AUTONOMOUS BRAKING FOR COLLISION MITIGATION PURPOSES BY MEANS OF MULTI SENSOR PERCEPTION

Rudi Lindl[1], Leonhard Walchshäusl[1] and Vassilios Paraschoudis[1]
[1] BMW Group Research and Technology, D-80788 Munich, Germany

ABSTRACT

A preventive safety application is presented in principle, which autonomously brakes in case of an inevitable accident in order to reduce the consequences of a collision. For an effective mitigation of collisions with preceding vehicles and vulnerable road users an efficient system for the perception of the environment combined with reliable decision measures for the activation of the actuator is required. Therefore, the potential of a sensor data fusion approach is examined since current off-the-shelf single sensor systems are far from the generation of a robust and accurate description of the area in front of the vehicle. Based on this environment description, a novel situation analysis algorithm evaluates the probability of a crash by computing the trajectories of the host vehicle and the obstacles. In case of an inevitable collision the concept application autonomously triggers the brakes in order to reduce the impact of the crash.

KEYWORDS
pre-safety application, situation analysis, collision mitigation, early fusion, autonomous braking, multi sensor perception

INTRODUCTION

European accident statistics prove the fact that most of the accidents with severely injured persons within urban areas happen through collisions of cars with vulnerable road users. This points out the urgent need for active and passive automotive safety systems as a significant contribution to the overall road safety.

Human failure without controversy is the number one accident cause. For that reason autonomous braking has high potential to mitigate crashes since machines are capable of reacting much faster and more efficiently than human drivers. An intelligent situation analysis based on a *perfect* environment perception system – which is not educible at the present time – has to decide when to take action. However, on the one hand this has great impact to the driver's sovereignty on the other hand an erroneous application of emergency braking caused by false alarms would greatly impede road safety improvement. Not lastly such an incident would represent a major setback for driver acceptance. Therefore, the control should only be passed over to the system if an accident is unavoidable. Although a crash cannot be prevented under all circumstances, the severity of injuries is greatly reduced as most of the kinetic energy is absorbed.

Focusing on a novel probabilistic situation analysis approach this paper offers the principle feasibility of a collision mitigation application for cars by means of autonomous braking. It is built on top of a multi-sensor perception system and currently aims for vulnerable road user protection.

Mertz [7] equipped a transit bus with two laser scanners to perceive the automotive environment. For all relevant and non-stationary objects random trajectories are generated which are distributed according to the means and variances of the relevant object states. The collision probability for one object is given by calculating the relation of its impact-trajectories to all random trajectories. Nishi [8] projects a visible predefined laser pattern on the road in front of a prototype car and records it with a video camera. Obstacles on the road lead to observable distortion effects of the laser pattern which triggers a warning. The range of the detection area is limited to ten meters in front of the vehicle. Fürstenberg [4] introduces a region of no escape (RONE) in front of the car where a car-to-pedestrian accident is unavoidable, if the pedestrian is detected inside this area. For environment sensing a multilayer laserscanner is used. Labayrade [6] proposes a collision mitigation system by means of autonomous braking. A warning area is generated which corresponds to the prediction of the path of the vehicle in the next second. If the intersection between the track and the warning area is not empty and the time-to-collision is below one second the brakes are engaged. The underlying obstacle detection system is based on a track-level fusion between stereovision and laser scanner. In contrast to our approach the angle between the own-car velocity vector and the velocity vector of a potential collision partner is neglected.

PERCEPTION SYSTEM

The focused application concept aims at collision mitigation by means of autonomous braking. This requires a perception performance of an unprecedented degree of reliability. From the application point of view one main ingredient for an effective collision mitigation system is a numerically precise estimate of the time-to-collision (TTC). This implies in turn a high degree of the actual perception availability in order to avoid perception machine inattentiveness, a high degree of reliability in order to avoid false alarms of 1st and 2nd kind and last but not least a high degree of measurement precision to ensure a reliable TTC estimate.

However, current off-the-shelf single sensor systems can hardly fulfill these challenging demands. Accordingly, BMW has set up an experimental car with a multi-sensor configuration as shown in figure 1 to research the potential of multi-sensor perception.

Sensor Configuration

Concentrating on the surveillance of the area in front of the vehicle, the cooperative sensors depicted in figure 1, operate on the basis of distinct physical principles and complement each other both in effective range and spatial accuracy.

The usage of a farinfrared (FIR) sensor, which is mounted at the right of the frontal bumper, guarantees both perception at bad lighting conditions and straightforward vehicle and pedestrian detection. Long and short range radar sensors are surveying the environment ahead providing a seamless transition in distance and field of view resolution. Moreover, a laser scanning device is mounted beneath the number plate to enhance the detection and tracking quality for both pedestrians and vehicles. The visual grey-scale cameras are used for supervising and controlling purposes only.

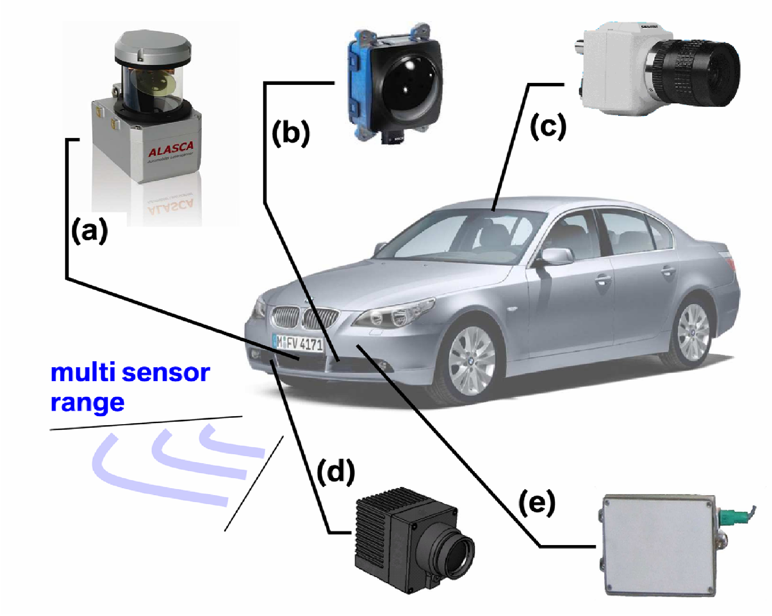


Figure 1 - BMW experimental car equipped with the following sensor configuration: (a) laser scanner, (b) long range radars, (c) grey-scale camera, (d) far infrared camera, (e) short range radars.

Early Fusion Concept

One important aspect for advanced driver assistance systems is a robust, accurate and reliable perception of the vehicle's environment as mentioned before and the generation of an adequate environment description.

Key component of a perception system is the way how the diverse and sometimes conflicting measurement data from different sensors are combined. In track-based fusion approaches for example several sensor data streams are processed independently from each other until the level of object data is reached. That way they run the risk that useful information is discarded in the object generation and data reduction process, as it does not seem to be significant enough from one sensor's point of view.

In contrast to track-based fusion *early fusion* combines data provided by multiple and even diverse sensors at an early stage of the data processing chain and performs a joint data interpretation with respect to a common model basis. In doing so, signatures of various sub-threshold findings in the data processing chain may interfere constructively and thereby contribute to an above-threshold result to form a distinctive, well-recognized object instantiation. Thus, an increase of robustness, reliability and consistency in the environment perception is expected as the input from an individual sensor can be processed in view and with the help of the other sensors.

Therefore, it is this paper's standpoint that an *early fusion concept* (cf. [1, 5, 9, 10]) is the more promising approach to exploit synergies of the different sensor data for the envisaged application.

COLLISION MITIGATION APPLICATION

A linear increase of velocity causes a quadratic increase in kinetic energy. Accordingly, even a slight decrease of vehicle speed has a great impact on the accident severity. This would benefit the passengers of the host vehicle as well as other affected road users, especially vulnerable pedestrians.

The object data provided by the perception system can be used to predict an upcoming accident. The system appraises whether there is enough time for the driver to prevent a collision or if a collision is unavoidable. Only in the case of an unavoidable collision the braking will be triggered autonomously. This occurs at that point in time, when warning the driver would be too late considering the human reaction time of about one second. The basis for this intra-system decision is a situation assessment which is shown in figure 2 and described in more detail in the following.

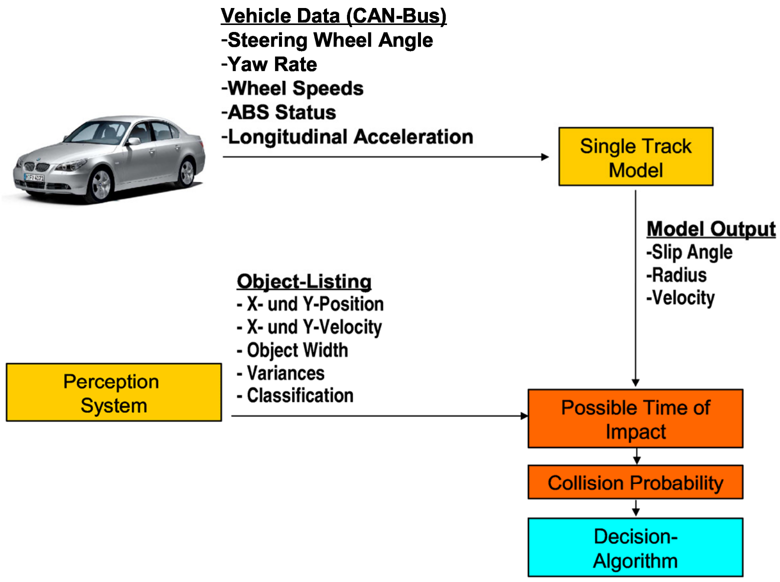
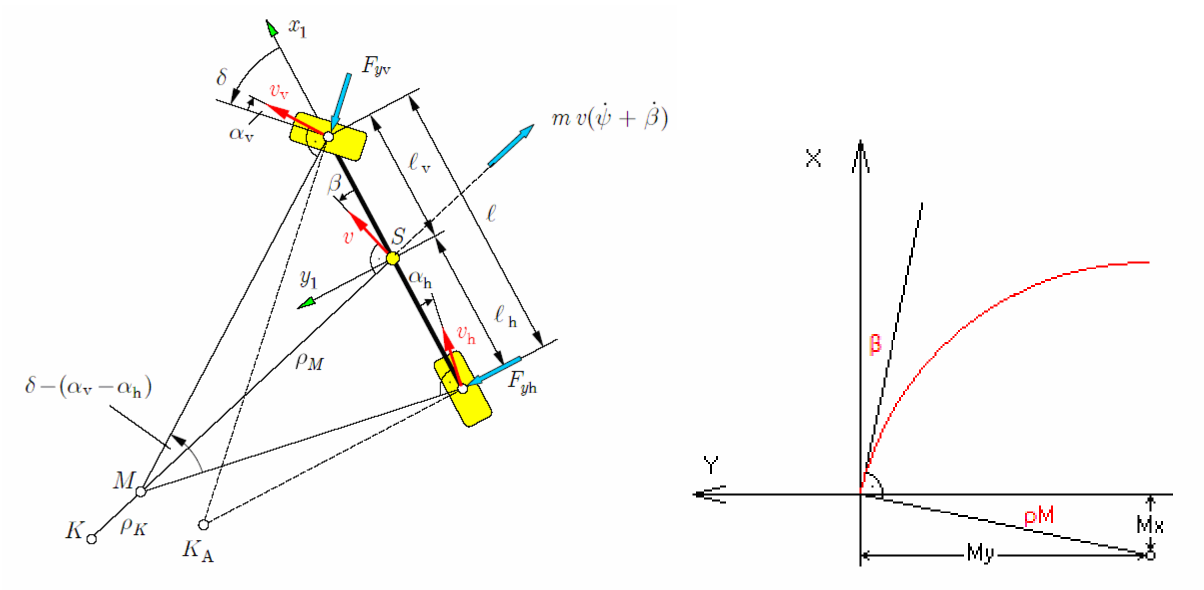


Figure 2 - Application Concept.

Single Track Model

The *Single Track Model* [3] depicted in figure 3(a) converts the kinematical vehicle data to mathematical parameters. These parameters are included into probabilistic algorithms to calculate the collision probability and the possible time of impact (see section on collision probability).



(a) (b)

Figure 3 - (a) Single Track Model [3]. (b) Driving trajectory (red curve) of host vehicle.

The output parameters β (vehicle body side slip angle), ρ_M (radius) and $|\vec{v}|$ (magnitude of host vehicle velocity) of this model are essential for the prediction of the motion direction of the host vehicle. It is assumed that the car moves on an orbital path depending on the pre-mentioned parameters. If the car moves straight forward β equals zero and ρ_M goes toward infinity.

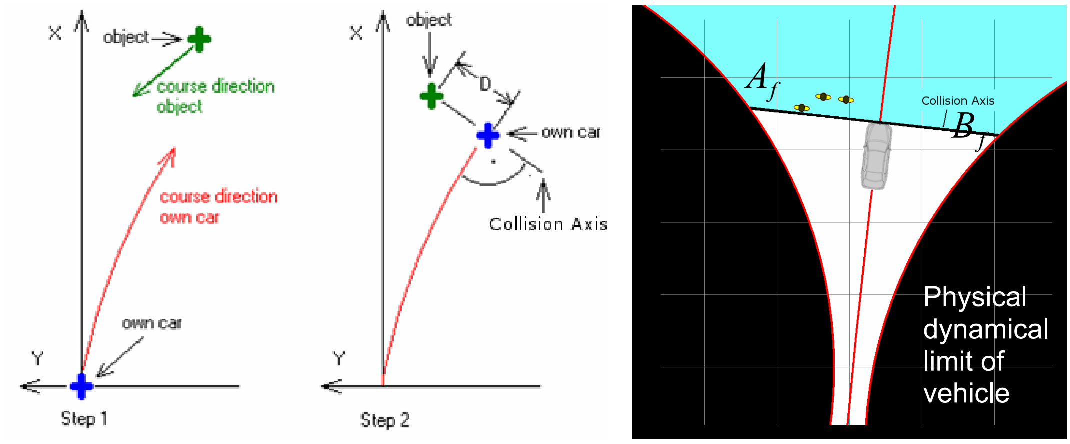
The time dependent trajectory of the host vehicle (see figure 3(b)) can be obtained by the two following formulas:

$$X_{(t)} = \rho_M \cdot \sin\left(\frac{|\vec{v}|}{\rho_M} \cdot t + \beta\right) - M_x \tag{1}$$

$$Y_{(t)} = \rho_M \cdot \cos\left(\frac{|\vec{v}|}{\rho_M} \cdot t + \beta\right) - M_y \tag{2}$$

Collision Probability

Based on the predicted trajectory of the host vehicle a time dependent collision axis, shown in figure 4, is defined. Under the assumption that the identified pedestrian keeps straight on, it is possible to calculate the time when the collision axis and the pedestrian trajectory will intersect (see figure 4(a) and 4(b)). This point in time marks the possible time of impact.



(a) (b)

Figure 4 - (a) Pedestrian and vehicle trajectories in current time and predicted time. (b) Pedestrian and vehicle are crossing the collision axis.

The single track parameters and the other characteristic quantities listed below are necessary for calculating the collision probability:

- Calculated distance D between vehicle and pedestrian on collision axis.
- Position variance of pedestrian σ_p^2 (provided by environment perception system).
- Vehicle width a and pedestrian width b .

However, the calculated trajectory of the host vehicle is only an assumption. It cannot be predicted with certainty where the driver will actually drive. For this reason the trajectory is treated as a probability distributed function. The further the covered distance of the vehicle the more inaccurate its predicted destination probability becomes.

The evaluation of the collision probability requires the calculation of areas under the probability distribution function. And this in turn requires integral operations. For simplification reasons it is determined that the position of pedestrians and the host vehicle are triangle distributed.

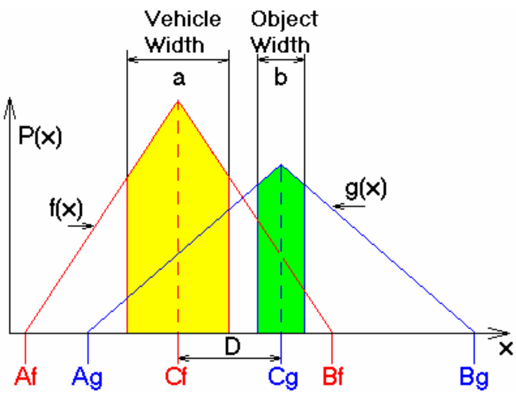


Figure 5 - Example of triangle distribution of vehicle and pedestrian position. The parameters a and b indicate the width of the vehicle and the pedestrian. $f(x)$ is the approximated distribution function of the car and $g(x)$ of the pedestrian.

Knowing the variance value σ_p^2 of the pedestrian (provided by the environment perception system) and the host vehicle dynamics the triangle parameters A_f, C_f, B_f and A_g, C_g and B_g can be calculated (see figure 4 and 5).

$$B_g = C_g - \sigma_p \sqrt{6} \tag{3}$$

$$A_g = C_g + \sigma_p \sqrt{6} \tag{4}$$

Based on these two triangle distributions and on the average distance D, the collision probability P_c can be calculated with the following equation.

$$P_c = \int_{A_g}^{B_g} \left(\int_{\xi - \frac{a+b}{2}}^{\xi + \frac{a+b}{2}} f(x) \cdot dx \right) \cdot g(\xi) d\xi \tag{5}$$

Decision Algorithm

The length of the braking distance S_b can be obtained by the equation

$$S_b = \frac{|\vec{v}|^2}{2 \cdot a} \tag{6}$$

where $|\vec{v}|$ denotes the magnitude of the host vehicle velocity in $\left[m \cdot s^{-1}\right]$ and a represents the deceleration in $\left[m \cdot s^{-2}\right]$. Additionally, the preconditioning of the brake unit has to be taken into account. For an activation of the brake unit, the following requirements have to be fulfilled:

- The remaining distance of the own vehicle to the collision axis has to be smaller than the braking distance S_b.
- The collision probability P_c has to exceed a certain threshold τ_c.
- The gradient of the collision probability curve over time $P_c(t)$ has to be positive.

EVALUATION

Evaluating a multi sensor collision mitigation system requires appropriate test materials and techniques. In the following these requirements are explained. Furthermore, first results are revealed.

Test Material

Ideally, real-world objects should be used for all test scenarios to achieve evaluation results close to reality. Due to safety and economic reasons this optimal evaluation cannot be performed. Thus, foam plastic or inflatable objects are widely used, but they lack the capability to reflect sensor characteristics like infrared radiation or radar reflectance. As especially in multi sensor networks this is a matter of particular interest we propose a modified mannequin (see figure 6(a)) with an integrated heating unit to approximate the infrared temperature distribution (see figure 6(c)) of a stationary pedestrian.

(a) (b) (c)

Figure 6 - Modified mannequin with heating unit to approximate the temperature distribution of a stationary pedestrian. (a) Modified mannequin. (b) Mannequin and real pedestrian. (c) Far infrared image of mannequin and real pedestrian.

Techniques

In spite of safety limitations, real-world objects can be used for the evaluation of the situation analysis part. For this purpose every tracked object is attached with a static lateral and/or longitudinal offset. With this technique of virtual position variation a safe vehicle pedestrian crash can be simulated. As an example a pedestrian walks on the pavement and is virtually moved to the middle of the road.

In order to cover a wide variety of critical situations we propose a simulation with virtual pedestrians which are placed into real ego motion recordings with an initial position, velocity and moving direction. Thereby, typical real-world driving behaviour can be combined with an unlimited amount of pedestrians. Currently, the evaluation is based on two different simulation models:

Pure virtual pedestrians: The simulation covers different starting positions in front of the car, 16 different initial moving directions and four different initial velocities. The virtual pedestrians do not change their dimensions, speed or moving direction during the simulation.

Semi virtual pedestrians: The dynamics and dimensions of a virtual pedestrian are based on the tracking results of the perception system. Thereby, a more realistic virtual pedestrian is created.

Results

Over 470 real traffic scenarios have been recorded for a simulation based evaluation. This data was used to extract typical vehicle dynamics and typical pedestrian behaviour. Both the pure virtual pedestrian and the semi virtual pedestrian model have been applied to gather the following results for a collision avoidance scenario. This scenario was chosen since the false alarm rate of collision avoidance is an upper bound for the false alarm rate of collision mitigation.

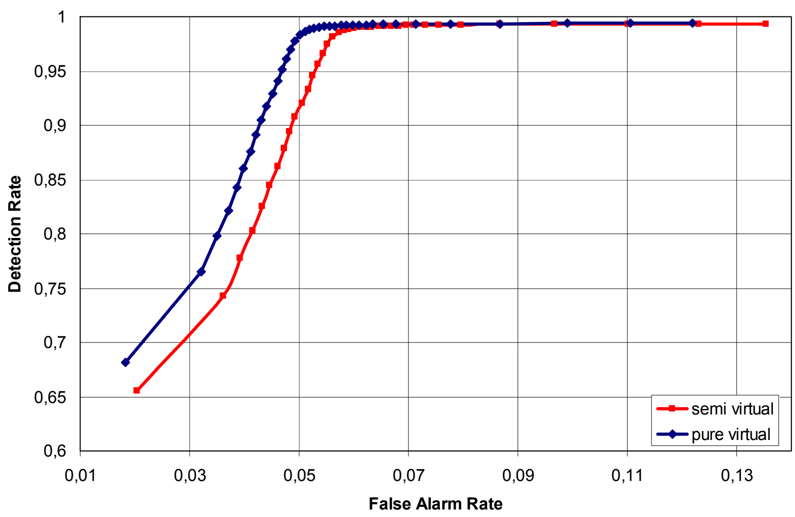


Figure 8 - ROC curves for collision avoidance generated with semi virtual and pure virtual pedestrian simulation.

The ROC curves depicted in Figure 8 were created by altering the threshold τ_c. The false alarm rate represents the percentage of incorrectly engaged brakes (no collision occurred) in relation to the total number of autonomous braking. The detection rate stands for correctly engaged brakes (collision would have occurred).

A lower threshold τ_c results in a decision based on higher uncertainties since a minor overlap of the triangle distribution (see section about collision probability) is sufficient. This in term results in both higher false alarm rates and detection rates. Accordingly, the false alarm rates and the detection rates decrease with a higher threshold. For semi virtual pedestrians the uncertainties increase even higher since the dynamic behaviour is non deterministic. Compare the two ROC curves depicted in figure 8.

CONCLUSION

A novel real time probabilistic situation analysis approach was proposed to facilitate a collision mitigation application for vulnerable road user protection provided that a perfect environment description would exist. A first evaluation has shown that the introduced situation analysis is capable to detect critical crash situations robustly and in time. The moving direction of obstacles is considered in order to reduce the false alarm rate. Furthermore the algorithm can be generalized to fit for arbitrary objects as long as they provide information about their position, dimensions, directional velocity and the corresponding variances. Finally, relevant test scenarios and novel evaluation techniques were introduced.

FURTHER WORK

Further testing has to evaluate the potential of the situation analysis with respect to both more complicated real world scenarios and a warning application. Environment context information like road condition, map data or intersection details can be utilized in order to improve the decision process. Other use-cases like rear-end collisions will be addressed in the future. In addition to these improvements, an extensive evaluation of the overall system performance is planned.

ACKNOWLEDGMENT

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