Rapid Detection of Fast Objects in Highly Dynamic Outdoor Environments using Cost-Efficient Sensors

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Abstract

In recent years driver-assistance systems have emerged as one major possibility to increase comfort and - even more important - safety in road traffic. Still, cost is one major hindrance to the widespread use of safety systems such as lane change or blind spot warning. To facilitate the widespread adoption of such safety systems, thus increasing safety for all traffic participants, the use of cost-efficient components is of crucial importance.

This paper investigates the usage of cost-efficient, widely used ultrasonic sensors for blind spot warning at high velocities. The normative aspects as well as the functional requirements originating from considerations on human-machine interaction and user-experience are discussed. A fuzzy-markov-chain based approach for the detection of fast objects is outlined. The proposed procedure is implemented on a regular electronic control unit (ECU) and qualitatively and quantitatively evaluated in real road traffic scenarios.

1 Introduction

During the last decade autonomous driving has made a huge jump from the first DARPA challenge [1, 2] over the last Urban Challenge [3, 4, 5, 6] to the latest experiments of Google in the field of autonomous driving. And although legal considerations and costs might be an insurmountable obstacle for a long time, driver-assistance systems have emerged as one major possibility to increase comfort and safety in road traffic [7].

Besides mainly introspective systems such as ABS and ESP recent developments [8, 9, 10] build more and more on exteroreceptive sensors to detect and react on potentially dangerous situations. To facilitate the widespread adoption of such safety systems the use of cost-effective components is of crucial importance. Ultrasonic sensors fulfill these requirements on cost-effectiveness. Consequently, they have been widely used in the automotive industry for periphery surveillance in context of low velocities [11, 12, 13]. A prominent example is the meanwhile ubiquitous parking assistant, giving feedback to the driver on the distance to possible obstacles while backing into a parking lot. However, the sensitivity of ultrasonic sensors to external disturbances such as gusts of wind or rain and their restricted range [14, 15] was for a long time prohibiting in context of high-speed applications, such as the detection of cars in the blind spot of the driver. Another hindrance is the comparably low amount of information contained in the signal. In contrast to more expensive radar, lidar or camera systems [16, 17] that offer an acceptable angular resolution, us-sensors often have a wide aperture. That makes it difficult to distinguish the source or location of an echo.

The work at hand investigates the use of cost-effective ultrasonic-sensors for the detection of objects in the blind spot of a driver at absolute velocities of up to $160\mathrm{km/h}$. It discusses the legal - it is normative - aspects of the application and provides a listing of functional requirements origination from human-machine-interaction (HMI) aspects. The work then illustrates the basic principles of an inverse-geometric-modeling approach that delivers descriptors which are incorporated via a fuzzy-markov-chain [18, 19] to deduce a believe on "A moving object within the blind spot". The discussed approach is implemented on an of-the-shelf electronic control unit (ECU) and validated simulative and experimentally.

Figure 1: View on road traffic through mirror [20]

2 Problem Formulation

2.1 Point of Departure

The general goal of the system is to assist the driver when changing lines by emitting a warning signal in the presence of traffic within its blind spot zone. In order to guarantee the applicability of the system within daily traffic situations, a set of obligatory preconditions must be defined. The blind spot zone is located at both sides of the car and ranges from $3\mathrm{m}$ behind the car to the cars side-mirrors. When traffic is entering the blind spot zone the system must not exceed a reaction time of 300ms. To avoid annoying the driver a low false-alarm rate is as important as the avoidance of unnecessary warnings. For instance if the driver overtakes another car no warning shall be issued, unless the other car starts accelerating as well and thus does not leave the blind-spot zone for some time. These situations are referred to as *front stagnation*. In terms of recognition rate the system is required to have no more than 2 false alarms and 5% missed alarms during a $100\mathrm{km}$ drive in a mix of inner city and outer city driving conditions. The operating range of the system must be designed to detect blind spot alerts to a speed difference between the host and traffic from 0 to $30\mathrm{km/h}$. Finally, computational requirements must suffice the performance of an of-the-shelf electronic control unit (ECU).

2.2 System Setup

The host vehicle is equipped with 12 ultrasonic sensors equally positioned at its front and its back side (**figure 2**). To detect an overtaking vehicle, the algorithm evaluates the measurements of three sensors on each side of the host (dark black cones in figure 2).

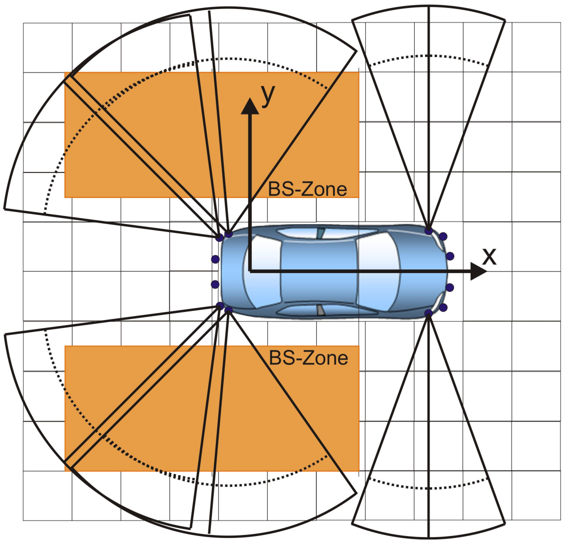


Figure 2: Outline of the host car setup with ultrasonic sensor cones and orange blind spot zone; The grid is composed by $1\mathrm{m}$ to $1\mathrm{m}$ tiles

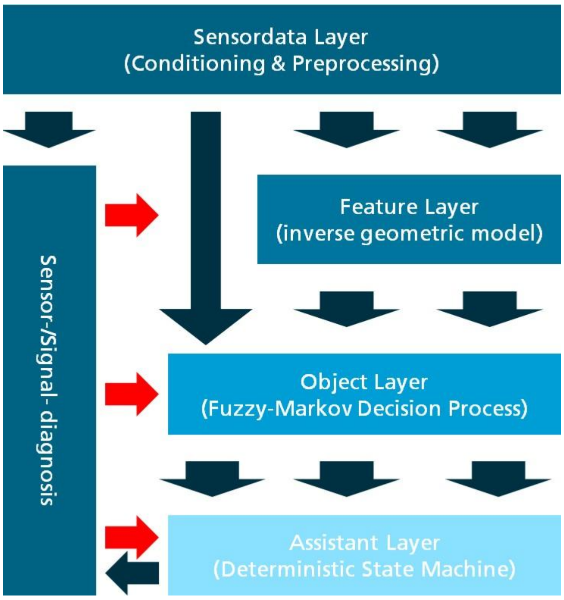


Figure 3: Signal flow and structure of the implemented algorithm

All other sensors are not used for blind spot detection. The aperture of the two resp. four rear sensors is approximately $75\,^{\circ}$ to cover the whole blind spot zone, while the aperture of the front sensors is set to $45\,^{\circ}$. This enables sharp measurements with the front sensor in order to detect incoming traffic from the front or outgoing traffic from the back. In case of traffic residing within the blind spot zone, the driver is notified by illuminating a red light in its side mirror.

For the deployment of the algorithm a regular electronic control unit (ECU) is used. During the design and experimental phase the algorithm was run on 64MHz Leopard (MPC5643L) with 128kB memory.

2.3 Algorithmic Design

The general architecture includes a sensor data layer to record and filter the ultrasonic measurements and odometry data of the host. The filtering is adaptive to alternating weather conditions to cope with the differing appearance of noisy data in presence of e.g. snow compared to sunny weather.

The preprocessed measurements are passed to the feature layer. This layer is concerned with the generation of higher level information by putting the host central ultrasonic measurements within a global world frame and aggregating the information coming from all sensors. Finally, an object layer abstracts the low level features to high level objects like dynamic or static objects, objects approaching from behind or from the car's front. The final decision on emitting a blind spot alarm is computed within the assistant layer that combines the information of all layers.

The most challenging precondition depicts the limitation of the processing requirements to the capabilities of a standard ECU. Therefore, several standard machine learning or probabilistic approaches like neural nets or the application of exact probability theory was not feasible. Instead a novel Fuzzy-Markov chain is proposed to approximate the exact probability theory. The procedure consists of a set of fuzzy rules followed by a standard Markov Decision Process to model the transitions between the individual system states. The fuzzy rules generate fuzzy probabilities for the three system states *vehicle within blind spot zone*, *infrastructure within blind spot zone* and *noise or nothing within blind spot zone*. In order to avoid an oscillation between system states, the resulting three fuzzy probabilities are passed to the Markov Decision Process, where a transition matrix models the state switching. Finally a logic unit evaluates the resulting Markov probabilities to make a final decision on emitting the blind spot warning.

3 Experimental Evaluation

3.1 Setup

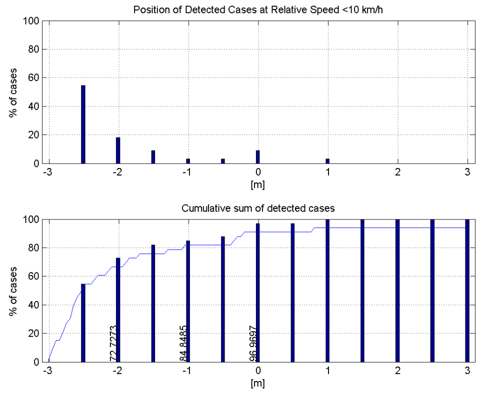
Extensive testing has been conducted to evaluate the proposed blind spot system within real traffic situations. To generate ground truth data, the host vehicle has been equipped with two laser scanners and four color cameras. The laser scanners have been attached to the left and right side of the host vehicle and the color cameras have been mounted on top of the car pointing in each direction to generate a 360° degree view of the host car's surrounding. 31 traffic situation have been defined that must be covered by the test drives ranging from standard overtaking situation to driving along a wall or turning around a pillar. The test drives have been manually annotated in accordance to the predefined traffic situation and the occurrence of blind spot situations where the alert must be emitted has been marked.

3.2 Conditions of the experiment

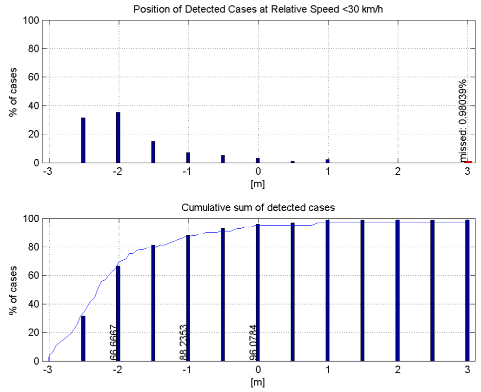
In order to guarantee meaningful evaluation results, extensive testing has been performed. The test set includes differing opponent vehicles like cars and motorbikes in 31 distinct traffic situations as described in section 3.1. Weather conditions during the test drives are ranging from dry roads and hot temperatures in the summer to snowy streets and temperatures below 0° in the winter. Furthermore, a mix of inner city roads, rural roads and Autobahn drives is covered by the testing data. In total over 3000 test cases and 2000 km of distance have been evaluated.

3.3 Discussion of Results

Figure 4 provides an overview of the testing results given the most common traffic situation where a vehicle is overtaking the host. The horizontal axis describes the distance between the opponent's to the host vehicle's rear axle at the moment where a blind spot alarm has been emitted by the system. Negative distances implicate that the overtaking vehicle was located behind the host's rear axle when emitting the warning, positive distances that the overtaking vehicle had already passed the host's rear axle when emitting the warning. It is distinguished between overtaking scenarios with a relative speed difference of overtaking and host vehicle no more than $10\mathrm{km/h}$ (scenario A) and overtaking scenarios with a relative speed difference of overtaking and host vehicle no more than $30\mathrm{km/h}$ (scenario B). Results show that for both scenarios, in 96.9% of all cases an alarm could be emitted before the overtaking vehicle has passed the hosts rear axle. Considering the missed rate, all vehicles could be detected for scenario A and only 0.98% of the passing traffic was missed within scenario B.



(a) Maximal relative speed host-traffic 10 km/h



(b) Maximal relative speed host-traffic 30 km/h

Figure 4: Evaluation of the detection rate in diverse environments (Innercity to Autobahn) and diverse relative and absolute velocities (0 - 160 km/h absolute; 0 - 30 km/h relative)

Tests on all scenarios have been conducted to evaluate the overall detection performance. Here, in 80% of all situations, an alarm has been emitted within a reaction time of 300ms. When extending the valid range of the reaction time to 1.5s even 96.9% of all cases have been detected.

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