A Wearable Functional Near-Infrared Spectroscopy (fNIRS) based Brain Interface

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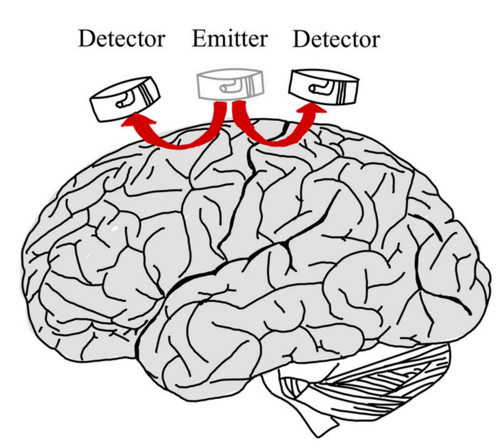
Background & Motivation

Functional Near-Infrared Spectroscopy (fNIRS) is a **non-invasive neuroimaging** method which uses near-infrared light to measure blood oxygen level in the cerebral cortex, based on the **modified Beer-Lambert Law** (mBLL).

$$\Delta OD(\lambda) = \varepsilon(\lambda) \cdot \Delta c \cdot L \cdot DPF$$

- OD: optical density
- ε : extinction coefficient
- c: concentration
- L: physical pathlength
- DFP: differential pathlength factor



The change in optical density (ΔOD) at a given wavelength (λ) reflects how much near-infrared light is absorbed as it passes through brain tissue. Measuring ΔOD allows us to estimate changes in oxy- and deoxyhemoglobin levels, which indicate brain activity.

Project Goals

To develop a **low-cost**, **accurate**, **non-invasive**, and **ergonomic** fNIRS device that prioritizes high mobility and ease of usability, exploring the potentials of fNIRS technology beyond clinical settings.

Key Requirements

Sampling Rate: The device should support a minimum sampling rate of 100Hz.

Real-time Logging: The design should be able to perform accurate real-time data processing and visualization while also keeping record of the data.

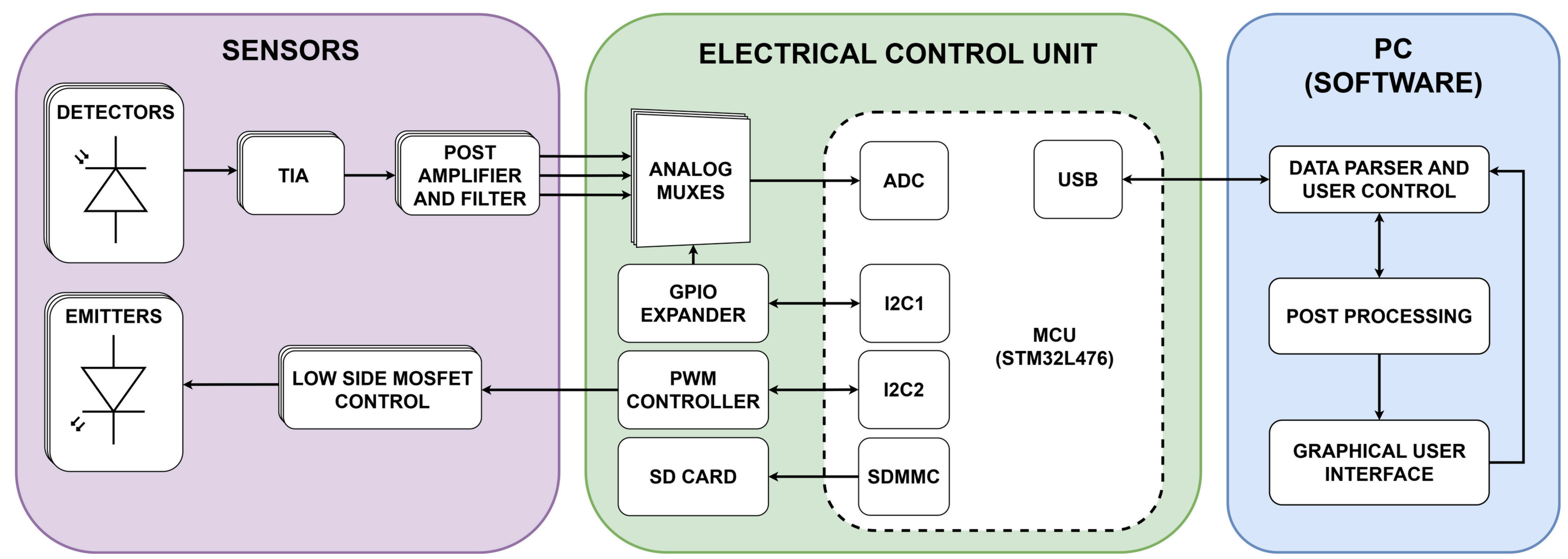
Cost: The net material and fabrication cost of the device should be below $1000.

Wearability: The assembled device can be worn, taken apart, and transported during use.

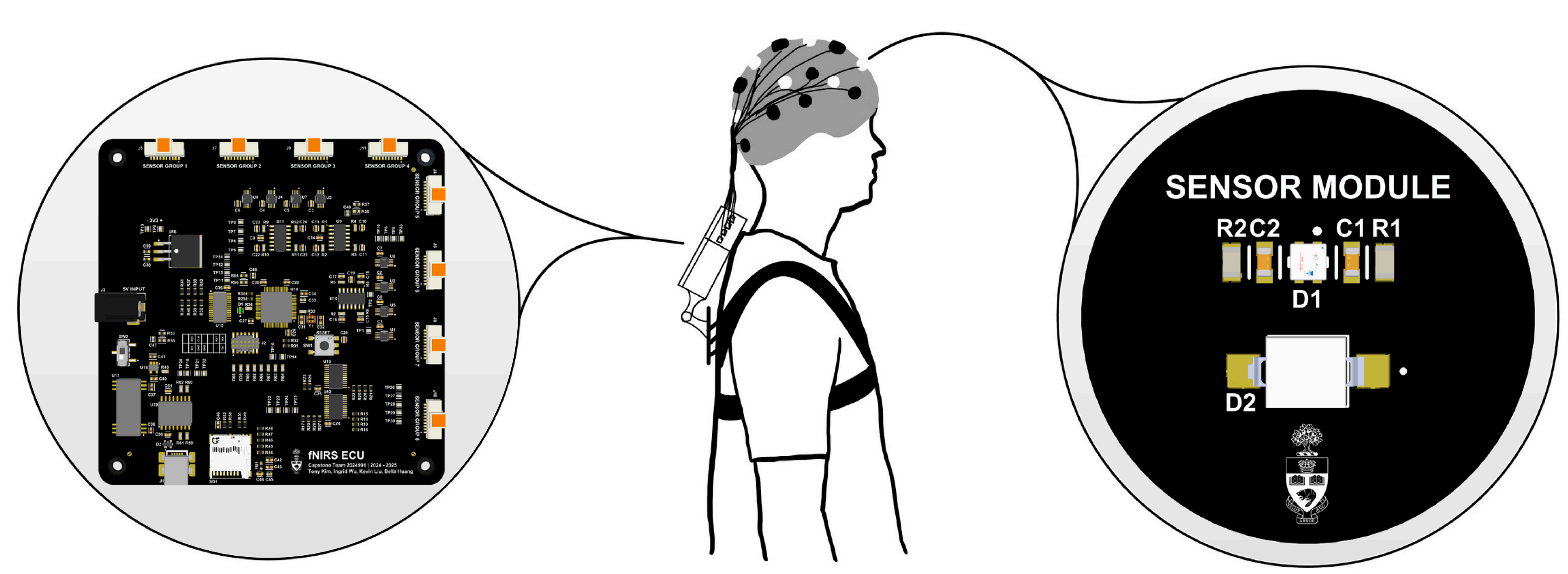
Non-invasiveness: The device should not puncture, burn, irritate the skin, or cause any form of physical harm or strain to the user.

Final Design

The fNIRS device integrates **custom hardware**, **firmware**, **mechanical**, and **software** components into a unified system. Sensors and an electrical control unit with firmware establish the foundation for signal acquisition and data transmission, while software handles analysis and graphical visualization. Finally, the mechanical components consolidate these elements into an ergonomic assembly.



The design includes 25 printed circuit boards based on two distinct cost-optimized layouts. The device supports up to **24 detector** channel readings with a sampling frequency of approximately 1kHz, and **8 dual-wavelength emitters** (660 nm and 940 nm) to accurately measure changes in oxy- and deoxy-hemoglobin concentration levels.



Electrical Control Unit

- Custom 4-layer PCB design
- Analog multiplexing utilizing 8 TMUX1104 inline with 12-bit ADC channels
- PCA9685 12-bit 16 channel PWM controller for emitters
- 80MHz STM32L476RET6 microcontroller

Sensor Modules

- Custom 2-layer PCB design
- Photodiode detection via transimpedance amplifier, 101 V/V post-AC gain, and 0.0796–159.2 Hz filter.
- RMS noise level of ~0.004 V
- Emitter wavelengths of 660 nm and 940 nm

Software Processing

- Parse and filter sensor data
- Apply ΔOD conversion, mBLL, and correlation-based signal improvement (CBSI)
- Graph raw ADC, ΔHbO, ΔHbR data and display on GUI
- User control for ECU to customize operation

Method & Results

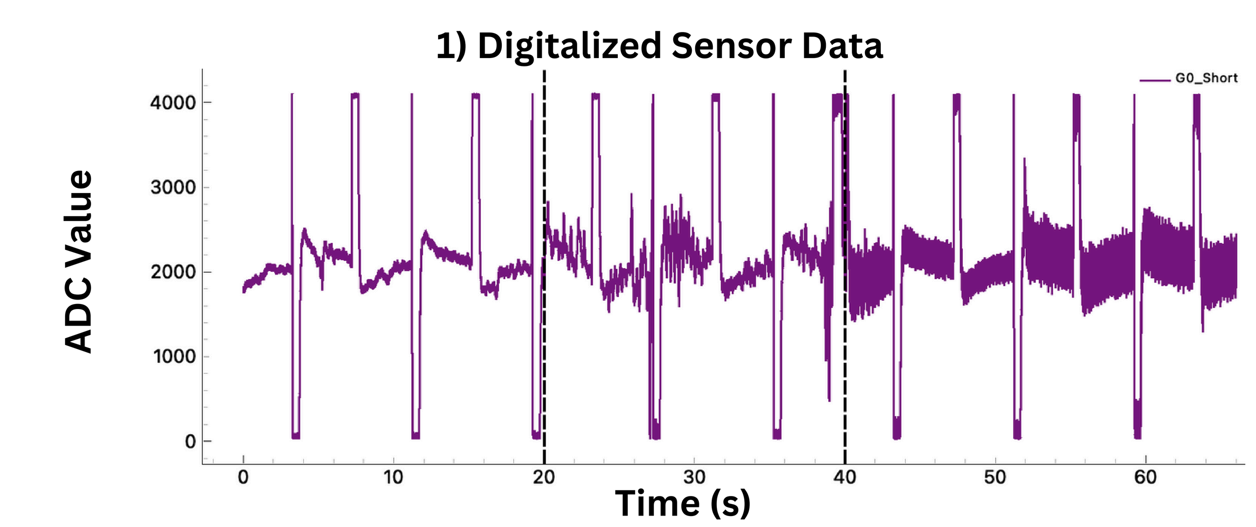
Method

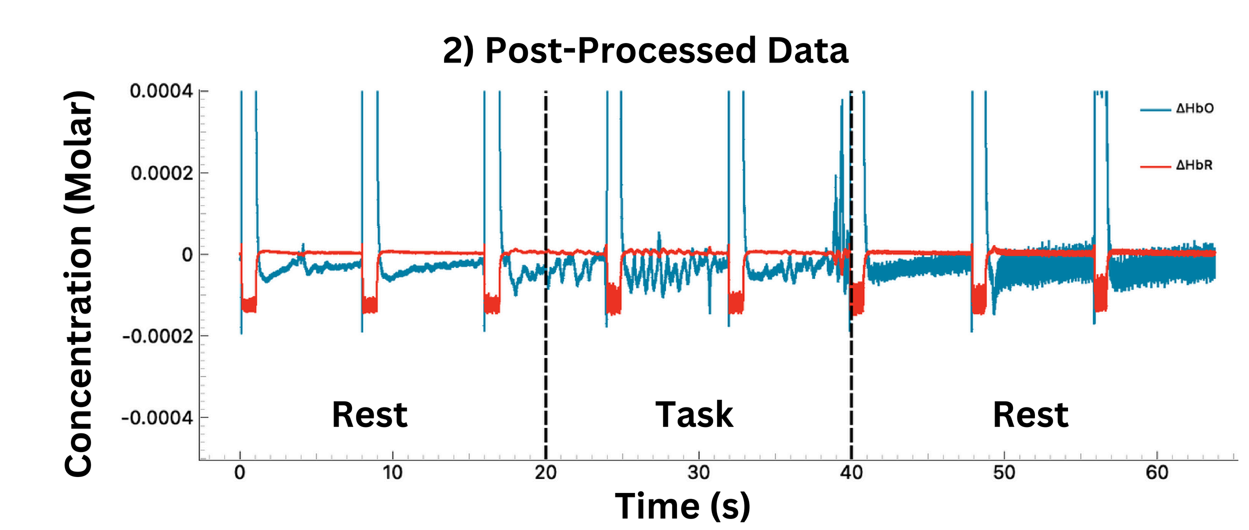
Participants completed a task sequence consisting of a 20-second resting period, followed by a 20-second computer-typing task, and concluded with another 20-second resting period while wearing the device.

Results

Below are two sample graphs of a single-channel recording targeting the primary motor cortex (M1).

1) Digitalized sensor data representing reflected light intensity 2) Post-processed data of the change in hemoglobin oxygenation levels using mBLL and CBSI.





Conclusion & Future Work

Conclusion

The team successfully designed and validated a low-cost, ergonomic fNIRS device and a web-based graphical user interface for real-time brain activity monitoring. The final system is able to map direct ADC output, as well as ΔHbO and ΔHbR trends that match theoretical expectations.

Future Work

Possible future work may include real-world validation through collaboration with clinical and neuroscience researchers, as well as integrating machine learning techniques for improved noise reduction, cognitive state classification, and trend analysis of fNIRS data.