Measurement of motor imagery brain activity for wearable neural interfaces

Abstract

The growing demand for reliable and reproducible electroencephalographic measurements has led to substantial advances in acquisition technologies and signal processing methodologies in both research and clinical contexts. This also applies to real-time brain-computer interface applications. The transition from wired to wireless electroencephalographic systems offers flexibility, wearability and usability. However, this transition introduces metrological challenges, particularly concerning acquisition delay and signal integrity. To ensure the accuracy, repeatability, and reproducibility of analyses based on electroencephalographic signals, a metrological approach is required to quantify and mitigate the sources of uncertainty.

This doctoral thesis first explores the delays in signal acquisition that occur with wireless electroencephalographic devices and assesses how these delays influence the identification of neural phenomena that are time-locked to specific events, such as the P300 component and movement-related cortical potentials. A measurement system was developed to investigate acquisition delays and their associated uncertainties. This system enabled the assessment of signal acquisition delays by measuring the time difference between the start and stop of a reference signal. The goal of this study was to assess the consistency and reliability of various devices. Furthermore, experiments with brain-computer interfaces were conducted to explore how acquisition delays affect the detection of time-locked neural responses. Statistical analyses revealed significant differences in acquisition delays depending on the device and its configuration, with delays ranging from a few tens of milliseconds to over one hundred milliseconds. These variations had a direct impact on the identification of neural phenomena, potentially leading to classification errors. However, compensating for the measured acquisition delay yielded promising results, particularly in enhancing the estimation of P300 latency when using cost-effective recording instruments.

Methods to enhance the reliability of electroencephalographic data were also explored. A comparison was conducted between different techniques for removing unwanted signal components, focusing on configurations that use a limited number of recording electrodes. A combined approach is proposed to improve the removal of unwanted components from electroencephalographic signals. This approach merges artifact subspace reconstruction with multivariate empirical mode decomposition. It proves particularly beneficial when only a few sensors are available, a scenario where traditional techniques are often ineffective. The approach was tested using two publicly available datasets: the first consisting of semi-synthetic data and the second containing experimental recordings. The analysis examined cases with one to four recording electrodes and compared the proposed method to artifact subspace reconstruction alone. Notably, the latter could not be applied when only one electrode was available, whereas the combined approach made this possible. The proposed approach effectively minimized artifacts caused by muscle activity, eye movements, and blinking in both semi-synthetic and experimental data. Interestingly, artifact subspace reconstruction alone performed similarly well on semi-synthetic data. However, when applied to real experimental recordings, it failed to operate correctly.

Then, methods for processing electroencephalographic signals in brain-computer interfaces that focus on imagined movements were examined. A metrological analysis of the literature was conducted to assess advancements in signal classification, pinpoint emerging trends, and tackle the challenges of achieving consistent outcomes. Special emphasis was placed on performance evaluation through a detailed metrological analysis, tacking into account factors like accuracy, uncertainty, repeatability, and reproducibility. The review included 89 studies. The findings indicated a growing dependence on brain-inspired computational models, which have shown to be particularly effective in distinguishing between different movement classes. However, the lack of standardized protocols created difficulties in assessing reproducibility.

In the context of motor imagery-based neural interfaces, it is important to monitor user's level of engagement. This is closely related to the actual generation of motor imagery-related brain

activity. Hence, this thesis also discusses how electroencephalography can be used to assess cognitive engagement in real time. A novel approach was created to categorize engagement levels across various tasks by analysing brain activity recordings. The research included twenty-three participants who took part in a modified attention test aimed at eliciting engagement. A classification model was developed to differentiate between engaged and resting states using signals acquired from eight electrodes. The model achieved an average classification accuracy of 90 % on independent test data.

Building on the insights from earlier chapters, the final chapter of this work focuses on the development and experimental validation of a wearable brain-computer interface that enables real-time control of a video game through self-paced motor imagery. Electroencephalographic signals were acquired using eight wet electrodes. A processing pipeline was established to classify three mental tasks: imagining the movement of the left hand, the right hand, or remaining at rest. This classification allowed for real-time control of an avatar in an endless runner game. The study involved twenty-three participants, and a custom metric was created to assess performance during gameplay. The mean classification accuracies for differentiating between left hand vs. rest, right hand vs. rest, and left hand vs. right hand were 73 %, 73 %, and 67 %, respectively. Participants who demonstrated higher classification accuracy during offline calibration exhibited better control of the avatar in the game. This research contributes to the development of wearable, self-paced neural interfaces for real-time applications, facilitating more natural and intuitive interactions compared to traditional synchronous systems. By moving beyond benchmark datasets and testing in an interactive gaming environment, this work lays the groundwork for future applications in mobile and everyday-use brain-computer interfaces.