Noncontact Exercise Monitoring in Multi-Person Scenario with Frequency-Modulated Continuous-Wave Radar

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***Abstract* — Monitoring exercise activities is crucial for athletes to reach specific fitness goals. Portable radars are an emerging technology for noncontact exercise monitoring. However, the existing works only relies on the Doppler effect caused by one motion in the sensor's field of view, which is not practical in scenarios with multiple moving targets. In this paper, the feasibility of using FMCW radars to monitor exercises when multiple moving targets are illuminated by the same sensor is investigated. By using the range capability of FMCW radars, interference rejection is achieved. Experimental results demonstrate the effectiveness of the noncontact exercise monitoring based on FMCW radars in the presence of multiple interferences.**

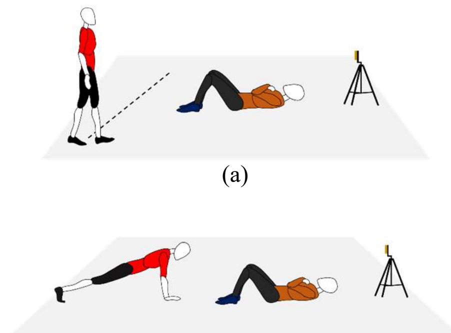
***Index Terms* — Noncontact exercise monitoring, FMCW radar, micro-Doppler, range profile.**

I. Introduction

Exercise is essential to keep the body's fitness and mind's health. Several works suggest that physical activity can reduce the risk of neurological diseases, and delay, prevent, or even treat memory loss. Furthermore, the regular practice of exercises can help to improve the productivity at work. Driven by the growing interest in tracking and monitoring exercises, various wearable devices based on accelerometers and camera-based systems can be found in the market. However, the long-term use of wearables is inconvenient. Camera-based sensor technologies are not robust to ambient light and infringe user privacy. In addition, cameras require large data storage and long processing time.

In the last decades, portable radars have emerged as potential solution to noncontact vital sign monitoring, human activity classification, and hand gesture sensing [1]-[3]. The time-frequency analysis of the Doppler radar baseband signals can reveal the micro-Doppler information caused by the movement of parts of the human body. In [4], WiFi devices took advantage of the Doppler effect to monitor and classify several bodyweight exercises. However, detecting the Doppler effect is not a complete solution. In realistic situations, other people and moving targets may exist. Therefore, the Doppler frequencies of other targets will interfere with the signatures of the analyzed exercise.

In this work, the feasibility of noncontact exercise monitoring based on FMCW radars in the presence of multiple persons is investigated. Micro-Doppler signatures are utilized to identify specific physical exercises and count the number of repetitions for each movement. As FMCW radars have range and Doppler capabilities, it is possible to separate the unwanted movements from the desired motions based on their different locations. The obtained results validate the potential and advantage of FMCW radars to monitor and identify exercises when multiple persons are in the sensor's field of view.



(a)

(b)

Fig. 1. Block diagram for noncontact exercise monitoring in the presence of (a) another walking human subject and (b) another person doing exercises.

II. Theory of Multi-Person exercise monitoring based on FMCW radars

Fig. 1(a) and (b) illustrate noncontact exercise monitoring based on FMCW radars in two scenarios. Fig. 1(a) exhibits one subject walking in front of a person doing sit-ups. Fig. 1(b) depicts a scenario where a person does push-ups in front of another person doing sit-ups. Both are simultaneously illuminated by a FMCW radar. If a conventional Doppler radar was employed in this scenario, the micro-Doppler produced by the two persons would interfere with each other. However, since FMCW radars possess range capability, it is possible to separate the two illuminated targets based on their range. Furthermore, the analysis of the micro-Doppler signatures of the sit-ups can still be carried out based on proper phase-deramping of FMCW response [1]. On the other hand, Fig. 2 shows the generation of the time-Doppler spectrogram based on a fast Fourier transform (FFT) to the raw-data matrix and a short-time Fourier transform (STFT) at the range of interest. The sampled beat signals of M different chirp intervals are sequentially arranged in rows of the raw-data matrix $\mathbf{R}(m,n)$, where $m = 1,2,3,\ldots,M$, $n = 1,2,3,\ldots,N$, and N is the number of sampling points for each chirp. The column-wise axis is referred to as slow-time, whereas the row-wise axis is called fast-time. The range profile is obtained after the application of the FFT over each row of the raw-data matrix $\mathbf{R}(m,n)$. In the range profile, a human doing exercises and a human walking by are labeled as P1 and P2, respectively.

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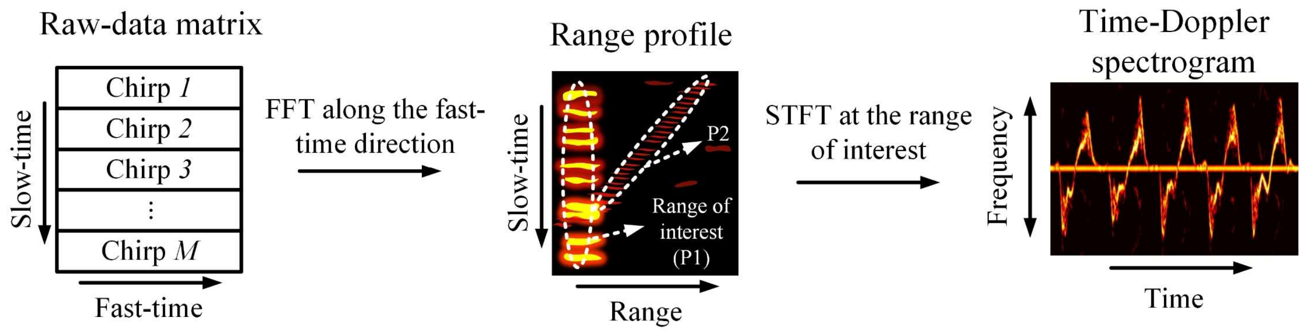

Fig. 2. Micro-Doppler extraction for the human subject (range) of interest from range profile.

Since P1 is closer to the radar sensor and periodically moving the body, stronger horizontal strips are observed, while the weaker trace in a diagonal direction corresponds to the trajectory of P2 walking towards the radar. Some surrounding clutters can be observed too. Besides, range-Doppler information can also be derived after the application of FFT to the range profile along the slow-time direction.

The time-Doppler spectrogram is extracted by performing the STFT to the range of interest with a sliding time window. The range of interest is the range at which the maximum Doppler signature is observed. In this paper, the minimum range of interest is 0.2 m and the maximum range of interest is 2 m. Since the abrupt moving parts of the human body provokes high energy characteristic echoes, the analysis of the micro-Doppler signatures of these movements can be used to count the number of repetitions for each exercise.

III. Experiments and Results

The block diagram for the FMCW radar used in this work is illustrated in Fig. 3. A 745-Hz sawtooth voltage signal excites a free-running voltage-controlled oscillator to generate a 600-MHz bandwidth frequency ramp with a center frequency around 24-GHz. After the 3-dB power divider, part of the signal goes through the transmitting antenna, and a local copy of the transmitted signal is mixed with the returned echoes by a six-port structure [5].

The six-port structure works as a mixer to down-convert the received radio frequency (RF) signal to zero-IF baseband. The coherence of the system is achieved by simultaneously sampling a reference signal associated with the linear chirps of the sawtooth wave and the beat signals. The beat signal and the reference signal are sampled by the audio card of computer at a rate of 96,000 samples per second.

To validate the feasibility of noncontact exercise monitoring based on FMCW radar systems, experiments were conducted in an indoor environment using the described radar sensor. The experimental setup of one person doing sit-ups while another walks towards the radar is exhibited in Fig. 4.

The distance between the radar and the head of the person exercising (sit-ups) was around 1 m. The radar was placed

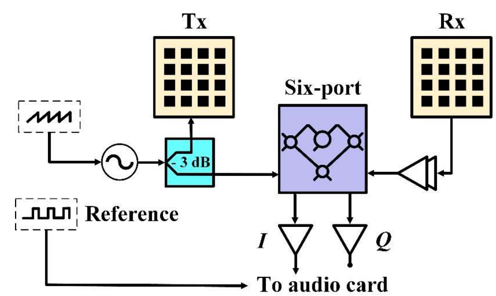

Fig. 3. Block diagram of the FMCW radar used in this work.

0.50 m above the floor. The other person walked towards the radar from a distance of 6.5 m to around 1 m away from the feet of the person doing sit-ups. Fig. 5 shows the range profile of the scenario depicted in Fig. 4, which contains the signatures of the two individuals and enables recognition of the movements performed by the closer person. The spectrogram of the micro-Doppler signatures of 5 sit-up repetitions is shown in Fig. 6. Initially, the back of the human subject was on the ground. As the back started to move up, a small positive frequency is seen. This corresponds to the accelerating phase of upwards movement. When the radial velocity of the back reached the maximum value, the maximum positive Doppler frequency of this sit-up repetition is seen in the spectrogram (i.e., point A). After that, the back started to deaccelerate until it reached a zero velocity, which corresponds to the zero-Doppler in the time-Doppler spectrogram (i.e., point B). In the second phase of the movement, the back started to move towards the ground and the radar. Because of that, negative values of the Doppler frequency are seen in the spectrogram. After reaching the maximum radial velocity at point C, the movement became slower. Eventually, the subject's back was again on the ground, which corresponds to point D on the spectrogram.

In Fig. 7, a more complex situation is depicted. A person did push-ups in line of sight with the radar while the other person was executing sit-ups. Fig. 8 shows the range profile for this scenario. The approximate range of the person

Fig. 4. Experimental setup of a human subject doing sit-ups while another person walking by.

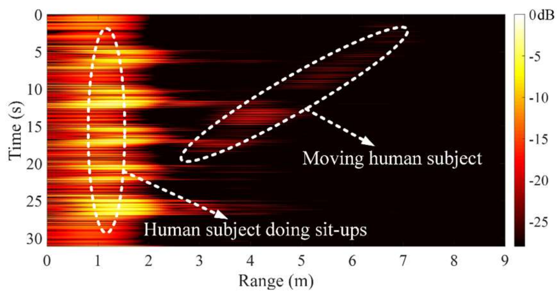

Fig. 5. Range profile with a person doing sit-ups while another person walking by.

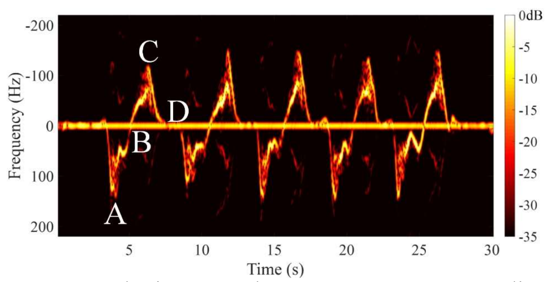

Fig. 6. Extracted micro-Doppler spectrogram corresponding to 5 sit-ups with another person walking by.

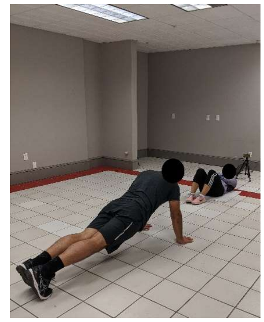

Fig. 7. Experimental setup of two human subjects performing different exercises in front of the radar.

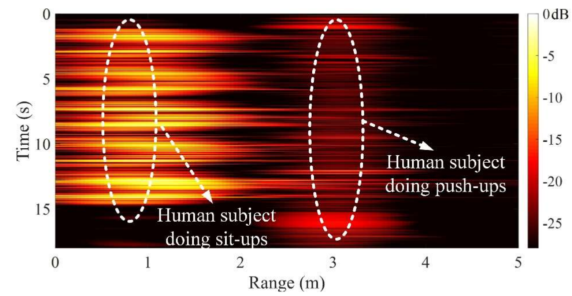

Fig. 8. Range profile with two human subjects perform different exercises in front of the radar.

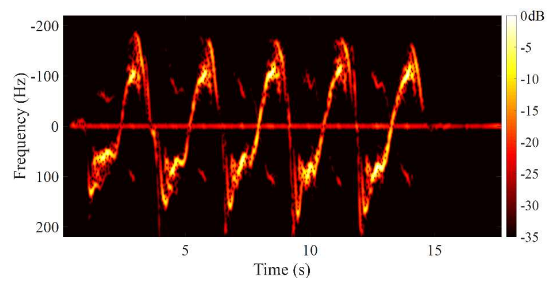

Fig. 9. Extracted micro-Doppler spectrogram corresponding to 5 sit-ups with another person doing push-ups.

doing push-ups is highlighted, and the stronger signatures are from the individual doing sit-ups.

Once again, thanks to the range capability, the FMCW radar was able to distinguish the movements, allowing the correct monitoring of the exercises performed by the person closer to the radar. In Fig. 9, the Doppler history at the range of interest, i.e., the person doing sit-ups, is shown, where 5 sit-up repetitions can be clearly identified.

IV. Conclusion

This paper investigates the feasibility of noncontact monitoring of multi-person exercises based on FMCW radars. Benefiting from the range discrimination capability, FMCW radars can easily detect specific exercises in the presence of multiple moving people and effectively remove potential interference. Future work will focus on automatic classification of different exercise movements.

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References

[1] G. Wang *et al.*, "Application of linear-frequency-modulated continuous-wave (LFMCW) radars for tracking of vital signs," in *IEEE Trans. on Microw. Theory Techn.*, vol. 62, no. 6, pp. 1387-1399, June 2014.

[2] C. Ding *et al.*, "Continuous human motion recognition with a dynamic range-Doppler trajectory method based on FMCW radar," in *IEEE Trans. Geosci. Remote Sens.*, vol. 57, no. 9, pp. 6821-6831, Sept. 2019.

[3] J. Lien *et al.*, "Soli: ubiquitous gesture sensing with millimeter wave radar," *ACM Trans. Graph*., vol. 35, no. 4, pp. 1–19, Jul. 2016.

[4] S. Li *et al.*, "WiFit: ubiquitous bodyweight exercise monitoring with commodity wi-fi devices," *2018 IEEESmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI*, pp. 530-537, 2018.

[5] G. Vinci *et al.*, "Six-port radar sensor for remote respiration rate and heartbeat vital-sign monitoring," *IEEE Trans. Microw. Theory Techn.,* vol. 61, no. 5, pp. 2093–2100, May 2013.