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A New Brain Imaging Device Based on fNIRS

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Abstract—**A new portable brain imaging device based on continuous-wave functional near-infrared spectrometry (fNIRS) is presented. The source-detector part is composed of a multi-wavelength LED and a silicon photodetector that are directly placed on the scalp of the subject. The dimensions of the proposed device are small, as it has to be mounted on the head of an adult person. Acquired data are transmitted in real-time to a laptop for post processing using Matlab. Time-multiplexed light is used to achieve a higher SNR while keeping the device safe for long-term wearing. Preliminary evaluation on adults gave the expected accuracy and compare well with fNIRS characteristics found in literature, that are collected from bulky equipment. With a noise figure of -47dB and a sampling rate of 23Hz, the presented device is appropriate to isolate hemodynamic variations, which are strongly related to local cerebral activity.**

Index Terms—**Biomedical Imaging, Data Acquisition, Infrared Spectroscopy, Optical Receivers, Portable Devices**

I. Introduction

FUNCTIONAL medical imaging is largely used in modern medical treatments, such as detecting and analyzing brain diseases. Measurement of cerebral activities can be achieved with electroencephalography (EEG), magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imagery (fMRI) or functional near-infrared spectrometry (fNIRS). Some of these techniques are frequently used in clinics; however, for a device where portability and continuous use is important (small weight, small size, little sensitive to electromagnetic fields, and specially non invasive), only continuous-wave fNIRS can be used [1].

The fNIRS technique monitors local hemodynamic changes, that are directly related to local cerebral activity. From the difference of intensity between incident and reflected lights of different wavelengths in the near-infrared spectrum, it is possible to derive relative values representing the blood volume and the concentrations of oxyhemoglobin (HbO_2), desoxyhemoglobin (HbR) and total hemoglobin (HbT) [2].

Actually, some fNIRS imaging devices were constructed and their functionality has been validated, but they are not portable [3], [4]. Some smaller and lighter devices were also tested, but it can only be used on infants' heads, as the light path is very short, and the baby's head is more transparent than an adult one [5], [6], [7]. In fact, as the light passing through the head becomes highly absorbed and scattered, only few of the emitted photons return back to the surface of the head. Consequently, the amplification of the received signal is a critical part in the proposed fNIRS circuitry. Some previous works have been achieved in Polystim laboratory, in creating a dedicated front-end circuit for this proposed device [8], [9]. We use these works as building blocks to accelerate the construction of the presented prototype. In this paper, we present a complete single channel circuit which represents the first development phase of a multichannel fNIRS portable imaging device.

The remaining parts of this paper contain a description of the circuit in section II, followed by its method of operation in section III. Section IV includes the details of the experiments we conducted, whose results are given in section V. The paper is terminated by a conclusion in section VI.

II. Circuit Description

The presented prototype includes an optode, which is the combination of the NIR emitter and receiver, and a control component. Fig. 1 shows a block diagram of this circuit. In this section, the optode, which is a critical component of the prototype, is described.

A. Near-Infrared Emitter

As light absorption and scattering are high, it is necessary to have a powerful but small light source. Such features can be found in the L4*730/4*805/4*850-40Q96-I multi-wavelength LED from Epitex. This LED has been successfully employed to build fNIRS devices for experiments on babies [5].

Additionnaly, as local hemodynamic properties are derived from the difference between the emitted and received light intensities, it is important to keep the emitted near-infrared light constant. To comply to this condition, we propose a dedicated circuit, which is shown in Fig. 2. This circuit

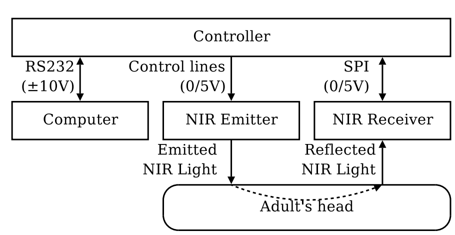

Figure 1. Top-level block diagram of the complete prototype

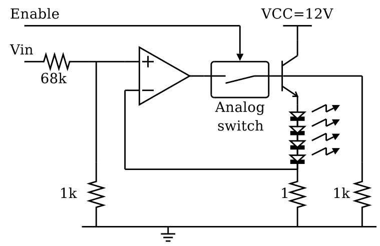

Figure 2. Regulator of the LEDs current

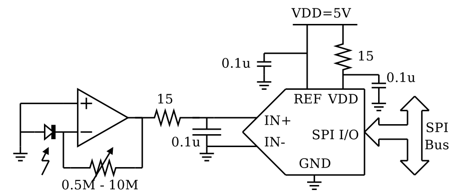

Figure 3. Simplified schematic of the fNIRS front-end

regulates the current circulating in the LEDs independently of their forward voltage. That can be obtained by constantly monitoring the voltage at the 1-ohm resistor upper node and comparing it with the V_{in} reference signal. Also, this circuit has the advantage of consuming much less energy than a resistor in series with the diodes. This LED driver is being cascaded three times, once for each wavelength, while the V_{in} node is common for the three components.

The operational amplifier (opamp) of this emitter must process inputs close to 0V. In order to operate this opamp in its linear zone, a -12V supply was used. A TL074 opamp was selected for its low distortion, reduced noise and small size. The activation of the LEDs is controlled by a DG441 analog switch. Finally, the needed current to operate the LEDs is provided by 2N2222 transistors.

B. Near-Infrared Receiver

As only a little part of the emitted light reaches the receiver, it is necessary to build a very sensitive photoreceiving circuit. In this case, a compromise between the signal-to-noise ratio (SNR) and the size for the photodetector and amplifier must be obtained. Moreover, the amplified signal needs to be accurately sampled in order to isolate hemodynamic variations. The proposed front-end circuit is shown in Fig. 3. It includes a photodetector, a transimpedance amplifier and an analog to digital converter.

Photodetector: Silicon photodiodes were adopted due to their small size and low power. Also, silicon semiconductors are more sensitive than gallium arsenide ones for the NIR spectrum, and are less noisy than germanium materials. In line with the high performance criteria, the FFD-200 Large Area Silicon PIN photodiode from Perkin Elmer was selected for its huge sensing area having a diameter of 5.1mm.

Transimpedance Amplifier: A custom DTMOS transimpedance amplifier designed in our laboratory is being used [9], which has an open-loop gain of 60dB, a noise figure of $107\text{nV}/\sqrt{\text{Hz}}$ at 1kHz and a unity gain bandwitdh of 2.73MHz.

Analog to Digital Converter (ADC): In order to acquire the received and amplified signal with the required accuracy, it is important to select an ADC with the needed resolution. In fact, the sampled signal is composed of DC and AC parts. The AC part is the one we want to isolate, because it contains information on oxyhemoglobin and desoxyhemoglobin concentrations in the blood [10]. Also, it is known that within this AC part, the information on hemodynamic changes has an amplitude of around 1% of the DC level [11], [12].

In order to tolerate small variations in the coupling between the optode and the head, the amplification factor is tuned to set the DC level at the middle of the output range of the transimpedance amplifier. Then, the required precision within the AC part of the signal is set to the needed value of around 1%. This precision is reached using an ADC with a 15-bit resolution. The AD7691 18-bit ADC from Analog Devices has been preferred for its very small size, high sampling rate, low consumption and SPI-compatible interface. Note that the voltage reference of the ADC is fixed to 5V, but the amplifier output swing is located in the 0.1V to 1.7V range. On the other hand, this low voltage range can be easily processed by the selected 18-bit ADC, which permits to obtain the required precision without any complementary scaling of the signal between the amplifier and the ADC.

Special attention was paid when placing components in order to obtain the highest possible resolution from the ADC. The power supply is also a key factor to improve the SNR; a 9V battery was used to minimize noise produced by the power sector.

III. METHOD OF OPERATION

Most fNIRS imaging devices modulate the light source from their emitters in the frequency domain, in an order of 1kHz (different modulation frequencies for different wavelengths). This technique has the advantages of substantially rejecting the power grid interference coming from light, and reading different wavelengths at the same time.

By using a LED as powerful as the L4*730/4*805/4*850-40Q96-I, it is not possible to proceed that way because of security reasons. In fact, the nominal light intensity for one wavelength is about $875\text{mW}/\text{cm}^2$, but the maximum permissible exposure on the skin is from $200\text{mW}/\text{cm}^2$ for 630nm, to $400\text{mW}/\text{cm}^2$ for 850nm [12]. In order to safely operate these LEDs and avoid any skin damage, we propose to time-multiplex the three wavelengths, so they are turned off most of the time.

To achieve a safe and efficient multiplexing, the controller is programmed according to the flowchart in Fig. 4. This method of operation can also reject most of the ambient

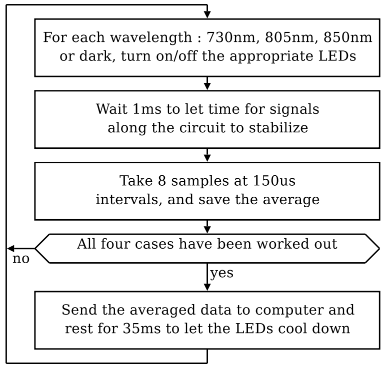

Figure 4. Sequence of operations of the controller

light, by subtracting the dark measurement from others. But there are the following other advantages besides the evident security improvement :

1) As the LEDs are kept off 80% of the time, the NIR emitter consumes very little energy. This is an important feature for a portable device that is powered with batteries. Moreover, this technique allows the emitter to power the LEDs up to their maximal light intensity, therefore we obtain a greater SNR.
2) It is simpler to implement this circuit in an integrated device, because no band-pass filter or demodulator is needed.
3) As signals are time-multiplexed, the gain of the trans-impedance amplifier can be roughly tripled without entering a saturation zone. The proposed device includes a very low-noise amplifier; thus by increasing its gain, the overall SNR will also be increased.

For an efficient operation and a small footprint, a TQFP AVR ATmega32 microcontroller was selected to control the LEDs and the ADC, and to communicate with the computer (via the serial port, using a MAX232 voltage converter).

IV. Validation Methodology

In order to analyse the performances of the presented circuit, two experiments were conducted. The first one was realized on a phantom and permitted to quantify the SNR of the prototype. The second experiment was performed on several adult persons, in order to record physiological data and to compare these results with fNIRS curves from litterature.

A. Phantom preparation

A prototype of the presented circuit was built. This circuit was placed on the forehead of an adult person, with a source-detector distance of 3.5cm; this distance has been shown to be optimal for readings in the cerebral cortex [13]. Then the gain was adjusted to get a signal up to 0.9V at the output of the amplifier.

Next, this same circuit with a similar gain was installed on a phantom, formed of an India ink solution in a 4cm-wide glass block placed between the emitter and detector. This test bench was covered with an opaque black material to avoid most of the ambient light. Water was finally added to the ink until the intensity of received light was almost the same as the intensity recorded on the forehead of the person. As a result, a phantom was obtained, which has approximately the same attenuation as a real head, but that is completely stable. This is important in order to obtain an accurate measurement for the noise of the complete chain.

B. Tests on the forehead

Before testing on persons, the average emitted light intensity has been measured and never exceeded $175\text{mW}/\text{cm}^2$, which is below the maximum permissible exposure [12]. Then, the circuit was mounted on the forehead of three healthy persons : one woman and two men. For a better optic coupling and to secure the coupling from motion artifacts, a flexible and light helmet was built using Velcro straps. The source and the detector were mounted on a foldable board that was fixed on the helmet. The amplifier and the analog-digital converter were also fixed on the head, near the detector.

For each experiment, the subject was seated in a chair, wearing the helmet. He/she was asked to avoid moving, including talking. To limit noise from the ambient light, a black hat was covering the top of the subject's head so the detector can only get light from the emitter. First, the gain of the system was ajusted by varying the amplifier resistor until appreciable DC signals were obtained. Then, using a software programmed specifically for this circuit, data for each wavelength were acquired for four minutes. Finally, the collected information was analyzed with Matlab.

V. Experimental Results

In this section, the noise figure for the overall circuit is presented, together with fNIRS curves from in-vivo acquisitions.

A. Noise figure for the proposed prototype

Using the phantom described above and ajusting the gain to bring the DC signals around 0.9V, a noise figure of -47dB was obtained from the ratio between the AC and DC parts of the recorded signal. As hemodynamic variations have an amplitude of around one percent of the DC signal, that means an order of -40dB, the proposed prototype can isolate hemodynamic signals with a precision of 7dB. Table I compares this noise figure to existing systems.

B. In-vivo results

Apart from the amplifier gain that has to be ajusted for each experiment, results from the three subjects are similar in their overall aspect. The experimental curves shown in Fig. 5 and 6 have been taken from one of those measurements.

Table I
COMPARISON OF SAMPLING RATE AND NOISE WITH OTHER SYSTEMS

System	Target	Portable	Sampling	SNR
This device	Adults	Yes	23Hz	47dB
Drexel Univ. [5]	Newborns	Yes	10Hz	67dB
Tufts, Harvard U. [4]	Adults	No	20Hz	>83dB

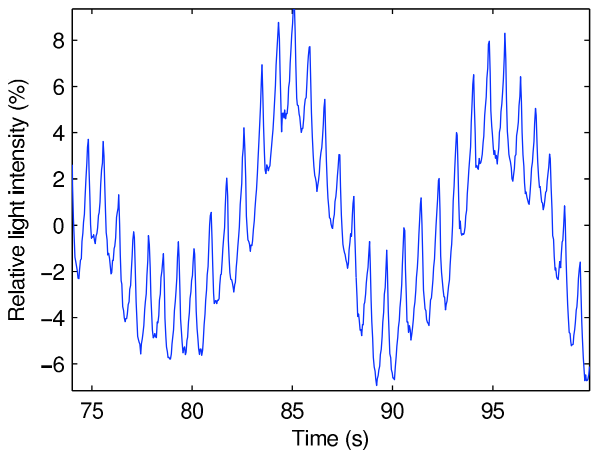

Figure 5. Raw NIRS signal at 850nm with a sampling rate of 23Hz

Fig. 5 shows a portion of the collected data at 850nm, with light intensity being relative to its DC part. Its high-frequency component is the heart beat, that is around 1.2Hz, while its low frequency is due to the Mayer wave, respiration and hemodynamic changes. Fig. 6 shows a frequency spectrum of the same signal, with its three main components being identified. These figures are comparable to the results obtained in other works [11], [12].

VI. CONCLUSION

In this work we presented a portable single-channel medical imaging device, using fNIRS. This device uses LEDs and a silicon photodiode to monitor changes in light absorption of the head. After in-vivo tests on subjects' foreheads, we

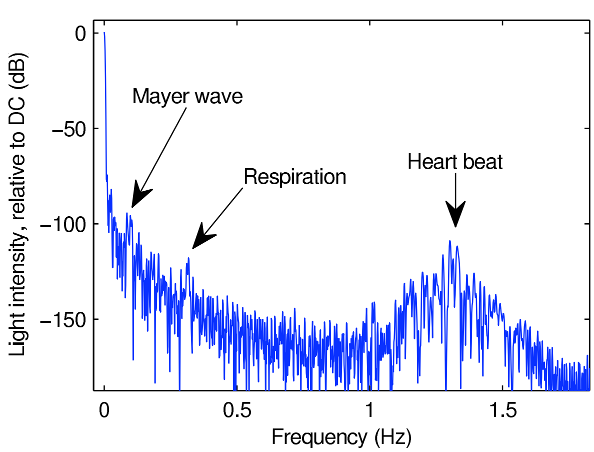

Figure 6. Power spectrum of the NIRS signal at 850nm

got encouraging results : we can clearly identify the Mayer wave, respiration and heart beat. The complete prototype has a noise figure of -47dB, which means the presented prototype can isolate hemodynamic changes with a SNR of 7dB.

As the sampling frequency of 23Hz is high compared to hemodynamic changes (less than one Hertz), a much higher SNR is expected with additionnal filtering. Additionally, we believe the SNR value can be improved with the reduction of both noise level and device size, in building a better circuit board. We also consider enhancing the emitter features by adding an independant control of the light intensity for each wavelength. In this manner it should be easier to find an optimal gain for the transimpedance amplifier, because the DC levels could then be the same for all wavelengths.

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