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A Sensor for Monitoring Pulse Rate, Respiration Rhythm, and Body Movement in Bed

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***Abstract*—A non-constraint cardiac vibration, respiration, and body movement monitoring system has been developed. The sensor system is designed to be easily installable under an existing bed mattress. The sensor consists of a 40-kHz ultrasound transmitter and receiver pair. The transmitted ultrasound is reflected on the mattress' undersurface, and the amplitude of the received ultrasonic wave is modulated by the shape of the mattress, and parameters such as respiration, cardiac vibration, and movement. The physiological parameters can be extracted from the reflected ultrasound by an envelope detection circuit. To confirm the accuracy of the developed system, measurements were performed on 6 normal male subjects aged 25.0 ± 6.7 years, using 2 pocket spring coil mattresses and a polyurethane foam mattress. The results revealed that the physiological parameters were monitored with an 84.2% average accuracy for all mattresses when the subjects lay on the beds in the supine, lateral, and prone positions.**

I. Introduction

NONINVASIVE and non-constraint physiological monitoring is the key for ambient assisted living and smart homes [1]. In particular, since physiological parameters such as heart rate and respiration rhythm during sleep are useful for diagnosing disorders like sleep apnea, sudden death syndrome, and heart diseases [2], many non-constraint monitoring systems, such as an image-based system [3], a sensor placed under the bed linen [4], pillow-type sensors [2, 5], mattress-type sensors [6–8], sensors installed under the bed mattress [9–11], and sensors installed under the supports of a bed [12, 13], have been developed. From the point of view of sensor durability, the image-based system is remarkable because the sensing is performed passively and the sensor has no physical contact with the bed or the subject. However, there is the aperture problem in the image processing when the bed linen and the clothes worn by the subject have less texture, thus leading to an estimation error. In addition, using a video camera may be considered to be an invasion of privacy. Many other systems are based on measuring pressure or vibrations applied to the bed, mattress, or pillow [3–6, 9–13]. The beddings vibrate as a result of various factors such as body movements, including turning over, and other physiological parameters such as respiration and cardiac vibrations, thus enabling these factors to be monitored via measurement of the vibrations. However, the sensors used may be limited by their durability: even though the vibrations caused by respiration and the heartbeats are very weak, all or part of the subject's weight is applied on the sensor; the repeated application of which deteriorates the sensor's sensitivity. The pillow-type sensors have a great advantage in terms of installation and maintenance, but continuous monitoring cannot be achieved when the subject's head is off the pillow. Recently, a capacitive sensing technique was applied to bed monitoring [14]. However, the sensor may be affected by electromagnetic noise. In addition, the safety of the energy applied to the subject's body needs to be investigated.

Thus far, we have developed several sensing systems to overcome the durability problem [7, 8]. In these systems, sensors are installed into a pocket spring coil mattress. The physiological parameters are obtained by measuring the shape change of the mattress. However, sensor maintenance becomes difficult because the sensor is in the mattress.

In this study, a new sensor system has been developed to overcome these problems. It has been designed to be sensitive to the vibration of the mattress, but not to the subject's body weight.

II. System Description

A. Apparatus

Figure 1 shows the sensor structure and the detection principle developed in this study. The sensor is composed of 2 aluminum guiderails (20 mm × 20 mm × 1960 mm), an ultrasound transmitter and receiver pair (T40-16/R40-16, Nippon Ceramic), a plywood board (1010 mm × 11 mm × 360 mm), and an aluminum support (20 mm × 20 mm × 110 mm). A wooden single-bed is used in this study. The bed's pedestal for supporting the mattress is made from a wooden board. Guiderails are placed on both the side-edges of the pedestal. The plywood board is placed on the guiderails at the position of 550 mm from the foot-side edge of the bed. Under

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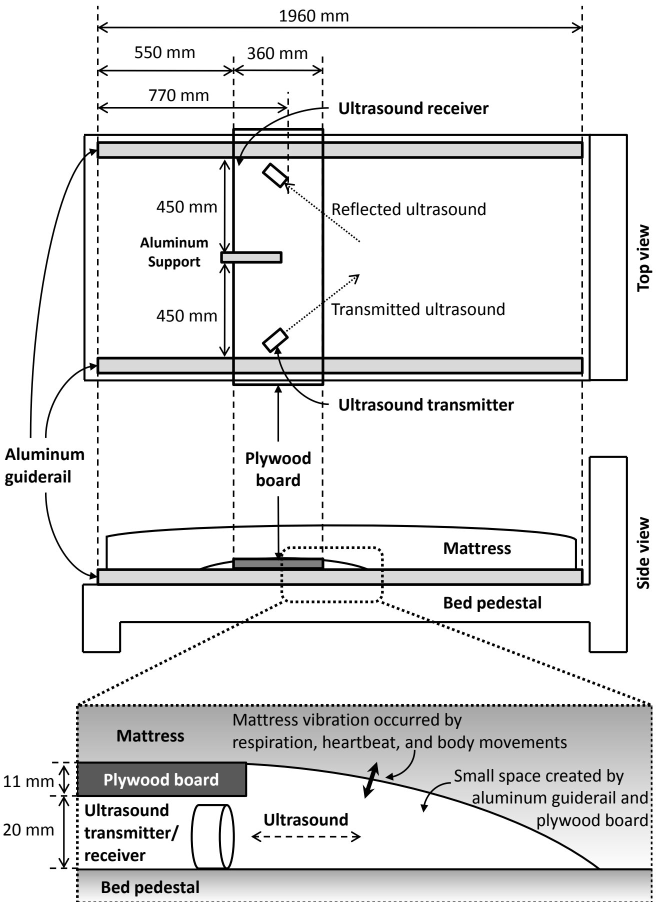


Fig. 1. Sensor structure and detection principle.

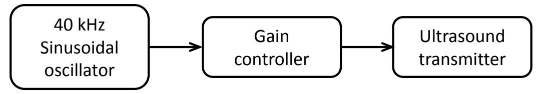
the plywood board, the ultrasound transmitter and receiver are set at a distance of 770 mm from the foot-side edge toward the head-side edge, with an inclination angle in order to efficiently receive the ultrasound reflected on the mattress' undersurface. The aluminum support is positioned under and in the middle of the plywood board to prevent the bending of the board by the mattress and the subject's body weight. The mattress is placed on the plywood board.

The mattress is slightly curved over the plywood board because the guiderails do not support the mattress. There exists a small space between the mattress and the bed pedestal. The ultrasound is transmitted toward the head side, and the receiver obtains the ultrasound reflected at the undersurface of the mattress. Respiration, heartbeat, and body movement result in vibration of the mattress. Thus, these parameters can be measured by observing the reflected ultrasound.

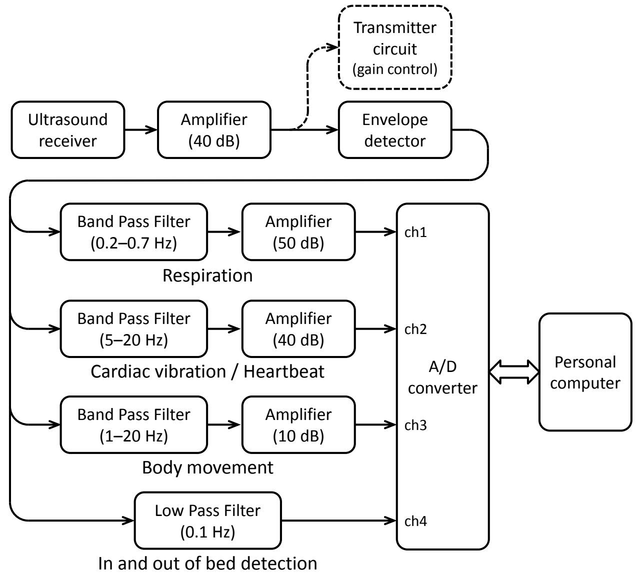
B. Sensor Circuits

Figure 2(a) shows the block diagram of the ultrasound transmitter. It consists of a 40 kHz sinusoidal oscillator, a gain controller, and an ultrasound transmitter. The driving voltage of the ultrasound transmitter is controlled within the range, 100 $mV_{p\text{-}p}$ to 20 $V_{p\text{-}p}$, by the gain controller.

Figure 2(b) shows the block diagram of the receiver circuit. The circuit is composed of 4 amplifiers, an envelope detection circuit, 3 band-pass filters, a low-pass filter, a 12-bit 8-channel analog-to-digital converter (NI USB-6009, National Instruments), and a personal computer for data logging. The ultrasound obtained by the receiver is first amplified, and then fed into the envelope detector. The ultrasound reflected on the mattress is amplitude-modulated by the vibration of the mattress. Thus, the lower frequency components (i.e., the vibration components) are extracted by the envelope detector. The detected signal is then fed into 4 circuits to obtain each physiological parameter: the respiration signal is detected by a 0.2–0.7 Hz band-pass filter and a 50 dB amplifier; the cardiac vibration signal is detected by a 5–20 Hz band-pass filter and a 40 dB amplifier; the body movement signal is detected by a 1–20 Hz band-pass filter and a 10 dB amplifier; and, the in and out of the bed signals are detected by a 0.1 Hz low-pass filter. When a large voltage change in the first amplified signal is detected, the transmitting ultrasound gain is modified by the gain controller, such that the amplified signal becomes 1.0 $V_{p\text{-}p}$.



(a) Transmitter circuit

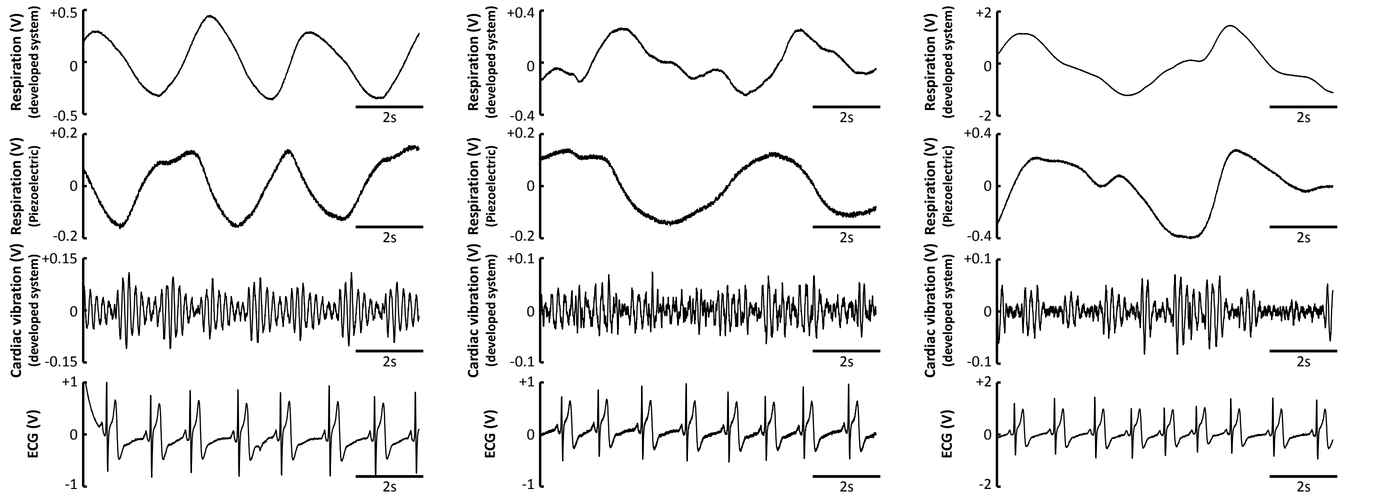


(b) Receiver circuit

Fig. 2. The block diagram of the sensor circuit.

III. EXPERIMENT

To evaluate the practicability of the developed system, a simple experiment was performed. Six healthy male volunteers aged 25.0 ± 6.7, with a BMI of 23.0 ± 2.8, participated in this experiment. Prior to the experiment, we obtained oral informed consent from all subjects. The subjects were requested to attach ECG electrodes to their both wrist and left ankle, and a piezoelectric sensor belt to their chest (Kynar Piezo Film, Pennwalt), before lying on a bed.



(a) Supine position (b) Lateral position (left side) (c) Prone position

Fig. 3. Representative example of obtained signals (pocket spring coil mattress).

Subjects were studied in the supine position, the left and right side lateral positions, and the prone position for 90 seconds each. The precise sleeping posture, including the position of the hands or legs, was not specified, and so, the subjects lay in their usual style. The respiration data obtained by the piezoelectric sensor and the ECG signal were simultaneously recorded and used as the reference. All signals were recorded at a sampling frequency of 200 Hz. The heartbeat detection ratio was calculated at 60 seconds, in order to avoid unstable signals that may occur immediately after a postural change.

In order to confirm whether the developed system was affected by mattress type, 3 mattresses were selected as follows: a hospital-type pocket spring coil mattress (Dream Pocket Parallel F1-P, Dreambed), a pocket spring coil mattress (Serta Posture, Dreambed), and a polyurethane mattress (MaxiFloat KE-801A, Paramount). Two different types of pocket spring coil mattresses were selected due to the differences in their softness: the Serta Posture is diversified in the head, waist, and leg areas, whereas the Dream Pocket Parallel F1-P is uniformly soft. All mattresses were evaluated in all subjects.

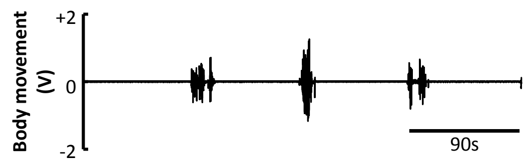


Fig. 4. Representative example of body movement detection.

TABLE I
HEARTBEAT DETECTION RATIO OF EACH MATTRESS AND POSTURE

Mattress type	Supine	Left lateral	Right lateral	Prone	Average
Pocket spring coil (F1-P)	94.1% (0.2%)	73.1% (18.7%)	77.1% (16.9%)	92.3% (0.6%)	84.1% (9.1%)
Spring coil (SertaPosture)	90.5% (0.0%)	68.6% (18.3%)	78.7% (16.7%)	97.7% (0.0%)	83.9% (8.8%)
Polyurethane	91.7% (0.9%)	76.0% (18.1%)	76.9% (16.9%)	94.8% (3.3%)	84.8% (9.8%)
Average	92.1% (0.4%)	72.6% (18.4%)	77.6% (16.8%)	94.9% (1.3%)	84.2% (9.3%)

The percentages outside and inside of the parenthesis indicate the detection ratio and the false positive rate, respectively.

IV. RESULTS

Figure 3 demonstrates the representative obtained signals. The respiration waveform obtained by the developed system is almost similar to the reference, but with a shift in the phase. The cardiac vibration obtained by the developed system consists of a high-frequency component. However, a rhythm synchronous with the heartbeat was confirmed. In the lateral position, the cardiac vibration signal obtained by the developed system was very weak, and detecting the rhythm was sometimes difficult. In the prone position, the signal strength fluctuated, and the fluctuation cycle was the same as the respiration cycle. Body movement was successfully detected as shown in Fig. 4, confirming that the subjects changed their posture every 90 seconds. All these parameters were evaluated using all 3 mattresses in all the subjects.

Table I shows the average heartbeat detection ratio and the false positive rate of each mattress and posture. The detection ratio was higher in the supine and the prone positions as compared to the lateral positions. All evaluated mattresses had a similar average detection ratio.

V. DISCUSSION

In this study, the sensor was placed at the foot side of the bed in order to obtain the vibrations occurring near the upper limbs. The heartbeats can be observed at the foot side, as there are arteries in the legs. However, the upper body was observed to obtain respiration signals.

The developed system is based on measuring the vibrations of the mattress, but the reference signals are obtained directly from the subject's body. Generally, the vibration propagation requires some time, and this causes a phase shift. This signal delay has been observed in all systems that monitor pressure or vibrations of a bed.

The frequency band of the filter for detecting body movement overlaps with that of the cardiac vibration detection. Body movement does not occur periodically, thus enabling the frequency band to be set at anything. In this study, the cut-off frequencies were set to achieve a higher response (f_l = 1 Hz), and to eliminate the alias noise in the sampled data (f_h = 20 Hz). The main difference is the amplifier gain, since the signal derived by the cardiac vibration detection circuit is easily saturated when the subject moves.

There exists a high-frequency component in the cardiac vibrations obtained by the developed system. The lower cutoff frequency of the band-pass filter was set at higher than the usual heart rate. Because the cardiac vibrations can be considered as a pulse and not a sinusoidal vibration, and such a "pulse" contains higher frequency components, we monitored the cardiac vibration in the higher frequency area. The merit of a higher setting is that it enables eliminating low-frequency noise and baseline fluctuations. Any high-frequency component can be eliminated by introducing another envelope detection circuit, if necessary.

The phase shift, the existence of a high-frequency component, and the fluctuations in the cardiac vibration signal were exhibited in all cases. Furthermore, the average heartbeat detection ratio was the same for all mattresses tested, suggesting that the developed system is not affected by mattress type.

The average heartbeat detection ratio and the false positive rates were 84.1 ± 3.0 % and 9.4 ± 1.5 %, respectively (excluding the results of the lowest and the highest detection ratio). The average BMI of our subjects was 23.6 ± 3.4 (range, 19.7 - 26.9), suggesting that the proposed system is not affected by the subject's BMI, though the sample size was inadequate to make a conclusive determination.

Though the heartbeat detection ratio is far lower than that of conventional methods (99 % in ref. [2]), the developed system enables monitoring the physiological parameters even while the subjects sleep in lateral postures.

During the experiment, the respiration reference signal could not be obtained at certain times. Prior to starting the experiment, the subjects were requested to wear a belt with an attached piezoelectric sensor. However, the belt was bent, especially when in the lateral position, which resulted in a failure to obtain the respiration reference. The developed system does not require wearing a belt, thus allowing the subjects to sleep in their most comfortable postures.

VI. Conclusion

A non-constraint physiological monitoring system was developed. The developed sensor can be easily installed under an existing bed mattress. The durability of the sensor is high, because the weights of mattress and the subject are not directly applied on it. Increasing the heartbeat detection ratio (and also decreasing the false positive rate) in lateral postures, as well as evaluating this system for a longer period of time during real sleep, with diverse volunteers is required in the future.

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