An FMCW radar sensor for human gesture recognition in the presence of multiple targets

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Abstract:
Hand gesture recognition is an emerging application of portable radar sensors. Most of existing works rely on Doppler-radar sensors for non-contact detection of hand motions. However, Doppler-radar-based hand gesture recognition utilizes only the Doppler effect to extract motion features, which imposes a stringent requirement that only one motion is in the field of view of the sensor, leading to limitations in practical applications. In this paper, we investigate the feasibility of using an FMCW radar sensor with range-Doppler processing to recognize human gestures when multiple moving subjects are present in the sensor's field of view. A custom-designed portable 5.8-GHz FMCW radar is used. By using range-Doppler processing in the range-Doppler domain, experimental results enable to verify the effectiveness of the proposed radar sensor in hand gesture identification with the existence of interferences from surrounding moving targets.

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Contents

SECTION I. Introduction

Based on optical cameras and image-processing algorithms, human gesture recognition for advanced human-machine interface has been extensively studied in the area of computer science [1]. However, the high demand of computational resources and the sensitivity to ambient light hinder a wide use of camera-based human gesture recognition solutions in daily life. On the other hand, Doppler-radar sensors show promising performance in non-contact applications such as human vital signs detection, structural health monitoring, or through-the-wall life detection [2]. Doppler-radar-based human gesture recognition is recently attracting significant interests in the microwave community and consumer electronics industry. Examples include experimental demonstration at 60 GHz by Google [3] and the study of motion trajectory reconstruction with Doppler-radar sensors [4]. Doppler-radar-based techniques utilize time-frequency analysis on the Doppler shift introduced by the movement of the hand. The advantage is that the idea can be implemented in low-cost devices with a simple front-end architecture. In addition, since the Doppler shift caused by hand movement is usually small, the required sampling rate of the analog-to-digital converter (ADC) is low, and low-power low-cost embedded digital signal processing is possible.

However, a Doppler-radar sensor only detects the Doppler shifts due to a single moving target, i.e., the motions of the hand in human gesture recognition. In more-common situations in which other moving targets exist, Doppler frequencies of other targets will overlap with the signatures of the hand gesture, thus making conventional methods to identify the gesture to fail.

In this work, a custom-designed FMCW radar sensor is used to investigate the feasibility to recognize human gestures in the presence of multiple moving targets. Compared with conventional Doppler-radar-based human gesture recognition, this work utilizes micro-Doppler and micro-range to recognize human hand gestures. Since the FMCW radar sensor provides both Doppler and range information of targets, it is possible for range-Doppler processing to separate targets located at different ranges, and to recognize gestures with the micro-Doppler and micro-range features. Experiments are carried out to demonstrate and analyze the range-Doppler signatures of human gestures in the presence of other moving targets. Frames of range-Doppler images corresponding to different states of a gesture are illustrated. In addition, the hand gesture of interest is separated from other unwanted motions. The obtained results confirm the advantage of an FMCW radar in human gesture recognition when multiple human subjects exist in the field of view of the sensor.

SECTION II.
Theory of Range-Doppler-Based Gesture Recognition

A coherent FMCW radar can continuously track the range history and extract the Doppler information of a moving target. With range-Doppler processing, both range and Doppler information can be distinguished in the range-Doppler map, thus permitting to reveal the features of the analyzed motion [5]. In this section, the theory of range-Doppler-based human gesture recognition with a custom-designed FMCW radar prototype are presented. In particular, two different cases of human hand gestures are studied in detail.

Figure 1 illustrates the gesture of lifting the forearm upwards in front of the radar sensor. The gesture is divided into four phases, i.e., P1, P2, P3, and P4, depending on the change of velocity and range. As shown in Fig. 1, at P1, the forearm starts to move with an increasing velocity toward the FMCW radar sensor, which appears as a low Doppler frequency in the range-Doppler image. At P2, the velocity of the arm toward the radar keeps on increasing with a small change in range. During this phase, a signature with higher Doppler frequency and a small range change can be observed in the range-Doppler evolution representation. When the forearm keeps on moving and gets away from the radar as indicated by P3 in Fig. 1, the radial velocity becomes negative, and the signature appears below the zero-Doppler line in the range-Doppler evolution figure. Finally, at P4, the forearm stops and the signature in the range-Doppler map returns to zero-Doppler. Based on the movement of the radar signature in the range-Doppler image, the gesture of lifting a forearm can be identified. The spectrogram in Fig. 1 shows the corresponding time-frequency analysis of the gesture with a Doppler radar.

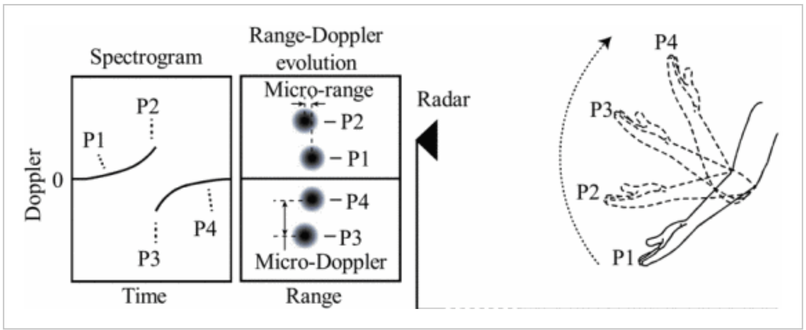
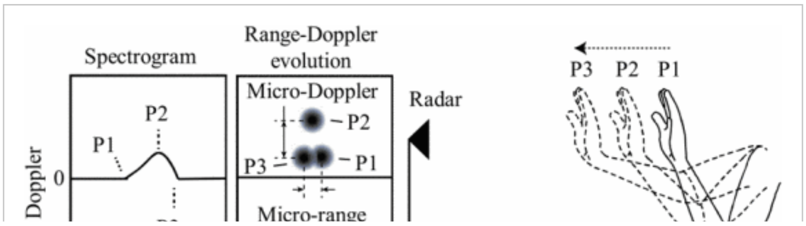


Fig. 1.
Illustration of the gesture of lifting the forearm upwards, and corresponding spectrogram and range-doppler image evolutions.



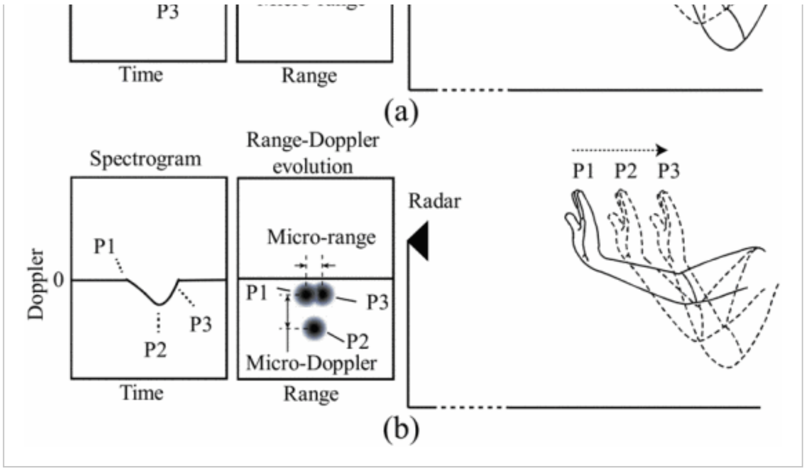


Fig. 2.
Illustration of the gestures of push and pull, and corresponding spectrogram and range-doppler image evolutions. (a) Push. (b) Pull.

Signatures corresponding to other gestures, e.g., pushing and pulling a hand, are illustrated in Fig. 2. Pushing a hand is described in Fig. 2(a) and divided into three phases, P1, P2, and P3, respectively. P1 is the accelerating phase with a relative low velocity, corresponding to a small Doppler frequency above the zero-Doppler line. The velocity of the hand reaches the maximum at P2, resulting in the maximum Doppler frequency for the range-Doppler evolution. After P2, as the hand movement slows down, the signature in the range-Doppler evolution figure returns to zero-Doppler. The micro-range effect can also be observed from P1 to P3 as the hand approaches the radar sensor. On the other hand, retracting the hand creates a range-Doppler signature in the opposite direction, which can also be divided into three phases, as can be seen in Fig. 2(b). As the hand moves away from the radar sensor, the signature appears below the zero-Doppler line. The spectrograms in Fig. 2 are the results corresponding to a Doppler radar after conventional time-frequency analysis.

Figure 3 demonstrates a more complex case when two moving targets are in front of the radar sensor. One human subject is making gestures and the other person is approaching the radar. For a Doppler radar, as shown in the spectrogram of Fig. 3, there is an overlap region where the Doppler frequencies of two moving targets add together, making it very difficult to separate them. However, for an FMCW radar, as shown in the range-Doppler evolution figure, it is possible to easily separate the two moving targets based on their ranges, and to recognize the gestures based on their micro-Doppler and micro-range signatures.

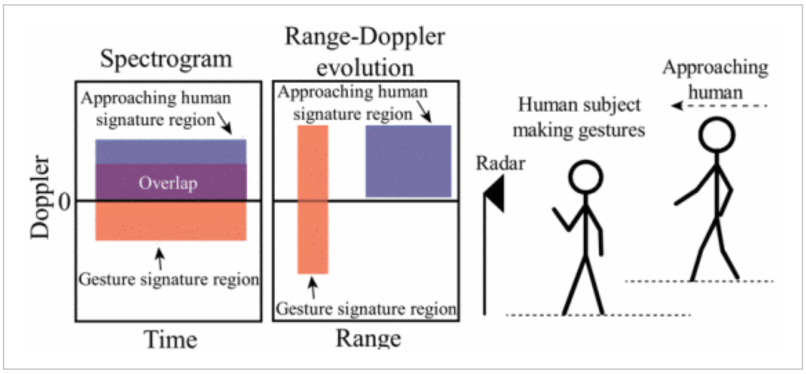


Fig. 3.
Illustration of a human making gestures while another human subject is approaching the radar, and corresponding spectrogram and range-doppler image regions.

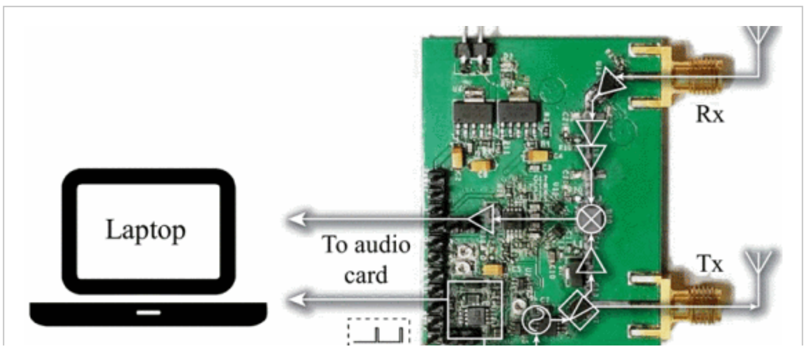


Fig. 4.
Photograph and block diagram of the FMCW radar sensor prototype.

Table I Parameters of the radar prototype

Center frequency f_c	5.8 GHz	Sampling frequency f_s	192 kHz
Transmitted bandwidth B	320 MHz	Frequency ramp period T	3.5 ms
Average transmitted power		8 dBm	

SECTION III.
Radar Prototype and Experiments

A custom-designed 5.8-GHz FMCW radar was used in the experiments. Fig. 4 shows the photograph and block diagram of the radar prototype. An operational-amplifier-based circuit is used to generate a "sawtooth" voltage to control a free-running voltage-controlled oscillator (VCO) to produce the modulated RF signal. The sensor utilizes a pair of 2×2 patch arrays (not shown in the figure). The baseband signal is sampled by an audio card of a laptop and subsequently processed. Each beat signal interval is aligned by means of a reference signal from the sawtooth generation circuit, thus achieving coherence. The basic parameters of the radar prototype are listed in Table I.

Experiments were carried out using the described FMCW radar sensor for human gesture recognition based on range-Doppler processing. Fig. 5 first shows the spectrogram of three basic gestures corresponding to conventional time-frequency micro-Doppler analysis. The changes of Doppler frequency versus time can be clearly seen in Fig. 5(a) and Fig 5(b). Fig. 6 and Fig. 7 show the results of the same human gestures detected by the range-Doppler processor enabled by the FMCW radar. Fig. 6 contains four frames for the gesture of lifting the forearm, corresponding to the four points in Fig. 5(a). The frames are in good agreement with the theoretical phases illustrated in Fig. 1. Fig. 7 shows the results of hand push and pull. In particular, Fig. 7(a)-(c) correspond to the theoretical evolution in Fig. 2(a), whereas Fig. 7(d)-(f) are associated with the theoretical history in Fig. 2(b).

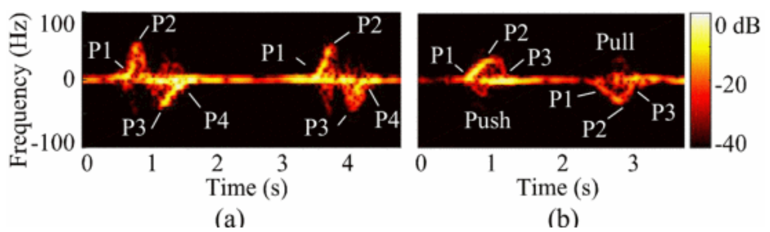


Fig. 5.
Spectrogram of human gestures corresponding to conventional time-frequency micro-doppler analysis. (a) Lift forearm. (b) Push and pull.

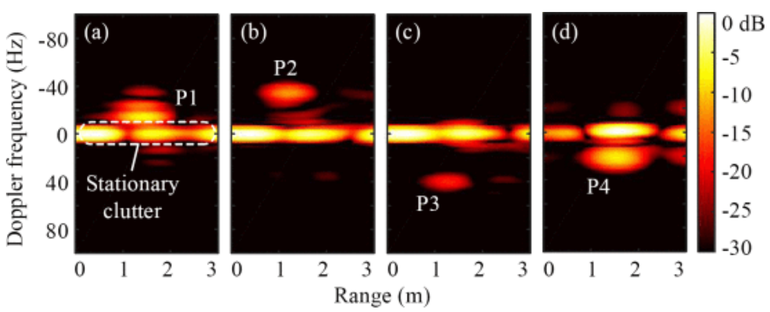


Fig. 6.
Range-doppler frames obtained when lifting the forearm. (a) Phase 1. (b) Phase 2. (c) Phase 3. (d) Phase 4.

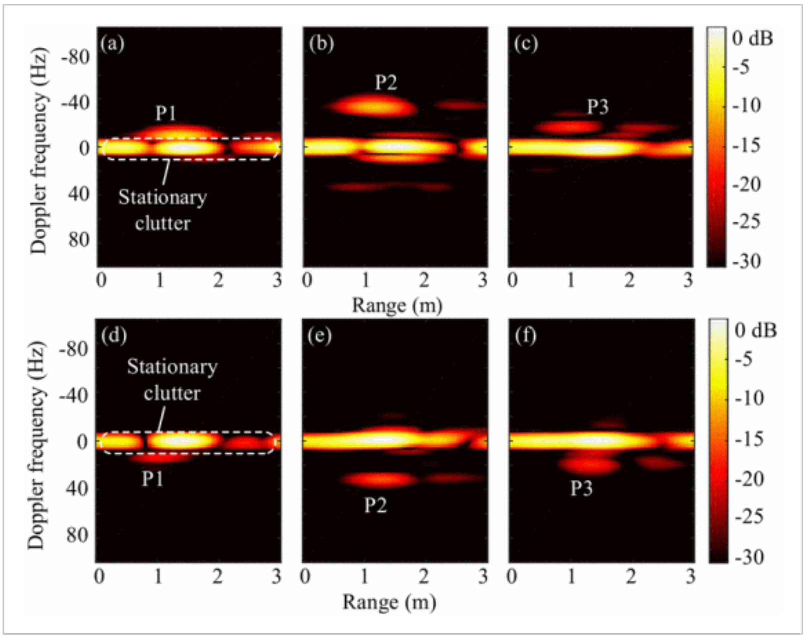


Fig. 7.
Range-doppler frames of the gestures of push and pull. (a) Phase 1 of push. (b) Phase 2 of push. (c) Phase 3 of push. (d) Phase 1 of pull. (e) Phase 2 of pull. (f) Phase 3 of pull.

Another experiment was carried out with two human subjects. As illustrated in Fig. 3, one person was making gestures in front of the radar, while the other was walking toward the radar. The limitation of conventional Doppler radars is manifest in Fig. 8-as the Doppler frequencies of two moving targets are added together in the spectrogram, it is almost impossible to recognize any gestures. Conversely, as shown in Fig. 9, with the range information provided by the FMCW radar, the signatures of the two persons can be easily separated, thus the gesture made by the closer person can be recognized. In particular, the gesture of lifting the forearm can be identified at the range of 2 m, while the other person was approaching the first one from a range of 4 m.

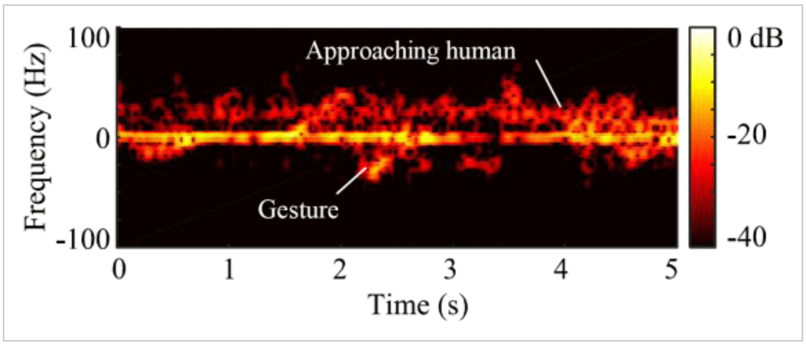


Fig. 8.
Spectrogram of two moving targets after conventional time-frequency micro-doppler analysis.

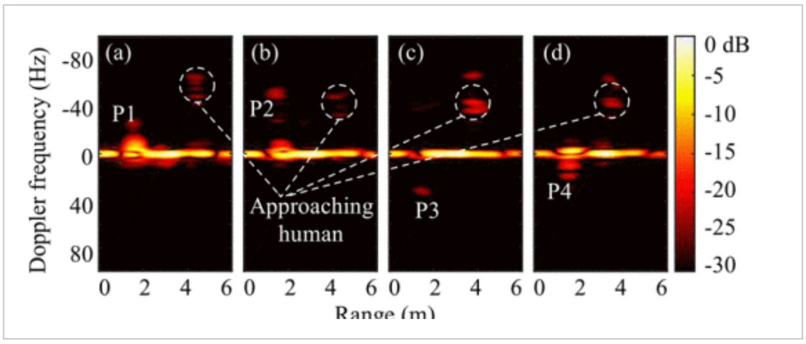


Fig. 9.
Range-doppler frames of gesture recognition with two moving targets. (a) Phase 1. (b) Phase 2. (c) Phase 3. (d) Phase 4.

SECTION IV.

Conclusion

A 5.8-GHz custom-designed portable coherent FMCW radar prototype was used for human gesture recognition based on range-Doppler processing. The comparisons between the results of conventional time-frequency micro-Doppler analysis and FMCW-radar-based range-Doppler processing has demonstrated that portable FMCW radars can recognize human gestures in the presence of multiple moving people. This work may pave the way for practical adoption of coherent radars to recognize human gestures.

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Keywords

INSPEC: Controlled Indexing
Doppler radar, feature extraction, gesture recognition, image motion analysis, medical image processing

INSPEC: Non-Controlled Indexing
FMCW radar sensor, human gesture recognition, portable radar sensors, Doppler-radar sensors, noncontact detection, hand motion, Doppler-radar-based hand gesture recognition, Doppler effect, motion feature extraction, range-Doppler processing, multiple moving subjects, field of view, range-Doppler domain, hand gesture identification, surrounding moving targets, frequency 5.8 GHz

Author Keywords
Micro-Doppler, micro-range, FMCW radar, gesture recognition, range-Doppler

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