Sensors and Materials, Vol. 36, No. 11 (2024) 5073–5083
MYU Tokyo

S & M 3852

Development and Application of a Smart Mattress and Integrated Health Management System for Real-time Monitoring Utilizing Theory of Inventive Problem Solving and Signal Processing Techniques

Chin-Chia Liu,[1] Der-Fa Chen,[1] Wei-Lun Huang,[1,2] and Chun-Kai Liang[1,3]*

[1]Department of Industrial Education and Technology, National Changhua University of Education Bao-Shan, No. 2, Shi-Da Rd., Changhua City 500208, Taiwan
[2]Medical Affairs Office, National Taiwan University Hospital, No. 7, Zhongshan S. Rd., Zhongzheng Dist., Taipei 100225, Taiwan
[3]SOLID YEAR CO., LTD., 18F.-11, No. 97, Sec. 1, Xin tai 5th Rd., Xizhi Dist., New Taipei City 221416, Taiwan

(Received August 26, 2024; accepted November 19, 2024)

Keywords: smart mattress, health monitoring system, TRIZ theory, signal processing

In this study, we aimed to develop a smart mattress for continuous health monitoring, utilizing the theory of inventive problem solving (TRIZ) to guide its innovative design. The system employs sensors to collect real-time heart rate and respiratory data, which are processed using finite impulse response filters and advanced signal processing techniques to accurately obtain heart rate and respiratory frequency. The physiological signals are transmitted to a cloud server, creating a comprehensive health management system that provides health monitoring, alert notifications, and management services through web platforms and mobile applications for both individuals and institutions, thereby enhancing the quality of health management. The smart mattress was validated through comparative analysis, demonstrating no significant differences in heart rate (p = 0.059) and respiratory rate (p = 0.170) measurements compared with medical-grade devices. In this research, we present an integrated hardware and software solution for smart devices and health management systems, applicable in various settings, including personal homes, healthcare institutions, and nursing facilities. The techniques and design principles employed in this study offer valuable insights and references for related research in health monitoring and management systems, with the potential for broader applications.

1. Introduction

According to the World Health Organization statistical report, the global life expectancy in 2019 was approximately 73.3 years, with a healthy life expectancy of 63.7 years. This indicates the possibility of being bedridden for about 9.6 years due to poor health or disability.(1) Additionally, newborns spend more than 70% of their day sleeping. The National Sleep

*Corresponding author: e-mail: yeslovetw@gmail.com
https://doi.org/10.18494/SAM5342

Foundation reports that newborns under three months old sleep about 14 to 17 h per day, infants aged 4 to 11 months sleep about 12 to 15 h, and toddlers aged 1 to 3 years sleep about 11 to 14 h.[2] Research indicates that approximately 3,500 infants die annually in the United States due to sleep-related causes, including sudden infant death syndrome, unexplained deaths, and accidental suffocation in bed. Establishing a safe sleep environment and monitoring infant sleep with timely alerts can prevent many of these incidents.[3] Therefore, we suggest that mattress-based smart home devices, owing to their non-wearable nature, long-term usability, and seamless integration into daily life, can be effectively implemented in personal home environments, medical institutions, and nursing facilities as smart care devices for health monitoring systems. This approach can enhance safety and improve care efficiency in health management for both individuals and institutions.

Smart mattresses are advanced products that integrate IoT and sensor technologies, offering various monitoring and assistive functions. While traditional models primarily focused on alleviating caregiving efforts, modern versions now monitor heart rate, respiration, and body movements, providing real-time alerts for physiological abnormalities.[4] Recent advances in noncontact monitoring technologies have introduced systems such as radar-based RF for detecting multiple vital signs and emergencies,[5] photoplethysmography for the optical measurement of vital signs,[6] and infrared sensors for nocturnal monitoring.[7] Accelerometer-based vibration sensors have also been employed for physiological signal detection.[8] However, these technologies face challenges, including electromagnetic interference and application limitations.[9] Some systems have integrated these sensors into mattresses to capture ballistocardiogram (BCG) signals, with effective noise filtering and signal processing techniques, such as Fourier and wavelet transforms, enhancing data accuracy.[10,11] Several studies have explored various designs for smart mattresses utilizing IoT technology. These innovations include sleep quality detection, intelligent wake-up services, and app-based or voice-controlled integration to improve sleep through regular physiological cycles.[12] Some research has concentrated on monitoring basic physiological signals such as heart rate and respiration, suggesting personalized alert systems for anomalies.[13] Noninvasive systems have also been developed, integrating sensors for position, movement, and environmental data.[14] In neonatal care, smart mattresses using electric potential sensors have been designed to rapidly measure vital signs, thereby improving the speed and accuracy of resuscitation assessments.[15] Building on the diverse designs of smart mattresses, recent advancements in personal health management systems emphasize the integration of smart devices with information systems. These systems, often utilizing wearable sensors and IoT technology, enable real-time health monitoring and management across home and healthcare settings.[16] By seamlessly combining hardware and software, these solutions provide personalized health metrics, enhancing the effectiveness of long-term care and telehealth applications.[17]

Currently, medical institutions and nursing facilities have not fully integrated mattress-based smart home devices with health monitoring systems. Additionally, there is limited research on the combined application and practical use of these technologies. Therefore, in this study, we explore the development and application of smart mattresses to enable continuous health monitoring, early warning systems, and health management services across various settings, including personal homes, medical institutions, and nursing facilities.

2. System Architecture

In this study, we aim to explore the development and application of a smart mattress designed to enhance user experience and improve health management quality. The experimental design included the initial development of the smart mattress prototype and its accompanying software. Following this, the hardware and software were integrated into a comprehensive smart mattress system. After conducting real-world testing and validation, the system was simulated for application in actual environments. The system architecture is illustrated in Fig. 1.

2.1 Smart mattress development

We employed the theory of inventive problem solving (TRIZ) methodology to innovate the design of a smart mattress. By analysing relevant literature and patents, key parameters from the TRIZ contradiction matrix were identified to guide the design process. The parameters targeted for improvement included strength (No. 14), ease of operation (No. 33), complexity of devices (No. 36), and difficulty of inspection and measurement (No. 37). Conversely, the parameters to avoid worsening were reliability (No. 27), measurement accuracy (No. 28), and adaptability (No. 35). This analysis led to the selection of inventive principles such as segmentation (No. 1), local quality (No. 3), dynamization (No. 15), and substitution of mechanical systems (No. 28). The technical contradiction matrix is presented in Table 1.

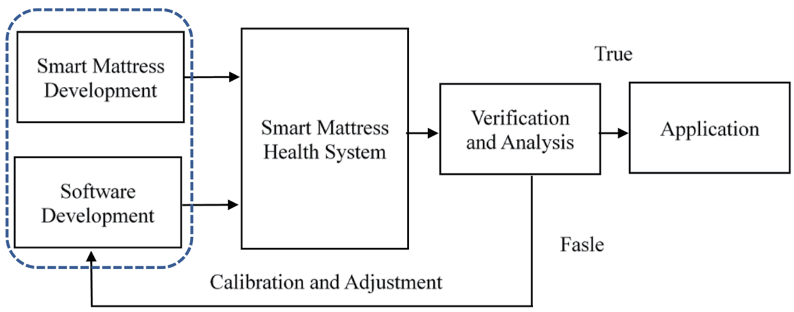


Fig. 1. (Color online) System architecture.

Table 1
Contradiction matrix of smart mattress.

	No. 27 Reliability	No. 28 Measurement accuracy	No. 35 Adaptability
No. 14 Strength	11, 3	3, 27, 16	15, 3, 32
No. 33 Ease of operation	17, 27, 8, 40	25, 13, 2, 34	15, 34, 1, 16
No. 36 Complexity of devices	13, 35, 1	2, 26, 10, 34	29, 15, 28, 37
No. 37 Difficulty of inspection and measurement	27, 40, 28, 8	26, 24, 32, 28	1, 15

The segmentation principle was applied in the design of the air cushion component, where the sensing device was separated from the air cushion. This design reduces device complexity, minimizes sensor failure rates, and allows for independent maintenance or replacement of components, thereby enhancing the overall durability and functionality of the smart mattress. The conceptual design is illustrated in Fig. 2.

We employed thermoplastic urethane as the material for the air cushion owing to its durability, elasticity, processability, and resistance to oil and water, which extends product lifespan. The air cushion is designed with grooves and localized apertures on its surface, reducing the contact area and enhancing the signal strength when pressure changes are detected by sensors. This design also addresses drainage issues, thereby improving adaptability and detection accuracy. Furthermore, the air cushion offers high sensitivity, is customizable in size, and is cost-effective for mass production, making it suitable for both household and institutional uses. Its foldable and portable nature enhances ease of movement and replacement, particularly in medical or care facilities (see Fig. 3).

TRIZ principles, including the principle of dynamics and the invention principles for substituting mechanical systems, guided the development of the airbag control device. The dynamic principle suggests transitioning from a static to a dynamic state to enhance system adaptability and performance, while the substitution principle advocates replacing traditional mechanical systems with nonmechanical alternatives. Consequently, the design of the airbag control device incorporates an air pump, sensors, and an exhaust valve, with a controller

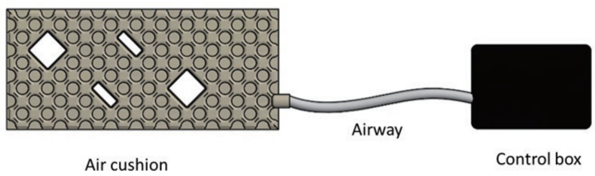


Fig. 2. (Color online) Air cushion and sensor device split design.

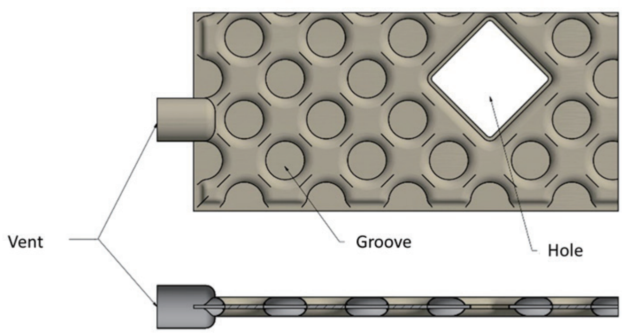


Fig. 3. (Color online) Air cushion surface design.

processing the signals. The pressure from the expelled air is converted using diaphragm principles, which are regulated by the exhaust valve to ensure effective signal capture, and processed by the sensor's internal chip. The air cushion and control device are connected via a joint, but prolonged use can lead to air loss in the airbag and variability in user weight, which may affect pressure detection accuracy. To maintain pressure within an acceptable range, the joint design includes channels for pressure detection, pressure relief, pressure boosting, and heart rate and respiration monitoring. A quick-connect fitting with four corresponding interfaces is integrated at the air cushion end to meet these functional requirements (see Fig. 4).

On the basis of the innovative design approach outlined, we present the development and design process of a smart mattress, combining theory with practice to meet user needs and drive innovation. The product design was simulated and analyzed using Inventor software (see Fig. 5).

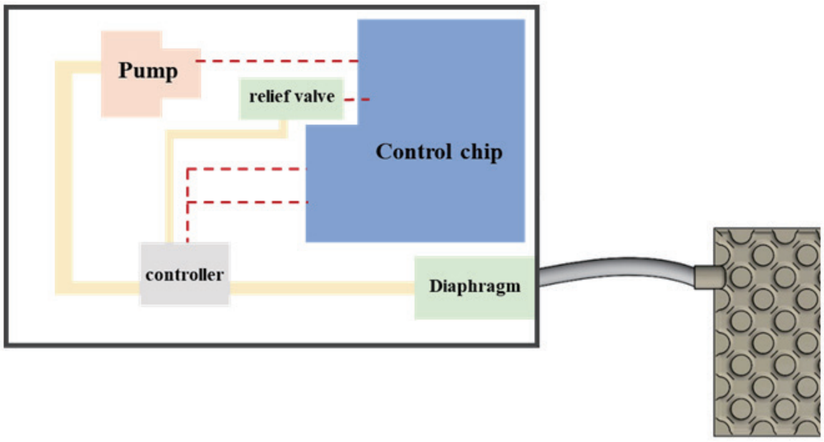


Fig. 4. (Color online) Airbag control device.

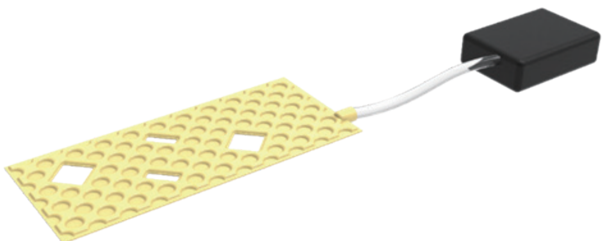


Fig. 5. (Color online) 3D simulation diagram of smart mattress.

2.2 Collection and processing of physiological signals

The developed smart mattress for physiological signal collection and processing comprises several hardware components: pressure sensors, capacitive microphones, a microcontroller unit (MCU), a high-resolution analog-to-digital converter (ADC), a filtering circuit module, an inflating/deflating module, and a transmission control module. Pressure sensors detect pressure variations on the mattress, while capacitive microphones capture raw heartbeat and respiration signals. These physiological signals are transmitted to the filtering circuit to remove potential noise and ensure signal clarity and accuracy. The filtered signals are then converted into digital form by the ADC module for analysis by the MCU. The MCU integrates the collected physiological signals and, on the basis of analysis, issues commands to the inflating/deflating module to control the electromagnetic valves, adjusting the air cushion's inflation and pressure levels. This hardware architecture, as illustrated in Fig. 6, connects various functions and processes, utilizing software algorithms to manage the signal collection and control of the smart mattress.

To collect low-frequency BCG signals, a finite impulse response filter is used to effectively extract useful signals while eliminating unwanted noise. The respiration and heartbeat signals are processed through different filter modules: a low-pass filter to remove high-frequency noise and smooth the signal, and a high-pass filter to eliminate low-frequency trends or DC components and highlight high-frequency elements. Following the filtering process, specific frequency ranges are extracted. To ensure accurate data, errors caused by body movements are eliminated during data processing. Techniques such as time-domain analysis, peak enhancement, and peak detection are employed to calculate precise heart rate and respiration frequency. The least mean squares (LMS) method and thresholding are applied in signal processing. The LMS method adjusts filter coefficients to minimize the difference (error) between the output and the desired signal. Thresholding distinguishes useful signals from noise based on predetermined thresholds, allowing for the detection of significant events (e.g., peaks) for feature extraction and signal segmentation. After identifying abnormal signals (e.g., body movements) and validating reasonable signal peaks and time differences, statistical analysis is performed.

Appropriate bandpass filters are configured on the basis of the frequencies of the respiration and heartbeat signals. The physiological and air pressure variation signals from the air cushion

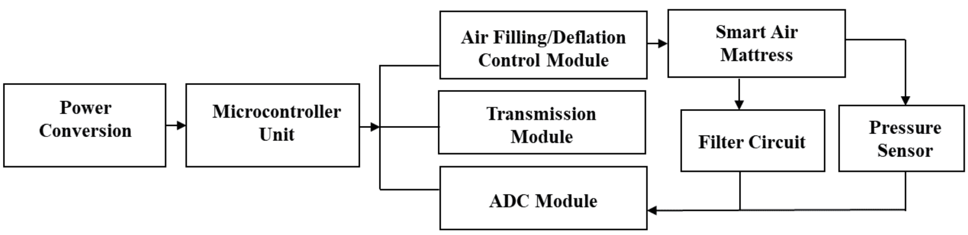


Fig. 6. (Color online) Hardware architecture.

are processed separately. The blue waveform represents the raw data of the physiological signals, whereas the filtered results exhibit fluctuations in amplitude and frequency that reflect changes in respiration or heartbeat during measurement. The green line represents the smoothed curve calculated using the LMS method, indicating the overall trend or average of the data. The red line denotes a reference or standard threshold, indicating the critical range of values (see Fig. 7).

To detect user turning movements, the collected signals were analyzed to identify abnormal patterns. When a user remains stable on the mattress, the signals are relatively consistent (see Fig. 8). Conversely, during turning or other body movements, the pressure exerted on the air cushion significantly exceeds that of respiration or heartbeat pressure. As a result, signals collected during these movements exhibit notiable distortion compared with normal respiration or heartbeat signals (see Fig. 9). This enables the identification and marking of anomalies during data processing.

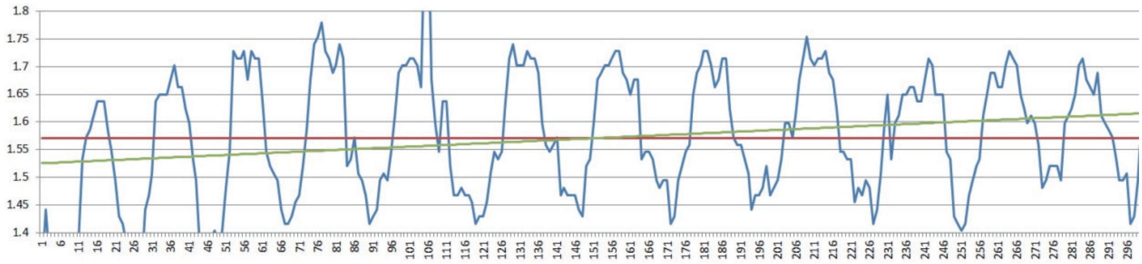


Fig. 7. (Color online) Signal processing schematic diagram.

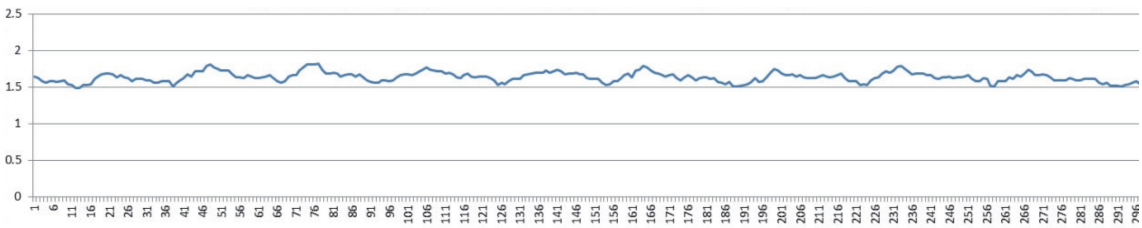


Fig. 8. (Color online) User stability signal diagram.

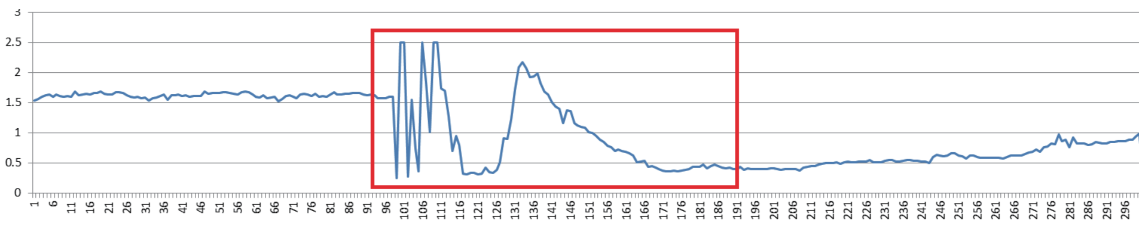


Fig. 9. (Color online) User movement signal diagram.

2.3 Development and construction of health management system

We integrated a physiological signal sensing device from the smart mattress, a database, an information system, and client-side devices to construct a comprehensive health management system utilizing web and mobile application development technologies. Through the collaborative operation of various modules, the system consolidates health management equipment and user data to facilitate the real-time collection, analysis, storage, and visualization of health information. Health devices, such as the smart mattress, transmit real-time data to the system using the message queuing telemetry transport protocol. The information management system analyzes this data and stores it in a database. Users can access the system via a web browser or mobile app, with access permissions customized according to their roles. Through client-side application programming interfaces and database interactions, users can view health monitoring data and perform institutional management functions. The system periodically backs up data to ensure stability and security.

The health management system comprises three subsystems: the monitoring dashboard, the bed and personnel management subsystem, and the health database. The monitoring dashboard offers a visual overview of user health, enabling administrators to efficiently manage and monitor users through graphical representations. The bed and personnel management subsystem streamlines bed allocation and staff scheduling in healthcare institutions, while the health database records and analyzes health data, supporting both manual input and data from peripheral devices (see Fig. 10). The mobile application for the health management system was developed for both iOS and Android platforms. The Android version was created using Kotlin in

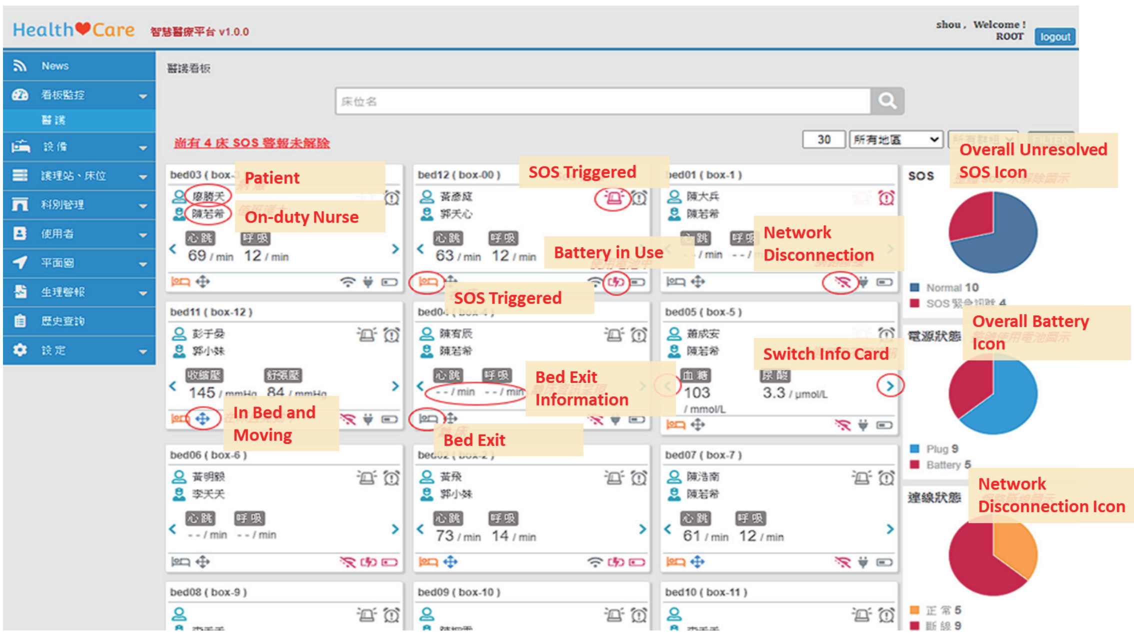


Fig. 10. (Color online) Dashboard of health management system.

Google's Android Studio IDE, whereas the iOS version was developed using Swift in Apple's Xcode environment. This app provides real-time access to health data, sleep analysis, notifications, and firmware updates.

3. Results and Discussion

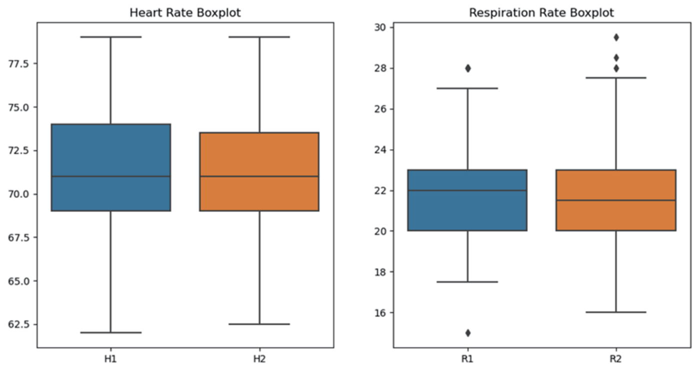
In the development of the smart mattress hardware, we utilized a programmable signal generator (model: SIGLENT SDG 1032X) for signal simulation and testing. This approach facilitated the setting and calibration of the functionality of related modules. Additionally, EasyWave software, provided by the manufacturer, was employed to validate signal and filtering processing results. By integrating the SDG 1032X signal generator with EasyWave software, we designed, imported, and output physiological signals, adjusting and testing them using the generator's various functions to ensure the effectiveness and accuracy of the filtering methods. Ultimately, the completed smart mattress was deployed in a real-world environment to confirm its capability for the continuous monitoring and recording of user physiological data, such as heart rate and respiration. The collected data and results were transmitted to the health management system and could be viewed in real time on both the web and the mobile app (see Fig. 11).

To validate the accuracy of the smart mattress, a paired sample t-test was conducted to compare heart rate and respiration data collected by the smart mattress with data from a commercial medical-grade device (OMRON HEM-7156). The validation data were gathered by research team members, with consent obtained, from various time periods, totaling 502 pre-test and post-test data points. The statistical results indicated that no significant differences were found in heart rate (p = 0.059) or respiration (p = 0.170), thereby confirming the accuracy of the smart mattress's data collection. Table 2 summarizes the results of the paired sample *t*-test, and Fig. 12 illustrates the distribution of heart rate and respiration values in box plots.

Fig. 11. (Color online) Illustration of smart mattress in practical application.

Table 2
Results of paired sample *t*-test verification.

Variable	Mean	SD	*t*-value	*p*-value
Heart rate			1.892	0.059
H1 (Existing device)	71.23	2.85		
H2 (Developed prototype)	71.17	2.84		
Respiratory rate			1.373	0.170
R1 (Existing device)	21.75	2.11		
R2 (Developed prototype)	21.57	2.20		



(Note: H1: Heart rate measured by existing device, H2: Heart rate measured by the device developed in this study; R1: Respiratory rate measured by commercial monitoring device, R2: Respiratory rate measured by the device developed in this study)

Fig. 12. (Color online) Box plot of comparative data for heart rate and respiratory rate measurements.

4. Conclusion

We successfully developed a smart mattress designed for continuous health monitoring, integrating both hardware and software to provide real-time physiological data collection and health management services. The system underwent rigorous testing and validation, demonstrating its potential for deployment in various settings, including home environments and healthcare facilities. The smart mattress was engineered with a focus on the accurate real-time monitoring of heartbeat and respiration rates, utilizing TRIZ principles to enhance design efficiency and durability. Additionally, a comprehensive health management system was created, featuring a user-friendly interface accessible via web and mobile platforms, which offers personalized health assessments and early warning alerts.

The techniques and design principles utilized in this study provide valuable insights for the development of health monitoring devices and health management systems. As sensor technologies and algorithms continue to advance, future research can concentrate on further optimizing these sensing technologies and monitoring systems to improve accuracy and broaden functionality. Furthermore, this model can be used for the development of additional medical and healthcare monitoring products and systems.

References

1 World Health Organization: World Malaria Report 2023. (WHO, Geneva, 2005) 8.
2 M. Hirshkowitz, K. Whiton, S. M. Albert, C. Alessi, O. Bruni, L. DonCarlos, N. Hazen, J. Herman, P. J. Adams Hillard, E. S. Katz, L. Kheirandish-Gozal, D. N. Neubauer, A. E. O'Donnell, M. Ohayon, J. Peever, R. Rawding, R. C. Sachdeva, B. Setters, M. V. Vitiello, and J. C. Ware: Sleep Health **1** (2015) 233. https://doi.org/10.1016/j.sleh.2015.10.004
3 Task Force on Sudden Infant Death Syndrome (2016): Pediatrics **138** (2016) e20162938. https://doi.org/10.1542/peds.2016-2940
4 Q. Zhan, D. Wu, J. Ma, G. Li, X. Wei, J. Zuo, and X. Wang: Proc. 13th Int. Conf. Signal Processing Systems (ICSPS 2021) 12171 (SPIE, 2022) 120–127. https://doi.org/10.1117/12.2631448
5 V. P. Tran, A. A. Al-Jumaily, and S. M. S. Islam: Big Data Cogn. Comput. **3** (2019) 3. https://doi.org/10.3390/bdcc3010003
6 H. W. Loh, S. Xu, O. Faust, C. P. Ooi, P. D. Barua, S. Chakraborty, R.-S. Tan, F. Molinari, and U. R. Acharya: Comput. Methods Programs Biomed. **216** (2022) 106677. https://doi.org/10.1016/j.cmpb.2022.106677
7 X. He, R. Goubran, and F. Knoefel: Proc. 2017 IEEE Sensors Applications Symp. (SAS, March, Glassboro, NJ, USA) (IEEE, 2017) 13–15. https://doi.org/10.1109/SAS.2017.7894087
8 F. Erden, A. Z. Alkar, and A. E. Cetin: Infrared Phys. Technol. **73** (2015) 88. https://doi.org/10.1016/j.infrared.2015.09.005
9 H. Abuella and S. Ekin: Proc. IEEE Sensors J. **20** (2020) 3859. https://doi.org/10.1109/JSEN.2019.2960194
10 A. J. D. Krupa, S. Dhanalakshmi, N. L. Sanjana, N. Manivannan, R. Kumar, and S. Tripathy: Biocybern. Biomed. Eng. **41** (2021) 1533. https://doi.org/10.1016/j.bbe.2021.09.006
11 S. Otis, N. Mezghani, and B. Abdulrazak: Proc. 2018 9th Int. Symp. on Signal, Image, Video and Communications (ISIVC) (IEEE, 2018) 93–98. https://doi.org/10.1109/ISIVC.2018.8709083
12 Y. Yue, J. Zhong, and L. Wang: Proc. 2020 Int. Conf. Machine Learning and Big Data Analytics for IoT Security and Privacy (SPIoT-2020) 2 (Springer International Publishing, Cham, 2020) 773–776. https://doi.org/10.1007/978-3-030-62746-1_119
13 Z. Li, A. Li, T. Chen, J. Liu, and T. Gao: Procedia Comput. Sci. **214** (2022) 329. https://doi.org/10.1016/j.procs.2022.11.182
14 M. Laurino, L. Arcarisi, N. Carbonaro, A. Gemignani, D. Menicucci, and A. Tognetti: IEEE Access **8** (2020) 45664. https://doi.org/10.1109/ACCESS.2020.2976194
15 R. Aviles-Espinosa, E. Rendon-Morales, Z. Luo, H. Dore, O. Anton, H. Rabe, and R. J. Prance: Proc. 2019 IEEE Sensors Applications Symposium (IEEE, 2019) 1–5. https://doi.org/10.1109/SAS.2019.8705971
16 H. H. Hsu, N. Y. Yen, T. W. Pai, and M. H. Chang: Biomed. Eng. Appl. Basis Commun. **26** (2014) 1440004. https://doi.org/10.4015/S1016237214400043
17 S. Mukherjee, K. Dolui, and S. K. Datta: Proc. 2014 IEEE Int. Advance Computing Conf. (IEEE, 2014) 400–405. https://doi.org/10.1109/IAdCC.2014.6779357