in the use of active electrodes, the power supply (battery versus mains powered) and the data transfer (optic fiber versus USB cable).

Despite the success of the delta-sigma converter topology, a few semiconductor companies continued with the research to increase the dynamic range of SAR ADCs beyond 16-bit. There are two reasons for this continuing interest in SAR converters. Firstly, they offer a lower power consumption. A SAR ADC can do a quick conversion at each sample instance, and remain in low power idle state for most of the time. An oversampling delta-sigma on the other hand, has to operate continuously. This makes a SAR ADC attractive for a battery powered system like the BioSemi designs. The second and most important reason for interest in SAR converters is a fundamental problem found in delta-sigma modulation. As noted above, a delta-sigma converter needs a feedback loop to keep the oversampling ratio within realistic limits. Any system with feedback is prone to resonances and oscillations. With delta-sigma converters, these resonances are seen as small peaks in the frequency spectrum, locked to the sampling clock. In audio applications they are known as “spurious tones” (the human ear, being a basic spectrum analyzer, is very sensitive to this kind of distortion). In spite of all efforts of manufacturers to reduce the spurious tones as much as possible, every delta-sigma converter is more or less prone to this problem, whereas with a SAR converter the problem is non-existing by design because there is no feedback loop in the converter. Please refer to:
https://www.analog.com/media/en/technical-documentation/technical-articles/m135_en-sar_adc.pdf).

Recently, 24-bit SAR converters became available, albeit at much higher costs than comparable delta-sigma converters. Because of the lower power consumption and total absence of spurious tones, we decided to develop the new ActiveThree system based on such a novel 24-bit SAR converter. To prevent aliasing, the converter is used with a 4x oversampling rate: 64 kHz internal sampling with 16 kHz output sample rate (with further downsampling in software). A steep internal decimation filter limits the analog bandwidth to 5 kHz and prevents aliasing of high frequency interference, allowing a simple low-pass filter preceding the converter. Although the cost of these precisely manufactured ADCs is high, we could keep the total price of the ActiveThree system similar to the preceding models by further rationalization of the production, a lower cost battery, and a simpler third-party charger. BioSemi is the first, and currently only company offering a biopotential measurement system based on this innovative SAR analog-to-digital converter technology (all competitors use either 24-bit delta-sigma or 16 bit SAR converters).

An example where spurious tones can present a problem is the study of the auditory processing in the brain with Frequency Following Response (FFR). With this method, researchers look for resonances in the EEG triggered by a repetitive stimulus. Reliable detection of small peaks in the frequency spectrum is essential with this method. Spurious tones generated by the ADC may be mistakenly recognized as oscillations with a physiological origin and thus leading to false conclusions. By using SAR converters in the ActiveThree, this potential source of error is eliminated, see the below clean noise spectrum.

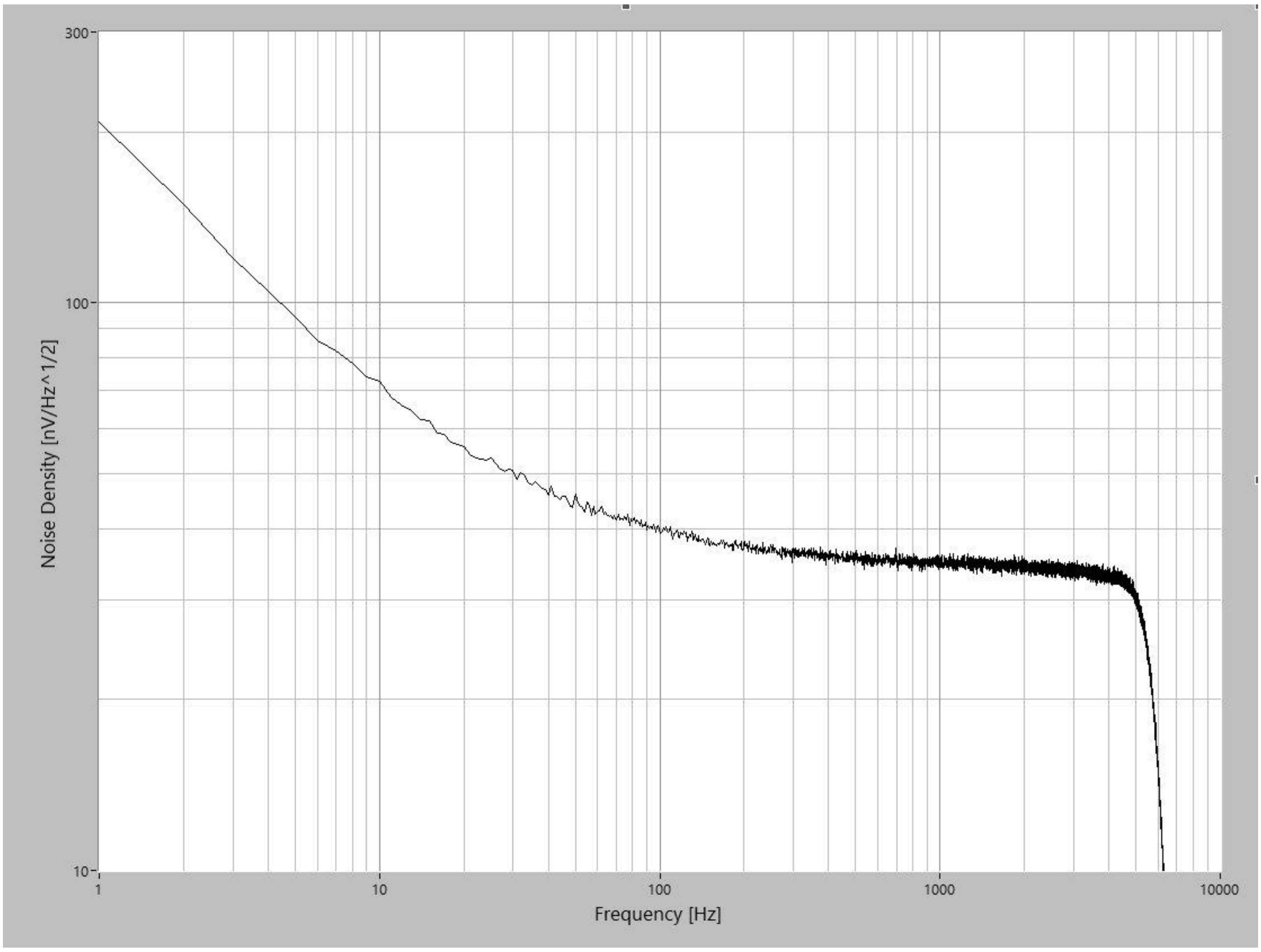

Fig. 1: Noise spectrum of 1 channel referenced to the average of 128 channels. The area under the curve (the total noise) is 2.8 uVrms. Note that spectrum is completely free of spikes by spurious tones.

2. Battery

The ActiveTwo system was powered by a 6V sealed lead-acid battery in a separate, relatively large and heavy battery box. A main problem of lead-acid batteries is the quite high rate of self discharge. Moreover, the cells are damaged beyond repair when discharged to a low voltage. In practice, this led to many service requests because users stored the batteries in an empty state for long periods (many months). For example: after the Covid shutdowns, we had to replace many batteries.

A major goal when developing the ActiveThree system was to make the battery power supply more reliable and easier to handle for the users. For upmost user convenience, we specified that the ActiveThree system should be powered by a single rechargeable battery with minimal self-discharge, it should be a standard cell (not in a bespoke battery box or battery pack) that is readily available everywhere, and the ActiveThree should be able to run for a full workday (> 8 hours) without battery replacement. Based on these specs, we selected the most produced rechargeable battery in the world: the Li-ion 18650 cell (https://en.wikipedia.org/wiki/18650_battery). This cell seems to be the sweet spot in the trade of between size, weight and capacity. The cell is used in many battery packs (from power tools to electric cars), but also as a standard replaceable cell in flashlights, camera's and many other appliances. Therefore, easy and cheap availability of chargers and replacement cells is secured.

However, the selection of a single 18650 cell as power supply presented a number of challenges in terms of circuit design. We wanted to avoid using step-up regulators because they pollute the power supply rails with high frequency interference which may increase amplifier and ADC noise. So, the entire circuitry has to operate on a maximum of 3.3 Volt (nearly empty battery), and with a maximum 0.3 Ampere current consumption to meet the > 8 hour playing time with a typical 3500 mAh cell. Fortunately, the widespread use of tablets and smartphones (all working on a 3.7 V Li-ion battery) has stimulated the semiconductor industry to develop low power components running on voltages of less than 3 Volt. By careful selection of recently introduced components we could design the ActiveThree circuitry with a quarter of the power consumption (both supply voltage as current consumption are halved) when compared with the ActiveTwo, without any compromise being made to the performance. All specifications are equal or better than found in the preceding model, see below table. Moreover, the new active electrodes with integrated high-frequency filter and optimized for low supply voltage remain compatible with the ActiveTwo's higher supply voltage. That developing all circuitry for 3.3 Volt operation was not a trivial task can be illustrated by the observation that all competing commercially available biopotential measurement systems operate with a supply voltage of 5 Volt (via USB) or higher (2 or 3 Li-ion cells in series, Power over Ethernet, etc.).

Subject isolation	BF (Body Floating)
Number of channels	0 to 136 monopolar active electrodes + 6 bipolar auxiliary sensors
Output sample-rate (down-sampling available in software)	16,384 Hz
Bandwidth (-3dB)	DC – 5.4 kHz, 0.002 dB ripple in passband
Low-pass response	140 tap FIR filter, -65 dB @ 8 kHz (Nyquist frequency)
High-pass response	fully DC coupled
Digitalization	24 bit SAR converter with 4x oversampling and integrated decimation filter, one converter per channel, synchronous sampling
Sampling skew and jitter	< 1 ns
Sample rate accuracy	0.8 Hz
Quantization-resolution	LSB = 31.25 nV, no missing codes
Gain accuracy	0.1 %
Anti-aliasing filter	1st order analog filter, -3dB at 7.8 kHz
Total input noise (Z_e < 10 kOhm), full bandwidth	2.8 uV_{RMS} (approx. 15 uV_{pk-pk}), see Fig. 1, noise spectrum
1/f noise (Z_e < 100 kOhm), 0.1 - 10Hz	2 uV_{pk-pk} , see Fig. 2, pink noise plot
Input current noise	< 1 pA_{rms}
Input bias current	< 100 pA per channel
Input impedance	600 MOhm @ 50 Hz (10^{12} Ohm // 5 pF)
DC offset:	< 2 mV
Input range	+200 mV to -200 mV
Intermodulation distortion, test signals: 2990 and 3010 Hz	< 0.01 %
Channel separation	> 100 dB
Common Mode Rejection Ratio	> 100 dB @ 50 Hz
Isolation Mode Rejection Ratio	> 160 dB @ 50 Hz
Power Consumption	0.5 Watt (6 channels) to 1 Watt (142 channels)
Battery capacity	3500 mAh, 3.7 V Li-ion 18650 type
Battery life	10 hours (142 channels) to 20 hours (6 channels)
Leakage current, normal operation	< 1 $uA_{rms.}$
Leakage current, single fault condition	< 40 uA_{rms}
Trigger inputs	16 inputs on optical receiver (isolated from subject section), TTL level
Trigger outputs	12 outputs on optical receiver (isolated from subject section), TTL level
Computer interface	USB2.0, Windows or Linux
Size of AD-box (width x depth x height)	162 x 149 x 62 mm
Weight of AD-box, including battery	0.8 kg
Environment	Indoor use: Temperature: +10°C to +40°C Humidity: 30 to 75%, non condensing Pressure: 700 hPa to 1060 hPa
Warranty	3 years (1 year on electrodes)
Conformity	EN61326 (EMC), EN60601-1 (safety)

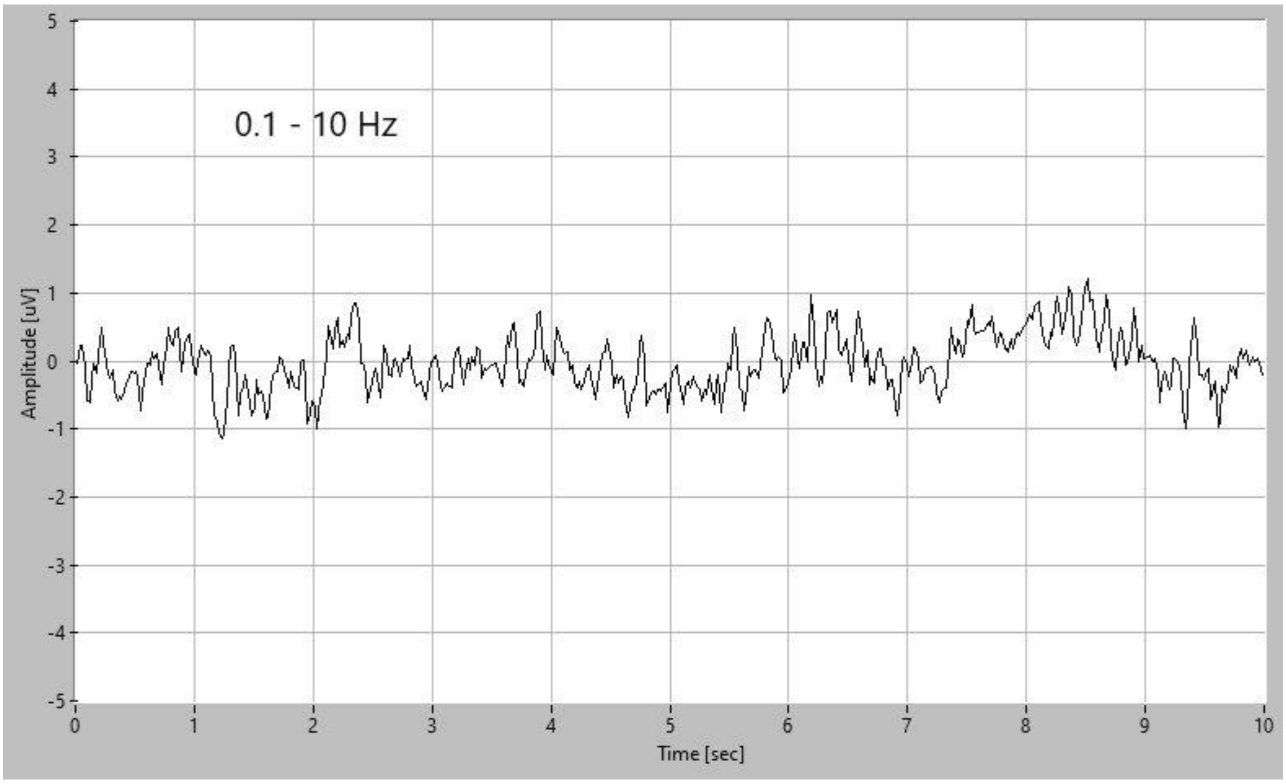

Fig. 2: Plot of the 1/f (pink) noise of 1 channel referenced to the average of 128 channels and filtered with a 0.1 - 10 Hz bandpass filter.

3. Auxilary sensors

The ActiveTwo was equipped with 3 extra inputs that could be configured (by BioSemi) for a range of auxiliary sensors for additional data such as finger response, Galvanic Skin Response (GSR), temperature, respiration, etc.. The idea was that customers would decide on the extra sensors when ordering a system. However, in practice researchers would often decide on upgrading their system with extra sensors or change the type of sensor at a later stage, which required adding or modifying the sensor module(s) inside the AD-box. The back and forth sending of systems involved in these sensor upgrades caused a lot of inconvenience for the users.

For the ActiveThree, we specified a more flexible setup of the auxiliary sensors. Instead of configuring the sensor specific circuitry inside the AD-box, we integrated these circuits in (if any) in the sensor assembly. This allows the six sensor inputs on the AD-box to be equal and universal. The ADC module for the 6 sensor channels is always installed in each ActiveThree AD-box. Every sensor can be connected to each of the sensor connectors. The AD-box recognizes the sensor type and transmits information to the ActiView acquisition software about which sensor is plugged into which connector. ActiView then configures itself automatically to display and save to file the actually connected sensors, without any user selection required.

The new sensor setup overcomes the limitations and inconveniences found in the ActiveTwo and competing designs.

The special Auditory Brainstem Reponses (ABR) electrodes in the ActiveTwo required installation of a dedicated module. In the ActiveThree the ABR electrodes interface directly with the universal auxiliary inputs (again to facilitate easy upgrade at a later stage). In addition, the ABR active electrode circuitry has been improved for even lower noise and wider bandwidth (high-pass frequency lowered from 100 Hz to 10 Hz and low-pass frequency increased from 3.3 kHz to 5.4 kHz).

4. Fixed speedmode

The ActiveTwo system used a “speedmode” switch to select various combinations of sample-rate and number of channels. Following the ActiveThree design philosophy of KISS (Keep It Simple, Stupid), the new system always transmits all installed channels on the maximum (fixed) sample rate of 16,384 Hz and a bandwidth of 5.4 kHz. Down-sampling to a lower sample-rate (to a minimum of 256 Hz) is performed in software with a 5th order CIC (https://en.wikipedia.org/wiki/Cascaded_integrator%E2%80%93comb_filter) decimation filter to prevent aliasing. This decimation filter is actually the same as the decimation filter used in the ActiveTwo ADCs. So, data with sample rates of 8 kHz and lower is measured with the same frequency response for both the old and new systems. The bandwidth of down-sampled data is 1/5th of the selected sample rate.

The new ActiView acquisition software detects which channels are installed in the AD-box, and which auxiliary sensors are connected. Only installed channels and connected sensors can be displayed and saved to file. This new setup greatly simplifies operation of the software: no risk anymore of polluting files with uninstalled channels, no risk anymore of forgetting to save connected sensors.

5. CMS/DRL

The basic principle of using a CMS/DRL feedback loop for safety and interference suppression is retained in the ActiveThree system. Again, the CMS/DRL circuit is used to limit leakage currents to a save (< 40 uA) level during fault conditions, and to switch off the power supply to the active electrodes when a defect is detected. The principle has proved itself in the past 20 years of ActiveTwo use, during which not a single dangerous situation has occurred. A simplified diagram of the operation principle is shown in Fig. 3.

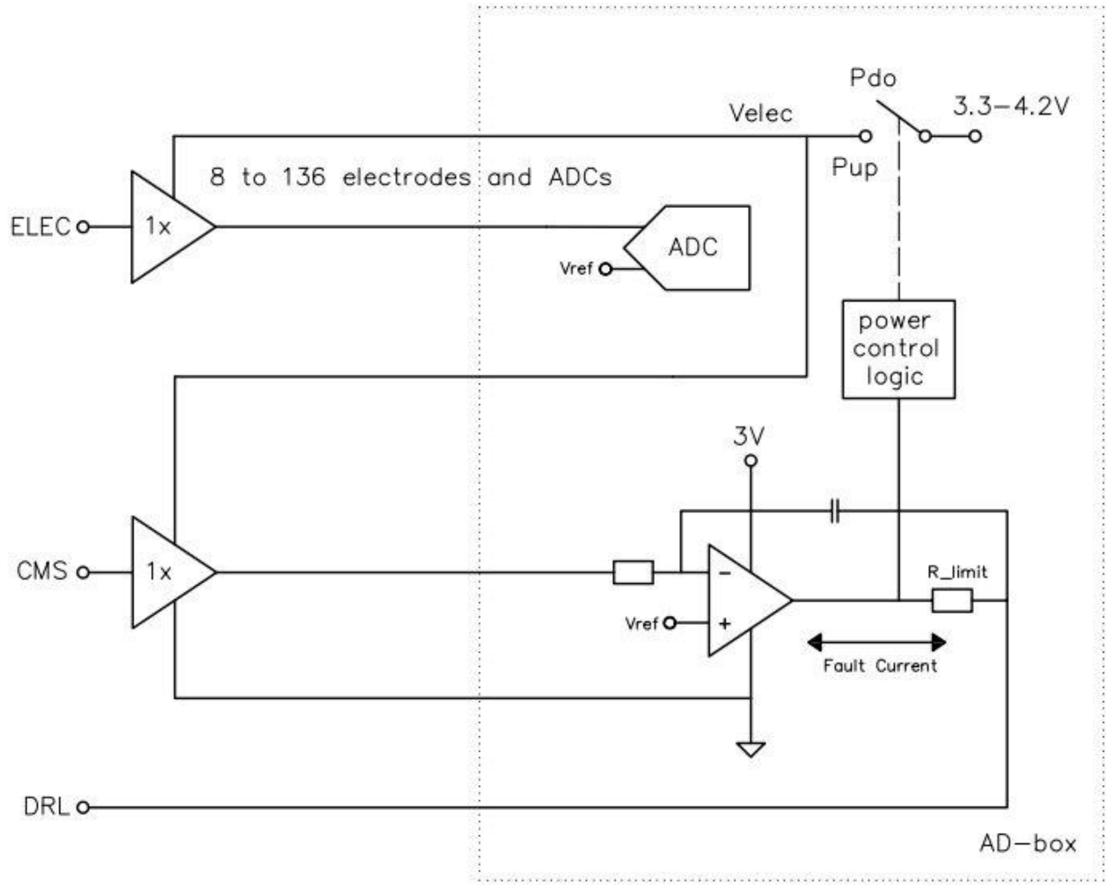

Fig. 3: Simplified diagram of the CMS/DRL feedback loop. The safety resistor R_limit limits any fault current to 40 uA. If the current flow through R_limit exceeds 10 uA, then the power supply to all active electrodes is switch off, which effectively protects the subject against dangerous currents due to electrode defects.

The CMS/DRL circuit in the ActiveTwo was developed 20 years ago with the focus on suppression of mains (50/60 Hz) interference. However, the ether of today is much more crowded with additional radio frequency signals from sources like WiFi, GSM, DECT, Bluetooth, etc. While redesigning the CMS/DRL circuit for the ActiveThree, special attention was paid to stability under difficult conditions and suppression of High Frequency (HF) interference, making the ActiveThree fully up-to-date for the difficult environments often encountered nowadays in terms of HF inference.

6. Final thoughts

Instrumentation changes are generally received by researchers with a critical attitude. For example: when BioSemi introduced the first commercially available system with active electrodes, this was received with skepticism. While researchers were excited about the advantages that this novel technology could bring, they would also hesitate to actually purchase the systems because of the fear that reviewers would not accept data measured without skin scrubbing and impedance checking. It took years before it was generally accepted that high quality data could be measured with active electrodes on the unprepared skin (and then the technology was quickly copied by competitors). The conservative attitude of the scientific community has been one of the reasons that we postponed the introduction of a new system until newly available technology could offer really significant improvements. Nevertheless, the ActiveTwo system was kept up-to-date in the mean time with many small upgrades “under the hood”.

A further aspect that played a role when designing the new system is the current situation in terms of availability of semiconductor components. In the past years, several mergers of semiconductor companies have lead to a situation where there are only a handful of large companies left. Older – often perfectly good - components are unexpectedly taken out of production in attempts to rationalize product lines. While in the past, in such cases it was often possible to switch to an equivalent component from a competing company, this is much more difficult nowadays. In order to secure a long service life of the ActiveThree, we took great care to select only the most recent components from reliable manufacturers for the new design.

To summarize, during the design process of the ActiveThree system, the three main goals were: incorporate two decades of intense customer feedback, use the latest available technology, and ensure reliable service and production for at least the coming ten years. I must admit that we are quite pleased with the result, and we are convinced that the ActiveThree will be a worthy successor to the ActiveTwo system.

Amsterdam, March 21st, 2024
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Director