Annals of Nuclear Energy 111 (2018) 595–607

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Development of an EEG-based workload measurement method in nuclear power plants

Moon Kyoung Choi [a], Seung Min Lee [a,b], Jun Su Ha [c], Poong Hyun Seong [a,*]

[a] Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
[b] Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon 34057, Republic of Korea
[c] Department of Nuclear Engineering, KHALIFA University, AbuDhabi 127788, United Arab Emirates

ARTICLE INFO

Article history:
Received 2 August 2016
Received in revised form 31 May 2017
Accepted 16 August 2017

Keywords:
Electroencephalogram (EEG)
Mental workload
NASA task load index (NASA-TLX)
Human performance
Operating support systems (OSS)

ABSTRACT

The environment of main control rooms of large scale process control systems such as nuclear power plants (NPPs) has been changed from the conventional analog type to the digital type. In digitalized advanced main control rooms, human operators conduct highly cognitive work rather than physical work compared to the case of the original control rooms in NPPs. Various operating support systems (OSSs) have been developed to reduce an operator's workload. Most representative techniques to evaluate the workload are based on subjective ratings. However, there are some limitations including the possibility of skewed results due to self-assessment of the workload and the impossibility of continuously measuring the workload due to freezing simulation for workload assessment. As opposed to subjective ratings techniques, physiological techniques can be used for objective and continuous measurements of a human operator's mental status by sensing the physiological changes of the autonomic or central nervous system. In this study, electroencephalogram (EEG) was used to measure the operator's mental workload because it had been proven to be sensitive to variations of mental workload in other studies, and it allows various types of analysis. Based on various research reviews on the characteristics of brainwaves, EEG-based Workload Index (EWI) was suggested and validated through experiments. As a result, EWI is concluded to be valid for measuring an operator's mental workload and preferable to subjective techniques. Furthermore, EWI was applied to evaluate the effects of OSSs on human operators through experiments. Finally, it is expected that the results of this study can be used to measure the operator's workload in NPPs.

1. Introduction

The operating environments of main control rooms (MCRs) in nuclear power plants (NPPs) have been considerably changed by adopting new human-system interfaces (HSIs) that are based on computer technologies (Chang et al., 1999; Kim, 1994). The design of instrumentation and control (I&C) systems for various plant systems is also rapidly moving toward fully digital I&C (Yoshikawa et al., 1997; Ohi et al., 2002). The roles of the operators in advanced MCRs hence has shifted from manual controlling to supervising the plant's status or decision-making (Sheridan, 1992). The operator's tasks are expected to require increased mental activities rather than physical activities. In advanced MCRs, the mental workload consists of the information processing workload required by a human operator to complete tasks and the emotional stress workload experienced by the operator (Sheridan and Stassen, 1979). If the mental workload exceeds the limit of the operator capacity, human performance will deteriorate (Norman and Bobrow, 1975). Thus, various operating support systems (OSSs) have been developed to reduce the operator's workload, and the effects of OSSs on human operators usually have been evaluated by using a self-report or a questionnaire that asks the operators to rate their level of mental effort during the tasks. This kind of approach has the advantage of operator acceptance and ease of use. However, it has some weaknesses such as dependence on the operator's memory as well as bias, and furthermore it has a possibility of skewed results due to the self-assessment of the mental workload (Ha, 2005; Charlton, 2002).

Nowadays, physiological techniques have received much attention due to rapid technology development. In contrast with subjective ratings, physiological techniques can be used for objective and continuous measurements of the mental workload of a human

* Corresponding author.
E-mail addresses: mk.choi@kaist.ac.kr (M.K. Choi), jewellee@kaeri.re.kr (S.M. Lee), junsu.ha@kustar.ac.ae (J.S. Ha), phseong1@kaist.ac.kr (P.H. Seong).

https://doi.org/10.1016/j.anucene.2017.08.032
0306-4549/

operator by sensing the physiological changes of the autonomic or central nervous system associated with cognitive workload. (Wilson, 2002).

The goal of this study is to propose a physiological signal-based workload measurement method for a more objective assessment. A literature survey on the suitability of physiological signals, especially electroencephalograms (EEGs), for measuring the mental workload of human operators in MCRs was conducted. The existing research on the principles of brainwaves was reviewed. Finally, an EEG-based workload measurement method is proposed in accordance with the environment of the MCRs, and it was validated with experiments.

The remainder of this paper is organized as follows. Section 2 presents the process for suggesting the EEG-based Workload Index (EWI). Section 3 presents the validation of the suggested measure through experiments. Section 4 presents an application for the suggested measure on evaluating how operating support systems affect the mental workload of a human operator. Section 5 presents the conclusions.

2. Development of EEG-based workload index (EWI) for measuring human operator's mental workload

2.1. Selection of a method for measuring workload

The mental workload of human operators can be evaluated by performance-based measures, subjective ratings, and physiological measures (Williges and Wierwille, 1979). The performance-based approach includes the measurements of primary tasks and secondary tasks. Primary task performance measures provide direct indications for interested task performance. However, they are not very sensitive to changes of workload, especially when operators have spare capability to increase their effort level, and hence the measures are not suitable for assessing cognitive workload associated with monitoring or decision-making tasks in NPPs. The measure of secondary task performance provides a more sensitive measurement of operator capacity compared to the measure of primary task performance. However, it has the drawback that the measurement itself contaminates human performance by interfering with primary tasks (Wickens and Hollands, 2000).

Subjective ratings techniques measure the cognitive workload experienced by a subject through a questionnaire and an interview. They have usually been used to assess workload because of a high degree of operator acceptance and easiness to use. There are representative subjective measures such as overall workload (OW), modified cooper-harper scale (MCH), national aeronautic and space administration task load index (NASA-TLX), etc. However, the subjective rating techniques have several disadvantages: (1) potential confusion of mental and physical workloads, (2) difficulty in distinguishing external demand/task difficulty from an actual workload, (3) unconscious processing of information that the operator cannot rate subjectively, (4) dissociation of subjective ratings and task performance, (5) the necessity of a well-defined question, and (6) dependence on an operator's short-term memory (O'Donnell and Eggemeier, 1986).

In contrast, physiological measures are known for being unobtrusive and objective, and can provide continuous information regarding mental efforts. Under a high workload, operators have to expend more mental effort in order to maintain an adequate level of performance. There is an underlying assumption that high workload levels are accompanied by increased emotional stress. This stress is then measured by physiological recordings and is related back to workload. Such mental effort results in a decrease in parasympathetic responses and an increase in sympathetic responses, which results in peripheral reactions. Physiological measures have been used in a number of real world environments to monitor operator workload (Kim, 2006). Electroencephalogram (EEG), evoked potential, heart rate-related measures, and eye movement-related measures are representative tools for cognitive workload evaluation based on physiological measurements.

In this study, EEG is selected to measure workload for the following reasons. Various studies based on tasks such as in-flight refueling mission (Brookings et al., 1996; Brookhuis and Waard, 1993), air traffic control (Donchin and Coles, 1988), and automobile driving (Boer and Veltman, 1997) reported that the EEG measures are sensitive to variations of mental workload in applied settings regarding arousal in vigilance situations. Brain signals of a subject can be measured quantitatively by an array of physiological sensors, some requiring contact with the subject's head through electrolyte sensors. EEG permits an objective workload assessment and can provide real-time evaluation, thus allowing the system designer to quickly and accurately identify usability problems as they occur. Detailed and various analyses of the results of brainwaves are also possible (Tran et al., 2007). In general, the power spectrum analyses have been mostly applied in existing experimental studies with EEG measurement.

2.2. Suggestion of EEG-based workload index (EWI)

Conventional EEG measuring methods are used to check if there are some changes in the brain. Most studies only focus on if there are changes in the EEG under certain circumstances. These studies use a comparison of before and after with a simple relative comparison of certain brainwaves. Conventional methods using EEG only explain the presence of changes in the brainwaves or the relative comparison of before and after. Thus, this section explains the suggestion that the EEG-based Workload index can supplement these drawbacks.

There are two methods to derive the power of EEG brainwaves. Absolute band power is the total energy intensity of an electrode on a certain region at different frequency bands. Relative band power is the relative power of a specific band to the total power. The relative band power, which is the fraction of power in certain frequencies to the power of all frequencies of brainwaves, should be used in order to accurately assess an individual's EEG power value because EEG power values differ from individual to individual.

In this study, the brainwaves in the prefrontal lobes of subjects were only considered because the prefrontal lobe is related to cognitive demands including aspects of perception, executive control, working memory, response selection, and problem solving (Duncan and Owen, 2000) and band pass filtering was conducted to remove the delta (0–4 Hz) band, which can be easily influenced by external noises such as neck movements or eye blinking. A literature survey of the characteristics of brainwaves according to frequencies was also conducted.

Theta waves (4–8 Hz) are related to memory performance, and are modulated by memory load and plays an important role during encoding and memory retrieval (Doppelmayr et al., 2002; Jensen et al., 2002; Klimesch, 1999). Theta waves are involved in daydreaming and sleep and also have benefits of helping improve creativity, and make people feel more acceptable. According to some research, distinct theta activity on EEG in the frontal midline area reflects mental concentration as well as a meditative state or relief from anxiety (Kubota et al., 2001). Enhanced theta brainwaves also induce a relaxed state of wellbeing and alleviate pre-performance anxiety. (Tilstone, 2003). Due to characteristics of tasks in NPPs demanding high cognitive work, it is thought that high theta power can be associated with reduced operator anxiety. In pilot experiments of this study with an NPP simulator, the theta power of subjects who felt high stress and showed low performance was lower