Non-contact Multi-Radar Smart Probing of Body Orientation based on Micro-Doppler Signatures

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***Abstract*—Micro-Doppler signatures carry useful information about body movements and have been widely applied to different applications such as human activity recognition and gait analysis. In this paper, micro-Doppler signatures are used to identify body orientation. Four AC-coupled continuous-wave (CW) smart radar sensors were used to form a multiple-radar network to carry out the experiments in this paper. 162 tests were performed in total. The experiment results showed a 100% accuracy in recognizing eight body orientations, i.e., facing north, northeast, east, southeast, south, southwest, west, and northwest.**

I. INTRODUCTION

Tracking and recognizing human activities have seen increased demand in modern smart homes to provide real-time services for attentive home care. Doppler radar sensor is an ideal device to carry out such tasks due to its noncontact and low-cost features [1]. Among the parameters that Doppler radar sensor can detect, micro-Doppler signature is a very useful feature for various applications because it carriers plenty of user-specific information [1]-[3].

Till now, a majority of existing studies have focused on gesture recognition or human tracking [1][3]. For human tracking, previous works treat human subject as a point target and find where the target is located. Not many studies have been performed to identify the direction of the human target's motion or the direction that the target is facing. Human target's motion direction is very important and useful in home care applications such as fall detection and other behavior prediction. Furthermore, identifying the direction that a human target is facing could be very helpful in smart home, gaming and other assistive services.

This paper focuses on identifying the direction that a human target is facing and the direction of the target's movement, based on micro-Doppler signatures that can be obtained from smart continuous-wave (CW) radar sensors. In order to recognize the direction, a multiple radar sensor network was formed by four 2.4-GHz AC-coupled CW Doppler radar sensors named as '*iMotion radar*'. A classification method based on micro-Doppler spectrograms was developed to identify the body orientations. In this study, eight directions, i.e, north, northeast, east, southeast, south, southwest, west, and northwest, were defined and recognized. To evaluate the performance of the radar system and the classification method, 162 tests were carried out. The experiments were performed by a human subject standing at the center of the multiple-radar system and repeating a specific movement with different body orientations. Experiment results showed an accuracy of 100% in recognizing the body orientation.

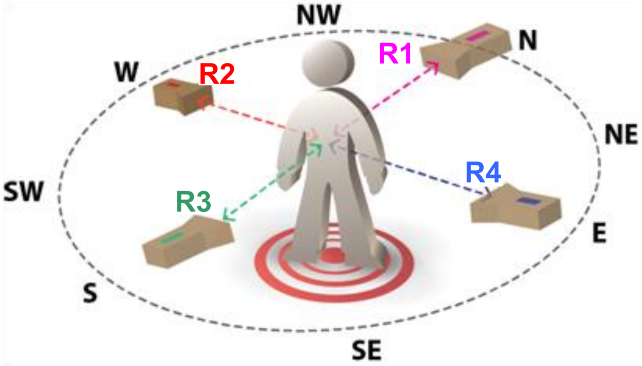

Fig. 1. Multiple-radar system for body orientation probing without any tag attached to the human target.

This paper is organized as follows. The multiple-radar system will be introduced in section II. Section III will explain in detail how to use micro-Doppler spectrogram for body orientation classification. Experiment results will be presented in section IV. Finally, section V will conclude this work and some discussions will be given.

II. MULTIPLE-RADAR SYSTEM

A multiple-radar system, which contains four identical 2.4-GHz '*iMotion radar*' sensors developed by the authors' research group, was implemented in this work. Fig. 1 shows the setup of this multiple-radar system. In this setup, four AC-coupled CW radar sensors (Radar I, Radar II, Radar III and Radar IV) were placed at four sides of a room and formed a 1.5m × 1.5m area. The height of this multiple-radar system is 1m above the ground. The horizontal plane was divided into eight directions. Each direction is 45-degree separated with its neighbors. The eight directions were defined as N, W, S, E, NW, SW, SE and NE, as labeled in the Fig. 1.

Fig. 2(a) is a simplified block diagram of the *iMotion radar* sensor, which has a 2.4-GHz AC-coupled direct-conversion architecture [2]. Fig. 2(b) shows a fabricated radar sensor with antennas. The size of the radar sensor board is 5cm × 5cm. Both the transmitter and receiver chains are designed and fabricated on the same board. As shown in the block diagram, the voltage controlled oscillator (VCO) generates a 2.4 GHz carrier signal and the signal is transmitted through the antenna on the Tx end. The local oscillator (LO) for the mixer in the receiver chain is also provided by the VCO

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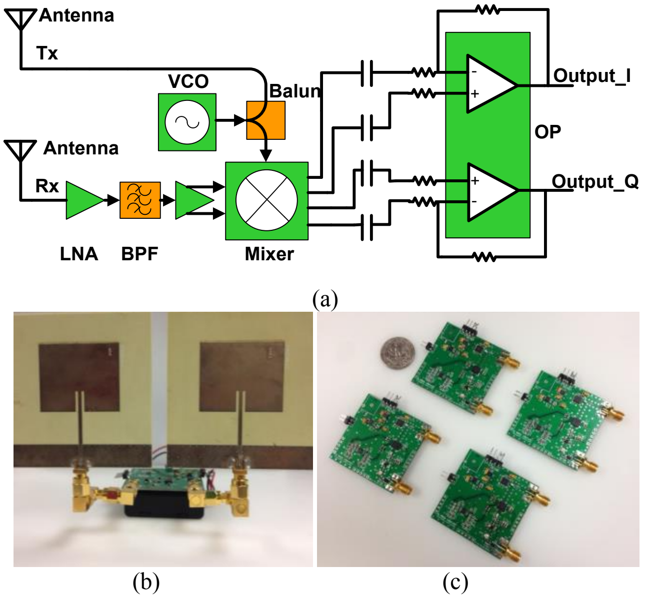


(a)

(b) (c)

Fig. 2. (a) Simplified block diagram of one 2.4GHz AC-coupled CW Doppler radar sensor (b) Fabricated *iMotion radar* sensor with antennas. (c) *iMotion radar* array standing with a quarter

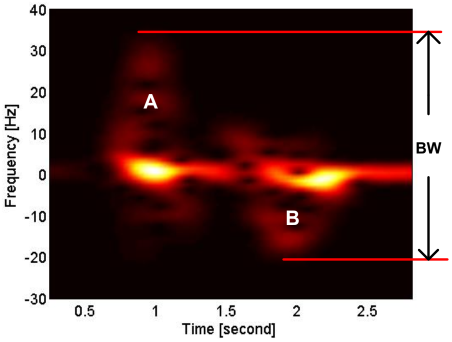


Fig. 3. A micro-Doppler spectrogram obtained by radar sensor when the human subject lifted the left arm toward the radar and moved the arm back.

through a balun. The measured power of the transmitter is about -3dBm, which is safe for human-related applications. The receiver chain includes an LNA, a band pass filter (BPF), a mixer and a baseband operational amplifier (OP). The output *I*/*Q* signals are digitized and transmitted to a laptop by a data acquisition module NI-USB6009 via an USB port. The sampling frequency used in this work is 500 Hz. Two 2.4 GHz patch antennas shown in Fig 2 (b) were adopted in this work. Fig 2 (c) shows the *iMotion radar* array standing together with a US quarter. The four radar sensors in this figure are used to form the multiple-radar system.

III. BODY ORIENTATION CLASSIFICATION

The micro-Doppler signatures detected by the four radars were used for body orientation recognition. The micro-Doppler signature was generated by applying Short-Time Fourier Transform (STFT) to the *I*/*Q* radar baseband output signals. An example of a micro-Doppler spectrogram is shown in Fig. 3. This spectrogram was observed when the human subject lifted the left arm towards the radar and took the arm back. The positive frequency shift, marked as A on the spectrogram, was caused by lifting the arm towards the radar while the negative frequency shift, marked as B on the spectrogram, was created by taking the arm back which means that the arm was moving away from the radar.

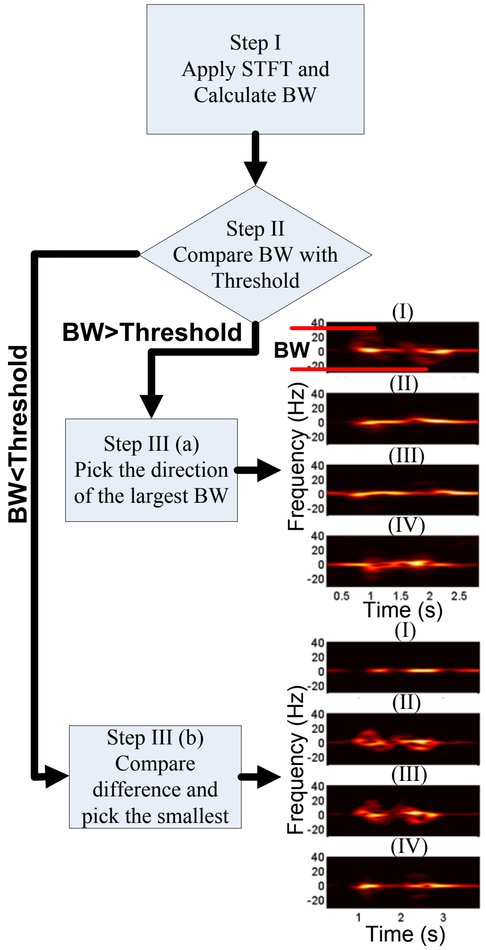
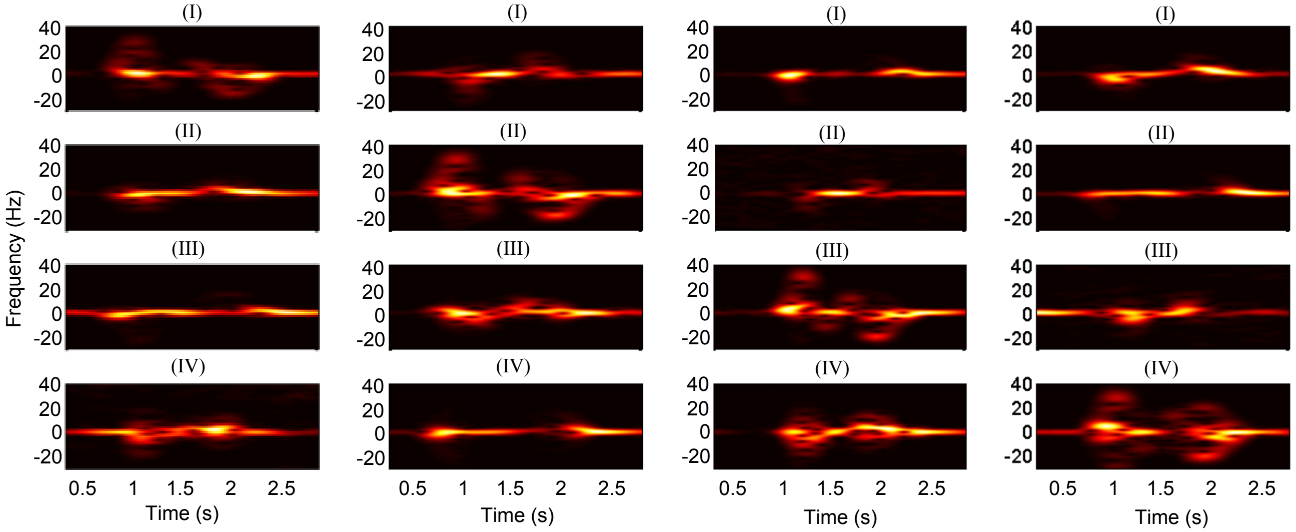


Fig. 4. Flow chart of the body orientation detection method

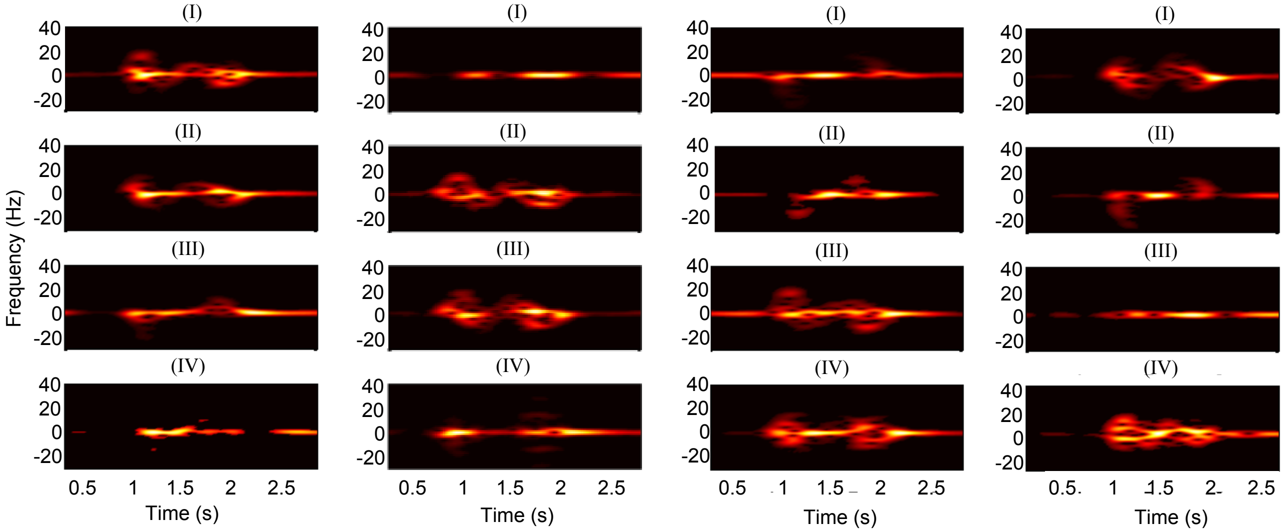
The spectrogram contains very useful information related to the movement. In this work, the bandwidth of the spectrogram is selected as one feature, which can be used to determine the body orientation. The bandwidth of the spectrogram is defined as the difference between the largest positive frequency shift and the largest negative frequency shift on the spectrogram. For example, Fig. 3 shows the bandwidth (labeled as BW) of the micro-Doppler signal when the human subject lifted her left arm towards one radar sensor and took the arm back. In this way, for each test, four radars in the multiple-radar system will capture four different micro-Doppler signatures. The difference between the four spectrograms will be calculated and used as another important feature to determine the body orientation.

The flow chart of this computation method is shown in Fig. 4. The first step is to apply STFT to the output *I*/*Q* signals of each radar sensor and generate corresponding spectrogram. In this work, a sliding window size of 1.024 second was adopted and Hamming window was used. Then the bandwidth of each spectrogram was calculated. It should be noted that no filter was used in this work and thus, all the physiological motion information will be preserved without any signal distortion.



(a) (b) (c) (d)

Fig. 5. Spectrograms captured by the four radars (I~IV) when the human subject performed the same movement facing the four type I directions: (a) N, (b) W, (c) S and (d) E.



(a) (b) (c) (d)

Fig. 6. Spectrograms captured by the four radars (I~IV) when the human subject performed the same movement facing the four type II directions: (a) NW, (b) SW, (c) SE and (d) NE.

There are eight directions defined in this work and they can be divided into two types. Type I includes the directions when the movement is vertical to one of the radars, i.e., N, W, S, and E. The other four directions – NW, NE, SW and SE, formed the Type II direction.

From the spectrograms obtained in each test, when the subject performed a movement in a Type I direction, the spectrogram of the radar in this direction has a large bandwidth that is significantly larger than the bandwidths of the other three spectrograms. When the object performed a movement towards a Type II direction, the two adjacent radars that are closest to the movement direction will generate two very similar spectrograms.

This phenomenon can be explained by the relationship between the Doppler frequency shift and the frequency of the transmitted carrier signal. Equation (1) shows this relationship as:

$$f_{\text{Doppler}} = 2 \times v_{\text{object}} \times \cos\theta \times \frac{f_{\text{Transimitted}}}{\text{c}} \tag{1}$$

where f_{Doppler} is the Doppler frequency shift, v_{object} represents the velocity of the object (i.e., the speed of the arm movement in this work), θ is the angle between the movement and carrier signal transmitted from each radar, $f_{\text{Transmitted}}$ is the carrier signal frequency (2.4 GHz in this paper) and c is the speed of light. The equation showed that in the multiple-radar system proposed in this work, the largest Doppler frequency shift happens when the movement is vertical to the radars. For a movement in a type II direction, the angles between the movement and the two adjacent radars are the same as 45 degree. Thus, the Doppler shifts of the two radars are the same and the generated spectrograms will be similar.

It should be noted that, if the movement is towards a Type I direction, theoretically, Radar I and Radar III produce the spectrograms with the same bandwidth. Radar II and Radar IV

Table I. Summary of the number of tests and results in each direction.

Direction	N		W		S		E	
# of tests	23		12		22		18	
	P*	F*	P	F	P	F	P	F
Result	23	0	12	0	22	0	18	0
Direction	NW		SW		SE		NE	
# of tests	25		14		19		29	
	P	F	P	F	P	F	P	F
Result	25	0	14	0	19	0	29	0

* P represents pass and F represents fail

produce the spectrograms with the same bandwidth. For the movement towards a type II direction, two of the radars' output signals can generate similar spectrograms and the other two radars can also produce similar spectrograms. But in practice, the human body will block some signal to the radar which the movement is getting far away from. Thus, the difference between the spectrograms can be easily differentiated and the features discussed above can be used to determine the direction.

The next step is to set a bandwidth threshold to determine the direction type. In this study, the threshold is empirically set to 50 Hz in order to obtain useful information as mush as possible. If one bandwidth is larger than the threshold, the movement can be decided as in a Type I direction. As shown in Fig. 4, the example for Step III (a) lists different spectrograms for Radars I, II, III and IV respectively. It could be clearly seen that the bandwidth for Radar I is higher than 50 Hz and is significantly larger than the other bandwidths. Therefore, the body orientation for this test is recognized as N.

If the bandwidths of the four spectrograms for one test are all smaller than the threshold, this direction is determined as a Type II direction. To find out which direction it is, the difference between each spectrogram will be calculated to find the smallest difference. As shown in the example for Step III (b) in Fig. 4, after calculation, the spectrograms of Radars II and III have the smallest difference. This result means the subject performed a movement toward the direction between Radars II and III. According to Fig. 1, this direction is defined as SW. Thus, the body orientation for this case is recognized as SW.

IV. EXPERIMENT RESULTS

In order to evaluate the multiple-radar system and the classification method, 162 tests were carried out. To complete the experiment, a human subject stood at the center of this multiple-radar system and performed a specified movement several times in each direction. In this paper, a movement of lifting the left arm and moving the arm back was performed.

Figure 5 shows the spectrograms captured by four radars while performing the four type I direction movements. As shown in Fig. 5(a), Radar I has the largest bandwidth and thus the body orientation is determined as N in this case. Radar II has the largest bandwidth in Fig. 5(b) and thus the direction is W. The directions were recognized as S and E for Figs. 5 (c) and (d), because Radars III and IV captured the largest bandwidth for these two tests respectively.

Figure 6 shows the spectrograms captured by four radars when performing the movement towards four type II directions. As shown in Fig. 6(a), after the calculation, the spectrograms of Radars I and II have the smallest difference. Based on this difference, the body orientation was recognized as the corner between Radars I and II, which is defined as NW in Fig.1. For Fig. 6(b), Radars II and III have very similar spectrogram and have the smallest difference. Thus, the body orientation was classified as SW in this case. Figs. 6(c) and (d) show the spectrograms while performing the same movement toward SE and NE. The classification results showed the two movements were toward SE and NE respectively, which means the body orientations for these two tests are successfully recognized.

Table I summarizes the number of tests repeated and the corresponding body orientation recognition results. 162 tests were performed and all the radar outputs had been automatically processed by the classification method implemented in a MATLAB script. The result shows a 100% accuracy, which means the classification method successfully recognized all the directions.

V. CONCLUSION AND DISCUSSION

This paper presents a body orientation probing method based on micro-Doppler signatures acquired by a multiple-radar system. Four AC-coupled CW Doppler radar sensors were used to design this system. 162 tests were carried out and the output signals were analyzed by an automated MATLAB script. Eight directions were defined and used in the experiments. The experiment results shows 100% accuracy in direction recognition, which suggests that the presented approach is an effective way to wirelessly probe body orientation for modern home care applications. It should be noted that no tag is required on the human target. In the future, different human target locations and better angular resolution will be pursued in determining the body orientation, and more body languages will be studied.

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