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Sleep Monitoring by a Specklegram Fiber Optic Sensor

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ABSTRACT:

Sleep monitoring is becoming more and more popular. This is due to the considerably large number of pathologies and illness related to sleep disorders.In this work a long-term-monitoring system based on a fiber-optic specklegram sensor is presented. The system has been tested under real scenarios and compared with a commercial wrist-based actigrapher. The results suggest that our sensor is highly accurate on detecting movements and can be far more precise than traditional wrist-based actigraphers.

Key words: Speckle, fiber optics, sleep, actigraphy, specklegram, monitoring.

1.- Introduction

Sleep problems such as delay of sleep-onset, difficulty staying asleep, or early awakening among others are known to affect wide percentages of worldwide population(1). Estimates from an epidemiological survey carried out by Ohayon (2) found that insomnia is suffered by nearly a third of the population. This is therefore a very prevalent and significant sleep disorder which is associated with reduced quality of life, increased healthcare cost and increased risk for serious psychiatric and medical comorbidities.

Insomnia and other sleep problems are studied using polysomnography (PSG) which is consider the current gold-standard for assessing sleep and diagnosing sleep disorders (3). Nonetheless, actigraphy can be a suitable tool for characterizing and monitoring circadian rhythm patterns and for providing a quantitative measuring of the sleep/awake time (3).

It could also fill the gap between the highly detailed, single-night assessments conducted in a sleep laboratory and single-variable wearable technology, such as wrist-worn technology used to monitor movement known as an actigraphy.

The work presented in this paper is a new application of speckle in the field of noncontact monitoring that complement previous works (4). Making use of the high sensibility of the speckle phenomenon in fiber optics, this technology is a noncontact alternative to the traditional wrist actigraphers.

1.2 - Speckle effect:

Speckle phenomenon in fiber optics is generated by the spread of a large number of modes with different phase velocities that is given when a coherent light is propagated through a multimode fiber. The propagation modes corresponding to different optical paths (used by the beams coupled into the fiber) suffer different phase delays. This condition generates an output speckle pattern projected by the end of the fiber (specklegram), composed of a large number of individual speckles (bright dots and dark areas).

There is a model (5) that determines the relationship between the speckle pattern variation and the perturbation to be measured. This model is limited to small perturbations and in order to extract this information, a differential processing method can be applied, being able to obtain the desired perturbation as the sum of the absolute value of the changes in all the signals. Consequently, the first step in every processing method is to compute the differential sequence. The value of each pixel of the frame n-1 is subtracted from the value of the equivalent pixel of the frame n (the next frame). The results for all the pixels areadded in absolute value assigned to the n-1 to n transition. This sequence is then buffered using a 6 seconds window to analyze both movement and heart rate.

Based on this approach a differential processing method can be applied to determine the relation between the speckle pattern variation and the external perturbation measured (ΔI_D) for every *i-th* pixel:

$$\Delta I_D\{i\} = \frac{1}{K * MN} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} \left| I_{nm}^{i-1} - I_{nm}^{i} \right| \qquad (1)$$

where K is the full scale value of the speckle pattern color map (e.g. K = 256 for 8-bit grayscale) and I_{nm}^{i} corresponds to the pixel of the *n,m* (considering NxM pixels) position of the *i-th* speckle pattern. The relation described by Eq. 1 assumes that the total intensity of the speckle patterns remains constant under the perturbation, being the computed value an amount that quantifies the power migration between individual speckles within the pattern.

With this differential processing method dynamic measurements can be obtained, being mainly limited by the sampling rate of the specific CCD camera of the specklegram sensor

2.- Sensor and method:

2.1.- Sensor design

The sensors consisted of a semiconductor laser emitting at 638nm wavelength, a CCD camera which produces data at a rate of 30 frames per second, and a plastic fiber optic 150cm long and 240µm diameter core. The POF was set inside two lateral seams of cotton fabric of 10 cm wide and 60 cm long.

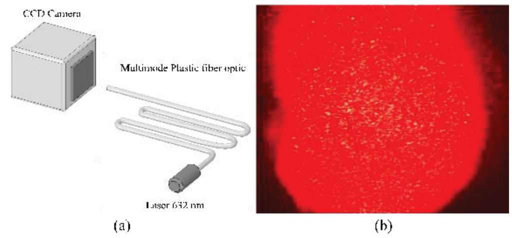

Fig. 1. (a) Schema of elements used: Laser emitting at 632 nanometers of wavelength, plastic multimode fiber optic, and CCD camera. (b) Representation of a specklegram frame captured with the CCD camera.

2.2.- Motion detection.

The specklegram sensor produces an intensity-change value every frame, representing the perturbation produced between 2 frames or time instants. The first step in every processing method is the differential processing. From this differential processing method a 1-dimensional and time-dependent intensity-change signal is obtained. This signal summarizes all the speckle perturbation information needed for further processing. The 1-dimensional signal obtained has to be interpreted transforming the intensity value into a time-dependent motion signal. The in-line processing method uses a time lapse of some previous points of pre-stored intensity signal to estimate the motion. This data is stored in a buffer, whose size must be defined according to the expected performance.

The buffer size is divided in two sections: the recent time window, comprehending the 20% most recent points, and the oldest time window, comprehending the previous 80% (Fig. 2a). Both sections are averaged by the number of points in each section, in order to obtain the mean intensity level of the recent and old status. The ratio among recent and old takes values near 1.0 when the signal is similar, but varies strongly when there is an intense motion. If the ratio deviates more than a stablished threshold, movement detection is triggered.

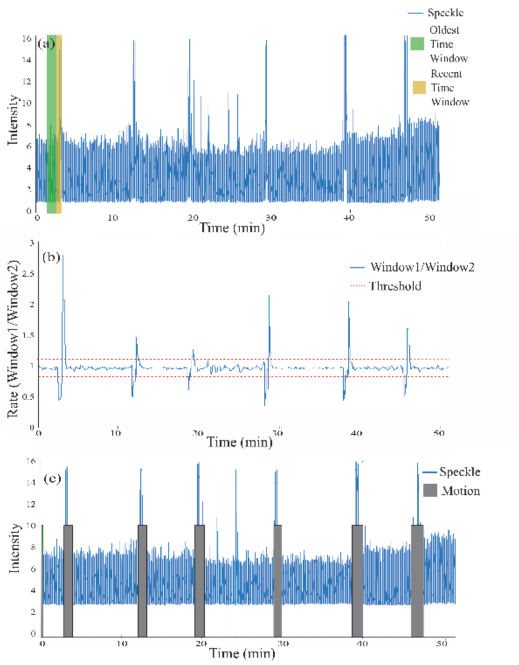

Fig. 2: Motion detection signals. (a) Raw data and two temporal windows. (b) Difference between windows. (c) Speckle and motion detected areas.

2.3- Actigraphy study.

Based on the motion records an actigraphy study was done. The monitored time was classified according to three different stages: Awake, deep sleep and non-deep sleep. The motion records were classified using actigraphy technique integration technique, which is assumed to be highly accurate (6). The results obtained from the speckle study were correlated with the ones obtained from a commercial wrist actigraphy (Fitbit Charge HR manufactured by Fitbit Inc.). This wrist actigraphy displays three different types of sleep states: awake, deep sleep and restless.

3.- Results:

All the samples were compared and studied as it is depicted in the figure 3 (Fig 3). This figure corresponds to the sample 2 in the table 1.

The results of the five different full nights of sleeps are presented in the table 1.

Table 1: Comparison between five speckle actigrapher and wrist actigrapher samples of full night of sleep.

Sample	S1	S2	S3	S4	S5
Motion correlation	3.2%	5.5%	5.4%	5.6%	10.1%
Awake correlation	0%	80%	20%	0%	15%
Sleep time speckle	8h 17m	7h 06m	7h 2m	8h 9m	7h 31m
Sleep time actigrapher	7 h 54m	7h 30m	7h 7m	7h 50m	7h 35m
Total correlation	77.2%	86.9%	70%	85.6%	74,4%

The results in table 1 exhibit three main facts. Firstly speckle and the wrist actigrapher correlate very poorly in terms of motion. Most of the times motion is detected by the speckle system but not by the wrist actigrapher as is shown in the figure 3 (Fig. 3). Nonetheless since speckle motion detection is so highly accurate (4,5) this can mean that the wrist actigrapher is highly inaccurate. Some authors have already documented this issue (7).

Secondly awake time detection fail in some occasions with both methods. This can be associated to the threshold values for awake detection. Nonetheless changing this values would not necessarily improve detection.

Finally, despite the previous discordances, the total time of sleep detected by both methods never differs more than a 5 percent in any case, and the general correlation is always greater than or equal to 70%.

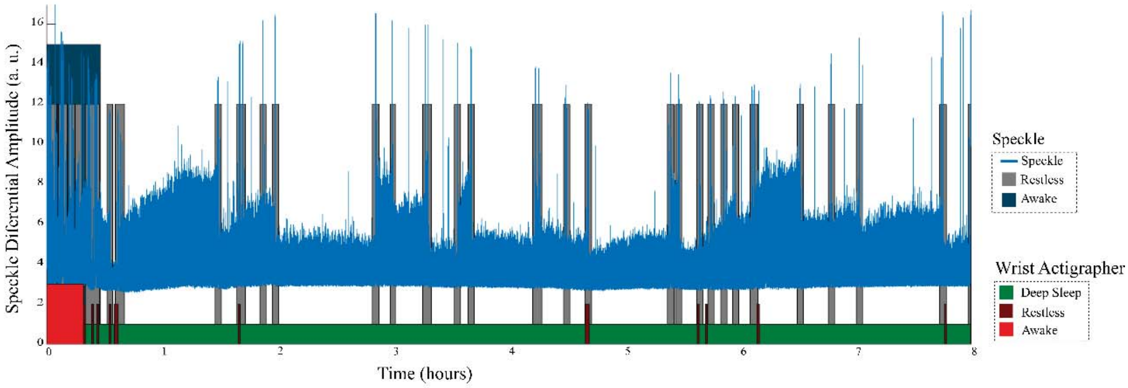

Fig. 3: Speckle and wrist actigraphy comparison for an 8 hours real sleep monitoring (Corresponding to Sample 2 on Table 1).

4.- Conclusions:

Although Speckle sleep monitoring lacks the capability to provide 24-h data it has the potential to fill the gap between the highly detailed, single-night assessments conducted in a sleep laboratory and single-variable wearable technology, such as wrist-worn technology. This is mainly because as opposed to wrist actigraphy, the speckle system does not fail detecting either small or quick movements. Moreover, the temporal data rate in the speckle monitoring is 30 values per second, which is a strong advantage compared to 1- to 5-minutes values of traditional wrist actigraphers.

Future works need to be done testing and comparing the accuracy of both systems, wrist actigraphy and speckle actigraphy, compared to polysomnography.

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