Chapter 1

Introduction

The first invention of RADAR (radio detection and ranging) can be dated around the beginning of the twentieth century. In fact, several researchers in different countries announced the birth of radar at similar times. All these works were based on the equations of the british physicist James Clerk Maxwell describing the behavior of electromagnetic waves in 1864. Inherent in Maxwell's equations are the laws of radio-wave reflection, which were first demonstrated in 1886 in experiments by the German physicist Heinrich Hertz. Some years later, the German engineer Chistian Hülsmeyer proposed the use of radio echoes in a detecting device designed to avoid collisions in marine navigation on the river Rhine. But until the 1930s no further interest in the radar technology was aroused. The threat of war along with growing technological advances all over the world prompted many countries to intensify their research in the field of radar.

Nowadays many peaceful radar applications can be found in our everyday life such as radar for weather analysis and prediction, for the discovery and rescue of avalanche victims, or just as the vandal-resistant automatic toilet flush. The first research activities in the field of automotive radar systems for road traffic situations were started in the 1970s with the aim of increasing the comfort and safety of road users in times of permanently growing traffic. But at that time, the geometrical size of a single radar sensor exceeded the size of a practical series product. The cost and the performance of such a system did also not meet the necessary requirements for comfort and safety applications in a passenger car. Since then, the fast development in microwave technology and microelectronic has led to an improvement concerning all these requirements. Today's radar front-ends are small enough to be integrated into a car, the necessary signal processing hardware is powerful enough to handle different algorithms and the reduced cost make it possible to develop new active comfort and safety applications.

This thesis will present a postprocessing architecture for an automotive radar network that has been implemented in a test vehicle and evaluated in real road traffic scenarios. Before this, different multi-sensor radar network concepts will be investigated and their characteristics in estimating the road users' kinematic states as well as interpreting typical road traffic scenarios will be discussed. It will be explained how different postprocessing algorithms can enhance the radar network's performance and what typical challenges

	Ultrasonic	Lidar	Video	Radar
Max. Range	−−	+	*o*	++
Range Accuracy and Resolution	+	++	*o*	++
Angular Accuracy and Resolution	− multiple sensors needed	++ scanning principle	++	Accuracy:+ Resolution:−[1]
Range Rate/ Velocity	−−	*o*	−	++
Extended Objects	−−	++	++	+
Obscuration (Rain, Snow, Fog)	−	*o*	−	++
Size / Packaging	visible	visible	visible	invisible
Cost	++	+	+	*o*

Table 1.1: Different sensor types and their suitability for automotive applications

have to be faced in the field of automotive radar processing.

This chapter will first present an overview of the different automotive radar applications and will explain the appropriate requirements of these systems. To develop an understanding for the system properties and especially for the postprocessing task in an automotive radar network, the basic radar measurement principles will be outlined. After this, two high-performance radar sensors and their measurement properties will be presented. With these radar front-ends, three different multi-sensor radar network concepts will be established and compared in respect of the different estimation criteria for automotive applications. Finally, the basic steps of a postprocessing architecture will be outlined.

1.1 Automotive Radar Applications

The safety of road users in times of permanently growing traffic has become a major topic for automotive companies in recent years. Many systems such as airbags, ABS (Antilock Braking System) with EBD (Electronic Brake Distribution) and brake assistant, ESP (Electronic Stability Program), SRS (Supplemental Restraint System), or the preventive belt pretensioner have been invented and the properties of car frames and bodies concerning the energy absorption have been optimized to protect the passengers inside a car. Most of these systems reduce the risk of getting injured if an accident happens or even the probability of losing the control over the car, but the ultimate solution to achieve the reduction of accidents are active safety systems that prevent cars from smashing into

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[1] Most of today's radar sensors are not able to resolve targets in the azimuth angular direction. To achieve such a resolution, a mechanically or electronically scanning antenna is required. Such radar sensors are under development, but are not available yet.

each other. The first simple collision avoidance features are already on the road as pricey adaptive cruise control options on a small group of luxury cars, but in the near future this technology will become widely available.

In the field of automotive comfort- and safety-applications, different sensors such as ultrasonic, infrared, lidar (light detection and ranging), or radar sensors as well as video cameras are currently under investigation. Table 1.1 shows the different criteria that are important to car manufacturers for their new applications and the appropriate suitability of the different sensor types. These requirements can be grouped into three main categories, namely sensor performance, sensor size/visibility, and cost. To be economically successful in all automotive segments, the cost of a single sensor should be around ten dollar in mass-production, and since design plays an important role in selling cars, the sensors must also be "invisible" in the car body. This means that the sensors should be small in size and that they can be hidden behind the front bumper, for example. No "holes" should be visible as it is the case for today's ultrasonic park distance control sensors. The requirements concerning the performance are depending strongly on the targeted application. Generally, it is advantageous to have a large set of measurement information available. For automotive applications, the measurements of today's sensors comprise

- range
- azimuth angle
- velocity
- object size

The evaluation of a sensor's measurement performance can be manifold. The characteristic values that are generally utilized to describe the sensor performance are

- the accuracy,
- the resolution,
- the maximum unambiguous range.

The measurement accuracy is defined as the standard deviation of the measurement relative to its expectation value. In the ideal measurement case, the expectation is the error-free measurement, i.e. the ideal measurement corresponding to the real target position. The resolution of a sensor is defined as the least necessary condition that leads to a separate detection of two neighboring objects of equal size with equal reflection properties, i.e. with the same radar cross section (see section 1.2.3). It depends strongly on the radar sensor's measurement principle. If no scanning receive antenna is utilized, then no resolution in the azimuth angular direction can be achieved. The range resolution of a sensor, i.e. the least necessary radial distance between two neighboring objects, depends directly on the bandwidth of the utilized transmit waveform (see section 1.2).

	ACC	Parking Aid	Blind Spot Surveillance	Lane Change Assistant
Update Rate:	≧ 20 Hz	≧ 10 Hz	≧ 10 Hz	≧ 20 Hz
T_{Cycle}	≦ 50 ms	≦ 100 ms	≦ 100 ms	≦ 50 ms
Range:				
Min. Range	1.0 m	0.0 m	0.5 m	0.5 m
Max. Range	200.0 m	8.0 m	5.0 m	150.0 m
Range Accuracy	0.25 m	0.05 m	1.0 m	1.0 m
Range Resolution	1.0 m	0.1 m	0.5 m	0.5 m
Azimuth Angle				
Angular field of view of a single sensor	±15°	±60°	±60°	±60°
Angle Accuracy	2°	2°	–	2°
Angular Resolution	5°	5°	–	5°
Velocity				
Min. Velocity	−360 km/h	−50 km/h	–	−360 km/h
Max. Velocity	180 km/h	50 km/h	–	180 km/h
Velocity Accuracy	0.45 km/h	0.1 km/h	–	0.45 km/h
Velocity Resolution	1.8 km/h	1.0 km/h	–	1.8 km/h

	Pre-Crash Warning	Collision Avoidance	Stop & Go (incl. ACC)
Update Rate:	≧ 100 Hz	≧ 100 Hz	≧ 50 Hz
T_{Cycle}	≦ 10 ms	≦ 10 ms	≦ 20 ms
Range:			
Min. Range	0.3 m	1.0 m	0.3 m
Max. Range	30.0 m	200.0 m	150.0 m
Range Accuracy	0.05 m	0.25 m	0.25 m
Range Resolution	0.25 m	0.25 m	0.25 m
Azimuth Angle			
Angular field of view of a single sensor	±60°	±15°	±60°
Angle Accuracy	2°	2°	2°
Angular Resolution	5°	5°	5°
Velocity			
Min. Velocity	−250 km/h	−360 km/h	−360 km/h
Max. Velocity	100 km/h	180 km/h	180 km/h
Velocity Accuracy	1.0 km/h	0.45 km/h	0.45 km/h
Velocity Resolution	3.0 km/h	1.8 km/h	1.8 km/h

Table 1.2: Suggested requirements for different automotive applications

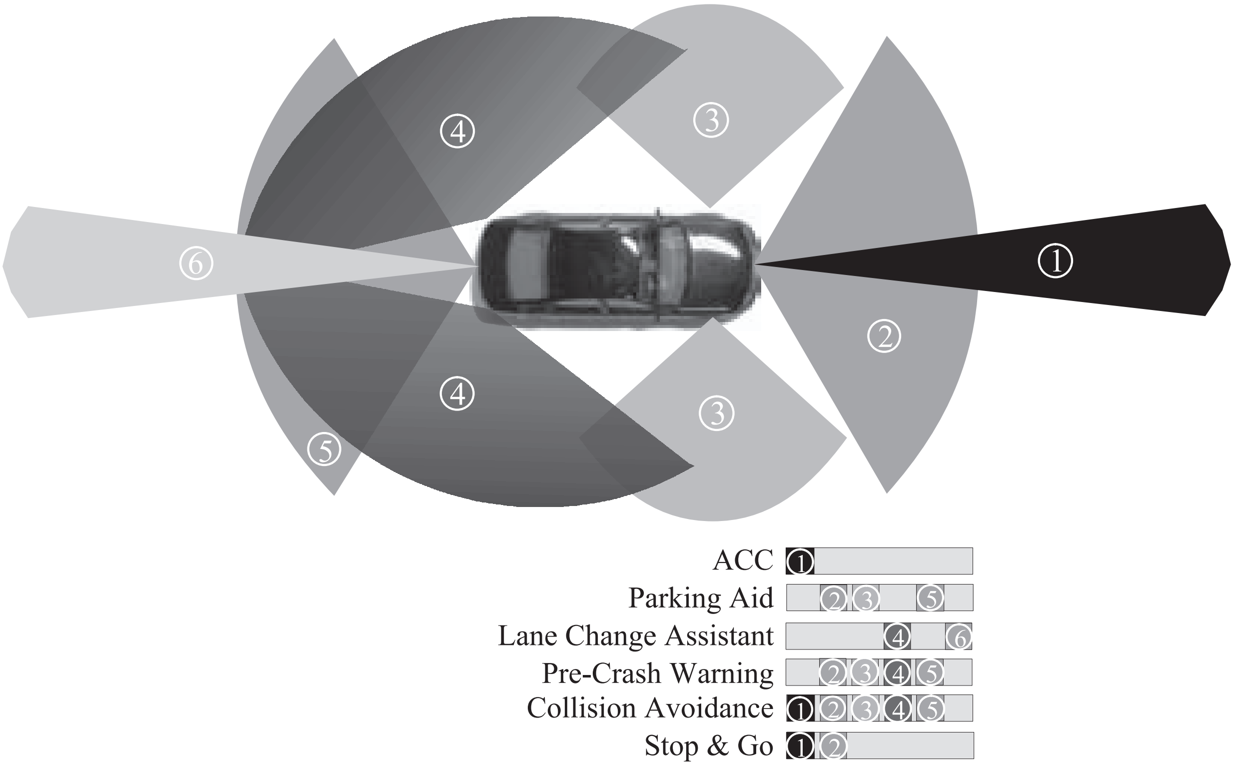

Figure 1.1: Automotive applications for a combined near- and far-distance sensor network

The maximum unambiguous range of the measurements is also an important criterion. Today's radar sensors can be grouped into three categories referring to the maximum detectable range of an object. So-called far-distance sensor can achieve a maximum range that lies within 150 and 200 m with a small azimuth angular coverage of about 10°. Near- and medium distance sensors cover a range area up to 20-50 m and have a wider azimuth angular antenna coverage that of about 60°-120°. Finally, the sensors must be robust and work with the same high performance in all weather conditions.

As shown in table 1.1 the ultrasonic sensors are low in cost but their maximum range is too small for many wanted automotive applications. Another disadvantage of this sensor type is the visibility in the car body, e.g. the "holes in the front bumper" known from today's park distance control systems. Nevertheless, these kind of sensors are favored for parking aid applications at the moment, because they are very low in cost and show an acceptable measurement performance for applications with very short distances. Lidar sensors and video cameras show a good range and angular measurement performance but this performance is not weather independent. This means that these sensors downgrade their measurement performance in rain or snow due to line-of-sight obstruction. In the case of lidar sensors many enhancements have been established by different sensor manufacturers, so that some of today's lidar sensors show an acceptable bad weather performance. But the robustness and weather independence paired with the invisibility of the sensors in the car body, the compact sensor size, and a high measurement performance are the big advantages of radar technology. Car manufacturers are investigating systems consisting of different sensor types in order to find the most versatile and low-cost combination. Figure 1.1 shows a versatile multi-sensor radar network covering the scan areas of different automotive applications. Such a complete radar network will probably not be implemented in a final product, nowadays. But since the number of driver assistance functions in a passenger car will increase in the future, this may be a possible sensor constellation in a few years. Figure 1.1 shows also a table summarizing the sensor combinations that are at least demanded by the different automotive application. Cost considerations will play a vital role in the implementation of each system. It will drive the system architectures to minimize the number of sensors on the vehicle in order to reduce component and installation cost. The performance requirements of a multi-sensor network also depend strongly on the targeted application. These application-dependent requirements are summarized in table 1.2. Concerning the functionality, the scan area, and the performance requirements, the different automotive applications can be characterized as follows:

- **ACC (Adaptive Cruise Control)**
  An ACC system is a convenience application for the driver and can be considered as an enhancement of the standard cruise control. While the standard cruise control performs best in low traffic environments with a very low number of obstacles in the own driving path, the adaptive cruise control enhances its performance to more dense traffic situations. The ACC system is able to decelerate if the own vehicle is approaching another slower moving car situated in the same lane and to accelerate again if such a slower moving car is changing lanes in order to give way. The required detection area of an ACC system is mainly the own lane as well as the two neighboring lanes at a greater distance in front of the own car. The first ACC systems are on the market Since 1998 and are now offered by several car manufacturers as an option for their luxury cars. Most of these systems operate with a 77 GHz far-distance radar sensor that can detect targets up to a maximum distance of at least 150 m ahead of the own car. The far-distance sensor is mounted in the front bumper, so that the scan area visualized in figure 1.1 is achieved. The update rate of an ACC system should be better than 20 Hz in order to decelerate in time if an obstacle is detected in the driving path of the own car. The first ACC systems were restricted to road traffic situations, where the own vehicle is moving faster than 80 km/h. But today's ACC systems are working properly at 30 km/h and will be enhanced in the future by additional near- or medium-distance sensors to achieve a stop & go functionality.

- **Parking Aid**
  The purpose of a parking aid system is to support the driver in a parking maneuver. The general action is the movement of a vehicle from an area where the traffic flows to an area close to the traffic flow where the vehicle can be left stationary. This includes a planning of the parking maneuver by checking the size of the parking lot in comparison to the size of the own car and the own driving capability. Such a driver assistance functionality can be achieved at different levels. The basic level is to inform the driver by optical or acoustical means if an obstacle at the front or

rear gets close to the host vehicle. This can be combined with an alert signal at a certain minimum distance, for example. The driver has to check by his own if the desired parking lot is suitable for his car and the planned parking maneuver. This functionality is already achieved by today's park distance control. At the next level of a parking support system, the driver is given information about the desired parking lot and maybe a recommendation about the vehicle path (steering angle, car speed). At the final level, the complete parking maneuver is done automatically by the car. The required scan area for such a parking aid system is ideally the whole near-distance area around the car (see figure 1.1) or at least the near-distance area in front and behind the front and rear bumper, respectively. One car manufacturer presented a system that is relying basically on two side-looking sensors mounted in the vehicle's right mudguard and on sensors covering the near-distance areas in front and behind the car. The side-looking sensors are measuring the size of the parking lot while the car is driving past it. Then, the car is informing the driver if a parking maneuver is possible. If this is the case, the driver assistance system is automatically steering the car while the driver is only controlling the speed of the maneuver. Such a system requires only a low update rate because the car's movement is very slow compared to normal road traffic maneuvers. The necessary maximum range of the sensors is very small, e.g. about 15 m. But it is important that the range measurements are very accurate to enable a precise parking maneuver.

- **Blind Spot Surveillance/ Lane Change Assistant**
  The purpose of these safety applications is to avoid a classical reason for accidents, a driver has overseen an obstacle being in the blind spot of his car or one that is approaching with high speed on a neighbored lane while the driver is maneuvering in the appropriate direction. Such an accident can simply be prevented if e.g. an acoustical or optical signal in the side rear mirrors informs the driver of the obstacle's presence in his car's blind spot area. The blind spot surveillance system requires a small detection area with a maximum range of 5 m at the location of the car's blind spot. Velocity measurements are not relevant for this application because it is a mere presence detection. The lane change assistant system can be considered as the logical extension of the blind spot surveillance system. At this, the driver is informed whether an obstacle will be situated on the right or left lane next to his car in the next moments. If he wants to change lanes in such a situation, a warning signal will appear. Since this application is preferred for highway-driving where high relative velocities may be measured, precise velocity measurements are necessary and the detection area of the side- and back-looking sensors must cover up to 150 **m** behind the own vehicle (see figure 1.1)for a lane change assistant with full functionality.

- **Pre-Crash Warning**
  The general function of the safety application "pre-crash warning" is to detect an unavoidable crash with an obstacle a short time before the impact occurs. If there is a high probability of such an impact, the safety restraint systems will be provided with the appropriate information and thus can react a few milliseconds before the crash occurs. A possible reaction to the information of the radar network will be

a faster airbag deployment in a combination with some degree of car deceleration. Since a crash can occur from every direction, the pre-crash warning system requires the whole near-distance area around the car for detection (see figure 1.1). The required update rate of such a safety application is very high because collisions with other vehicles may occur at very high relative speeds. It is extremely important, that the pre-crash warning system detects an unavoidable crash as early as possible with an extreme low false alarm rate, so that the system can react properly.

- **Collision Avoidance/ Warning**
  A collision warning system has to give the driver information that is indicating the need for urgent action to avoid a collision. The warning has to be provided in the advanced phases of a dangerous situation in order to draw the driver's attention to the need of performing an emergency braking, lane changing, or other collision avoidance maneuvers. If these necessary actions are performed automatically by the vehicle, the application is called collision avoidance system. Since collisions can occur from every direction, the scan area of the sensors must cover the whole near-distance area around the car. But in contradiction to the pre-crash warning system, the driver or system must be able to react quickly enough to avoid the collision. This gives a certain importance to the area where the obstacles with the highest relative velocity approach from, the area in front of the car. Thus, such a collision warning/avoidance system requires a far-distance sensor in the front bumper covering up to 200 m in range. For the same reason, the update rate of such a safety system must be very high in order to detect possible collisions as early as possible.

- **Stop & Go**
  The stop & go functionality is an enhancement of the adaptive cruise control enabling it to be utilized in more traffic scenarios than a simple ACC system. The main difference from today's ACC systems is that the stop & go system shall be able to bring the vehicle to a complete stop and also to accelerate it again. Because of this functionality enhancement, the stop & go system will further extend the usability of today's ACC systems to more dense traffic situations, such as city traffic and congested highway scenarios. Due to the demands of a close target detection and an early reaction in cut-in situations, the stop & go system requires additional near-distance sensors with a wide azimuthal scan area. These sensor are mounted in the front bumper as shown in figure 1.1. The update rate must be slightly higher than the one of an ACC system, because the stop & go system should work in dense traffic scenarios, where obstacles can suddenly appear in the driving path from different directions.

Because of the fact that all applications have a great impact either on the response of the driver to a warning signal or directly on the speed and maybe somewhere in the future on the steering angle of the car, they share a key requirement:

- high reliability

The newest field in today's radar signal processing research is the classification of road users by distinguishing between pedestrians, cyclists, passenger cars, and large trucks. The first results in this new automotive radar signal processing area have been promising and the above described applications will be enhanced by using more information about the detected objects in the future.

In the following, this thesis will concentrate on radar networks consisting of near- or medium-distance sensors that are needed for the parking aid, blind spot surveillance/lane change assistant, pre-crash warning, collision avoidance, and stop & go systems.

1.2 Radar Measurement Principles

Before introducing the considered radar sensors and the possible radar network concepts, this section will give a brief introduction to radar transmit signals and the underlying measurement principles. As already mentioned in the previous section, the most common measurements available from today's automotive radar sensors are

- range
- azimuth angle
- velocity
- object size

The principle of a radar bases on the reflection of a transmit signal at an object. A radar sensor is determining the range between itself and the detected object by measuring the time delay τ between the transmit and the receive signal, i.e. the duration that it takes the electromagnetic wave to travel this two-way path with the speed of light c [Roh01]. The corresponding **range** r can be calculated from the time delay τ

$$r = \frac{c \cdot \tau}{2} \tag{1.1}$$

The **radial velocity** measurement of an object bases on the Doppler frequency shift $f_{Doppler}$ between the transmit and the receive signal. This shift is given by

$$f_{Doppler} = \frac{-2 \cdot v_r}{\lambda} \tag{1.2}$$

where λ is the wavelength and v_r is the radial velocity of the object relative to the radar sensor.

To determine the **azimuth angle of the object's direction**, different techniques can be applied. The oldest one is the physical moving of an antenna beam through the desired azimuth angle range. A more modern approach is an electronic beam steering with array