Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Design and Implementation of a Wireless (Bluetooth®) Four Channel Bio-Instrumentation Amplifier and Digital Data Acquisition Device with User-Selectable Gain, Frequency, and Driven Reference

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Abstract— **A portable, multi-purpose Bio-instrumentation Amplifier and Data AcQuisition device (BADAQ) capable of measuring and transmitting EMG and EKG signals wirelessly via Bluetooth® is designed and implemented. Common topologies for instrumentation amplifiers and filters are used and realized with commercially available, low-voltage, high precision operational amplifiers. An 8-bit PIC microcontroller performs 10-bit analog-to-digital conversion of the amplified and filtered signals and controls a Bluetooth® transceiver capable of wirelessly transmitting the data to any Bluetooth® enabled device. Electrical isolation between patient/subject, circuitry, and ancillary equipment is achieved by optocoupling components. The design focuses on simplicity, portability, and affordability.**

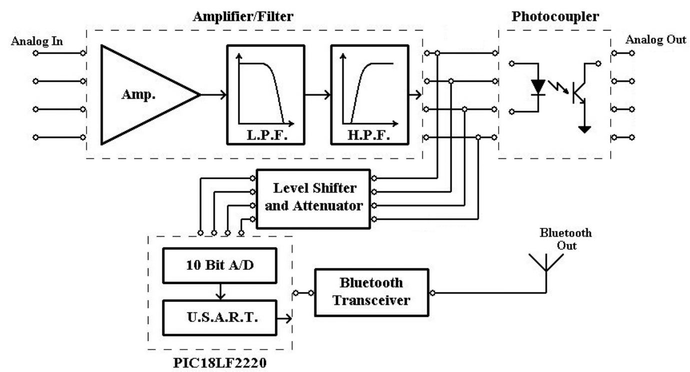

Fig. 1. Block diagram of BADAQ

I. INTRODUCTION

The measurement of electrical signals naturally produced by the body using either surface or invasive electrodes has become a routine part of both clinical diagnosis and medical research. The amplification of these signals is most commonly done using an instrumentation amplifier, for which many well-known designs exist. The frequency content and amplitude of the signals produced by the body are also very well known [3]. This allows the characteristics of the filters needed to eliminate noise from the detected signals to be easily determined.

The amplitudes of the signals produced by the body, whether they are obtained for electrocardiography (EKG), electroencephalography (EEG), or electromyography (EMG), are typically measured in millivolts [1], which is several times the noise level of present day electronics. Of these signals EMG signals have a frequency range between 10 Hz and 1 KHz [1]. Although the design of amplifier and filter stages for measuring these signals is relatively straightforward, there is still a great deal the engineer can do to increase the usefulness of a bio-instrumentation amplifier (bio-amp).

Since the analysis of EKG, EEG, and EMG signals is commonly done using a computer, a bio-amp which digitizes the signal is desirable. Multi-channel capability is a useful feature, as it is common that more than one signal is analyzed in parallel. Furthermore, a bio-amp with user-selectable gains and frequency cutoffs greatly increases its utility, making it possible to analyze different types of signals with the same device. Finally, mobility is a very helpful feature, as it allows the bio-amp to take measurements free of cumbersome cabling, enabling the user to record data outside of the lab, which allows for the study of dynamic activities in a wide variety of settings.

This paper details the design of a multi-purpose Bio-instrumentation Amplifier and Data AcQuisition device (BADAQ) capable of measuring and transmitting EMG and EKG signals wirelessly via Bluetooth®. The BADAQ uses common topologies for instrumentation amplifiers and filters, implemented using commercially available, low-voltage, high precision operational amplifiers (op-amps). The output of four independent, filtered, amplifier channels are provided as input to the on-board analog-to-digital converter (ADC) of an 8-bit microcontroller. The microcontroller is used to control a Bluetooth® transceiver which sends the digitized signal to any Bluetooth® enabled device. Analysis and additional signal processing may then be performed by the receiving device using software such as MATLAB®.

II. DESIGN AND IMPLEMENTATION

Initial design decisions centered on selecting a topology for the instrumentation amplifier and filter stages and specifying the required frequency ranges and gains. These decisions were made with the underlying goal of versatility in mind. Other considerations included the operating voltages and power supply circuitry.

The Cooper Union for the Advancement of Science and Art supported this work

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Our design, shown in Fig. 1, consists of four independent and identical gain-selectable instrumentation amplifiers, each followed by a low-pass, frequency-selectable filter stage and a fixed high-pass filter stage. Both the instrumentation amplifier and filter stages are implemented using OPA277 op-amps from Texas Instruments. The output of these amplifiers, after passing through optocouplers (National 4N25), is available to the user as analog output via SMA connectors. The amplifier output is also used internally, after being suitably biased and attenuated, as the input to the on-board ADC of a microcontroller (Microchip PIC18LF2220). This microcontroller interfaces with a Bluetooth® module (WBTV42, Wintec Industries) to transmit the acquired signals to any Bluetooth® capable device.

A. Amplifier and Filter

Shown in Fig. 2 is the schematic of a single channel of the amplifier with driven reference and attached filters. Op-amps X1, X2 and X3 comprise the instrumentation amplifier stage; it is a common design which was chosen for its high differential gain and large common mode rejection ratio (CMRR) [2]. The value of resistor R1 controls gain of the amplification stage and our design allows the user to switch between the resistor values of 82 kΩ, 15 kΩ and 7.5 kΩ for gains of 100 V/V, 500 V/V, and 1000 V/V respectively. The driven reference op-amp is used to increase the CMRR of the bio-amp. It is a unity-gain inverting amplifier whose input is the common-mode signal of a user-selected channel whose output is used as the bio-amp's reference electrode.

Op-amps X4 and X5 comprise two Sallen-Key filters which together make up the 4-pole low-pass filter (LPF) stage. The LPF eliminates high frequency noise introduced by other electronic equipment or radio interference, and provides an anti-aliasing filter for the analog-to-digital conversion. A Sallen-Key filter was chosen because its characteristics are well documented, it has a flat pass-band, and is capable of achieving a high quality factor (Q) [4]. Changing the values of capacitors C1-5 and C1-4 together with C2-5 and C2-4 moves the upper 3 dB point of the filter. Our design allows the user to switch between capacitor values of 1.5 nF and 3 nF to shift the upper 3 dB frequency from 1000 Hz to 500 Hz.

Op-amps X6 and X7 comprise two Sallen-Key filters which make up the high-pass filter (HPF) stage. The HPF is used to eliminate low frequency noise, which is typically introduced by movement of the electrode cables [2].

Simulation and experimental results of the amplifier and filter design and implementation are shown in Fig. 3 and Fig. 4.

B. Power Supply and Protection Circuitry

The BADAQ runs on ±3.3 V because it simplifies the design and allows the use of low voltage digital components. Using ±3.3 V also makes it possible to power the device with a single 9 V battery, greatly increasing its portability.

The power supply circuitry consists of two adjustable positive voltage regulators (National LM338) connected in series. With an input voltage of at least 8 V, the first voltage regulator outputs a constant 6.6 V, which is input to the second voltage regulator, which then produces a constant 3.3 V. The digital components use the output of the second voltage regulator as V_{dd}, this range was selected for the digital components because it is regulated at least twice and is thus that much more immune to power supply spikes. This set-up functions equally well regardless of the source of the 8 V, meaning that in situations not requiring the device to be worn by the subject, the BADAQ can be powered by any external 9 V DC supply.

Since the analog output of the bio-amp is often connected to expensive and sensitive devices powered by line voltage, it is desirable to isolate the output from the rest of the bio-amp. This isolation means that any externally connected equipment is not at risk of being damaged by a power-surge in the bio-amp, and the subject connected to the bio-amp is not at risk of getting shocked by any stray signals accidentally fed into the output of the bio-amp. To achieve this, the 4N25 optocoupler is placed at the output of each of the four channels.

C. Analog-to-Digital Conversion

The PIC18LF2220 was chosen because it can operate on a 3.3 V power supply, its firmware can be programmed in-circuit, it can run on a 40 MHz clock, it has a multi-channel 10-bit ADC, an on-board Universal Synchronous/Asynchronous Receiver/Transmitter (USART) capable of bit rates up to 921.6 kbps, and is available in both a 28 pin DIP and SOP package. The output of the analog channels is first attenuated to limit it to 3 V peak to peak, then biased to be positive with respect to ground, and finally input into 4 of the ADC channels of the microcontroller.

The firmware of the microcontroller is written in its device-specific assembly language. On power-up, the microcontroller configures its ADC before waiting for the instruction to begin data acquisition. Upon receiving this signal, the microcontroller begins sampling all four channels sequentially. After each sample, the microcontroller transmits the two data bytes while the next channel is being sampled. After one sample from each channel has been transmitted, the microcontroller checks whether it has received a stop signal. If so, the microcontroller returns to its idle state. Otherwise, the process repeats.

The sample rate of the microcontroller is governed by the bit rate of the USART. The higher the bit rate, the higher sample rate can be. The minimum sample rate is twice the highest frequency content of the sampled signal (the Nyquist rate), 2 KHz. In order to obtain measurements of the actual sampling rate achieved, a digital output pin on the microcontroller is toggled for each channel each time a conversion has been completed; the period between toggles yields the sampling rate.

Experimental results of the microcontroller performing an analog-to-digital conversion as described above and transmitting the data using Bluetooth® are shown in Fig. 5.

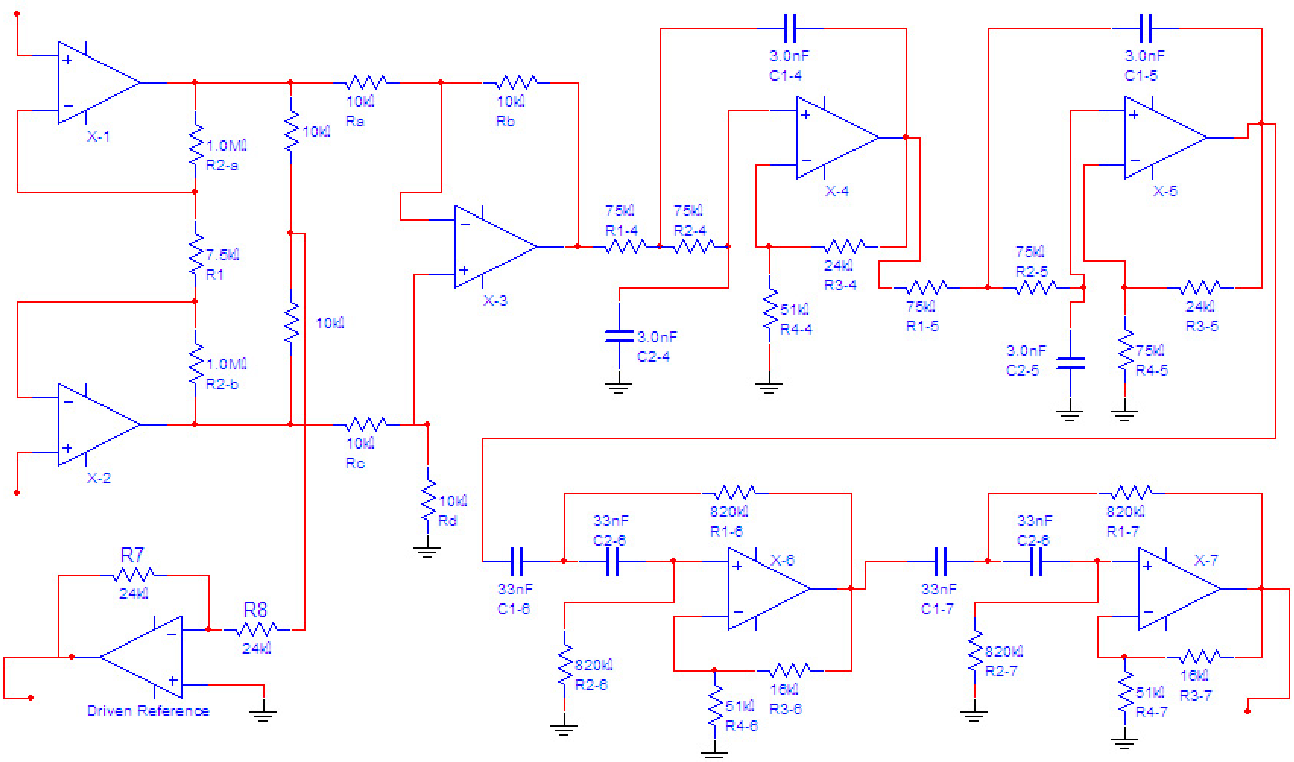

Fig. 2. Bio-instrumentation amplifier with attached filter. Shown with values for gain of 1000 V/V, a lower 3 dB point of 10 Hz and an upper 3 dB Point of 500 Hz

D. Bluetooth®

The WBTV42 Bluetooth® module from Wintec Industries was chosen because it is available in a convenient 24-pin DIP package, operates on 3.3 V, has an on-board transceiver, is capable of data rates up to 921.6 kbps, and has a USART interface. The Bluetooth® module can operate in two modes relevant to this application: Serial Port Profile (SPP) and Host Controller Interface (HCI). In SPP mode, it appears to the remote computer as an RS232 serial port, achieving speeds of up to 115.2 kbps. In HCI mode, it can achieve speeds up to 921.6 kbps, but requires more complex firmware on the microcontroller.

The Bluetooth® module communicates with the microcontroller using its on-board USART and a set of AT-commands. As soon as a Bluetooth® pair is established and a "virtual serial port" is set up by the remote computer, it is up to the remote computer to send the start byte, at which point the microcontroller begins transmitting data and continues to do so until instructed to stop.

E. Computer

The data generated by the microcontroller's ADC is transmitted raw, without any processing other than a byte separating every four samples. This means that it must be parsed before any processing occurs. An excellent program to use for this is MATLAB®, as it can perform the parsing, making the data immediately available for analysis. Since the Nyquist rate has been satisfied for the acquired signals they can be resampled as desired by the user [3].

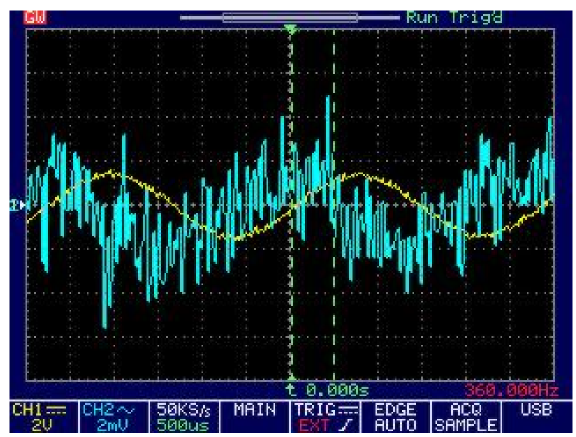

Fig. 3. Oscilloscope screen capture of the output from a single channel shown against an approximately 3 mV Peak-to-Peak, 350 Hz, sine wave input provided by a function generator.

III. CONCLUSION

We have detailed the design of a device capable of amplifying, filtering, measuring, and wirelessly transmitting electrical signals produced by the body. If implemented on a printed circuit board, this device is small enough to be worn by the patient/subject and is versatile enough to

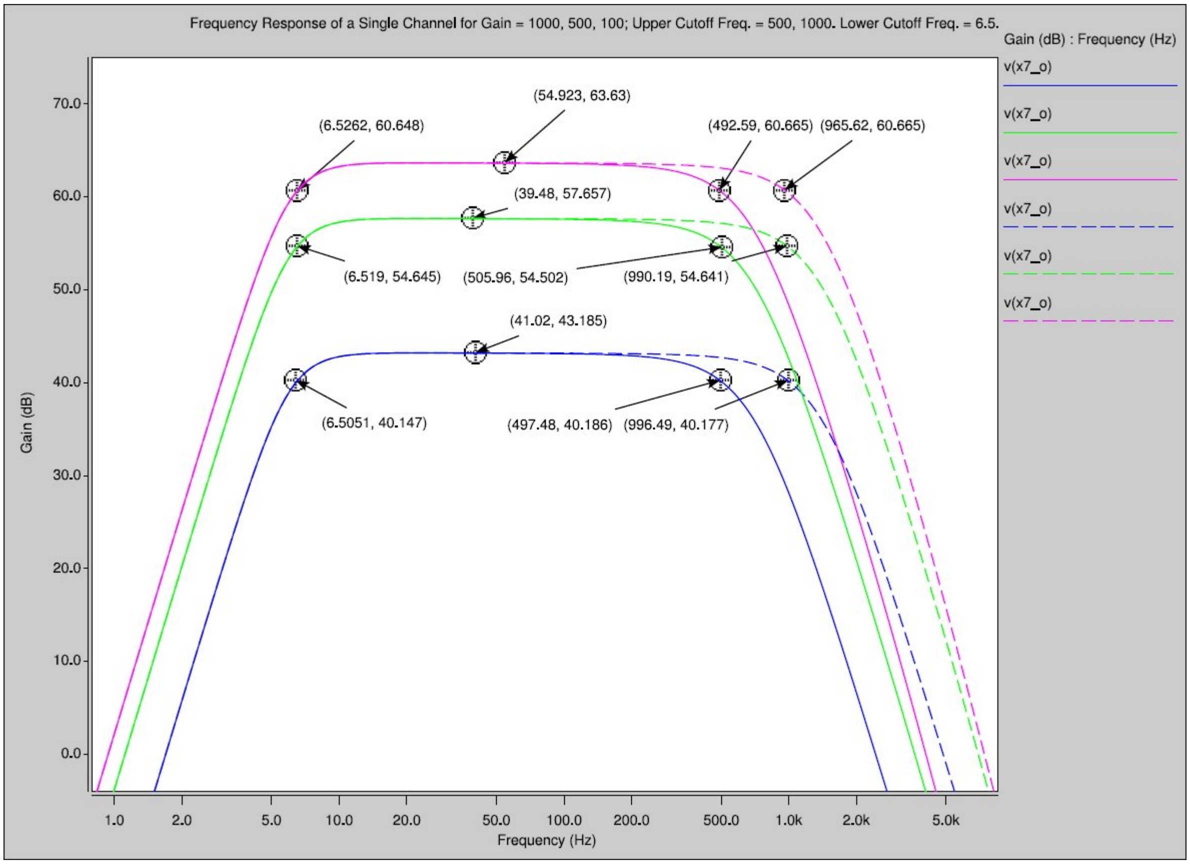

Fig. 4. hSPICE(r) generated plots of the channel characteristics showing the three different gain settings and the two different frequency cutoffs, the simulations were done using the model file for the op-amps provided by the manufacturer. Experimental measurements match these simulation results reasonably well, with deviations due to the tolerances of the component values. This deviation was expected and designed for, so for example, the channel was designed to have a gain of 1500 V/V (63 dB) for the highest setting, while it was experimentally measured to have a gain of approximately 1000 V/V, which meets our gain requirements.

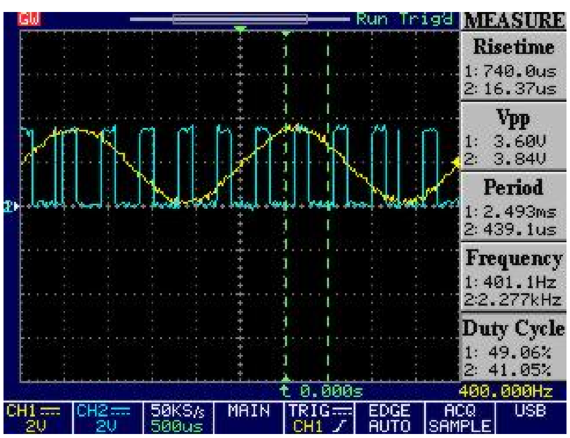

Fig. 5. The input to one of the ADC channels of the microcontroller is shown against the output of a pin which toggles for every sample made on that channel. The sampling rate achieved by the ADC is determined from the frequency of the bit toggle, shown on this screen capture as CH2. Various signal statistics for both the signal being sampled and the bit toggle are shown on the left hand of the figure. This oscilloscope screen capture was taken with two channels being sampled by the microcontroller and the data being transmitted using Bluetooth®.

measure both EKG and EMG signals. It can digitize and wirelessly transmit the measured signals using Bluetooth®, making it ideal for mobile and in-situ data acquisition. It is also simple enough to build in any moderately equipped electrical laboratory using breadboards and other off-the-shelf components.

IV. ACKNOWLEDGMENTS

The authors would like to thank Glenn Gross for his help with obtaining components, lab space, and equipment. We would also like to thank Yifei Huang, Andy Wu, Yuriy Mykula, Alex Scolnik and Michael Dooley for lending a helping hand.

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