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Operator functional state classification using least-square support vector machine based recursive feature elimination technique

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ABSTRACT

This paper proposed two psychophysiological-data-driven classification frameworks for operator functional states (OFS) assessment in safety-critical human-machine systems with stable generalization ability. The recursive feature elimination (RFE) and least square support vector machine (LSSVM) are combined and used for binary and multiclass feature selection. Besides typical binary LSSVM classifiers for two-class OFS assessment, two multiclass classifiers based on multiclass LSSVM-RFE and decision directed acyclic graph (DDAG) scheme are developed, one used for recognizing the high mental workload and fatigued state while the other for differentiating overloaded and base-line states from the normal states. Feature selection results have revealed that different dimensions of OFS can be characterized by specific set of psychophysiological features. Performance comparison studies show that reasonable high and stable classification accuracy of both classification frameworks can be achieved if the RFE procedure is properly implemented and utilized.

1. Introduction

With the development of modern automation techniques, the complexity in control systems has been significantly increased. Human operators are becoming supervisors and the decision makers in human-machine collaboration systems (HM systems). On one hand, operators are required to act appropriately based on visual and auditory information related to system status. However, operators may ignore critical clues due to the limited cognitive capability when large information flow occurs [1]. On the other hand, since computers or mechanical controllers are utilized to replace the roles of human in control loops [2], the out of the loop (OOTL) state of operators may lead to the loss of situation awareness (SA) and prevent the operator from manually coping with unforeseen emergency events in time [3]. In order to avoid operator performance degradations caused by both factors above, researchers are becoming interested in studying how to maintain the optimal operator functional state (OFS) of HM systems.

Potential application areas of OFS assessment are transportations (driving, railway and shipping), process control systems (chemical and nuclear plants) and the manned space flight, where the risk of accident is closely related to the poor performance of human operators [4]. Furthermore, adaptive automation (AA) has been proposed for OFS preservation. AA allows HM systems to allocate proper type and amount of tasks between the operator and the computer dynamically. Meanwhile, particular auxiliary strategies are used in AA to reduce the complexity of specified task [2–4]. The implementation of AA is based on the results of OFS assessment. When

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OFS is effective, tasks allocation remains unchanged; when risky OFS caused by OOTL states occurs, several tasks will be assigned to operators to keep the engagement, and when risky OFS caused by high cognitive load is detected, several tasks for operators will be reallocated to computers temporarily and particular auxiliary strategy is activated. Hence, operators can be attentive while cognitive overload is avoided.

OFS can be determined indirectly by the task performance, subjective evaluation and psychophysiological measurements [5–7]. The last approach is considered to be superior since psychophysiological signal is continuously and objectively available [5,8]. Psychophysiological measurements based on electroencephalogram (EEG), electrocardiogram (ECG), electrodermal measurement (EDM), electromyogram (EMG), electrooculography (EOG) are gradually explored in OFS assessment issues [8–11]. The primary objective of this paper is to build OFS classifier with stable accuracy while it could interpret different aspects of OFS via the change of specific set of psychophysiological features. Several typical psychophysiological measurements (EEG, ECG and EOG) have been examined in our study.

Mental workload (MWL) caused by the transient cognitive demand is often considered as the most important factor affecting OFS. A series of reported works verified that the degree of MWL incurred by different task complexity levels could be classified by the change of the EEG power spectral density (PSD) [12,13]. Several extended works [14,15] have examined MWL assessment by EEG specified in air traffic control tasks. On the other hand, heart rate (HR), heart rate variability (HRV) and blood pressure, which represent the activities of parasympathetic nervous system (PNS), were also studied [16–18]. Combinations of different psychophysiological measurements were examined for overcoming the insensitivity of the single indicator on particular individuals [19,20]. Other factors affecting OFS are fatigue (represented by the decrement of alertness) [21] and SA [22]. Fatigue accumulation is significant when the operator performs long-time-duration and low-cognitive-demand tasks (e.g. driving). Different psychophysiological indicators were examined and successfully classified by artificial neural network (ANN) or fuzzy inference systems (FIS) for this issue [23–27]. Meanwhile, the operator is in risky OOTL states when SA decreases [2,3]. Particularly, the SA assessment model in the flying and air traffic control task has been studied [28,29].

Recent reported works are paying attention to improving the stability and accuracy of the OFS assessment results [30,31]. Christensen et al. [31] examined three pattern recognition methods, i.e., ANN, linear discriminant analysis (LDA) and support vector machine (SVM), for the purpose of achieving classifiers with stable generalization capacity. They found that the change of data distribution between days significantly undermined the classification accuracy while the extension of training sets is considered to be an effective way to improve the accuracy.

When mentioned to the implementation of AA [32–37], the reliable results of OFS assessment can provide real-time feedback to the task allocation scheme. In this way, the closed loop system is expected to be built for OFS preservation. Particularly, Pope et al. [33] proposed a "bio-cybernetic loop" system to improve the operator engagement in a crew management task, which is an important aspect of SA.

In this paper, a new interpretable and comprehensive OFS assessment framework based on SVM is proposed for coping with several crucial issues. Firstly, despite ANN has been demonstrated as an accurate OFS classifier, the relationship between transitions of different OFS and specific psychophysiological features is difficult to be clarified. Secondly, since evaluating single aspect of OFS (e.g. MWL) is always considered, a question received less attention in the literature is how to distinguish different types of risky OFS simultaneously (e.g. high MWL, high fatigue and low SA). Thirdly, improving real-time OFS assessment accuracy via pattern recognition methods is becoming critical. Particularly, unstable psychophysiological features may change in different or even contradictory modes across days [31]. The generalization capacity of classifiers cannot be insured in this case.

Attempting to provide an available solution for these issues, SVM-based recursive feature elimination (RFE) scheme is adopted [40,41], which is an effective feature selection method proposed by Guyon et al. for coping with related gene selection for cancer diagnosis. On one hand, RFE scheme is expected to eliminate insensitive and noise psychophysiological features while improve the accuracy of OFS assessment. On the other hand, the most sensitive features can be focused on to interpret the origin of OFS transitions.

In our previous work [38], standard SVM classifiers [43] have been employed to cope with OFS classification issue while the computational efficiency for determining the optimal classifier parameters is not satisfactory. In this work, least square support vector machine (LSSVM) [42] was used for RFE implementation and building classifiers. The modification from SVM to LSSVM significantly improves the training speed while the high generalization capability is preserved. Reported works in Refs. [44,45] have validated the performance of LSSVM for binary EEG classification problem in the background of fatigue assessment and epilepsy diagnosis. Furthermore, the LSSVM-RFE and LSSVM classifier were combined together to build OFS classification framework for coping with the psychophysiological data collected from two new experiments. The simpler case for binary classification was considered at first. A part of this task has been examined in our previous work [39] under the same methodology for two-class OFS classification using psychophysiological datasets with only 17 features [19]. Additionally, two OFS classification tasks where each has three classes are considered. In this case, one task is to simultaneously recognize high MWL and fatigued state from normal OFS. The other is to differentiate overloaded MWL and load-free (base-line) states from the acceptable MWL states. In this case, the decision directed acyclic graph (DDAG) [50] with multiclass LSSVM-RFE classification framework is developed. For each classification task, the study which compares the offline and simulation online OFS classification scheme is made to demonstrate that the stable features selected by RFE scheme could be beneficial for improving real-time OFS classification accuracy. Related experiments for psychophysiological data acquisition are designed based on the Automation-enhanced Cabin Air