Drowsiness Detection by Electrooculogram Signal Analysis in Driving Simulator Conditions for Gold Standard Signal Generation

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Abstract: Detection of drowsiness while driving is a leading objective in advanced driver assistance systems. This work presents a new index to assess the alertness state of drivers based on the EOG dynamics derived from a polysomnography device. More than 15 hours of laboratory tests were analyzed in order to detect drowsiness while doing cognitive activities. The proposed method has a sensitivity of 92, 41% and a VPP of 93,41% in detecting drowsiness. The results show that the proposed index may be promising to assess the alertness state of real drivers.

1 INTRODUCTION

Drowsiness is one of the main causes of vehicle accidents. A recent study showed that 20% of crashes and 12% of near-crashes were caused by drowsy drivers (NHTSA VSR, 2006). The morbidity and mortality associated with drowsy-driving crashes are high, perhaps because of the higher speeds involved combined with delayed reaction time (Faber, 2004).

Driver behaviour monitoring, and the reliable detection of drowsiness and fatigue is one of the leading objectives in the development of new Advanced Driver Assistance Systems (ADAS). Of the use of biomedical signal analysis to detect drowsiness in real vehicles appears the need of an objective gold standard to compare with the selected signals, in this case thoracic effort. The most objective signal to assess the sleep onset phase is Electroencephalography (EEG). The problem associated to this signal is that, in real environments (i.e. vehicles) the actual devices used in hospital environment to acquire de data presents artefacts due to vibration and movements of the vehicle that masks the real EEG signal.

The aim of this work is validate the EOG signal as a new Gold Standard and the EOG acquisition device as a good quality device to ensure the optimal quality of the data. The EOG signal is a highly robust to artifacts signal related to EEG valuable to compare with our drowsiness detection index based on thoracic effort variability (TEDD) in real environments. (Rodríguez-Ibáñez, 2011)

2 PRIOR WORK

2.1 EEG and EOG Signals as Gold Standard

During active wakefulness (i.e., when the person is awake and pursuing normal activities), the EEG is characterized by high frequencies (i.e., 16 to 25 Hz) and low voltage (i.e., 10 to 30 microvolts). EOG readings during wakefulness exhibit Rapid Eye movements (REM).

During relaxed wakefulness (i.e., when a person is awake but has his or her eyes closed and is relaxed), the EEG is characterized by a pattern of alpha waves with a frequency of 8 to 12 Hz and an amplitude of 20 to 40 microvolts. EOG readings

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show slow, rolling movements (Roehrs, 2011), increase of blinking frequency and lots of saccadic response at the transition to NREM sleep onset (Dinges, 2005).

2.2 EEG and EOG Signals Acquisition in Real Driving Environments

The most important handicap in the field of drowsiness detection in real driving environments is the fact that the filtration of the low amplitude biomedical signals in order to eliminate vibration and movement artifacts is a very complex work that, in most cases, also affects the original signal of interest.

Hundreds of real vehicle tests have been made in the last three years with the objective of finding a biomedical signal robust to artifacts and also related to sympathetic-vagal system to provide drowsiness information in real vehicle tests.

The EEG signal has always been the most objective signal to define drowsiness in laboratory conditions but in real vehicle tests the EEG signal presents several problems as artefacts and the fact that the EEG codifications Rechtschaffen & Kale's method (Rechtschaffen & Kale, 1968) is only recommended with closed eyes. According to the EEG-EOG studies there is a relation between EEG waves and EOG patterns that allows generating an objective Gold Standard signal for drowsiness detection from EOG signal.

For the first real vehicle tests the EEG and EOG signal was acquired with a Bitmed eXim Pro polysomnography device. The EOG signal quality was good before and after filtering the vehicle vibrations and movement artifacts but the EEG signal was lost in the filtering process due to the fact that the frequency of the vibrations was the same frequency that the waves of interest (theta and alpha waves).

Following this results, currently we have focused on find new devices that avoids the problem of the artifacts in EEG signal. Two different tests have been made in real vehicle with two different polysomnography devices:

- Nicoletta wireless device
- Bionic EEG holter that provides active electrode technology

Although both systems show improvements in the EEG signal quality it hasn't enough quality to extract the drowsiness information. The filtering solution had the same problems that with other polysomnography devices.

Taking in to account this results and the fact that the EEG and the EOG signals are physiologically related we recommend the use of EOG data as Gold Standard in real vehicle tests. This work proposes different indexes based on slow eye movement's detection, blinking frequency and saccade movement's inhibition.

3 MATERIALS AND METHODS

3.1 Measurement Protocol

The participants in the test were 17 male and 6 female with ages between 20 and 29 years and no clinical conditions. These tests were designed and performed in laboratory conditions.

To perform these tests the setup was equipped with a biomedical monitor (Bitmed eXim Pro, BitMed) and a webcam. The biomedical signals selected as significant for this test were the external observer (video), Electrooculography (EOG) and thoracic effort. The thoracic effort signal was measured in all cases using an inductive band located at the middle trunk above the diaphragm. The EOG signal was measured with four Electromyography (EMG) single electrodes: two were located in the outer cantus of each eye in the case of the horizontal EOG setup, and two more electrodes located in the upper part and in the lower part of the right eye (Fig. 1). The EOG and the respiratory signal were sampled at 100 Hz.

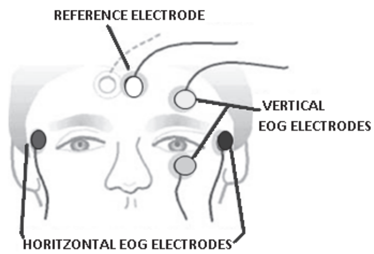


Figure 1: EOG instrumentation.

Video signal was recorded to generate the external observer variable.

3.2 Test Design

The test was designed to classify the different eye movements and set a level of eye activity or eye inactivity (related to drowsiness). The test setup consists of a vehicle seat and a 19'' inches monitor in front so the subject of the tests can see the patterns classification video seated on the vehicle seat. The test has two parts:

a) Patterns classification part.

Once the subjects are seated and connected to the acquisition systems the first part starts and they were asked to watch a 5 minutes video with the objective of follow the point on the video movements of the point in the screen represents the movement of the eye for the following patterns of interest:

- Saccadic movement
- Compensation movements
- Blinking
- Fixed gaze
- Seeking movements
- Slow Eye Movements (SEM)

The monitor has to be no more than 15 cm far from the face of the subject.

b) Drowsiness state classification part

The subject rest relaxed in the seat for over 20 minutes with eyes open.

3.3 Patterns Classification

The patterns selected as indicative of drowsiness where the following:

3.3.1 Saccadic Movement

Saccadic movements are defined as rapid symmetric eye movements with the objective of constantly change the retinal focus from one point to the next point in the visual path.

There is a linear relation between the size of the saccade and the velocity of the ocular movement. The mean duration of saccadic movements ranges between 30 and 120 ms.

In an awaken state these movements are mostly voluntary and they are used to redirect the gaze to the point of interest of the scene. In fatigue and drowsy states the saccadic speed decreases (Galley, 1989, 1993, 1998; Sirevaag & Stern, 2000) and the latent period between saccades increases.

3.3.2 Compensation Movement

Compensation movements are reflex movements that imply the coordination of both eyes. These movement works as an object fixation mechanism while moving head or body. The most important is the Vestibulo-Ocular Reflex (VOR) with a response time of 16ms.

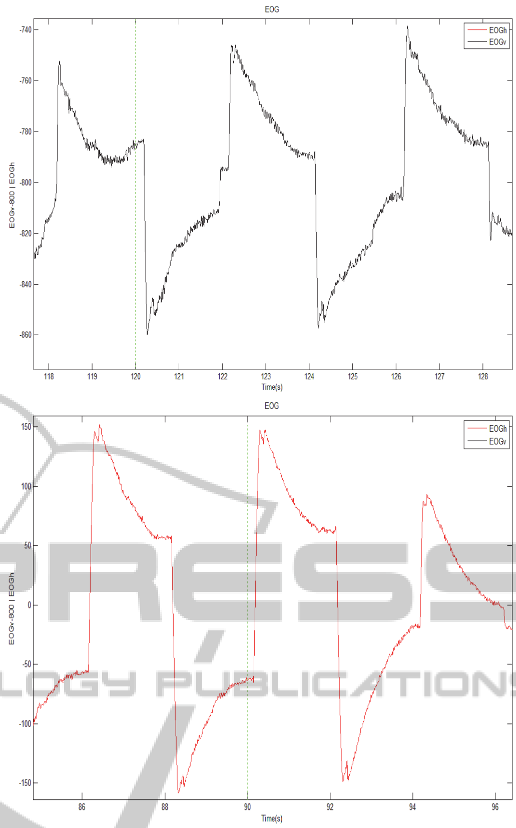


Figure 2: EOGv saccades (black) and EOGh saccades in red. Filter: band-pass 0.2-30Hz.

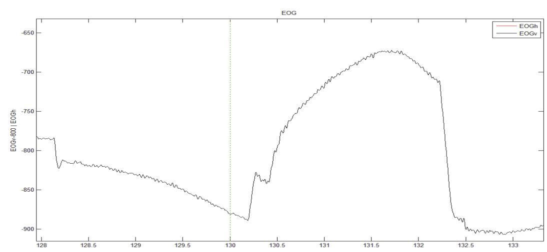


Figure 3: Compensation movement in EOGv signal. Band-pass filter 0.2-30Hz.

3.3.3 Blinking

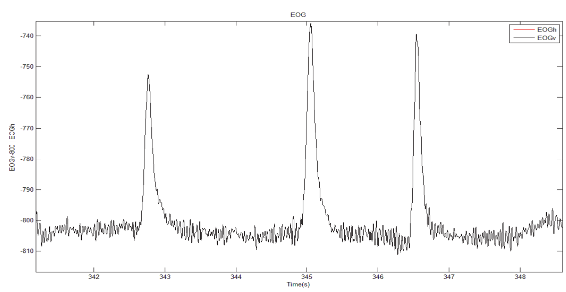


Figure 4: Blinking pattern on EOGv signal. Band-pass filtering 0.2-30Hz.

Blinking is the rapid closing and opening of the eyelid that provides moisture to the eye by irrigation using tears and a lubricant that the eyes secrete. The mean frequency of blinks in a normal subject is 12 to 19 blinks per minute. This frequency can be influenced by internal or external factors. Fatigue and drowsiness decreases the blinking rate and increases the percentage of eye closure time.

3.3.4 Fixed Gaze

The fixed gaze or ocular movement fixation can be a characteristic pattern of interest in one point or low cognitive activity depending on the duration of the pattern. In a normal context the fixed gaze duration ranges between 200ms and 350ms with open eyes. In phases of fatigue or drowsiness the fixed gaze time can reach 3 seconds becoming an ocular lost of activity (Salthouse and Ellis, 1980); (Viviani, 1990).

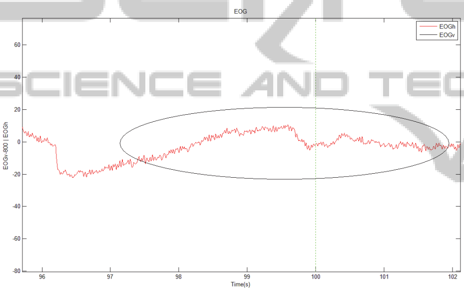


Figure 5: EOGh fixed gaze pattern. Ban-pass filter 0.2-30Hz.

3.3.5 Seeking Movements

Seeking movements are coordinated movements between two eyes with the porpoise of follow slow visual stimuli. Their function is to stabilize the dynamic visual image in the retina with velocities between 1 and 30º/s.

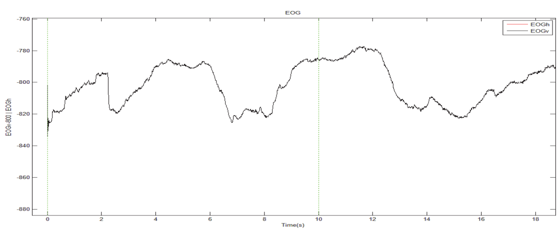


Figure 6: Seeking movement in EOGv signal. Band-pass filter 0.2-30Hz.

3.3.6 Slow Eye Movements (SEM)

Slow eye movements are eye movements with duration between 1 and 3 seconds mostly detected in the horizontal component of the EOG. This movement is characteristic of drowsiness states. Its characteristic of sleep onset with eyes closed but this pattern can also be seen with open eyes in drowsy drivers fighting for not to fall sleep.

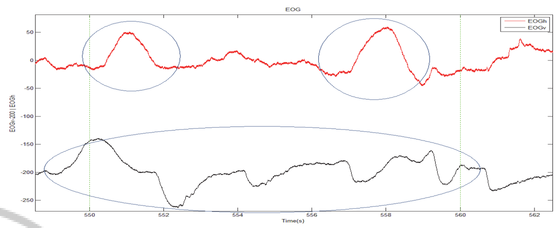


Figure 7: SEM. Band-pass filtering 0.2-30Hz.

3.4 Drowsiness Indicators

Awaken estate has been defined as a state of high activity and information interchange between the subject and the environment (Phase 0), Fatigue as a state of lack of energy and motivation (Phase 1) and drowsiness as a state related to the sleep onset. Only some of the EOG patterns explained have direct relation with the sleep onset:

Blinking – An increase of the blinking frequency in addition to an increase of the percentage of eye closure are indicative of sleep onset.

Saccade – The number of saccades and the detection of fixations combined can be an index to estimate the ocular activity assuming saccades as activity and fixation as no activity. There is a direct relation between the reaction time of the subject and the velocity of the saccade movement.

Slow Eye Movements (SEM) – During the transition of awake to sleep is very common the appearance of slow eye movements (SEM), like pendulum low frequency (0.1-1hz) movements in the horizontal line of the eye.

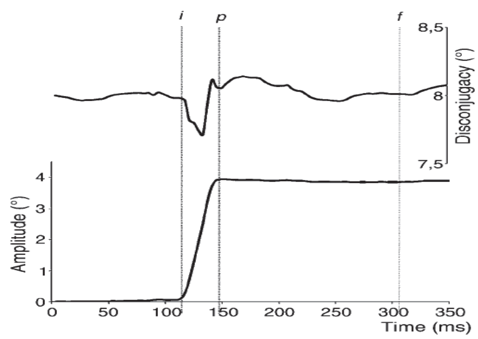


Figure 8: Determination of the beginning and the final of the saccade movement. Binocular motor coordination during saccades and fixations while reading: A magnitude and time analysis (Vernet et al., 2011).

4 EOG SIGNAL PROCESSING

4.1 Preprocessing

A non-linear filter preprocessing of the signal has been done. The filter used was a non linear filter derived from the Hodrick-Prescott (1) filter with the objective of removing repeated oscillations in the signal. Cutoff frequency at -6dB.

$$H_{2,\lambda}(\omega) = \frac{1}{1 + 2^2\lambda(\cos\omega - 1)^2} \quad (1)$$

In secondly a band pass filter has been done. The high pass filter at 0.1 Hz filtered the baseline eliminating the electrode polarization effects and the movement artifacts. The low pass filter at 30Hz eliminated the Electromyogram (EMG) artifacts of the signal.

4.2 Processing

As seen in the literature, the most representative EOG patterns used to estimate the sleep onset are saccade, blinks and slow eye movements. This investigation was focused on the analysis of blinking and saccade patterns as explained below.

4.2.1 Blinking Detectors

The analysis was divided in two blocks (Fig.9): erosion and detection.

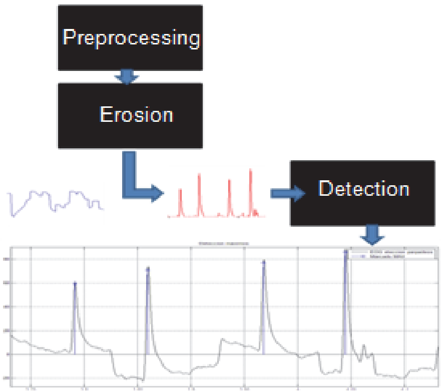


Figure 9: Block diagram of the blinking detection algorithm.

First the signal passes the erosion block, where the abrupt swings are eliminated (Fig.10). Then the filtered signal passes to the blinking detection module.

The objective of the erosion module is to stand out the blinking patterns from the rest of artifacts and saccade oscillations with the interpolation of the obtained "yRET" signal and its posteriors calculation of the very low frequency oscillations obtaining "FPA 1Hz" signal. Finally the "FPA 1Hz" signal is subtracted from the "yRET" signal to obtain C signal.

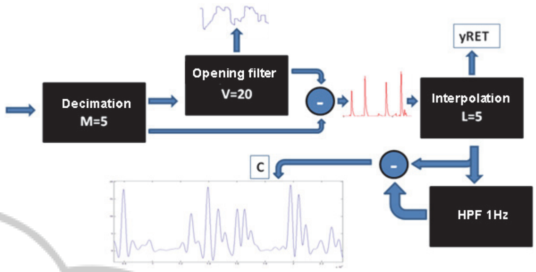


Figure 10: Erosion block.

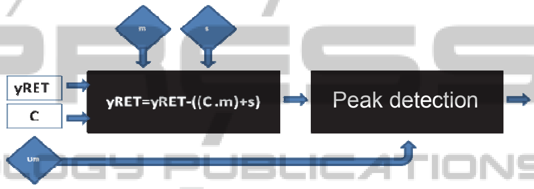


Figure 11: Detection block.

In the detection block C signal is processed with the objective of stand out the low frequency oscillations to avoid remaining artifacts. Finally the subtraction of yRET signal from C is done and the detection of peaks with a fixed threshold 'Um' gives the resultant signal with the blinks detected.

4.2.2 Saccade Detectors

The saccade detection algorithm developed analyzes the horizontal EOG signal with an adaptation of the known Murty-Rangaraj method based on the detection of QRS segment in EKG signal (Rangaraj, 2002).

As shown in the picture below (Fig. 12) the analysis is divided in three blocks: The preprocessing block explained in E.1, The Murty-Rangaraj adaptation block and the saccade detection block.

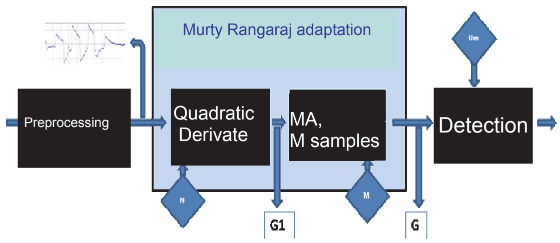


Figure 12: Block diagram of the saccade detection algorithm.

Murthy-Rangaraj method consists in a pre-filtering of the signal followed by and estimation of the first weighted quadratic derivate (2). The resulting signal was later filtered with a moving average filter (3) in order to smooth the obtained result.

$$g_1(n) = \sum_{i=1}^{N} | x(n-i+1) - x(n-i) |^2 \underbrace{(N-i+1)}_{\text{Smooting}} \quad \text{N: windowwidth} \tag{2}$$

$$g(n) = \frac{1}{M} \sum_{j=0}^{M-1} g_1(n-j) \tag{3}$$

Next step was the maximum and minimum identification of the signal in order to detect the position of the saccade using a fixed threshold.

5 STATISTICAL ANALYSIS

For each minute of recording, the phases obtained by the EOG different drowsiness detection algorithms were compared the GS signal, in this case a combination of three external observers evaluating minute by minute the state of the subject using a video recording of the tests. To estimate the sensitivity and specificity of the different EOG methods a match signal was calculated having the number of false positives, false negatives, true positives and true negatives.

According to Table 1 (Stone EA, 2005), sensitivity (Sens) and specificity (Spec) for each phase is defined as:

Table 1: Sensitivity and Specificity definition.

		Gold Standard	
		PHASE 0	PHASE 2
EOG index	PH0	*TN*	*FN*
	PH2	*FP*	*TP*

$$\text{Specificity} = \frac{\text{TN}}{\text{TN} + \text{FP}} \qquad \text{Sensitivity} = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

Stone EA, et al. 2005.
Annu. Rev. Genomics Hum. Genet. 6:143–64

being the Sensitivity the proportion of actual positives which are correctly identified as such giving information about how good is the detection algorithm, and the Specificity the proportion of negatives which are correctly identified.

6 RESULTS

The results for the analysis of the EOG signal with de blinking detection algorithm shows positive results with a sensitivity of 92,41% and a VPP of 93,41% (Figure 14) comparing the results of the algorithms with the Gold Standard. The results with the saccade detection algorithms shows also good results but, in this case, it has to be improved with a module that allows the detection of the beginning and the final of the saccade pattern in order to improve the pattern detection, yet the results are very promising for drowsiness detection porpoises with sensitivity values of 85,1% and VPP values of 95,4% (Figure 15).

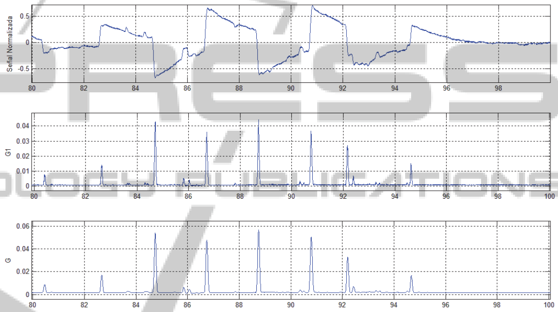
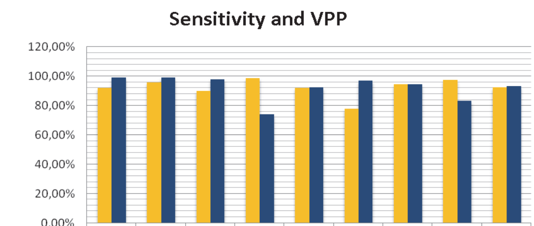


Figure 13: Example of the saccade detection in horizontal EOG.



	P1	P4	P5	P8	P9	P13	P17	P18	TOTAL
Sensitivity	92,06%	95,91%	89,82%	98,72%	92,19%	77,89%	94,44%	97,58%	92,41%
VPP	99,15%	99,15%	98,04%	74,04%	92,55%	96,88%	94,44%	83,13%	93,41%

Figure 14: Blinking detection algorithm results.

	S1	S5	S6	S7	S8	S9	S11	S12	S13	S14	S15	S16	S17	S18	S19	S21	TOTAL
Um	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
VP=0	115	108	106	93	113	115	119	100	157	122	127	73	104	76	108	100	1736
FP=1	14	9	3	1	16	7	0	6	7	4	1	9	1	1	1	1	81
VN=2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FN=3	24	5	22	17	4	23	23	19	15	13	20	36	28	10	18	27	304
Detected events	153	122	131	111	133	145	142	125	179	139	148	118	133	87	127	128	2121
%TP=0	75%	89%	81%	84%	85%	79%	84%	80%	88%	88%	86%	62%	78%	87%	85%	78%	82%
%FP=1	9%	7%	2%	1%	12%	5%	0%	5%	4%	3%	1%	8%	1%	1%	1%	1%	4%
%TN=2	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
%FN=3	16%	4%	17%	15%	3%	16%	16%	15%	8%	9%	14%	31%	21%	11%	14%	21%	14%
Sensitivity	82,73%	95,58%	82,81%	84,55%	96,58%	83,33%	83,80%	84,03%	91,28%	90,37%	86,39%	66,97%	78,79%	88,37%	85,71%	78,74%	85,10%
VPP	89,15%	92,31%	97,25%	98,94%	87,60%	94,26%	100,00%	94,34%	95,73%	96,83%	99,22%	89,02%	99,05%	98,70%	99,08%	99,01%	95,54%

Figure 15: Saccade detection algorithm results.

7 CONCLUSIONS

The results confirmed the viability of the sleep onset detection using related to drowsiness patterns in the EOG signal as blinking frequency and saccade movements' appearance. Some misdetection of the algorithms may be due to the inter-subject variability mostly regarding the shape of the saccade pattern.

Future work will be focused in the improvement of the saccade detection algorithm by including the detection of initiation and end of the saccade pattern in order to make more specific the detection and accurate the calculation of the variable velocity of the saccade.

The future objective is to use the EOG signal as Gold Standard in vehicle tests replacing the EEG signal that shows low quality signal in real environments.

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