5

Results and Discussion

The following chapter will provide a brief system overview. Afterwards, the scope and limitations of the fNIRS instrument design will be discussed.

5.1 System Overview

In the course of this work, several prototypes and a final version of a modular multi-channel fNIRS system based on continuous wave technology were designed. Using lock-in detection, programmable amplification and adjustable regulated LED currents, the instrument is suitable for functional brain activity indication based on fNIRS signals.
Figure 5.1 shows the final fNIRS instrument that was implemented in this work.

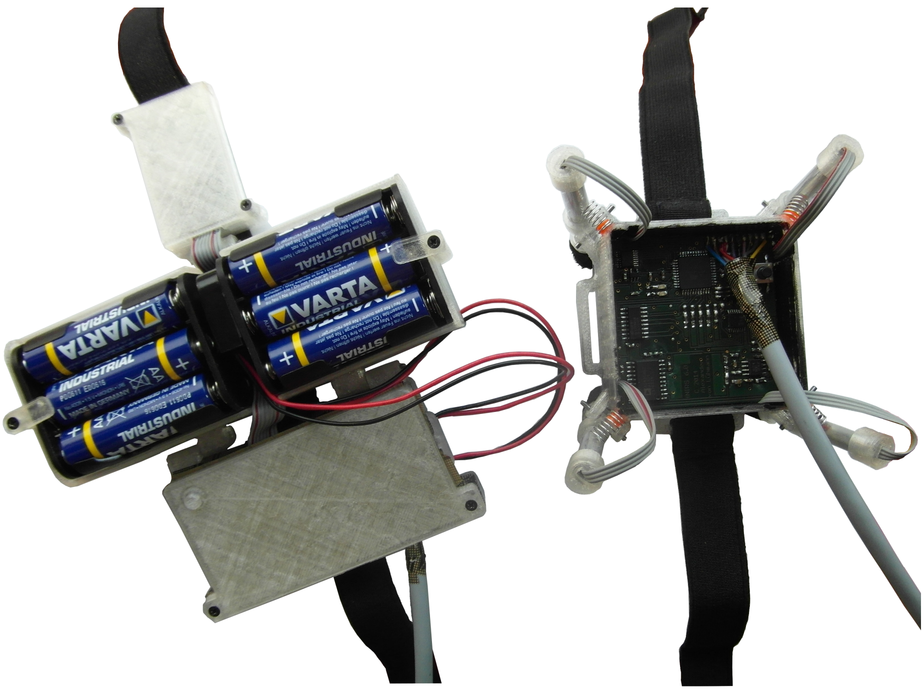

Figure 5.1: Finished NIRS instrument. Left: multi-unit mainboard module for upper arm, right: NIRS module.

The final version consists of a mainboard, a communication module and a battery package that are encapsulated by custom 3D-printed housing elements interconnected by rotary joints, and a 4-channel spring-loaded fNIRS module. Wearing the mainboard module on the upper arm and the fNIRS module on the head using flexible ribbons and hook-and-loop fastener, the user can move freely and is bothered as little as possible by the instrument.
The electrical and functional characteristics of the fNIRS instrument are summarized in tab. 5.1.

Power Charact.	Power Consumption	max: $200\,mA$, stand-by: $80\,mA$
	Battery Supply Voltage	max: $\pm 10\,V$, min: $\pm 7.5\,V$
Signal Charact.	Meas. Wavelengths:	$750\,nm$ & $850\,nm$
	LED Type	Epitex L750-850-04A
	Photodiode Type	Burr-Brown OPT101
	Max. Sampling Rate	$14\,Hz/7\,Hz$
	Conversion Depth	$16\,Bit$
	Signal Drift fNIRS module max.	approx. $-1 \cdot 10^{-6}\,V/s$
	Overall Signal Drift without cooling	approx. $-3 \cdot 10^{-5}\,V/s$
Instrument Charact.	Lock-In Amplification	
	Programmable Amplification	$G = 0.688 - 88$
	Time-Division Multiplex	
	Current Regulation	
	Current Adjustment	4 Levels: 25, 50, 80, $100\,mA$
Communic. Interfaces	Mainboard: UART	9600 bps, 8 data, 1 stop, no parity
	UART Access	Bluetooth (AMB2300)/Serial Cable
	8 Characters Control Set	”G”,”S”,”E”,”C”,”R”,”T”,”P”,”H”
	23 Bytes CSV Output Format	|M#;C#;L#;S#;ADC;Timer;CRLF|
	NIRS Module: $5\,Bit$ parallel	Bit3:0 |RST|TRIG|CH1|CH0|

Table 5.1: Characteristics of NIRS instrument.

The instrument's hardware functionality was constantly evaluated and improved during the design process of evaluation, prototype and final versions. The main results of these iterative design and evaluation steps are

- A new stand-alone fNIRS system concept based on modularity and scalability
- An optimized adjustable current regulator and modulation circuit based on AD824A high-precision amplifiers with negative decoupling.
- A lock-in-based signal extraction module with programmable amplification and $2\,Hz$ 3rd-order low-pass filter
- An UART-based Bluetooth/Serial communication interface for instrument control, signal acquisition and data transmission
- A 4-channel spring-loaded mechanical concept for NIRS probe attachment for better robustness against movement artifacts and higher user comfort.

The overall system drift for the single fNIRS module was specified to be maximum $-1 \cdot 10^{-6}$. For the overall instrument without additional cooling, a significantly higher drift of approximately $-3 \cdot 10^{-5}$ was measured. The main influencing factor of system drift was determined as the temperature increase of the ADC caused by power supply heating.
The verification of the hardware functionality was done by acquiring qualitative physiological data (pulse, blood pressure/cerebral blood volume) and quantitative BCI experiments with a commercial laser-diode-based reference system (Artinis Medical Systems Oxymon Mk III) were conducted. In two 32-trial mental arithmetic experiments with two subjects, similar signal trends and classification accuracy (mobile fNIRS: 62.9% and 75.0%, Oxymon: 69.23% and 65.63%) indicated comparable performance and the instrument's capability of measuring functional brain activity.

5.2 Scope and Limitations

While the hardware evaluation and physiological verification of the designed fNIRS instrument indicates a sufficient signal quality and hardware functionality, there are still several elements in the design that can be further optimized for better instrument performance:

- As this work focused on the system concept and signal generation and extraction elements, the design of the **power supply** was secondary and can be further optimized. Even though the implemented linear-voltage-regulator-based symmetric supply appears to be sufficient at this point, several improvements are suggested for later versions of the instrument:
  A new design for a next-generation power supply should include additional high-frequency filters against noise pickup from external sources and enhanced stabilization to minimize LED current modulation influences on the rest of the system. Also, the use of more efficient voltage regulators would be desirable to further enhance battery life and decrease heating effects, which would minimize the system drift influences resulting from ADC temperature rise. Either active or passive cooling of the power supply unit or a physical/thermal separation of the power supply and ADC unit could further reduce system drifts.
- A considerable improvement of the instrument's performance can be achieved by enhancing the mainboard's **analog-to-digital converter** functionality. As became apparent during the iterative design process, the currently implemented ADC (LTC2486) offers high conversion depth but significantly limits the maximum time resolution that can be used for the instrument's channels. As the maximum sampling rate of $14\,Hz$ has to be shared by all active channels, the time resolution of each signal significantly decreases with each additional channel that is used. Especially, when the Nyquist theorem is to be applied with respect to the $2\,Hz$ 3rd-order low-pass filter, not all 4 channels can be used simultaneously with the $16\,Bit$ ADC.
  However, this big disadvantage can be easily eradicated by simply improving the current mainboard design to a next-generation design with either several parallel ADCs or a new fast ADC with sufficient quantization depth. The only reasons this was not done in the final instrument were the limited time and expenses that exceeded the scope of this Master's thesis.

In a first step, however, the 10 *Bit* 150 *ksps* ADC module of the mainboard's microcontroller was additionally implemented for a higher sampling rate in trade-off with lower quantization depth. BCI trials showed sufficient system performance despite the low quantization depth, probably based on the high pre-amplification of the detected optical signal before analog-to-digital conversion.
This reveals a positive aspect of the instrument's design concept: With the NIRS module being designed for stand-alone usage, any control and acquisition equipment can be used and the performance is adaptable to user requirements.

- As the evaluation of the **lock-in detector** revealed, the attenuation of the detected signal due to a phase shift is acceptable but can be further minimized. To improve the lock-in performance, an analog adjustment of the PWM reference phase could be implemented. This would enable overall phase shift compensation.
  Alternatively, a potentially superior approach for a next-generation design could be developed using the microcontroller for digital lock-in demodulation. This bears several advantages: reduced cost of hardware components, reduced power consumption and an adjustable phase shift correction and thus higher precision.

In the course of the experiments, some advantages of the instrument regarding user comfort and usability were noticed: The use of the commercial reference system required longer preparation times for optode fixation and was often uncomfortable and static because of the weight of the optical fiber guides and the lack of cushioning of the optodes. In contrast, the wearable system designed in this work could be applied within several seconds and was generally perceived less cumbersome during the experiments.