32-Channel Ultra-Low-Noise Arbitrary Signal Generation Platform for Biopotential Emulation

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***Abstract*—This paper presents a multichannel, ultra-low-noise arbitrary signal generation platform for emulating a wide range of different biopotential signals (e.g. ECG, EEG, etc). This is intended for use in the test, measurement and demonstration of bioinstrumentation and medical devices that interface to electrode inputs. The system is organized in 3 key blocks for generating, processing and converting the digital data into a parallel high performance analogue output. These blocks consist of: (1) a Raspberry Pi 3 (RPi3) board; (2) a custom Field Programmable Gate Array (FPGA) board with low-power IGLOO® Nano device; and (3) analogue board including the Digital-to-Analogue Converters (DACs) and output circuits. By implementing the system this way, good isolation can be achieved between the different power and signal domains. This mixed-signal architecture takes in a high bitrate SDIO (Secure Digital Input Output) stream, recodes and packetizes this to drive two multichannel DACs, with parallel analogue outputs that are then attenuated and filtered. The system achieves 32-parallel output channels each sampled at 48 kS/s, with a 10 kHz bandwidth, 110 dB dynamic range and μV-level output noise.**

I. Introduction

Over the past decade, we have witnessed significant progress in medical device technology but also consumer electronics for lifestyle monitoring. This has been predominantly due to advances in microelectronics through improvements in energy efficiency and integration density. There has also been a shift in paradigm from centralized primary care provided in hospitals and clinics to personalized healthcare and wellbeing in the home and work environment [1]. This has seen technology that was once only available in bulky bedside monitors find its way into portable everyday devices such as mobile phones, smart watches and fitness monitors [2].

Fundamentally, such devices aim to measure as many physiologically-relevant biosignals as possible, and interpret these for a wide range of medical and lifestyle applications. These biosignals can be obtained through a variety of sensors and transducers that observe the electrical, magnetic, optic, acoustic, mechanical, chemical, thermal, etc, activity. Of these, it is often the electrical signals that are of interest, due partly to the ease of accessing but also the inherent compatibility with connecting to electronics. Electrical activity can be observed by placing electrodes in contact with tissue that changes the ionic current flowing in the tissue, to an electronic current. These underlying biopotential signals originate from electrically-excitable cells, such as myocytes and neurons [3], and can be observed in organs such as the heart, brain and muscles. A set of the most important and commonly observed biosignals are shown in Fig. 1.

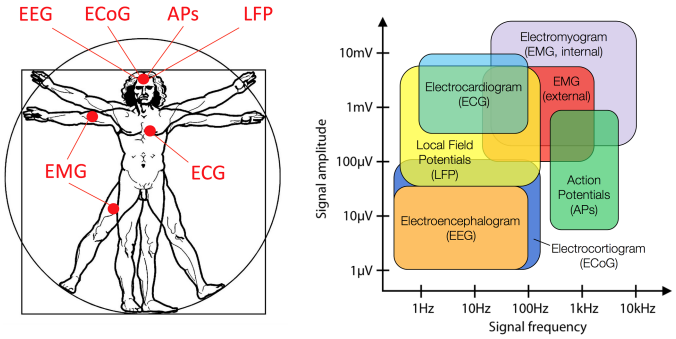

Fig. 1. Origin and characteristics of commonly observed biopotential signals.

Despite the growing number of commercially-available medical devices, the evaluation and test of these instruments remains a technically demanding and time-consuming task. This in particular becomes a highly arduous challenge when dealing with invasively recorded signals, for example, extracellular action potentials (APs) observed within neural tissue. Due to this invasive nature, it is particularly challenging to obtain relevant and realistic test signals to assess front-end devices (for example, in characterising biopotential amplifiers). For this reason, there is a clear need for tools that effectively mimic biosignals, firstly for test and calibration purposes but also in demonstrating functionality in the absence of biological tissue.

Although there is a great abundance of electronic test equipment for signal generation, characterisation and analysis, these predominantly target mainstream electronics applications and are thus constrained in some way when used in assessing biosignals. Instruments such as waveform function generators, direct digital synthesizers (DDS)/arbitrary signal generators, low noise instrumentation amplifiers, and spectrum analysers are typically used, but are all far from ideal for this application. For example, function generators, can generate high fidelity test signals, but are limited to standard waveform profiles (e.g. sinusoidal, triangular, etc). On the other hand, DDS and arbitrary waveform generators can synthesize appropriate waveform profiles, but are limited in dynamic range, noise performance, and typically only available with single or dual channel output. Characterization of biosignal instrumentation thus typically requires the use of multiple instruments, together with custom low noise amplification and/or attenuation cir-

cuits. This complexity, in addition being a very laborious task, also ultimately compromizes the quality of the generated test signals [4].

This paper describes a novel biosignal emulation platform that addresses this problem. The system presented exploits high performance components used in consumer electronics to achieve the demanding requirements. The multichannel functionality is made possible using a DDS based on a Raspberry Pi-3, the high dynamic range output is achieved using a precision audio DAC, and ultra low noise/low level output, using a custom attenuation circuit. The system reads the datastream direct from a SD card, and as such, any arbitrary waveform can be generated in Matlab or alternatively be played back from experimental biosignal recordings.

The remainder of this paper is organized as follows: Section II discusses the key challenges in emulating different biosignals; Section III details the system design; Section IV presents the prototype system and key specifications; and Section V concludes the paper.

II. Challenges in Biosignal Emulation

As previously mentioned, biopotential signals are observed typically by placing an electrode in contact with tissue. Depending on the source of the biopotential, the proximity to the electrode, the electrode geometry (i.e. size, shape) and biological topography, the characteristics of the measured signal will vary. For example, using a non-invasive technique such as electroencephalography (EEG) typically involves large area electrodes in contact with the scalp, and this observes the activity of many thousands to millions of neurons at a proximity of the order of centimetres (through the skull). On the other hand, invasive techniques such as intracortical microelectrodes recording AP activity will observe the activity of only a few neurons, with at most a few 100 microns proximity (through just the tissue). These two applications will observe very different signals, and will each have their own set of challenges, such as in-band interferers, electrode non-idealities, etc that will ultimately impact the signal to noise ratio (SNR).

Two key parameters therefore in describing the signal characteristics are the signal level (voltage) and bandwidth (frequency content) – see Fig. 1. Biosignals in general all tend to be at very low frequencies (sub-Hz to 10 kHz) and at low signal magnitudes (μVs to mVs). This makes it challenging to design recording electronics (due to instrumentation noise) [5], and for the same reason also to generate such signals. If we compare these signal characteristics to those generated by most electronic test instruments, biopotential signals are at significantly lower amplitudes, but additionally can shift significantly in range due to technique, location, and electrode characteristics. As a result it is essential that any system that emulates biopotential signals has an exceptionally high dynamic range (DNR) whilst also maintaining a low noise floor (and thus a high SNR). For example, an extracellular recording will consist of an electrode offset potential of ≈100mV, LFPs of ≈5 mV, and APs of ≈50-100 μV [5], [6].

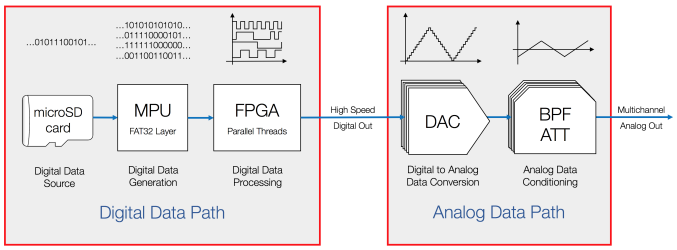

Fig. 2. Basic system concept showing data path for biosignal emulator.

Furthermore, it is often needed to record multiple biopotentials in order to recover the biosignal of interest, for example [7]. Any biopotential emulator should thus also be able to generate multisource signals, further increasing complexity.

III. System Implementation

In order to realize a system that generates signals that meet all these requirements a mixed-signal architecture is needed, shown in Fig. 2.

The target waveforms are first stored on non-volatile memory (SD card). This is accessed using a microprocessor unit (MPU) that transfers the data to a FPGA for synchronization and recoding the data into parallel streams. This is then reserialized and fed into a multichannel high resolution DAC to generate the analogue waveform. This is finally filtered and attenuated, to generate the emulated biopotential signal. This datapath has been divided into 3 sub-systems (microcontroller, FPGA, and analog boards) so as to isolate the supplies and minimize feedthrough. The architecture is shown in Fig. 3.

A. Raspberry Pi 3 Board – Digital Signal Generation

The biopotential signals to be generated are stored in a binary file in a microSD (Secure Data) card and organized in a 2D

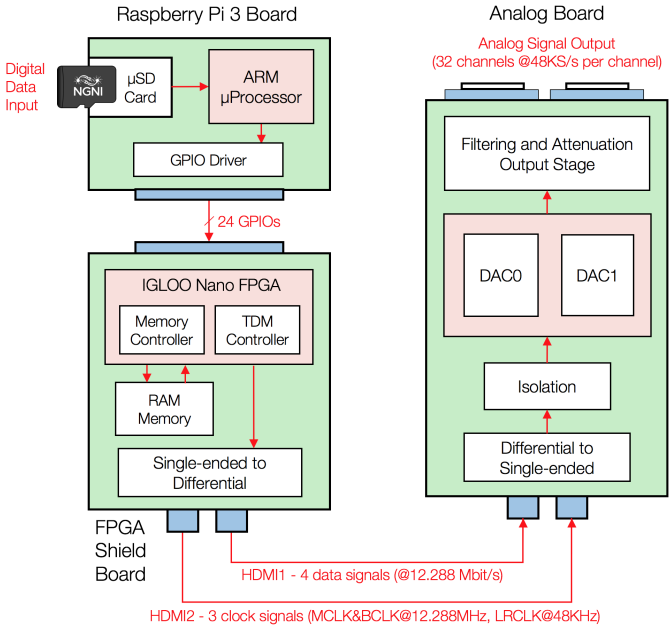

Fig. 3. System architecture of the biosignal emulator showing dataflow through the 3 sub-systems: Raspberry Pi 3, FPGA board, analog board.

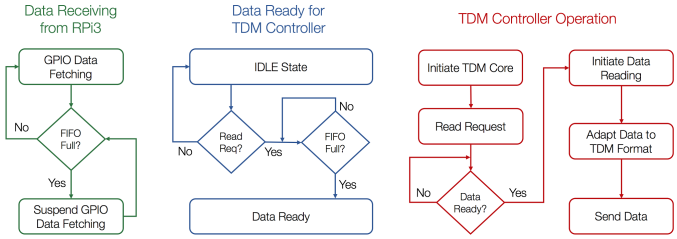

Fig. 4. FPGA operation showing 3 parallel processes implemented in Verilog.

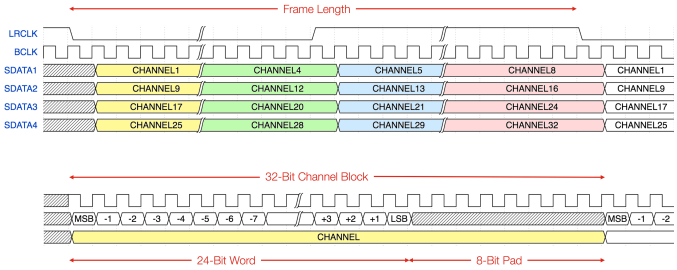

Fig. 5. Timing diagram of the TDM8 data format (8-ch. per serial data line).

array in channel/sample order (24-bit per sample). The SD card is directly inserted into the standard RPi3 board with the System-on-Chip (SoC) that includes the Microprocessor Unit (MPU) and various interfaces. The RPi3 runs a real-time operating system (Linux-based Raspbian OS) with embedded SD card driver. This is configured to read and send a 24-bit parallel output to the FPGA shield board through the General Purpose Input Output (GPIO) port, thus achieving a high speed parallel data transfer. In order to synchronize this data interface, a clock signal and channel indicator are also transmitted to the next stage.

B. FPGA Board – Digital Processing (Binary Data Stream)

One challenge with using the Raspberry Pi 3, is its real-time OS does not guarantee precise timings on the GPIO outputs. The output DAC however requires a precisely timed 12.268 MHz clock/data input. An FPGA (Microsemi IGLOO® nano) with external memory is thus used to provide a intermediate buffer and ensure precise timing. Furthermore, the FPGA generates two parallel threads (re-ordering/encoding the data) for driving the two DAC controllers in the required format.

1) PCB Design: The FPGA board is designed as a shield to be plugged to the RPi3 board through the GPIO connector. This connects the low power 3×3 mm size AGLN250 IGLOO® nano FPGA to the RPi3 GPIO pins, also to a 4 Gbit external RAM (Cypress S34ML04G200). The FPGA output signals (single-ended) are converted to fully-differential pairs using a line driver (TI SN65LVDS389) to implement low-voltage differential signalling (LVDS), a low power physical layer protocol specification. The two pairs of differential signals are then transmitted via two HDMI connectors through shielded twisted pair copper cables to increase noise immunity.

2) Verilog Design: The operation of the FPGA is described in the flowchart shown in Fig. 4. The parallel data from the RPi3 is latched by the FPGA and pushed into a 1k-deep 24-bit wide first-in-first-out (FIFO) data buffer. A FIFO-full signal is issued to suspend data being received and avoid data loss. When instead, a read-request signal is issued by the DAC controller, the memory's Finite State Machine (FSM), dedicated to accessing both internal and external (4Gbit RAM) memory, determines whether there is data available. If so, it fetches the remaining data into the FIFO and presents it to the 24-bit internal port connected to the DAC controller. This adapts the data to the format required by the DAC (a non-standard Time Division Multiplexed (TDM) audio interface), which allows multiple channels of data to be transmitted on a single data line. In this particular case, the TDM8 mode is chosen: transmitting 32-channels over 4 serial data lines (8 channels each). The serial interface also requires 3 clocks, a frame synchronization clock LRCLK, serial bit clock BCLK and master clock MCLK (timing diagram shown in Fig. 5).

C. Analog Board – Data Conversion & Signal Conditioning

The core function of this biopotential emulation platform relies on two high performance DACs (Analog Devices ADAU1966A – 16-channel, 24-bit, 110 dB, -95 dB THD, 32-192 kHz) originally designed for high-fidelity audio applications. These require either the standard Inter-IC Sound (I2S) input (for stereo signals) or a high-speed TDM input if requiring more than two serially transmitted signals. Due to the ultra-low noise/distortion requirements of this system, special care was taken in the PCB layout to minimize crosstalk between the high speed digital inputs and low level analog outputs. Additionally, two separate power domains were defined (for digital and analog), with PCB floorplan partitioned appropriately, as shown in Fig. 6. Each power domain is powered from independent 3.3 V linear regulators that are both driven from a 5 V external Li-Ion battery.

1) Digital Domain: The digital section is further divided into two sub-sections to prevent noise from the FPGA and RPi3 (high speed domain) appearing at the digital input pins of the DACs (to prevent coupling through to the converted signals). This is achieved using low-power digital isolators (Silicon Labs SI8640EC) for recovering the single-ended data and clock signals from the differential signals (in TDM8 format) received through the two HDMI input connectors.

2) Analog Domain: The 32-channel analogue outputs (i.e. converted signals) are finally passed through individual passive

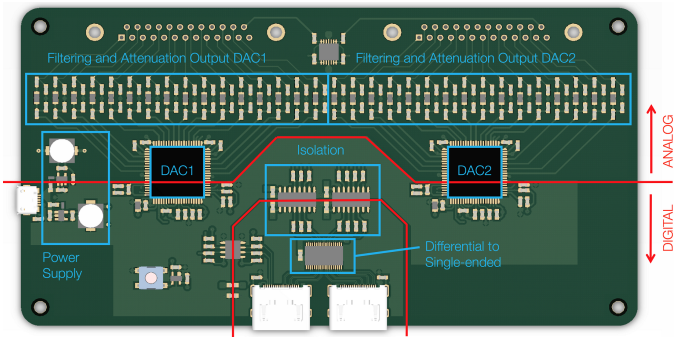

Fig. 6. Analog board layout w/ annotated floorplan & analog/digital partition.

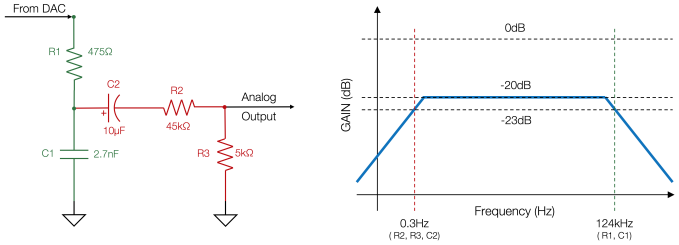

Fig. 7. Output passive network design for filtering oversampling noise (from high resolution DAC), and attenuating the output to a sub-μV equivalent LSB.

bandpass filters (BPF) and attenuation circuits. These remove the DC component and attenuate high frequency noise that is introduced by the oversampling DAC. The filtered output signal is then attenuated using a simple potential divider to achieve a sub-μV level LSB, without affecting the dynamic range. This passive network design is shown in Fig 7. Finally, to ensure good matching between the different output channels, we have ensured a perfectly symmetric design of this output stage (i.e. passive network), in addition to using low tolerance passives.

IV. Device Prototype

A prototype of the biopotential emulation platform has been fabricated and assembled (shown in Fig. 8). Here the FPGA shield is plugged into the RPi3 board (shown on left) through the GPIO connector and connected to the DAC board (shown on right) through two HDMI cables (black cable transmitting the 3 clock signals, and white cable transmitting the 4 serial data signals). The complete system is powered by a rechargeable battery using micro-USB cables.

Thanks to the high performance multichannel audio DACs, the platform is able to emulate 32 analog biopotentials, with a wide output dynamic range of 110 dB. The Total Harmonic Distortion plus Noise (THD+N) at the output of the DAC, which represents the unwanted component of the output signal (noise and distortion) compared to the total output signal, is -95 dB. Due to the attenuation stage, the output range of the generated signal is shifted (with same dynamic range), which means that also the noise level is attenuated. The required sampling rate is 48 kHz (24-bit word per sample), which translates into a minimum throughput from the the RPI3 to the FPGA of 36.9 Mbit/s (1.5 Mbit/s per GPIO). To avoid data loss, a speed of at least 3 Mbit/s per GPIO is ensured.

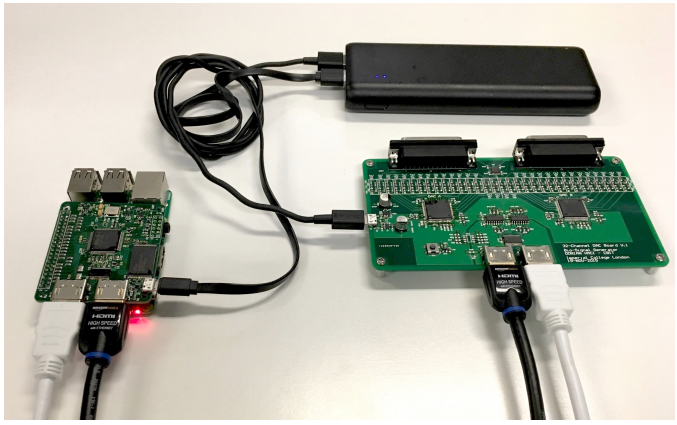

Fig. 8. The complete biopotential emulation platform prototype.

V. Conclusion

We have described the complete system design of a 32-channel biopotential emulation platform. By combining a Raspberry Pi 3 embedded platform, with custom logic, high-end data converters, and a passive output network, a system has been realized that overcomes many of the challenges posed by biosignal emulation using standard electronic test instruments. It has been shown how through a modular architecture good isolation of the digital signal path can be achieved using low voltage differential signalling through screened twisted pairs, solid-state isolation, and careful board design. The system specifications are given in Table I.

TABLE I
System Prototype Specifications

Parameter	Value
Full-Scale Output Voltage	141 mV_{pp}
Output Noise Level	0.45μV
Output Resistance	4.5 kΩ per channel (1 Hz-1 kHz)
Output Band-Pass Filter -3 dB BW	0.3 Hz-124 kHz
DAC Output THD+N	-95 dB (-1 dB FS signal)
DAC Sampling-Rate	48 kS/s
DAC Digital Filter Pass-Band Ripple	0.01 dB (@48 kHz)
Communication Protocol	Parallel GPIO and TDM Interface
RPi Throughput (per GPIO)	3 Mbit/s (minimum)
TDM Interface Total Bit-Rate	49.152 Mbit/s

Acknowledgements

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