Vital signs monitoring system based on piezoelectric film sensors

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Abstract. The demand for health services for the elderly has become an urgent problem to be solved. In order to solve the problems of elderly people who are prone to sudden disease during sleep, difficulty in night care, and the unconstrained requirements for health monitoring, an unconstrained vital signs mattress monitoring system was proposed. An intelligent mattress with built-in thin film piezoelectric sensors was developed to realize the real-time monitoring of vital signs such as heart rate, respiratory rate and body movement state. At the same time, medical and health resources are integrated to provide personalized and precision health care services for the elderly including safety monitoring, health management, etc. and build a smart health and elderly care service system. The experimental application shows that the system can effectively prevent accidents, improve both the efficiency of care and the level of health care services.

1. Introduction
At present, the aging problem of the world's population is increasingly serious [1, 2]. China has become the country with the largest number of elderly people, and the aging is accelerating. By the end of 2019, China's elderly population aged 60 and over is about 254 million, accounting for 18.1% of the total population, and the proportion of people suffering from one or more chronic diseases is as high as 75%. The number of the elderly with dementia and disability is more than 48 million. The high prevalence of chronic diseases and high mortality have become a great challenge for Chinese society. The rigid demands of the elderly for medical care, rehabilitation care and other services are increasing. However, with the family miniaturization, empty nest, rapid urbanization and population mobility, more and more families are facing the problem of lack of caregivers. The demand for health services for the elderly has become an urgent problem to be solved.

In order to solve the problems of elderly people who are prone to sudden disease during sleep, difficulty in night care, and the unconstrained requirements for health monitoring, this paper proposes a vital signs mattress monitoring system based on thin film piezoelectric sensors, which uses the high-
sensitivity thin film piezoelectric sensor built into the mattress to collect Ballistocardiogram (BCG) signals of the elderly during bed rest or sleep. The vital sign parameters such as heart rate, respiratory rate and body movement state are extracted by real-time analysis of the signal, and the parameters are uploaded to the cloud service platform through Wi-Fi. Combined with electronic health archives, the system provides personalized and precision health management services such as safety monitoring and health management for the elderly. The developed vital signs mattress monitoring system is suitable for families, nursing homes and other occasions, especially for people who need 24-hour monitoring, such as mentally retarded, disabled adults, the elderly who need monitoring.

2. Working principle and system architecture

2.1. Working principle

Along with life activities (existence), the human body produces various vibrations. These vibrations range from large movements such as body movements and turning over to tiny vibrations such as heart beats and breathing. In the process of human heart beating, blood will spray into the blood vessels all over the body, causing slight vibration of human body. BCG signal can be obtained by detecting this weak vibration [3-4]. BCG signal can extract heart rate, respiratory rate and other parameters in real time, which is especially suitable for non-contact vital signs signal monitoring [5-8].

Polyvinylidene fluoride (PVDF) piezoelectric film sensor has the characteristics of high piezoelectric coefficient, good flexibility, corrosion resistance and wide frequency response range, etc. [9-10]. It can be directly contacted with the skin or coupled with the machine through the middle layer, especially suitable for monitoring physiological signals of human body. This paper designs and realizes a vital signs signal acquisition system based on the PVDF piezoelectric film sensor. The principle is as follows: The core of the piezoelectric film sensor is the PVDF piezoelectric film, which has positive piezoelectric effect [9]. It can convert the micro dynamic pressure signal of human organs into charge signals. After the charge amplifier circuit, the charge signal is converted into a voltage signal. After the amplification and filtering processing, it is read to MCU by ADC. The physiological parameters such as heart rate and respiratory rate were obtained after the algorithm processing.

2.2. Overall architecture

The structure block diagram of the monitoring system is shown in Figure 1.

![Figure 1. The architecture of the vital signs mattress monitoring system.](image-url)
The weak vibration signal of human body is monitored by PVDF thin film piezoelectric sensor, then the vibration signal is converted into a voltage signal through charge amplifier circuit, and then the high-frequency noise and power frequency interference are filtered by low-pass filter and 50Hz notch filter. The digital voltage signal after analog-to-digital conversion is processed by microprocessor, and the parameters such as heart rate and respiratory rate are extracted in real time, which is uploaded to the cloud platform through Wi-Fi wireless communication. Based on the cloud platform, a personal dynamic electronic health file is established, and a personal health data center is constructed by combining the monitored vital signs such as heart rate, respiratory rate and body movement state. The system provides personalized and accurate health management services such as safety monitoring and health management through website and App. When the elderly feels unwell, they can also give an active alarm through the alarm module.

3. The system design

3.1. System hardware design

The intelligent mattress consists of a sponge mattress with a built-in PVDF thin film piezoelectric sensor and a control box connected to the mattress. The selected thin film piezoelectric sensor is a comb-shaped large area piezoelectric thin film sensor, as shown in Figure 2. The waviness allows the sensor to be flexible and comfortable. The sensing area size is 600 mm × 190 mm, the thickness is 0.28 mm, the piezoelectric sensitivity is 50 PC/N. The sensor's large detection area and good ergonomics structure enable that the output signal of the sensor is more accurate. The sensor is wrapped by two layers of cotton protective layer and spread directly in the sponge mattress. The control box is composed of microprocessor, amplifier and filter module, high-precision AD sampling module, wireless transmission module, power module, alarm module, etc.

The body vibration signals generated by human heartbeat, respiration and body activity are collected by the thin film piezoelectric sensor implanted in the mattress. The vibration signals mainly include BCG signals, respiration signals, body movement signals and noise signals.

The PVDF piezoelectric thin-film sensor collects extremely weak charge signal, which is converted into voltage signal by charge amplifier circuit [9]. The signal amplitude obtained by the charge amplifier circuit is very small, only a few millivolts, and the power frequency interference is very serious. Considering that filtering out power frequency interference may cause signal attenuation, the signal is first amplified, and set a zero-phase shift low-pass filter with a cut-off frequency of 30 Hz to eliminate high-frequency noise in the signal; Double T-Notch filter with cut-off frequency of 50Hz is used to filter out power frequency interference. The high-precision AD sampling module with a sampling rate of 100 sps is used to sample the amplified and filtered signal. The collected vibration signal is shown in Figure 3.

3.2. Signal collecting and processing

3.2.1. Body movement state. The sampled output signal is a mixed signal, because the energy and amplitude of the body movement signal are very high, when there is body movement, it is difficult to separate the heartbeat and respiratory signal, so the body movement of the sampled output signal is determined first.
The body movement state is divided into three states: out-of-bed, body movement, and calm. The amplitude of the out-of-bed signal is very small, because there is no person on the piezoelectric film, basically there is no pressure transformation. When the signal stably outputs the small signal in a certain time range, it is judged as out-of-bed state. The movement of a person in sleep state can be roughly divided into slight body movement and larger amplitude body movement. Among them, slight body movements include small arm stretching, head tilt, and small body twisting, etc., which is mostly completed within 2-3 seconds; large body movements include turning over, large arm and leg movements, large body twisting movement, etc., which is usually completed within 3-5 seconds. Frequent body movements will affect people's sleep quality, violent and irregular body movement may indicate the danger of life. This design only considers body movements with larger amplitudes. Set the amplitude threshold to judge the occurrence of body movement. When the amplitude of the signal is greater than the amplitude threshold, and the body movement lasts for more than 5 seconds from the beginning to the end, it is judged as a body movement state, otherwise, it is judged as a calm state. The default minimum duration of a body movement is 5 seconds. The heart rate and respiratory rate are not extracted and calculated during body movement or out of bed.

3.2.2. Heart rate. The respiratory frequency of human body is between 0.1 Hz and 0.5 Hz, the frequency range of BCG signal is between 0.6 Hz and 20 Hz, and the main energy is concentrated between 4 Hz and 16 Hz. After sampling, the BCG signal and the respiratory signal are superposed together, the respiratory signal is stronger than the BCG signal, and the frequency is lower. Hamming window FIR filter is used to filter the corresponding frequency bands of respiration and heartbeat respectively. The Filter Design & Analysis Tool in MATLAB is used to design the FIR band-pass filter of 4 Hz to 16 Hz to extract the BCG signal. A filtered BCG signal waveform is shown in Figure 4. The respiratory signal is extracted by FIR band-pass filter of 0.1 Hz ~ 0.5 Hz, and a filtered respiratory signal waveform is displayed in Figure 5. In order to transplant the filter into the microprocessor, integer is used instead of floating-point number to represent the filter coefficient, and integer is used in the whole filtering process to improve the filtering efficiency.
Figure 5. The filtered respiration signal.

When calculating heart rate, the general situation is to calculate the average heart rate, that is, count the number of heartbeats in a period of time, and then convert it into heart rate. The system is mainly used to monitor the health of users, so the detection results should be real-time and not fluctuate too much. Therefore, the system is to count the heartbeat intervals detected within 30 seconds, then calculate the average value of these heartbeat intervals, and finally convert them to heart rate.

BCG signal is synchronous with heartbeat signal and has pseudo periodicity [11]. The most obvious BCG signals are the I, J and K waves, where the J wave amplitude is the largest. A typical BCG signal waveform is shown in Figure 6. By calculating the J-J interval of adjacent cycles, the interval of one heartbeat can be obtained [12-14]. In order to improve the operation efficiency and real-time performance of the system, the adaptive difference threshold method is selected to detect the J wave [15-17].

Figure 6. The BCG signal waveform diagram.

The specific implementation process is as follows:

- Suppose that the sampling sequence of BCG signal is \( f(i), i = 1, 2, \cdots, N \), \( N \) is the length of signal, its first-order difference expression as in Equation (1), and its second-order difference expression as in Equation (2):

\[
\begin{align*}
    y(i) &= f(i+1) - f(i) \\
    z(i) &= y(i+1) - y(i)
\end{align*}
\]

The maximum point of BCG signal corresponds to the zero crossing point and the minimum point respectively in the first-order difference and the second-order difference.

The initial threshold is set by the self-learning method. The threshold self-learning is carried out within the first 30 seconds of BCG signal sampling sequence \( f(i) \) divide this period into equal parts, and each segment of data contains at least one complete BCG signal. In this study, a period of 3
seconds was used, that is, 10 segments were divided. The maximum value \( \text{Max}_i \) of each segment is calculated by the difference method, the maximum value and the minimum value of these 10 maximum values are removed. The arithmetic mean of the remaining eight maximum values is used as the initial difference threshold, which is recorded as \( \text{Th} = \frac{\text{sum}(\text{Max}_i)}{8} \). The purpose of removing the maximum value is mainly to eliminate the occasional peak interference, resulting in missed detection caused by the excessive threshold; The minimum value is removed to avoid false detection caused by too small threshold. According to the second order difference minimum, the maximum point set \( J_1 \) within 30 seconds is obtained.

- When the human body is calm, the heart rate is between 0.5 Hz and 2.5 Hz, and the interval of adjacent J waves is not less than \( 0.4 f_i \). \( f_i \) is the sampling frequency of the vibration signal. Remove the maximum points in \( J_1 \) where the interval of adjacent points is less than \( 0.4 f_i \), and the amplitude is less than the adjacent points, and recorded as \( J_2 \).
- Use \( \text{Th}/2 \) as the initial threshold to judge the set \( J_2 \) data points and remove the maximum points smaller than the threshold, and recorded as \( J_3 \).
- In the process of continuous monitoring, the amplitude and shape of BCG signal will change with time. The detection threshold should be modified in real time to improve the reliability of algorithm detection. After 10 J wave peaks were detected continuously, the threshold is dynamically updated with the 30-second sliding window method. The principle of dynamic threshold updating is as in Equation (3):

\[
\text{Th}_{\text{new}}(i) = 0.7 \times \text{Th}' + 0.3 \times \text{Mean}(f''(i))
\]

(3)

Where: \( \text{Th}_{\text{new}} \) is the latest threshold; \( \text{Th}' \) is the previous threshold; \( \text{Mean}(f''(i)) \) is the average amplitude of the peak points in the window.

- Calculate the interval \( JJ(i) \) between all adjacent J peak points in the sliding window, and find the average value \( JJ_{\text{mean}} \). If \( JJ(i) > 1.5 JJ_{\text{mean}} \), there is J-wave missing between these two points. By finding the maximum value point between these two J-wave peak points, add it to the \( J_4 \) peak point set, and recorded as \( J_4 \).
- After the processing of the above steps, calculate the mean value \( JJ'_{\text{mean}} \) of the interval between the \( J_4 \) peak points, and the average heart rate is \( f_{\text{HR}} = 60 f_i/ JJ'_{\text{mean}} \).

3.2.3. Respiratory rate. The quality of the respiratory waveform after separation is better than that of the BCG waveform, and the waveform characteristics are obvious. The respiratory rate was also calculated by calculating the average respiratory interval.

The detection algorithm of respiratory wave is as follows:

- Firstly, the respiratory signal data is processed with smooth filtering to achieve the effect of smoothing the signal and reduce the interference of high-frequency burr noise. Assume that the acquired respiratory signal data sequence is \( R(i) \), the data \( R(i) \) is transformed by the Equation (4).

\[
R(i) = \frac{R(i-1) + R(i) + R(i+1)}{3}
\]

(4)

- Obtain all maximum points of respiratory wave by first-order and second-order difference. At this time, the identified peak points contain pseudo peaks with too small interval.
- When the human body is calm, the respiratory frequency is between 0.1 Hz and 0.5 Hz, and the interval between two consecutive breaths is not less than \( 2 f_i \). If the interval between adjacent maxima is less than \( 2 f_i \), the extreme points with smaller amplitude will be removed.
Calculate the interval $RR(i)$ and the average interval $RR_{mean}$ between the maxima, if $RR(i) > 1.4RR_{mean}$, remove the change point.

After the above steps, the average respiratory rate is $f_{RR} = 60f_s/RR_{mean}$.

3.3. Design of the platform of vital signs mattress monitoring

Based on the cloud computing center of Shandong province, a dynamic electronic health archive for the elderly is established, and the personal health data center was built by combining with the monitored vital signs such as heart rate, respiratory rate and body movement state. Information resources are integrated to provide personalized and precision health management services such as safety monitoring, health assessment, health guidance and health consultation for the elderly.

The platform of vital signs mattress monitoring is divided into intelligent mattress monitoring service website and android mobile client software, which communicates with the cloud server using HTTP protocol; The service website adopts B / S architecture, and use SQL Server 2008 R2 database system. The Android App is specially developed for caregivers and children of the elderly. Caregivers and children of the elderly can view monitoring information in real time, receive warning information and obtain personalized health management services through the mobile App. The main functional framework is shown in Figure 7, mainly including: (1) system management module; (2) safety monitoring module; (3) health management service module. The designed App display interface is shown in Figure 8.

![Figure 7. The function module of vital signs mattress monitoring system.](image)

3.3.1. System management module. The user management is used to input, edit and view the basic information and guardian information of the elderly, also includes health records information such as disease history, medication history, surgery history, health examination information, allergy symptoms, sleep conditions, etc. The operation configuration is used for equipment management and maintenance, such as device binding, unbinding, and alarm range setting of heart rate, respiratory and other physical parameters; The operation log records the key operation and alarm information of the system.

3.3.2. Safety monitoring module. Real-time display of heart rate, respiration rate, in/out of bed, frequency of out of bed, out of bed time, continuous body movement monitoring information of the elderly. According to the individual health characteristics and care situation of different users, the personalized warning range is set and managed in different time periods. When the elderly has sudden abnormal situations such as high or low heart rate and respiratory rate, etc. active alarms are provided based on the mobile phone App to push alarm message or send mobile SMS, which effectively prevent accidents. The sleep quality of the elderly was analyzed according to sleep habits, turning times, body movement state and other information, and a visual sleep report was presented through the App.
3.3.3. **Health management service module.** The heart rate, respiratory rate and sleep status of the elderly were monitored and tracked for a long time to determine the development direction and severity of the disease and generate periodic health assessment reports. The system integrates medical information resources to provide personalized and precision health management services such as health assessment, health guidance and health consultation for the elderly.

4. **System verification and demonstration application**

The developed intelligent mattress can monitor the heart rate, respiratory rate and body movement state of the human body in an unrestricted way in real time. The length, width and thickness of the commonly used intelligent mattress are 65, 20 and 1.5 centimeters respectively. In the actual detection, in order to make the system detect the complete BCG signal to the greatest extent, the mattress should be placed under the human shoulder blades, close to the heart. The tester should lie still on the mattress to avoid frequent body movements overwhelming the BCG signal. This paper tests the whole system to verify the feasibility of the system. First of all, the system was preliminarily verified in the laboratory environment, and then demonstrated in the family, nursing home, rehabilitation center and other scenes, which further confirms the practicality of the system.

In laboratory tests, 7 healthy subjects aged 22-38 years old and 8 healthy elderly people aged 60-65 years old were recruited. The tester is required to lie flat under resting conditions, trying to simulate the human body in the sleeping state. The heart rate and respiratory rate were measured simultaneously with the contact medical monitor as the standard data. Each tester conducted 10 minutes of experiments each time, a total of 5 times, and 75 groups of data were obtained. Some test results are shown in Table 1. The experimental results show that there is a ± 2 error between the heart rate and respiratory rate monitoring data obtained by the monitoring system developed in this paper and the data obtained by the medical monitor. Considering the actual application, the impact of ± 2 error on health monitoring is acceptable, which can fully meet the actual application.

The system has been demonstrated and applied in families, nursing homes and rehabilitation centers, covering more than 100 people. The waveform of heart rate and respiratory rate of a user during sleep obtained by using the mobile App is shown in Figure 9. With this system, the caregivers do not need to patrol at night. When an accident happens to the elderly, the system can send an emergency alarm to remind the caregivers to deal with it in time, effectively prevent the accident,
solve the problems related to insufficient caregivers, untimely care, inadequate night care and so on. At the same time, it provides daily monitoring data for medical care, so that doctors can find diseases in advance from the waveform of heart rate, respiratory rate and sleep, reduce the risk of disease hidden dangers and the trend of severity, and improve the quality of health care services. The demonstration application results further verify the practicability and convenience of the system.

**Table 1.** The comparison of heart rate and respiratory rate test results.

| Heart rate (Times/min) | Measuring error | Respiratory rate (Times/min) | Measuring error |
|------------------------|-----------------|-------------------------------|-----------------|
| Mattress               | Monitor         | Measuring error               | Mattress        | Monitor         | Measuring error |
| 62                     | 60              | +2                            | 16              | 15              | +1              |
| 78                     | 78              | 0                             | 20              | 19              | +1              |
| 80                     | 82              | -2                            | 22              | 20              | +2              |
| 58                     | 56              | +2                            | 13              | 13              | 0               |
| 62                     | 64              | -2                            | 15              | 16              | -1              |

**Figure 9.** The data graph.

5. **Conclusions**

The system realizes the undistorted recording of the body movement state and the real-time monitoring of physiological parameters when the elderly is lying in bed. The system changes the traditional methods of health monitoring which can only be carried out by using electrodes and wires, so as to realize the non-contact vital signs monitoring and the active alarm of abnormal state. At the same time, the system can provide personalized health management services for the elderly, improve both the efficiency of care and the level of health service. The practical application shows that the system has a broad application prospect.

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