Automatic Detection and Prediction of the Transition Between the Behavioural States of a Subject Through a Wearable CPS

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Abstract

The PRESLEEP project is aimed at the fine assessment and validation of the proposed proprietary methodology/technology, for the automatic detection and prediction of the transition between the behavioural states of a subject (e.g. wakefulness, drowsiness and sleeping) through a wearable CPS (cyberphysical system). The Intellectual Property (IP) is based on a combined multi-factor and multi-domain analysis thus being able to extract a robust set of parameters despite of the, generally, low quality of the physiological signals measured through a wearable system applied to the wrist of the subject. An application experiment has been carried out at AVL, based on reduced wakefulness maintenance test procedure, to validate the algorithm's detection and prediction capability once the subject is driving in the dynamic vehicle simulator.

1 Introduction

Drowsy driving is a very risky factor that usually evolves into fatal road accidents. The development of technologies capable of predicting sleep onset at the wheel represents one of the greatest challenges in the field of accident prevention systems.

A non-intrusive device is needed that can not only classify but also predict sleep onset, in order to alert in advance the driver.

2 FED4SAE project: A wearable CPS for the automatic detection and prediction of the awake, drowsiness and sleeping stages (PRESLEEP)

PRESLEEP is a R&D project funded through the FED4SAE (Federated CPS Digital Innovation Hubs for the Smart Anything Everywhere Initiative) framework. The project is aimed at the fine assessment and validation of the proposed proprietary methodology/technology, for the automatic detection and prediction of the transition between the behavioural states of a subject (e.g. wakefulness, drowsiness and sleeping) through a wearable CPS.

The background know-how relies on accurate medical and engineering analysis, previously performed by the SAT core team, which resulted in several patents filing.

The methodology relies on the deep analysis of physiological features primarily extracted through the photoplethysmography (PPG) technology.

PPG is a non-invasive optical technique for detecting microvascular blood volume changes in tissue bed beneath the skin, which are due to the pulsatile nature of the circulatory system.

PPG has important implications for a wide range of applications in cardiovascular system assessment, vital sign monitoring, blood oxygen detection, and became a mandated international standard for monitoring during anesthesia. It is worthy to note, however, that the single spot monitoring and the need to apply a PPG sensor directly to the skin limit the pulse oximetry applicability in situations such as perfusion mapping and healing assessments or when free movement is required.

Moreover, the conventional PPG sensors need to be firmly attached to the skin in order to get a good a high-quality signal. The introduction of fast digital cameras into clinical imaging monitoring and diagnosis systems as well as very advanced solutions based on ultra-short-range RADAR technology, the desire to reduce the physical restrictions, and the possible new insights that might come from perfusion imaging and mapping inspired the evolution of the conventional PPG technology to imaging PPG (IPPG). IPPG is a noncontact method that can detect heart-generated pulse waves by means of peripheral blood perfusion measurements.

The PRESLEEP project is focused on the following objectives:

- complete development of the methodology for the automatic detection and prediction of the transition between behavioral stages based on physiological parameters extracted through contact reflective PPG technology;
- complete development of the wearable CPS prototype with particular respect to the embedded SW coding of the proprietary algorithm for the automatic detection and prediction of the transition between behavioral stages

- verification and validation tests on the wearable CPS operating in realistic environmental conditions at AVL
- detailed definition of the wearable CPS (Hardware/Software) specifications for the further industrialization process with a selected supplier.

It is very important to note that the original aspect of the proposed methodology is the additional contribution provided by the real time assessment of the emotional stages. Moreover, the IP will initially run on a wearable CPS but a parallel activity based on IPPG technology has started.

Consequently, a wide range of applications, where the drowsiness of the subjects is a relevant factor, can be successfully addressed.

3 A multi-factor and multi-domain analysis: an innovative approach for the assessment of the behavioural states

The proposed methodology has been developed extrapolating from the PPG signal all the information that carries on. This has been done collecting data from the time and the frequency domain.

From the frequency domain; from the latter, is possible to import the fundamental frequencies that compose the signal, instead, for the former, the time domain analysis has been performed acquiring and analyzing the signal in its amplitude and its frequency.

3.1 Related works

In literature, there are plenty of scientific works aimed at develop methodologies able to classify the awake and the sleep phases. Some of them use the information coming from the driving experience, more precisely the steering angle, the acceleration and deceleration of the vehicle (Pomerleau, 1995; Sayed & Eskandarian, 2001; Thiffault & Bergeron, 2003; Sałapatek, 2017)[1][2][3][4]; others, instead, extract information from the camera, analyzing the facial behavior.

There are also works aimed at analysing the acquired biological signals such as the ECG (Electrocardiogram), the EEG (Electroencephalogram) or the PPG.

(Jabbar et al. 2018) shows a method based on a deep learning algorithm implemented on an Android application. This approach has been developed towards real-time drowsiness detection analysing the facial landmark key point, with an accuracy of more than 80%; the network has been trained using the data coming from 18 subjects [5].

Even focalizing its method on the analysis of the facial landmarks, (Mehta et al. 2019)'s work computes two parameters: Eye Aspect Ratio (EAR) and Eye Closure Ratio (ECR), in order to detect driver's drowsiness based on an adaptive thresholding algorithm. This system has been tested using a random forest classifier on 50 volunteers, demonstrating an accuracy of 84% [6].

(de Naurois et al. 2017) presents a novel and a multifactorial study that includes three types of measurements, elaborated by an artificial neural network, in order to detect drowsiness. There are three types of measurement: physiological, behavioural and mechanical. The physiological ones are acquired using the ECG and the PPG; consequently, the heart rate, the action of the autonomic nervous system and the respiratory rate are extracted. Behavioural measures include the blinking frequency and its duration, the PERCLOS (percentage of time eye closed) and the position of the head. The car measurements contain all the information coming from the driving manoeuvre, from the steering angle to the acceleration pedal angle. The methodology was tested on 21 participants (average age ± SD: 24.09 ± 3.41 years; 11 men and 10 women) in a realistic simulator, demonstrating an accuracy of 96% with a prediction on micro-sleep between 15s and 5 minutes in advance [7].

(Awais et al. 2017) proposes a method capable of detecting the sleepiness state using a multi-factor and multi-domain system. It acquires data from ECG and EEG, then they are classified using a support vector machine (SVM). Heart rate, heart rate variability, including LF / HF ratio, are extracted from the ECG, while a series of features have been extracted from the EEG, including time-domain complexity and statistical measures, that are the absolute and relative powers in the domain frequency. By combining the information coming from the two signals, it is possible to achieve an accuracy level of about 80%, testing the system on 22 subjects in a simulator-based driving environment [8].

The works of (Boudreau et al. 2013) and (Chouchou et al. 2014) are focused on the demonstration that there is a close correlation between the heart rate variability (HRV) and the action of the autonomic nervous system (ANS), therefore with the sleep stages [9][10]. The methodology proposed by (Li et al. 2013) has the purpose of detecting drowsiness by monitoring HRV.
This has been done in three different ways:

- the first one is FFT-based and takes into account 1-minute time-window;
- the second one is still FFT-based, but considers a 3-minute observation window;
- the third one is wavelet-based, from which entropy and kurtosis are extracted. Then, a support vector machine (SVM) performs a classification.

Considering an experimental activity with 4 subjects (3 males and 1 female), the FFT-based approach produces an accuracy of 68.8%, a sensitivity of 62.5% and a specificity of 75%. Instead, the wavelet-based approach provides a 95% of accuracy, sensitivity and specificity [11].

The methodologies mentioned above offer less effective solutions, neither in terms of robustness nor in prediction.

3.2 Proposed method

The proposed methodology has been developed considering an observation window where several physiological parameters are extracted and analysed concurrently in the frequency domain and in the time domain.

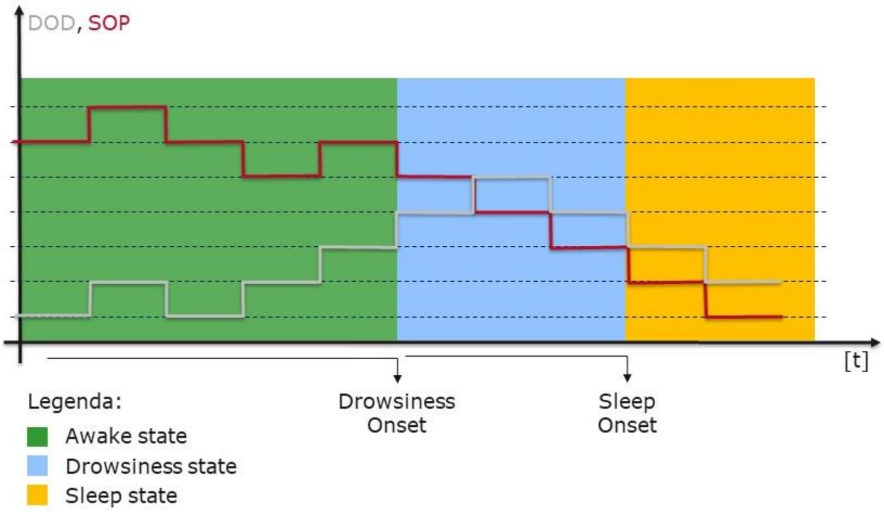
3.2.1 Frequency domain analysis

The proposed algorithm monitors cardiocirculatory activity through some parameters derived from the analysis in the frequency domain. The prediction of falling asleep is carried out by detecting the microsleep, which in sleep medicine is seen as “K” phases on the EEG signal. Usually, the microsleep anticipates the falling asleep step of some minutes.

Two parameters DOD (Drowsiness Onset Detection) and SOP (Sleep Onset Prediction) have been defined and extracted from the PPG power spectrum.

DOD and SOP change over time as a function of the action of the Autonomic Nervous System (ANS). Then the action of the sympathetic nervous system and the parasympathetic nervous system are correlated to behavioural state of the subject.

When DOD exceeds a predefined value, the microsleep is detected thus identifying the drowsiness onset. As a consequence, sleep onset is predicted when SOP is below a predefined value able to subdivide the data related to the awake state



from the data related to the sleep state.

Fig. 1. The behaviour of DOD and SOP over the time, indicating the phases according to their values.

The monitored phenomena have a dynamic nature, therefore learning and adaptive control for individual self-calibration of the physiological parameters of the subject are included.

3.2.2 Time domain analysis

The analysis in the time domain is closer to the daily sleep medicine activity, where the quality of sleep phase is analysed. In particular it is relevant to observe the variation of the PPG signal changes in terms of amplitude and frequency during the different behavioural phases. The automation of this medical procedure requires some mathematical operators such as the standard deviation, the mean value, the percentile, etc.
This time domain analysis is also used for the automatic recognition of emotional stages parameters:

- Average NN, is the average time between normal heartbeats. Low values denote an elevated heart rate that could indicate excitement, physical activity and coffee assumption. Higher NN values typically denote resting.
- SDNN, is the standard deviation of the time between heartbeats and can be used to estimate physiological stress.
- RMSSD, is the root mean square of successive differences of heartbeats and it has been used to predict the perceived mental stress.
- SDSD, is the standard deviation of successive differences between adjacent NNs.
- NN50, is the number of adjacent NN intervals that differ from each other by more than 50 ms (NN50) and requires a 2 min epoch. The proportion term pNN50 is NN50 divided by the total number of NNs. A high percentage indicates complexity in heart rate variability, correlated with good psychological and physiological state.

4 Application experiments and validation of the results

The application and the validation activity have been subdivided into 3 different steps:

- algorithm development and validation using MATLAB, Inc, analysing the complete polysomnographic analysis recorded during the night;
- implementation of the algorithm in a wearable device;
- algorithm validation in a realistic environment.

These validation tests have been performed with respect to the falling asleep step, so, the microsleep that does not necessarily lead to a sleep phase are classified as false positive.

4.1 Algorithm development and validation

This validation phase has been focused on the behavioural analysis of a number of healthy adult subjects (21 acquisitions, 20 complete registrations, 9 males and 11 females, average age 44.3 years, interval 18-81 years). The data have been continuously acquired, for about 12 hrs (8.00 pm, 8.a.m day+1) and including the night sleep. Then the data have been analysed by medical doctor expert in sleep medicine in order to classify the different behavioural stages along the timeline.

This first validation step has shown very good result reaching almost 95% in terms of sensitivity, specificity and accuracy.

The algorithm, in these cases, can predict the phase of falling asleep with an average of almost 5 minutes.

4.2 Algorithm implementation in a wearable device

For a real-time acquisition and detection, the algorithm has been implemented on a wearable device. The system is composed of a powerful wearable development platform, named Hexiwear, and a Raspberry PI. The first one acquires the signal, elaborate it and send the results in to the Raspberry PI through Bluetooth, where they are displayed and then saved in a log file.

Fig. 2. Wearable CPS and data logger

4.3 Algorithm validation in a realistic environment

Another validation step has been done with an application experiment, once the subject is driving/driven in the dynamic vehicle simulator at AVL (Graz,AT).

A relevant activity has been performed in order to integrate the WCPS into the SW environment of the dynamic vehicle simulator, as shown in the figure below:

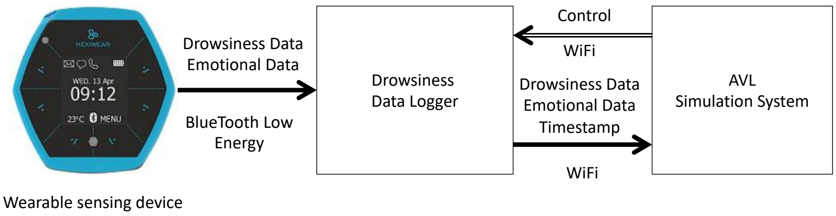


Fig. 3. WCPS integration into the AVL IODP environment

The objective of the AE is to validate the algorithm's prediction capability once the subject is driving/driven in the Dynamic Vehicle Simulator (DVS).

This is considered the most reliable and realistic test which can be carried out to detect the transition between behavioural states until drowsy/sleeping conditions.

Maintenance of Wakefulness Test (MWT) is considered a useful clinical test for the evaluation of excessive sleepiness by the Task Force of the American Academy of Sleep Medicine (AASM). It requires the patient to fight against sleepiness in a soporific condition and it is considered as a validated, objective measure of the ability to stay awake.

According to the medical literature and taking into account the main object of such a study, it is reasonable to execute a Reduced Maintenance of Wakefulness Test (R-MWT). The R-MWT uses a limited set of sensors, which are essential to assess the transition from drowsiness to sleep state.

The objective of such a test is to compare physiological parameters recorded by a standard polysomnography and the WCPS during a R-MWT performed in a simulated driving context. In particular, in the case of a transition from wakefulness to sleep state, during the driving simulation, the WCPS's ability to predict and identify falling asleep will be verified.

The study has been approved by the technical and scientific committee of J Medical Center (Torino, Italy). All participants will receive details about the study and then will sign written informed consent before undergoing the test.

This activity focused on acquiring data for validating the algorithm in a realistic environment. Although the noisy room, the validation has given good results. The analysis has been conducted on a number of healthy adult subjects (21 acquisitions, 9 males and 11 females, average age 44.3 years, range 18 - 81 years). Then the data analysis has been performed by medical doctor expert in sleep medicine, thus basically confirming the high sensitivity and specificity values obtained in the previous experimental activities.

The algorithm, in these cases, can predict the falling asleep phase with an average of almost 3-4 minutes.

Fig. 4. The final Application Experiment on the Dynamic Vehicle Simulator at AVL

5 Further steps and conclusions

The PRESLEEP project has supported the development of an innovative methodology to analyse the behavioural transition of a subject through a multi-factor and multi-domain IP running in real-time on a wearable CPS.

A realistic Application experiment has been carried out on the Dynamic Vehicle Simulator at AVL.

It has been proven that the algorithm predicts the time horizon when the subject will fall asleep (at least 5 min before the sleep onset) and detects the drowsiness onset (1 min resolution).

Further analysis based on a new set of experiments, in different operating conditions, are planned and will be performed in Q1-2020.

A preliminary discussion regarding the exploitation of the result with a selected industrial partner is on-going.

A feasibility study concerning the application of the IP on contactless PPG technology (e.g. short-range RADAR) is currently under development.

Shortly, the purpose of the application is a wearable CPS worn during the driving experience, then the short-range RADAR installed in the car will provide at the data acquisition.

6 Acknowledgment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 761708.

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7 Keywords

Please provide keywords.

Keywords: Cyber Physical System, embedded SW, biomedical engineering