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A Wearable Respiration Monitoring System Based on Digital Respiratory Inductive Plethysmography

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***Abstract*—In this paper we present a wearable device for continuous monitoring of respiration signal and the associated algorithm for signal evaluations. The device took advantages of a proven respiratory inductive plethysmograph (RIP) technology and a wireless body sensor networks (BSN) development platform. The textile RIP sensor was integrated into a suit that could be comfortably worn around thorax or abdomen for monitoring respiration during sleep. A smart signal processing algorithm was implemented for extracting the dynamic respiration rate. The results of *in-situ* experiments from ten healthy subjects suggested that our system worked as intended. Due to the high reliability and low cost of our system it is believed to meet the future demands on home-based monitoring and diagnosis of sleep disorder-related diseases.**

I. Introduction

THE last decade has witnessed a rapid surge of interest in novel monitoring devices for pervasive home healthcare [1]. The development of wearable or implantable Body Sensor Networks (BSN) offers an excellent platform to establish such healthcare systems for chronic disease management and personalized medicine, as well as represents the latest evolutions of diagnostic tools [2]. A BSN enables the ubiquitous and long-term monitoring of a subject's health state at home, which is beneficial in many cases since the subject might be disturbed psychologically in a hospital environment.

Dynamic monitoring of respiration conditions during sleep plays a vital role in the diagnosis and treatment of sleep apnea, sudden death syndrome and other sleep disorders [3]. To date, most sleep medicine researchers have primarily focused on sleep monitoring in a relatively artificial environment, i.e. a sleep laboratory, using polysomnography (PSG) technology [4]. Despite the many technical advantages of the PSG in capturing detailed physiological measurements over the course of one or two nights, it is not well suited to tracking sleep over prolonged periods in the 'free-living' conditions [4]. Doppler radar [5] and Electrocardiogram (ECG) [6] are used for respiration measurements, but both are indirect methods with less measurement accuracies [7].

There are some researches on RIP-related technologies and a preliminary device was also proposed [8]. In this paper we present a wearable device for wireless monitoring of dynamic respiration conditions such as rhythm, breathing mode and depth, during sleep. Body motion was measured using a 3-D accelerometer embedded in the device.

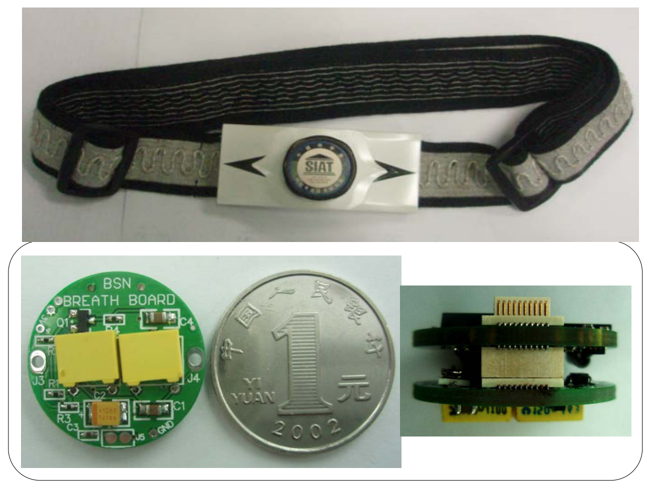

Fig.1. Photos to show the wearable device and the electronic boards.

II. System

The system we have developed was consisted of a wearable textile-based sensing belt, a compact electronics module that connected with the belt, and a base station device that connected with a PC. Fig. 1 demonstrated the complete system as well as the different electronics modules.

A. Wearable device

For long-time physiological monitoring, it is highly desirable that the sensors were designed into the garment in an unobtrusive manner [9]. The sensor belt contains a flexible wire and has high resistance to washing processes and cyclic mechanical deformations [9]. The sensor, featuring a proven RIP technology, delivers a highly sensitive and reliable respiratory effort tracing. A precise quality signal is then generated according to the measure of the shifts in chest or abdominal circumference, Fig. 2 illustrated the correlations between the expansions of the belt and the resultant inductance changes, which suggested a good linearity of

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approximate 6.6 nH per centimeter displacement (R^2=0.96). The initial inductance of the belt without any deformations was approximately 2.9 uH.

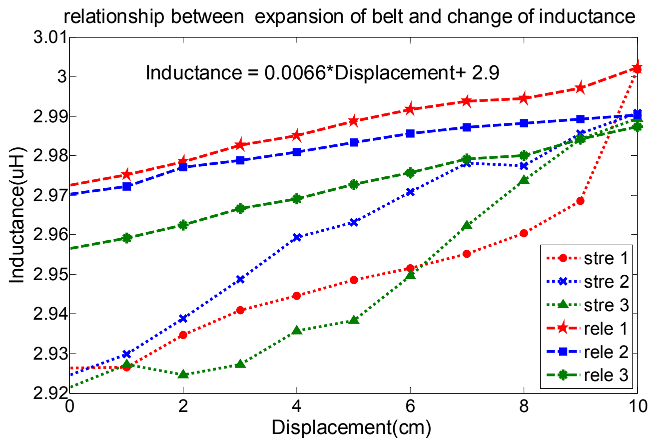

Fig. 2. The correlation between the expansion of the belt and the resultant inductance change. The belt was stretched and then released for three times, demonstrating the obvious effects of hysteresis.

The RIP electronics board (Fig. 1, bottom left) was consisted of a DCDC circuit model, a resonance circuit and a waveform conversion circuit. A low-power DC/DC boost converter (TPS61040 from TI) was used to power the resonance circuit.

Our design adopted the classic LC oscillator circuit. Once worn, during subject's breathing the inductance of the belt varied. According to the resonance condition:

$$f_0 \approx \frac{1}{2\pi\sqrt{L\dfrac{C_1C_2}{C_1+C_2}}}$$

The respiration efforts in thorax or abdomen could be measured by extracting the dynamic changes of the resultant resonance frequencies. The selection of the two capacitors that were indicated in the above equation is vital and the metalized polyester film capacitors were satisfactory. The capacitance was approximately 60 nF.

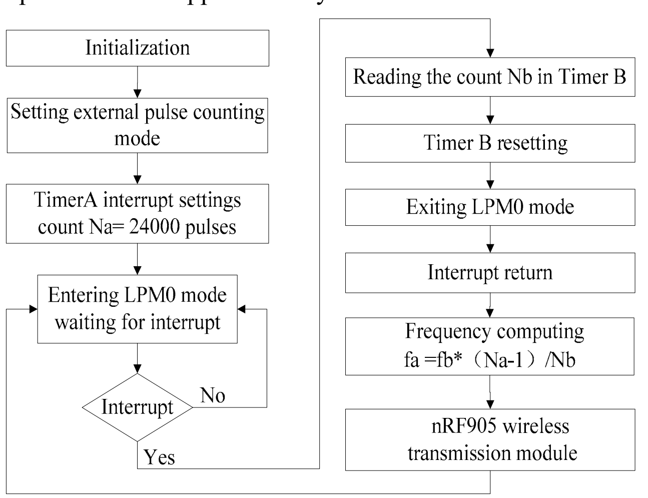

Fig. 3. Flow chat of the embedded software. The primary goal of the software was to calculate the resonant frequency.

In the waveform conversion unit, a differential comparator LM393 was used to rectify the sine-wave oscillation into digital pulse.

A BSN node board was also developed [10]. The BSN node board and the RIP electronics board were with the unified form factor of 23 millimeter in diameter and were stacked together for respiration measurements (Fig. 1). The BSN node board integrated an ultra low-power microprocessor (MSP430F149 from TI) and a 3-D accelerometer. Fig. 3 depicted the flow chart of the embedded software that was implemented into the microprocessor. A high precision in frequency calculation was obtained with the method of equal precision measurement. The digital respiration signal demodulated from the variational frequency has less interference and distortion.

B. Signal processing

There were three types of interferences that affected the signal quality during dynamic monitoring of respiration conditions, i.e. motion artifact, RF interference and the hysteresis of the wearable sensor. After intensive tests, a threshold-based criterion was set to evaluate the respiration signal quality. If the signal quality was too poor, this signal episode was discarded without further processing. This way the processing time was significantly reduced and the signal integrity was guaranteed. The criterion was briefed as below:

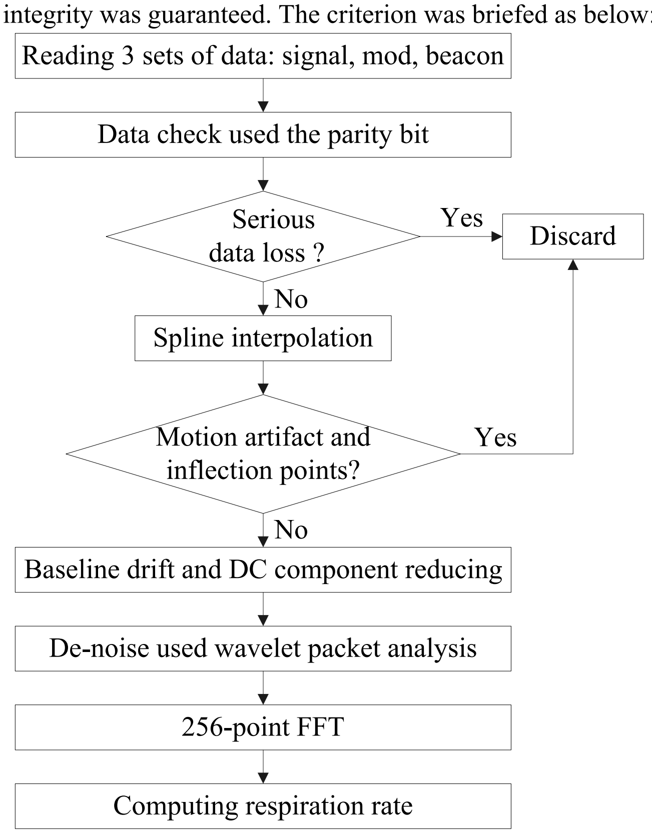

Fig. 4. Flow chart of the signal processing unit.

- Serious data loss. Discard the data, if the number of data loss was more than fifteen within five seconds. Otherwise, we did the interpolation to make the data consecutive. The sampling rate was set to be 10 Sps.

- Serious motion artifact. A one-dimension wavelet analysis was utilized and a noise figure was calculated using decomposed signals. A sliding window with 0.5 second interval was passed over the waveform, it tracked the rapid variety of the respiration signal. Comparing with the normal signal, we detected the distortion of the waveform. The signal which interfered by motion was neglected without analysis.

After signal quality evaluation, dynamic respiration rates were calculated according to the raw signal's spectrum characteristic [11]. Fig. 4 illustrated the flow chart of the signal processing unit, implemented in a PC [12]. Fig. 4 is self- explanatory.

III. RESULTS

Extensive bench-testing was carried on to verify the hardware platform. The wireless link proved to be highly reliable. Using an 800mAh Li-poly battery the system could operate up to 6 hours, which is sufficient for over night sleep monitoring. Table I listed the specifications.

TABLE I
SPECIFICATION SHEET OF THE HARDWARE MODULE

ITEM	PARAMETER
PCB Size (diameter)	23 mm
Peak power consumption	140 mW
Radio transmission range	20 m
Static current in the belt	0.025 uA
Precision of the frequency	1e-5
Centre of resonance frequency	380 KHz
Belt inductance without deformations	2.9 uH
Resistance of the sensor belt	0.9 Ohm
Capacitance of the sensor belt	60 nF

Wear-ability tests were also carried on. 15 subjects participated in the experiment. They were asked to wear the device for four hours. 14 out of the 15 subjects felt comfortable.

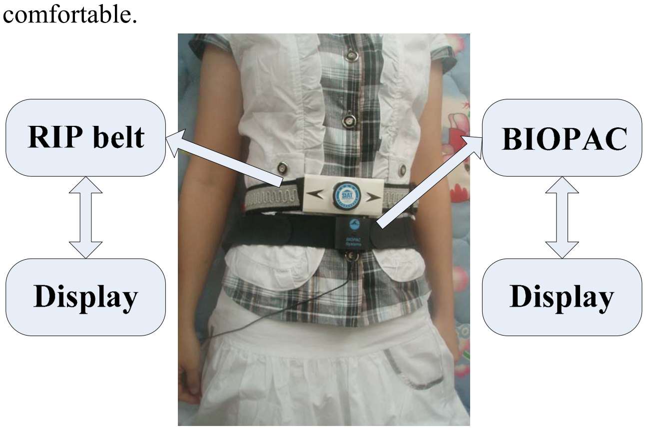

Fig. 5. The in-situ experiment setups.

In-situ dynamic respiration experiments were conducted with 10 healthy subjects (aged 24±2), in both natural and air-conditioned rooms while the subjects were sleeping on a sheet [13]. Fig. 5 showed the experiment setup. Subjects slept while wearing the belt around the abdomen or thorax. At least five-hour data was acquired wirelessly from every *in-situ* experiment.

A commercial product (MP150 from BIOPAC, which uses a piezoelectric-based sensor belt and provides a wired solution) was used for performance comparisons (Fig. 5). Fig. 6 depicted the respiration data acquired by the two methods. A relative error a was calculated to be approximately 15 % for this particular data episode.

$$a = \sum_{i=1}^{L} \frac{|R_i - B_i|}{B_i} \qquad a = 15$$

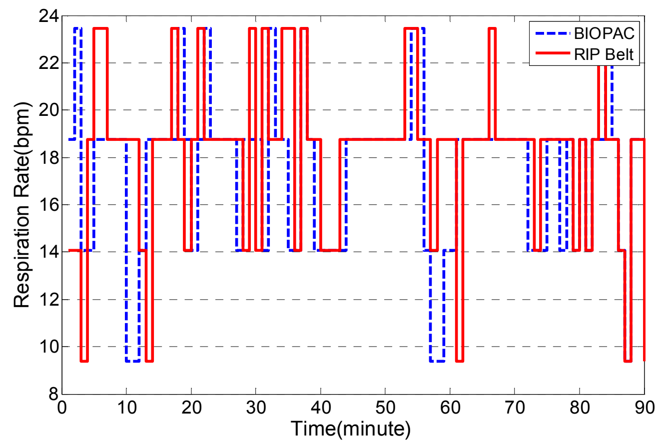

Fig. 6. Respiration data acquired from the two methods. A RSP100C module was used with the MP150. Data were calculated every minute.

Fig. 7 illustrated the step-by-step respiration signal processing procedures. We could obtain de-noise signal though the one-dimension wavelet packet. A threshold de-noise method was utilized.

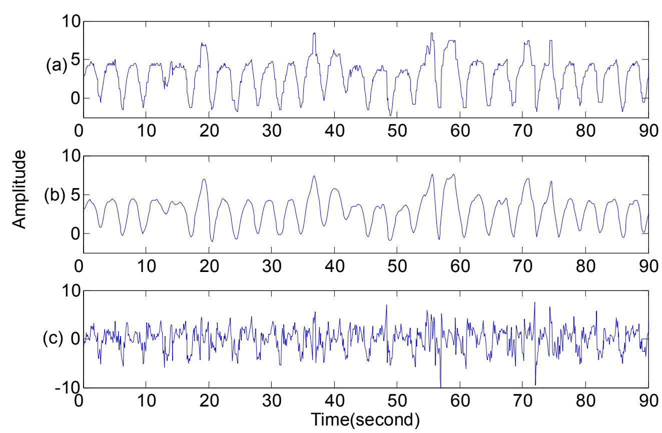

Fig. 7. The signal processing procedures. (a) the raw respiration signal; (b) the processed signal after wavelet transformation and re-construction; (c) the residual signal.

Fig. 8 illustrated a 6-hour dynamic respiration rate monitoring result. Data with poor signal quality was discarded without further processing.

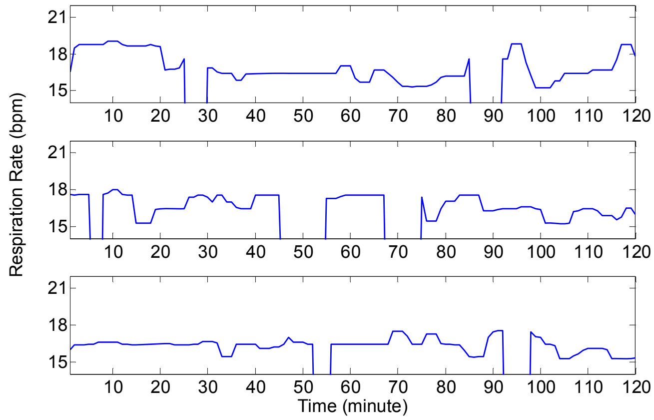

Fig. 8. The respiration rate of one subject over 6 hours during sleep. One subplot represents two-hour data episode. The poor signal was discarded according to the criterion.

Fig. 9 illustrated the percentage of the data that succeeded the threshold-based criterion. By averaging approximately 83 % of the whole data sets were effective data sets.

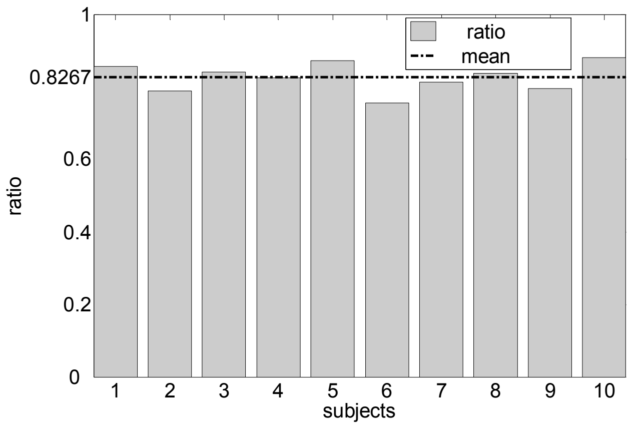

Fig. 9. The percentage of effective data acquired from 10 subjects.

IV. Conclusions

In this paper, a wearable system was developed for dynamic monitoring of body respiration during sleep. A highly-sensitive digital RIP textile sensor was used for signal acquisition. A signal processing algorithm was elaborated to retrieve the sensor data. The digital frequency-counting approach implemented in the processing algorithm outperformed the conventional amplitude-based solution in terms of the algorithm robustness. Intensive *in-situ* experimental results suggested that the system worked as intended. It is believed that the wireless system is a good candidate to meet the future demand on home-based sleep monitoring [14].

In the future, we will carry on more *in-situ* experiments with both healthy subjects and patients with sleep disorders [15]. We will also investigate more advanced signal processing and calibration methods to reduce the hysteresis effects of the sensor belt. After that, we will focus on biofeedback research using our system.

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