Brian Computer Interface (BCI) Application: Real-time Ball Mind Control using VersaSens EEG Headset (VersaBrain)

Contact Persons:

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Project description

The project aims to implement a real-time brain–computer interface (BCI) application that controls the vertical position of a ball on a computer screen through mental concentration. Cortical activity generates electrical signals known as electroencephalogram (EEG) signals, which can be recorded non-invasively from the scalp. As these signals propagate through the skull and scalp layers, they become significantly attenuated, resulting in low amplitudes typically ranging from 10 to 100 μV. EEG signals span frequencies from approximately 0.5 Hz to 45 Hz and are conventionally grouped into distinct bands, each associated with specific physiological or cognitive states. In this project, the beta band (12–30 Hz) is of particular interest, as it is commonly linked to concentration, attention, and stress. By computing the power spectral density within this frequency range, the user's concentration level can be estimated.

In this project, an EEG headset based on VersaSens [1], referred to as VersaBrain, will be used for real-time signal acquisition and processing. VersaSens is a modular, multimodal, extendable, and reconfigurable edge-AI platform developed at the Embedded Systems Laboratory (ESL). It includes three sensing modules and two processing modules, with the possibility of integrating additional custom-designed modules, providing a flexible foundation for a wide range of applications. For this project, VersaBrain is equipped with one sensing module (ExG) for real-time EEG acquisition and one processing module (Main) for data storage, on-device processing, and Bluetooth Low Energy (BLE) transmission. Optionally, the co-processor module (HEEPO), featuring the HEEPOcrates SoC [2] and offering hardware-acceleration capabilities, may be integrated as a co-processor unit.

For this BCI application, VersaBrain acquires real-time EEG signals from its frontal electrodes (Fp1 and Fp2) at a sampling rate of 200 Hz. In addition to data collection and storage, the processor must compute the power spectral density (PSD) of the beta band over short signal windows, whose optimal length should be experimentally determined. The computed PSD values must then be transmitted in real time to a computer, tablet, or mobile device, where they are converted into the vertical position of a ball. Higher levels of concentration correspond to increased beta-band power, which should lower the position of the ball on the screen, whereas lower concentration results in reduced beta power and consequently a higher ball position.

Because this is a real-time application, the PSD computation, wireless data transmission, and visualization script must be designed and optimized to avoid any perceptible latency. While PSD calculation is recommended for estimating concentration levels and driving the ball’s movement, alternative signal-processing methods or machine/deep learning approaches may also be employed, provided that (i) the end-to-end real-time application runs smoothly on the sensor within its energy and memory constraints, and (ii) the full system, including the receiving device, operates without visible latency.

Mandatory tasks:

Completion of the following tasks is required to pass the exam and obtain a grade of 4. Failure to complete any of these tasks will result in **no pass**:

1. Become familiar with EEG signals, their frequency bands, and the physiological and cognitive states associated with each band.
2. Become familiar with VersaSens, including its hardware architecture, firmware framework, and practical usage, in particular the ExG module, and the Main module.
3. Characterise and configure the ExG module for the BCI application, including sampling frequency, gain, and all other required parameters. Test and validate real-time synchronous signal acquisition and data storage and data streaming over BLE.
4. Design and implement the on device beta band PSD algorithm for real-time signals acquired by the ExG module.
5. Design and implement PSD data transmission from the sensor to a computer.
6. Develop a python script to receive the transmitted data and map them to the vertical position of a ball on the screen. (A partially implemented version is available in the repository, but it must be adapted for use with real-time signals from VersaBrain.)
7. Integrate the developed components on both the sensor and the computer, to form a complete end-to-end BCI pipeline.

8. Test the whole pipeline using VersaBrain headset with real-time EEG signals and produce a short a demonstrative video showcasing functionality of your application.
9. Prepare and deliver a complete documentation package for upload to the VersaSens GitLab repository, including all Python code, c/c++ code, and the firmware.

Optional tasks:

Completion of each task will contribute an additional 1 point to the final grade:

1. Use HEEPocrates SoC for beta band PSD computation. In this case, HEEPocrates must receive the real-time signals form the main processor nRF5340 through SPI interface, process them, and return the results to the nrf5340.
2. Test the full pipeline using the VersaBrain headset and the HEEPocrates SoC with real-time EEG signals. Produce a short video showcasing the application's functionality and submit all documentation to the same repository.

Type of work

- 25% software design.
- 50% Firmware design.
- 20% Testing and performance evaluation.
- 5% Preparation and delivery of the complete documentation package.

Desired skills:

- Strong background in C and Python programming
- Knowledge of EEG physiological signals
- Experience with embedded software development, RTOS environments and Zephyr
- Familiarity with version control systems (Git)

Soft skills:

- Scientific curiosity
- Good communication skills
- Advanced English

Refrences:

[1] Najafi, Taraneh Aminosharieh, et al. "VersaSens: An Extendable Multimodal Platform for Next-Generation Edge-AI Wearables." *IEEE Transactions on Circuits and Systems for Artificial Intelligence* (2024).

[2] Machetti, Simone, et al. "HEEPocrates: An ultra-low-power RISC-V microcontroller for edge-computing healthcare applications." *Europractice, March* (2024).