Preliminary Assessment of a Smart Mattress for Position and Breathing Sensing

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Abstract. Sleep is a one of the most important activity for maintaining the health and well-being of each subject. In order to monitor continuously the quality of sleep of the general population in non-invasively way, we developed an innovative sensorized "smart" mattress (SmartBed). SmartBed is equipped with sensors to detect environmental and subject-related information. In particular, SmartBed is equipped with accelerometers and a sensing textile matrix able to detect the distribution of pressures of a subject laying on the mattress. The purpose of this work is to demonstrate how the sensing textile matrix is not only able to detect how the subject is positioned on the mattress over time, but also it allows to detect other physiological parameters and in particular the subject's respiratory activity. In this work, we show that: (i) the sensing textile matrix allows a precise position detection; (ii) it is possible to extract accurately the respiratory frequency from the sensing textile matrix by using a specifically tailored algorithm. In conclusion, the sensors integrated in SmartBed make possible to detect important information (position and respiratory activity) to determine the quality of a subject's sleep in a robust, accurate and non-invasive way.

Keywords: Sleep analysis · Sensing mattress · Smart textile · Breathing monitoring

1 Introduction

Individual experience of insufficient or inadequate sleep is one of the most common health problems. About 65% of the Italian population report generic disorders during the night, while 10% suffers from pathological disorders related to poor sleep [1]. These subjects often report drowsiness during the day, absenteeism at work and reductions in performance. Inadequate sleep may become the cause of accidents even on the road. Furthermore, insomnia can lead to more complex pathologies [2] not only of a metabolic nature (such as diabetes or dyslipidemia) and cardiovascular diseases (such as myocardial infarction or hypertension), but also cognitive and psychopathological (such as depression and anxiety disorders). Currently, through polysomnography it is possible to

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evaluate the quality of sleep of patients [3]. Unfortunately, polysomnography is highly invasive, and the lack of comfort prevents the subject from sleeping in a natural situation and does not allow a measurement that reflects reality. For all these reasons the development of a systematic, preventive, personalized and non-invasive method for the analysis of sleep is particularly important.

To overcome these limits, we aim at developing a smart-bed [4]: a sensing and intelligent mattress that can collect and process physiological data (heart rate, breathing rate), environmental parameters, movements and positions of the patient.

As a relevant subsystem of the smart bed we have designed a sensing textile, integrated in the mattress, able to detect the distribution of pressures when a subject is laying on the bed. The pressure signals obtained can be used to detect the subject position and movements and extract the subject breathing rate. This work is focused on a preliminary assessment of the pressure sensing matrix in the detection of subject position and respiratory frequency. We discuss the sensor structure, the signal acquisition methodology, the recognition of subject position and the possible solutions to determine the patient's respiratory activity.

2 Materials and Methods

2.1 Pressure Sensing Matrix

We have developed the pressure sensing matrix, designed to map the pressures exerted by a person's body in terms of position coordinates and intensity, by employing an array of piezoresistive sensors, inspired by [5]. Each individual transducer consists of a piezoresistive textile capable of modifying the electrical properties when a deformation is applied. The material is composed of a single solution from colloidal particles of conductive (for example carbon black) dispersed in a matrix polymer.

For the realization of the sensor related to a single mattress (190 × 90 cm), a surface of about 125 × 75 cm was built based on a matrix of 15 × 13 sensing areas, where 15 are

(a) (b)

Fig. 1. **a)** Inner layer of CARBOTEX 03-82 (black layer, currently crawled in the direction of the lines); external PET layers with conductive stripes of row (15) and column (13) arranged orthogonally between them. **b)** Internal layer of CARBOTEX 03-82 cut into strips (black part); horizontal row and vertical column conductive tracks (silver parts) sewn onto the PET layer.

horizontal rows and 13 vertical columns, with equally spaced detection areas. With this design, positions of the head and feet are not considered. The pressure-sensitive layer is a conductive fabric (CARBOTEX 03-82 of SEFAR AG), while for the upper and lower layers a PET fabric was used, again from SEFAR AG and designed following our specifications, in which equidistant metallic strips are integrated (see Fig. 1 and Fig. 1b). The described detection architecture introduces parasitic resistances in directions transversal to the conductive strips, which create relevant cross-talk in the measurement. For this reason, we decided to cut the pressure-sensitive layer also into strips, in the direction identified by the lines (see Fig. 1b).

2.2 Data Acquisition

As indicated above, the crossing of a line (with index i) and a column (with index j) forms the sensitive element of the structure: the sensing area (taxel). By feeding the specific i-th row with a voltage and reading the voltage value on the j-th column, it is possible to measure the resistance of the identified element (i, j). Repeating the operation for all the combinations of row and column, the data of all the sensitive surface are obtained. This was achieved thanks to an Arduino Mega 2560 board and a protoboard that implements a voltage divider for reading. The board has 16 analog inputs and 54 digital inputs; then, to set the connection, the 15 lines have been connected to the digital inputs (imposing 3 V) and the 13 columns to the analog inputs. Through the Arduino IDE development environment, it was possible to program the card and perform the reading; the latter, for the elimination of any noise, is followed by a simple arithmetic average, every 10 acquisitions.

2.3 Subject Position

We have developed a Matlab Grafical User Interface that display the acquired resistance value as a false color image. Processing was performed using the MATLAB environment. Using a Master-Slave approach, the Matlab application was used as master, while the Arduino board worked as slave: the Matlab environment ask the data by writing a predefined code on the serial port and, in response, the Arduino board sends a complete reading on the same serial (the resistance value of the 195 sensing areas). Data are then saved to be processed off-line. This type of communication allows to manage the sending and receiving of data and therefore to control the sampling frequency (fc = 4 Hz). Once the vector has been received, the distribution of the pressures for each sensing area is displayed. A linear interpolation was used to improve the overall quality of the image.

2.4 Breathing Detection

The main objective is to detect the respiratory act and the frequency associated with it. These, in fact, are parameters of fundamental importance within the sleep analysis, not only to hypothesize the phase but also to identify possible sleep apnea. Finally, the last purpose was to understand how the subject position influences the accuracy of breathing detection.

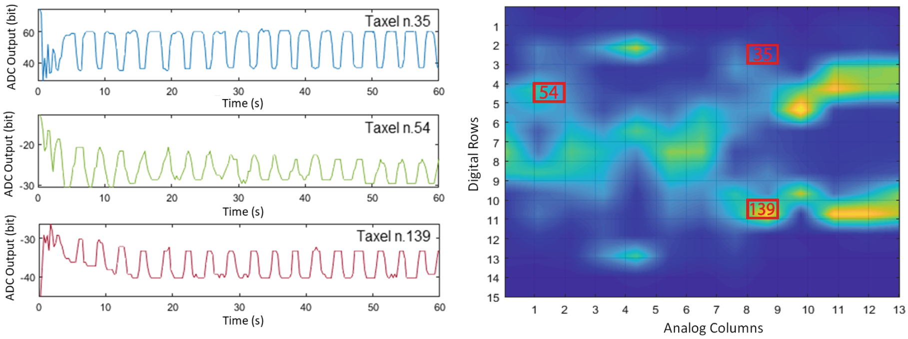

Fig. 2. Periodic trend of the three sensing areas found by visual inspection, test in deep breathing; (Right) Image of the subject in supine position and identification of significant sensing area

By acquiring the signal and performing a visual analysis we observed that certain sensing areas show a periodic trend coherent with breathing activity (see Fig. 2).

For the determination of the respiratory frequency we developed a Fourier transform based procedure (FFT algorithm in Matlab).

3 Results

3.1 Position

Different subjects lay down on the mattress and assumed different typical sleeping positions, in the following pictures we report the reconstructed interpolated. It is possible to notice how some specific areas of the subject can be easily recognized (Fig. 3).

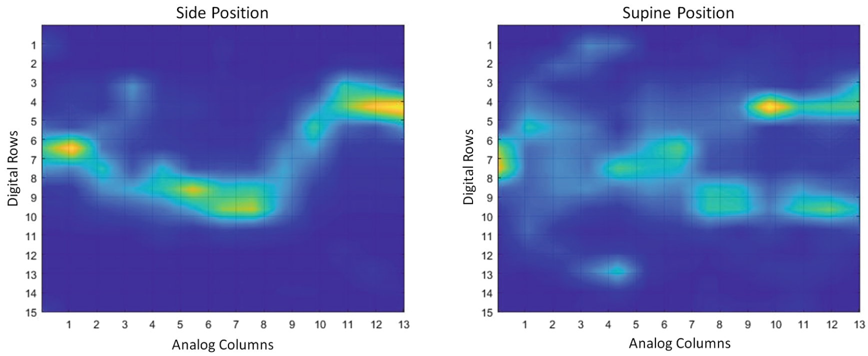

Fig. 3. Image of subject lying in different positions

3.2 Respiration

We acquired data from subjects lying on the mattress versus a ground truth (breathing cannula with a NTC-3950 termistor).

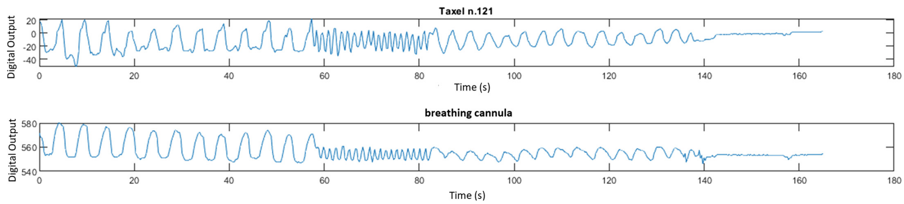

Fig. 4. Trend over time of a significant sensing area and of the cannula; demonstration of the significance of the smart-bed signal.

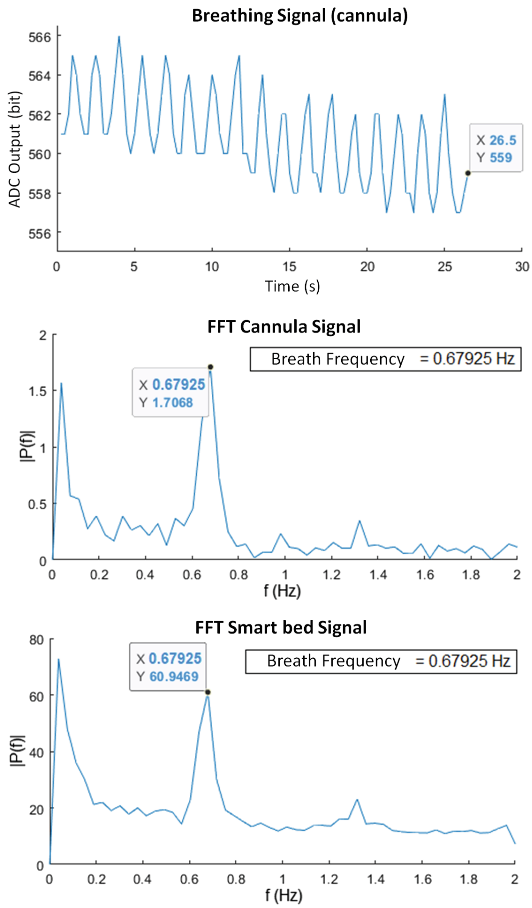

Fig. 5. Rapid breathing pattern in supine position; FFT from the cannula signal and from the sensing mattress, as can be verified the peak values of the first harmonics coincide; in the box the value of the respiratory frequency extracted from the algorithm.

In a first experiment (see the comparison of Fig. 4), the tests were conducted according to the following pattern: deep breathing for 60 s, fast for 30 s, normal for 60 s and finally apnea for 15–30 s; in the supine and prone positions.

By using the FFT based algorithm, we made a first attempt was to demonstrate that the sensing mattress had the ability to identify the patient's respiratory rate (always comparing it to the ground-truth) in time slots in which breathing variable. Subsequently, we investigated the performance in the four possible lying positions (supine, prone and from the side). To prove that the mattress could determine the respiratory rate, the subjects were asked to breathe with a constant frequency, in the range of 60 s for deep and normal breathing, 30 s for the fast and about 15 s for the 'apnea; in all positions. As regards the Fourier analysis, performed on the sensing area, very promising results have been obtained by performing the sum of the modules of the Fourier transforms of each sensing areas in the considered time period. All the respiratory modalities have been correctly recognized (i.e. the peaks of the first harmonic coincide for ground truth and mattress). Considering the different lying positions, the least reliable results are those in which the subject is lying on his side. An explanatory image is shown in Fig. 5.

Following these investigations, other tests were conducted with a total duration of about 165 s, in which the patients' respiratory rate was variable; therefore the subjects were asked to breathe in the following way: deeply for 60 s, quickly for 30 s, normally for 60 s and in apnea for the remaining time. The calculation of the FFT, in this case, was determined with a more complex algorithm in which it is calculated on mobile time windows of 30 s, within the entire test period (always 165 s). The choice of the width of the floating window must be adapted to the total duration of the experiment. In our case, we choose a 30 s time window. From the results obtained it can be seen that the

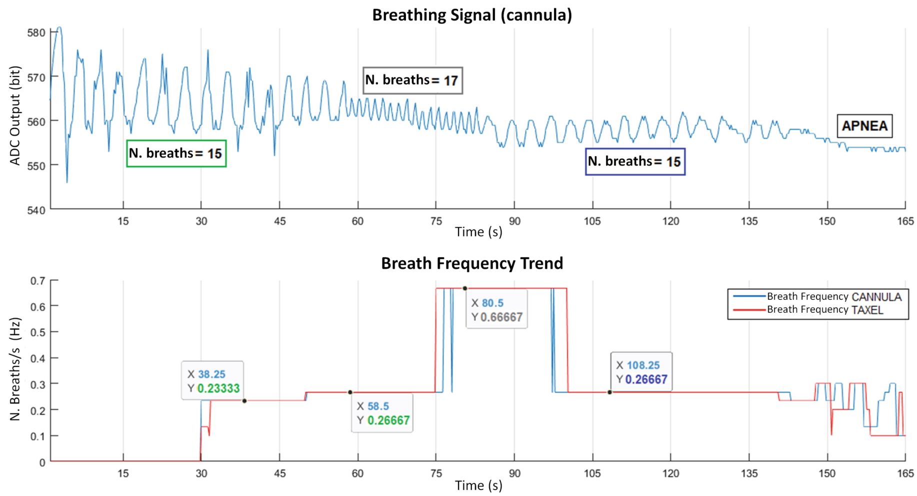

Fig. 6. Analysis related to a subject in a supine position; (Above) Respiration trend detected by the thermistor and n. breaths corresponding to each mode; (Bottom) Trend of respiratory rate over time with values highlighted for each phase; as you can see the values of the respiratory frequencies coincide between the smart-bed and the cannula, reflecting reality.

smart-bed, using the algorithm developed, appropriately recognizes the respiratory rate in almost all positions (on the side there is the greatest probability of error), while, as regards respiratory modalities, apnea (for the choice of the 30 s window) and occasionally normal breathing are more difficult to identify. Fig. 6 shows an explanatory image of the analysis.

4 Conclusions

In this work, we investigated the capability of detecting the position and breath of subject on a sensing mattress to perform a non-invasive sleep analysis.

Future developments include the improvement of algorithms, in part already implemented, for the best apnea capture and for solving problems related to the side position. For the purposes of greater accuracy in the results, it could be advantageous: to use thresholds on the peaks relating to the FFT signals to eliminate spurious identifications of the respiratory frequencies, perform a moving average with an adaptive window (at present only one version is available with a constant window) on the data deriving from the sensorized mattress that would reduce the noise in apnea acquisitions.

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