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Summary and Outlook

Functional Near-Infrared Spectroscopy is an emerging technology that provides a new modality for brain activity measurements. With advantages such as hazard-free application, motion artifact robustness and the possibility to miniaturize hardware, fNIRS may enable new applications in the BCI context, in clinical tools and diagnosis and further contribute to new insights in brain research and neuroscience.

In this work, a modular, multichannel, wireless fNIRS instrument using continuous wave methodology was designed and evaluated. Consisting of a NIRS module and a control and acquisition mainboard, the instrument provides stand-alone fNIRS functionality. Using UART interface Bluetooth data transmission and a battery power supply, the system is suitable for mobile applications.

The hardware design of the instrument focused on a lock-in detection approach with programmable amplification and a silicon NIR light detector with integrated trans-impedance amplifier for noise reduction. For optimal signal performance, two NIR light wavelengths ($750 + 850\,nm$) were chosen in accordance with the current state of research with regard to optimal NIRS wavelength selection. For lock-in modulation, current adjustment and regulation, a high-precision current regulator concept was iteratively designed and improved.
Complementary to the fNIRS module concept that provides stand-alone usage via a custom $4\,Bit$ parallel interface, a mainboard for module control and acquisition of the analog fNIRS signal was designed. Providing the fNIRS module supply voltages from a symmetric regulated voltage supply, the mainboard also serves as acquisition unit (using a 4-channel $16\,Bit$ ADC) and communication interface. With the implemented set of 8 ASCII control bytes, the instrument can be used via any serial UART communication interface such as an operating system's HyperTerminal, the MathWorks Matlab serial interface or a stand-alone executable LabView graphical user interface that was designed in this work.

The software design is based on two Atmel Corp. AVR microcontrollers. On the NIRS module, the first microcontroller controls the PGA, current adjustment, and channel multiplexer, creates a $3.125\,kHz$ modulation PWM square-wave reference and processes the incoming control signals based on an interrupt routine design.
On the mainboard, the second microcontroller provides SPI and UART interfaces for ADC data acquisition and user communication, processes user controls and generates control signals for the fNIRS modules.

For data communication, logging and processing, the LabView graphical user interface was developed. It provides simple instrument control, graphical display of the acquired fNIRS data and a data saving routine for file generation including a header carrying instrument configuration information and the acquired data for further post-processing and documentation.

Mechanical designs were done using 3D printing technology and CAD software.
The fNIRS module body housing is based on a double spring-loaded quad-probe design for good mechanical adaption to the surface of the head while ensuring irradiation and detection perpendicular to the surface and maximizing user comfort.
The body housing of the mainboard unit consists of three parts that are connected via rotary joints and carry the Bluetooth module, the mainboard and battery packs. Using flexible ribbon and hook-and-loop fastener, the mainboard unit can easily be fixated on the upper arm of a subject wearing the fNIRS instrument.

The instrument's hardware was evaluated for signal and noise performance and verified by acquisition of physiological data.
Hardware evaluation indicated that there is still room for improvement in the lock-in amplification module, power supply design, signal acquisition and drift properties of the instrument.
To improve the lock-in performance, attenuation effects resulting from phase shifts between modulation reference and detected signal can further be minimized, e.g. by using digital lock-in demodulation or analog phase correction. The power supply design can further be improved by better decoupling from the high-frequency current modulation impacts and external electrical interference. To use several fNIRS modules/many active channels at the same time, a larger number or faster ADCs have to be implemented on a next-level mainboard design. For static solutions, any number of stand-alone fNIRS modules can be used and controlled, e.g. with LabView DAQ equipment or any other data acquisition equipment that allows customized parallel control of the modules interface.
The overall system's signal drift for continuous use of one channel in speed mode was evaluated and linearly approximated as $-3 \cdot 10^{5}\, V/s$. The main factor causing this drift was determined to be the ADC's temperature increase caused by power supply heating on the mainboard. The drift of the stand-alone fNIRS module was evaluated as approx. $-1 \cdot 10^{-6}\, V/s$, which is in the order of the current regulator sensing resistance's TCRs. To further reduce the overall drift, thermal decoupling (physical separation) of the ADC from the power supply or power supply cooling techniques such as passive heat conduction elements or a mini fan integrated in the body housing could be applied.

For verification of the physiological value of the fNIRS instrument's signals, qualitative examination of the effects of heart rate and head blood pressure on the signals were conducted and confirmed the basic functionality of the instrument. To compare the designed instrument with commercially available fNIRS instrumentation, brain computer interface experiments for brain activity acquisition during mental arithmetic were conducted. The results showed comparable system performance, the classification results showing a better cross validation accuracy (CVA) of 69.23% (Oxymon) vs. 62.9% (mobile fNIRS) for the commercial reference system in single-channel trials and a better performance of the designed mobile fNIRS system in two-channel trials (CVA of 75.0% (mobile fNIRS) vs. 65.63% (Oxymon)).

The evaluation of the fNIRS instrument for mobile, modular, stand-alone brain activity measurements makes the design approach promising for future applications.