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An infrared-based device for non-invasive monitoring of eyelid movement during sleep

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Increased movement of eyes and eyelids is characteristic of the rapid eye movement (REM) sleep stage, making it an important indicator in sleep monitoring. A prototype device was designed to detect this activity in a non-invasive way by means of measuring infrared light intensity reflected off the eyelid. The system converts the light intensity into current through a photodetector, as well as performing analog signal processing and analog to digital conversion (ADC). The data is transmitted wirelessly to a computer, where the results can be displayed, stored and analyzed with dedicated software, which also provides control over the device. The hardware is embedded in a mask, which is put over the patient's eyes. User safety was considered in terms of mechanical and electrical dangers, as well as optical damage to the eyes. The device was tested on a sleeping subject.

Key words: sleep, eye, movement detection, infrared, rapid eye movement

Introduction

The aim of this project was to create an inexpensive sleep monitoring tool for the home user. Human sleep is divided primarily into two stages: Rapid Eye Movement (REM) and Non Rapid Eye Movement (NREM) sleep [12,13]. The former is characterized by chaotic, fast movements of the eyes, which cause a flutter of the eyelids. This movement can be detected in a number of ways [2,7,10], with varying degrees of invasiveness. As this phenomenon can be used to distinguish between sleep stages in a simple, inexpensive way, it provides a valuable tool for sleep monitoring which can be performed at the patient's home. The recordings can then be used for sleep research and diagnosis. An inspiration for the presented design was a patent [8] describing a non-invasive method based on recording infrared light intensity reflected off the eyelid. Eye movements make the eyelids flutter, which leads to a change in how the light is reflected and dispersed by them – and thus to a change of the measured signal.

Design

The device should be safe, portable and easy to use. A completely wireless operation had to be provided in order to maximize user comfort. The minimal wireless operating time was assumed to be at least 10 hours as the measurement is to continue throughout the whole of the patient's sleep.

Figure 1 shows the general concept of the device. The central unit controls the infrared light emitter, which illuminates the eyelid. The reflected light intensity is measured by the detector and converted into an electrical signal, which is subsequently amplified and filtered before the A/D conversion. The digital signal is then sent to the computer, either through a serial port (RS232) or wirelessly via the Bluetooth module, which is the default mode of operation. Dedicated software displays and stores the received data, while also enabling control of the device's mode of operation. The user interface comprises light and sound signals via a small buzzer and a light-emitting diode (LED).



Figure 1. Block diagram of the designed eyelid movement monitor

Safety

Safety was a major concern in the design. There are a number of possible dangers involved. Firstly, mechanical: As the user moves in bed during the night, various elements of the device could come in contact with their skin and eyes, causing possible damage. Therefore, the hardware was mounted in a rigid frame at a safe distance from the eyes. Secondly, an optical danger arises due to infrared light being invisible to a human eye. It is possible that the patient wakes up during the night and unwittingly looks straight at the radiation source, causing possible heat damage to the retina.

Supposing the worst-case scenario of irradiation lasting more than 10 seconds – i.e. continuous - from a source infinitesimally close to the eye, the safe luminance is given by [3,9] as:

$$L_{\rm max} = 6 \cdot 10^4 \, \frac{W}{m^2 \cdot sr}$$

An infrared-based device for non-invasive monitoring...

The maximal luminous intensity of the used infrared diode L-934F3C is P = 80 mW/sr. Supposing the worst possible scenario with the emitter infinitesimally close to the illuminated surface,

$$L = \frac{4P}{\pi d^2} = \frac{4 \cdot 0.08}{3.14 \cdot 2.9^2 \cdot 10^{-6}} = 1.22 \cdot 10^4 \frac{W}{m^2 \cdot sr}$$

Consequently, the luminance level can be considered safe even under unfavourable conditions.

Lastly, the use of a low-voltage battery power supply [14] and wireless communication ensures electrical safety.

Software

A Java-based computer application with a graphic user interface was created. This software makes it possible to control the device and to process the received data. Classes from the RxTx library [10] were used for implementation of serial port terminal. Both UART and Bluetooth communication modes are handled by the software in the same way, that is as a stream of characters from a serial port – a real or virtual one, respectively. The received data are visualized in real time on a dynamic chart, based on the JChart2D library [1]. The data can be saved in Microsoft Excel file format. For this purpose classes from the library JExcelApi [6] were used.

Hardware

The control unit is PIC16F88 (Microchip Technology, USA) microcontroller. It has 16 configurable input/output pins, one of which is connected to a built-in 10-bit A/D converter (ADC). Other features used in the device are: interrupt on input level change, which enables handling button interaction outside of the main program loop; built in internal oscillator and Universal Synchronous Asynchronous Receiver Transmitter (USART) units; in-circuit serial programming, enabling firmware changes without removal of the microprocessor.

To measure the infrared light intensity, a PT-204-6B phototransistor (Everlight Electronics Co. Ltd., Taiwan) with a current/voltage converter circuit (CVC) was used (Figure 2) [4]. The CVC is based on a LM358 (Texas Instruments Inc., USA) operational amplifier – its high input impedance and low output impedance ensures correct cooperation of the phototransistor, the CVC and the ADC.

Preliminary tests indicated that the changes of reflected light intensity related with eye movements were on the level of no more than few percent of the direct current signal. To remove the uninformative part of the signal, a first-order high-pass filter was first used. Its RC constant was set to 220 ms. In order to eliminate the noise related to artificial lighting source (most notably at the frequency of 50 Hz and 100 Hz, see Figure 3), a first-order low-pass filter was subsequently used. Based on the results of experiments conducted, 99% of signal power spectrum was found to be between 0 and 10 Hz. Finally, the low pass filter cut off frequency of 16 Hz was chosen after taking into consideration interpatient variability. The proposed filter section ensures the noise level reduction below the threshold of the ADC least significant bit.



Figure 2. Current to voltage conversion circuit



Figure 3. Acquired signal showing five intentional eye left-right movement of the user's eyes, with periods of rest before and after the activity

An infrared-based device for non-invasive monitoring...

The printed circuit board was mounted in a comfortable, darkened mask (Figure 4).



Figure 4. Assembled device. (1) Emitter-receiver unit (2,3,4) User interface: LED, buzzer and internal buttons (5) Bluetooth/RS232 connection (6) In-circuit serial programming connection (7) Amplification and filtering units



Figure 5. Power spectral density analysis of a preliminary measurement without signal filtering

Testing and conclusion

The device and software were tested in the expected measurement conditions with simulated noise – the user was lying on a bed with the mask on and an artificial lighting source (incandescent light bulb) nearby. As the eye movements in the state of wakefulness are similar to those in the dream state [5], intentional movements of an awake patient were used for testing. Five of them were recorded, shown in Figure 5. As can be seen, the signal changes with a much higher amplitude during eye movements than during rest periods, possibly enabling to distinguish between REM and NREM sleep stages.

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