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The Design and Realization of Sleep-monitoring System Based on Body-movement Signals

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***Abstract*—Based on the Internet of Things (IoT), and the techniques of sensors, we developed a kind of sleep-monitoring system, which can make a live surveillance of several life characters of subjects, such as their heart rates, breath rates, and times of body-movements per epoch, and then, built up models to illustrate different sleeping periods, judging the sleeping status of the subject. This article briefly introduces the consistence of hardware, and the algorithms of exploiting information and dividing sleeping states of the system.**

Keywords—Internet of things, body movement signals, sleep monitoring.

I. Introduction

With the improvement of people's living quality, the public's concern towards their own health status keeps increasing [1]. The quality of sleeping strongly influences people's working efficiency, and it is also an objective reflection to the body's status. Therefore, several kinds of sleep-monitoring equipment have emerged to satisfy people's requirement in realizing their own sleeping qualities. However, the limits of these current facilities are also obvious: Some sophisticated medical-standard methods, like polysomnography (PSG), requires at least one pair of electrodes attached to the subject's body directly, causing a sense of inconvenience; some other devices, like the popular hand bands, also need the subject to wear the product during sleep [2]. To free the subject from additional devices, we developed a novel sleep monitoring system based on the discern and process of body-movement signals, and with the assistance of heart beat and breath signals. The difference is that the devices of sensors are arranged under the mattress, so the customers are free from electrodes or wearable devices, they just need to sleep as they always do, and their sleeping statuses will be automatically recorded by our system.

The theory is that, when the heart is pumping blood outside, a force reverse to the flooding of the blood will be generated by the body, leading to the vibration of the whole body with the same frequency of the heartbeat. At the same time, with each breath, the thorax experiences a cycle of expansion and compunction [3]. Both the heart beat and breath lead to the movement of the body, the movement signal then transmits to a solid-state mattress, and eventually being captured by the piezoelectric sensor. Such signals feeble notwithstanding, the piezoelectric sensor is still delicate enough to detect the vibration [4]. After transmitting and possessing by algorithms, the heart beat signal, breath signal and the signal to the movement of the subject on the bed, are detached from the original signal.

II. The Acquirement of Signals

The slave computer of our system consists with the sensing unit of electrophysiological signals, the analogy end of signal possessing, the analogy signal-digital signal shifting unit, the micro controller unit, the communicating unit, and the power system. As shown in Fig. 1, the system collects the original elecphysiological signal from the sensors; the analogue front-end (AFE) makes a pre-treatment of that original signal to improve the stability of signal transmission and its resistance toward noise; the processed signal is sent to the second-level sampling units, the high-quality analogue-to-digital converters (ADC) will translate it into digital signal; the converted signal is sent to the communication unit by micro-controller, who is also responsible for the control of time sequence and fundamental process of digital signal, and then submitted to the upper computer by means of the transmission control protocol (TCP).

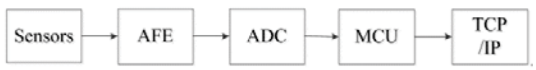

Fig. 1. The structure of hardware

III. The Processing of Signals

A. The Algorithms of Exploiting Heart Rate and Breath Information

The original body-movement signals of a healthy person in resting state is shown in Fig. 2. From the Figure we can conclude that there is a significant periodicity of the signal, so, it is able to utilize fast Fourier transform (FFT) to project the wave function to the spectral space [5], and thus get the heart rate and breath rate.

The upper computer firstly selects the channel with the highest amplitude form all the signal channels of sensors to calculate, as the higher the amplitude is, the clearer physiological information the signal is able to carry. To improve the resolution of results, we let one epoch to be 60-second length, and calculate the subject's heart rate and breath rate in a 2-second interval, when T is larger than 60, use the discrete data from time (T-60) to T to do FFT. For a normal person during rest, the breath rate is around

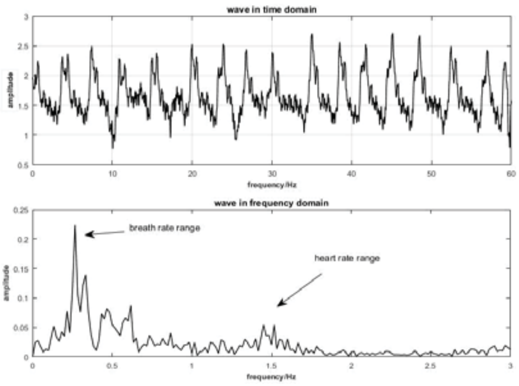

Fig. 2. The time-space and spectrum-space waveform of the body-movement signal

10 to 18 times per minute, the pulse rate is five times as the breath rate. Therefore, the breath frequency is around 0.16Hz to 0.3Hz, and the heartbeat frequency is about 0.83Hz to 1.5Hz. We select the maximum points of the spectrum in these two frequency intervals respectively, to get the breath rate and heart rate at that moment. When t = T + 2N (N is a positive integer), repeat the whole process above. Finally, the data of heart rate and breath rate in one minute are gained, save their average values into the database.

B. The Algorithm of Body Movement

The body movements of human during sleep can be divided into slight movements and large-amplitude movements. The slight movements include the low-amplitude stretches of arms and legs, the lean of head, and the slight distort of body, who often complete in 2 to 3 seconds; the large-amplitude movements consists the turn-over of body, the large-amplitude movements of arms and legs, and body's large distortion, the lasting time is usually 3 to 5 seconds. For the sensitive mattress, each body-movement is strong enough to let its signal curve reach full amplitude, in other word, reach its maximum or minimum value, as shown in Fig..3. Accordingly, we pick the original data from T to (T+2), counting how many of them reach the maximum or minimum value, and thus get the time of body movement during these two seconds. Finally, we accumulate the total time of body movement in a whole minute, and save the result into the database.

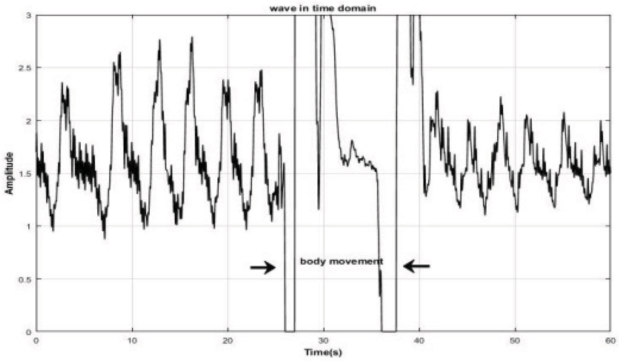

Fig. 3. The waveform of body movement

It is worth noting that resulted by the body movement, other physiological signals, like heart beat and breath signals, are missed in the original signal. As a result, we give the value of heart rate and breathe rate at time (T-2) to time T, to maintain the consistency of the result.

C. The Algorithm to Discriminate Different Sleeping Stages

The sleeping of normal human holds a periodicity, every period, similarly, can be more meticulously divided into different sleeping stages. A lot of clinic researches illustrate that there are several physiologically characters that match different sleeping stages, such as heart rate, breath rate, body temperature, the secretion of digestive juice, the concentration of blood Oxygen, the body movement, and so on. Our program takes advantage of the current available characters, like heart rate, breath rate, and body movement data, to judge the sleeping qualities of customers by building up models illustrating the relationship between these characters and sleeping stages. The concrete algorithms are shown in Fig..4, where the expression of $f(x,\ x_{mean},\ p_1,\ p_2)$ is determined by function (1). Therein x is the value of heart rate, breath rate, body movement time length during a particular second, or the mathematical mean value/ standard deviation in 9 epochs ($movement_{mean}$ or $movement_{var}$, see function (2) and (3), or a sum of values in 9 epochs that higher than an adjustable threshold ($movement_{>threshold}$, see function (4)).

$$f(x, x_{mean}, p_1, p_2) = \frac{1}{1+\exp[p_1(x-p_2 x_{mean})]} \tag{1}$$

$$movement_{mean}(t) = \frac{1}{9}\sum_{t-4}^{t+4} movement(i) \tag{2}$$

$$movement_{var}(t) = \sqrt{\frac{1}{9}\sum_{t-4}^{t+4}[movement(i) - movement_{mean}(i)]^2} \tag{3}$$

$$movement_{>threshold}(t) = \sum_{t-4}^{t+4}\begin{cases} movement(i) - threshold, & movement(i) > threshold \\ 0, & movement(i) \leq threshold \end{cases} \tag{4}$$

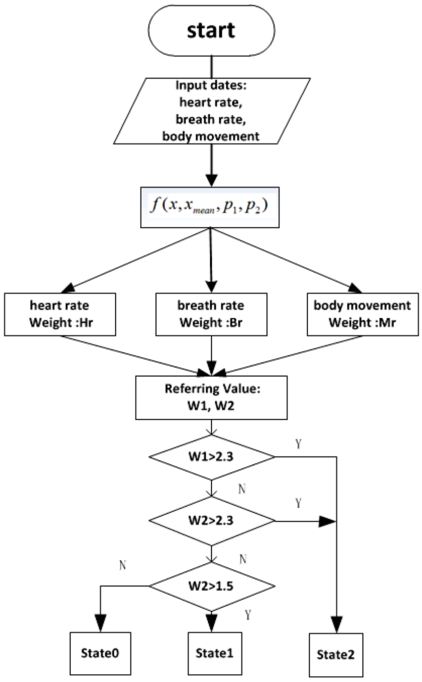

Fig. 4. Algorithms of body-movement's measurement

Calculate the first-stage referring value (W_1) of the parameters by adding up the weighted values of heart rate and breath rate. If this gained value is so small, then there must be something wrong with the heart beat or breath of the subject (either too fast or too slow); if it looks well, then calculate the second-stage referring value (W_2), which is most determined by the parameters related to body movement. If the second-stage value is larger than particular experiment-determined thresholds, then the sleeping status is judged to be deep sleep or light sleep, otherwise, the system will estimate that the subject is not sleeping. The expressions of them are as follow:

$$W_1(t) = \sum_{t-4}^{t+4} a_i f[heart\ rate(i)] + b_i f[breath\ rate(i)] \tag{5}$$

$$W_2(t) = A \cdot W_1(t) + B \cdot \begin{Bmatrix} m_1 \cdot movement(t) + m_2 \cdot movement_{mean}(t) \\ +m_3 \cdot movement_{var}(t) + m_4 \cdot movement_{>threshold}(t) \end{Bmatrix} \tag{6}$$

IV. Results and Conclusions

From Fig..5, we notice that the system is qualified in steadily and accurately monitoring several physiological characters of the subject, including heart rate, breath rate, and body movement, and thus give out the discrimination of sleeping stages. For instance, from 00:30 to 03:30, the average breath rate is 16.026 times per minute, the average heart rate is 60.89 times per minute; while during 03:30 to 06:30, the average breath rate reduces to 14.83 times per minute, which is coherent with the clinical results that the breath rate will gradually reduce with the prolonging of sleep [6]. To justify the accuracy of our system, we compared our results of sleep stages with the current devices. The standard sleep monitoring device is polysomnography (PSG) [3], however, restricted by our research conditions, such an expensive equipment is unavailable. Therefore, we used video surveillance and several commercial sleep-monitoring products to make comparisons [7], finding that the coherency was greater than 80%. So, we conclude that our system is able to give reference to the judgement of sleep quality with high reliability.

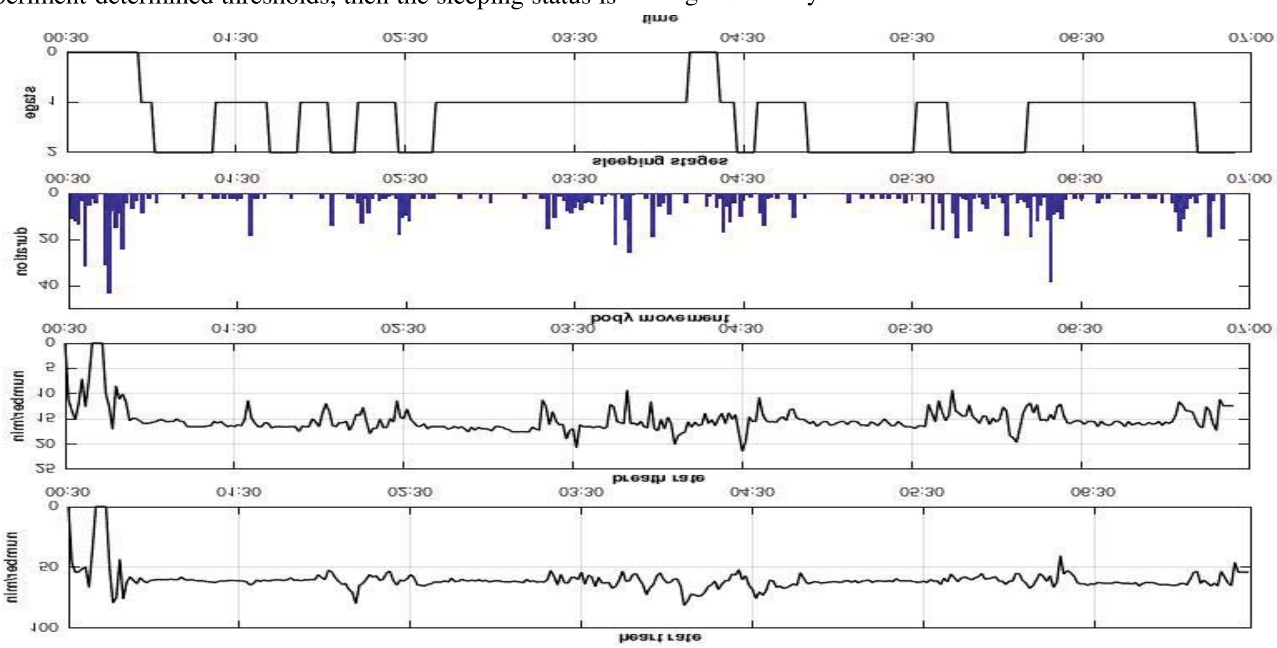

Fig. 5. results of sleep-monitoring

V. Conclusions

Our novel sleep-monitoring system frees customers from and wearable devices, and they do not need to manually set up the device to start working. The customers will be free to work and rest at their preferences, and the device will automatically do its jobs, figuring out all the physiological characters, including heart rate, breath rate, body movement, times of getting up at night, judging the sleeping quality, without any direct connections with customers. The accuracy and reliability of our system may not be as good as PSG, nevertheless, its low-cost and usability make its usage in the field of elder-care and smart-home facilities available.

In addition, our system is able to exploit the sleeping information of customers during a long time and without breaks, so has a wide range of potential usages, such as helping to acquire numerous clinical data, proposedly analyzing the individual sleeping character, providing data-based supports to the speculations and precautions of chronical diseases, and monitoring brachychronic disease, such as respiratory arrest.

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