Smart Mattress Cover for unobtrusive monitoring of sleep-quality correlates in real-life

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***Abstract*—This paper presents the design, the development, and the preliminary testing of the Smart Mattress Cover (SMC), a non-obtrusive, mass-production suitable system for real-world data acquisition of physiological sleep parameters correlates. The SMC integrates a fabric-based pressure sensor matrix and two accelerometers within a flexible, user-friendly design. Preliminary laboratory tests demonstrates the system's capability to detect sleep-related physiological parameters, including respiratory activity, heart rate and subjects movement.**

***Index Terms*—non-invasive sleep systems; real-world monitoring; physiological parameters.**

I. Introduction

The increasing popularity of non-obtrusive devices and the *Healthcare 4.0* paradigm has driven advancements in real-world data monitoring [1], [2], particularly through wearables and e-textiles [3]. Sleep is a crucial parameter for long-term health assessment as inadequate sleep is linked to several medical conditions [4], [5]. Unfortunately polysomnography, the sleep analysis gold-standard [6], has drawbacks such as invasiveness, discomfort, and lack of long-term monitoring. To address these challenges, researchers have proposed several "in-bed" solutions [7]–[16]. However, literature systems are often designed for use in hospital settings and embed many single sensors over a large surface area. To the best of our knowledge, none of the existing solutions have been adopted in real home settings. In this work we present the design, development, and preliminary testing of the Smart Mattress Cover (SMC) system: a mass-production suitable textile-based pressure matrix sensor integrated with two accelerometers designed for sleep analysis in real-world context. The SMC is equipped with an innovative fabric-based pressure sensor matrix and a set of 3D accelerometers able to potentially acquire signals correlated with the following physiological parameters (PP): (i) normal respiratory activity (RA), (ii) abnormal breathing events (e.g. apnoea, cough strikes), (iii) heart rate (HR), (iv) subjects' movement. In fact, the PP's combined information can lead to the computation of a sleep quality index [13]. Furthermore, the selected PP are relevant for the European Project TOLIFE [17] within which the SMC was conceptualised. TOLIFE focuses on managing Chronic Obstructive Pulmonary Disease (COPD) by predicting patients' exacerbations and estimating their health status using a *Healthcare 4.0*-based non-obtrusive sensor kit and AI-based analytics tools [18]–[21]. The SMC, part of this kit, extracts sleep-related information correlated to COPD exacerbations [22].

II. Materials & Methods

A. Requirements Analysis

The SMC's design prioritized the end-user perspective and system's objectives, beginning with a requirement analysis for both clinical and technical needs. Clinically, based on literature [13], [16], [18], we identified two main parameter categories: physiological and environmental. In this work we focused on the physiological one. Based on sleep analysis literature and TOLIFE's aim, the chosen PP are: (i) normal RA; (ii) abnormal breathing event (e.g. apnoea phases, cough strikes, hypo- or hyper-ventilation); (iii) HR; (iv) subjects' movement. Regarding the technical needs we identified: usability/ergonomics; sensor, safety and production requirements. We defined the following sensor requirements as essential: (i) low invasiveness; (ii) reduced device dimension; (iii) trade-off between system architecture complexity and single sensor's number; (iv) flexibility; (v) mass-production suitability and robustness. Given the SMC's intended real-world use in various homes environment, we also considered usability and ergonomics aspects such as softness, ease of installation and use.

B. Sensor design and fabrication

The SMC's design concept aimed to fulfil our requirement analysis. The SMC is a textile-based mattress cover comprising (Fig. 1a, 1b): (i) a fabric-based multi-layer pressure sensor array called *Pressure Matrix* (PM); (ii) a set of two digital 3D accelerometers (ACC); (iii) a microcontroller unit (MCU) with a custom front-end circuit. By sensing the pressure applied by the subject lying in bed is possible to extract direct (e.g. movement) and indirect information (e.g. RA and HR). We chose to place the SMC over the mattress but beneath the bedsheets in the thoracic patient's area to maximize data information (Fig. 1a). The PM is a three-layer structure comprising two external conductive layers and one internal pressure-sensitive layer. The sensor array structure forms a 4x10 matrix (4 rows and 10 columns), totalling 40 single-sensing elements over an area of 40x50 cm (Fig. 1b, 1c). The rows and columns are conductive paths perpendicular to each other. The intersection of the m-th row, the internal

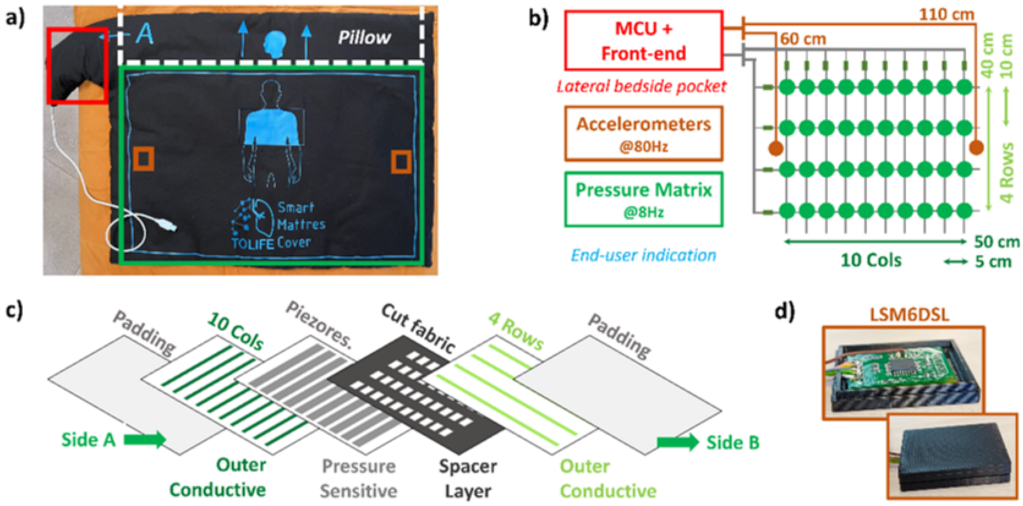

Fig. 1. a, b) The Smart Mattress Cover (SMC) prototype and its bed positioning: over the mattress, under the bedsheet, near the pillow, in the thorax patient's area. The SMC comprises a pressure matrix (PM in green; a fabric-based multi-layer pressure sensor array composed of 40 sensing elements arranged in a 4x10 matrix), a set of two digital 3D accelerometers (ACCs in orange), and a microcontroller unit with a custom front-end (MCU in red). The SMC's sensing area has a surface of 40x50 cm; c) Detailed view of the PM's layer architecture: two padding outer layer, two external conductive layer (4 rows and 10 cols), internal piezoresistive pressure-sensing layer (10 strips), spacer layer. The intersection of the n-th row, the internal layer and the m-th column forms the pressure sensing element. d) ACC's detailed view, they are integrated in a custom-made PCB and enclosed in a custom-made PLA case.

layer and the n-th column forms the single-sensing element. Rows are aligned along the PM's height (40 cm) and columns span its length (50 cm); they are equally distributed with 10 cm between rows and 5 cm between columns (Fig. 1b). The outer layers are flexible patches fabricated with the screen-printing technique (Ag-based ink over a polyester substrate) in which the conductive paths were designed. The patches are manufactured by Chiaramonti S.r.l. (Prato, Italy) and applied with a pressure-activated glue over a fabric substrate. The inner layer is the piezoresistive CARBOTEX03-82 from Sefar AG (Heiden, Switzerland), cut and sewn into strips along the columns. This process leads to crosstalk noise reduction, as well as cost and material savings [24]. Furthermore, an internal fabric spacer layer, cut at row and column intersections (Fig. 1c), is incorporated between outer layers; it physically separates and insulates the conductive external layers ensuring higher signal-to-noise ratio and avoiding spurious single-sensor activation. All the above fabric layers were laser-cut and placed using reference points, gathering a precise alignment in production sew phase. For estimating the HR by analysing vibrations induced by heart movement, we employed two digital 3D accelerometers (ACC), specifically the LSM6DSL by STMicroelectronics. Each ACC is integrated into a custom-made PCB with a dedicated microcontroller (ATMEGA328P). The ACCs are positioned on the PM's lateral border (Fig. 1a, 1b), at 60/110 cm (respectively the nearest and the further) from the MCU. ACCs are sewn internally within the PM's layers; therefore, they are enclosed into a 3D-printed custom-made PLA case (Fig. 1d), designed to be small and thin to minimize invasiveness. The MCU consists of an Arduino Due board and its analog front-end developed on a custom-made PCB, managing both ACCs and PM readings. For ACCs, we established a master-slave UART communication architecture (RS-485 protocol); ACC's data are sampled at 80 Hz each. For PM's reading, we relied on the *Resistive Matrix Method* technique [13], [15], [23], [24]. Each sensing element's electrical equivalent is a variable resistor whose electrical resistance decreases as the pressure applied increases. The resistance variation is measured with a single-leg voltage divider, with a fixed resistance of 6.8 kΩ. We employed a multiplexed reading front-end, connecting rows to digital and columns to analog pins, to reduce the number of dedicated pins required and ensure compatibility with more development boards. An analog multiplexer scans the column by reading the voltage at the voltage-divider, while an analog demultiplexer supplies power sequentially to rows. PM's sensing elements are sampled at 8 Hz. The MCU is encapsulated in a 3D-printed customised PLA case that fits into a pocket within the SMC's, positioned bedside next to the mattress (Fig. 1a). Finally, we highlight the following design consideration: to enhance comfort we added two external padding layers (Fig. 1c); to suit different real-home environments we designed the SMC for use on both sides (A or B; Fig. 1a); to allow users to sanitize the SMC we added a removable cover with a zip; for ease of installation we included external drawing as user guidance (Fig. 1a, 1b).

C. *Preliminary Testing*

To test the SMC's performance regarding our clinical requirements, we performed a comparison with a reference system (the BE Plus LTM by EB Neuro) able to acquire thoracic and abdominal respiration (via elastic bands) and heartbeat (via bipolar limb leads with 3 electrodes). We asked 10 healthy subjects, lying on a laboratory bed, to complete the following protocol: normal breathing (1 min), hypoventilation (2 min), talking (1 min), hyperventilation (30 s), normal breathing (1 min), full lung apnoea (30 s), normal breathing

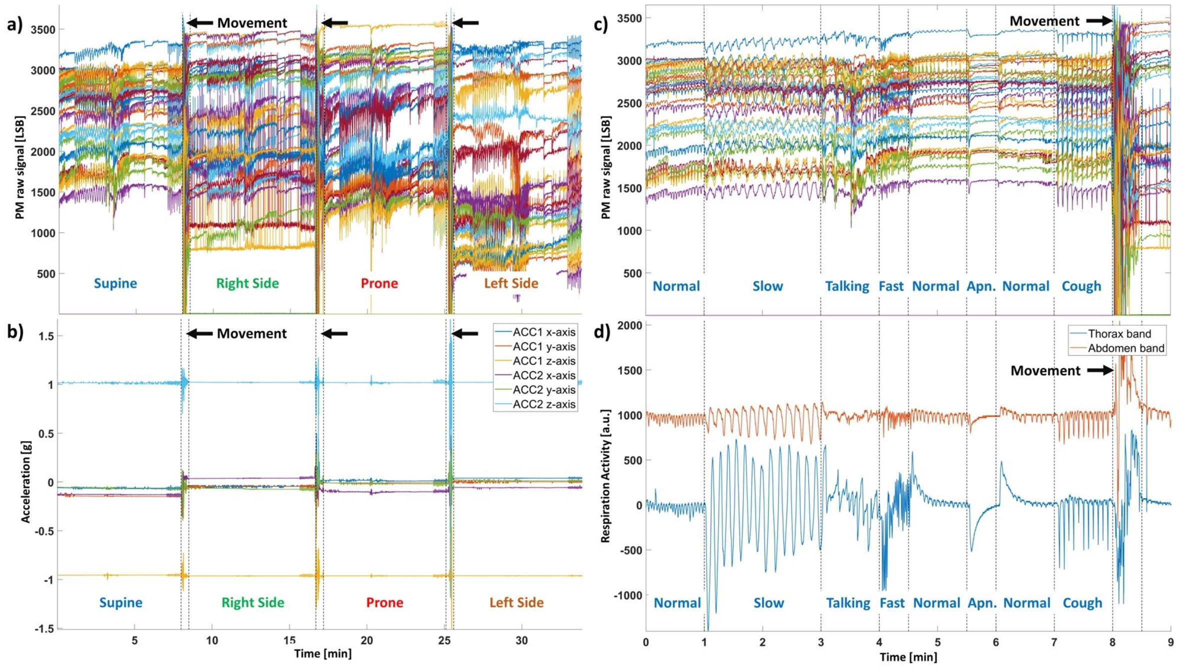

Fig. 2. a, b) PM's 40 pressure sensors raw signals and ACC's raw data during the protocol's phases (supine, prone, left and right side): movement instants are recognizable, while breathing modulation is clearly visible in the PM's signals; finally, the heart rate is hidden in the ACC's data. c, d) Magnified view of PM's raw data and reference signals during the supine phase. Focusing on the breathing modulation activity (from slow to fast) and abnormal respiratory events (such as apnoea or cough strokes), they are clearly recognisable from the PM's signals.

(1 min), cough (1 stroke every 5 s for 1 min). The procedure was repeated 4 times for each bed's position (supine, prone, left and right side) with total duration of 34 min.

III. Results & Discussion

The first achievement is the SMC's prototype development (Fig. 1), meeting our sensor requirements. The SMC is compact minimizing the invasiveness: 40x50 cm internal sensorised area and 75*85 cm total system dimension, substantially smaller than any other "in-bed" solution (1*2 m, 2.5*1.5 m, 188*90 cm, 180*90 cm area respectively in [9]–[11], [13]). The SMC has a reduced number of sensing elements compared to other systems (40 against 320, 160, 8192 or 195 respectively in [7], [9]–[11], [13]). Flexibility was achieved using fabric materials, conductive flexible patches and few hard components, allowing for fold-ability which also facilitates packaging. SMC's usability was reached with softness and few components to install. Finally, we obtain mass production suitability through a focus on creating a repeatable production process that minimizes cost and production time; to date we have manufactured 25 complete systems. The second result is the SMC capability to acquire PP correlates. Fig. 2a shows the raw pressure signals extracted by the PM. The four phases in different positions (supine, prone, left and right side) are clearly recognizable, as well as the changing position instants. The focus on a specific position reveals the protocol breathing modulations and events: normal respiration, hypo- and hyper-ventilation, apnoea, and cough stroke (Fig. 2c). Fig. 2d shows the thorax and abdomen reference signals. The visual inspection comparison between the PM's raw data and the reference reveals the SMC's capability of tracking the RA modulation. Moreover, we implemented a preliminary breathing rate (BR) extraction algorithm based on the FFT computation on overlapped moving-windows. Compared to the reference BR we obtained promising results (RMSE=0.1034±2.88*10^{-6} [Hz] for thorax band, RMSE=0.1072±3.2*10^{-6} [Hz] for abdomen band). Fig. 2b shows ACC's raw data, from which the subject's movement are clearly detectable. In addition, we preliminarily implemented a moving auto-correlation algorithm to extract HR from ACC's raw signals [25] (relative RMSE=0.135±0.0112).

IV. Conclusions

In this work, we presented the design and development of the Smart Mattress Cover (SMC), an innovative unobtrusive system for detecting physiological sleep parameter in real-world contexts. We developed the SMC chasing the best trade-off between complexity, non-invasiveness, mass production suitability and ease of use. To the best of authors' knowledge, the SMC is both one of the smallest systems in terms of dimensions and with the fewest sensing elements. Nonetheless, despite its low complexity, we have preliminarly demonstrated its capacity to acquire the desired sleep PP correlates. As future development, we aim to extensively test the SMC developing algorithms for BR and HR estimation, subjects' position, movement, and abnormal respiratory events identification. Finally, we intend to add environmental data collection, enabling future sleep quality index computation.

Acknowledgment

Research funded by European Union's Horizon Europe Research and Innovation Programme under grant agreement No. 101057103 – project TOLIFE. We acknowledge the support of CrossLab & ForeLab laboratories of DII - University of Pisa.

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