

論文 / 著書情報
Article / Book Information

題目(和文)	予測誤差デコーディングに基づく汎用性のあるブレインコンピュータ インターフェイス技術之探究
Title(English)	Investigation of universal brain-computer interface technology utilizing prediction error decoding
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出典(和文)	学位:博士(学術), 学位授与機関:東京工業大学, 報告番号:甲第12602号, 授与年月日:2023年9月22日, 学位の種別:課程博士, 審査員:小池 康晴,中本 高道,金子 寛彦,葭田 貴子,永井 岳大
Citation(English)	Degree:Doctor (Academic), Conferring organization: Tokyo Institute of Technology, Report number:甲第12602号, Conferred date:2023/9/22, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	論文要旨
Type(English)	Summary

(博士課程)
Doctoral Program

論文要旨

THESIS SUMMARY

系・コース : Department of, Graduate major in	情報通信 ライフエンジニア リング	系 コース	申請学位 (専攻分野) : Academic Degree Requested	博士 Doctor of (学術)
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要旨 (英文 800 語程度)

Thesis Summary (approx.800 English Words)

<p>Objective: In the context of natural motor imagery tasks, our objective is to achieve planar multi-degree-of-freedom Brain-Computer Interface (BCI) control by utilizing a reduced number of common electrodes for distinct measurement of participants' brain signals.</p> <p>Existing Issues: Motor imagery-based BCIs face several challenges, including low signal-to-noise ratios, prolonged training times, and extended data processing windows. The conventional practice of constraining motor imagery to predefined categories aligned with large cortical regions exacerbates these issues when there is a mismatch between the predefined categories and the intended control actions. Furthermore, prolonged use of fixed-category BCIs can lead to participant fatigue. In practical BCI applications, cost constraints impede technology adoption. Although existing channel selection techniques can reduce redundancy and individualize costs by decreasing the number of channels used, most methods lack universality. Therefore, achieving widespread and cost-effective applications remains a significant challenge.</p> <p>Methodology: Taking inspiration from human internal models during movement, we propose that the pivotal prediction error signals generated by the internal forward model can be indirectly decoded to enhance the discriminability of electroencephalography (EEG) signals during natural motor imagery. Initial experiments investigated the decoding of prediction error signals induced by pronounced movement stimuli, demonstrating the potential of prediction error decoding in addressing existing challenges. To expand on this approach, it is crucial to incorporate subliminal sensory stimulation-induced prediction error decoding. Referring to a parallel collaborative study, we utilized Galvanic Vestibular Stimulation (GVS) with lower-strength currents. We randomly stimulated the vestibular organs in four directions on a plane, inducing prediction errors in participants. By concurrently decoding prediction error signals in both front/back and left/right motor imagery domains and combining pairwise consistent prediction error decoding results, we inferred participants' intended motor imagery and achieved control over planar multi-degree-of-freedom movements. Corresponding validation experiments for front/back and left/right motor imagery demonstrated that prediction error signals significantly improve EEG signal discriminability during natural motor imagery while also requiring shorter data processing windows. Furthermore, leveraging the parameter sparsity of Sparse Logistic Regression (SLR) algorithm, we developed a channel optimization algorithm that identifies shared channels across participants with substantial decoding information, enabling efficient detection of EEG signals using fewer electrodes.</p>

Significance:

Participants can engage in motor imagery more naturally without the need for prior training. The introduction of external stimuli-induced prediction errors enhances the separability of EEG signals, increases signal-to-noise ratios, significantly reduces data processing windows, and utilizes user-friendly sensory stimuli with lower intensity levels. The incorporation of a dual-decoder design enables planar multi-degree-of-freedom control, leading to the development of a novel branch in EEG-based BCI known as the "Hybrid Method". The proposed channel optimization algorithm demonstrates universality and minimal data processing requirements, making it both academically innovative and commercially relevant, thereby contributing to advancements in both academic and commercial BCI domains.

Research Interconnections:

The investigation titled "Exploration of the Existence and Feasibility of Prediction Error Decoding for Practical Application" focuses on prediction error decoding for achieving planar multi-degree-of-freedom control. This research encompasses experiments involving significant/subliminal sensory stimulation-induced prediction errors. To address the challenges of cost and universality in applying these techniques to BCIs, a separate investigation is conducted, termed "Investigation of Channel Optimization Techniques for Low-Cost and Universal BCIs". Together, these studies contribute to the overarching theme of "Investigation of Universal Brain-Computer Interface Technology Utilizing Prediction Error Decoding", ultimately enabling planar multi-degree-of-freedom BCI control with fewer common electrodes during natural motor imagery tasks.

Limitations and Improvements:

In the application of prediction error decoding techniques, a detailed investigation into the relationship between the stimulation current intensity of GVS and the resulting prediction errors is warranted. We hypothesize that there may exist a 'threshold' at lower current values, below which the decoding accuracy would start to decline towards chance levels. Identifying this 'threshold' is not only meaningful from a user-friendly perspective but also provides a basis for elucidating the connection between prediction errors and sensory feedback at the decoding level. Furthermore, it is imperative to consider in more depth the neural physiological mechanisms underlying the generation of prediction error signals. Additionally, distinguishing between prediction errors and seemingly similar but distinct Error-Related Potential (ErrP) signals that often manifest 200-500 ms after an error occurs is essential. Leveraging detection and analysis of participants' ErrP signals when errors arise in prediction error decoding can further refine motor control by aiding in error identification and providing feedback to participants, thereby significantly enhancing BCI system accuracy and reliability. Trials involving disabled populations are also necessary as they constitute a primary user group for this technology. Equally pivotal is conducting online testing to validate system stability. To address universality concerns in BCI applications, our proposed simple optimization algorithm relies on SLR and related statistical methods; however, further extensive analysis of statistical criteria is required. Factors such as temporal distribution of feature selection and feature preference across different tasks should be explored more extensively.

備考：論文要旨は、和文 2000 字と英文 300 語を 1 部ずつ提出するか、もしくは英文 800 語を 1 部提出してください。
Note : Thesis Summary should be submitted in either a copy of 2000 Japanese Characters and 300 Words (English) or 1 copy of 800 Words (English).

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