High Resolution Automotive Radar Measurements of Vulnerable Road Users – Pedestrians & Cyclists

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***Abstract*— Several years after successful entry into automotive market radar sensors conquers more and more complex fields of automotive applications like Lane Change Assist or Automatic Emergency Braking systems. Future sensor generations will be challenged by constantly demanding resolution requirements not only determined by consumer rating organizations like EuroNCAP, but also by the challenges induced by highly automated driving features. To satisfy these needs detailed and more accurate information of objects in the vehicle's surrounding and their multi-dimensional extent will be mandatory. To gain information about radar characteristics of pedestrians and cyclists this paper provides measurements captured with a high resolution experimental radar setup. The results are analyzed and the found radar characteristics are discussed in detail, to serve as a basis for future development of sensor hardware and signal processing algorithms.**

Keywords— automotive radar; micro Doppler;

I. Introduction

With Adaptive Cruise Control radar sensor technology successfully entered the automotive market in the late 90^{th} of the last century. Since then radar sensors were subject to constantly increasing requirements due to the development of more and more complex applications like Lane Change Assistance (LCA) or Automatic Emergency Braking systems (AEB). AEB systems for active pedestrian safety will be rated by EuroNCAP from 2016 onwards. Although many current systems will be able to comply with these tests, constantly improving mitigation performance of future AEB systems is already on the development roadmap. Consequently, sensor performance has to be increased in the following years, too. Furthermore, a bunch of novel active safety functions are still waiting already in the engineer's drawers or on their desks to become new candidates for protocol adoption beyond 2016 [1]. Most likely the AEB test protocols will be extended in a first step for cyclists and/or for enhanced emergency braking systems that support the driver in situations when a high level of attention is required, like at turning maneuvers with oncoming traffic, at dangerous intersections or at night.

On top of the functions addressed by consumer rating organizations the challenge of highly automated driving will provoke advanced requirements for future sensor generations. Highly detailed and accurate information of the surrounding area of the vehicle will be requested. Furthermore the estimation of the physical dimension, orientation or even the classification of nearby road traffic participants will become mandatory. Because their performance is not significantly deteriorated by adverse environmental conditions like darkness at night, fog, rain or backlight, future radar sensors are among the environmental perception candidates that will face advanced resolution requirements claimed by novel applications and functionalities to improve robustness, performance and safety of the overall system.

In a first step this paper aims to obtain detailed knowledge of the radar characteristics of vulnerable road users (VRU). Therefore high resolution automotive radar measurements of pedestrians and cyclists are provided, extensively analyzed and discussed. The gained knowledge will be used to specify resolution requirements of next generation radar sensors. Further it provides very important information for specification of VRU radar characteristics, which are vital to construct test dummies with identical radar reflection behavior. This is needed for a proper system's operation during future assessment tests.

II. Measurement Setup

To enable high resolution measurements an experimental radar sensor configuration was used based on off-the-shelf automotive radar chips. To assure easy and simultaneous analysis of range and Doppler characteristics, the so called frequency modulated continuous wave (FMCW) chirp sequence modulation was applied. Thereby the modulation dependent characteristics as given in TABLE I. were used.

TABLE I. Modulation Characteristics

Bandwidth B	Measurement time T	Range resolution Δd_r	Velocity Resolution Δv_r	Max. unambiguous velocity v_{max}
> 1 GHz	80 ms	0.11 m	0.025 m/s	100 km/h

The received and down-converted radar signals of the successive chirps are filtered, digitalized and processed by a two dimensional Fast Fourier Transformation (FFT). As a result, the so called range-Doppler spectrum is achieved and can be used to analyze the range and velocity of different scattering points reflected from one physical object.

Based on accident analyses results [2], [3] the decision was taken to investigate pedestrians and cyclists in both

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longitudinal (respectively radial) and lateral movement. In scenarios with radial movements the VRUs were measured at an angle of 0 degrees to the boresight of the sensor and in a distance up to 10 m. For the lateral scenarios the VRU moved along a lateral, perpendicular line to the radar boresight at a distance of 7 m. Thereby an angle from ±30 degrees in relation to the boresight was transcended. The experimental radar's object separation capabilities were tested with a pedestrian walking speed of 2 m/s (7.2 km/h, slightly above average) and a cyclist driving velocity of 3.3m/s (12 km/h). An aluminum mountain bike with 26 inch rims, a front suspension fork and with some plastic mudguards was chosen to represent a *standard* bicycle for the measurements.

III. High Resolution Pedestrian Measurements

A multiple point reflection model and the theoretical behavior of the reflection points from a pedestrian in accident scenarios was already presented in [4]. The possibility of distinction between standing objects and radial walking pedestrians by automotive radar was thereby shown in simulations. For a more detailed evaluation of pedestrian's radar characteristics Fig. 1 shows a high resolution range-Doppler spectrogram of several successive measurement cycles captured from a radial walking pedestrian.

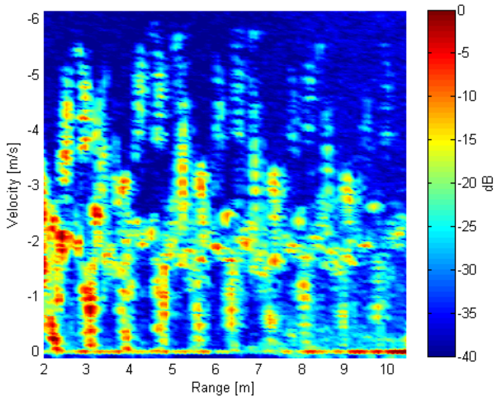

Fig. 1. High resolution range-Doppler spectrogram over successive measurement cycles of a radial moving pedestrian.

Instead of a few significant scattering centers the range-Doppler spectrogram shows a lot of different scattering centers with a large dynamic range of power levels. These findings support the theory of distributed scattering characteristics of pedestrians and also illustrate the fidelity limitations of multi point simulation models. Looking closer to the spectrogram of Fig. 1 reveals a quite higher density of scattering points around a velocity of 2 m/s. This is caused by the body center. In contrast, the legs and especially the feet show a velocity distribution between zero and a maximum of up to three times the pedestrian's walking velocity of 2 m/s. Additionally the limbs show less reflecting power with more fluctuation in scattering characteristics compared to the torso. This makes a continuous detection of the extremities difficult, especially at long ranges. Nevertheless the velocity distribution over time shows potential for unique classification criteria.

Following accident analyses and statistics a high amount of injuries and fatalities occur in the case of laterally moving VRUs [2], [3]. Due to the radial measurement principle of microwave radar the measured velocity of a laterally moving object differs significantly from the velocity in walking direction. Fig. 2 illustrates the relationship

$$v_r = v_y \cdot \sin(\varphi) \tag{1}$$

between the radial velocity v_r and the lateral velocity v_y. Thereby the measurable velocity of a detected object depends on its angle, respectively its longitudinal (d_x) and lateral position (d_y), its velocity and its moving direction.

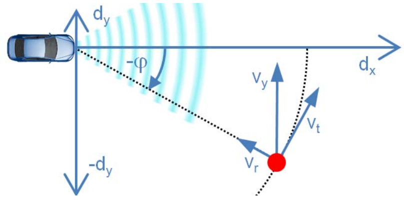

Fig. 2. Relationship between the radial velocity v_r and lateral velocity v_y

According to (1) laterally moving objects near the radar's center line show very small radial velocities. Theoretically these components disappear for an angle of zero degrees to the radar boresight. Because of the high resolution of the experimental sensor setup and the pedestrians extend small radial components can still be recognized in the range-Doppler spectrum. Fig. 3 shows different positions of a laterally moving pedestrian. Fig. 4a to 4e provide the corresponding range-Doppler spectra to confirm the previous statements.

Fig. 3. Laterally moving pedestrian at different positions and angles

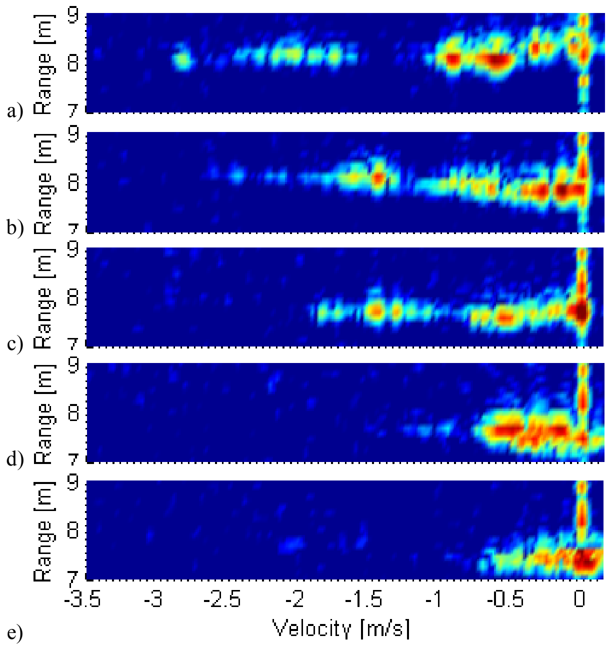

Fig. 4. Range-Doppler spectra of a laterally moving pedestrian at different lateral positions to the sensor

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Fig. 4a shows the distribution of the radial velocity of a laterally moving pedestrian at d_x=7 m and d_y=3.9 m. Taken the peak velocity in walking direction of 5.8 m/s from Fig. 1 leads to a radial peak velocity of 2.8 m/s, which also appears as peak velocity in Fig. 4a.

A closer look to Fig. 4e indicates that in contrast to theory a laterally moving pedestrian still shows a small velocity spread even at a position of zero degrees to the sensor's center line. This is caused by the angular spread of the pedestrian's limbs. Even when the main body reaches the center line, the limbs are located a few centimeters to the left or to the right. The assumption of a perpendicular peak velocity of 5.8 m/s at a lateral offset of 0.5 m theoretically leads to a radial velocity component of 0.4 m/s, as also shown by Fig. 4e.

IV. High Resolution Cyclist Measurements

Fig. 5 provides selected range-Doppler spectra of a radially approaching cyclist at different ranges and at different measurement instances, respectively times.

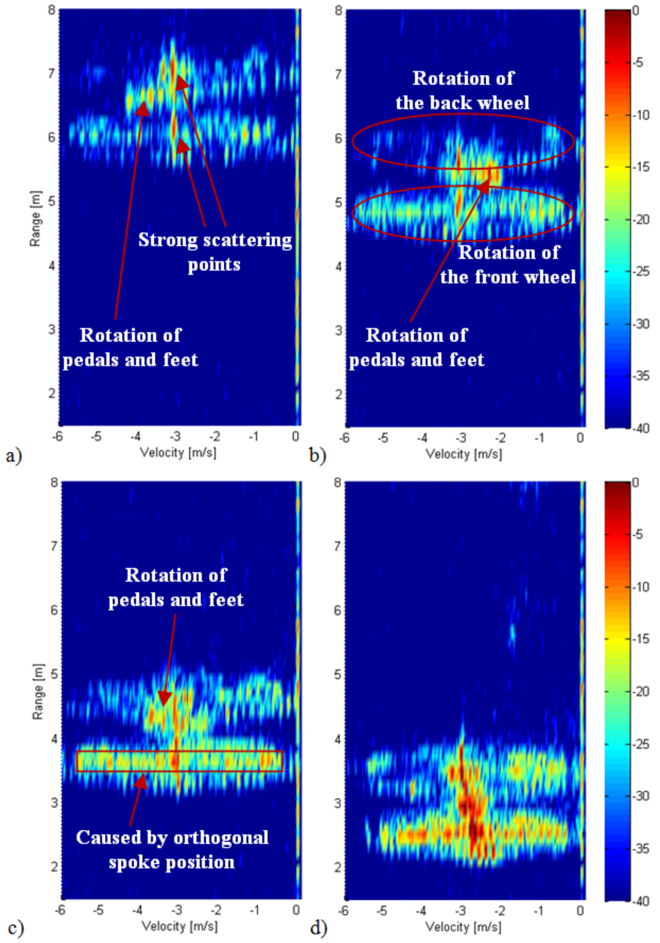

Fig. 5. High resolution range-Doppler spectra of a radial moving cyclist

At first sight the spectra of Fig. 5a and Fig. 5b of the cyclist show two scattering points of stronger power level in a radial distance of approximately 1.0 m. These are caused by the wheel hubs itself or by the vertical rods of the frame and fork. Because these strong scattering parts are connected together by the frame the measurements show exactly the same velocity for both strong scatter points.

Additionally to the stronger scattering points each of the range-Doppler spectra of Fig. 5a-d show two areas of higher density of scattering points distributed in the velocity domain. These are caused by rotations of the two wheels. According to the driving physics of a bicycle the maximum occurring and measurable velocity at a wheel in driving direction is twice the driving velocity over ground of the bicycle. Because the bicycle approached during the measurement on the center line of the sensor the front wheel masked the back wheel, which deteriorates the detection capability of the back wheel. The reflected power level of the wheels is 10 dB to 20 dB below the power level of the strong reflections stated previously. For this reason the range-Doppler spectrum of a bicycle especially in larger distance with increased free space loss shows a rod like shape. Caused by the fast rotation of the wheels there are always some spokes in orthogonal position to the radar rays. Especially this spokes cause stronger reflections than the others, analogue to the reflection characteristic of a cylinder. That's why a vertical line is formed in the range-Doppler spectra at the position of the front wheel.

After a detailed comparison of Fig. 5a-c an additional rotation located between the two wheels can be identified. This is caused by the rotation of the derailleur, foot pedals or the feet, respectively knees, of the cyclist. The reflected power of these rotating parts is also larger than the power level of the reflections caused by the wheels.

To keep the bicycles driving velocity nearly constant during the whole scenario the cyclist passed the radar sensor on the right side instead of stopping in front of the sensor. The range-Doppler spectra of the measurement cycles captured immediately before passing the radar sensor therefore show smaller velocity components. This effect is caused by the angular offset and can be seen at the shape of the front wheel in the spectrum of Fig. 5d. At this position of the bicycle a direct line of sight between the sensor and both wheels is possible, which leads to higher power levels of the reflections of the back wheel.

Furthermore, it is obvious that the range bins of the spectra are a little bit blurred. This is caused by a rather large measurement time of approximately 80 ms in which a cyclist with a velocity of 12 km/h passes a distance of 0.27 m - more than two FFT range cells of the used experimental radar setup.

Analog to the measurement procedure conducted for pedestrian a laterally moving cyclist was investigated. Fig. 6 shows the positions of the cyclist at selected measurement cycles and Fig. 7 provides the corresponding range-Doppler spectra. Fig. 7a shows the range-Doppler spectrum of the cyclist with its center located at an angle of approximately 20 degrees to the boresight of the sensor. Because of its lateral extend of 1.8 m the reflections of the bicycle are spread over a given angular range. Depending on the associated lateral extend of the reflection points the measured radial components of the velocity behaves according to (1). Therefore the velocity spread of the front wheel is smaller than the spread of the back wheel. Nevertheless, the most interesting point is that the shape of the bicycle, consisting of two rotations and the two stronger reflections, can be recognized in the spectra of Fig. 7a and Fig. 7e. This offers the possibility for a shape-based classification of cyclists in lateral motion.

Another interesting aspect is that analog to the characteristics of a laterally walking pedestrian a laterally moving cyclist shows a small but recognizable velocity spread at a position of zero degrees sensors boresight. This allows distinguishing between laterally moving cyclists and stationary targets in front of the sensor. Fig. 7c shows the range-Doppler spectrum of a laterally driving cyclist with 12 km/h at the center line of the sensor. A distance of 1.1 m between the wheel hubs leads to radial components of their velocities of ±0.27 m/s. As stated before wheels are moving twice as fast and are located in a lateral distance of 0.87 m to the center line of the sensor. Therefore (1) leads to maximum radial components of the wheels itself of ±0.84 m/s.

Fig. 6. Laterally moving cyclist at different positions and angles

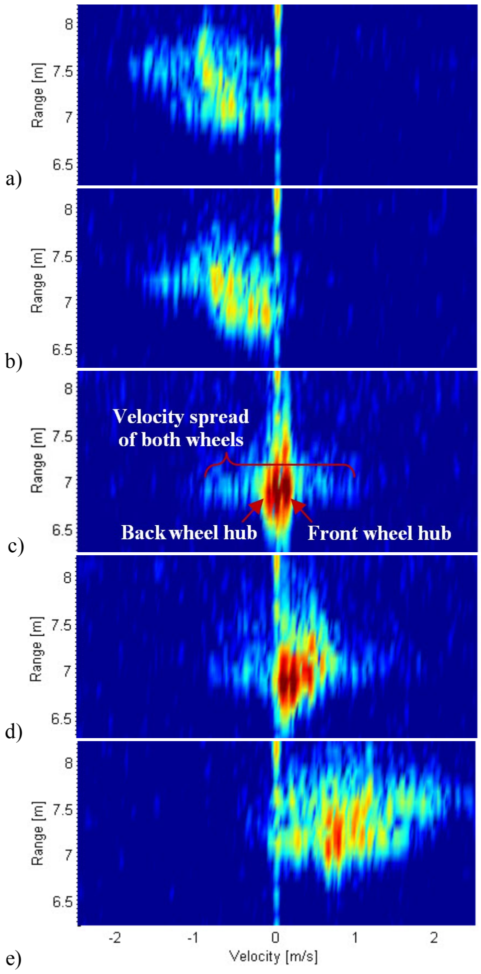

Fig. 7. Laterally moving cyclist at different lateral positions to the sensor

V. Conclusion

High resolution radar measurements of pedestrians and cyclists have been presented in this paper. They may not only serve to evaluate and validate the theoretical relation between lateral and radial velocity components, but enable novel insights in radar specific characteristics of vulnerable road users. These may play an important role for the specification of future system assessment methodologies and for the design of system performance testing facilities. Besides, the knowledge of VRU specific radar characteristics is even more important for the development and verification of object classification algorithms. With their help the accident mitigation capabilities of the overall active safety system can be improved while maintaining or even decreasing false intervention rates. As a further step in developing, adequate clustering algorithms are necessary to group the bunch of detected scattering points reflected by each individual physical object. This will enable determination of object specific classification features or the estimation of multi-dimensional extents of all road traffic participants.

A more or less open point is still the realization of high resolution automotive radar sensors. Both high sample rates and long measurement times will require advanced memory spaces. In contrast, the requirement for higher measurement update rates restricts the available measurement time and engenders huge data transfer rates with a growing demand for computational power. Reliable, cheap and bullet proof concepts with the best trade-off between effort, cost and performance will be the major challenge of future radar sensor development.

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