A Modular and Wireless ExG Signal Acquisition System with a Dense Array of Dry Electrodes

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***Abstract*—A modular, configurable, wearable bio-potential signal measurement diagnostic system is developed. The system is wirelessly configurable for multiple numbers of channels from 1 to 256 channels according to their field of applications. EEG (Electroencephalography), ECG (Electrocardiography), EMG (Electromyography) can be measured with the system by encapsulating in a cap, in a vest and in a hand sleeves respectively. Active dry electrodes with 19 Au-Pins are utilized. It achieves a high signal quality due to high special resolution. An electrode-bus containing eight of such dry electrodes is designed utilizing the modern hard-flex PCB concept so that it can be molded like an S and be placed on the area of measurement. A Meridian-ADC digitalizes the amplified analog signal with a 24-bit Δ∑-ADC. The central component of the system is an Island-controller, incorporating an AVR-µC and a Wi-Fi-module with an external patch antenna.**

I. Introduction

Biomedical signals such as electrocardiogram (ECG), electroencephalography (EEG), Electromyography (EMG) are used to diagnosis and treatment of various diseases. These signals have very low amplitude and low frequency. The signal bandwidth of EEG and ECG signals range from 0.1 to 200 Hz and the amplitude of EEG in in the range between 2-100 µV whereas the ECG signal amplitude lies in the range of 0.1 to 1 mV [1]. It requires meticulous design methodologies in order to acquire and store these signals. A low noise, low voltage and low power consumption, densely integrated amplifier is one of the key circuit which is needed to detect such small level signals under battery power [2]. To detect the seizure of epilepsy patients a long time monitoring system is required and the patient is required to stay in the hospital during the recording of the bio-signals. It is also uncomfortable for patients to wear conventional head-box containing wet passive electrodes which hinders the patient's degree of freedom. Nowadays there are some prototypes being developed for mobile sensing though Bluetooth [3]. There is an increased demand in sports physiology to record the vital parameters with dry electrodes due to its minimal scalp preparation time and wireless data transmission facility. Moreover, it eradicates the risk of strangulation with wireless data transferring mechanism.

II. System Design

A. System Overview

The following gives a brief synopsis of the hierarchical system which was developed within the project. The system is applicable in three possible scenarios.

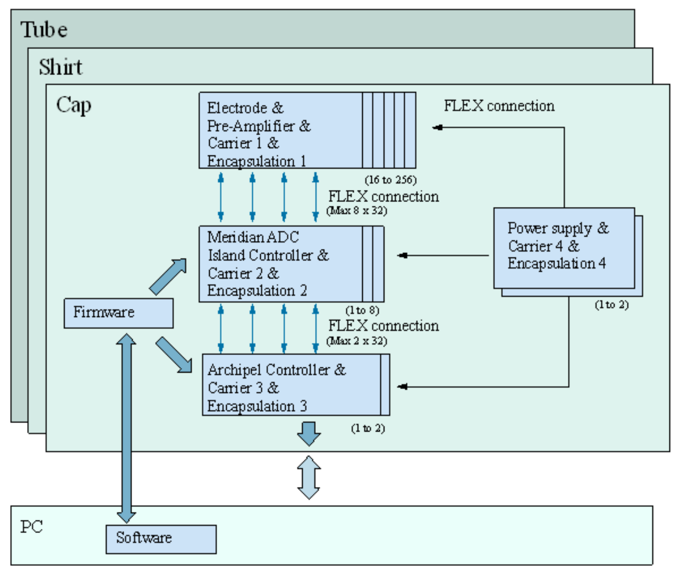

Figure 1 Detailed overview of the hierarchical system components and their interconnections in the three main application scenarios.

It can be encapsulated in a tube, shirt and cap to record EMG, ECG, EEG respectively. The system consists of three main signal processing units. The first unit is the signal pre-processing directly after measuring it from the skin of the body. This close proximity of the amplifier to the skin reduce the EMI and mechanical disturbance on the wires carrying the bio-potentials[4].In this unit the bio-potential signals are measured with dry electrodes and amplified by an instrument amplifier. This unit is named electrode-bus. Secondly the recorded signals are digitalized using an low-noise 24-bit Δ∑-ADC in the Meridian-ADC unit. In the third part of signal processing the digitalized signals are sent to an Archipelago-controller via UART (Universal Asynchronous Receiver/Transmitter). At the end the data are transmitted to a PC either via a USB (Universal Serial Bus) or a Wi-Fi connection.

This hierarchical system concept allows it to be configured from 1 up to 256 channels by varying the number of the Meridian-ADCs, Island-controllers and Archipelago-controllers.

B. *Prototype I*

In the first prototype a complete system consisting of all the four components were developed. It was a successive development of a project our department in which a self-localizable novel wireless electrodes for EEG measurement [5]. The electrode-bus was designed with a low noise, high CMRR (common mode rejection ratio) instrument amplifier from TI (Texas Instruments Inc.). Active dry electrodes are produced for bio-potential signal recording where each of the electrodes has a diameter of 7.5 mm and contains 19 Au-pins contacts to the human body.The electrode-bus was realized in the hard-flex based PCB (printed circuit board) technology so that it could be easily encapsulated in a cap. Each of the bus containing 8 dry electrodes and its design allows it to be reduced in the range of 1 to 7 electrodes according to the application requirement by cutting it laterally. The Meridian-ADC is designed in a standard PCB technology with the possibility to connect it with the electrode-bus from 2 different sides. The patient's reference is conducted into this module through a micro-coax connector. This provides a good shielding to the reference signal. The core of the Island-controller and Archipelago-controller is an AVR-µC. The Island-controller communicates with the Meridian-ADCs via SPI (Serial Peripheral Interface Bus) protocol. The patient's reference is generated in Archipelago-controller. The possibility to actively buffered patient's reference is considered on this board.

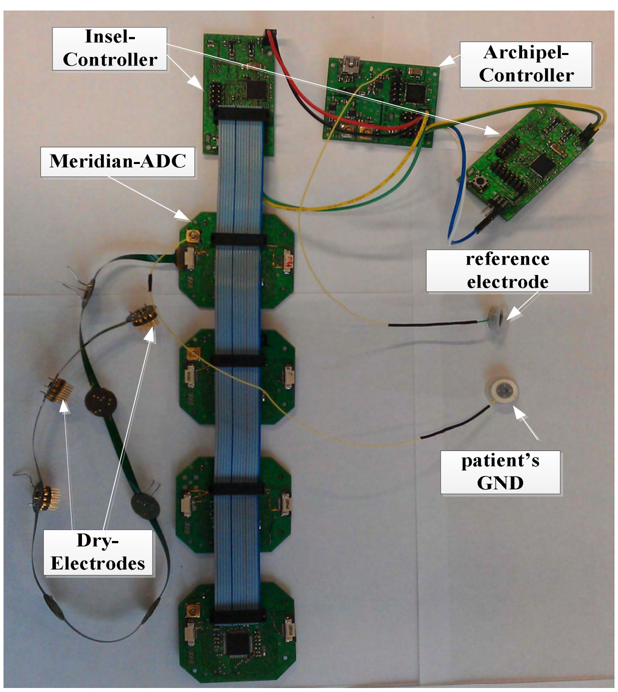

Figure 2 The composition of prototype I with an electrode-bus containing 8 electrodes and is connected to a Meridian-ADC through a ZIF-connector. Four Meridian-ADCs are then connected to an Island-controller via a flat-band cable. An Archipelago-controller is tied to two Island-controllers via normal wires.

C. *Prototype II*

In the second prototype the system was optimized for a 64-channel where the Island-controller and Archipelago-controller are reduced to a single Island-controller. It executes both communicating with the Meridian-ADCs and transmitting the data with a Wi-Fi-module. Due to its high channel density and at a sample rate of 1 kHz, Wi-Fi communication was preferred. A Wi-Fi module with data rate to power consumption scalability was chosen for this application. To achieve the 256 channel constellation four of such Island-controllers are to be connected through a common UART-Bus so that the data measurement gets started on all channels simultaneously. One among the four acts as a master which initiates the measurement routine. To protect the user from the emission of radio wave an external patch antenna was designed which is hold away from Island-controller.

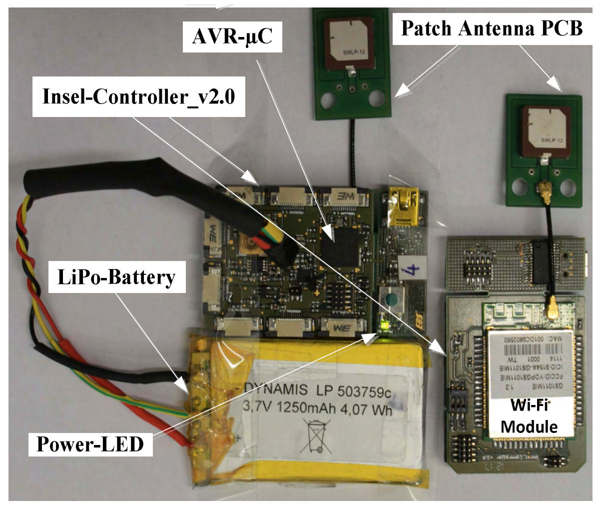

Figure 3 The second prototype of Island-controller. It is powered with a LiPo-Battery and the external patch antenna is connected through miniature coaxial RF connector.

III. SOFTWARE

Two separate real time operating system were developed for realizing functional purpose of the Island-controller and Archipelago-controller. One of which resides in Island-controller which executes measurement routines according to the command sent from Archipelago-controller. It forms a bidirectional communication between the µC and the Meridian-ADCs as well as with Archipelago-controller over serial interface. The number of channels, number of presents Meridian-ADCs, lead-off detection settings can be imposed over the firmware. The Archipelago-controller undertakes the responsibility to communicate with the PC-based visualization and analysis software which was written in Labview.

A. *Description of the firmware of Island-controller*

The following state-diagram shows the different states of the firmware and their state transitions.

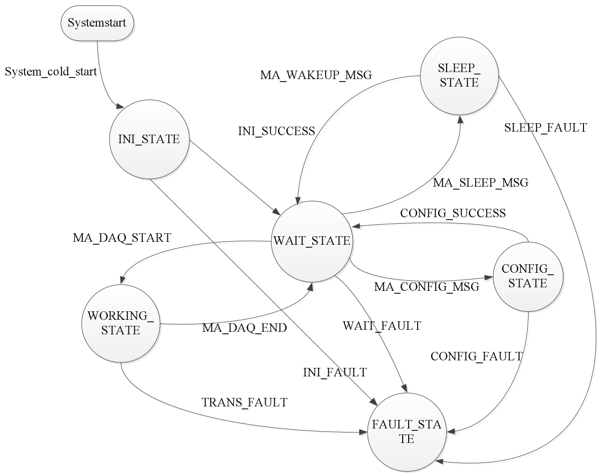

Figure 4 State diagram of the firmware of Island-controller

It has also a fail-safe state to protect the proband in case of any failure in the system.

B. Description of Firmware of Archipelago-controller

The firmware has five working states. It allows user to start the measurement and acquire measurement data upon request. Various measurement routines including setting the digital gain, sample rate, digital filter settings can be set with it.

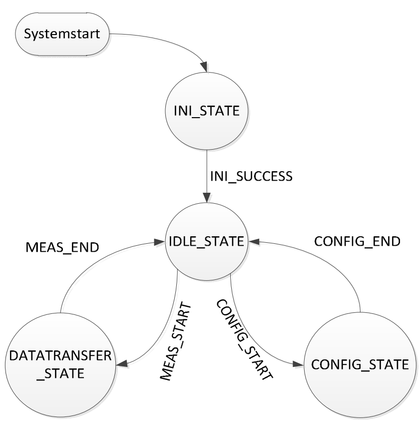

Figure 5 State-diagram of the firmware of Archipelago-controller

IV. RESULTS

Several test scenarios were developed to test the prototypes in lab. The system was developed following the high quality recording of bioelectric events mentioned employing the patient's GND as driven right leg and reference electrode as the Wilson central terminal were adopted from [6]. Firstly a test set-up was used to perform calibration test. In this test a sinus signal with low frequency was fed in the electrodes and data was observed in the GUI (graphical user interface). In the second test a short circuit measurement was performed to figure out the noise level of the system.

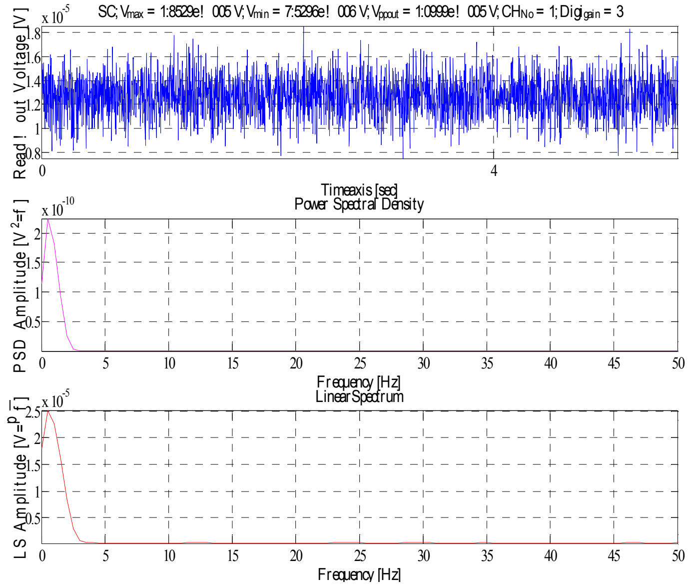

Figure 6 Top: It shows the white noise measured peak-to-peak approximately 11 µV. Middle: The PSD (power spectral sensity) of the measured noise is plotted with respect to frequency domain. Bottom: The linear curve in dependence to frequency is plotted at the end.

After evaluating the noise level of the system it was possible to decide that it is capable of recording ECG, EEG signals. For demonstration one channel ECG measurement by placing the dry electrodes in lower arm and the reference and patient's GND electrodes on the opposite hand was carried out. A slow sub-Hz drift was visible using the dry electrodes or it could also result from the patients motions. It is visible that due to the high CMRR of the instrument amplifier, the 50-Hz peak from the mains was eliminated.

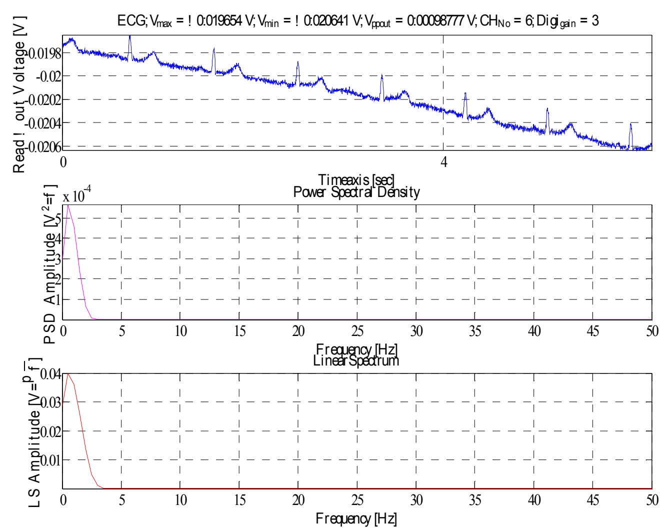

Figure 7 Top: ECG measurement on a proband with dry electrode. Middle & Bottom: The PSD curve linear spectrum for the noise analysis.

At last an EEG measurement on a proband was executed where the dry electrode was placed near to naison and the reference and patient's GND were positioned near to the electrode.

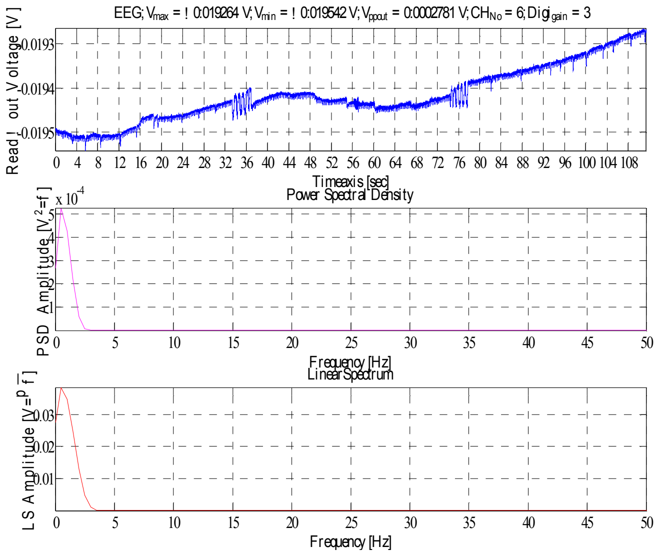

Figure 8 Top: The raw data from EEG measurement with dry electrode is plotted. Middle & Bottom: PSD and linear spectrum curve were produced for the noise analysis in frequency domain

In the above measurement the proband was instructed to keep his eyes open first 33 seconds and then blinked his eye five times and then closes his eye for another 38 seconds and again blinked five times. In the last phase of the measurement some calculations were done by the proband keeping his eye closed. The eye-blinks are clearly visible in the plot. It also shows a sub-Hz drift.

V. Conclusion

In this paper the concept, development, tests of two successive prototypes were discussed. The second optimized 10-layered Island-controller PCB has a dimension of 3.4 x 4.3 cm^2 which easies its encapsulation in EEG-cap. The estimated power consumption of the entire system is approximately 675 mA in full configuration of 256 channels and 1 kHz sampling rate. The raw data from measurement show very good signal quality and the entire system from the first prototype exhibits less than that of 11 μV/√Hz of white noise. The system is capable of executing three main bio-potential measurements i.e. ECG, EEG, EMG. After assembling and mounting the system in a cap continuous, long-time remote monitoring of bio signals are possible. A prolonged EEG acquisition is required for chronic seizure detection by epilepsy patients. Another achievement of this system lies in the modular and flexible assembly. Its high channel density and usage of dry electrodes make it a candidate to be in utilized in cognitive research as well.

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