Research on intelligent mattress based on improved SMS structure sensing fiber

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Abstract. The contact-type vital signs detection system affects the user's comfort and causes inconvenience due to its monitoring through skin contact. And most of the non-contact equipment precision is not high, or the cost is too high. To solve the above problems, this article is based on the physiological activity of slight vibration in multimode optical fiber micro bending deformation which results in the change of light intensity principle, considering the singlenode-multimode- singlemode(SMS) fiber of the structure of the sensor has simple structure, low cost, high sensitivity, but get the signal to noise is bigger, the accuracy is not high, this paper designs a kind of intelligent mattress based on modified SMS sensing optical fiber. The mattress can obtain ballistocardiogram signal in real time by changing the small light intensity, and obtain the heart rate, respiration rate and other information through the algorithm processing signal. In this design, the sensing fiber of the mattress is embedded in a small core fiber to solve the shortcomings of signal noise interference and instability obtained by the SMS structure fiber, and then it is embedded in the mattress by means of serpentine routing, and uses the covering material of the mattress adjusts the micro-bending period of the optical fiber to reach the critical mechanical period, so that the mattress has high sensitivity. Through in the laboratory and SMS type sensor for heart and breath signal are compared, and contrast and by Fast Fourier Transform (FFT) in frequency domain signal is analyzed, the vital signs of signal more clearly this mattress stable noise smaller, replace the tester for many times after tests, get the signal of high accuracy, the error is very small. The experiment shows that the mattress can detect non-sensory vital signs, facilitate the user to monitor his/her physical condition in real time in daily work and life, and timely inform the family members and medical staff in case of emergency, so as to avoid the occurrence of accidents.

Key words: Optical fiber sensing, Ballistocardiogram, Heart rate, Respiration rate.

1. The introduction
In today's society with extensive coverage of mobile networks, remote health monitoring provides a portable and effective health detection method for the medical and health field. In this way, users can be monitored at any time by their physiological conditions, realizing remote medical and health
protection services for users. It provides a health warning method for the growing chronic diseases and other health problems in today’s society. Remote health monitoring also enables people to find health problems earlier and treat them in time, which conforms to the current medical model of early detection and early treatment, and contributes an indispensable help to the construction of social health medical system.

In the current medical field, health monitoring mainly monitors cardiopulmonary function, and the detection of heart rate and respiration rate is an important prerequisite for monitoring and analysis of cardiopulmonary function. At present, there have been several methods to detect respiration rate and heart rate, such as Photoplethysmography (PPG) method [1], Electrocardiogram (ECG) signal method [2] and Ballistocardiogram (BCG) signal method [3]. Among them, most of the vital signs monitoring methods based on ECG signals are contact devices, which often need to be in contact with human skin through wires and detection electrodes. Wearing for a long time will cause discomfort to the user, and in some special environments such as strong magnetic fields[4]. The equipment is susceptible to severe interference and should not be widely used. Although the sensor based on PPG detection method achieves non-invasive detection, most of its equipment is still contact equipment, which causes inconvenience to users. Moreover, the equipment has high requirements for the position or power of the light source, so it is not suitable for daily monitoring of vital signs. In recent years, BCG signal-based non-contact monitoring method has been paid more and more attention by researchers. BCG signal can be detected by the following methods: electromagnetic wave scanning [5], piezoelectric signal sensor [6], optical fiber sensor [7], etc. Among them, electromagnetic wave scanning equipment is easily affected by the external environment, and electromagnetic radiation is also harmful to the human body. Although the piezoelectric signal sensor has high sensitivity, the device itself is electrified, with low safety and short service life. It is easy to be interfered under strong magnetic field environment. The fiber optic sensor has high sensitivity, can be used in the environment of strong magnetic fields, and the small size is convenient for embedding into mattresses and other daily necessities for monitoring. Therefore, it has a good advantage to detect BCG signal through the fiber optic sensor. However, the current monitoring device based on fiber Bragg grating sensor has a complex system structure and production process [8][9][10], and the acquired signal needs to be demodulated through wavelength, resulting in high system cost and complex demodulation methods. Most monitoring systems based on the principle of interference either need to undergo phase demodulation [11], resulting in complex demodulation methods and high system cost, or interference signals are vulnerable to the effects of environment, polarization and phase fading and cannot accurately extract complete respiration and heartbeat signals. And the single-mode-multimode-single-mode (SMS) fiber structure sensor based on the principle of inter-mode interference in multimode fiber [12] has attracted more and more attention from scholars due to its simple structure, easy processing, low cost, and high sensitivity. However, this kind of sensor has problems such as poor signal definition, unstable signal, and high noise.

In this paper, a smart mattress based on an improved SMS sensor fiber is designed to solve the problems of the above detection methods of respiration rate and heart rate. By inserting a small-core fiber into the SMS sensing fiber, the obtained BCG signal has less noise and higher accuracy, which is convenient for real-time analysis and processing of the signal to obtain vital signs such as heart rate and respiration rate. The smart mattress designed in this paper is non-contact and completely sensorless, and has a very broad application prospect in the field of health care. The organizational structure of this paper is as follows: Section 1 is the introduction which puts forward the significance of the research and the problems to be solved; Section 2 is the system structure and working principle; Section 3 is the design and implementation of the detection system; Section 4 is the test and verification of the whole system; Section 5 is the conclusion of this paper.

2. System structure and working principle

The structure block diagram of the system is shown in Fig. 1. The system consists of a light transmitter, a mattress embedded with sensing fiber, a photoelectric conversion module, a vital sign signal
extraction and analysis module, and a Bluetooth and WIFI communication module. The optical transmitter and the fiber mattress constitute the front part of physiological signal collection. Photoelectric conversion module, vital sign signal extraction and analysis module constitute the signal extraction part. The BCG signal is converted into an optical signal and then the optical signal is converted into an electrical signal. The obtained electric signal passes through the signal amplification circuit, and the high-precision AD acquisition module transmits the voltage signal to the MCU after sampling. The MCU performs algorithm analysis on this signal. The Bluetooth and WIFI communication circuit communicates the MCU with the external device and sends the calculated physiological signal to the upper computer through serial port for real-time display and analysis.

![System structure diagram](image)

**Fig. 1** System structure diagram

Breathing will cause the expansion and contraction of the human chest, and cause the tiny vibration of the human body. When the heart beats, the blood will be sprayed into the blood vessels of the whole body, and it will also cause the tiny vibration of the human body. Since the sensing fiber is very sensitive to the weak vibration, it is very convenient to detect this BCG signal.

As the sensing fiber is squeezed by tiny vibrations, it causes micro-bending loss of the fiber, which changes the intensity of the transmitted optical signal. The principle is: Small vibrations exert a force of $F$ on the sensing fiber (as shown in Fig. 2), causing the fiber amplitude and micro-bending period to vary by $\Delta X$ and $\Delta \lambda$, respectively, which improve the sensitivity of the sensor. According to the theory of fiber micro-bending, the variation of the propagation coefficient $T$ of light propagating in the micro-bending fiber is

$$\Delta T = \left(\frac{\Delta T}{\Delta X}\right) \Delta FK_f^{-1}$$  \hspace{1cm} (1)

Where, $\Delta F$ is the small vibration caused by respiration and heartbeat, $\frac{\Delta T}{\Delta X}$ is a sensitivity coefficient, and its size depends on the value of the deformer $\Delta$, $K_f$ is the force constant of the optical fiber sensor, and its value is

$$K_f^{-1} = \frac{Y^2}{48n^2K_f^2\eta}$$  \hspace{1cm} (2)

Where, $Y$ is the effective Young’s modulus of the optical fiber, and $\eta$ is the number of bending intervals.

When the fiber is serpentine, the period of the bent fiber varies with the slight vibration, which is then converted into the deformation amplitude of the fiber $X$. When people lie on the intelligent mattress embedded with sensing fiber, the tiny vibration caused by human heartbeat and respiration will change the cycle of fiber micro-bending, and then cause the change of fiber Angle and amplitude $X$, which improves the sensitivity of the sensor.

According to the mode coupling theory, when the fiber has periodic micro-bending along the axis, the optical power is coupled between the longitudinal modes. At this time, the critical mechanical period of the fiber micro-bending is
Where, $R_{fc}$ is the radius of the fiber core, $n_0$ is the refractive index of the fiber core, and $N, A$ is the numerical aperture of the fiber.

In this case, the periodicity of the bent fiber will significantly increase the micro-bending loss and greatly improve the sensitivity of the sensor. Through the derivation of the above formula, it can be obtained that when $\Lambda = \Lambda_0$, the sensitivity coefficient is the largest and the propagation coefficient variation of the light propagating in the micro-bending fiber is also the larger. The light detector converts the change of light intensity into an optical signal, and then converts the optical signal into BCG signal of human body by using the photoelectric conversion module, so as to prepare for the signal feature extraction of subsequent devices.

![Fig. 2 Schematic diagram of fiber force microbending](image)

This paper designs an improved sensing fiber based on SMS type sensing fiber (as shown in Fig. 3), as shown in Fig. 4. Considering that only one mode of fundamental mode light can be transmitted in single-mode fiber, when the light is transmitted from single mode to multi-mode fiber, due to the large core diameter of multi-mode fiber, the fundamental mode light excitations all kinds of higher-order modes in multi-mode fiber. And the fundamental mode light in a small area in the middle of the fiber core in various modes is the signal that needs to be acquired. When single-mode fiber and multi-mode are used for welding, it is difficult to ensure the absolute alignment of the centers of the two fibers, and the welding point change of the refractive index [13] will cause the energy of the higher-order mode to be mixed into the fundamental mode energy, causing the light energy to be greatly affected by the interference effect [14], the signal accuracy is affected, and the modulation is inconvenient. To solve these problems, in this paper, a segment of fiber with a very small core diameter is fused behind the multi-mode fiber, so that only the most concentrated central part of the fundamental mode energy is accepted. In this way, even if the fiber is slightly deviated from the core, the higher-order mode energy received is still very limited and can be basically ignored. At this time, the received optical signal eliminates the influence of the unstable factors caused by inter-mode interference, making the stability and detection accuracy of the system greatly improved.

![Fig. 3 SMS fiber structure](image)
3. System design and implementation

3.1. Fiber optic mattress

The optical fiber mattress is located in the physiological signal collection part of the system, which is used to collect the weak BCG signal of the user. The wavelength of the laser used in this design is 1550nm; Single-mode fiber uses G.655 fiber designed by YOFC company, with core diameter of 10um, cladding diameter of 125um, coating diameter of 245um, effective group refractive index of 1.469. The multi-mode fiber is YOFC 50/125 um multi-mode fiber, with a core diameter of 50um, a numerical aperture of 0.2, and a refractive index of 1.477. The critical period is about 1.16mm when applied to formula 2.3. G.652 type fiber is used for small-core diameter fiber, with core diameter of 5um, cladding diameter of 124.5um, coating diameter of 235um, effective group refractive index of 1.467. Multi-mode fiber is located in the center part of the mattress. By sandwiching the upper and lower layers of soft covering materials, the fiber is protected and the stability and reliability of the mattress are improved. At the same time, the covering material is embroidered with the micro-bending of the upper fiber and the lower fiber respectively for the optical fiber [15],[1] The fibers are parallel to each other and the adjacent two are now spaced at a critical period $\Lambda$. Its structure is shown in Fig. 5. The fiber is distributed uniformly in the center of the mattress in the way of snake-like routing (as shown in Fig. 6). Moreover, the characteristics of multi-mode fiber are utilized to improve the optical coupling efficiency and greatly enhance the sensitivity of the mattress to detect vital signs signals. The fiber mattress structure is composed of a mattress embedded with sensing fiber, a fiber incidence port and a fiber reception port. Among them, the light source signal emitted by the laser is emitted from the incident port and transmitted to the optical receiver through the optical fiber mattress.
3.2. Signal acquisition and preprocessing

As the signal received by the receiver is very weak, it causes great difficulty to the subsequent analysis, so the signal needs to be preprocessed.

For the amplification of weak signals, considering that the amplification effect of the first-stage spanning resistance amplification circuit is not enough, and the method of increasing the feedback resistance of increasing the amplification factor will introduce greater noise, the second-stage amplification circuit is chosen to amplify the weak signals. When working, the high-precision AD sampling rate is set to 256sps. Since the original BCG signal obtained is the superposition of heart rate signal and respiratory signal, the filtering algorithm is selected to separate the two signals in the software. Adults have a breathing frequency between 0.16Hz and 0.50Hz under resting conditions, and a heartbeat frequency between 0.50Hz and 3.00Hz, which can separate the two signals and suppress noise through a bandpass filtering algorithm. In this design, Butterworth bandpass filtering algorithm [16] is adopted to design a bandpass filter of 0.5-20Hz to separate signals. After the above preprocessing, the algorithm is used to extract the signal's characteristic values more accurately.[16]

3.3. System Implementation

We used the above design method to make a mattress prototype. For the convenience of use, the filtered data will be transmitted through Bluetooth or WIFI serial port to the upper computer software. The software is written by MATLAB, which can display the original signals collected, the respiration and the heartbeat signals processed by the software. The software display interface is shown in Fig. 7. And the software can record the measured data in the background for further analyzing and processing.

![Software display interface](image)

**Fig. 7** Software display interface

4. Experimental Verification

In order to compare the respiration and heart rate signals detected by the improved SMS smart mattress and the improved SMS smart mattress, and to verify the accuracy of the improved SMS smart mattress in BCG signal processing, we created these two kinds of mattresses respectively in the laboratory. By analyzing and comparing the heart rate and respiratory signal waveform measured by the same tester on two kinds of mattresses and the frequency spectrum obtained by Fast Fourier Transform (FFT), the signal obtained by this design mattress is more clear and stable. Then the heart rate and respiration rate measured by the mattress were calculated by the maximum peak point corresponding to the spectrum peak, and the results obtained by the ECG blood pressure monitor and the tester counted by themselves were compared to verify the accuracy of the intelligent mattress in the processing of vital signs.

This experiment tested SMS smart mattress for the first time in the laboratory. In the test, the subjects were asked to lie flat on the mattress under the condition of steady breathing, which simulated the condition of human body in sleeping state. After many experiments, the waveform and spectrum of heart rate signal are shown in Fig. 8, in which point A in Fig. 8 (a) is the heartbeat peak, and the circled part is the signal of one heartbeat action, and the heartbeat peak appears periodically. The
marked part in the fig. 8 (b) is the peak frequency point. The waveform and spectrum of respiratory signal are shown in Fig. 9. Point B in Fig. 9 (a) is the peak sampling point of respiration. The circled part is the signal period of a breathing action, and it can be seen that the signal changes periodically. The marked part in the figure 9 (b) is peak frequency point. Through experiments, it can be concluded that SMS smart mattress can indeed measure the respiration rate and heart rate, but the detected signal noise is large, the spectrum peak is not obvious, and the signal is unstable, which will bring trouble to the subsequent signal processing and affect the accuracy.

![Fig. 8 Heart rate waveform and spectrum detected by SMS sensor](image)

**Fig. 8** Heart rate waveform and spectrum detected by SMS sensor

![Figure 9. Respiratory waveform and spectrum detected by SMS type sensor](image)

**Figure 9.** Respiratory waveform and spectrum detected by SMS type sensor

In order to solve the problem of the above signals, this experiment made a mattress based on the improved SMS sensor fiber proposed in this paper in the laboratory. After repeated tests in the laboratory, the heart rate signal waveform and spectrum were obtained, as shown in Fig. 10. The respiratory peak is more obvious in the signal waveform, and the waveform of a heartbeat action is more clear. The waveform and spectrum of the respiratory signal are shown in Fig. 11, in which the signal waveform is smoother, noise interference is less, and the peak of the respiratory wave is more obvious and stable. The time taken for a breathing action is relatively stable, which more accurately reflects the true state of the tester under the resting condition.
By observing the spectrum, it can be found that the main frequency peak is obvious, the noise is small, and the signal quality is high. The maximum frequency point of heart rate signal $f_{\text{max}}$ is about 1.1Hz, and then the measured heart rate is about 66 beats /min through the formula $H = 60f_{\text{max}}$. After comparison, it can be found that the data are similar to the measured heart rate of 64 beats /min through the electrocardiogram blood pressure monitor. The frequency point of the maximum value of the respiratory signal $f_{\text{max}}$ is about 0.4Hz, and the measured respiration rate can be calculated by the formula $H = 60f_{\text{max}}$ as 24 breaths /min. The tester can get 24 breaths per minute by counting by himself. The data comparison shows that the signal accuracy is good. According to this method, we changed different testers to conduct multiple tests, and the data obtained is shown in Table 1 below.
Table 1. Comparison table between measured data and standard data

| Standard heart rate(times/min) | Measured heart rate(times/min) |
|-------------------------------|-------------------------------|
| 70                            | 73                            |
| 62                            | 63                            |
| 63                            | 66                            |
| 75                            | 78                            |
| 67                            | 69                            |

(a) Comparison of measured and standard heart rates

| Standard breathing rate(times/min) | Measured breathing rate(times/min) |
|-----------------------------------|-----------------------------------|
| 21                                | 21                                |
| 23                                | 23                                |
| 18                                | 18                                |
| 21                                | 21                                |
| 23                                | 24                                |

(b) Comparison of measured respiration rate with standard respiration rate

According to the data in the table, it can be seen that the measured data are close to the standard data and the error is within an acceptable range. It can be concluded that the signal of smart mattress based on the improved SMS sensing fiber is more accurate than that of SMS sensing fiber, with less noise interference and high accuracy of detection data.

5. Conclusion

This paper presents a smart mattress based on an improved SMS sensing fiber. By extracting the BCG signal generated by the user's physiological activities, the vital signs such as respiration rate and heart rate of the user can be detected in real time. By adding a small core diameter fiber on the basis of SMS fiber, the sensor fiber in the mattress significantly reduces the influence of higher-order mode energy on the fundamental mode energy in multi-mode fiber, improves the stability of the system, and makes the extraction of vital sign data more accurate and effective.

This mattress has been tested in many nursing homes in Wuhan, and the results show that the data measured by the mattress under zero load and no sensation are highly correlated with the data measured by the medical equipment in the nursing home, so it has a broad application prospect in the field of medical health.

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