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Separation of Simultaneous Multi-Person Noncontact Physical Activity Signals Using Frequency-Modulated Continuous-Wave Radars

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***Abstract*—Portable microwave radars are an emerging technology for remote recognition of human movements such as gesture commands, gait, and physical activities. Existing radar-based works on noncontact physical activity monitoring do not consider extracting individual signals from multiple targets doing exercises simultaneously when illuminated by the same radar sensor, which might be very useful in realistic environments where several people exercise nearby. In this work, the radar-based remote recognition of two human subjects simultaneously doing different exercises is proposed. Also, a strategy to find the range bins associated with the two targets of interest is detailed. Experimental results demonstrate that it is possible to detect and differentiate the exercises performed by each subject and count their corresponding number of exercise repetitions.**

Keywords—exercise monitoring, FMCW radar, human activity monitoring, multiple people monitoring, remote sensing.

I. Introduction

The health benefits of regular exercising are hard to ignore. It not only benefits people's bodies by keeping joints moving well and muscles strong, but it also prevents diseases like diabetes, asthma, heart diseases and improves memory and thinking [1]. As the number of people seeking a healthy lifestyle increases each year, the demand for high performance in exercise also increases. Supervising physical activities is crucial to achieving high efficiency. Several works investigated the use of contact/noncontact solutions such as wearable sensors and camera-based systems for remote physical activity monitoring [2]-[3]. However, wearable technologies may be uncomfortable during prolonged use, and camera-based monitoring relies on light conditions, may collect the user's private environment, and demand high computational load.

Portable radar technology has been increasingly employed for noncontact human activity surveillance. Due to its privacy-preserving advantage and insensitivity to light conditions, radars are an effective tool to monitor the exercises done by human subjects. A study presented in [4] shows that it is possible to detect human gestures in the presence of multiple targets using range-Doppler images. In [5], experiments were performed to monitor a subject doing sit-ups using a frequency-modulated continuous-wave (FMCW) radar with fixed antennas' beams. In the first experiment, another person was walking behind the target during the sit-ups; in the second experiment, a different exercise was performed behind the target. In both experiments, it was possible to detect and count the exercise of one person. However, to the best of the authors' knowledge, the radar-based monitoring of multiple people simultaneously doing exercises has not been reported yet.

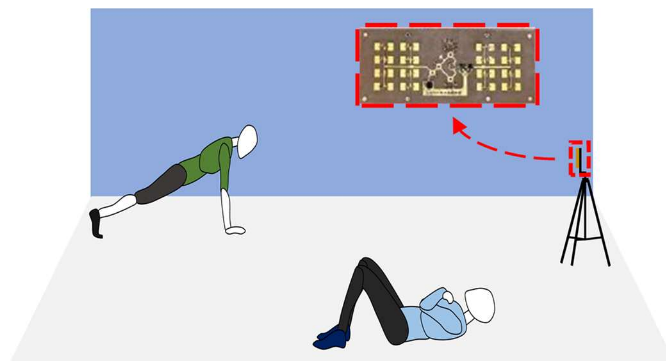

Fig. 1. Block diagram for the separation of simultaneous multi-person physical activity signals with a subject doing sit-ups and another doing push-ups.

This work investigates the simultaneous noncontact physical activity monitoring of multiple people using an FMCW radar without beamforming capability. By taking advantage of the range discrimination capability of FMCW radar and the high amplitude variation of the spectral power due to each exercise's repetitions, it is possible to differentiate the micro-Doppler signatures of both targets of interest from possible stationary clutters in an indoor environment.

II. Theory Of Multi-Person Physical Activity Monitoring Using FMCW Radars

The block diagram for the multi-person noncontact physical activity monitoring based on FMCW radars is shown in Fig. 1. Two subjects are doing exercises simultaneously. One subject is doing sit-ups, while another is doing push-ups. The human subjects are placed at different ranges. The fixed-beam radar illuminates both subjects and potential stationary clutters at all times. By taking advantage of the range discrimination capability of FMCW radars, it is possible to differentiate both subjects from each other since their distances to the radar do not

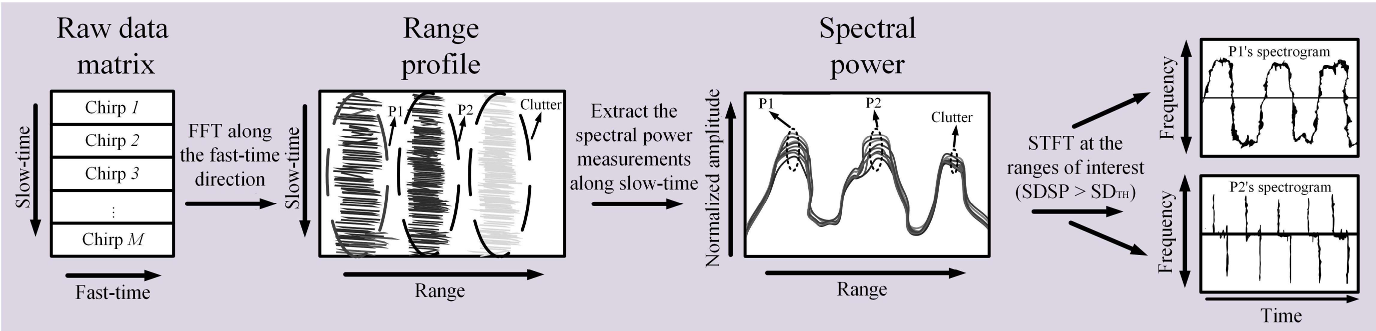

Fig. 2. Digital signal processing mechanism used to extract the time-Doppler spectrograms of the targets of interest.

vary over time. Herein, both subjects will be referred to as targets of interest.

Fig. 2 shows the data processing mechanism used to extract the time-Doppler information that contains the micro-Doppler (mD) signatures associated with the physical activities simultaneously done by both subjects. Initially, the sampled beat signal is consecutively chopped using a reference signal to determine each received chirp's starting and end points. The sequence of chirps is arranged as rows of the raw-data matrix. Since each chirp corresponds to significantly small-scale time measurement, each row belongs to the fast-time dimension, while each column belongs to the slow-time dimension. A fast Fourier transform (FFT) is applied along the fast-time dimension of the raw-data matrix to generate the range profile. P1 represents the subject doing sit-ups in the generated range profile, and P2 represents the subject doing push-ups. Stationary clutters are also highlighted. To determine the range bins of the targets of interest, the average spectral power along the slow-time dimension is extracted. It should be noted that the points of local maxima of the obtained curve coincide with the range bins (estimated range bins) related to P1 and P2. However, the range bins of stationary clutters are also retrieved. To distinguish the range bins associated with stationary clutters from the range bins associated with the moving targets of interest, the periodic changes on the spectral power of the estimated range bins are evaluated. Since the range bins of P1 and P2 have their spectral power periodically changed due to the repetition of the exercises, the standard deviation of the spectral power (SDSP) associated with P1's and P2's range bins along the slow-time will be higher than the standard deviation of the spectral power associated with range bins of stationary clutters. After choosing the threshold value for SDSP (SD_{TH}), the ranges of interest are correctly selected, and the short-time Fourier transform (STFT) is applied to them to retrieve only the mD signatures of the physical exercises done by P1 and P2.

III. Experimental Results

Experiments with two subjects simultaneously doing different exercises were performed in an indoor environment to verify the feasibility of the proposed radar-based exercise monitoring application. A custom-designed 24-GHz FMCW with no beamforming capability was employed. The block diagram of the 24-GHz FMCW radar used in this work is shown in Fig. 3 [6]. The bandwidth of the transmitted FMCW signal was set as 800-MHz, which corresponds to a range resolution of 18.75 cm. The audio card of a computer was used to sample both the beat signal and the reference signal at a rate of 96 kSa/s. The chirp repetition rate was set as 596-Hz. The experimental setup is shown in Fig. 4. One human subject (P1) was placed at 0.8 m, while another (P2) was at 2.2 m. During the observed time, P1 did five sit-ups, and P2 did seven push-ups. The distance between P1 and P2 was 2 m, and the radar was placed 0.5m above the floor. The radar constantly illuminated both subjects, and the stationary clutters.

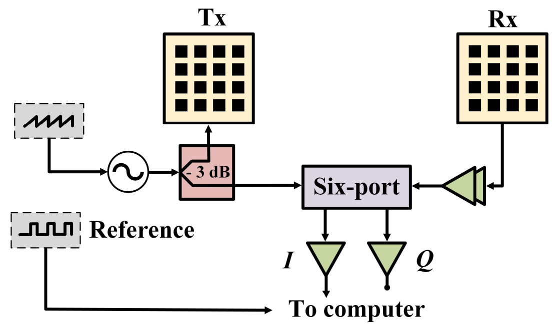

Fig. 3. Block diagram of the used FMCW radar sensor.

Fig. 5 depicts the range profile. The RF reflected signals coming from P1 were weaker than the reflected echoes coming from P2, although P1 was closer to the radar sensor. When P1 moved his back towards the ground, part of his body left the radar field of view since P1 was too close to the radar and the sit-up exercise required the subject to lay on the floor. On the other hand, P2's body was always illuminated by the radar signals. The two powerful signatures at 3.3 m and 4.4 m correspond to clutter signals generated by pillar walls with large radar cross-section. The periodic repetition of the exercises introduced variations on the spectral power measurements at the P1's and P2's ranges along the slow-time dimension. Fig. 6 illustrates the spectral power measured from 21.76 s to 24.76 s for the range profile. The amplitude variations of the normalized spectral power due to P1's and P2's movements are significantly higher than the amplitude variations of the spectral power measurements associated with the stationary clutters [7].

The extracted mD spectrograms for the five sit-ups done by P1 and the seven push-ups done by P2 are shown in Fig. 7 and Fig. 8, respectively. Fig. 7 details the mD signatures for the sit-ups. At first, P1 adjusted his position by moving his back towards the ground, as confirmed by the negative-frequency signatures. Then, P1's back started its uprising, moving away

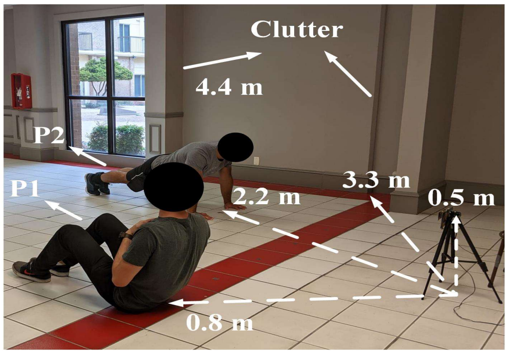

Fig. 4. Experimental setup.

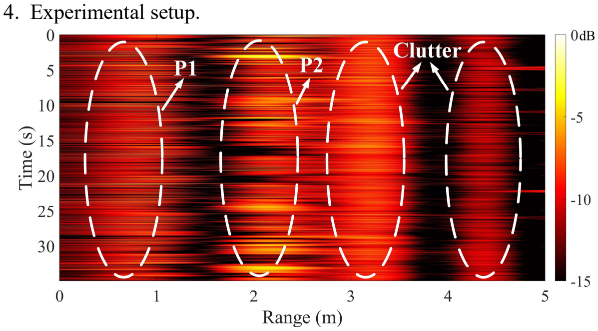

Fig. 5. Range profile. The range bins of P1, P2, and stationary clutters are highlighted.

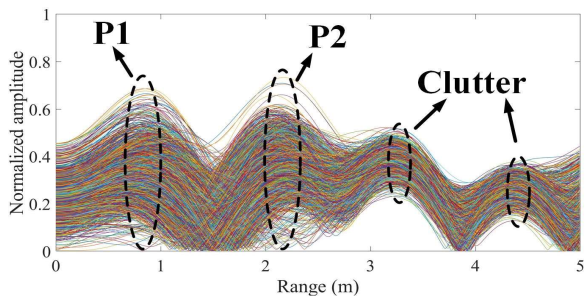

Fig. 6. Spectral power measurements associated with the range profile. The amplitude fluctuations of the signatures associated with P1, P2, and the stationary clutters are highlighted.

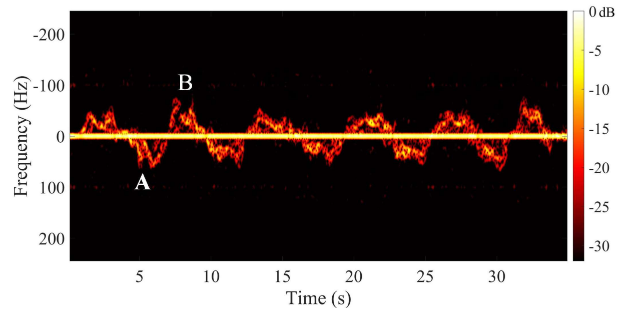

Fig. 7. Extracted micro-Doppler spectrogram associated with the five sit-ups done by P1.

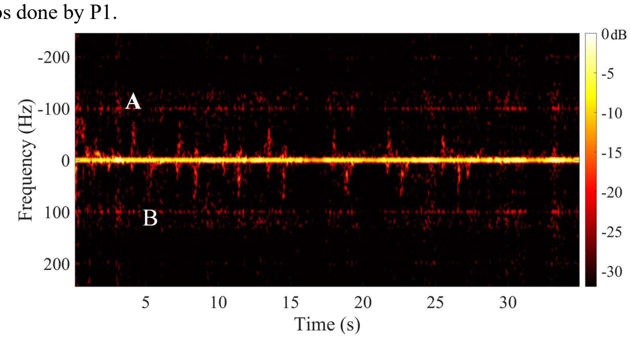

Fig. 8. Extracted micro-Doppler spectrogram associated with the seven push-ups done by the P2.

from the radar (region A). After reaching the ground, P1 started moving his back towards the radar, as confirmed by the negative-frequency signatures (region B). Analogously, P2 started moving his torso towards the ground. The radar detected the radial component of P2's motion, as confirmed by the negative-frequency signatures (region A). After reaching the ground, P1's torso started the uprising part of the exercise. The radar flagged the radial component of P2's movement as positive-frequency signatures on P2's time-Doppler map. Since radar-based detection only has the radial component of the corresponding movements, part of the retrieved mD signatures is distorted. However, the corresponding mD signatures of both exercises can be recognized, and the number of repetitions for each physical activity (five sit-ups done by P1 and seven push-ups done by P2) can be correctly evaluated.

IV. Conclusion

This paper presented the separation of simultaneous multi-person noncontact physical activity signals by an FMCW radar with no beamforming capability. An algorithm capable of differentiating the movements of the targets of interest and stationary clutters was also detailed. Experimental results demonstrated the feasibility of using FMCW radars to detect the physical activities of two people placed at different ranges and count the number of repetitions for each exercise. Future works will focus on testing the limits of multi-person radar-based detection and proposing classification techniques for different types of exercises.

Acknowledgment

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