Paper

24 GHz radar sensors for automotive applications

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Abstract — Automotive radar systems using integrated 24 GHz radar sensor techniques are currently under development [1]. This paper describes a radar network consisting of four sensors distributed behind the front bumper of an experimental car. Each single sensor measures the target range with high accuracy. A multilateration technique is used in the radar network for precise azimuth angle estimation even in multiple-target situations. The system performance is shown in real traffic situations for parking aid, stop & go and blind spot applications.

Keywords — automotive radar, radar network, radar sensors.

1. Introduction

Automotive radar systems in the 77 GHz domain were recently introduced into the passenger car market as a security and comfort system for the driver. These adaptive cruise control systems (ACC) have a maximum range of 150 m and measure the target range, Doppler frequency and angle using three adjacent and overlapping antenna beams with high resolution and accuracy [2].

For parking aid applications additional ultrasonic sensors with a maximum range of 2 m are used, having limited potential to extend the functionality to other applications like stop & go support of a narrow beam long range radar. For this reason radar systems in the 24 GHz domain which have good performance in range and azimuth angle measurement are of interest and can therefore be applied in different automotive applications like:

- **parking aid** with higher precision, longer range and higher update rates than conventional ultrasonic systems;
- **blind spot detection** with a very cheap sensor technology;
- support of adaptive cruise control systems in **cut-in- and stop & go-situations** due to the fact that the short range sensors can have a higher beam-width than the forward-looking long range sensor;
- **pre-crash detection** with very high detection update rates.

The system described in the following chapters was mainly tested in parking aid and stop & go scenarios with good results and still remaining potential for additional applications.

2. Radar sensor for the frequency 24 GHz

A detailed technical description of the used 24 GHz radar sensors is shown in [3]. The measurement technique is based on a pulse radar principle with very short pulse length of 350 ps and a pulse repetition frequency of 4 MHz. Table 1 shows the main features of the high resolution radar sensors. The sensor measures the target range only, but with high resolution and accuracy. The maximum range is 20 m, the range accuracy is ± 3 cm and the achieved range resolution is approximately 6 cm due to the very short transmit pulses.

Table 1
High resolution radar features

Parameter	Min.	Typ.	Max.	Unit
Range	0.15		20	m
Pulse width	300	350	400	ps
Duty cycle		0.175		%
Avg. power	−22	−20	−19	dBm
Peak power	4	5	6	dBm
Power EIRP			20	dBm
S/N	30	32	34	dB

A block diagram of a sensor is shown in Fig. 1. The complete range up to 20 m can be scanned by setting the adjustable delay for the transmit pulses used for the mixer. The reflected and received pulses are mixed down with the

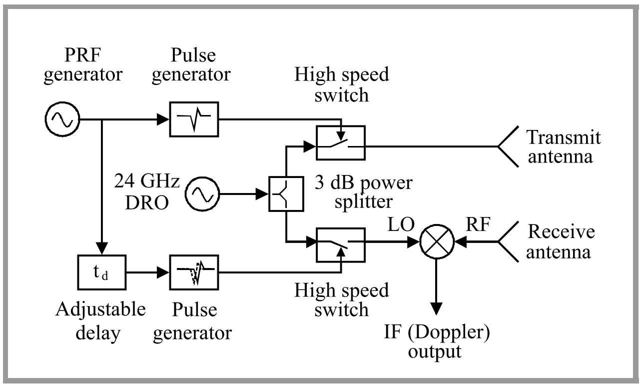

Fig. 1. Sensor block diagram. Explanations: IF – intermediate frequency, LO – local oscillator, PRF – pulse repetition frequency (in this case 4 MHz), RF – radio frequency, t_d – delay time, DRO – dielectric resonator oscillator.

delayed transmit pulses. The sensor output is an analog IF-output signal.
Reflecting targets in the sensor's field of view result in amplitude peaks of integrated pulses energy in the sensor IF-output signal. The corresponding amplitude depends on the target's radar cross-section and on the signal phase. The sensor IF-output signal is processed using conventional envelope detection methods. For signal baseline adaptation a special filtering is used. The signal difference between IF-output and estimated baseline is then applied to a CFAR threshold calculation algorithm taking the signal noise into consideration. The noise-adaptive threshold is used for the envelope detection. Range information of all detected targets is then sent to the radar decision unit for the following data fusion and azimuth angle estimation.

3. Radar network architecture

An experimental car fully equipped for adaptive cruise control usage [2] has been used for tests and to obtain realistic data. The front bumper of the vehicle is equipped with a short range radar sensor network consisting of four sensors with separate control units and a central processor for the data fusion as shown in Fig. 2.

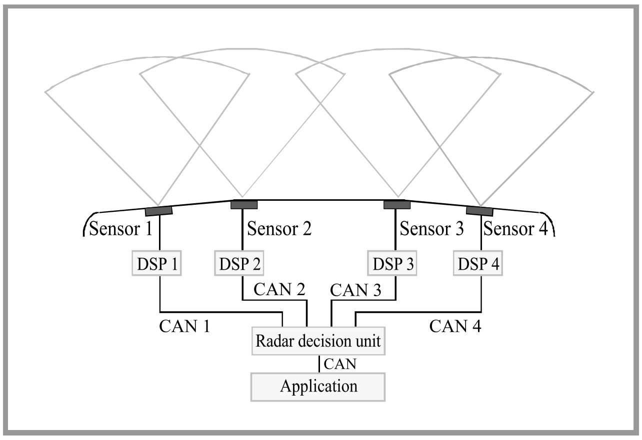

Fig. 2. System architecture overview. Explanations: CAN – controller area network (a serial automotive bus), DSP – digital signal processor.

The sensor IF-output signals are processed separately in the DSP control units and four target lists are sent to the central processor (radar decision unit) via CAN bus. Each single sensor measures the target range only. The data fusion is performed in the radar decision unit. Output of this central processor is an object map including distance information for all detected objects as well as an estimated relative velocity and the angular positions of the objects in azimuth.
For the object map update rates of 20 ms are achieved so far which is planned to be reduced in future. The object maps are finally used by further vehicle applications e.g. for activating the vehicle brakes.

4. Data fusion overview

The radar decision unit uses single sensor range information for angle estimation of the detected objects and for estimation of relative velocities of all detected objects in the sensor's field of view. The processing steps performed in the radar decision unit are shown in Fig. 3.

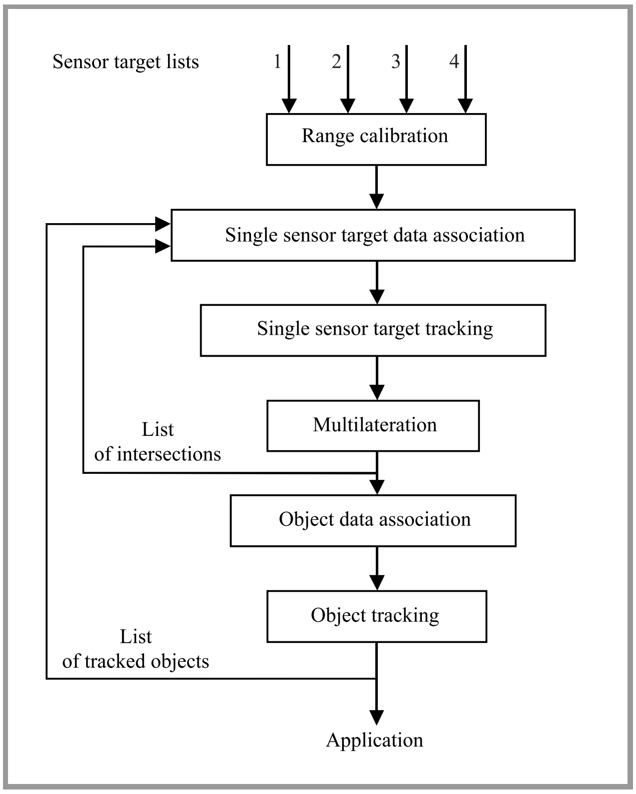

Fig. 3. Data fusion overview.

The transmitted sensor target lists are first corrected concerning their range information. Due to the fact that the distances between the sensors within a vehicle bumper are very small, a very precise range measurement is of great importance for very accurate angle estimation. A measured distance precision of approximately ± 3 cm in a complete measurement range of up to 20 m is necessary to achieve precise angle estimation results.
The data fusion is separated into more than one tracking step. First a single sensor target data association finds the correct sensor target tracks for the targets detected in the last cycle for each sensor separately. The single sensor target tracker tracks the targets in order to close detection gaps caused by limited probability of detection. A radial velocity for each tracked single sensor target can be estimated with very high precision because of the sensor's very precise distance measurements. This is done by conventional α-β-tracking filter techniques.
Due to the fact that the sensor shown in Fig. 1 has only a single channel IF-output, the signal amplitude even of reflectors with high radar cross-sections can be very tiny depending on the signal phase and in some cycles the target might not be detected. That explains the importance of the single sensor tracker.

The sensor tracks are applied to least-squares estimation techniques to really make usage of the redundancy in the system to minimise the errors of estimated range and angle information in the multilateration step. The resulting distance error for the detected and measured object is less than the error of a single sensor distance measurement due to the least-squares estimation. The output information of the multilateration step is a list of intersections for all detected objects. This is an update of the position information for all objects including distance and angle. These intersections are associated to object tracks in the next step and then tracked by the object tracker.

The resulting output of the complete data fusion is a list of tracked objects. For all objects distance, angle and estimated velocity are calculated and delivered to the specific application like the ACC distance control algorithms.

The feedback of all obtained information within the data fusion process showed to be very important for all data association steps. The list of intersections and the list of the resulting tracked objects are used for data association in the single sensor tracker as shown in Fig. 3.

In parallel to the described processing using least-squares methods for position calculation, Kalman-tracking filters were implemented and first simulated. Similar results can be achieved with Kalman-filters with the difference that the Kalman-filter comprises the steps of multilateration and object tracking in Fig. 3 within a single optimal filter algorithm. This makes the Kalman-filter the more elegant way of filtering with finding a precise position solution for the detected objects in parallel. The Kalman-filter was processed in a serial structure in this case. For the current system the least-squares method was preferred, but further optimisations will surely include a Kalman-filter.

5. Experimental results

The experimental system integrated in an experimental car is shown in Fig. 4. The sensors can be covered by an additional radome in the shown bumper or mounted directly behind a normal vehicle bumper. This makes the complete radar system invisible compared with an ultrasonic system, an interesting feature for design aspects. Different traffic situations were tested with this system.

Until now the considered traffic scenarios included many parking aid situations to achieve good performance in a less critical application. But also stop & go tests e.g. the passing of parked cars or the following of other cars were performed successfully. The system shows good performance to support a long range radar in stop & go and cut-in situations. Blind spot surveillance only needs presence detection with precise distance measurement which can be done very well with a single sensor.

Fig. 4. Experimental vehicle equipped with a short range radar sensor network.

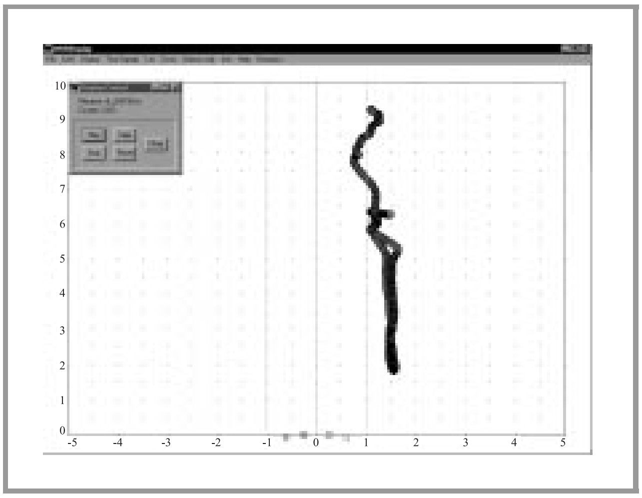

Fig. 5. Object trajectory when approaching and receding a street lamp post.

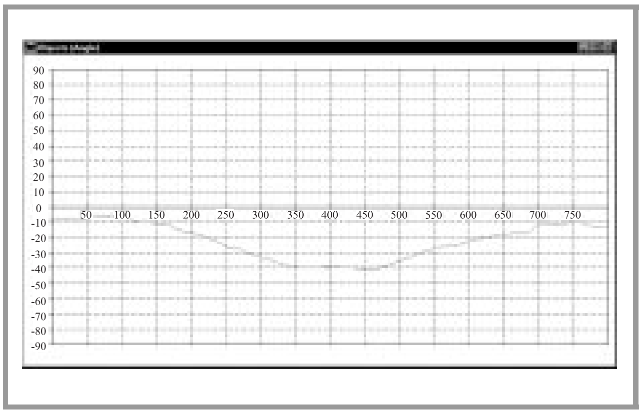

Fig. 6. Estimated angle for the last 800 cycles (16 s).

Figure 5 shows a recorded situation in an *x-y*-plot where the experimental car approached and receded a lamp post (10 cm diameter) on the right side of the road. The driving lane is indicated with two straight lines at ±1 m from the vehicle center line. The maximum distance shown is 10 m. The calculated trajectory of the object during the complete measurement is shown. An estimated angle of the object in this situation can be seen in Fig. 6. The angular range in this measurement is between approximately 5° up to 40°. Precision of the estimated angle is high in short distances where all sensors detect the object and redundancy maximises the accuracy. Additionally no false alarms can be observed in the data fusion output during the whole measurement (Figs. 5 and 6).

6. Conclusion

It was shown that new radar technology in conjunction with modern digital hardware are well suited for interesting automotive applications meeting the key product parameters like performance, size, price and high update rates. Beyond already introduced ACC radar systems, additional applications can be covered with a multifunctional short range radar network in vehicles. This article shows an interesting sensor concept which can be used for such a system. An experimental vehicle is equipped with such a sensor network to get experiences with measurements in realistic street situations. The system architecture was described and an overview of the signal processing steps was presented. Especially the data fusion part comprises very important parts of the complete processing to achieve high accuracy with this system. Convincing results from realistic street traffic situations confirm the feasibility of the complete system and are encouraging for further research activities.

References

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