Poster: Continuous and Fine-grained Respiration Volume Monitoring Using Continuous Wave Radar

Phuc Nguyen[1], Xinyu Zhang[2], Ann C. Halbower[3], and Tam Vu[1]
[1]University of Colorado, Denver, [2]University of Wisconsin-Madison,
[3]University of Colorado School of Medicine and Children's Hospital Colorado
{phuc.v.nguyen, tam.vu}@ucdenver.edu,
xyzhang@ece.wisc.edu, ann.halbower@childrenscolorado.org

ABSTRACT

An unobtrusive and continuous estimation of breathing volume could play a vital role in health care, such as for critically ill patients, neonatal ventilation, post-operative monitoring, just to name a few. While radar-based estimation of breathing rate has been discussed in the literature, estimating breathing volume using wireless signal remains relatively intact. With the presence of patient body movement and posture changes, long-term monitoring of breathing volume at fine granularity is even more challenging. In this work, we propose for the first time an autonomous system that monitors a patient's *breathing volume with high resolution*. We discuss the key research components and challenges in realizing the system. We also present an initial system design encompassing a continuous wave radar, 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. Our implementation shows promising results in estimating breathing volume with fine granularity.

Categories and Subject Descriptors

J.3 [**Computer Applications**]: Life and Medical Sciences

General Terms

Design; Human Factors; Algorithms

Keywords

Radar technique; Mobile health; Breathing volume monitoring; Fine-grained estimation.

1. INTRODUCTION

Continuous and fine-grained breathing volume monitoring plays an important role in health care. While abnormality in breathing rate is a good indication of many respiratory diseases such as [5], fine-grain breathing volume information is required in many others. Patients with lower airway diseases such as chronic obstructive pulmonary diseases (COPD), cystic fibrosis, or tuberculosis, for example, could be diagnosed when sudden drops in breathing volume are frequently detected [3]. In many instances, patients with lung disease only show their symptoms during sleep, in which cases long-term monitoring is needed. In another important health care practice, breathing volume of prematurely-born, or preterm, babies is closely and continuously monitored. A decrease of breathing flow and volume must be promptly detected even before it causes oxygen desaturation in order for doctors to give an effective neonatal ventilation intervention. In a recent study on the effects of sleep apnea during pregnancy [1], it has been shown that early detection of the sleep disorder could results in a significantly better pregnancy. However, many patients only start developing apnea for a short period of time. Hence monitoring them non-invasively to get breathing volume and flow limitation is critical. In all above mentioned health care practices, the symptoms can only be detected with an accurate and fine-grained (in time) breathing volume monitoring technique over an extended period of time.

In previous work, breathing rate can be estimated using camera [8], laser [6], or infrared (IR) [4], but these approaches cannot be applied in cases where the subject wears a thick shirt, a jacket or covered by a blanket. To overcome these issues, Doppler-based radar techniques have been investigated to estimate respiration rate while penetrating through clothes or blankets [7, 9, 11, 2]. The concept is to transmit a continuous wave signal (sometimes with modulated frequency), which will bounced back when hits the human chest, and then demodulates it to estimate the chest movements and breathing rate. The respiration rate is usually estimated based on phase shift [7], harmonics distribution [9], distance measured by frequency modulation continuous wave (FMCW) [2, 11]. In contrast, there is not much works done in finding breathing volume. Massagram *et al.* [10] described a calibration technique to estimate the tidal volume relying on peak to peak calibration between reconstructed DC coupled and breathing volume. However, this work has made many impractical assumption about subject's posture and movement between training and testing. For example, it assumes that the human body doesn't move through out the whole estimation process. It also assumes, more importantly, the radar is pointing to the same point on the subject's body through out the monitoring process, from the training phase to the testing phase. Last, but not least important, it can only provide a coarse-grained volume estimation with low accuracy.

Fine-grained and long-term breathing volume estimation is hard due to the following 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. In addition, phase shift is fluctuated as the distance between the radar and subject is changed, or influenced by the imperfection

MobiCom'15, September 07–11, 2015, Paris, France.
ACM 978-1-4503-3619-2/15/09.
DOI: http://dx.doi.org/10.1145/2789168.2795177.

of the hardware circuitry, or the non-linear/abnormal breathing behavior of the subjects.

- A minor non-respiratory movement could cause significant volume estimation error. That movement makes radar beam to new area on human's body, which leads the estimation inaccurate because different areas on the human chest move differently (while they reflect the same breathing volume). Therefore, the radar needs to know exactly which posture the subject is sleeping as well as where the radar is beaming to on subject's body.
- Posture change or body part's 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 found to replace the current area.

2. SOLUTIONS AND SYSTEM DESIGN

Basic principle and system overview. Phase shifting of the received signal is considered as the input of our analysis. The principle relationship between the phase $\phi(t)$ and traveling distance $d(t)$ of a wireless signal is formulated by $\phi(t) = 2\pi d(t)/\lambda$, with λ is the wavelength. Hence, by analyzing the phase change of the received signal, distance change between radar and chest surface can be inferred.

We design a system operating with the concepts as in Figure 1, the phase shift captured on receiving signal is converted into the normalized chest position. The chest position is then used to estimate the breathing volume if there is no random body movement presence. If body movement is detected, the system will predict the new posture as well as new cross section area. The radar is then navigated to the new location and direction, where it can see the chest movements clearly. We estimate the posture and cross section area by comparing the features of upcoming and trained signals on both time and frequency domains. The following discussions in this section describe the solutions more in details.

Estimating volume in fine-grained, not the rate. The amplitude of chest position change reflects the level of breathing volume change. The distance between subject's chest and radar might change every breathing cycle this leads to inaccuracy of estimating the actual chest position. To overcome this issue, we delay one breathing cycle to normalize the receiving signal so that the chest position can be inferred correctly. This method removes the effect from the change of distance between human chest and radar. After normalizing the received signal, we then convert the phase shift $\phi(t)$ into the chest position $x(t)$. Let $v_c(t)$, $v_\phi(t)$ be the velocity of chest movement and phase shift, respectively. Then, $v_c(t) \approx v_\phi(t)$. The $x(t)$ is as an integration of $v_c(t)$ over time. We calibrate the chest position $x(t)$ with the breathing volume estimated by ground-truth devices.

We use Bayesian back-propagation neural network technique to find the correlation between chest position and breathing volume. As such relationship lightly repeats every breathing cycle, a network that could take the history information into account for predicting the upcoming value as a good reference. Bayesian interpretation of regularization has been investigated.

Dealing with non-periodic or irregular body movement during sleep. When the subject changes his posture, the system first has to recognize which posture that the user is sleeping. Three common sleeping postures investigated in our system include: soldier, left foetus, right foetus (when the subject sleeps on his back, his left, and his right, respectively). We compare the features of upcoming signal with that of the trained ones to get the current posture's name (class). K-nearest neighbors algorithm (k-NN) technique has been used to estimate the human posture. Nineteen features of the data are considered: min, max, median, variance, range,

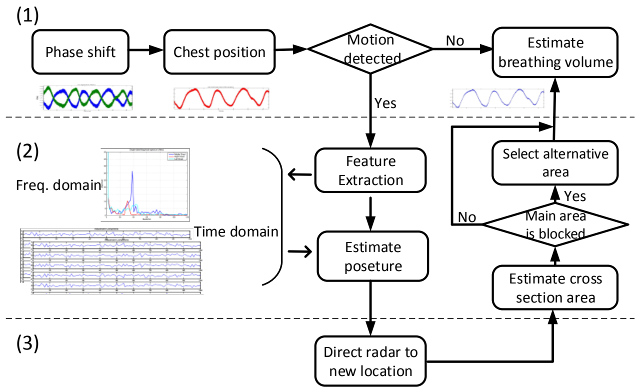

Figure 1: System overview. (1) Breathing estimation without the presence of random body movement. (2) Key components that handle posture change and blocking radar's visibility situations. (3) Motion control system to navigate the radar to the proper location.

signal dispersion, asymmetry, peakness, first, second, and third quartiles, inter quartile range, mean crossing rate, absolute area, signal's energy, entropy, dominant frequency ratio, heart range crossing rate, and respiration range crossing rate. Moreover, we also built a rail as in Figure 2 supporting 360^o pan, tilt, and slide directions to navigate the radar to proper location.

Different areas on the chest wall move differently with the same breathing volume changes. We need to distinguish the movements of different areas on human chest, and know exactly where radar is beaming to in order to estimate the breathing volume correctly. To address this, we narrow down the beam-width of radar transmitter so that the size of each referenced area (left rig-cage, right rig-cage, and abdomen) is close to the size of radar cross section. Extracting the features and compares with that of each referenced area, we can know where the wireless signal is hitting on the human chest. In addition, the radar sometimes cannot see the chest movements during sleep because the radar's vision has blocked by human's parts, such as arms. We apply the results of above observation to find the new area on the chest where radar's visibility isn't blocked. Then, the breathing volume is inferred from the movements on new cross section area. We select the left side as the main area because it contains both breathing and heart beat information. The other two alternative areas, which would be used when the main area is blocked, are the right chest and abdomen areas.

3. EXPERIMENT SET UP AND RESULTS

We evaluate the performance of the system on different parameters and environment set up. The radar uses continuous wave technique and operates at frequency 2.4 GHz AC coupled, with the sampling rate is at 1 kHz. The experiment set up is shown in Figure 2.

Training. As breathing volume depends on human's health, height, weight, chest area and so on, the training step must be performed for each subject before starting the monitoring process. The training output include: (a) correlation function between chest position and breathing volume for three postures when radar is located in front of the chest, (b) features of signal received when user in soldier, left foetus, right foetus postures when radar is located in the middle of the rails, (c) features of the signal received when radar is beam to subject's left rig-cage, right rig-cage, and abdomen. Those results are used to estimate the breathing volume, estimate the current posture and cross section area.

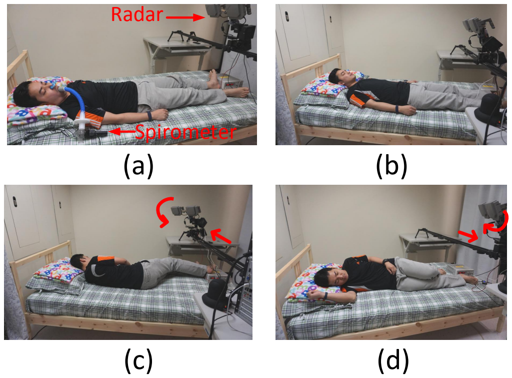

Figure 2: An experiment set up and example execution of our proposed system. The spirometer is used as a ground-truth for training (a). Then, the subject is sleeping on (b) his back, (c) his left and (d) his right side while his breathing activities are monitored by the radar.

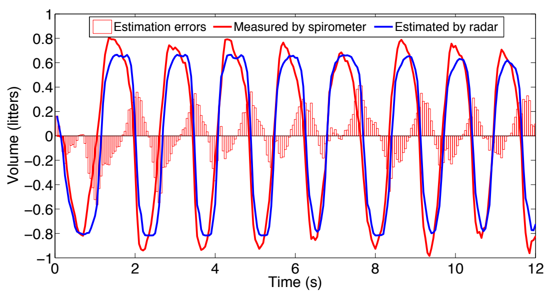

Figure 3: Breathing volume estimated by radar and measured from ground-truth device

Fine-Grained Breathing Monitoring. We use radar to estimate the breathing volume and then compare that with the ground-truth values measured by spirometer. The results area showed in Figure 3. As can been from the figure, the breathing volume and rate are precisely estimated. However, we still need to improve the performance of volume estimation, the errors come from the imperfect relationship between chest movement and breathing volume. This problem would be fixed by improving calibration technique. In addition, Figure 4 shows the results of obtaining respiration volume using our technique, and an approximation based on the breathing rate (assume that breathing volume function has a form $V(t) = Asin\omega t$, $f = \frac{2\pi}{\omega}$ is the breathing rate). Results show that we obtain better results in fine-grained estimation.

Detecting posture. In this experiment, the subject frequently changes his posture and checks the response from the radar. We detect three main postures when the radar is located in front (soldier), on the left side (right foetus) and right side (left foetus) of the human body by comparing the features of receiving signal with the trained ones. We repeat this set up in 50 times for each postures, radar can detect successfully 49/50, 50/50, and 45/50 times when subject sleeps on his back, his right, and his left, respectively. Note that because the system has to collect data as the input for estimation, this process takes at most 20 seconds.

Detecting location of cross section area over human chest. The subject frequently moves his chest in front of the radar so that radar points to three different locations: left rig-cage, right rig-cage, and abdomen randomly. We repeat this set up in 50 times for each location, our radar can detect successfully 41/50, 44/50, and 35/50 times for left rig-cage, right rig-cage, and abdomen cases, respectively. These results can be improved if we continue narrowing the beam-width of the radar transmitter because the movements of areas would be captured separately. This process also takes at most 20 seconds.

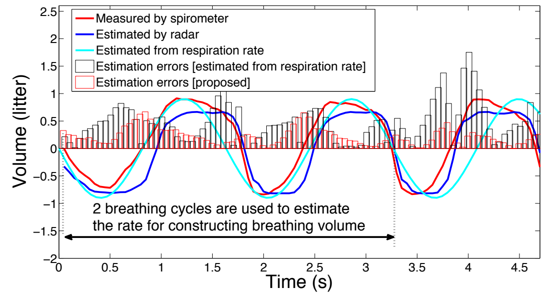

Figure 4: Results of breathing volume estimation using our approach and approximating from breathing rate using sine function. The results are compared with the values measured by ground-truth device (the errors are absolute values).

4. CONCLUSION AND FUTURE WORKS

We have presented an autonomous radar system to monitor breathing volume during sleep. The system is now capable to estimate the breathing volume accurately based on the reflected signal while dealing with random body movements. For the next step of our research, we attempt to optimize the system so that it can be used in practical sleep study. We also want to improve the system's performance in terms of time and accuracy for posture/area detection and breathing volume estimation.

5. REFERENCES

[1] Pregnancy and sleep. http://sleepfoundation.org/sleep-topics/pregnancy-and-sleep.
[2] F. Adib et al. Smart homes that monitor breathing and heart rate. *ACM CHI*, 2015.
[3] R. Balkissoon et al. Chronic obstructive pulmonary disease: a concise review. *The Medical Clinics of North America*, 2011.
[4] L. Boccanfuso and J. O'Kane. Remote measurement of breathing rate in real time using a high precision, single-point infrared temperature sensor. *IEEE BioRob*, 2012.
[5] S. R. Braun. Respiratory rate and pattern. *Clinical Methods: The History, Physical, and Laboratory Examinations*, 1990.
[6] A. Bulanova et al. The analysis of breath air by laser spectroscopy method for diagnosis of COPD. *European Respiratory Journal*, 2014.
[7] A. Droitcour et al. Range correlation and I/Q performance benefits in single-chip silicon doppler radars for noncontact cardiopulmonary monitoring. *IEEE Trans. on Micro. Theory Techn.*, 2004.
[8] Lewis et al. A novel method for extracting respiration rate and relative tidal volume from infrared thermography. *Psychophy.*, 2011.
[9] L. Lu et al. Doppler radar noncontact vital sign monitoring. *Neural Comp., Neural Devices, and Neural Prosthesis*, 2014.
[10] W. Massagram et al. Tidal volume measurement through non-contact doppler radar with dc reconstruction. *IEEE Sensors Journal*, 2013.
[11] R. Nandakumar et al. Contactless sleep apnea detection on smartphones. *ACM Mobisys*, 2015.