Determination of Locations on a Tactile Sensor Suitable for Respiration and Heartbeat Measurement of a Person on a Bed

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Abstract— Sleep monitoring systems that can be used in daily life for the assessment of personal health and early detection of diseases are needed. To this end, we are developing a system for unconstrained measurement of the lying posture, respiration and heartbeat of a person on a soft rubber-based tactile sensor sheet. The respiration and heartbeat signals can be detected from only particular locations on the tactile sensor, and the locations depend on the lying location and posture of the measured person. In this paper, we describe how to determine the measurement locations on the sensor. We also report a realtime program that detects the respiration rate and the heart rate by using this method.

Fig. 1. Setup of our sleep monitoring system, and photos of the SR sensor with and without a person on it.

I. INTRODUCTION

Monitoring of respiration and heartbeat while sleeping provides basic and important information for the assessment of personal health and early detection of diseases. For use in daily life, the monitoring should be non-invasive and unconstrained, and use of the measurement apparatus should be simple and easy.

Many methods for unconstrained measurement of respiration and/or heartbeat have been proposed. For example, in [1], [2], pressure sensors in air- or water-sealed cushions under a mattress are used to detect respiration and heartbeat. Flexible piezoelectric film sensors in [3] and loadcells in [4] are also used for measurement. These methods do not obtain pressure distribution and cannot distinguish the lying posture of the person on a bed. When two or more persons, or a person with a pet, are on a bed, their pressure changes mix and cannot be measured separately. In addition, each method has individual problems: air-sealed cushions are several centimeters thick and so are not sufficiently thin, piezoelectric film sensors must be placed near the heart of the measured person, and loadcells are relatively expensive and setting them is not easy.

We are developing a method of measuring the posture, the respiration rate, and the heart rate of a lying person by using a soft, flexible, and thin tactile sensor [5]. Respiration and heartbeat are extracted from pressure changes over time obtained by the tactile sensor. These signals are small compared with the load of the person's weight. In particular, heartbeat signals are faint. To measure them, we improve their signal-to-noise (S/N) ratio by averaging oversampled data. The averaging process takes time and can be performed only at a limited number of locations on the tactile sensor.
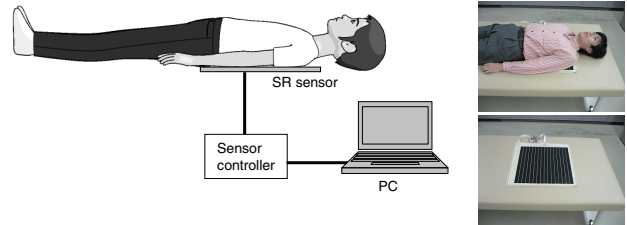
In this paper, we explain that the suitable locations for the heartbeat measurement depend on not only the lying location on the sensor but also the lying posture of the measured person. Then we show that the locations suitable for heartbeat measurement, especially in the prone and supine postures, are not suitable for detecting respiration. Therefore the oversampling measurement should be performed at the location for respiration detection, in addition to the location for heartbeat detection.

In the following sections, we first explain our measurement system. Next we mention how to detect respiration and heartbeat. Then we explain that the measurement must be performed at suitable locations determined by the lying location and posture of the measured person. We describe our realtime measurement system, then conclude this paper.

II. SETUP OF THE MEASUREMENT SYSTEM

The setup of our sleep monitoring system is shown in Figure 1. The measured person lies on a tactile sensor. It is an unconstrained measurement system because the person can take a favorite lying location and posture as long as he/she is on the sensor. We developed an *SR (Smart Rubber) sensor* [6] as the tactile sensor.

The SR sensor is a rubber-based capacitive tactile sensor. It has a structure consisting of two rubber sheets with a thin dielectric layer put between them, as shown in Figure 2. Carbon-filled conductive rubber is printed on the rubber sheets to form electrodes. The electrodes on the upper and lower sheets cross orthogonally, and each crossing part becomes a capacitor, which we refer to as a *cell*. All the cells in the two-dimensional array constitute the tactile sensor.

When pressure is applied, the dielectric layer deforms and the distance between the upper and lower electrodes becomes shorter. As a result, the capacitance of the cell increases. By scanning the capacitances of the cells, we can detect the two-dimensional pressure distribution on the sensor.

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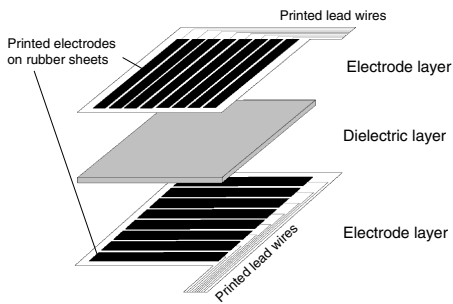
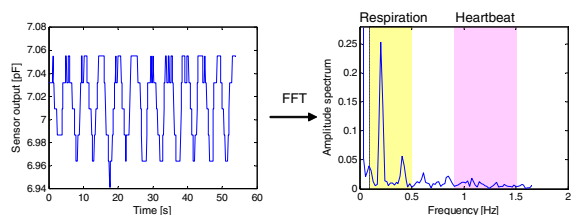Fig. 2. Schematic structure of the SR sensor.

Fig. 3. Time series of SR sensor output and its FFT result.

Fig. 4. Time series of 36-times oversampled averaged SR sensor output and its FFT result.

Because the SR sensor is soft and flexible, it is not uncomfortable for the person lying on it. The current sensor has 16×16 cells, and the pressure-sensitive area is 478 mm×478 mm and 3.5 mm thick. A larger bed-size sensor is desirable and, in principle, can be made, but currently we use this size of sensor because of its availability.

The SR sensor is connected to a controller, which obtains the pressure distribution by scanning. In the current system, measuring one cell takes 184 μs, which means 47 ms for the whole sensor sheet. The pressure distribution is sent to a PC, where the lying posture, the respiration rate, and the heart rate are detected by pattern recognition and signal processing.

III. EXTRACTION OF RESPIRATION AND HEARTBEAT FROM PRESSURE

In our method, respiration and heartbeat signals are extracted from the time series of pressure obtained from the tactile sensor, by using signal processing. When a person lies quietly on a bed, the respiration has a frequency range of approximately 0.1–0.5 Hz, and the heartbeat has a frequency of approximately 0.9–1.5 Hz; thus, they can be extracted by, for example, bandpass filters. When only frequencies are required, we can obtain them by finding the peaks in the bandwidths. We already confirmed that respiration and heartbeat frequencies detected by this method agree with those obtained by commercial measurement apparatus [7], which used a respiration sensor with a band measuring the breast circumference and a heartbeat sensor recording the electrocardiogram (ECG).

Generally, in tactile sensors that measure pressure distribution, high-precision devices cannot be adopted for each element constituting the two-dimensional array because of cost and size limitations. Consequently, the S/N ratio of the pressure detected by tactile sensors is not high. Our SR sensor also has this problem, but the detection of respiration is still possible. For detecting heartbeat signals, which have smaller changes in pressure compared to respiration, however, we need to suppress noise and perform highly precise measurements. We improve the S/N ratio by sampling the pressure at a rate much faster than the signal frequency (oversampling) and averaging the results. As is well known, by averaging N-sampled data, the noise amplitude becomes $1/\sqrt{N}$, if the noise is random. The noise can be a mix of discretization noise, thermal noise, the influence of parasitic capacitance, and so on, but here we do not further pursue the details.
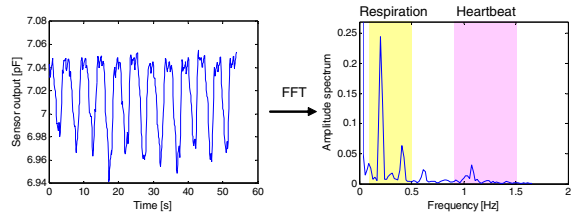
Figure 3 shows a time series of the pressure detected by an SR sensor cell at a certain location near the heart and its fast Fourier transform (FFT) result for a person lying on the sensor in the supine posture. As the sensor output, we adopted the capacitance of the cell before it is converted to pressure. We can easily find the respiration component, which is the large oscillation. Fluctuations caused by the heartbeat are imposed on this signal, but they are small and inarticulate. In the FFT result, the peak in the respiration bandwidth is distinctive, but a clear peak cannot be found in the heartbeat bandwidth. Figure 4 shows the 36-times oversampled averaged signal and its FFT result, where the measurement was made simultaneously with that in Figure 3. The measurement accuracy is much improved, and we can find changes possibly caused by the heartbeat. Actually, a distinctive peak exists in the heartbeat bandwidth in the FFT result.

By averaging oversampled signals in this way, we can attain the S/N ratio needed for heartbeat measurement. However, if we apply this method to all the cells in the SR sensor, too long a time is needed to realize the sampling frequency for respiration and heartbeat measurements. Thus, we confine the precision measurement to a limited number of cells. We refer to the cells as *precision cells*. We adopt 36-times oversampled averaging for heartbeat detection. Then, using the current 16×16 SR sensor of 184 μs sampling time for one measurement, it is possible to measure the whole pressure distribution at 10 Hz, while simultaneously performing the precision measurement in 4 cells at 20 Hz. Because the number of precision cells is limited, we must set them at locations suitable for the measurement.

We also detect respiration from the FFT result of output of the precision cells. If the locations for heartbeat measurement is also suitable for respiration detection, all of the 4 precision
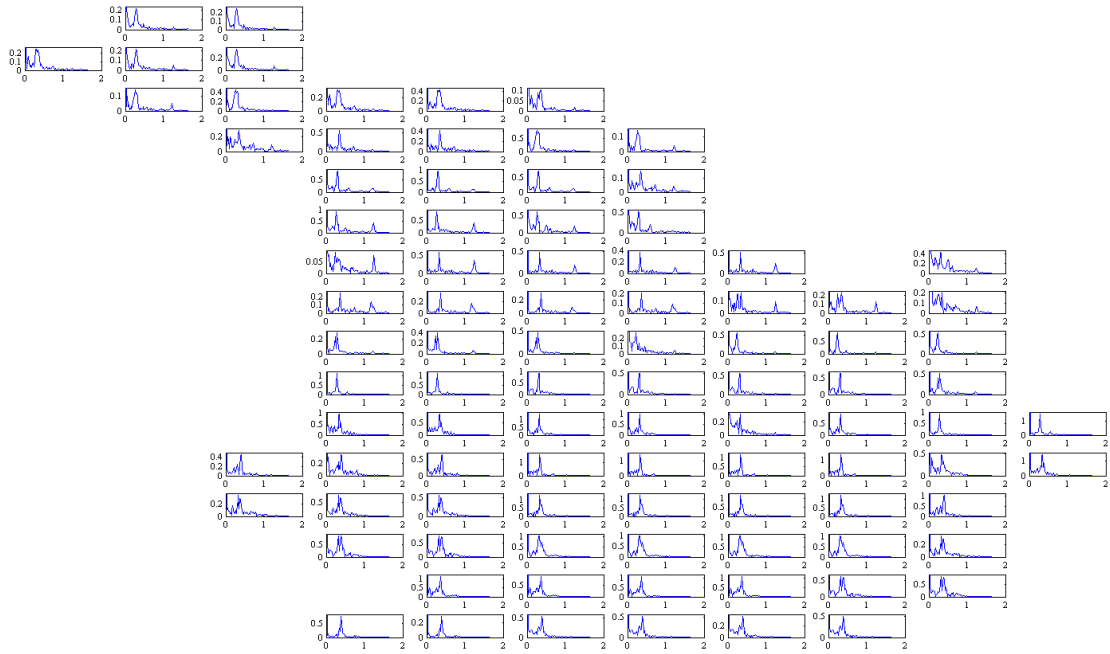
Fig. 5. Spectra of pressure from different cells when a person in the prone posture was on the sensor. Cells without pressure are omitted.

cells can be set there. If not, respiration needs to be measured at a different location from the ones for heartbeat detection. In this case, we set 1 precision cell at a location suitable for respiration detection.

IV. LOCATIONS FOR RESPIRATION AND HEARTBEAT MEASUREMENT

We investigated the suitable locations on the tactile sensor for respiration and heartbeat measurement. From all participants in this study, we received written consent. First, to determine locations for heartbeat measurement, we performed precision measurements at all the cells responding to the weight of the measured person. When we perform a 1024-point Fourier transform that provides a sufficient frequency resolution, the necessary measurement time is more than 51 s for one cell. In the current system, only 4 precision cells can be set at the same time; thus, we must shift their locations and perform the measurements repeatedly. When half of the cells are responding to the weight, a 16×16 SR sensor requires an approximately 30-min measurement time in total. We conducted this precision cell measurement for 4 postures: supine, prone, right lateral, and left lateral. During that time, the measured person kept the lying posture as steadily as possible. We performed the FFT on each measured cell.

The obtained spectra of the pressure for a prone posture, as an example, are shown in Figure 5. We made a program that automatically detects the peak in the heartbeat bandwidth. The original pressure distribution and the heartbeat magnitude detected by this program are shown in Figure 6. These figures illustrate that cells at limited locations can detect pressure changes caused by the heartbeat. We determined the suitable places for heartbeat detection for the four lying postures, on the basis of the experimental results, such as Fig-
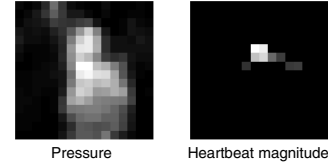

Fig. 6. Original pressure distribution and the detected heartbeat magnitude from the spectra in the prone posture.
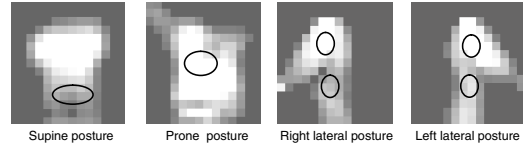

Fig. 7. Suitable locations for heartbeat detection. The circles show suitable precision cell locations for different lying postures.

ure 6, of the heartbeat peak magnitude and distinctiveness. The results are shown in Figure 7. Different measurement locations are selected for each lying posture.

The magnitude and phase of the oscillation induced by respiration differ at each cell. Though the respiration magnitude can be seen in Figure 5, the phase cannot be obtained from this measurement, because the measurement of all cells was not conducted synchronously. We investigated respiration phases to avoid the situation where, by adding output from cells with different phases, the respiration signals offset each other. We performed synchronous measurement at all the cells, then performed the FFT on the results, for the four lying postures. The respiration magnitude and phase were determined from the peak in the respiration bandwidth.

Figure 8 shows the results, where respiration phase is indicated by the relative value from the phase of the peak
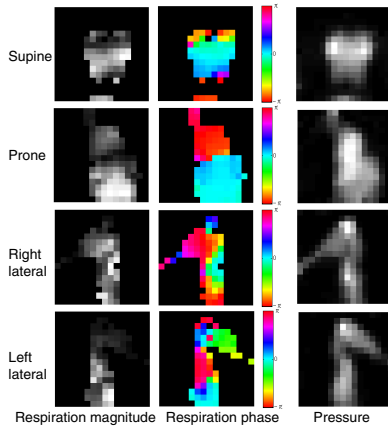
Fig. 8. Respiration magnitude and phase, measured with the pressure, for the four postures.
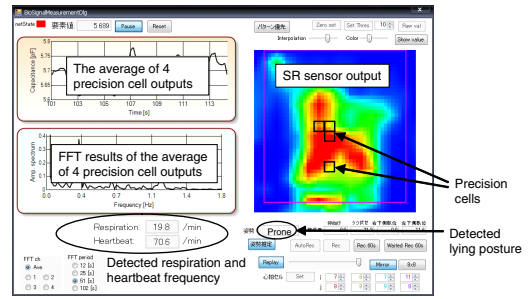

Fig. 9. Realtime program detecting lying posture, respiration, and heartbeat.
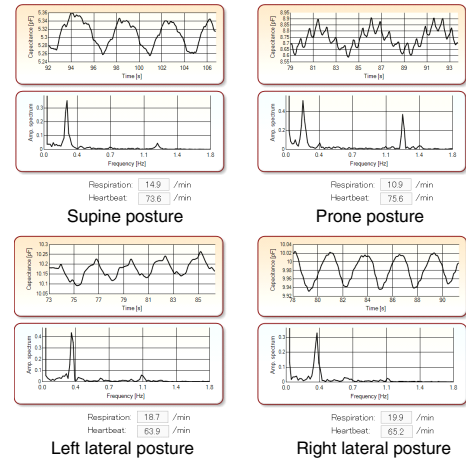

Fig. 10. Average output of precision cells, its spectra, and detected frequencies from the four postures.

magnitude cell. This figure, together with Figure 7, shows that, in supine and prone postures, the respiration magnitude is small at the locations for heartbeat detection. This is partly because the phase changes by π at the locations. If all precision cells are set for heartbeat detection in these postures, the respiration oscillation may interfere and reduce even smaller when averaged. To avoid this, we set 3 precision cells at the heartbeat detection locations, and the remaining 1 precision cell to a location for respiration detection, in the supine and prone postures. The distributions of the respiration magnitude and phase in the lateral postures are more changeable, and the regions of the same respiration phase are mosaic. In addition, the respiration magnitude is not small at the locations for heartbeat detection. Therefore, we set 2 precision cells at each circle in Figure 7, in the lateral postures.

V. REALTIME PROGRAM

To actually use the proposed method of measurement location determination, we need to detect the lying person's location and posture. We developed a method for determining them from the pressure pattern by using machine learning, the details of which is in [5]. Then we developed a program that outputs in realtime the lying posture, the respiration rate, and the heart rate of the person on the SR sensor (Figure 9). The four precision cells are automatically set to the suitable locations determined by the method in this paper, according to the location and posture of the lying person. The FFT is applied to the average of four precision cell outputs containing respiration and heartbeat signals. By finding the peaks in the corresponding bandwidths, the respiration rate and the heart rates are detected. For the FFT, 1024-point data during approximately 51 s are used. Samples of the average of the precision cell output, its FFT result, and detected frequencies for the four postures are shown in Figure 10.

VI. CONCLUSIONS

The suitable locations for precision cells are determined using data from one person, in this paper. We will investigate whether the locations are general, using data from more

persons. In future work, we will establish an unconstrained measurement system that does not disturb natural sleep. Our final goal is to develop a sleep monitoring system for deciding the quality of sleep and detecting diseases.

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