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Exploiting Millimeter-Wave Radars to Enable Accurate Gesture Recognition for the Metaverse Environment

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Abstract. This contribution aims to demonstrate the potential of highly integrated millimeter-wave radars in the framework of metaverse applications. In detail, a 122 GHz radar is mounted on glass frames, with the task to detect hand gestures, thus enabling more immersive and interactive user experiences. Current metaverse glasses exploit camera sensor to recognize the user gestures. The proposed system has the purpose to overcome the known limitations of the current camera-based technology, mainly due to the poor radial range detection accuracy and performance dependance on the light conditions. In this contribution, some gestures whereby a camera-based system could fail are properly detected during the experimental activity. The radar detection mainly exploits the phase-analysis to extract the displacement and the micro-Doppler signature. This work paves the way for the next generation interactive systems in the metaverse environment whereby the radar technology might be exploited along with the traditional sensors to provide an advanced, complete, and reliable interaction to the users.

Keywords: millimeter-wave radar · metaverse · micro-Doppler signature · gesture recognition · target displacement detection

1 Introduction

An impressive growth of the metaverse market is expected in the next years, which is estimated to rise up to $ 800 billion in 2024 [1]. Gaming, social experience, education, and healthcare are among the main technical applications [2]. This work is focused on the sensing systems which enable the users to interact with virtual objects and environments. Metaverse glasses are designed to provide a collaborative virtual space where the real and digital worlds converge. To provide a seamless experience, the accurate tracking of the hand-gestures is fundamental to enable the natural interactions with the virtual environment and it is usually provided by high-quality cameras.

However, cameras show well-known limitations related to the capability of detecting the radial range of the objects and to the strong dependance on the light conditions [3]. To overcome these limitations, in this contribution a 122 GHz radar has been mounted on the glass frames, pointing to detect hand-gestures. The very high working frequency

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allows a great integration of both the transceiver and the antennas in a 5 mm × 5 mm chip. Together with premium performance in terms of accuracy, and resolution, the current MMICs working beyond 100 GHz have a limited maximum range of a few meters and great care should be paid on the analysis of the down-converted In-phase and Quadrature (I/Q) signals after the IQ mixer [4–9].

Indeed, the mm-wave receivers present I/Q channels phase and amplitude imbalance due to different circuit non-idealities, which in turn degrade the orthogonality of the received signal. Two example of use cases have been reported to demonstrate the feasibility of the proposed solution.

2 Measurement Setup and Results

The core of the system is a 122 GHz radar by Indie Semiconductor, formerly Silicon Radar GmbH, placed on a very compact board and mounted on a demo glasses, as shown in Fig. 1. Exploiting radars working at very high frequency is a fundamental step to decrease the total system size, particularly concerning the critical space occupied by the antennas, for an effective integration with the glasses.

As an example, in [10], a 24 GHz radar has been exploited for the task of detecting the eye-blinking and head-movement. However, it might hardly be integrated on the glass frames without affecting the user's comfort.

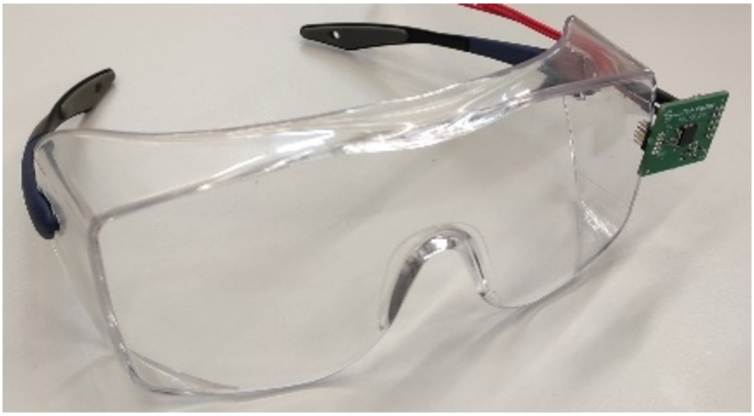


Fig. 1. Picture of the demo glasses equipped with the mm-wave radar.

The radar works in Doppler mode while the down-converted data are amplified and captured by exploiting custom boards realized with internal laboratory facilities, i.e., by exploiting the microwave circuit board plotter LPKF ProtoMat S103.

As shown in Fig. 1, the accurate radar positioning has been studied and the board has been mounted on the left side of the glasses for a better focusing of the antenna radiation beam on the left arm. However, different positioning and the simultaneous detection of both hands might be possible by exploiting MIMO radars. The phase of the received signal $\varphi(t)$ can be exploited to detect the displacement $x(t)$ of the hand as reported in Eq. (1).

$$x(t) = \frac{\varphi(t)}{4\pi f_c} c \quad (1)$$

where f_c is the operating frequency and c is the speed of the light.

The Doppler frequency component f_d can be exploited to detect echoes from moving targets by estimating their speed as reported in Eq. (2). In detail, f_d is the difference between the transmitted and received frequencies and it is also called Doppler shift.

$$v = \frac{f_d}{2} \lambda \quad (2)$$

where λ is the wavelength of the carrier signal.

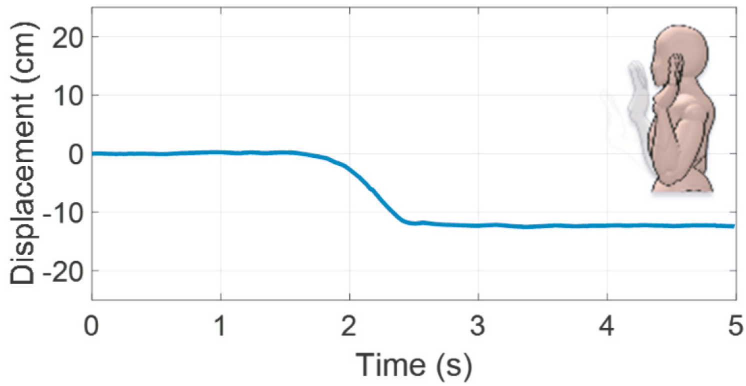
The extracted displacement might be exploited to distinguish between gestures of different extents whereas the Short-time Fourier Transform (STFT) is necessary to estimate how the frequency content of the signal changes over time. It is applied on the down-converted signal to recognize the characteristic micro-Doppler signature resulting from the different gestures.

The STFT of a signal is computed by sliding a window of a fixed length over the signal and by computing the Discrete Fourier Transform (DFT) on every single part of the windowed signal. Thus, the signal is partitioned in many segments and the windowed data are overlapped at the edges to guarantee a better reconstruction of the spectrum. The algorithm adds a complex value in a matrix for each windowed signal, thus each value is characterized by magnitude and phase for each point in time and frequency. The length of the window is a key parameter to set both the time and the frequency resolution. The longer the window, the higher the frequency resolution. Instead, a reduced window is the better choice if the analysis is focused above all on the frequency variations over time. Therefore, a short window allows to capture the temporal instant in which the Doppler frequency of the signal has been changed.

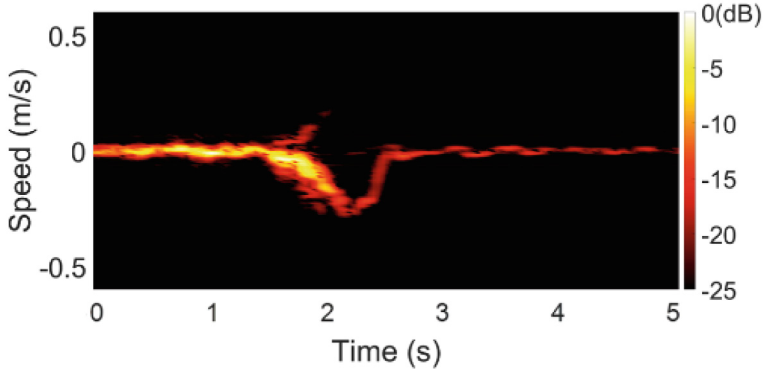
In detail, Fig. 2a shows the displacement of about 12 cm due to the halt command depicted in the figure inset while the Fig. 2b shows the relative micro-Doppler signature for this command. The main speed contribution is due to the stretching of arm resulting in a moving away from the radar and thus in a negative strip. The first section of the arm stretching is characterized by an acceleration as a consequence of the speed increase. Instead, a slowing down distinguishes the last part of the movement.

The displacement of the invite-to-move closer gesture is shown in Fig. 2c and it is like an oscillating motion cause to the continuous movement with the hands' fingers. Consequently, the relative micro-Doppler signature is characterized both negative and positive speed components as shown in Fig. 2d.

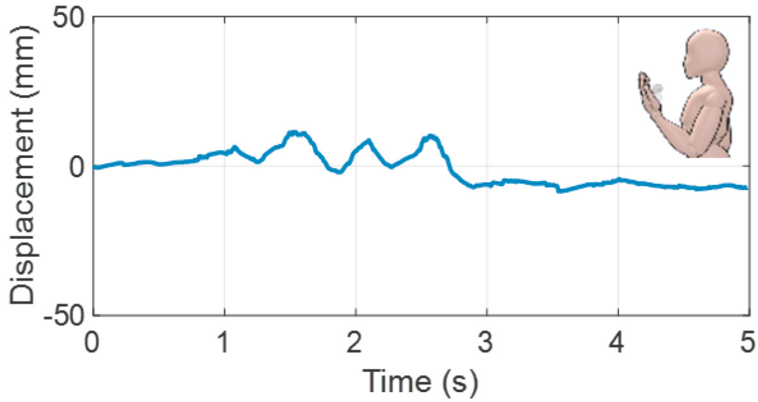
Both the two gestures have been properly recognized, thus demonstrating the effectiveness of the proposed solution and its potential to support the camera-based systems for metaverse applications. Further studies will be carried out to analyze the performance in presence of a moving subject and the detection reliability for more gestures with both hands.



(a)

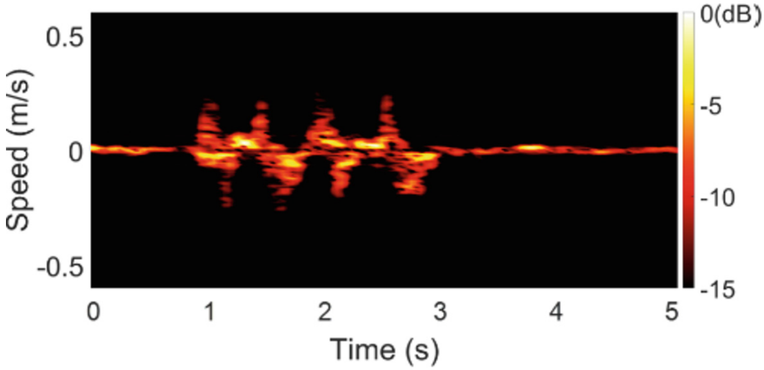


(b)



(c)

Fig. 2. Halt: (a-b) displacement and micro-Doppler signature and invite-to-move-closer: (c-d) displacement and micro-Doppler signature.



(d)

Fig. 2. (*continued*)

3 Conclusions

In this paper, a 122 GHz radar is used in the framework of metaverse applications. It has been mounted on the glass frames, with the purpose to detect hand gestures. Compared to the current camera technology, the proposed system has a better radial range detection accuracy and the performance do not depend on the light conditions. The system effectiveness has been proved by analyzing some possible use cases by means of phase-analysis and the micro-Doppler signature detection.

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