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Continuous body movement-robust respiration rate detection based on FMCW mm-wave radar using non-negative matrix factorization algorithm: short communication

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ABSTRACT

This study presents a novel approach to monitoring respiration rate using frequency modulated continuous wave (FMCW) mm-wave radar, aiming to overcome the limitations of traditional non-contact method. 14 participants were involved in an experiment involving alternating periods of stillness and left-right continuous body shaking. Data analysis involved non-negative matrix factorization (NMF) and template matching techniques. Respiration measured by radar were compared with ground truth measurements. Results demonstrated accurate respiration detection even during continuous body movement, with significant correlation observed between radar-based and ground truth measurements. This study pioneers radar-based respiration monitoring under continuous body movement conditions, offering promising implications for practical applications.

1. Motivation

Respiration rate is an important vital signal, which reflects the respiratory system [1]. Traditional respiration rate monitoring mainly use temperature based, motion based, piezoelectric sensor [2]. While these contact sensors can obtain precise measurements, they may cause discomfort and skin irritation, limiting their utility to patients with severe burns, infections disease, and mental illnesses. To overcome the drawbacks of contact sensors, non-contact vital signal monitoring such as frequency modulated continuous wave (FMCW) mm-wave radar have garnered increasing interest in recent year [3, 4].

Generally in FMCW mm-wave radar, respiration was detected by the phase measurement at the range bin of the target chest. But in practical application, the range bin detection of the chest is susceptible to disruption from various clutter and interference, such as body movement. Small and random body movement can be solved using (1) physical method: using multiple radar to retrieve signals through the correlation between sensors [5], (2) data-driven method: using CWT to identify the locations of artifacts and then applied a moving average filter to smooth these identified artifacts [6].

However, how to detect vital signals during continuous body movement remains a challenging topic. Considering that even during the continuous body movement, vital signal, i.e. the chest movement can be still detected by the radar system, but only in a different phase, and is hidden under noise caused by continuous body movement. We hypothesized there exist one particular pattern of displacements measured using radar that can finely represent the respiration even there was a body shake. The purpose of this study is to propose a novel approach to detect respiration rate under continuous body movement using FMCW mm-wave radar.

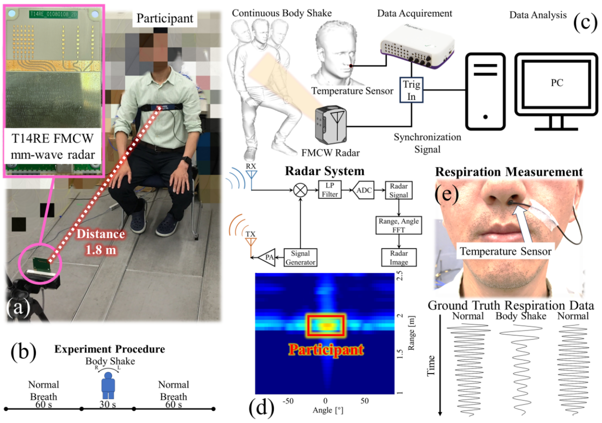

Figure 1: Overview of the experiment. (a) experiment environment. (b) procedure. (c) experiment system. (d) radar system block diagram and radar image. (e) temperature sensor for measuring ground truth respiration data.

2. Subjects and Experiment

14 health participants volunteered in the experiment (age: 24.3 ± 4.0 y.o., height: 173.1 ± 4.0 cm, weight: 65.1 ± 10.5 kg). The study purpose, experiment process were explained to all participants orally, and written context were obtained. This study was approved by the Ethic Committee of Department of Engineering, Kyoto University (No. 202223).

To validate the proposed method, we conducted an experiment involving continuous body shaking. Fig. 1 (a)

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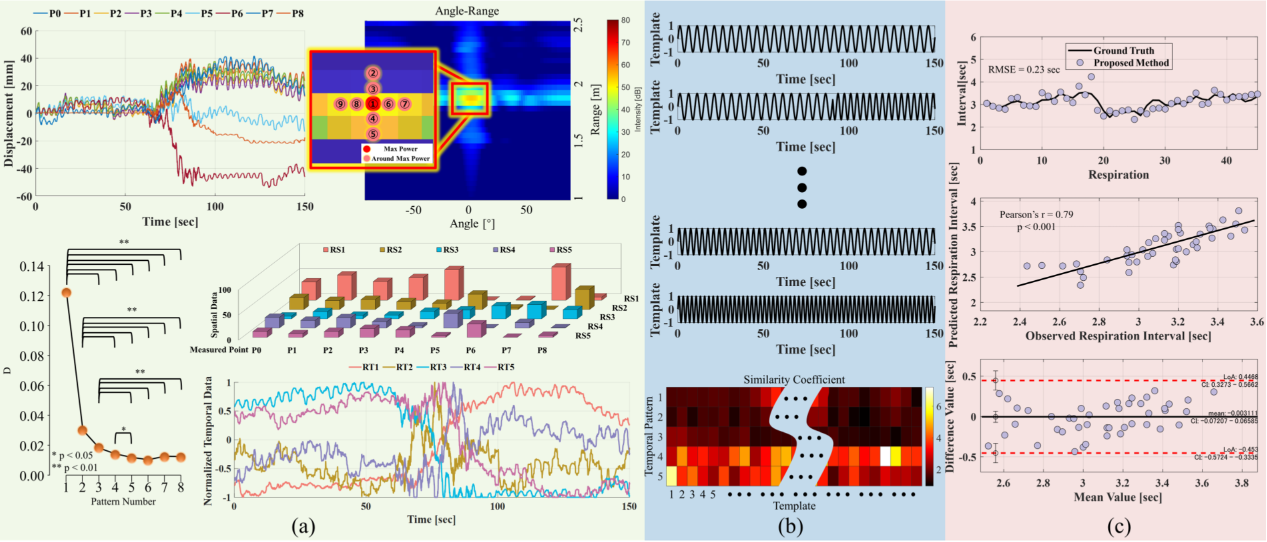


Figure 2: Example of data analysis. (a) radar data analysis and reconstruction. Friedman test was performed, * p < 0.05, ** p < 0.01. (b) example of template matching. (c) cross-check using ground truth respiration data.

provides an overview of the experiment. All participants were seated 1.8 meters away from an FMCW mm-wave radar (T14RE S-Takaya Electronics Industry, Okayama, Japan) [7]. Initially, participants were instructed to remain still for the first minute. Subsequently, they were asked to shake their bodies left-right for 30 seconds at a self-selected frequency, followed by another minute of remaining still, as depicted in Fig. 1 (b). A digital thermometer (AP-C052 Polymate MP6000) was attached under their noses to record respiration, serving as ground truth. The radar and thermometer signals were synchronized using a trig in signal (see Fig. 1 (c)). The structure of the radar system is illustrated in Fig. 1 (d). The radar image $I_p(t, r, \theta)$ was calculated following the previous study [8], t, r, θ represent time, range, and angle, respectively. An example of respiration during the experiment is shown in Fig. 1 (e).

3. Data Analysis

3.1. Radar Data Analysis

Fig. 2 (a) top right displays a time-averaged radar image, $\overline{I}(r)$, after the suppression of static clutter. The point of maximum power, which corresponds to the estimated location $r_1 = \arg\max_r \overline{I}(r)$, is marked by a red ① at a range of 1.8 meters and an angle of 0 degrees. We selected eight neighboring points around this maximum power point.

3.2. NMF and Template Matching

We utilized non-negative matrix factorization (NMF) to reconstruct the radar displacement data for the nine measured points. The NMF can be calculated as follows:

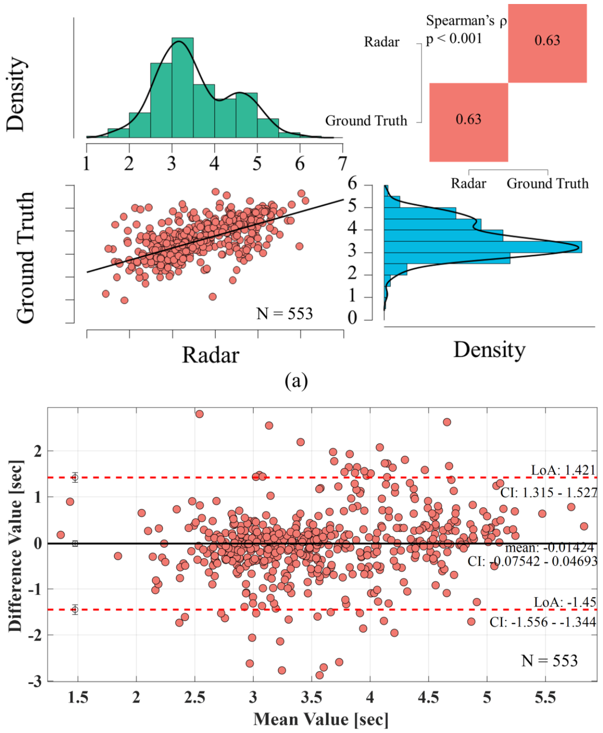
$$RD = \begin{pmatrix} RS_1 & \cdots & RS_i \end{pmatrix} \begin{pmatrix} RT_1(t) \\ \vdots \\ RT_i(t) \end{pmatrix}, \tag{1}$$

where RD represents the radar data, RS denotes the reconstructed spatial pattern, and RT indicates the reconstructed temporal pattern. The variable i represents the number of measured points. The fundamental concept of NMF is to establish an optimization process to determine matrices RS and RT by minimizing the reconstruction error D [9]: $argmin\ D = argmin\ ||RD - RS \cdot RT||$. We reconstruct the nine points data using NMF for 20 times for each pattern, and calculate each D index, then using repeated ANOVA to find the significant difference, we define the pattern where there was significant difference among the lowest D. In Fig. 2 (a) bottom left, there were five patterns in the radar data. Then the original radar data were reconstructed to five RS and RT (Fig. 2 (a) bottom right). As we only need temporal information to detect respiration number and interval, RT data were later used for template matching.

Considering that normal respiration frequency ranges between 0.2 and 0.4 Hz, and given that respiration did not change dramatically during the experiment, we prepared 21 sine curve signals as template data. These templates had frequencies ranging from 0.2 to 0.4 Hz, with an interval of 0.01 Hz between each period.

$$Template = \sum_{k=1}^{P} \sum_{i=1}^{N} sin(2\pi \cdot TF_i \cdot Period_k), \tag{2}$$

where $P = 3$ is the number of experiment periods, $N = 21$ is the number of template frequency $TF_i = 0.2 + 0.01(i - 1), i \in \{1 : 21\}$. Fig. 2 (b) top depicts examples of template data. Then, we calculate the similarity correlation between five reconstructed patterns and 9261 (21^3=9261) template signals by calculating the euclidean distance, and then used the template data that had the lowest correlation index $Temp_L = argmin \sqrt{(RT - Template)^2}$ as the predicted respiration data, see Fig. 2 (b) bottom.



(a)

(b)

Figure 3: Results of cross-check using ground truth respiration data. (a) result of Spearman's correlation, green data represent predicted (radar) data, and blue data represent ground truth data. (b) result of Bland Altman analysis. N = 553.

3.3. Cross-check using Ground Truth Data

We validated the respiration measurements obtained using our proposed method against the ground truth respiration using three metrics: (1) Root Mean Square error (RMSE), (2) Correlation analysis, (3) Bland-Altman analysis. Fig. 2 (c) depicts an example of the respiration validation process. The RMSE of the respiration intervals between the ground truth and our proposed method was 0.23 seconds. We observed a significant correlation between the two sets of measurements, and the Bland-Altman plot demonstrated high accuracy of the proposed method.

4. Results and Discussion

A total of 553 respiration were detected across 14 participants. The RMSE for the detection was 0.73 seconds. Fig. 3 (a) illustrates the correlation results between radar-based measurements and the ground truth. Spearman's correlation analysis revealed a significant relationship between the radar-based and ground truth respiration data, with a correlation coefficient (ρ) of 0.63, $p < 0.001$. Fig. 3 (b) shows the mean difference in respiration intervals between radar and ground truth measurements, which is -0.01 seconds, with limits of agreement within $< \pm 1.5$ seconds. These results indicate that the proposed method is highly feasible for detecting respiration even during the continuous body movement.

To the best of our knowledge, this is the first study to utilize a single FMCW millimeter-wave radar to detect respiration under continuous body movement. By reconstructing multi-point radar signals and employing template matching techniques, we were able to predict respiration rates with acceptable accuracy. However, there are limitations to this study. We only considered continuous body movements in the left-right direction. Future research should investigate the effects of front-back body movements on respiration detection. Additionally, the current data analysis was performed offline. Developing a real-time, continuous body movement-robust radar analysis algorithm is a necessary next step for future studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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