Wireless Ambulatory ECG Signal Capture for HRV and Cognitive Load Study Using the NeuroMonitor Platform*

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Abstract— **The heart rhythms, controlled by the autonomic nervous system, can fluctuate with varying cognitive loads that can be captured with electrocardiogram (ECG) and heart rate variability (HRV) metrics. In this paper, we report customization of a wireless, ambulatory NeuroMonitor device originally developed for collecting electroencephalogram (EEG) signals as a platform for ECG and HRV data collection. The overall gain is altered to 93.86, while the band pass filter was set to 0.5 Hz to 126 Hz. The four independent inputs were connected to left arm, right arm, left leg and right leg. ECG signal and HRV data was collected during relax state and elevated cognitive load conditions. The signals were digitized at 256 sps and wirelessly transmitted to a remote computer for analysis. These cardiac signals were filtered and plotted using MATLAB. We demonstrate successful data collection that enables multiple applications of NeuroMonitor platform as an ambulatory physiological parameter monitoring hardware for long duration study of patients in natural settings.**

I. Introduction

Electrocardiogram (ECG) and heart rate variability (HRV) is an important factor for quantitative estimation of autonomic nervous system function [1]. Neural response along with cardiac signal analysis might be co-analyzed for a complete physiological state of a patient suffering from neurological disorder like epilepsy [2], as well as other disorders such as sleep disorder, or generic strong mental states including scare, stress, joy, or hypertension. Ongoing research aims to establish an understanding of the effect of major depression on cardiac morbidity, or to relate R-R signal analysis during complex partial seizures [3]. Alteration to autonomic function such as a reduction in HRV can impair the body's capacity to cope with challenging situations of elevated stress, such as seizures [4]. Many neurological disorders should co-analyze Electroencephalography (EEG) with ECG and/or HRV, for instance, to perform complete physiological evaluation before treatment [2]. A simple, noninvasive cardiovascular evaluation may identify an alternative diagnosis in many patients, including patients with apparent epilepsy symptom. Algorithms for seizure detection and prediction are primarily based on neuronal responses such as electroencephalogram (EEG) [5-6], but incorporating cardiac signals in complete assessment might be beneficial.

Cognitive load such as mental stress, happiness and depression might have influence to the neuronal signals that would affect the rhythms of the heart, causing HRV. For instance, the vagal (high frequency [HF]) component of heart rate variability (HRV) predicts survival in post-myocardial infarction patients and is considered to reflect vagal antagonism of sympathetic influences [7]. Neuronal correlation to vagal tone involves mental stress tasks that include cognitive and emotional elements. Thus, for many diagnosis and prognosis of neuronal disorders, neuronal responses such as EEG should be co-analyzed with cardiac signals such as ECG and HRV.

Traditionally, EEG and ECG signals are recorded with completely different types of equipment. This is especially problematic for patient monitoring in home (or outdoor) for long duration. With a vision of patient-centric healthcare for future generation, it will be particularly useful to be able to collect both EEG and ECG simultaneously using the same device. We previously have demonstrated our in-house developed "NeuroMonitor" device that can capture EEG data from 4-monopolar or 2-bipolar montage [8]. In this paper, we demonstrate that the developed NeuroMonitor device is also able to capture ECG signals by slightly altering the analog front end (AFE) to record ECG signals using 3 electrodes method. The captured data can be stored to the onboard microSD card or be transferred to a remote device like a smart phone or a computer. Collected ECG data can be analyzed to determine HRV and cognitive load. The uniqueness of this work is, we demonstrate that the same hardware platform can be utilized for both EEG and ECG signal collection, thus can be of practical benefit and usability for simple monitoring system development for home (or outdoor) monitoring of patient. This also demonstrates the potential for simultaneous collection of EEG and ECG data by increasing the number of channels of the NeuroMonitor platform for co-analysis. A photograph of the NeuroMonitor device is shown in Fig. 1.

II. Hardware description

The NeuroMonitor [8] platform is a custom developed embedded device that consists of an analog data acquisition unit, a filtering unit, a programmable microcontroller, a Bluetooth communication module, and a few other components as depicted in Fig. 2. The printed circuit board (PCB) was designed and validated by Cadence Allegro SPB 15.5 (Cadence Design Systems, Inc., San Jose, CA, USA) and measures only 5.58cm X 2.03cm X 0.91cm, and was fabricated through Advanced Circuits (Aurora, CO, USA). This section describes different sections of the hardware.

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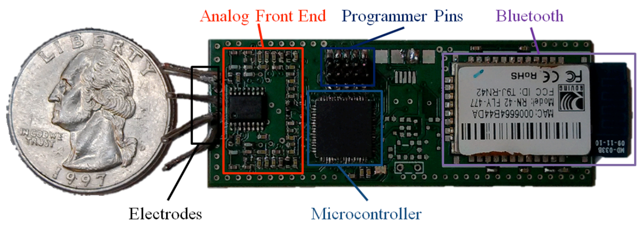

Figure 1. Photograph of the NeuroMonitor device (Originally developed for ambulatory EEG data collection [8]) alongside a USA quarter.

A. Analog Data Acquisition

The device has 4 independent inputs to obtain data from the electrodes. In this work, 3 of these 4 inputs have been utilized to obtain ECG data. Those 3 electrodes are connected to left arm (LA), right arm (RA) and left leg (LL). Right leg (RL) electrode is used here as a reference which is connected to the ground of the device. An instrumentation amplifier (ISL28270, Intersil Americas, Milpitas, CA, USA) obtains signal from Lead I and Lead II. . A 496 mV reference voltage was added to the reference pin of the instrumentation amplifier. A gain of 26.5 was set to amplify the signal before filtering. Unipolar power supply of 3.3 V powers the device from a 900 mAh rechargeable Li-Ion battery.

B. Filtering Stage

Three analog filters were implemented in this NeuroMonitor device. A notch filter (f_c = 60 Hz) is used to remove the utility power line interference from buffered signals. However, the implemented notch filter is measured to have the cutoff frequency at 58.5 Hz due to mismatch in PCB traces, component tolerances, and parasitic such as resistances, capacitors and inductance from the traces.

After removing the utility power interference using the notch filter, a two-stage (active 2nd order chebyshev-I with a gain of 1.61 and a passive 2nd order) low-pass filter with cut off frequency of 126 Hz was used as an anti-aliasing filter. A high pass filter immediately follows with a cutoff frequency at 0.5 Hz that removes DC offset related to slowly varying artifacts such as muscle movement and baseline wandering from the signal. Finally, a DC offset is added using the microcontroller-housed digital-to-analog converter (DAC) after the high pass filter to offset the signal for maximizing range and proper sampling by the microcontroller-housed analog-to-digital converter (ADC).

C. Amplification Stage

A final amplification using a non-inverting amplifier having a gain of 2.2 was incorporated in the hardware, which results an overall gain of 93.86 for ECG measurement. Note that the original overall gain of NeuroMonitor for EEG measurement was 703 [8].

D. Microcontroller Unit (MCU)

The processing unit of this device is a Programmable System On a Chip (PSoC-3) embedded microcontroller (Model: CY8C3866LTI-030, Cypress Semiconductor Corp., San Jose, CA, USA) that implements Intel's 8051 MCU architecture, operating at 67 MHz with 64 kB of flash memory and 8 KB of SRAM. The PSoC contains both analog and digital components ranging from operational amplifiers, FAT32/UART/USB controllers, ADC, DAC, analog multiplexors, digital filters, registers, capacitors, timer, etc. The components can be routed internally (programmable) and has been maximally utilized in this design. Due to the availability of both analog and digital components, the PCB footprint was less as the component count was minimized. The average power required during data acquisition and simultaneous transmission of data via Bluetooth was 135 mW. All components were surface mount type (SMT). The device weighs only 27g (excluding battery and electrodes).

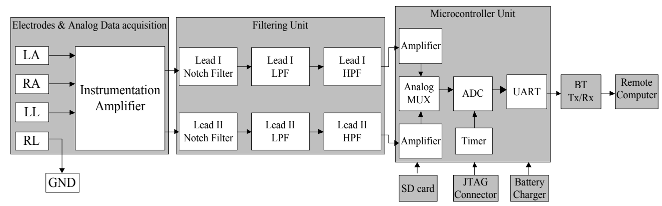

Figure 2. Block diagram of dataflow path of the NeuroMonitor device used for ECG data collection.

E. Bluetooth Transceiver

A Bluetooth transceiver (Model: RN-42, Roving Networks, Los Gatos, CA, USA) was used to transfer data wirelessly to a remote computer. This low-power Bluetooth module consumes 3 mA during sniff mode, and 25 mA during normal operation, peaking at 45 mA when transmitting. The sniff period is set to 100 ms to optimize power consumption. The frequency band of this wireless module is the ISM (2.4GHz - 2.5GHz). This Class-2 module can transmit data up to 20 m. The baud rate of the UART communication is 115.2 kbps, while the Baud rate of Serial Port Profile (SPP) for the Bluetooth was set to 300 kbps.

F. Other Components

The device has the ability to be configured to operate in online or offline modes. In online mode, the Bluetooth is used to transfer data continuously to monitor the subject in real-time. For offline mode, a microSD card is included within the platform that can store weeklong ECG data. The board also implements a microUSB port to communicate with a computer, as well as to recharge the Li-Ion battery. The device can operate up to 90 h with interrupt driven clocking based power optimization technique in a single charge with a 900 mAh Li-Ion battery (described elsewhere).

III. DATA PROCESSING

ECG data has been captured with 3-electrode (RA, LA, RL) method, and processed using MATLAB (Mathworks Inc., Natick, MA, USA). By using this method, 6 different types of ECG signals are obtained with HRV analysis of a subject under different cognitive loads. Lead I (I), Lead II (II), Lead III (III), augmented vector right (aVR), augmented vector left (aVL) and augmented vector foot (aVF) signals are given below respectively:

$$I = LA - RA \quad (1)$$

$$II = LL - RA \quad (2)$$

$$III = LL - LA = II - I \quad (3)$$

$$aVR = RA - ½(LA+LL) = -(I + II)/2 \quad (4)$$

$$aVL = LA - ½(RA+LL) = I - II/2 \quad (5)$$

$$aVF = LL - ½(RA+LA) = II - I/2 \quad (6)$$

A. *Data Processing in MCU*

The MCU has a delta-sigma ADC to convert the analog data to digital. A single sample operation mode is used with 16 bit resolution to capture Lead I and Lead II data. The sampling rate is controlled by a timer that generates an interrupt every 3.9 ms (sampling rate of 256 sps). When the timer generates the interrupt, the microcontroller executes interrupt service routine (ISR) where ADC conversion starts by calling an application programming interface (API).

After the successful completion of a conversion of Lead I, the digital data is saved into a temporal variable. ADC data conversion is stopped to prevent the leakage between samples, and then the analog multiplexer is switched to the other channel to obtain Lead II ECG data. Lead II ECG is saved to another 16-bit variable and the conversion of the ADC is stopped. The analog multiplexer is then switched back to Lead I position so that the system is ready for the next interrupt.

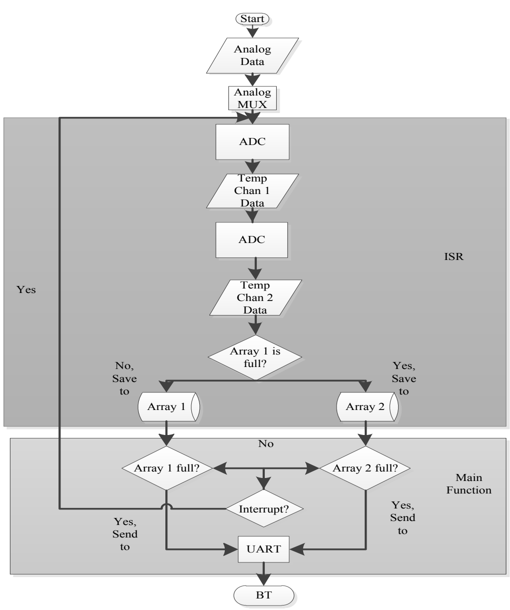

Figure 3. Flow chart of software for real-time data collection with the microcontroller of the NeuroMonitor device.

Two 16-bit variables are split into 4 bytes. Two 8-bit wide arrays (buffers) of size 512 Byte each is used to temporarily store these values. Two flags are used as mutex to check which array is full. If the array is not full, then data is saved in the same array. When the array is full, then a flag is set, and data is saved in the other array.

When saving the data to the arrays, the lower significant byte of the Lead I data are saved first and the higher significant byte of Lead I in the next consecutive address. For the data from Lead II, the same scheme is used. When the array is full, the data will be transferred wirelessly through the Bluetooth module to a remote computer, which is implemented in the main loop of the firmware. It requires 35.55 ms to transmit one complete array of 512 B, whereas to fill one array (buffer), it requires 499.2 ms – satisfying the latency timing constraint. The complete flow chart of the MCU data processing is shown in Fig. 3.

B. *MATLAB Data Processing*

MATLAB is used to receive, analyze, and display the results. A simulated serial communication using a COM port is used to read the data incoming from the NeuroMonitor device. Data is then divided in Lead I and Lead II. The data is then converted to mV using eq. (7) and eq. (8).

$$\text{Lead I} = ((\text{Chan1})*3.3*1000) / (65536*93.28) \quad (7)$$

$$\text{Lead II} = ((\text{Chan2})*3.3*1000) / (65536*93.28) \quad (8)$$

Lead I and Lead II data have been filtered in MATLAB for clearer results using an IIR notch filter with a quality factor of 200. Then, a Parks-McClellan optimal FIR low pass filter of order 250 with a cut off frequency of 54 Hz is used.

After filtering the Lead I and Lead II signal, equation (3)-(6) is used to obtain Lead III, aVR, aVL and aVF ECG signals. Finally, the 6 ECG signals are plotted in MATLAB. HRV is also calculated and plotted from Lead I data. The complete flow chart for MATLAB data processing is shown in Fig. 4.

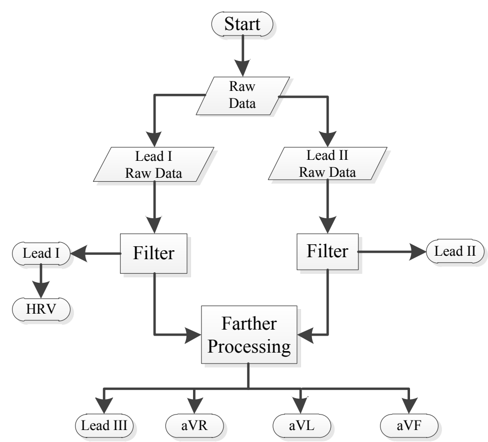

Figure 4. Flow chart for MATLAB data processing.

IV. RESULTS

A 2 mV_{pp} sinusoidal signal at 5 Hz was used as input to both channels for testing the functionality of the data acquisition stage. Data was then transferred to a remote computer and analyzed in MATLAB. The frequency and the amplitude were functionally verified.

For practical data capture testing, ECG data collection from four (N = 4) individuals (subjects) were performed for this pilot study. Representative results from Lead I and Lead II ECG data of Subject 1 are shown in Fig. 5 along with the filter responses in different stages, while Lead III, aVR, aVL and aVF ECG data are shown in Fig. 6.

From the collected ECG data, HRV for time-domain method can be computed as standard deviation of the average NN intervals (SDANN) over a short period. Heartbeat per minute (BPM) can be computed by dividing 60 with the interval between two consecutive heartbeats in seconds. HRV represents the physiological phenomenon of variation in the time interval between heartbeats.

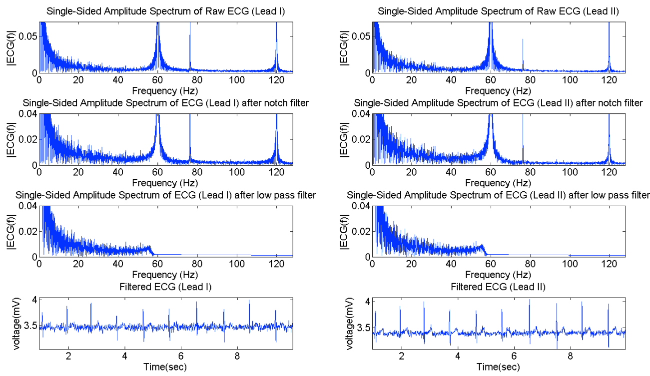

Figure 5. Lead I and Lead II ECG data before and after filtering

Data for the study of HRV under cognitive load condition was collected from another subject. ECG is recorded during relax situation for some time then a scary video is played. A timer was set to track the timing when the subject is scared. ECG data is analyzed after the experiment. A window of 10 seconds ECG data is plotted during relaxes and stress conditions. HRV is also plotted in Fig. 7. It can be observed that the BPM of the subject increases under stress compared to relax condition indicating higher cognitive load.

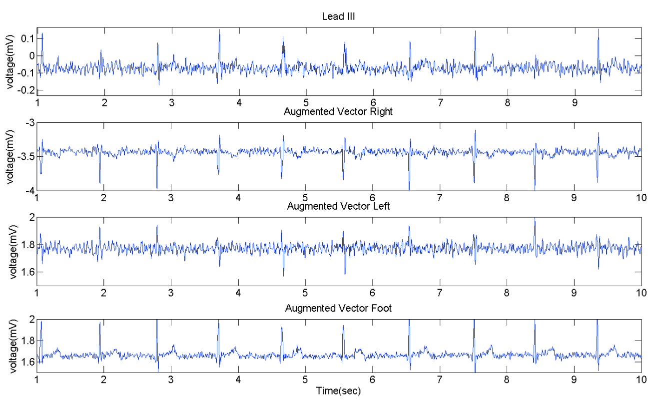

Figure 6. Lead III, aVR, aVL and aVF ECG data.

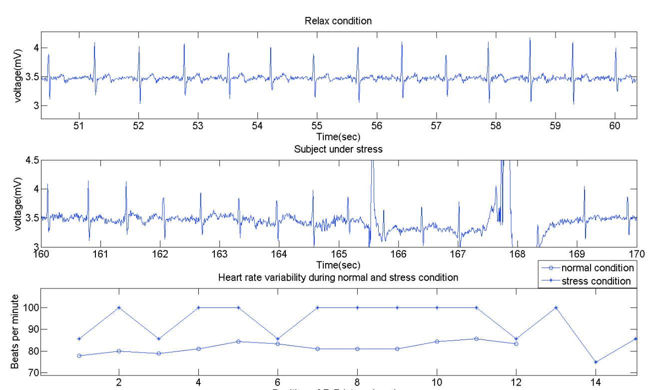

Figure 7. ECG and Heart rate variability beat per minute (bpm) of a subject under cognitive load.

V. Conclusion

In this work, we have demonstrated that the previously developed NeuroMonitor platform for EEG data collection can also be utilized for ECG data acquisition by altering the bias voltages and gain of amplifiers. The device could capture continuous ECG data and allows HRV monitoring of a patient during normal daily activities, as the device is small, ambulatory, allows wireless connectivity or on-board storage, and operates for a long duration. The study shows increase of BPM (from ~80 at rest to ~95 under stress) representative of the state of the mind of the subject.

Simultaneous EEG and ECG can be captured with the NeuroMonitor platform by adding 3 channels for ECG in addition to EEG channels. Compared to commercially available ECG or EEG devices, this platform has advantages of size, weight, power consumptions, functionality and computing ability. Future research directions could include co-analysis of alpha and beta band activities obtained from EEG data collected from prefrontal cortex combined with simultaneous HRV and cognitive load analytics from ECG data to strengthen the ability to non-invasively determine the physiological states of the subject under various conditions with distinct mental tasks in an unsupervised or minimally-supervised environment.

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