Emotion Estimation Using Single-Channel EEG and Heart Rate Variability for Industrial Applications

Chen Feng
Department of Information Science and Engineering
Shibaura Institute of Technology
Tokyo, Japan
i042370@shibaura-it.ac.jp

Narumon Jadram
Functional Control System Graduate School
Shibaura Institute of Technology
Tokyo, Japan
nb23107@shibaura-it.ac.jp

Yuri Nakagawa
Functional Control System Graduate School
Shibaura Institute of Technology)
Tokyo, Japan
nb23112@shibaura-it.ac.jp

Midori Sugaya
Department of Information Science and Engineering
Shibaura Institute of Technology
Tokyo, Japan
doly@shibaura-it.ac.jp

***Abstract*—The industrial world is shifting from mass production to meeting individual needs, requiring guidelines to incorporate emotions and preferences. Traditional questionnaires fall short in capturing detailed real-time emotion changes. Therefore, we propose a novel approach using Electroencephalography(EEG), which reflects central nervous system activity, and heart rate variability(HRV), which reflects autonomic nervous system activity, to estimate emotions in real-time by analyzing arousal and valence. Based on the 2D Arousal-Valence model, we plot EEG and HRV data onto this model to visualize emotion changes caused by external stimuli. Using this proposed method, we conducted joint research with the home and personal care sector to evaluate emotional responses to aroma products, and with the automotive sector to assess drivers' emotional states. These studies demonstrate the value of academic research in guiding the industrial sector, particularly through emotion estimation based on EEG and HRV. Our findings suggest that these technologies offer valuable insights into consumer emotions, which can help improve product design and user experience. Ongoing collaboration between academia and the industrial sector is crucial for overcoming challenges in interpreting physiological signals and effectively integrating these methods into practice.**

Keywords—emotion estimation, industrial application, EEG, heart rate variability, arousal, valence

I. Introduction

Globalization and IT advancements have driven corporations to seek innovative solutions and form partnerships with academic institutions[1]. Our research team has been focused on developing advanced emotion estimation technology based on physiological signals, aiming to enhance human-centered product design. This academic research caught the attention of industries, which recognized its potential to meet their goals and needs. Consequently, under Japan's framework for academic-industrial collaboration[2], we initiated joint research projects. These collaborations aim to integrate industrial requirements with our research, exploring new academic value while addressing practical challenges. Emotion estimation methods vary, from natural language processing[3] to nonverbal cues like facial expressions[4] and gestures[5], each with its own limitations such as subjectivity, delayed feedback, and potential inaccuracy in varying contexts. In contrast, physiological signal-based methods offer objective, real-time emotion estimate however are not yet widely adopted. Our work highlights these approaches, bridging academic research and industrial innovation. In the industrial sector, the demand for easily accessible and effective techniques to estimate emotions from physiological indexes is on the rise[6]. It is crucial that such methods are usable as tools and include visualization capabilities. In this study, we introduce emotion estimation technology based on Electroencephalography(EEG) and heart rate variability (HRV). We also showcase joint research with industries utilizing this technology.

II. Emotion Estimation method

In 2017, we proposed a method to estimate emotions[7] using arousal-valence model based on Russell's circumplex model of affect[8]. This model associates arousal with EEG indexes reflecting central nervous system activity[9] and valence with HRV, which is calculated from R-R intervals (RRI) and reflects autonomic nervous system activity[10]. By plotting EEG and HRV data onto the arousal-valence model, we can visualize real-time emotion changes caused by external stimuli. To investigate the reliability of our emotion estimation method, we conducted a preliminary study[11] in 2018 using consumer-grade single-channel EEG sensors to measure EEG indexs and PPG sensors to calculate HRV indexes. We hypothesized that the emotional intelligence of participants influences the accuracy of emotion assessment. Therefore, individuals with high emotional intelligence (20% of the sample) were selected based on their ability to discern emotions. Emotion estimation was performed by correlating their X (valence) and Y (arousal) values with the Russell's circumplex model of emotion[7](Figure 1, left), yielding a strong correlation (r=0.94), validating our method's reliability[12]. To meet the robust needs of the industrial sector, we developed the emotion visualizer, a tool that enables real-time, simplified measurement and visualization of emotional states. This tool facilitates the practical application of our research in various industrial contexts, providing valuable insights for human-centered product design.

Figure 1: Proposed method(left); Experimental scene (middle); Comparison of comfort and arousal results of one participant(right)

III. Applications for Industrial Sector

We have established our methodology and pioneered seed technology in academia using government funding. Participating in the 2019 Japan Science and Technology Agency (JST) New Technology Briefing[13], we received offers from multiple industries, driving joint research forward. Here, within the scope of this publication, we outline the evaluations conducted by applying our methodology to the industrial sector. Over the past five years, we have engaged in approximately 20 joint research projects, each covering a diverse array of topics and applications. In this chapter, we use examples from our collaborations in the automotive sector and home and personal care sector to illustrate the application and evaluation of our methodology, highlighting its versatility and efficacy in addressing industrial needs.

A. *Detecting Driver States Using EEG and HRV-Based Emotion Estimation*

Emotion recognition is critical in the automotive industry as a driver's emotional state significantly impacts traffic safety[14]. Negative emotions like anger and stress impair a driver's perception and judgment, leading to accidents[15]. While autonomous vehicles aim to reduce human error, in conditionally automated vehicles, drivers must take control when the system limits are reached[16]. During automated driving, drivers may become drowsy, which poses risks when they need to retake control. Thus, it's essential for drowsy drivers to achieve and maintain high arousal for safe driving. However, high arousal with low comfort can induce negative emotions, affecting performance. To address this, we collaborated with an autonomous driving company to find methods for waking drowsy drivers comfortably. We propose using EEG and HRV indexes to measure a comfortable arousal state, characterized by high arousal and comfort. Experiments with an autonomous driving simulator compared two stimuli for waking drivers(Figure1, middle). Participants slept during autonomous driving and took control upon waking. Results showed EEG and HRV indexes effectively assessed differences in the comfortable arousal effects of aroma and wind(Figure1, right). These findings suggest that emotion estimation technology based on EEG and HRV can enhance driving safety and comfort, benefiting the automotive industry.

B. *Comparing Emotional Impact of Different Olfactory Stimuli Using EEG and HRV*

Our emotion estimation method has also been applied in the home and personal care industry, where understanding consumer emotional responses to products is crucial. In the modern information society, people face constant stress from complex work environments and interpersonal relationships[17]. Aromatherapy is gaining attention as a stress relief method[18]. To quantify the psychological effects of these aromas, Tip et al. conducted a study based our emotion estimation method based on EEG and HRV to evaluate psychological states during aroma inhalation[19]. The study involved presenting seven different olfactory stimuli to participants while collecting EEG and HRV data. Analysis revealed that olfactory stimuli significantly impact psychological states, with immediate responses that normalize over time. Significant differences in EEG and HRV indexes were observed between pleasant and unpleasant odors, particularly among males aged 20–30. The delta wave and RMSSD indexes showed potential for evaluating psychological states across different populations. Tip et al. concluded that EEG and HRV can effectively evaluate psychological states in response to olfactory stimuli. By visualizing these psychological states on emotion map, they provided insights into appropriate EEG frequency bands for evaluation. This research not only demonstrates the potential of using EEG and HRV for real-time emotion estimation but also offers valuable applications for marketing and product design, enhancing understanding of consumer emotional responses to various olfactory products.

IV. Conclusion

Our joint research with various companies has demonstrated the value of using physiological signals for emotion estimation, particularly in the automotive and home and personal care industries. Additionally, our research encompasses a wide range of applications, evaluation of entertainment industry works[20][21], including packaging design[22] and interior design[23]. The growing number of collaborations each year highlights the increasing demand for these innovative methods. We have made significant progress in constructing emotion models using machine learning on extensive physiological data, indicating potential for enhancing product design and user experience. However, challenges remain, such as accurately interpreting physiological signals and integrating these methods into existing industrial processes. Continued collaboration between industry and academia is essential. Advancing research methodologies and effectively applying these findings in practice will require efforts from both universities and companies. This synergy can help that emotion estimation techniques become more valuable and widely adopted, ultimately bridging academic research and industrial innovation.

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