Detection of Slow Moving Targets using Automotive Radar Sensors

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***Abstract*—Detection of (slow-moving) pedestrians in an urban environment is a highly sophisticated task. This paper presents a signal processing technique suitable for frequency modulated continuous wave (FMCW) radar sensors using chirp sequence modulation, allowing observation of slow-moving targets with high resolution capability in range and velocity. Velocity and range resolution can be improved through linear prediction without requiring higher bandwidth or longer measurement time. To verify the signal processing technique, measurement results are presented at the carrier frequency of 79 GHz.**

***Index Terms*—Chirp sequence modulation; pedestrian detection; linear prediction; 76-81 GHz; radar; range resolution; velocity resolution.**

I. Introduction

Nowadays, automotive radar sensors are widely used for driver assistance systems to realize comfort and safety functions. Due to the increased traffic density in mega cities, the demand for pedestrian protection is increasing. Extended environmental information is required to assure stable and reliable safety functions. Radar sensors are essential for delivering robust target information, effectively monitoring pedestrians in critical situations and to avoid or mitigate accidents. To monitor slow moving pedestrians good separation abilities in angle, range, and velocity have to be considered for radar sensors. The field study [1] shows that the traveling speeds of pedestrians vary depending on the situation, weather condition, and age of the observed person. As an example, the mean pedestrian speed for 7123 differently-aged pedestrians while crossing a street with traffic lights under different weather conditions is 1.25-1.51 m/s (4.5-5.4 km/h) [1]. If a pedestrian is walking close to a still standing car, the separation ability in range or angle of the radar sensor might not be adequate enough. Hence, the separation can be done in velocity. However, a good velocity resolution is depending on the measurement time of the sensor, which can be in contradiction to the available observation time of the pedestrian.

II. Range and Doppler Processing

Frequency modulated continuous wave (FMCW) radars are commonly used for automotive applications. On the radar sensor market, several modulation techniques based on FMCW processing exist. One realization is the chirp sequence modulation, also known as fast chirp modulation. This modulation technique has the advantage of processing range and velocity independently. System parameters like range and velocity resolution are often fixed for a given radar sensor. By using signal processing techniques as presented in this paper, the resolution capability for range and velocity can be improved without changing the hardware setup, and they can be adapted to the observed scene.

A. Chirp Sequence Modulation

Different tier-one suppliers for original equipment manufacturer (OEM) of radar sensor systems are currently using the chirp sequence modulation instead of triangular FMCW modulation.

This technique offers the following advantages:

- Independent range and velocity processing.
- Easy target suppression in certain velocity areas.
- Reduced ambiguity for velocity processing.
- Variable adjustment of the minimum an maximum velocity within the unambiguous velocity span.
- Fast processing due to standard signal processing like Fast Fourier Transformation (FFT) processing for range and velocity.

The chirp sequence modulation is mostly based on the transmission of saw tooth FMCW signals with the transmit frequency f_{tx} and having a steep slope S as depicted in Fig. 1. One frequency ramp (chirp) sweeps through the bandwidth B, within a very short chirp time T, e.g. 20-200 μs, at the center frequency f_{c}. Successive K chirps are transmitted with a constant ramp repetition interval T_{RRI} in the measurement time T_{meas}. The back-scattered and down-converted time domain signal of all chirps $s_{\mathrm{IF}}(t)$ for one moving target having a radial velocity v_{r} in the distance R results in [2]:

$$s_{\mathrm{IF}}(t) = e^{j\cdot 2\pi\cdot(2f_{\mathrm{c}}\cdot R/c_0)} \cdot \sum_{k=0}^{K-1} e^{j\cdot 2\pi\cdot\left[\frac{2f_{\mathrm{c}}\cdot v_r\cdot T_{\mathrm{RRI}}\cdot k}{c_0} + \left(\frac{2f_{\mathrm{c}}\cdot v_{\mathrm{r}}}{c_0} + \frac{2B\cdot R}{T\cdot c_0}\right)\cdot t\right]} \cdot \mathrm{rect}\left(\frac{t - k\cdot T_{\mathrm{RRI}}}{T}\right). \quad (1)$$

To obtain the radial velocity v_{r} of one target, each received and quantized time signal with N samples of one chirp k has to be processed by a Fast Fourier Transform, followed by an FFT of K complex sampling points within each same range cell. In total, $N/2\cdot K$ FFTs are required to obtain the unambiguous range and velocity information. To determine the target velocity, a constant velocity is assumed during the measurement time T_{meas}. This time has to be adapted to avoid range cell migration, causing range Doppler coupling which effects neighboring range and velocity bins [3]. This means a moving target has to be within one range cell during the transmission and reception of the chirp sequence as shown in Fig. 2. Hence, the used bandwidth has to be adjusted to avoid a degradation of the velocity resolution.

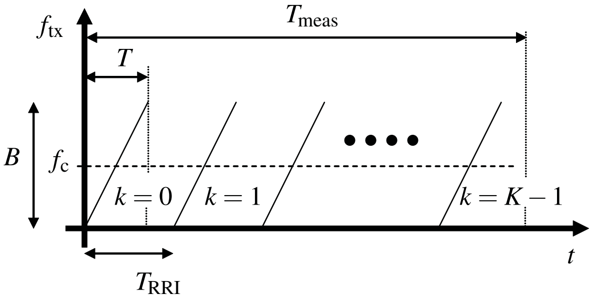

Fig. 1. Chirp sequence modulation scheme with K successive chirps.

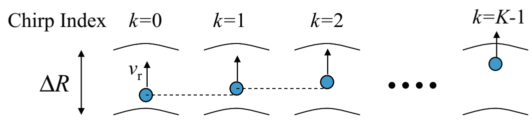

Fig. 2. Target movement in one range cell (no range cell migration) during T_{meas} of one chirp sequence.

If the target is moving with a constant velocity v_r the range of the target resulting from the FFT differs slightly and causes a constant phase difference $\Delta\varphi$ between each of two successive chirps. Hence, target velocity and constant phase difference are direct proportional. The rotation of the complex range vector with constantly increasing phase caused by the target movement in one specific range cell is depicted in Fig. 3. The signum and hence the rotation direction of all complex range samples depends on the target moving direction. Applying the Fourier transform to all range samples situated in one specific range cell results in one discrete frequency peak, if only one target is observed. This frequency corresponds to the relative velocity of the target.

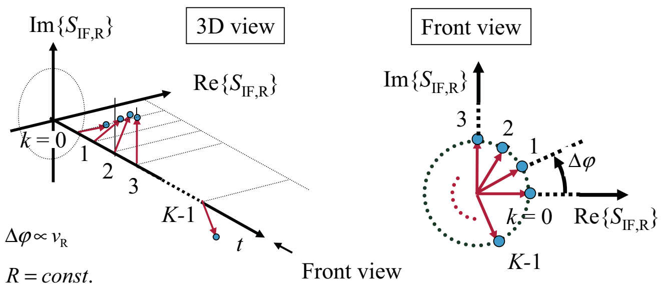

Fig. 3. Scheme of the phase shifted complex range samples k of one chirp sequence, containing a moving target at one fixed range cell.

B. Improvement of Doppler Resolution

The velocity resolution Δv in chirp sequence modulation is defined as [2]:

$$\Delta v = \frac{c_0}{2 f_c \cdot T_{RRI} \cdot K} \tag{2}$$

By increasing the amount of chirps K with a constant T_{RRI} the velocity resolution can be improved. Consequently, the measurement time T_{meas} will be increased and results in an augmentation of the number of complex range samples for each observed range cell.

The extended measurement time is a contradiction to the required fast observation time necessary in order to take appropriate action to mitigate car-pedestrian accidents, especially in the urban environment. Also, the radar sensor should provide as much velocity information as possible for the following Kalman tracking in a short sensor cycle time to stabilize the target information during the overall observation time. Of course, the observation time of slow moving targets is also influenced by the field of view and squint angle of the radar sensor, as well as the relative velocity and distance between sensor and target.

The conflict between short measurement time and high velocity resolution can be tackled by signal post-processing. Spectral signal estimation methods, like the auto-regressive (AR) linear prediction, which will be applied in the following, show a robust performance if sufficient signal-to-noise ratio (SNR) is assumed. The aim of linear prediction is to determine the coefficients of an underlying AR model by minimizing the forward and/or backward prediction error [4], [5]. In this way the original number of measurement values can be artificially extended by predicting successive samples. Fig. 4 shows the scheme of the artificial increase of the K measured complex range samples by AR linear prediction. Fig. 4 assumes, that one target is moving with a constant velocity without taking system noise into consideration. It can be seen that the prediction of the samples results in a harmonic extension of the original signal. Fourier Transformation of this extended signal results in a narrower frequency peak. Increasing artificially the amount of chirps by the AR linear prediction does not influence the measurement time but improves the velocity resolution. Of course, the order of the underlying AR model limits the amount of detectable velocities, and has to be adapted to number of physical targets, and the angular/range cell size.

C. Improvement of Range Resolution

Linear prediction also opens the way for improving the range resolution by an artificial increase of the bandwidth. The down-converted FMCW time domain signal for each chirp can be extended by AR linear prediction in the same way as for the improvement of the velocity resolution. Adding the predicted time domain samples to the real measurement samples results in an artificial increase of the chirp duration T. Considering a constant FMCW slope S augments the bandwidth artificially and improves the range resolution ΔR:

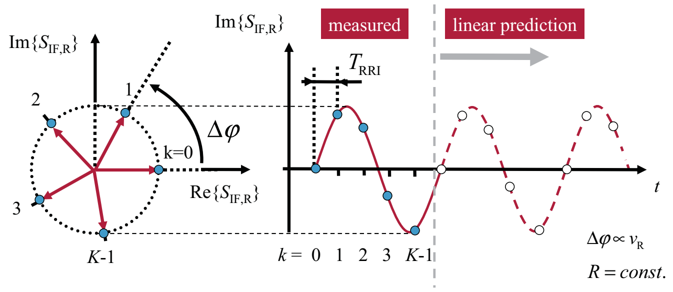

Fig. 4. Scheme of the extension of the complex range samples by AR linear prediction processing one target at a fixed range cell, and constant velocity.

$$\Delta R = \frac{c_0}{2 \cdot B} = \frac{c_0}{2 \cdot S \cdot T}. \quad (3)$$

Fig. 5 presents measurement results of a pedestrian standing still in front of a car at the distance of 9.5 m with a spacing of 0.6 m to the car. The center frequency of the radar sensor was adjusted to 79 GHz with a bandwidth of 0.5 GHz in curve 1 of Fig. 5. It can be seen that the first peak of the car and the peak of the pedestrian are merged. These two targets can only be discriminated by a local minimum of only 1.5 dB beneath the received power of the pedestrian. By increasing the bandwidth from 0.5 GHz to 1 GHz the theoretical range resolution improves from 0.3 m to 0.15 m, and the pedestrian and the closest main scattering center of the car can be separated clearly as seen in curve 2. Avoiding to increase the bandwidth physically AR linear prediction offers the opportunity to increase the bandwidth artificially. Curve 3 was originally measured having a bandwidth of 0.5 GHz which was artificially increased to 1 GHz by using AR linear prediction with the order of 50. Comparing the target separation of the extrapolated signal of curve 3 with curve 2 shows a similar range separation capability.

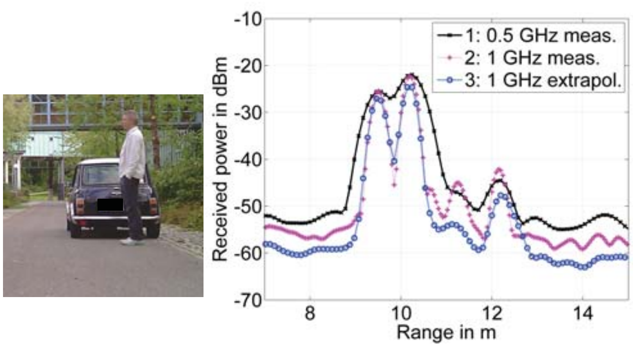

Fig. 5. Measurement result of the chirp sequence modulation at 79 GHz observing a pedestrian standing still in front of a parking car using B=0.5 GHz and 1 GHz. Range resolution improvement to corresponding B=1 GHz is obtained by AR linear prediction of the measured signal of B=0.5 GHz.

Of course, using AR linear prediction increases the signal processing demand. However, predicting these additional samples by applying parallel processing enables to compensate the additionally required calculation time. This can be done by processing each received chirp directly after receiption. Applying AR linear prediction provides a variety of advantages. It improves the range separation of a radar sensor with a limited physical bandwidth. Furthermore, this technique allows high range separation capability combined with a short ramp repetition interval T_{RRI}, enabling to increase the unambiguous velocity. Moreover, the required range resolution can be adapted to the observed scene by post-processing focusing on the region of interest.

III. Observation of a Moving Pedestrian

A. *Chirp Sequence Processing Model*

A radar signal processing model for automotive radar sensors was designed on the basis of the chirp sequence modulation. This model can determine the range and velocity from the time domain signal by adjusting the input parameter of the given radar system. The radar sensor delivers the received and down converted time domain signal of all chirps to the input of the range processor which can use AR linear prediction to increase artificially the bandwidth. After windowing and Fourier transforming the time domain signal of each chirp, the velocity processing is applied. To improve the velocity resolution, all complex range samples of each range cell can again be extended by AR linear prediction. Applying windowing again reduces the leakage effect for FFT processing. A range and velocity matrix is provided at the output of the signal processing model.

B. *Processing Results of Measurement Data*

In the following, the chirp sequence processing model was applied to the monostatic radar sensor [6] using a vertical polarized lens horn antenna with a one-way half power beam width of 3.5°. The radar sensor, mounted at the height of 60 cm, was operating at the center frequency of 79 GHz. The still standing car was located at the distance of 10 m with no lateral displacement to the sensor. The slow moving pedestrian was passing the car with a spacing of 60 cm to the body shell with a walking speed of 4.5 km/h. Comparing the influence of range resolution on the separation of the car and the pedestrian, measurements were done with a bandwidth of 0.5 GHz and 1.35 GHz. The unambiguous maximum velocity between ±21.69 km/h is mainly limited due to the sweep time of the signal generation using a phased-locked loop (PLL) stabilized synthesizer. The applied radar sensor parameters are shown in Table I.

The measurement results of pedestrian passing the car without AR linear prediction are depicted in Fig. 6 and Fig. 7. It can be observed that the main scattering centers of the car at 10.4 m, 11.5 m, and 12.2 m show a velocity of 0 km/h. Fig. 6 illustrates that one merged peak of the car and the pedestrian appears at the distance of 10.5 m and the velocity of 4.5 km/h as using a bandwidth of 0.5 GHz. This is caused by the interaction of the back-scattered waves of the body shell and the pedestrian. Such an interference can degrade the separation capability or even result in a loss of detection of the two targets. In Fig. 7 it is shown that increasing the bandwidth

TABLE I
TECHNICAL DATA OF THE RADAR SYSTEM USING CHIRP SEQUENCE MODULATION

Parameter	Measurement	Measurement using AR lin. pred.
Carrier frequency	79 GHz	79 GHz
Bandwith	0.5/1.35 GHz	0.5 GHz
Polarisation	vertical	vertical
Amount of Chirps	32	32+64 artificial
Chirp duration	144 μs	144 μs
Ramp rep. intervall	160 μs	160 μs
Velocity Resolution	1.36 km/h	0.45 km/h
Max. Range	49.9 m	49.9 m
Max. velocity	±21.69 km/h	±21.69 km/h

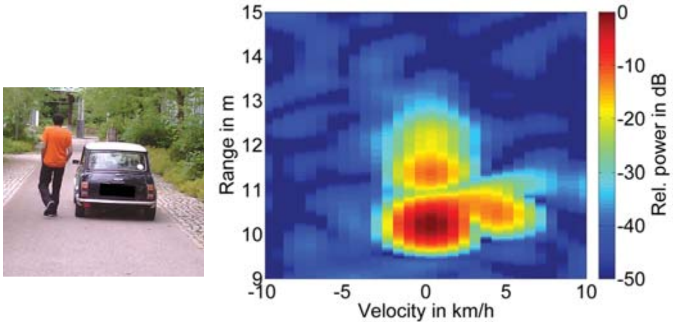

Fig. 6. Measurement result of a pedestrian passing a car, using a bandwidth of 0.5 GHz (at a carrier frequency of 79 GHz).

to 1.35 GHz improves as well the separation of the merged peaks. Hence, applying a higher bandwidth reduces the effect of interference between the scattering centers of the car and the passing pedestrian.

One further technique to separate the merged peaks is to apply AR linear prediction for velocity processing in combination with a reduced bandwidth of 0.5 GHz. Fig. 8 illustrates the measurement results by artificially increasing the number of chirps to 96 (32 real chirps + 64 artificial chirps). By this processing the velocity resolution was improved from 1.36 km/h to 0.45 km/h, and hence the car and the pedestrian are separated.

IV. CONCLUSION

Signal post-processing techniques, like the auto-regressive linear prediction, enables FMCW radar sensors with chirp sequence modulation to improve significantly range as well as velocity resolution at a given operational bandwidth. Hence, slowly moving targets like pedestrians can be identified at an early stage, to avoid or mitigate an accident. The proposed chirp sequence processing model can be applied to analyze the effect of varying radar system parameters, and can be connected to real radar sensor systems. Furthermore, it is shown that the separation of a vehicle and a nearby pedestrian

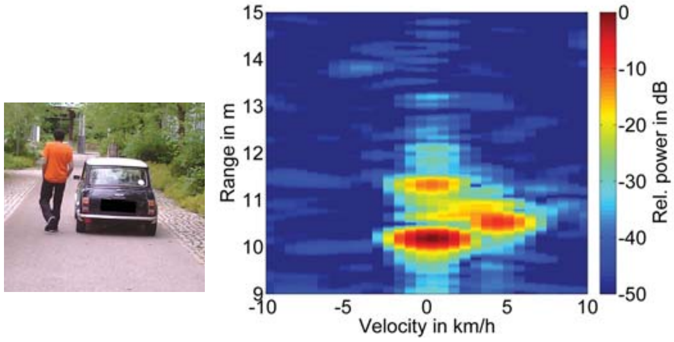

Fig. 7. Measurement result of a pedestrian passing a car, using a bandwidth of 1.35 GHz (at a carrier frequency of 79 GHz).

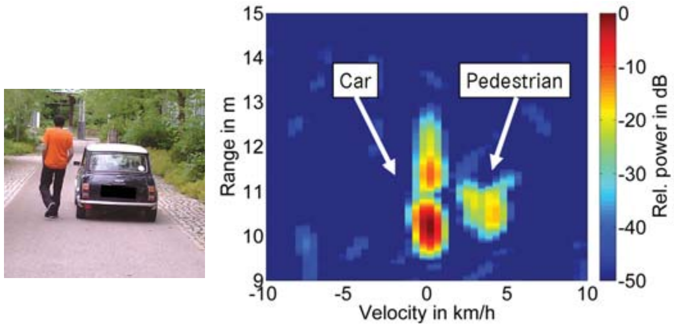

Fig. 8. Measurement result of a pedestrian passing a car, using a bandwidth of 0.5 GHz at a carrier frequency of 79 GHz (AR linear prediction is applied to velocity processing).

can be improved by increasing the bandwidth or by improving the velocity resolution artificially.

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