COOPERATIVE SENSOR TECHNOLOGY FOR PREVENTIVE VULNERABLE ROAD USER PROTECTION

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ABSTRACT

In the proposed cooperative sensor system, pedestrians carry a reactive transceiver which is interrogated by a localization and tracking unit in the car. The prototype system applies Round-Trip Time-of-Flight (RTOF) techniques for the determination of the distance between the transponder and the demonstrator vehicle. A smart antenna array integrated into the car is used to determine the Direction-of-Arrival (DoA) of the transponder's response signal. Knowing the distance and azimuth angle relative to the car, the pedestrian's position and movement are calculated. These data are used as input for a highly reliable collision warning and collision mitigation system.
The sensor system is capable of addressing a huge number of communication partners within each measurement cycle. Additionally, secure burst identification is ensured for a robust localization and the suppression of unwanted co-channel interference. This is achieved by using pseudo random coded signals with a Time Division Multiple Access (TDMA) method. The distance accuracy was improved by introducing a new mirror technique in combination with an interpolation algorithm. The prototype localization system set up at 2.4 GHz covers a range up to 200 m in free field condition. With the current system a distance resolution with centimeter accuracy and an angular measurement accuracy of about 1 degree have been achieved.
Based on this low-cost transponder-based localization system, a preventive vulnerable road user (VRU) protection system has been designed and integrated in a test vehicle. The system is capable to provide a warning to the driver if a crash is likely and to autonomously brake the vehicle if the crash is unavoidable.

INTRODUCTION

Protection of vulnerable road users (VRU) is subject to intense research [1] [2]. Generally speaking, VRU protection systems can be divided into two different groups as shown in Figure 1.

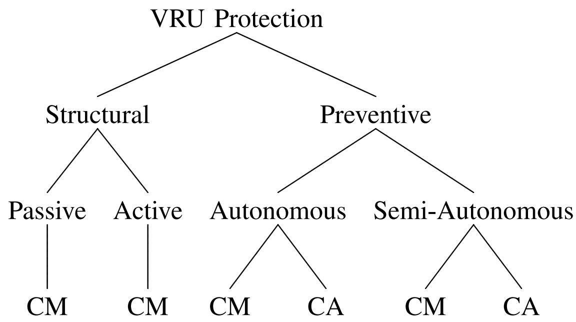

Figure 1: Classes of VRU Protection Systems.
CM: Collision Mitigation Systems
CA: Collision Avoidance Systems

Up to now, mainly re-active protections systems based on structural measures have found their way to the market. In these systems, passive measures like special construction of crash bumpers or active measures like active hoods are taken to minimize the risk of injury or fatality for the VRU after a crash. Common to all re-active systems is, that action only takes place *after* the VRU gets in contact with the vehicle. As a consequence, collision avoidance (CA) is impossible with re-active protection systems and a finite risk of injury and fatality will always be present. As derived recently from accident studies [3], structural measures of pedestrian protection feature only poor effectiveness. To overcome the drawbacks of the structural, re-active approach, preventive protection systems have been proposed [3] [4]. In these systems, protective measures are taken *before* the contact between vehicle and VRU takes place [5]. Protective measures range form fully autonomous emergency braking to preconditioning of the brake system and to warning of the driver, paving the way for both highly effective collision mitigation (CM) systems and for collision avoidance. Although impressive progress has been made, still a large percentage of pedestrian accidents cannot be covered by state-

of-the-art preventive VRU protection systems. This is due to the fact that in these systems, VRU detection, classification and behavioral prediction requires a non-occluded line-of-sight contact between vehicle and VRU [6]. However - as German accident studies have shown [7] - more than 40% of all killed pedestrians were fully or partially hidden until shortly before the impact upon the vehicle and could thus not be protected by current preventive safety systems.
As known from electromagnetic theory, communication to optically hidden partners is possible when using appropriate wavelenghts. To establish a useful communication channel, the wavelength has to be comparable to the size of the objects occluding the line-of-sight contact [8] [9]. Based on this principle, a cooperative sensor system is proposed to detect, localize and track VRUs, predict their behavior and activate protective measures when appropriate [10]. In our approach, a VRU carries a miniature transponder acting as an intelligent radar reflector interrogated by the vehicle. The coded response of the transponder clearly identifies the pedestrian as VRU; the delay of the return signal allows for range determination while its direction-of-arrival indicates the azimuth angle between vehicle and VRU. Careful choice of the system's operation frequency along with intelligent tracking techniques and novel VRU behavior modeling allows for the detection and localization of VRUs even if occluded to the driver. In the Bavarian research project AMULETT, a prototype pedestrian protection system based on 2.5 GHz cooperative sensor technology [11] has be realized an tested. Details on this system along with test results are presented in this work.

COOPERATIVE SENSOR TECHNOLOGY

Distance Measurement

Autonomous distance measurement between two objects mostly uses the Round-Trip Time-of-Flight (RTOF) principle. For the focused application, this corresponds to the time for the signal from the car to the pedestrian and vice versa. Additionally, a fixed waiting time T_w is added on the side of the pedestrian to eliminate the influence of passive reflections and to distinguish the answers from different pedestrian sensors. The distance Δs can then be computed by the totally elapsed time T_p:

$$\Delta s = \frac{T_p - T_w}{2} c_0. \quad (1)$$

Δs is the distance, T_p the elapsed time, T_w the waiting time and c_0 the speed of light.
A variation of the waiting time T_w makes it possible to address different pedestrians [12]. We used a time slot order in which each pedestrian sensor answers in a multiple of a fixed waiting time $n \cdot T_w$ (Figure 2).

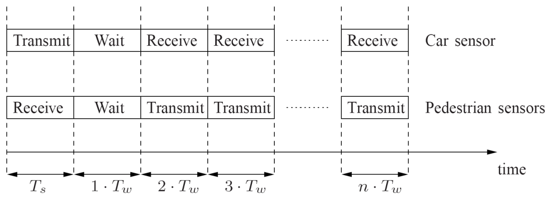

Figure 2: Time slot order in one transmission cycle.

The car sensor starts a measurement cycle by transmitting a data burst with length T_s. All of the pedestrian sensors listen to that burst and answer after an individual waiting time $n \cdot T_w$.
The measurement procedure is carried out by employing a signal correlation technique. The data bursts are encoded with pseudo random codes which are known on each sensor. By correlating the received input signal with the random code the exact time of arrival ΔT can be determined (Figure 3).

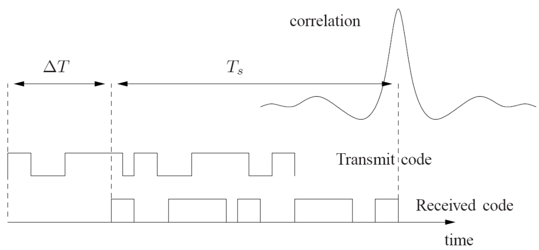

Figure 3: Schematic of a signal transmission between two sensors.

By interpolating the digital correlation result, an even higher distance resolution in a range of a few centimeters has been achieved.
The advantage of this method is a simple modulation and demodulation hardware. In fact, it can be carried out on almost every available transceiver chip providing sufficient bandwidth. Another advantage is the low latency of the measurement procedure. In dependence on the bandwidth, only a few microseconds are necessary to get an adequate correlation result. The downside of this method is an increasing need for processing power, but this can be easily applied in a Field Programmable Gate Array (FPGA) or a Digital Signal Processor (DSP).

Direction-of-Arrival (DoA) Estimation

If the correlation unit of the distance measurement identifies a received signal as valid response of a transponder, a trigger is given to the DoA measurement device. The incident electromagnetic wave is sampled spatially at six antennas of the antenna array installed behind the windshield of the test vehicle. Therefore, distance and angle estimation perform their calculations within one communication cycle. Phases and amplitudes of the incident signal are used to determine the DoA using the Multiple Signal Classification (MUSIC) algorithm. This subspace-based method is based on the eigenvector decomposition of the covariance matrix

$$R_{uu} = E[u(k)^H u(k)], \tag{2}$$

where $u(k)$ is the received signal at the antenna array. By splitting the eigenvector space into signal space and noise space the MUSIC spectrum is obtained [13]. This MUSIC spectrum is evaluated for incident angles from 0 to 180 degree, whereas peaks in the spectrum indicate the DoA of the transponder signal (see Figure 4). In the localization unit the MUSIC algorithm estimates all incident signals including the multipath. For each hypothesis a quality value is determined, based on the evaluation of the MUSIC spectrum in combination with the power of the received signal.

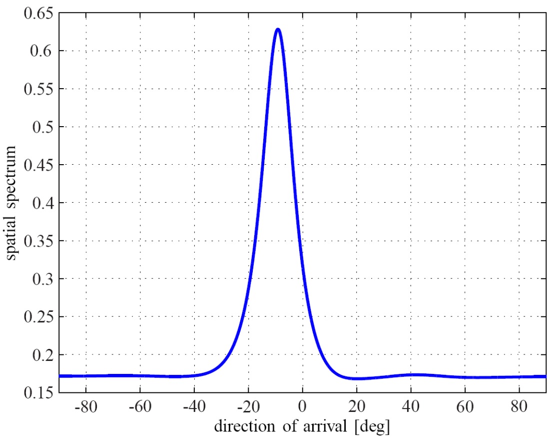

Figure 4: MUSIC spectrum for a transponder located at -9 degree azimuth.

The MUSIC spectrum as well as the correlation results of the distance measurement are used for an adaptive tracking of pedestrian positions.

Object Tracking

An extended KALMAN-FILTER is used to track the obtained transponder positions. Unlike the standard KALMAN-FILTER [14] state transition and observation models don't necessarily have to be linear functions of the state. In the transponder tracking system the observation model h which maps the state variables in cartesian coordinates to the measurement variables in polar coordinates is defined as:

$$z_k = h(x_k) \tag{3}$$

where z_k is the measurement vector

$$z_k = \begin{pmatrix} r \\ \phi \end{pmatrix} \tag{4}$$

and x_k is the state vector.

$$x_k = \begin{pmatrix} x \\ y \\ v_x \\ v_y \end{pmatrix} \tag{5}$$

As function h can't been applied directly to the KALMAN-FILTER equations the partial derivative, the JACOBIAN matrix, needs to be computed [15]. The resulting observation matrix H and the state transition matrix F using a constant velocity model are applied for the tracking of the pedestrian. F is stated as

$$F = \begin{pmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{6}$$

where T is the sample time of the system. Taking ego motion parameters of the vehicle like velocity and yaw rate into account, an estimation for movement of the pedestrian in a global coordinate system can be given and used as input for a collision assessment algorithm.

Signal Preprocessing

The principles of the distance measurement as well as the angle measurement allow for a calculation of several hypotheses. In case of multipath propagation under non-LoS conditions the main maximum in the correlation result or in the MUSIC-spectrum might represent a reflected signal arriving from a different direction than direct transponder signal [16]. In these cases positioning based on these maximium values is insufficient. Therefore the secondary maxima are taken into account.

Based on the lastest tracking results the current distance and angle measurements are investigated to determine the correct distance and azimuth information as input for the next tracking cycle. Fig. 5 shows two possible DoAs derived from the MUSIC spectrum, where the smaller peak indicates the azimuth angle of the transponder.

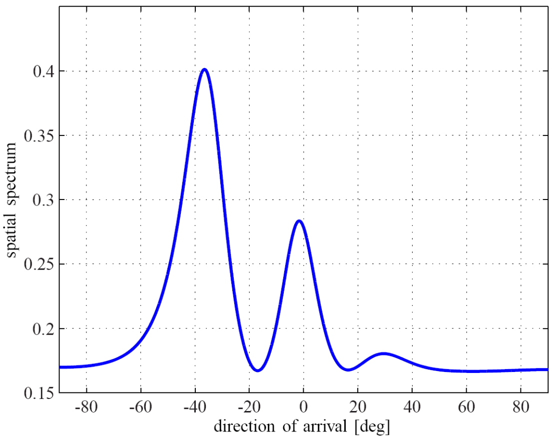

Figure 5: MUSIC spectrum for transponder at -1.4 degree and multipath signal impinging at -37 degree

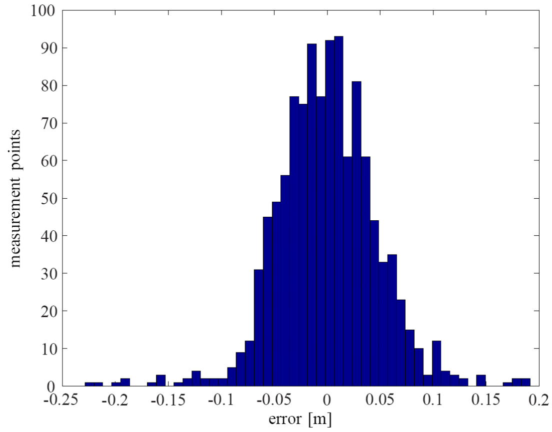

Figure 7: Histogram of the distance error in reference to a DGPS System

As a matter of fact the standard deviation of 4.7 cm is partly caused by the DGPS System inaccuracy. The difference values between both systems are shown in Figure 7.

MEASURED PERFORMANCE OF COOPERATIVE LOCALIZATION SYSTEM

Quality of Distance Measurement

For the characterization of the RTOF sensor a test scenario with a moving car and a fixed pedestrian position was used. The car moved with an approximate speed of 12 km/h straight in the direction of the pedestrian. The measurement started at a distance of 180 m to a distance of 2 m directly in front of the car. As reference a differential GPS (DGPS) system [17] with an accuracy down to 2 cm was used. Fig. 6 shows an extract of the distance values of both systems.

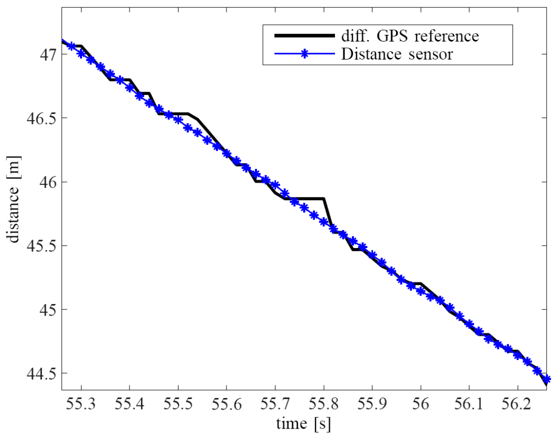

Figure 6: Distance values in the sector from 47 m to 43 m

It became obvious during the measurement campaign, that a DGPS system with a accuracy of 2 cm is no longer sufficient to characterize the system completely.

Quality of Direction-of-Arrival Estimation

To evaluate the performance of the DoA estimation several measurement setups have been chosen. Fig. 8 shows results of a measurement where a pedestrian moved circular in front of the test vehicle carrying the transponder and a differential GPS system as reference.

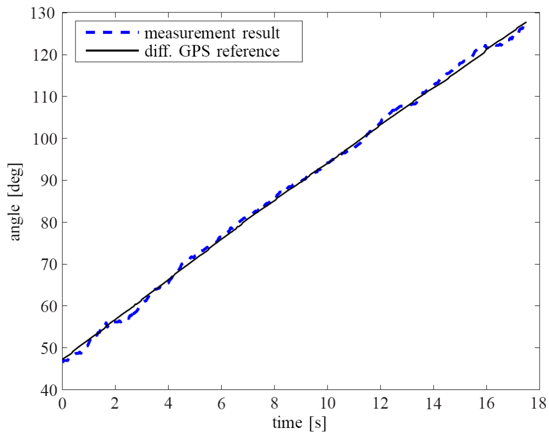

Figure 8: DoA values in the sector from 50 to 130 degree

The distance was kept constant at 15 m in this measurement. This procedure allows for an exact evaluation of the variance and the absolute deviance in dynamic scenarios covering proposed sensor range.

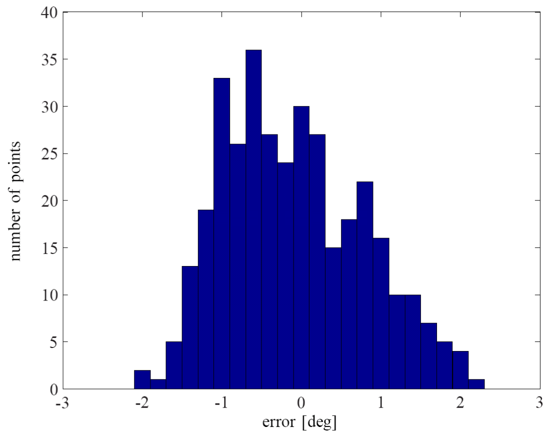

Figure 9: Histogram of DoA values in the sector from 50 to 130 degree

The measurements were repeated several times in different distances and recorded. They showed reproducible results. The standard deviation was determined to be betwen 0.7 and 0.9 degree in all measurements. The differences between the measured angles and the reference for a distance of 15 m are printed in Figure 9. The standard deviation in this example is 0.85 degree.

Performance in Non-Line-of Sight (non-LoS) scenarios

A measurement campaign has been conducted to determine the localization accuracy in a typical urban scenario under non-LoS conditions. While the car drives on the street a pedestrian is standing beside the road occluded by parked cars (Figure 10). Starting at a distance of 20 m the sampled output of the tracking system is compared to the reference system for a transponder height of about 85 cm.

As expected the distance and azimuth angle accuracy decrease compared to the LoS scenario. The distance information shows a mean difference of 0.7 m and a standard deviation of 0.3 m. For the estimated angle a mean difference of 2 deg and a standard deviation of 2.1 deg were calculated. Altogether these results affirm the usability of the cooperative sensor system for pedestrian protection.

Figures 12 and 11 show results of the cooperative sensor system. The tracking output and the reference data are displayed in polar coordinates for a separate evaluation of the two measurement principles.

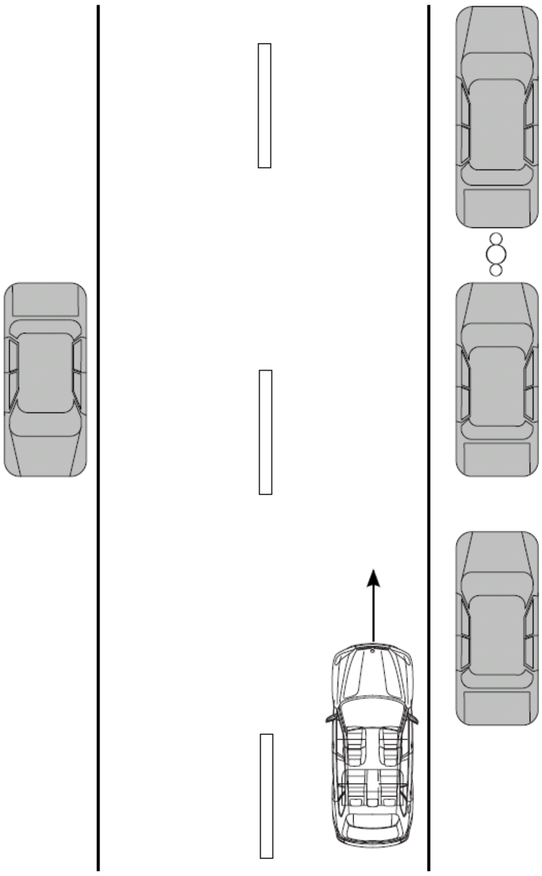

Figure 10: Urban non-LoS scenario with pedestrian occluded by parked cars

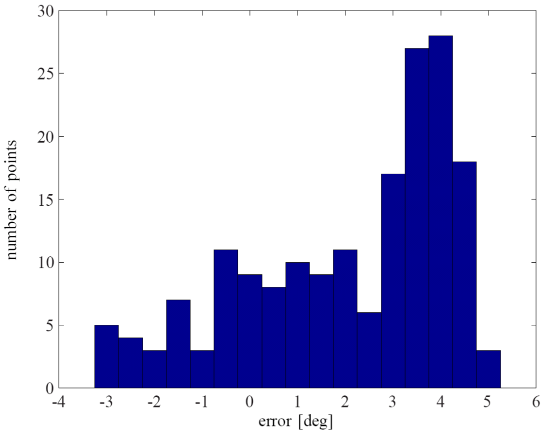

Figure 11: Histogram of error of tracked DoA data in non-LoS scenario

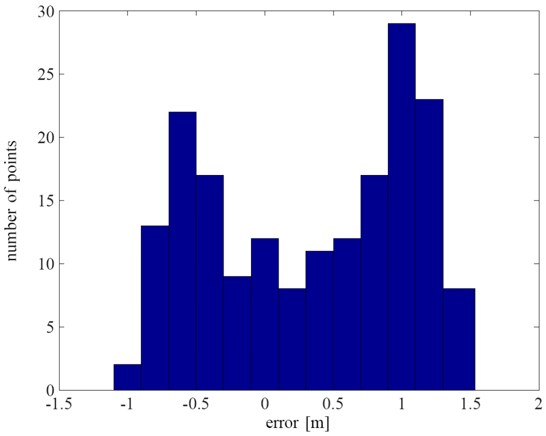

Figure 12: Histogram of error of tracked distance data in non-LoS scenario

CONCLUSION

A cooperative sensor approach for pedestrian protection has been presented. The implemented localization principles have proven to provide contact even without Line-of-Sight (LoS) between communication partners. Positioning accuracy has shown to be sufficient as basis for a highly reliable pedestrian protection system. Even in worst case multipath scenarios without LoS the localization unit has shown to provide adequate results. The clear identification of pedestrians, the positioning accuracy and the sensor range offer the potential to cover a wide range of accident scenarios which cannot be covered with state-of-the-art sensors.

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