WiKiSpiro: Non-contact Respiration Volume Monitoring during Sleep

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ABSTRACT

Respiration volume has been widely used as an important indication for diagnosis and treatment of pulmonary diseases and other health care related issues such as critically ill patients neonatal ventilation, post-operative monitoring and various others. Most of existing technologies for respiration volume monitoring require physical contact with the human body. While wireless-based approaches have also been discussed in the literature, there are still limitations in terms of estimation accuracy and time efficiency preventing these approaches from being realized in practice. In this paper, we present an automated, wireless-based, vision-supervised system, called *WiKiSpiro*, for monitoring an individual's respiration volume. In particular, we present a system design encompassing a wireless device, motion tracking and control system, and a set of methods to accurately derive breathing volume from the reflected signal and to address challenges caused by body movement and posture changes. We present our preliminary results of *WikiSpiro*, and identify possible challenges for future research and development.

Keywords

Mobile healthcare; RF-sensing; breathing bolume monitoring.

1. INTRODUCTION

Continuous respiratory rate and volume monitoring play an important role in health care. While an abnormality in breathing rate is a good indication of respiratory diseases such as interstitial lung disease (too fast) or drug overdose (too slow), *fine-grained breathing volume information* adds valuable information about the physiology of disease. Common obstructive airway diseases such as asthma and chronic obstructive pulmonary disease (COPD), for example, are characterized by the decreased flow rate measure at different breathing volumes. A constant loss of lung volume in these diseases not only indicates acute changes in the disease stability but also reveals lung remodeling and other irreversible states of diseases. Further, patients with lower airway diseases such as cystic fibrosis or tuberculosis could be diagnosed when sudden drops in breathing volume are frequently detected. Therefore, continuous and fine-grained breathing volume measurements could offer rapid and effective diagnostic clues to the development of disease progression [4].

Current techniques for breathing volume monitoring are obtrusive: airflow is measured from the nose and mouth qualitatively or at best semi-quantitatively with a pressure manometer or an impedance chest belt [3]. Non-obtrusive approaches are apparently more attractive and usable. So far, however, the literature has mainly focused on the problem of breathing monitoring using camera [5], infrared (IR) signal [2], radio signal [1] devices, and various others. While these breathing rate estimation solutions are accurate and practical, little progress has been made along the line of breathing volume estimation.

In recent work, we have developed a breathing volume estimation from afar system, called *WiSpiro* [7, 6]. Derived from this, *WiSpiro* uses directional radios to continuously monitor a person's breathing volume with high resolution during sleep from afar. It relies on a phase-motion demodulation algorithm that reconstructs minute chest and abdominal movements by analyzing the subtle phase changes that the movements caused to the continuous wave signal beamed out by *WiSpiro*. In addition, *WiSpiro* relies on the received signal strength and phase of the bounced off signal to estimate human posture and where radar is pointing to on the chest. However, *WiSpiro* maintains the following limitations: (1) The posture estimation requires several minutes and there is no breathing volume is inferred during this period, (2) *WiSpiro* can only recognize a limit number of postures, and (3) The posture estimation is inaccurate and affected by background environment.

In this paper, we present a hybrid radio-camera system to estimate breathing volume during sleep, called *WiKiSpiro*. *WiKiSpiro* estimates breathing volume by observing the effect of chest movements on the phase of reflected signal.

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WiKiSpiro has also the ability to work with the presence of random body movement. *WiKiSpiro* autonomously tracks the large-scale movements of the patient by observing the skeletal posture obtained by a depth-based camera sensor, and moves the radar to a proper location in order to maintain its an orthogonal view of the patient's chest. However, *WiKiSpiro* still presents several challenges:

- Respiration volume information is buried in the very minor phase shift of the reflected signal. That is in sharp contrast with respiration rate where a simple peak count applied on the phase shift time series might reveal the accurate estimation of the rate.
- A minor body movement could cause significant volume estimation error. That movement directs the radar beam to a new area on patient's body, which leads to an inaccurate estimation because different areas on the human chest move differently (while they reflect the same breathing volume). Therefore, the radar needs to know the patient's posture while sleeping as well as where the radar is beaming to on patient's body.
- Posture change or body part movements, *e.g.* subject's arms, also might block the chest movements to be seen by radar. In this case, an alternative area on human chest that isn't blocked should be targeted by the radar device.
- Vision-based techniques can be well adapted for skeletal estimation and chest orientation, but are still subject to visual occlusions, skeletal posture ambiguities, clothing, blankets, and joint position accuracy. These challenges are consistent with all vision-based monitoring techniques including our work using chest surface reconstructions for tidal volume estimation [10].

2. SOLUTIONS AND SYSTEM DESIGN

WiKiSpiro is created to continuously monitor a patient's breathing volume during sleep. While Figure 1 (a) shows the conceptual design of *WiKiSpiro*, we sketched its functional architecture as in Figure 1 (b). *WiKiSpiro* includes three main components: *volume estimator*, *radar navigator*, and *one-time trainer*. Those components are designed to solve challenges mentioned earlier.

Volume estimator. *WiKiSpiro* builds on a decoding technique that extracts subject's frontal movement due to breathing, heart beat, and random body movement from the reflected radio signals. It continuously tracks the minute frontal body movement by analyzing the phase shift and signal strength of the signal captured by the receiving radar. This movement information is then combined with a prior knowledge, learned through a one-time training process, to estimate fine-grained breathing volume.

Radar navigator. To consistently provide an accurate tidal volume estimate using a directional radar system, *WiKiSpiro* requires a continuous patient tracking system to direct and retarget the volume estimation radar system. To address this problem, a vision-based monitor is introduced to address the challenges in optimal radar targeting when the patient moves during sleep, changes their sleeping posture, or occludes their chest from the receiving radar with their arms or posture. This visual system complements the directionality

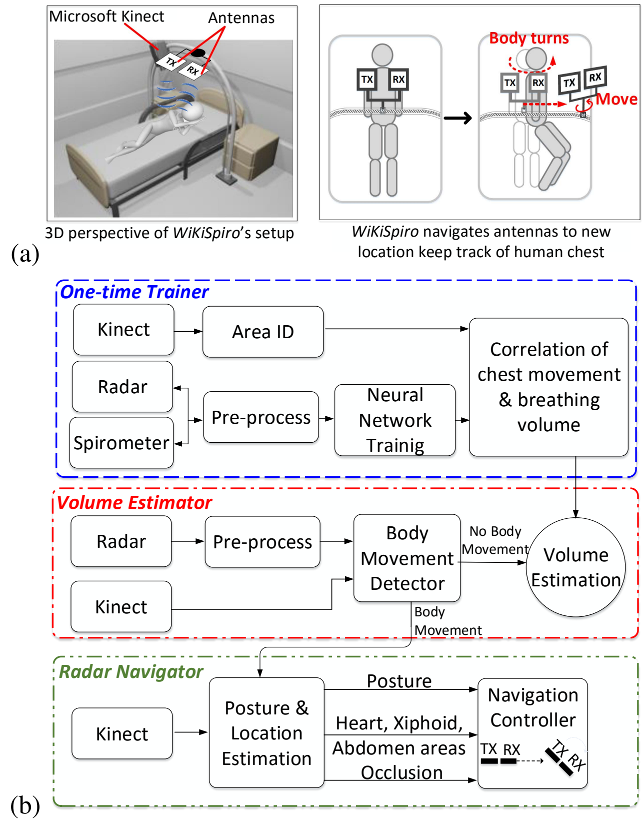

Figure 1: *WiKiSpiro*: (a) conceptual design and (b) overview architecture.

of the radar system by providing an accurate skeletal posture estimation to define the optimal orthogonal direction to the patient's chest. This directionality is then used to redirect the radar to the appropriate position on the track rail.

One-time trainer. A training step is required to establish the correlation between human chest movement and breathing volume because this correlation depends on chest size, age, breathing patterns, and so on. The trainer uses neural network to establish the relationship between body movement and beaming area with the breathing volume. Given an instance of chest movement at a known area on human chest as an input, the output of the function is a corresponding breathing volume. Secondly, the system needs to know exactly where it's pointing, so that it uses the correct correlation function for estimating breathing volume from the chest movement. The human posture and the location where the radar is beaming to are inferred by our vision technique.

3. IMPLEMENTATION AND RESULTS

We have implemented *WiKiSpiro* as in Figure 4. The hardware setup is composed of three main components: a radio transceiver, a radar navigator, and a depth camera (Kinect 2.0). The radio transceiver hardware is developed from a WARP kit v3 board [8]. The transmitter sends single tone continuous wave at 2.4 GHz. On the other hand, a receiver captures reflected AC-coupled signals, convert to base band, and output discrete I/Q samples with 100 kHz baseband sampling rate. The radio hardware is mounted on a mechanical

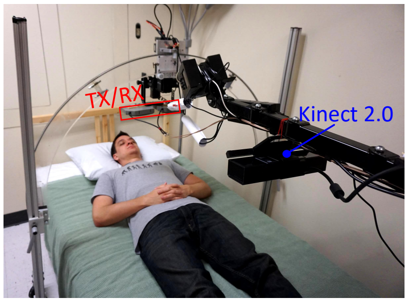

Figure 2: *WiKiSpiro*'s setup.

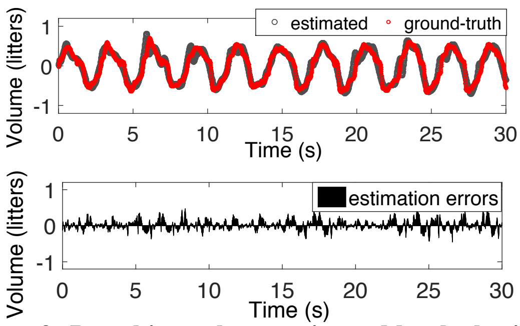

Figure 3: Breathing volume estimated by the basic *WiKiSpiro* algorithm for a stationary person.

motion control system which is steered by a PC host in real-time. The control system supports 360 pan, tilt, and slide movement. To navigate the radar to proper location and orientation, the motion control system is driven by our radar navigator algorithms which are implemented on the PC host. The whole system is mounted across and on top of a twin-size bed on which experiments are conducted.

A subject sleeps on the *WiKiSpiro* testbed wearing his normal clothes. We use a spirometer as a ground-truth to evaluate *WiKiSpiro*'s volume estimation accuracy and train its algorithms when necessary. The training process was done within 9 minutes. After training, the participant was asked to sleep normally for 30 minutes while *WiKiSpiro* is running. We plot 30 seconds of data as in Figure 4. The mean error is $0.02l$ and maximum error is $0.05l$.

To overcome the challenges associated with identifying this orientation using a radar solution, a reduced vision-based skeletal tracking technique is applied to the limited domain of the sleep environment to establish an approximate estimate of the patient's skeletal posture. This posture is then utilized to define the patient's chest orientation to optimize the direction of the radar on the track rail.

Obtaining an optimal radar position for monitoring a patient's tidal volume is defined by determining the rail position that places the radar beam as orthogonal to the patient's chest as possible. To obtain this estimate, a skeletal posture estimation is formed for the joints related to the chest (head, spine, and shoulders) using the depth image from the Kinect, to generate an estimated chest directional vector.

The resulting chest orientation estimate is then used to re-orient the radar device to the position from which it can obtain the most accurate tidal volume reading. This is achieved in a three step process: (1) Using the depth image stream of the Kinect device, the recorded region of the patient within

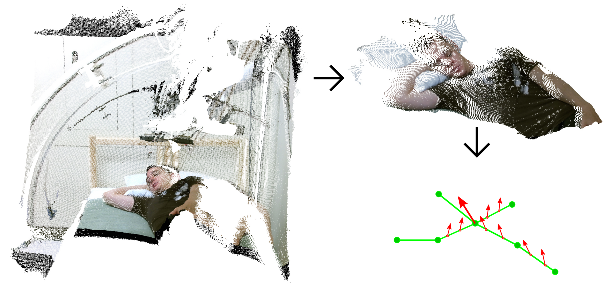

Figure 4: Depth image of the sleep environment used to identify the chest region (left). The resulting segmentation (top right) provides a basis for a reduced skeletal estimate (bottom right).

the bed is segmented by exploiting the limited motion within the sleep environment and using standard point-cloud segmentation techniques such as planar segmentation and region-growing [9]. (2) From the reduced surface data collected in the segmented depth image, a cross-sectional body orientation approach [11] is used to define estimates of the patients head and chest. This information is then used to provide a rough approximation of a reduced skeletal frame. (3) The resulting skeletal estimate is then used to define an estimate of the chest orientation. This radar reorientation is then executed after each movement event detected during the monitoring period. With our technique, the chest orientation is detected every few seconds regardless of the light condition.

4. CONCLUSION AND FUTURE WORK

We have presented the first sketch of an automated, wireless-based, vision-supervised system to monitor breathing volume during sleep. We shown the preliminary results of the system obtained by wireless-based technique. A vision technique has been developed to estimate the human posture during sleep and to identify radar beam orientation. We are implementing the remaining components and aim to conduct in-hospital clinical trials after development is complete.

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