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Instrumentation Development for Real Time Brainwave Monitoring

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Abstract

The human brain functions through a chemically-induced biological process which operates in a manner similar to electrical systems. The signal resulting from this biochemical process can actually be monitored and read using tools and having patterns similar to those found in electrical and electronics engineering. The primary signature of this electrical activity is the "brain wave", which looks remarkably similar to the output of many electrical systems. Likewise, the device currently used in medical arenas to read brain electrical activity is the electroencephalogram (EEG) which is synonymous with a multi-channel oscilloscope reading.

Brain wave readings and recordings for medical purposes are traditionally taken in clinical settings such as hospitals, laboratories or diagnostic clinics. The signal is captured via externally applied scalp electrodes using semi-viscous gel to reduce impedance. The signal will be in the 10 to 100 microvolt range. In other instances, where surgeons are attempting to isolate particular types of minute brain signals, the electrodes may actually be temporarily implanted in the brain during a preliminary procedure. The current configurations of equipment required for EEGs involve large recording instruments, many electrodes, wires, and large amounts of hard disk space devoted to storing large files of brain wave data which are then eventually analyzed for patterns of concern.

Advances in sensors, signal processing, data storage and microelectronics over the last decade would seem to have paved the way for the realization of devices capable of "real time" external monitoring, and possible assessment, of brain activity. A myriad of applications for such a capability are likewise presenting themselves, including the ability to assess brain functioning, level of functioning and malfunctioning.

Our plan is to develop the sensors, signal processing, and portable instrumentation package which could capture, analyze, and communicate information on brain activity which could be of use to the individual, medical personnel or in other potential arenas. To take this option one step further, one might foresee that the signal would be captured, analyzed, and communicated to a person or device and which would result an action or reaction by that person or device. It is envisioned that ultimately a system would include a sensor detection mechanism, transmitter, receiver, microprocessor and associated memory, and audio and/or visual alert system. If successful in prototyping, the device could be considered for eventual implementation in ASIC form or as a fully integrated CMOS microsystem.

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Introduction

In order to begin development of a real-time brain activity monitoring device, the investigators needed an input signal which mimicked human brain activity in both the steady state and failure mode. Epilepsy is one such brain malfunction, or failure mode, and is marked by the sudden violent electrical discharge in the cerebral cortex. These violent electrical discharges result in epileptic seizures which may take the form of temporary unconsciousness or impaired or altered consciousness, and which are preceded and followed by periods of normal brain activity. Epilepsy occurs in 1% of the population worldwide and affects approximately 50 million people. It is among the most common of the brain disorders second only to stroke. The epilepsy brain wave pattern was chosen as the input signal for this effort.

For decades doctors and scientists were able to see and identify the signature waveforms for the various types of epileptic seizures as captured on EEGs. It seemed a logical next step that they should be able to develop a method to capture and identify the impending failure mode and predict seizure onset. Over time it became apparent to researchers in the clinical setting that the signal they were capturing on their instruments was registering only several seconds before the physical manifestation of the seizure. The advance signal they were seeing was therefore, not the predictor of electrical system failure, but the onset of the cascading electrical system malfunction.

Seizure prediction, as opposed to seizure detection, has proven elusive.

Engineering technologies have been used to decode brain signals, search for dynamic mechanisms, and identify precursor conditions in the brain signal.

University researchers, Chris Sackellares M.D. and Leonidas Iasemidis, Ph.D. working under a grant from the Veterans Administration, have made great strides in predicting seizure onset based on nonlinear dynamics and sensed changes in the spatio-temporal characteristics in brain activity prior to a seizure. In its normal state the brain activity, as sensed from multiple electrode EEG channels, indicates a high level of chaos at each electrode location and among and between locations. In the epileptic brain the pattern loses this randomness and its normal electrical chaotic functioning, and initiates a higher amplitude, slower frequency signal which quickly moves to other brain locations and causes convergence in amplitude and phase. These characteristics can be quantified through sequential estimates of the short term largest Lyapunov exponent as the measure of chaos. These researchers have demonstrated that quantifiable measures start to vary hours before a seizure occurs and indicate a transition state in the brain. Use of this multidimensional, non-linear, multi-channel analysis seems to offer the best hope as a tool for seizure prediction.

The epilepsy brainwave pattern was chosen for the input signal for this effort for a variety of reasons:

- the unique qualities of intensity and high amplitude
- apparent randomness
- rapid movement between steady state signal and malfunction or failure signal, and back again
- complexity and elusiveness of gleaning the emergent failure signal from the steady state signal
- software-intensive requirements
- system integration challenge posed by requirements for mathematics, algorithms and software
- system engineering challenge posed by requirements for sensing, signal identification and signal processing, real- time signal and data analysis, communication, and device fabrication

There is a very real and compelling need for accessible, portable, real-time, brainwave analysis instrumentation and there are numerous applications which could be envisioned. Current techniques require clinical settings for any medical analysis purposes and even in those settings the systems currently in use could be significantly improved. Savings of time and money could be realized if analysis of brain signals could be done in doctor's offices as opposed to special clinics or hospitals. Within hospital and clinical settings patients could be more comfortable and results could be better if the individual could carry a small EEG device with either streamlined external electrodes or implanted electrodes. Alternately, discrete and comfortable electrodes, either internal or external to the brain, could send signals to recording devices without use of wires.

Such a capability would also be useful in a variety of military and civilian environments. Such applications might discern patterns of brain signal variation caused by stress, unconsciousness, sleep-deprivation, altered consciousness, mental illness, or death. Such a capability might prove useful to military personnel in battlefield conditions, agents on assignment, or key personnel in national security and homeland security positions such as nuclear power plant workers, air traffic controllers, emergency and disaster relief workers, pilots and astronauts.

This effort was conducted in collaboration with the referenced researchers Dr. Chris Sackallares M.D., of the University of Florida/ Gainesville, and the UF/G MEMs organization, and Leonidas Iasemidis, Ph.D. of Arizona State University/ Harrington Department of Bioengineering [See references page 24]. The objective of the collaboration was to utilize SNL recognized expertise in the areas of sensors, engineering sciences, signal processing, computation and modeling, applied mathematics, research and development in engineering and

electromechanical systems, and system integration in order to further develop an approach which could be tested for efficacy in real-time seizure prediction and notification. A follow-on activity would be to determine if a device could be prototyped and tested and, if successful, to determine if such a device would be a candidate for a microsystem application.

Hardware Considerations

The central controller chosen to control all intelligent functions for the instrument is Phytex's phyCORE-MPC555 single board computer. Phytex sells a rapid development kit [Fig. 1(a)] for this product that contains an evaluation board [Fig. 1(b)] with multiple inputs and outputs, header strips for access to all of the I/O pins, and a 30 day trial copy of Metrowerks CodeWarrior software for programming in the C programming language. When programming is complete the main module can be inserted into the motherboard of the customers instrument. The phyCORE-MPC555 module has a subminiature credit card size (72 x 57 mm) and uses Motorola's 32-bit PowerPc MPC555 embedded microcontroller (40MHz).

(a)

(b)

Figure 1 (a) Phytex phyCORE -MPC555 Rapid development kit. (b) MPC 555 development board.

The MPC555 comes in a limited external SRAM version [Fig. 2(a)] and a fully fitted 8 MB version [Fig. 2(b)] with flow-through synchronous external BURST-SRAM. All signals and ports of the MPC555 extend to two Molex high density 160 pin header connectors. This allows the programmed controller module card to be easily inserted into the instrument motherboard either before or after programming. This controller module, while powerful, was especially attractive for its built-in 32 channels of ADC, the maximum number of scalp electrode inputs that were being considered for the final instrument. One of our goals was to at least match the data acquisition rate of the Nicollet BMSI System 6000

presently being used in hospitals throughout the world to acquire and record EEG signals. The BMSI 6000's digitization rate for 32 channels is 400 Hz.

Figure 2 (a) Phytel phyCORE -MPC555 basic (b) MPC 555 fully loaded (8 MB)

Figure 3 Grass Telefactor Scalp electrodes

Scalp electrodes were purchased from Grass Telefactor [Fig. 3]. Most scalp electrodes for brain wave acquisition are terminated with a DIN 42-802 touchproof connector plug that mates with the data acquisition equipment . A

search was performed to find such connectors for our instrument so as to be compatible with industry standards and thus avoiding potential problems in controlled environments such as a clinic or hospital. After an exhaustive search, these connectors were found at only one company in the United States, Plastics-One Inc. The color coding on these connectors match the industry standard of red for positive (differential), black for negative (differential), and green for common (a common potential ground usually referenced at a patient's neckline).

Electronic Design

It was decided that all internal components for the instrument would reside on three printed circuit boards. First the vertically oriented scalp electrode input board, or headboard, which would include the electrode input jacks and header strip to make the 90 degree mechanical translation to the second board. The second board, the signal conditioning board/boards, would contain all electronics for 32 plus channels of electrode and reference data. These channels comprise the highly selective bandpass filter and gain stages from the scalp electrode inputs. Finally the third board, the motherboard, would receive the signals from the signal conditioning board via a header strip and contains the voltage regulators, serial port drivers, and high density Molex connectors configured to receive the pre-programmed phyCORE-MPC555 module.

Signal levels from external scalp electrodes for normal brainwave activity are in the 10 to 50 microvolt range with seizure amplitudes in the hundreds of microvolts. The bandpass analog front end circuitry was designed to have a fixed voltage gain of approximately 2500. Thus bringing the amplitude into a convenient voltage range for signal conditioning and signal processing. All front end electronic circuitry was simulated in PSpice [Fig. 4 , 5] to verify operation before breadboarding and eventual implementation on the printed circuit board. A bandpass frequency response of 0.5 to 100 Hz is accomplished with an eight order filter design in the signal conditioning gain stages.

Figure 4 Simulation Model for the front-end filtering network and differential instrumentation amplifier .

Figure 5 Simulation model for the second and third gain and filtering sections of the front end signal conditioning amplifier .

The designed eighth order bandpass frequency response of 0.5 to 100 Hz was implemented in PSpice. The PSpice results [Fig. 6] were identical to the response observed on a breadboarded version giving us confidence to proceed to the final pc board version .

Figure 6 PSpice simulation of the frequency response and gain of a single differential channel of the signal conditioning board, exhibiting eighth order bandpass response, pulse shaping and high gain to a swept sinusoidal input voltage of approximately 100 microvolts amplitude.

For the first run of pc boards the decision was made to produce a two-layer "transitional" signal conditioning board [Fig. 9] to test the design of only four channels with the completed final version headboard and motherboard. Then if there was a detected layout flaw, it could be changed before the final 32 multilayer or 16 channel two-layer boards were sent to manufacturing and assembly. This "transitional" board would also allow us testing of the entire system while waiting for the manufacture and assembly of the more complicated final signal conditioning boards.

Printed Circuit Board Layout

Figure 7 Sixteen channel signal conditioning printed circuit board layout

Mechanical Layout

Figure 8 Headboard printed circuit board with DIN 42-802 electrode connector inputs.

Figure 9 Four channel prototype signal conditioning transitional board

Figure 10 Mother board before component population

Figure 11 Three board assembly: Headboard, 4 channel transitional signal conditioning board, and motherboard.

Figure 12 Mother board with high density Molex connectors installed.

Figure 13 Motherboard with Phytex MPC555 microcontroller module installed.

(a)

(b)

Figure 14 (a) Instrument enclosure. (b) View of 32 channel electrode input board

Figure 15 Initial bootup

Testing

One of the goals was to receive and store 32 signal channels of EEG data as fast as the Nicolet BMSI model 6000, which has a 400 Hz data acquisition rate. Our instrument was able to acquire and store 32 channels at a rate of 2500 Hz. Leaving plenty of bandwidth for internal signal processing software techniques to be implemented and still maintain a system response greater than 400 Hz.

A model 220 brain wave function generator [Fig. 16 (a)] manufactured by Medi_Cal Instruments was used to provide the necessary amplitude levels of 5 to 500 microvolts (with 50 microvolts being typical for most scalp electrode signal amplitudes).

Also used for testing was a digital EEG simulator [Fig. 16 (b)] made by EEG Technology. This instrument has a EEPROM memory programmed to simulate 32 channels of EEG signals that mimic an epileptic seizure. The instrument continuously outputs a circular EEG pattern with a sixty second duration. Both instruments were used to test the completed signal conditioning board and microcontroller for proper signal conditioning and data acquisition.

(a)

(b)

Figure 16 (a) Brainwave Function Generator (b) EEG Simulator

Both of these testing instruments were invaluable for simulating actual brain wave activity during our testing. Actual output from signal conditioning transitional board using the simulated input is shown [Fig. 17,19]. Frequency response and gain tests performed on the final signal conditioning board were identical to the PSpice and breadboarded test results and responded identically to small component changes in all three versions giving the design team great confidence in the robustness of the signal conditioning design and implementation. Signals in the narrow passband were aggressively amplified and stable, signals outside the narrow passband were rigorously attenuated. Data entering the controller via any of the 32 channels of ADC was easily manipulated. Several types of analysis on the incoming data and results were written to a simple LCD display on the instrument [Fig. 15].

Figure 17 Tektronics scope display of actual output of the transitional signal conditioning board. Input used was the seizure pattern from EEG simulator.

Figure 18 Epileptic seizure EEG simulation generator used to drive the instrument

Figure 19 Actual signal conditioning board output. Input signal provided by EEG Technology's simulator with epilepsy pattern generation.

Results

The instrument performed well acquiring and signal conditioning the input signals from scalp electrodes. The single board computer was compact, easy to program and performed very well digitizing the data and doing simple routines, indicating it was up to the task of handling a computing intensive algorithm. It was demonstrated that we could acquire and store data from all 32 channels at a 2500 Hz rate. Our software testing was limited to simple routines written in the C programming language to demonstrate functionality. Without the availability of the epileptic seizure prediction software that we had hoped to run on the instrument, we were limited to testing with simple routines such as peak amplitude detection and others. The instrument performed well and could be used for future testing when/if the seizure prediction software or other brainwave processing intensive software becomes available.

Conclusions

This prototype instrument performed well as a portable real time brain wave data acquisition system. Further testing with software that makes decisions based on the present conditions of the person's brain waves being monitored could be possible. Miniaturization of this unit would be an easy task even with the presently used integrated circuits and the same electronic design. Ultimately this system could include a sensor, transmitter, receiver, microprocessor and associated memory, and audio and/or visual alert system. This device, through miniaturization, could be considered for eventual implementation in ASIC form or as a fully integrated CMOS microsystem . The possibility of a microsystem running a rigorous real time signal processing algorithm incorporated into a headband or baseball cap with a simple "early warning alert", be it an audio tone or visual alert, is not far off.

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