IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received June 10, 2021, accepted July 13, 2021, date of publication August 9, 2021, date of current version August 13, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3102281

Noncontact Sleep Monitoring System Under a Mattress

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ABSTRACT Sleep quality and duration are critical indicators of individual health. Traditional methods of monitoring them either were limited to the application environment or resulted in discomfort. To overcome these existing limitations, we propose a noncontact sleep monitoring system placed under the mattress, named SleepMatrix, to provide users with a comprehensive picture of their real-time to long-term health status. SleepMatrix is a sleep monitoring system that consists of two parts: a front-end sensor array and a cloud-edge data processing system. The data-driven system, based on the Internet of Things, can be flexibly deployed in environments from homes to transportation, and a variety of centralized control and monitoring functions can be flexibly deployed under different application scenarios. At the same time, users can view real-time and historical data through supporting applications and understand the sleep monitoring results. SleepMatrix is a complete and systematic sleep monitoring tool that can help people understand their health status and its evolution from a new perspective and therefore may contribute greatly to informing users of potential illnesses.

INDEX TERMS SleepMatrix®, sleep monitoring, sleep stage, the Internet of Things, flexible deployment.

I. INTRODUCTION

Sleep problems are a growing concern for global public health because poor sleep is associated with impairments in motivation, emotion, and cognitive functions as well as increased risks of serious medical conditions (e.g., diabetes, cardiovascular disease, and cancer), even when the symptoms are below the threshold of clinical sleep disorders [1]–[4]. Recent estimates showed that the prevalence of sleep problems was as high as 56% in the USA, 31% in Western Europe and 23% in Japan [5]. Therefore, an increasing demand for long-term stable detection and analysis of various sleep indicators, including sleep posture, sleep duration, sleep quality, etc., has emerged. With the application of technologies such as sensors, computers and medical physiological engineering in clinical practice, the understanding of sleep physiology and pathology is increasing daily. Sleep medicine, as a new cross-discipline frontier in modern medicine, has been gradually established and developed. To date, many studies on sleep medicine, especially sleep monitoring technologies, have been carried out. McDowell *et al.* [6] presented a noncontact alternative method of sleep profiling that was deemed to be more suitable for long-term monitoring than the current clinically approved techniques. To verify the method, he conducted a controlled trial and demonstrated that a random forest classifier using features calculated from optimally placed static accelerometers could produce a sleep/wake classification accuracy of 92%. Pallin *et al.* [7] compared a novel noncontact biomotion sensor, which provided an estimate of both sleep time and sleep-disordered breathing, with wrist actigraphy in the assessment of total sleep time in adults suspected of having obstructive sleep apnea syndrome. He concluded that the biomotion sensor provided a viable alternative to actigraphy for sleep assessment of obstructive sleep apnea syndrome. Kahn and Kinsolving [8] proposed a method of monitoring a user's movements and determining when the user entered into a sleep session. The method further identified the sleep session as a power nap or a longer sleep and woke up the user at a predetermined time based on a combination of user preferences and measured information regarding the sleep session.

The gold-standard sleep assessment uses polysomnography (PSG) with various sensors to identify sleep patterns and disorders [9]. However, due to the high cost and limited

The associate editor coordinating the review of this manuscript and approving it for publication was Giovanni Pau.

availability of PSG, many people with sleep disorders are left undiagnosed. The use of PSG equipment requires many cables connected to the human body. It provides accurate and comprehensive information for professional medical analysis but seriously hinders the user from occasional nocturnal movements such as turning over and getting up at night, which seriously limits daily life applications [10]. Alternative solutions such as wristwatch-like actigraphy were proposed by recording hand-related locomotor activities via a built-in piezoelectric accelerometer. This requires good contact between the device and wrist, but in fact, it is difficult to keep good contact for a long time during sleep [11]. This highlights the urgent need for cheap and effective noncontact sleep monitoring programs.

However, sleep monitoring also has certain limitations. Roomkham *et al.* [4] presented an extensive review of recent sleep monitoring systems and the techniques used in their development, discussed their performance in terms of reliability and validity, and considered the needs and expectations of users. This review highlighted a number of challenges to current studies: a lack of standard evaluation methods for consumer-grade devices, limitations in the populations studied, consumer expectations for monitoring devices, and constraints on the resources of consumer-grade devices.

Two of the most prevalent examples in the market include Beddit from Apple and S+ from ResMed [9]. Beddit is a thin strip sensor placed under a bedsheet. Its embedded pressure sensor measures the heart (ballistocardiograph) and respiration rate and body movement to discriminate the states of awake, light sleep, and deep sleep. A recent validation study compared the performance of Beddit with PSG over ten subjects, and the result showed poor agreement between them, with a Cohen's kappa of 0.101 on average. In addition to nonwearables, the S+ device offers a noncontact sleep monitoring platform with its Doppler radar system to monitor breathing, body posture, and movement. An evaluation comparison study of PSG over 27 subjects showed similar or slightly better agreement (87.6%) with PSG than actigraphy (85.1%) in sleep/wake detection. However, S+ still showed limited agreement when analyzing specific sleep stages (65%). Noncontact sleep monitoring systems based on Doppler radar are also being actively researched to measure more physiological information types and provide higher accuracy.

This paper proposes a monitoring system, named SleepMatrix, which can carry out long-term stable, reliable and economical noncontact monitoring of sleep, in response to the problems and challenges faced by existing sleep monitoring technologies. SleepMatrix has a powerful front-end sensor array and an advanced edge cloud integrated data processing system to provide users with comprehensive perception of real-time to long-term health situations. The data-driven system based on the Internet of Things (IoT) can be flexibly deployed in homes, hospitals, nursing homes, schools, dormitories, hotels, and various transportation equipment. In different application scenarios, a variety of centralized control and monitoring functions can be flexibly deployed. At the same time, apps can also provide powerful real-time and historical data access for individual users. The SleepMatrix imperceptible under-body sleep monitoring system is a complete and systematic long-term health management tool that can help people understand their own health status well to prevent and detect various diseases early.

The remaining sections of this paper are organized as follows: Section II describes the components and the key technologies of the SleepMatrix research program. Section III introduces the monitoring indicators and corresponding functions of the research program. Section IV describes a set of experiments used to verify the accuracy of the system and the results. Section V gives the conclusion.

II. RESEARCH PROGRAM

The SleepMatrix noncontact sleep monitoring system is composed of a sleeping mattress and a data center [12]. The two components are interconnected through a wireless network. Fig. 1 is the SleepMatrix design framework.

A. KEY TECHNOLOGIES OF SLEEPMATRIX

As shown in Fig. 2, the sleeping mattress is composed of mattress equipment, a main controller and an IoT connector.

(1) The main job of the mattress equipment is to integrate the data collected by the sensor and forward them to the main controller. There are 64 impact sensors arranged in a matrix under the mattress, which are used to sense the limb movements and cardiopulmonary behavior of the bed user. As shown in Fig. 3, every group of eight sensors in the horizontal direction is connected to an acquisition controller to form an ''equipment unit''. The acquisition controller consists of an ARM 32-bit Corte-M3 microprocessor chip, an analog-to-digital (A/D) converter and a CAN chip. The signal collected by the sensors is converted into a digital quantity, marked and packaged, and transmitted to the controller through a CAN bus. There are two main purposes in designing the acquisition controller. First, to deploy the sensor matrix flexibly, multiple sensor sets are regarded as a device unit. Through the acquisition controller for data acquisition conversion, it is convenient to manage the sensor. Second, the acquisition controller exchanges data with the main controller through the CAN bus, which can easily add and remove equipment units to achieve the optimal acquisition effect.

At the data transmission level, the data of every four sensors form a ''basic data group'' (green group and red group in Fig. 3), and the data generated in each basic data group together form a ''data frame''. The frame contains five datasets, namely, a CAN ID and four sensor datasets. The sensors are sorted from left to right. The data frame format is shown in Fig. 4.

When the mattress equipment is working, it always reserves one equipment unit to collect data at a higher rate (180 Hz) and uses the other seven equipment units to collect data at a lower rate (20 Hz). In theory, the normal heart rate

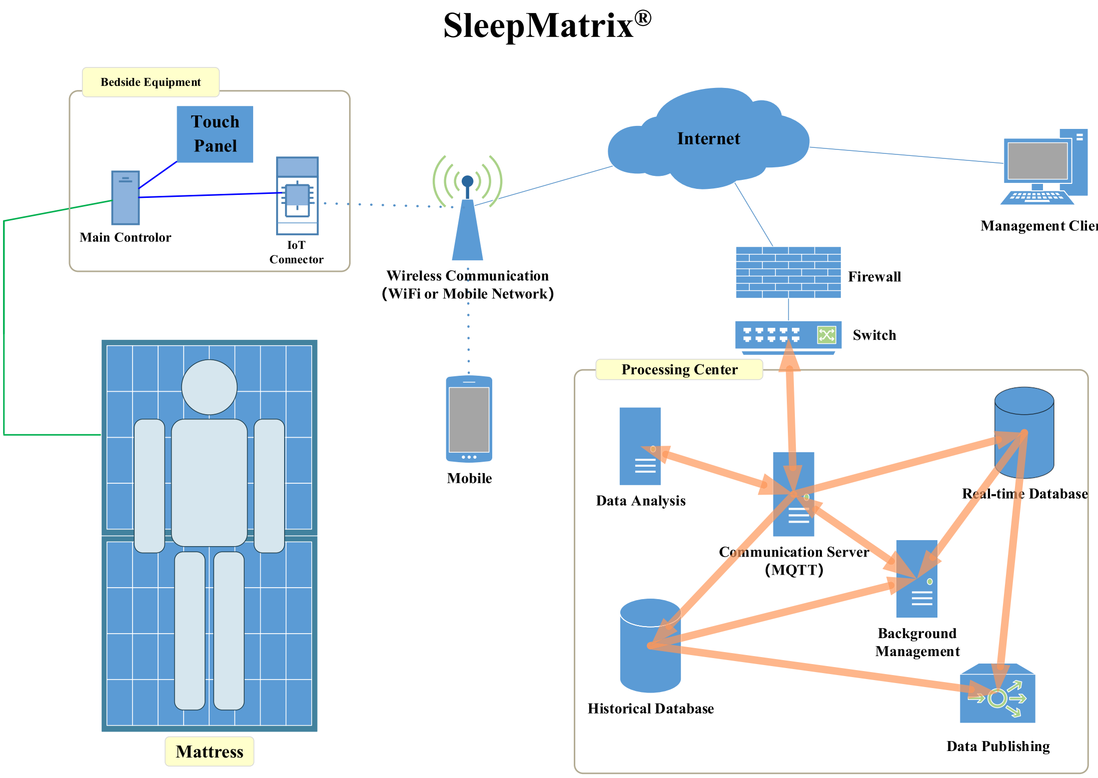

FIGURE 1. SleepMatrix® system design framework.

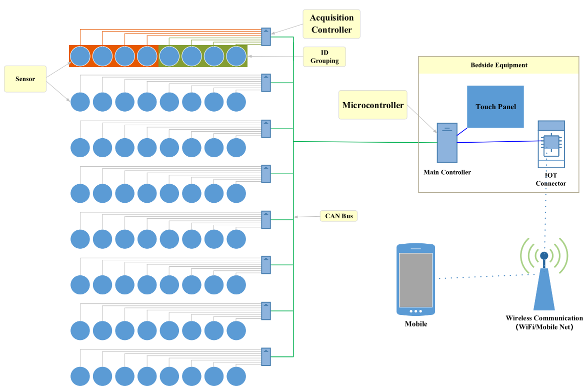

FIGURE 2. Block diagram of the SleepMatrix system.

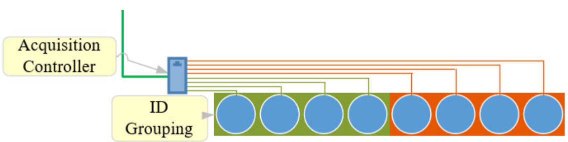

FIGURE 3. "Equipment unit" composition diagram.

Data Frame				
1	2	3	4	5
CANID	1#Sensor Data	2#Sensor Data	3#Sensor Data	4#Sensor Data

FIGURE 4. The composition of the data frame.

will not exceed 150 bpm in the resting state [13], [14], and a sampling rate of 20 Hz can obtain sufficient fine data resolution. According to this sampling rate, the whole device will generate 1280 data points per second. The results measured by other heart rate measuring devices are also in this range, such as smart bracelets and Apple Beddit.

The IOT connector needs to conduct communication with the acquisition controller, perform secondary encapsulation of data, run the MQTT protocol, maintain network connections and carry out other tasks. After many comprehensive tests, when the data volume of the hardware and software system of the device continues to exceed 4800 bits per second, this will lead to a large processing delay, insufficient memory and other unstable situations, such as restart. In addition, during the operation of the device, the network quality may be poor or even interrupted, or the internal transmission of the device may be unstable. As a result, the transmission of the cloud center will be interrupted for a short time. Before these interrupts are automatically recovered (usually taking several minutes), the device needs to keep the data collected during this period in the cache. When transmission is restored, the device needs to store the data in the cache. The device needs to send the data in the cache to the cloud as soon as possible. This function will occupy the transmission bandwidth between the acquisition controller and the connector.

Therefore, sufficient bandwidth must be reserved for this function.

After theoretical analysis and long-term experimental verification, as long as a group of equipment units carry out high-frequency sampling (180 Hz) at the position where the pulse signal is strongest, the limit state data of an abnormal heart rate can be captured well. Therefore, the various units of the device do not have to work together at the same sampling rate; that is, at one time, it may be that only one unit of the device is working at a 180 Hz sampling rate, while the other units are working at a 20 Hz sampling rate. In this way, normal heartbeat shock, respiratory shock and body movement and posture-related data can meet the needs of calculation and analysis through low-frequency sampling. The device unit, which operates at high frequency, can detect the impulse signal of an abnormal heartbeat. When there is no abnormal heartbeat, it can also be combined with the low-frequency sampling data to further guarantee the quality of analysis and calculation. At the same time, this solution avoids the hardware cost spike due to the excessive cache capacity requirement.

The device unit working at the high-frequency sampling rate is not fixed. The algorithm will analyze and identify the set of device units with the highest signal-to-noise ratio (SNR) and give instructions to the acquisition controller to make this device unit work in the high-frequency mode and have the other units work in the low-frequency mode.

With this mechanism, the device generates data at a rate of approximately 2560 data points per second, thus reserving more than 2000 data points per second of bandwidth for processing the data in the cache. In the actual test, when processing the cached data, the system can process more than 4000 data points per second, which ensures data adequacy and real-time performance and keeps the transmission bandwidth and storage capacity in a good balance.

Due to different changes in the acquisition and transmission rates, the data frame generated by each basic data group uses two different CAN IDs, namely, the ID of the high-speed mode and the ID of the low-speed mode. The data processing program changes according to the ID. The mattress equipment confirms the rate mode of the received data frame and sends a command to the acquisition controller to specify a certain equipment unit to work in the high-speed mode. The purpose of this mechanism is as follows: the data processing program automatically determines which equipment unit is closest to the heart position and selects this equipment unit to collect heart shock signals at a high speed, ensuring the sufficiency and timeliness of the data; only one necessary equipment unit works in high-speed mode, and the data volume of the entire mattress remains unchanged so that the transmission bandwidth requirements and storage capacity requirements are controlled at a better balance.

Based on the above solutions and details, the mattress equipment can achieve sufficient, real-time transmission with integrity, continuity and correctness. The data of the bed users collected by the sensor are transmitted to the CAN bus connected to the main controller. The acquisition controller with the CAN communication function can also receive commands from the main controller to carry out the instructions the main controller issues regarding the adjustment of the working status of the equipment.

(2) As the advanced control unit of the local equipment, the main controller can control the data processing and transmission of the equipment status display.

In terms of displaying the status and control functions of local devices, SleepMatrix uses a touch screen as a medium for human-computer interaction, which perfectly meets the main controller's display output requirements and the control command input requirements for the device. Fig. 5 shows a variety of functions of the main controller, including health indicator measurement, basic device information display, network and cloud connection status, data acquisition speed and storage, and alarm clock settings. These features allow users to better use SleepMatrix.

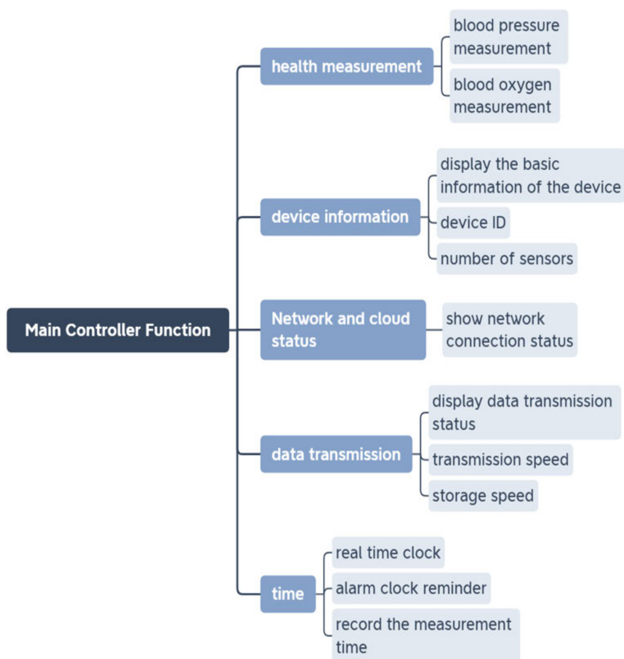

FIGURE 5. Main controller function.

In terms of data processing and transmission functions, after receiving the data frame from the mattress device, the main controller compresses and composes the data frame and then caches and dumps the backup locally. The backup is transmitted to the data center through the Internet of Things connector for further analysis and processing.

First, the main controller compresses the data based on the principle of effective bit data extraction. The data width of each sensor upload is 16 bits, and the actual accuracy of the sensor is 12 bits, which results in 4 redundant bits. Based on this principle, the main controller splices the effective number of bits in a fixed manner, thereby achieving a data compression ratio of 75%.

After the main controller accumulatively receives 28 compressed data frames, they form a data body. The main controller then adds the necessary components and related information to form a data packet, including the packet header, function code, time stamp, sensor ID, packet number, data body, serial number, check code and packet tail. The header and tail of the data packet are used to mark the beginning and end, the time stamp and sensor ID are used to mark the data, and the check code adopts a CRC check to ensure the accuracy of the received data. Because of the large amount of data transmitted, the packet number is composed of the numbers of the data queue and data group. The data queue is the data collected by a single sensor, and the data group is a data set collected by multiple sensors. Table 1 shows a detailed description of the necessary components of the data packet and related information.

TABLE 1. Data packet generated by the main controller.

Number	Name	Description
1	Packet header	Header of the data packet, the fixed value 0xAABB
2	Function code	The agreed function code, which indicates that the data packet is sensor data
3	Time stamp	The collection time
4	Sensor ID	The unique identification of the mattress matrix sensor
5	Packet number	Packet number
6	Data body	Data frame formed by the compressed data
7	Serial number	Serial number from 0 to 65535
8	Check code	Verification of the data from the start of the function code to the verification serial number
9	Packet tail	Tail of the data packet, the fixed value 0xBBAA

After completing the construction of the data group package, the system transfers the data package to the cache and local storage and waits for the data request from the IoT connector to send the data to the IoT connector. The cache and local storage are established with the following considerations: due to the connection between the network and the server through the connector, some network-related exceptional situations may occur, such as a network delay or even network disconnection and reconnection, which result in an inability to request and transmit data quickly. Therefore, after the main controller generates the data packet, it first puts the data into the cache and waits for the request of the connector. As long as the connector has no other transactions, it will continually request data from the main controller. If the data packet is fed back by the main controller within a reasonable waiting time, it will be sent to the data center. In some special cases, such as a long period of network disconnection, the main controller's cache alone cannot retain a large amount of data. Thus, the main controller has another function to ensure data integrity: external storage. The main controller can have an SD card inserted. When the main controller generates a data packet, it writes the data packet to the SD card as well as writing to the cache. Therefore, even if the transmission to the data center cannot be recovered for a long time or the cache is not large enough to retain these data, the SD card can save the data for several days. After receiving the command, the main controller uploads the data to the SD card. The system composed of an idle request mechanism, a large-capacity cache and a large-capacity memory card ensures the timeliness, integrity and continuity of data. This data transmission mechanism can ensure that the sampled data are continuous and none are missing in most cases.

In the data forwarding step, the Internet connector requests data from the main controller when it is idle to meet the data integrity and continuity requirements for the final data analysis.

(3) The Internet connector is mainly responsible for connecting to the Internet, connecting and logging into the server, encapsulating the data requested by the main controller again according to the agreed rules, and uploading them to the message queuing telemetry transport (MQTT) server in the data center.

The ESP8266 chip is selected as the connector to the Internet of Things, and it has a 2.4 GHz WiFi connection. The chip uses Nodemcu firmware, which provides the complete MQTT protocol library. The chip can be configured to work in access point (AP) mode and station mode and accesses the server via WiFi.

The IoT connector sends a data request to the main controller at idle time. The request information includes the function code, sensor ID, and data packet serial number. After the main controller receives the command, it will complete the verification and return the data packet. The IoT connector will also check the data.

As shown in Fig. 6, the data received from the IoT connector will be analyzed in three respects.

After the IoT connector receives the agreed-upon number of data packets, the data will be combined into a larger data packet, as shown in Table 2. The structure of the data packet is divided into six parts. The sensor data are a data group, which is composed of data packets, and each data packet is composed of data frames.

After the IoT connector has assembled the data packet, it will send the data to the data center for processing via the Internet.

B. KEY TECHNOLOGIES OF THE DATA CENTER

The data center consists of a communication server (MQTT broker server), a cache server (memory database), and a historical database. It mainly completes the storage and analysis of data (Fig. 7 shows the MQTT interface).

The server used in this paper is an open-source Internet of Things MQTT messaging server developed based on the Erlang/OTP platform, and the release version is EMQ X 2.2.The server can stably host large-scale MQTT client connections; supports distributed node clusters and fast low-delay message routing; features message server extensions and support to customize a variety of authentication

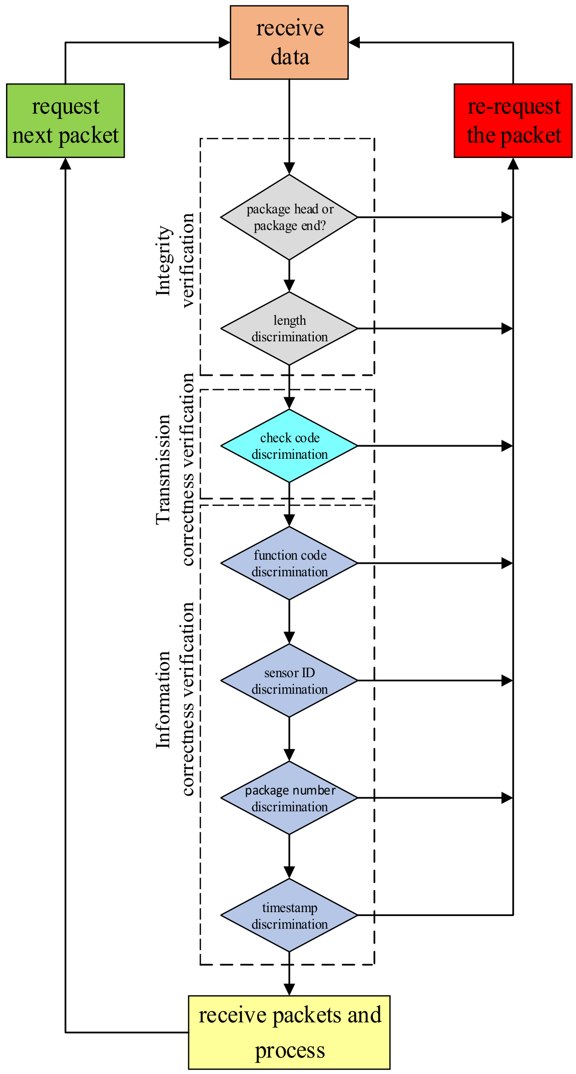

FIGURE 6. Data verification process for the IoT connector.

methods and ensure the efficient storage of messages to the back-end database; and supports complete IoT protocols, including MQTT, MQTT-SN, COAP, LWM2M, WebSocket, and private protocols.

After receiving and sending the data packet uploaded by the IoT connector through the Internet, the communication server verifies the data according to the agreed-upon rules. If the verification result is correct, the data package is further disassembled, and valid data will be obtained and transferred to a historical database for further analysis and processing.

The SleepMatrix device data message topic consists of the following layers: a business classification ID message property flag; a business classification ID, where different IDs indicate the business classifications of data messages, such as "H0000000", which represents the sleep monitoring system mattress equipment data; a device ID, which is the unique ID representing each specific sleep monitoring device; a subdevice ID; and a message attribute mark. The distribution quality of all messages is set to 2 to ensure message accessibility.

TABLE 2. Data packet generated by the IoT connector.

Number	Name	Description
1	Flag byte	A specific value representing the type of the uploaded data packet
2	Sensor ID	The unique identification of the mattress matrix sensor
3	Sending time	The current time of network transmission
4	Timestamp	The data collection time recorded by the main controller
5	Data	Sensor data
6	Serial number	Serial number from 0 to 65535 to indicate the order of the data packet

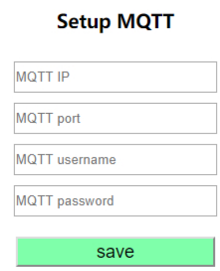

FIGURE 7. Setup of the MQTT interface.

Data storage is divided into three layers. The first layer is the system cache (Kafka message queue). The cache continually stores complete and continuous data within a certain time limit (such as one week) for high-speed reading to ensure packet integrity, transmission correctness, and information correctness. First, the integrity of the data packet is checked through the header, trailer and packet length. Then, the parity bit is used to check the correctness of the data packet on the transmission error level. Finally, the function code, sensor ID, packet sequence number and time stamp are judged to check the correctness of the data packet on the information level.

While receiving, analyzing and processing data, the data center can also send data request commands according to the needs of the work process. The data center communicates with the IoT connector through the network and then forwards the data to the main controller through the IoT controller. The main controller finds the corresponding data according to the command and uploads them from local storage.

C. CLOUD EDGE INTEGRATION FRAMEWORK

The cloud edge integration framework shown in Fig. 8 is a superb technical solution with a strong redundancy capability and good flexibility. The redundancy capability of the system is reflected in the following ways:

(1) Central storage redundancy. The data center achieves data security redundancy through clusters, arrays and multiple centers.

(2) Additional redundancy of equipment. The external storage of the device can store complete data for dozens or even hundreds of days, which is equivalent to a short-term historical data backup. In other words, many devices together constitute a "distributed historical database". This gives

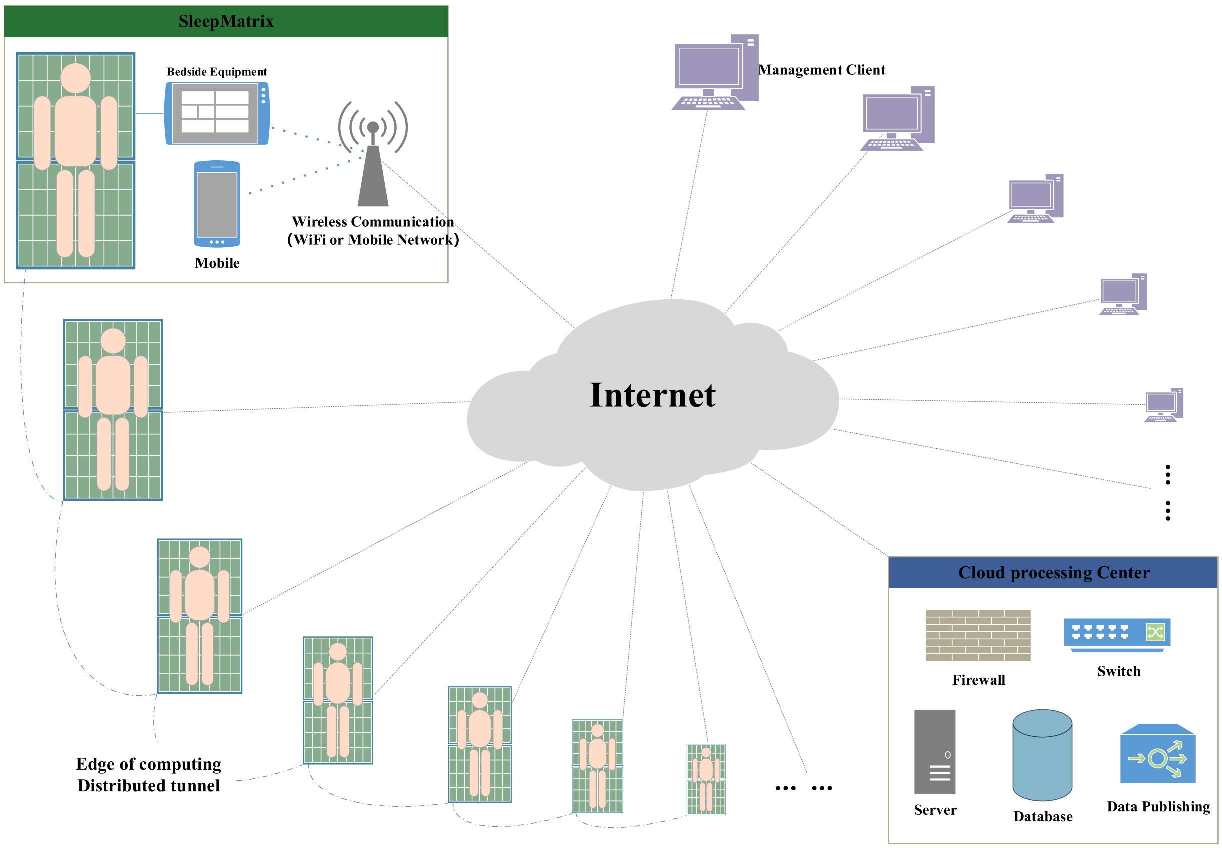

FIGURE 8. Cloud center.

the short-term historical data more sufficient redundancy protection.

The flexibility of the system is reflected in the following ways:

(1) The data center and the terminal equipment can be bound or unbound arbitrarily. The IoT connector has its own wireless hotspot. After connecting the IoT connector through the hotspot, the data center can be configured and connected to the public or private data center, as shown in Fig. 8. This means that a set of devices can be used, from individual user-oriented to organizational user-oriented, or vice versa.

(2) Central computing and edge computing are interlinked. Some computing work can be done not only by the cloud but also on the device side. The center, when necessary, divides some large-scale computing tasks into parts and assigns them to the idle devices of its subordinates to achieve dynamic distributed computing to maximize the computing power of the system.

(3) Terminal equipment interwork. In some scenarios, multiple devices (or management terminals) can form a group, and interactive logic between terminals can be established through an "edge-distributed tunnel" to form an end-to-end connected network. Therefore, this is a seamless integration of cloud processing and edge processing. The function and performance of the system will have great room for improvement in the future.

D. SIGNAL PROCESSING

After the introduction to each part of the system, this section explains how to extract the respiratory signal and heartbeat signal from the original signal collected by the sensor.

First, the signal collected by each sensor is filtered to separate the respiratory signal b_i and heartbeat signal h_i of each channel, where i is the channel number and the value of i is in the range 0-63. Because the respiratory signal has a lower frequency component while the heartbeat signal has a higher frequency component, the respiratory signal is filtered out through a low-pass filter with a cutoff frequency of 0.5 Hz, and the heartbeat signal is filtered out through a high-pass filter with the same frequency.

Next, according to the generated respiratory signal and heartbeat signal, the autocorrelation method is used to estimate the respiratory cycle and heartbeat cycle, from which the respiratory frequency and heartbeat frequency can be extracted. The specific method is as follows: for each respiratory signal b_i, slide correlation calculation is performed once every second. The following formula represents the autocorrelation sequence $c_i^n(\tau)$ calculated at n seconds:

$$c_i^n(\tau) = (\sum_{k=0}^{K-1} b_i(nf_s + k) b_i(nf_s + k + \tau))/Norm \qquad (1)$$

where f_s is the signal sampling frequency, K is the autocorrelation statistical period, and τ is the autocorrelation slide length. $Norm$ is the normalized coefficient, defined as follows:

$$Norm = \sqrt{\sum_{k=0}^{K} b_i(nf_s + k)^2 \sum_{k=0}^{K} b_i(nf_s + k + \tau)^2} \quad (2)$$

The maximum value $c_i^n(T_i)$ is selected from the autocorrelation sequence $c_i^n(\tau)$ in channel n, denoted as $Corr_i$, where

$$T_i = \max_{\tau}(c_i^n(\tau)) \quad (3)$$

Through the above steps it can be estimated that the period of the signal in channel i is T_i and the autocorrelation coefficient is $Corr_i$. Finally, a maximum value $Corr_m$ is selected from the 64 autocorrelation coefficients, which indicates that the respiratory cycle extracted from channel m, where the maximum value is located, has the highest accuracy in extracting the respiratory cycle. Therefore, when the respiratory signal period T_m extracted from the channel is the respiratory period of the user at second n, the reciprocal is the respiratory rate br_n. Based on the same method, the heart rate hr_n can be estimated.

III. MONITORING INDICATORS

From the perspective of human physiology, SleepMatrix provides users with a comprehensive picture of their health status from real-time to long-term periods in terms of sleep quality, breathing, heartbeat, body movement, blood oxygen, etc.

A. SLEEP QUALITY

The quality of sleep is one of the most critical influences on people's health status and quality of life [2], [5]. During sleep, human brains transit through repeated cycles of nonrapid eye movement (NREM) and rapid eye movement (REM). There are usually 4-5 sleep cycles per night, and each cycle lasts for 90 to 110 minutes. International sleep medicine divides sleep into five stages: the falling-asleep period N1, light-sleep period N2, deep-sleep period N3, deep-sleep period N4, and rapid eye movement period. SleepMatrix monitors the user's sleep stages and uses the Pittsburgh Sleep Quality Index (PSQI) to evaluate sleep quality. The PSQI is composed of 18 scores, including the time to fall asleep, sleep duration, sleep efficiency, and presence of sleep disorders. Each item is scored on a scale of 0-3. The cumulative score of each item is the factor score, and the sum of all the factor scores is the total score of sleep quality, namely, the PSQI. A lower PSQI indicates better sleep quality. $PSQI < 7$ indicates good sleep quality, and $PSQI \geq 7$ indicates poor sleep quality (i.e., sleep disturbance) [15]. SleepMatrix can assess the user's sleep quality through long-term monitoring, and therefore, the user can master his or her own health status and make adjustments accordingly.

B. OBSTRUCTIVE SLEEP APNEA HYPOPNEA SYNDROME (OSAHS)

OSAHS is a common respiratory disorder that occurs during sleep. Its main manifestation is that respiratory airflow drops or even disappears frequently during sleep, which leads to intermittent hypoxemia and wakefulness and excessive sleepiness during the day. Long-term OSAHS induces a series of chronic diseases, such as hypertension, coronary heart disease, arrhythmia, stroke, diabetic insulin resistance, and an increased incidence of traffic accidents [16]. The microsensor array attached to the SleepMatrix converts the deformation signals caused by the relaxation and contraction of the thorax during the breathing process into electrical signals. Extensive thoracic movements increase the amplitudes of the corresponding electrical signals. Therefore, we can monitor the user's breathing frequency and breathing intensity accurately through the collected signals. In addition, a specific signal waveform, which has an abnormally high amplitude and long inspiratory time, will appear when transient obstructive apnea occurs. The abnormally high amplitude stems from the activation of assisting respiratory muscles when a blockage appears in the airway, which causes abnormal enlargement of the thorax. The longer inspiratory time results from the same process of inspiratory dyspnea. SleepMatrix monitors the user's respiratory rate, respiratory intensity and times of transient obstructive apnea to ensure that OSAHS can be diagnosed as early as possible.

C. ARRHYTHMIA

Arrhythmia is a common type of cardiovascular disease whose diagnosis is complicated. An electrocardiographic (ECG) examination must be conducted to confirm the diagnosis. Traditional ECG equipment has a short monitoring time, which makes it difficult to capture sporadic and short-term arrhythmia and asymptomatic arrhythmia [17], [18]. SleepMatrix allows users to monitor their heartbeat throughout the night. The microsensor array attached to the SleepMatrix converts the microvibration signals caused by the heart beating during sleep into electrical signals, forming specific heartbeat waveforms. The ejection phase generates the peak of the waveform, as it gives the strongest shock to the chest wall. The highest wave is pivotal for heart rate counting. SleepMatrix provides users with stable and reliable noninvasive heart rhythm detection to ensure that diseases related to abnormal heart rhythm can be detected early.

Blood pressure, pulse and oxyhemoglobin saturation are also vital signs of human health. Normal blood pressure ranges from 60/90 mmHg to 90/140 mmHg. The pulse frequency is normally 60-100 beats per minute. The arterial oxygen saturation is normally 95%-100%. Regular monitoring provides a reference for the health management of normal people. Continuous monitoring is mainly used for postoperative patients, postpartum infants and mothers and patients with chronic diseases because the basic vital signs of these people are fairly changeable [19]. SleepMatrix provides two modes of self-checking for these monitoring indicators to ensure that it satisfies the demands of users in different scenarios.

IV. PRELIMINARY STUDY

To verify the correctness of the results obtained by the system, we carried out an initial investigation involving 20 subjects. They were of three age groups: 8 subjects in 20-30 years old, 8 subjects in 35-45 years old and 4 subjects in 50-60 years old. The test period was 14 days. Each subject lay in the Sleepmatrix for two hours a day. According to the designed data collection method, seven units (56 sensors) are sampled at 20 Hz, and one unit (8 sensors) is sampled at 180 Hz. Based on the data collected, the respiratory rate and heart rate of the subjects were calculated. The evaluation of each subject was carried out with two methods: equipment monitoring and human observation. Equipment monitoring is the SleepMatrix. Written informed consent was obtained from all subjects.

Fig. 9 shows the actual test scenario, in which the subject lay on the SleepMatrix and his sleep conditions were monitored. The figure indicate the main controller, IoT connector and sensor. There are 64 sensors under the subject. The device worn on the arm was used to actively measure blood pressure. It was not necessary to wear the device if blood pressure was not being monitored, and there were no restrictions. Both the original signal and the extracted respiratory and heartbeat signals are shown. Monitoring sensors were located under the mattress to monitor the entire sleep process. The experiment began measuring after ensuring that the device was stable for different periods.

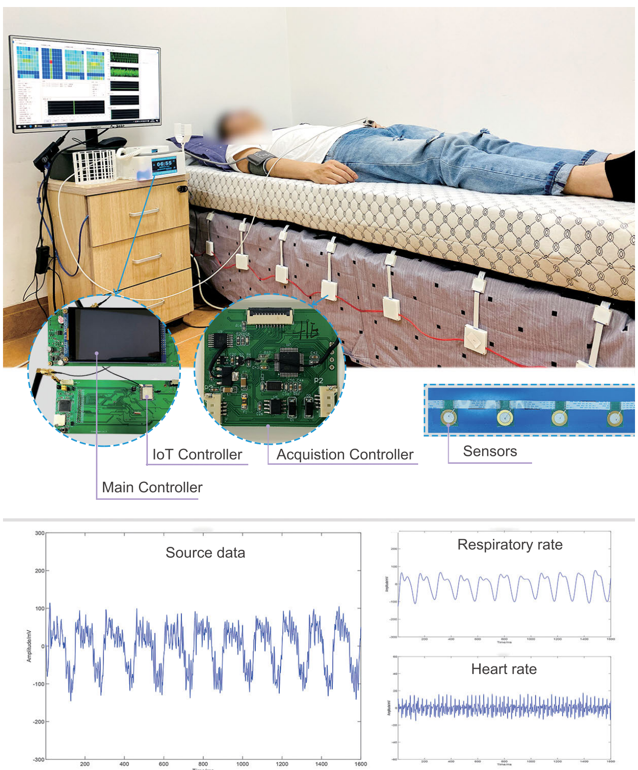

FIGURE 9. SleepMatrix data acquisition.

The measurement error and error stability were obtained by calculating the average error and variance of the results by manual observation. Equation (4) shows the formula for calculating the quasi-average error e:

$$e = \frac{\sum_{i=1}^{N} (x_i - x_i')}{N} \tag{4}$$

where x_i is the result of equipment monitoring, x_i' is the result of manual observation, and N is the number of subjects. Equation (5) shows the calculation of the final average error E of the scheme:

$$E = \begin{cases} e, & \text{Test item is a pseudo-continuous value} \\ \lfloor e \rfloor, & \text{Test item is an integer value} \geq 0 \\ \lceil e \rceil, & \text{Test item is an integer value}<0 \end{cases} \tag{5}$$

where $\lfloor e \rfloor$ is the smallest integer greater than e, and $\lceil e \rceil$ is the largest integer less than e.

Equation (6) shows the variance calculation of the scheme error.

$$D^2 = \frac{\sum_{i=1}^{N} (x_i - x_i' - E)^2}{N} \tag{6}$$

In the process of collecting monitoring data, multiple sensor signals were collected through analog-to-digital converters. First, the data had to be removed by a low-pass filter, and then sampled to 40 Hz and sent to the host computer. In the host computer, the heartbeat signal and respiratory signal were separated from each channel, and then the heartbeat cycle and respiratory cycle were detected. Based on the detection results of the heartbeat cycle and respiratory cycle for each channel (including the cycle length and detection confidence), as well as the short-term energy of the signal, it was determined whether there was a person on the bed, and whether the person was at rest or in motion.

Fig. 10 shows the real-time monitoring results of a certain subject. In the upper left part of the picture, the intensity of the color reflects the change in energy detected by the sensor as the subject's breathing and heartbeat fluctuated. The respiration and heartbeat results are presented in the form of curves through the monitoring analysis algorithm. The right side of the figure shows the intensity of respiration and heartbeat. Real-time monitoring constantly updated the monitoring analysis results. Monitoring logs were also generated to record the working status of the device and make it easy to view historical data. The monitored data were uploaded to the cloud.

Table 3 shows the error analysis we obtained after the experimental tests.

The results show that the measurement error between this solution and manual observation meets the allowable range of error in the "Technical Review Specification for Sleep Breath Monitoring Products".

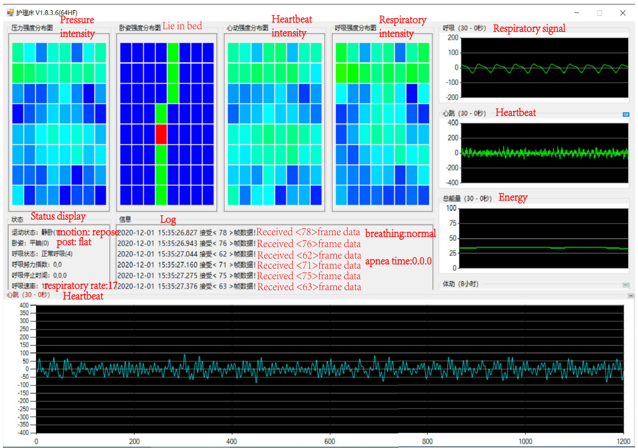

FIGURE 10. Real-time SleepMatrix monitoring results.

TABLE 3. Experimental results.

Number	Measurement items	Measurement error
1	Breathing frequency measurement	$\leqslant \pm 1\%$time/minute
2	Heart rate measurement	$\leqslant \pm 2\%$times/minute
3	Heartbeat signal curve tracking	$\leqslant \pm 8\%$
4	Heart rate variability measurement	$\leqslant \pm 8\%$

TABLE 4. Comparative advantages.

Name	Ibed 5	Sleep Number 360 Smart Bed	Apple Beddit 3.5	SleepMatrix
Price (CNY)	20000	7000-43000	1050	5000
Sensor deployment mode	single point	single point	line	Multipoint Matrix
Repose monitoring	Yes	Yes	Yes	Yes
Respiratory rate	Yes	Yes	Yes	Yes
Heart rate	Yes	Yes	Yes	Yes
Cloud	Yes	Yes	Yes	Yes
Posture monitoring	No	No	No	Yes
Apnea Monitoring	No	No	No	Yes
Body movement monitoring	No	No	No	Yes

As we know, a person sleeps with several different gestures each night. We have considered carefully that if the system would be affected by various gestures. The principle of measuring respiration rate and heart rate is the deformation and vibration of the chest. So theoretically, the sleeping position shouldn't have a significant effect on the results. But further experiments are needed to confirm this. Currently, the existing test results are relatively accurate. We consulted the relevant doctors and were highly satisfied with the test results. However, they are limitations due to the lack of patient test data. We plan to move clinical trials forward as soon as possible so that more data can be analyzed. But this takes a lot of preparation and work, including the deployment of equipment, the coordination of staff, and the arrangement of testing patients. In order to compare and explain the economic applicability and advantages of this system, the similar products in the market were investigated. From the comparison of Table 4, it can be seen that this system is economical and also has a comprehensive function. It has great advantages and prospects in application. We will move forward with the relevant testing work faster, and further optimize and improve the system. We hope the system will be available to the public as soon as possible.

V. CONCLUSION

In this paper, we proposed a noncontact and cost-effective sleep monitoring system, SleepMatrix. We also conducted an experiment to verify the accuracy and stability of the system. The evidence from the study suggests that the underpad, unobtrusive SleepMatrix is suitable for long-term, stable and reliable sleep monitoring. This sleep monitoring system provides deeper insight into conventional health management by detecting potential disorders and making corresponding adjustments as well as monitoring changes in sleep disorders, OSAHS, or postoperative recovery.

The small sample size and single test environment are limitations of the study in this paper. In the future, the system will be enhanced in 3 respects. First, we will increase the sample size, expand the test group, and increase the number of testers, which is long-term and difficult work. Second, we will work with the medical system to conduct a more scientific and accurate evaluation of the monitoring results. Finally, we will improve the system functions of analyzing and processing data so that the system can better adapt to the next large-scale analysis work.

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