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Technical Abstract

The PReVENT subproject UseRCams aims at the development of a new 3D camera capable to achieve improved VRU protection and collision mitigation. This document describes the functional requirements and sensor specifications for the intended road safety applications and recognition tasks, comprising:

- near to intermediate front and side distance range of cars (20m-25m)
- lateral proximity of trucks (blind spot surveillance)
- 3D-algorithms for object (obstacles, pedestrian) detection and classification independently of surface reflectivity and ambient illumination conditions
- performance investigations with car/truck demonstrators on typical traffic scenarios and obstacle occurrence

The application-specific requirements for the 3D camera system have been analysed considering various traffic scenarios and relevant accident statistics. For each field of application, suitable design and performance-specifications have been defined and stipulated with respect to the overall goal of traffic object detection and classification.

The R&D challenges associated with the development of a new generation of low-cost 3D-sensors in full custom-design solid-state micro system technology are clearly addressed and the benefits of the UseRCams 3D camera over the state-of-the-art technology are demonstrated.
Executive Summary

Sub-project *UseRCams* is devoted to the development and customisation of a range camera that yields object distance information for every single pixel of its images. The camera resulting from this SP is to be utilised in later periods of the development cycle as a superior perception device for active safety applications.

In this document, the system requirements for three distinct types of application scenarios in the field for accident mitigation and road user protection are derived, and the suitability of the distance range camera for these scenarios are carefully analysed and established.

For all three types of scenarios, namely

- front-end collisions between a car and other road users in either urban environments or other medium speed situations,
- side-crash situations for cars involving stationary as well as mobile obstacles (e.g. trees or other vehicles) and
- blind area surveillance and protection of frontal and lateral truck adjacencies,

it was found, that the camera offers outstanding potential in view of the required perception performance, but also with respect to sensor size, power consumption, package requirements and future production costs.

Despite of the fact that industrialised versions of the camera will require distinct optical modules and distinct firmware, the discussions of the sub-project partners have shown that a common demonstrator camera is sufficient to cover the experimental needs of all three afore specified types of applications.
1 Introduction

Currently available sensors employed for the dynamic surveillance of the vehicle environment provide neither the degree of reliability and robustness, nor the required richness of the perceptual output that would be required for safety critical applications. Radar sensors, for instance, yield excellent distance and velocity measurement precision, but virtually no lateral resolution. Passive video cameras (in the visible as well as in the infrared frequency range) feature excellent lateral resolution, but the state-of-the-art computer vision processes required for scene interpretation are often unfit to identify all the relevant obstacles, not to speak of their distance-, speed-, class- and size-attributes. Multi-channel Lidar scanners exhibit much better lateral resolution as compared to radar sensors, but they come with comparatively slow scanning repetition rates, considerable physical size and comparatively high production costs.

In contrast, the pulse-operated range camera to be developed in SP UseRCams features distance information per pixel with a relative precision as high as 3%, an image repetition rate of up to 200 Hz, lateral and elevation aperture angels of 60 and 16 degrees, respectively, and a resolution of 64 x 8 pixels with a fill factor close to 100%. Production cost will be as low as that of an ordinary CMOS camera, plus about half that cost for the required Laser illumination module.

Despite of all these advantages, there are some limitations, however, which come about by the eye-safety requirements to be satisfied by the Laser module of the range camera. Because of the limits imposed by the regulations on the emitted Laser power (Laser class 1), there is an inevitable trade-off between the covered distance range and precision, the horizontal and vertical fields of view, the angular resolution, \(i.e.\) the number of pixels) and the image repetition rate.

Accordingly, a major effort and achievement of the present document consists in (i) the identification of suitable accident and application scenarios for the range camera, (ii) the establishment of the relevant system requirements derived for these scenarios and (iii) the resolution of the various conflicts of aims that result from these requirements.

The core of these achievements is stipulated in subsequent chapters of this document. The latter employs a top-down approach that is structured along the following lines: The subsequent chapter 2 is devoted to application requirements derived from a careful analysis of various pre-selected accident scenarios. This pre-selection of special accident scenarios does already account for the technical constraints of the range camera imposed by the eye safety regulations \(c.f.\) section 3.4 for a description of these constraints and the resulting conflict of aims). Chapter 3 deals with the fundamental technical principles that have been adopted for the pulse-operated range camera, and it also gives a description of the resulting technical advantages, challenges and conflicts of aims. In chapter 4, the currently decided technical sensor specifications are given, with special emphasis of (i) the image sensor chip, (ii) the Laser illumination and optics modules, (iii) the camera system hardware and its hardware interface(s) and (iv) the application interfaces (API) for the data representations of the sensor output and sensor parameter feedback. Chapter 5 gives special clues as to future refinements of the camera specifications, describes the role of the experimental camera configured for the derivation and validation of the desired camera properties, and also comprehends
some concluding remarks concerning the evolution of the specification process during the course of the project.

All the chapters characterised so far are attributed as 'IP Public'. In contrast, the annex *Details of the Sensor Customisation and Module Requirements* will be treated as SP confidential.
2 Application Requirements Derived From Various Accident Scenarios

Five sub-project partners, namely three car manufacturers (BMW, CRF and Renault), the truck vendor Volvo and the automotive supplier SiemensVDO have analysed various types of accident scenarios for which the range camera shows a clear potential to contribute to road user protection and accident mitigation. In this analysis, certain global technical constrains that come about by eye safety requirements with regard to the employed Laser source have already been taken into account. (A detailed description of these constrains, the resulting conflict of aims and its resolution is given in section 3.4).

The scenarios under consideration comprise

- front-end collisions of a car with other road users (such as pedestrians, cyclists and other vehicles) either in urban environments or in other intermediate speed situations (i.e. relative velocities up to about 50 km/h) - cf. sections 2.1 to 2.3,
- side-crash situations of cars with various stationary as well as mobile obstacles (e.g. trees and/or other vehicles), cf. section 2.4 and
- frontal and lateral blind area surveillance for trucks, cf. section 2.5.

Derivation and the results of this analysis are given in the remaining sections of this chapter. Section 2.6 is devoted to some reconsideration of these distinct scenarios w.r.t to the range camera system to be developed in this SP.

2.1 Requirements for collision mitigation of cars as provided by BMW

It was already mentioned in the introduction of this document, that the specification details of the camera are to cope with the limited Laser power imposed by eye safety regulations. This results in a trade-off between essential features such as distance range and precision, angular resolution (i.e. the number of pixels), field of view (i.e. size of the aperture angles), and image repetition rate (cf. section 3.4 for details on such conflicts of aims).

Accordingly, the prospects of the camera are most promising for applications in the near to immediate distance range with a lateral field of view of about 60 degrees. This has been already taken into account by devoting the accident analysis given in this and the following sub-sections to rear-end collisions and to pedestrian collisions caused by passenger cars.

2.1.1 Analysis of relevant accident scenarios

Front to rear-end collisions and collision with pedestrians contribute a significant percentage to the total number of accidents caused by passenger cars. Fig. 2.1.1-1 shows that in 2001 about 17% and 9% of the accidents on German roads belong to these two categories, respectively.
Fig. 2.1.1-1: Type of accidents on German roads in 2001. It is seen that accidents involving passengers and rear-end scenarios account for more than a quarter of the accidents.

Of the total number of 6977 fatalities related to all accident types depicted in fig. 2.1.1-1, 861 were caused by collisions of a vehicle with a pedestrian. This accounts for 12% of the total death toll. In urban areas, this type of accident caused an even more dramatic share of 34%, namely 593 of the 1726 fatal accidents. The following more detailed analysis of pedestrian / car collisions makes reference of [2], [3], [4] and [5].
According to fig. 2.1.1-2, 72% of the accidents in which pedestrians are involved are accidents caused by cars and in about 70% of these collisions, the impact occurs at the front site of the vehicle, *cf.* fig. 2.1.1-3.

The precise impact point at the front-end of the vehicle shows a comparatively small bias of about 10% in favour of positions closer to the nearest side walk (*i.e.* to the right hand side in countries with right hand side traffic).

![Figure 2.1.1-4: Road location](image)

![Figure 2.1.1-5: Type of road](image)

![Figure 2.1.1-6: Road infrastructure](image)

Regarding street location and road characteristics, it is seen from figs. 2.1.1-4 and 2.1.1-5, respectively, that almost 90% of the collisions between cars and pedestrians occur in urban areas and 58% of those on straight roads (as opposed to intersections or junctions). In addition, more than 50% of these accidents happen on unprotected roadways without any traffic light or crosswalk (*cf.* fig. 2.1.1-6).
This gives already essential clues as to the most frequent scenarios in which car-pedestrian accidents occur, and thereby provides valuable conclusions as to the specifications of the perception system required for pedestrian protection.

Finally, information about the velocity distribution of the collision partners at time of impact is given. Concerning the pedestrians, this is illustrated in figs. 2.1.1-7 and 2.1.1-8 whereby 1.25 and 2.5 m/s should be assumed for normal walking and running speed, respectively.

![Figure 2.1.1-7: Direction of pedestrian approach](image1)

![Figure 2.1.1-8: Speed of pedestrian at time of impact](image2)

![Figure 2.1.1-9: Vehicle speed at the time of impact with the pedestrian](image3)
The histogram of car velocities depicted in fig. 2.1.1-9 indicates that more than 90% of the car pedestrian accidents occur at vehicle velocities below 15m/s (54 km/h) and about 70% at speeds below 10m/s (36 km/h).

It is these very facts about the velocities of the collision partners and the prevalent road scenarios that constitute the relevance and provide the specification details for the range camera as applied to collision mitigation (and avoidance) of accident situations between pedestrians and passenger vehicles. This will be discussed in more detail in section 2.1.3.

As compared to pedestrians, vehicles have by far not the degree of agility to conduct, for instance, a 90-degree change of direction within fractions of a second. For front- to rear-end collisions between vehicles the most relevant parameters are rather those describing the relative longitudinal speed and (the build up of) acceleration between potential collision partners.

Since the detection range of the camera is limited to distances of about 20 to 30m, the potential deceleration build-up of a heading vehicle cannot be detected from its very beginning. Therefore, the accident data at hand has been used to reconstruct the emergence of the danger situation by estimating the relative speed and the relative deceleration of the crash candidates at a point of time where their distance fell short of 20m – a distance for which a confirmed detection of the heading vehicle and its kinematical properties is assumed. Since the estimation of the precise numbers for the relative speed and deceleration values includes some ambiguities,

![Worst Case Estimate for German Front- to Rear-End Collisions (Initial Detection Distance: 20 m)](image)

**Figure 2.1.1-10a:** Relative velocity of heading and trailing vehicle at a point of time when their relative distance falls short of 20m; the worst case figures correspond to velocity estimates at the pessimistic end of the scale. Also depicted are estimated deceleration values of the heading vehicle. Basis: study of German front- to rear-end collisions as analysed in ref. [6]
best-case and worst case estimates are given, respectively, for a variety of front- to rear-end crashes on German as well as on American roads. Here, the so-called worst case scenarios hints at velocity estimates on the more pessimistic end.

![Diagram](image)

**Figure 2.1.1-10b:** Same as in figure 2.1.1-10a, except for the estimates on the relative velocity; these represent the optimistic end of the available range, here; cf. ref. [6]

In figs. 2.1.1-10a+b and 2.1.1-11a+b the results of these estimates are shown in a histogram-type illustration, for a set of about 20+ accidents, respectively, that occurred on German and US American roads. Although the statistical significance of the data is limited due to the comparatively small number of cases, there are two clear tendencies to be read from these figures:

i. For the majority of 65 to 85% of the pre-crash situations, the relative velocity between heading and trailing vehicle amounts to less than 15m/s when their distance D falls short of 20m.

ii. At that point of time, the deceleration value of the heading vehicle scarcely exceeds 5m/s²; values of 3 to 4 m/s², rather, appear more typical.
**Figure 2.1.1-11a:** Relative velocity of heading and trailing vehicle at a point of time when their relative distance falls short of 20m; the worst case figures correspond to velocity estimates at the pessimistic end of the scale. Also depicted are estimated deceleration values of the heading vehicle. Basis: study of US American rear-end collisions as analysed in ref. [6]

**Figure 2.1.1-11b:** Same as in figure 2.1.1-11a, except for the estimates on the relative velocity which here represent the optimistic end of the available range; cf. ref. [6]
Before drawing further conclusions from the accident analysis given here, the following section will provide some additional clues as to the performance of an average driver in typical emergency situations.

2.1.2 Driver Performance / Example for Some Collision Avoidance Potential

It is well known, that average drivers react quite ineffectively when confronted with an emergency situation. This is seen from the driving simulator data depicted in fig. 2.1.2-1: only a very small fraction of the test persons who where confronted with an emergency situation succeed in building up the maximum brake pressure gradient of about 4000 bar/s. Still, only a minority of the test persons succeeded in building up a mere quarter of the possible maximum brake pressure gradient.

Source: Driving simulator study by Bosch utilising real braking system. All test persons were exposed to an emergency situation

Source: Driving simulator study by Bosch utilising real braking system. All test persons were exposed to an emergency situation

Figure 2.1.2-1: Braking performance of test persons in emergency situations; it is seen that an overwhelming majority of test persons do not succeed in building up the maximum brake pressure. An electronic brake assistant can improve this by applying maximum pressure once a certain threshold is exceeded. The accident avoidance of such an approach is illustrated in fig. 2.1.2-2.

In fig. 2.1.2-2, potential accident avoidance estimates for an electronic brake assistant are given, upon the assumptions that (i) a preconditioning of the brake has already taken place prior to the initial actuation of the brake pedal and (ii) the driver is automatically being helped to maximum brake pressure once a critical value of 1000 bars/s is exceeded (which is interpreted as an emergency situation).
Figure 2.1.2-2: Accident Avoidance / Mitigation Potential of an electronic brake assistant. The estimates given in the figure take into account (i) pre-conditioning of the brake (ii) the semi-autonomous increase of brake pressure in emergency situations and (iii) the driver warning (to make sure that breaking is activated at all).

For the electronic brake assistant, the active intervention of the human driver is still an essential ingredient, since the system is designed to depend on the results of a machine perception system of limited reliability (producing false alarms) and thus leaves the ultimate responsibility with the driver (for reasons of product liability, that is).

With the applications of function group Collision Mitigation and Road User Protection, however, the ansatz to leave the responsibility of action with the driver is rendered obsolete, since these functions, by definition, take only effect if the time to an imminent collision falls short of the human reaction and/or response time. It is self-understood, that these functions are to rely on perception systems that produce virtually no false alarms.

2.1.3 Geometry and kinematics of relevant accident scenarios

The accident categories rear-end and pedestrian collisions will be considered in more detail now, with the aim of deriving the camera specifications from the geometric and the kinematical aspects, with special consideration of machine generated reaction and response times.

2.1.3.1 Accidents between passenger cars and pedestrians

In section 2.1.1 it was shown, that the fast majority of collisions between passenger vehicles and cars occur on straight roads, in situations in which the driver is unaware of the imminent danger. Accordingly, the pedestrian is hit by the front end of the car. Such pre-requisites imply some geometric situation as depicted in fig. 2.1.3.1-1. Concerning the required distance range of the environmental perception,
there is a clear anisotropy to be observed, which derives from the vast speed differences between car and pedestrian. As shown in figure 2.1.3.1-1 in quantitative detail, a comparatively short distance range of less than 10m is sufficient at an aperture angle of 30 degrees, while the maximum distance range is essential at the central lines of sight close to the vehicle axis. This anisotropy can be used to redistribute the emitted Laser power accordingly, thereby gaining distance precision and/ or distance range in the central field of view.

Fig. 2.1.3.1-1: With respect to pedestrians and other low-speed road users, there is a clear anisotropy of the required distance range of the 3D camera. This is so, because of the large difference in speed: a longitudinal car velocity of 15m/s exceeds the lateral speed of a fast walking person for a factor 10. For a car moving only half as fast (i.e. just 27km/h), the speed ratio between car and pedestrian still corresponds to an angle smaller than 12 degrees. Details accounting for the system reaction times and car dimensions are given in section 2.1.3

Apart from the geometric situation, the impact velocity of the vehicle is the most significant factor in car-pedestrian collisions since it is the decisive factor as to the severity of the injuries suffered by the accident victims. According to the histogram of fig.2.1.1-9 and the fact that most pedestrian collisions occur in urban scenarios, it is reasonable to assume that the typical vehicle speed amounts to 15m/s or less when the emergency situation arises. As can be clearly seen from figs. 2.1.3.1-2a…c, there are two kinematical parameters, which are most relevant for the degree of accident mitigation and/or avoidance.

The first one is given by the (machine generated) delay time, that is, by the interval of time between the first perceptual indication of the potential collision between car and pedestrian and the point of time at which a full emergency breaking reaction is triggered. Fig. 2.1.3.1-2a illustrates a situation with an initial perception distance of 20m and an initial car velocity of 54km/h. It is clearly seen, that the effect of an emergency reaction depends crucially on the short response time of only 0.5s. (In order to realise such short response times, the consolidation of the perception process and the pre-conditioning of the brake system are to be conducted in parallel). If the reaction time amounted to as much as 1s (corresponding to a non-braked
travelling distance of 15m of a human driver), there would be almost no mitigation effect by breaking, independent of how determined the subsequent deceleration manoeuvre would be executed.

The second crucial kinematical parameter is given by the vehicle deceleration that will be achieved during the emergency braking process. Provided that the delay period is short enough to ensure that sufficient time for an emergency braking is available in the first place, the deceleration value decides whether there will be a collision at all, and, if so, what the related impact velocity will be (for illustrations of different speed situations, cf. figs. 2.1.3.1-2b and c, respectively).

![Graph showing the relationship between distance and velocity with different deceleration values.](image)

**Fig. 2.1.3.1-2a-c:** (see figures above and below) Breaking distance with regard to a still (or low speed) object assuming an initial car velocity of 54, 36 and 27 km/h, respectively, a pre-conditioning phase of 0.5s and a variety of deceleration values. [1m/s corresponds to 3.6 km/h]. Blue vertical lines mark the transition between accident avoidance and accident mitigation at certain example distances of 20, 12 and 7[m], respectively. It is seen, that ultra-fast reaction times and full fledged braking is required to achieve some significant reduction in damage - As a matter of experience, the reaction time of an average driver is usually greater than 1[s], and the maximum applied deceleration rate in emergency situations rarely exceeds 0.5[g].

In this section, it has been shown that machine-based accident mitigation strategies can reduce the severity of injuries and even avoid casualties in car-pedestrian collisions. In the following section, comparable clues will be derived for the case of front- to rear-end collisions caused by passenger cars.
Fig. 2.1.3.1-2b: see Figure 2.1.3.1-2a...c, above

Fig. 2.1.3.1-2c: see Figure 2.1.3.1-2a...c, above
2.1.3.1 Front- to Rear-end collisions caused by passenger vehicles

Like with accidents between cars and pedestrians, the geometry of the perception field required for the mitigation of front- to rear-end collisions between vehicles is characterised by a comparatively narrow strip parallel to the axis of the trailing vehicle (which is to include both adjacent lanes of the vehicle in question). This is visualised in fig. 2.1.3.2-1, which features some geometrically undistorted bird's view of a medium-speed follow-up situation on a multi-lane road. As with car-pedestrian encounters, a comparatively short distance range of a few meters is sufficient at an aperture angle of 30 degrees, while the maximum distance range is required at the central lines of sight close to the vehicle axis. This anisotropy can be used again to redistribute the emitted Laser power accordingly, thereby gaining distance precision and/or distance range in the central field of view.

**Figure 2.1.3.2-1**: Bird's view of a medium-speed follow-up scenario. The figure reflects true geometric proportions. At 15 m/s [54 km/h] a distance of 25m corresponds almost to a "two-second-distance" (corresponding to 30m). It can be also observed, that a comparatively narrow strip of about 5 m on each side of the vehicle is sufficient for these kind of scenarios. This restricts the required distance range at angles off the vehicle axis and thereby allows redistribution of the emitted Laser power in favour of the central field of view, thereby increasing detection range in these directions. For different reasons, this holds also true for scenarios involving pedestrians as shown in fig. 2.1.3.1-1.

Concerning the kinematics of the rear-end crash scenarios, one has to consider the distance, the relative velocity and the relative acceleration of the potential collision partners. For constant deceleration values, the time-dependent distance between two vehicles is given by

\[
D(t) = D_0 - (v_T - v_H) t + \frac{1}{2} (a_T - a_H) t^2 .
\] (1)
Here, \( v_H \) and \( v_T \) denote the velocity of the heading and trailing vehicle, respectively, and \( a_H \) and \( a_T \) represent their deceleration values and \( D_0 \) their initial distance. For all these parameter values positive numbers are assumed; accordingly, the sign conventions in eq. (1) have been chosen in such a way that the vehicle velocities contribute some decrease to \( D(t) \) if \( v_T > v_H \), and an increase if the trailing vehicle decelerates stronger than the heading car, \( i.e. \) if \( a_T > a_H \).

The value \( D(t_C) = 0 \), corresponds to a collision if the determinant of the quadratic equation in \( t \) is non-negative, \( i.e. \) if \( (v_T - v_H)^2 - 2D_0 (a_T - a_H) \geq 0 \) and if at least one of the two solutions for \( t \) is positive. If this is the case, the (smaller) positive solution corresponds to the time-to-collision value \( t_{TTC} \):

\[
t_{TTC} = \frac{\{ (v_T - v_H) - \sqrt{[ (v_T - v_H)^2 - 2D_0 (a_T - a_H) ]} \}}{(a_T - a_H)}. \tag{2}
\]

Collision avoidance thus requires appropriate TTC estimates, which in turn are to be based on appropriate measurements of the relative speed and deceleration.

For collision mitigation, a most relevant parameter is the relative speed \( v_C^{rel} \) of the collision partners at the point of time when the encounter occurs:

\[
v_C^{rel} = -(v_T - v_H) + (a_T - a_H) t_{TTC}. \tag{3}
\]

Insertion of the value for \( t_{TTC} \), eq. (2), yields

\[
v_C^{rel} = -\sqrt{[ (v_T - v_H)^2 - 2D_0 (a_T - a_H) ]}, \tag{4}
\]

providing the ratio of final to initial relative kinetic energy effective in the crash:

\[
\frac{E_f}{E_i} = 1 - 2 D_0 (a_T - a_H) / (v_T - v_H)^2. \tag{5}
\]

It should be emphasised, that the eqs. (2), (3) and (5) degenerate for initial distances that correspond to time intervals already very close to the crash – see footnote\(^1\).

The expression of eq. (5) for the reduction in kinetic energy and the accident tables shown in figs. 2.1.1-10a,b and 2.1.1-1a,b allow the following example estimates: if \( D_0 = 20 m, a_T - a_H = 5 m/s^2 \) and \( v_T - v_H = 54 km/h \), the reduction in kinetic energy is as high as 89%, corresponding to a final value of \( v_C \) which is only 1/3 of the initial one.

Even if a system response time of \( 1/2 \) s were taken into account (which reduces the initial distance at which braking sets in for about 7.5m to 12.m), the energy reduction would still amount to 45%.

The situation here is quite comparable with that of car pedestrian accidents: the illustrations given in figs. 2.1.3.1-2a...c are equally valid for the present accident

\(^1\) In such situations one observes \( 2D_0 (a_T - a_H) \ll (v_T - v_H)^2 \), and the square root in eq. (2) can be Taylor-expanded w.r.t. \( 2 D_0 (a_T - a_H) / (v_T - v_H)^2 \). This yields the following 1st order approximations for eqs. (2), (4) and (5), respectively: \( t_{TTC} \approx D_0 / (v_T - v_H), \ v_C^{rel} \approx -(v_T - v_H), \ E_f / E_i \approx 1. \) That is, once the imminent crash is already too close, the only remaining measures consist in the limitation of the peak acceleration values during the crash. Such measures may consist in the reversible triggering of active body devices such as active bumpers and/or active hoods, in the activation of seat belt pretensioners and also in the pre-conditioning of the air bags (prior to their irreversible firing which requires that the crash does physically occur). Such applications are in fact addressed by certain functions of both the APALACI and COMPOSE sub-projects of IP PReVENT.
category, if the vehicle speed and deceleration is interpreted as **relative** speed and **relative** deceleration, respectively.

A direct consequence of this is in the conclusion that the trailing vehicle is scarcely in a position to build up a relative deceleration of – say – 1g, if the heading vehicle already decelerates at a significant rate. On the other hand we have seen in section 2.1.2, that he readiness of human drivers to apply some full scale emergency braking is scarcely existent.

---

**Figure 2.1.3.2-2:** Errors of distance, relative speed and relative deceleration resulting from simulations with a corresponding Kalman filter. Here, an RMS distance resolution and error of 20cm, a measurement repetition rate of 100 Hz and a discrepancy of up to 0.5 m/s² per 200 ms from the assumption of constant deceleration have been adopted. It is seen, that the observed velocity and deceleration figures converge well within 600ms, but that the stationary error of the deceleration assumes an asymptotic value of about 1.5 m/s²; this derives from non-vanishing values of the 3rd derivative of the distance that violate the model assumption of constant deceleration. It should be noted, that eqs. (1)…(5) are invalid in this case; the behaviour of the heading vehicle becomes thus unpredictable at any rate. If the acceleration a is assumed to be constant, the velocity and acceleration converge to 0 within a period of time of about 0.75 s.
For the sake of completeness the following remarks should be supplemented to this case study:

- Even with a heading vehicle that features only moderate braking, the relative deceleration value is seriously jeopardised if the achievable friction is strongly limited due to adverse weather conditions. If the actual friction coefficient is comparatively small, it seems most likely that the maximum deceleration is already exhausted by the preceding vehicle – which means that the relative deceleration \( a_{\text{rel}} \) would be close to zero in this case.

- Upon the assumption of a high penetration rate of autonomous emergency braking systems, the applied degree of deceleration is bound to be quite situation-adequate (i.e. adapted to the degree of imminent danger) in order to relax the rear-end scenarios of vehicles that conduct an emergency braking procedure.

According to eqs. (2) and (4), the estimation of the imminent danger (be it the time to collision or the anticipated relative crash velocity) requires measurement of the following kinematical parameters: the relative distance, the relative velocity and the relative deceleration.

With a type of sensor that allows only direct measurement of distances, the differential parameters relative speed and relative deceleration are only to come by in due time if (i) the distance measurements are rather precise, if (ii) the measurement repetition rate is sufficiently high and (iii) if the assumption of constant acceleration is essentially valid. This has been shown in simulation runs applying a suitable Kalman model that features the essential camera parameters (see figs. 2.1.3.2-2 and 3).

With a relative precision of distance measurements of 20 cm or less and a measurement repetition rate of 50 to 200 Hz, the 3D camera is in a good position to satisfy these essential features as long as the pre-requisite of constant deceleration holds reasonably true. If this is not the case, the forecast of the time-to-collision and/or of the crash velocities (cf. eqs. (1) to (5)) becomes difficult to predict at any rate.

In this section, it has been shown that a machine-based accident avoidance / accident mitigation system can clearly outperform the average human driver. This is so, despite of the fact that the system is based on a perception device of some limited distance range of only about 20 to 30m. The outstanding performance of the mitigation system as compared to human drivers is rather based on

- some best possible system response / delay times of only \( \frac{1}{2} \) s or less,
- the maximum deceleration value of up to 10m/s\(^2\) and
- a perception device that produces virtually no false alarms.

The range camera to be developed in SP UseRCams appears to be a superior candidate for the type of accident mitigation perception device proposed in this section.
Figure 2.1.3.2-3: Same as in fig. 2.1.3.2-2, except that the RMS error (and resolution) of the distance measurement has been assumed to amount 5cm. It is seen, that the values of the kinematical parameters distance, velocity and acceleration converge considerably faster as compared to the case of distance RMS values of 20cm (cf. fig. 2.1.3.2-2). The increased precision of the distance measurements has little effect, however, on the residual error in the acceleration value, which mainly results from the influence of non-constant acceleration.
2.2 Front-end collision analysis provided by CRF

The available data about traffic accidents in Italy, issued by ISTAT (Italian Institute of Statistics), are related to 2002. This statistic reports 237812 accidents with 6736 dead persons and 337878 injured persons.

73.6% of these accidents and 43% of the total number of dead persons occurred in urban areas.

The total of accidents are categorized in following types:

- *Head-on collisions* (7.2%)
- Frontal-lateral collisions (36.3%)
- Lateral collisions (11.2%)
- Bumper to bumper collision (19.2%)
- Crash against stopping vehicle (3.3%)
- Crash against a pedestrian (6.6%)
- Crash against unexpected objects (3.0%)
- Road departure (10.3%)
- Others (train, motorcycle falls, etc.) (3%)

Within the urban application area, CRF intends to conduct experiments with the 3D camera sensor in front-end crash scenarios.

As countermeasures of these types of accidents, the field of applications include:

- *Collision mitigation*: functionality able to assist the driver during the braking phase in case of an unavoidable crash; this phase starts as soon as possible, typically 1-2 seconds before the impact.
- *Pre-fire*: the seat belt pretension actuator pulls back the belt in order to better restrain the driver close to the seat and keep him in the best protective position during the collision; the decision for the actuator is expected typical at 200-150 ms value before the impact.

From the architectural point of view, these applications can be represented, like in the following figure, by 3 consecutive main units.

![Diagram of front-end collision mitigation system](image)

*Figure 2.2-1: Architecture of front-end collision mitigation system*

Each block must respond in a short time and this is critical especially for the pre-fire application; in the more severe cases both the response delay and the actuation jitter are of the order of few tens of milliseconds.

Here after all main application related specifications are detailed.
Reference vehicle speed
In the urban area, one should consider reference speed of ego-vehicle and other vehicles in the surrounding up to 50 km/h; to take into account speeds of up to 70 km/h should be also reasonable.

Obstacles classification
In urban areas, many different types of objects can be on the road; the possibility of the sensor to classify obstacles would be nice because the behaviour of collision mitigation system and pre-fire system could take in account the type of obstacle. The main classification would be:

- Vehicle
- Pedestrian
- Cyclist or motorcyclist
- Pillar
- Others (barrier, etc)

Distance Range
For this requirements many different scenarios can be taken in account:

- Approaching vehicles (relative speed up to 100 km/h)
- Standing objects (relative speed up to 50 km/h)
- Slowly leaving objects

The distance range that is considered adequate is around 25-30 meters.

An example to justify this distance range requirement is shown in the following picture: the case of a possible collision with a standing obstacle at a speed of 50 km/h.

The sensor should estimate with good accuracy the relative speed of the approaching obstacle in order to have a precise computation of the Time to Impact. This leads to the additional requirement of a good sensor resolution in distance range.

![Figure 2.2-2: Example of required distances and times for a collision with standing obstacle at speed of 50 km/h](image-url)
**Sensor Aperture Angle**

In urban areas, the vehicle moves at low speed so the lateral dynamics (yaw angle, yaw rate) of the vehicle is typically quite high; a sensor horizontal aperture angle of about 60 degrees should cover most urban front crash scenarios;

The system must be capable to work without false alarms in case of passing objects in the very near distance. This leads to the additional requirement of a good angular resolution that has to be provided by the sensor system.

![Road & Vehicle Trajectory](image)

**Figure 2.2-3:** The vehicle trajectory can change quite suddenly at low speed (<50 km/h).

**Sensor position, field of view, resolution**

On standard sedan vehicle, the better sensor mounting position should be in the centre, behind the windscreen, close to the rear-view mirror.

![H angle = 60 deg](image)

**Figure 2.2-4:** Horizontal field of view

In the following table, the computation of the field of view and the resolution at different distances is given, upon the assumption of having 64 pixels in each row.
At 25 meters distance the resolution should be enough to detect an obstacles like a pillar or a pedestrian.

Similar calculation has been done for the vertical resolution; considering the camera mounting position for a standard car, the field of view to be covered is around 20 degree (it depend on the dimension of the hood). If the hypothesis is to have 8 pixels each sensor column, the angular resolution is 2.5 degrees.

![Diagram showing vertical field of view](image)

**Figure 2.2-5:** Vertical field of view

The following table shows the sensor vertical resolution at different distances in the mentioned hypothesis.

<table>
<thead>
<tr>
<th>distance [m]</th>
<th>Vres [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.114</td>
</tr>
<tr>
<td>4</td>
<td>0.152</td>
</tr>
<tr>
<td>5</td>
<td>0.192</td>
</tr>
<tr>
<td>10</td>
<td>0.384</td>
</tr>
<tr>
<td>15</td>
<td>0.576</td>
</tr>
<tr>
<td>20</td>
<td>0.768</td>
</tr>
<tr>
<td>25</td>
<td>0.960</td>
</tr>
</tbody>
</table>

The possibility to detect objects with this resolution, should be verified in the experimental phases.

### 2.3 Front-end collision analysis provided by SV

Most front-end collisions with pedestrians occur in urban traffic situations. Therefore, the speed of the involved vehicles is typically 50 km/h or less. Walking pedestrians reach a characteristic speed of up to 6 km/h. It is assumed that approximately 0.5 seconds will be needed to detect a pedestrian in front of the vehicle and an additional 0.5 seconds for preconditioning of the brakes to achieve full braking performance. The 3D camera will be mounted nearby to the rear-view...
mirror at the windshield in forward-looking orientation as indicated in Figure 2.3-1. The distance of the camera to the front end of the vehicle is of the order of 2 meters and that to the vehicle sides amounts to about 0.9 meters.

![Figure 2.3-1](image)

**Figure 2.3-1**: Front-end collision scenario with a pedestrian

Detection of a pedestrian and preconditioning of the brakes takes about 1 second. A vehicle travelling with the speed $v_V$ drives within 1 second the distance of $s_{1sec}$:

$$s_{1sec} = v_V \times 1\, \text{s}$$

If an emergency braking is initiated at the vehicle speed $v_V$ with full braking performance of approximately 10 m/s$^2$ the required braking time $t_{brake}$ for stopping the vehicle is:

$$t_{brake} = \frac{v_V}{10\, \text{m/s}^2}$$

The braking distance $s_{brake}$ for full performance braking is:

$$s_{brake} = 0.5 \times 10\, \text{m/s}^2 \times t_{brake}$$

The total stopping distance $s_{ges}$ including the pedestrian detection time, preconditioning of the brakes and required braking distance therefore is:

$$s_{ges} = s_{1sec} + s_{brake}$$

The relationship between these values is shown in Fig. 2.3-2. For urban traffic with vehicle speeds up to 50 km/h, the driving distance $s_{1sec}$ is higher than the braking distance $s_{brake}$ at full braking performance. The total braking distance $s_{ges}$ is about 24 meters at a vehicle speed $v_V$ of 50 km/h.
Figure 2.3-2: Speed dependency of the braking and stopping distance

The pedestrian movement $s_P$ with speed $v_P = 1.5 \text{ m/s}$ while stopping the vehicle within the stopping time $1s + t_{brake}$ is:

$$s_P = 1.5 \text{ m/s} \times (1s + t_{brake})$$

To avoid collisions between vehicles driving along with speed $v_V$ and pedestrians crossing the path of the vehicle with speed $v_P$ the 3D camera has to cover at least the stopping distance of the vehicle. As the distance of the camera to the front end of the vehicle is up to 2 meters the required total measurement range of the 3D camera in the longitudinal direction is:

$$d_{Cam \_x} = s_{ges} + 2\text{m}$$

The distance of the 3D camera to the sides of the vehicle is up to 0.9 meters. Therefore, the required total measurement range of the camera in the lateral direction is:

$$d_{Cam \_y} = s_P + 0.9\text{m}$$

The required observation range of the 3D camera is shown in Figure 2.3-3. Pedestrians outside the blue lines are not at risk of a collision with the vehicle. A vehicle travelling with 50 km/h has a stopping distance of about 23.5 meters and therefore requires a longitudinal measurement range of 25.5 meters. A pedestrian can walk about 3.6 meters within the stopping time of the vehicle and therefore requires a lateral measurement range of 4.5 meters. For lower vehicle speeds the stopping time and distance becomes smaller and also the walking distance of the pedestrian becomes smaller. Therefore, the required measurement range of the camera is much smaller for lower speeds but the required aperture angle becomes larger because of the smaller relative speed between vehicle and crossing pedestrian.
The required distance measurement range of the 3D camera for a certain observation angle is:

\[ d_{Cam} = \sqrt{(d_{Cam_x}^2 + d_{Cam_y}^2)} \]

The required aperture angle for detection of the pedestrians is:

\[ \alpha = \arctan \left( \frac{d_{Cam_y}}{d_{Cam_x}} \right) \times \frac{180^\circ}{\pi} \]

The relationship between the required measurement range and the measurement direction is shown in fig. 2.3-4. For a vehicle speed of 50 km/h, the required measurement distance range is up to 26 meters at an aperture angle of up to ±10°. For lower speeds the required measurement range becomes smaller but the aperture angle increases. For a vehicle speed of 10 km/h the required measurement distance range is up to 6 meters at an aperture angle of up to ±30°.

Figure 2.3-3: Required observation range of the 3D camera

Figure 2.3-4: Required measurement distance range characteristics
From the considerations regarding the front-end collisions with crossing pedestrians we can derive the following requirements for the 3D camera measurement range:

- **Minimum distance**: 2 m (vehicle front end)
- **Maximum distance**: 26 m for $\alpha = \pm 10^\circ$ ($v_v = 50$ km/h)
  6 m for $\alpha = \pm 30^\circ$ ($v_v = 10$ km/h)

This allows the design of an optimised beam shape for the active Laser illumination of the 3D camera.

### 2.4 Side crash prediction application provided by RENAULT

The interest of Renault in subproject *UseRCams* is to investigate possible utilisation of a 3D camera sensor for side crash prediction. The Time to Impact (TTI) horizon to be considered is $[0; 30\, \text{ms}]$, and one would like to be able to have 10% accuracy for this TTI measurement. The requirements for the performance of such a device will also be derived from accident analysis.

#### 2.4.1 Accident analysis

According to the SETRA database, lateral crash scenarios happen on the following conditions (see figure 2.4.1-1):

**Figure 2.4.1-1**: Side crashes environmental conditions

More precisely, these scenarios can be divided into seven main categories (table 2.4.1-1):
Table 2.4.1-1: Side crash main categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>I – Loss of control in straight road against fixed obstacle</td>
<td>26%</td>
</tr>
<tr>
<td>II – Loss of control in curve against fixed obstacle</td>
<td>18%</td>
</tr>
<tr>
<td>III – Loss of control in straight road against moving obstacle</td>
<td>13%</td>
</tr>
<tr>
<td>IV – Loss of control in curve against moving obstacle</td>
<td>12%</td>
</tr>
<tr>
<td>V – Crossing collision at intersection</td>
<td>17%</td>
</tr>
<tr>
<td>VI – Collision at intersection / left-turn</td>
<td>9%</td>
</tr>
<tr>
<td>VII – Intersection: Left-turn and inverse direction</td>
<td>3%</td>
</tr>
<tr>
<td>(Other collisions at intersections)</td>
<td>2%</td>
</tr>
</tbody>
</table>

Hence, most of the side crash fatal accidents (more than 80%) have the following characteristics (table 2.4.1-2):

<table>
<thead>
<tr>
<th>Category</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obstacles</td>
<td>Poles of metal, wood, plastic, Trees, Walls, Vehicles</td>
</tr>
<tr>
<td>Relative speed between the vehicle and the obstacle</td>
<td>6 to 23 m/s</td>
</tr>
<tr>
<td>Incidence angle of impact</td>
<td>-45° to +45°</td>
</tr>
</tbody>
</table>

Table 2.4.1-2: Side crash main characteristics

2.4.2 Requirements and specifications for a 3D Image Sensor

The requirements for performance of such a device can be derived from accident analysis.

2.4.2.1 Camera mount point and perspective

Considering the target application, the sensor should be installed with a side-looking orientation and perspective. The optimal localisation, taking integration constraints into account, remains to be defined.

2.4.2.2 Distance range

The distance range to be covered can be obtained considering requirements for Time to Impact (TTI) and relative velocity. The ideal minimum distance should be equal to 0 m, the maximum distance should be equal to 2 m approximately. Anyway, since we understand that a zero minimum distance is hard to achieve with a camera sensor, we will require a minimum distance of 20 cm for the purpose of this project.

2.4.2.3 Velocity range

As mentioned in accident analysis, 80% of all side impacts occur with a relative speed between the vehicle and the obstacle between 6 and 23 m/s.

2.4.2.4 Distance and Velocity accuracy and resolution

The accuracy on TTI measurement will of course depend on the precision of measure of the position and the speed of the obstacles.
Since a 10% precision should be convenient for TTI, simple estimation shows that we shall choose to settle a needed precision on the measure of radial distance of ±0.02m which imposes a precision on the evaluation of the radial speed of ±0.5m/s.

The resolution of the system represents its objects dissociation ability. For the 3D camera, we have to consider the radial distance resolution and the image resolution. These resolutions must be defined according to the need. Here, we shall consider a radial distance resolution of about the aimed for measurement accuracy which is approximately ±0.02 m, and a lateral resolution of ±0.05 m to ±0.1 m.

Concerning the velocity resolution, we will keep the same requirements as for velocity precision: radial speed resolution needed is equal to ±0.5 m/s.

### 2.4.2.5 Horizontal (lateral) field of view

For side crash prediction, all the obstacles having an angle of incidence within an approximate -80° and +80° should be detected if 100% of the cases shall be covered. Anyway, this horizontal field of view of 160° should be very difficult to achieve with a camera.

For the project purpose, considering the available number of horizontal pixels, we will choose to study a sensor with final horizontal field of view = 90° that will enable us to detect the obstacles having an angle of incidence included between -45° and +45° (80% of all side crash accidents). So the desired area of detection to be covered is then the one presented in figure 2.4.2.5-1:

![Figure 2.4.2.5-1: Desired area of detection (horizontal)](image)

The resolution of the system determines its objects dissociation power. For the 3D camera, we have to consider the radial distance resolution and the image resolution. These resolutions must be defined according to the need. Here, we shall consider a radial distance resolution about the aimed for measurement accuracy which is approximately 2cm, and a lateral resolution of 5cm to 10cm.

Considering an angle of 90°, at 3m a lateral resolution of 5cm means a resolution of 0.5° to 1°. For the purpose of this application, we will require a 1° lateral angular resolution.

With this hypothesis, the horizontal width of the detection area at 3m is equal to 6m. This means one needs 120 pixels to get a lateral resolution of 5cm, or 60
pixels to get a lateral resolution of 10cm. For the purpose of this application, we will require 64 pixels for the width of the sensor matrix.

2.4.2.6 Vertical field of view

The vertical field of view depends on the position and the orientation of the sensor. For example, an elevation angle of $120^\circ$ would be compliant with the specifications if the sensor is installed 1 meter above the ground, because it will enable us to detect almost any dangerous side obstacle. Anyway, for the purpose of the project, considering the available number of vertical pixels, we will choose to study a sensor with a final vertical field of view $= 20^\circ$ (figure 2.4.2.6-1).

![Figure 2.4.2.6-1: Desired area of detection (vertical)](image)

Considering this angular compromise, a vertical resolution of 10 cm means a resolution of 3.8°. Since the final sensor matrix will be 4 to 8 pixels high, for the purpose of this application, we will then get a 2.5° to 5° lateral angular resolution.

2.4.2.7 Image repetition rate

Concerning image repetition rate, 10ms is sufficient for the first step, which corresponds to 100Hz.

2.4.2.8 Environmental conditions

The developed system should be usable whatever the meteorological conditions are: strong brightness, sun facing the camera, night, and of course normal conditions of illumination. And of course, the system equipped with 3D camera sensor should have a very low false alarm ratio.

2.5 Truck applications: frontal and lateral blind spot surveillance (VTEC)

2.5.1 Introduction to front and passenger side proximity warning

Many truck accidents occur because the driver cannot see sufficiently well all round the vehicle. Recently, aids such as reversing cameras have improved the situation but there are still large areas around the truck that are hidden from view.
Figure 2.5.1-1 illustrates the typical blind areas, which are not covered by direct or current indirect vision.

![Figure 2.5.1-1: Blind spots as seen from drivers' position in a truck](image)

Generally, visibility around the truck can be divided into three levels:

1. Direct vision through the windscreen and side windows
2. Indirect vision through the rear-view mirrors, front mirror and close-quarter kerb mirror
3. Indirect vision via cameras that cover areas concealed from direct view and from indirect view through mirrors.

The driver’s workload increases, regardless whether additional mirrors and/or camera-solutions combined with displays are the solutions to cover more and more of the current blind-zones. Therefore, there is a real need for having a detection system that helps the driver to focus his attention to relevant mirrors, displays or blind spots. With UseRCams sensors this will be possible.

### 2.5.2 Functional description

Automatic blind spot surveillance using the UseRCams sensor will result in a proximity warning function, which will be operable when the truck drives at low speed and will warn the driver when a vulnerable road user or an obstacle is in the frontal or in the passenger-side lateral blind spots of the vehicle. The warnings will be presented to the driver either by use of a warning display in front of the driver, or by use of an audible warning. A combination of these is also possible.

### 2.5.3 Relevance from accident statistics

The relevance for proximity warnings in front-end and passenger-side lateral blind spots – with special consideration to truck specific accidents - has been covered in detail in the PReVENT consortium-confidential deliverable D50.30: User Needs State of the Art and Relevance for Accidents, page 44f.

The main scenarios covered by the proximity warning application developed in this project are following:

(The percentage figures in the bar to the right refer to the share of all truck accidents with injured unprotected road users in Europe.)

Front-mounted sensor addresses: truck-front vs. unprotected when taking off.
Passenger-side mounted sensor address: truck side vs. unprotected when turning or lane driving

The focus in this project is vulnerable road users, mainly pedestrians. Other type of incidents may also be covered but these are not the primary goal of this project.

2.5.4 Scenario description and environmental considerations
The proximity warning function will be active at vehicle speeds < 10 m/s. Other scenario parameters are listed below.

- maximum sensor response time (for new objects): 0.2 s
- max. vehicle speed: 10 m/s
- min. vehicle speed: 0 m/s
- dynamic mounting pitch angle: +/- 3 degrees, (due to cab movements)
- obstacle max speed: 10 m/s
- obstacle min speed: -10 m/s
- environment: The environment where the system should operate can differ in terms of number of pedestrians, road infrastructure, buildings, lighting conditions etc. The main emphasis should be on urban environments since this is the area where most low speed manoeuvring occurs.
- road condition: The system shall be operable on all road surfaces, (asphalt, gravel, etc.) and both on dry, wet and snow covered roads.
- Weather condition: The obstacle detection should work in all weather conditions.

2.5.5 Required Camera Detection Area
The required camera sensor detection area is 8 by 5 meter for the front mounted sensor and 4 by 10 meter to cover the lateral blind area at the passenger side, see sketch in figure 2.5.5-1 (note: the sketch is not to scale)
2.5.6 Choices for Camera Mounting

The location of the camera is of importance, since the camera lens must remain relatively clean in order to function properly. The cameras will therefore be mounted at a spot where there is least dirt accumulation and where they cause the least possible disruption in the flow of air around the cab. The location has also been selected to permit standardized installation in several cab models and also to avoid the risk of damage in minor bumps and scrapes.

Possible mounting position can be found in figure 2.5.6-1 The primary choice for the front-end camera location is just below the windsreen (number 2 in figure 2-5-3) and for the side mounted sensor it is behind the passenger door, way up (number 17 in figure 2.5.6-1)
The location of the front camera sensor at approximately 2 meters above the ground implies a horizontal viewing angle of 120 degrees and vertical of 70 degrees to cover the desired area shown in figure 2-5-3.

2.6 Applications Scenarios Reconsidered w.r.t. Object Detection and (Size) Classification

The 3D camera applications aimed at by the car manufacturers have very different requirements regarding the observation range and aperture angle. For the front camera applications the required aperture angle is 60° and the distance range up to 25 meters. The blind spot application for trucks requires 120° and up to 10 meters range while the side crash application aims at 160° for up to 1.5 meters. Despite of this, the 3D camera prototype system for the side crash application will be investigated with an aperture angle of 90°.

The achievable lateral distance resolution for a 3D camera sensor with 64 pixels per line is shown in Figure 2.6-1. For the front camera applications with an aperture angle of 60° the lateral resolution at the maximum distance of 25 meters is about 41 cm. For the side crash application with an aperture angle of 90°, the lateral resolution at a distance of 1.5 meters is about 4 cm. For the blind spot truck application with an aperture angle of 120°, the lateral resolution at the maximum distance of 10 meters is about 33 cm. When the 3D camera sensor is used in the 128-pixel mode the achievable lateral distance resolution can be improved by a factor of 2.
The aspect ratio for a spherical lens is 3.47:1 because of the 64 x 8 pixel arrangement and the rectangular pixel size of 130 µm x 300 µm. The achievable elevation for the different opening angles of the optics is summarized in the following table.

<table>
<thead>
<tr>
<th>Aperture</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>60°</td>
<td>17.3°</td>
</tr>
<tr>
<td>90°</td>
<td>26.0°</td>
</tr>
<tr>
<td>120°</td>
<td>34.6°</td>
</tr>
</tbody>
</table>

The vertical distance resolution for a camera sensor with 8 pixel lines is shown in fig. 2.6-2. For the front camera applications with an aperture angle of 60°, the vertical resolution at the maximum distance of 25 meters is about 95 cm. For the side crash application with an aperture angle of 90°, the vertical resolution at a distance of 1.5 meters is about 8.5 cm. For the blind spot truck application with an aperture angle of 120°, the vertical resolution at the maximum distance of 10 meters is about 75 cm.
3 Technical Advantages, Challenges and Constraints

3.1 Introduction

The range camera to be developed in SP UseRCams provides distance information for every single pixel of its images. This constitutes a major advantage as compared to a variety of other perception devices.

In comparison with short-range radar devices, for instance, the lateral resolution in both directions perpendicular to the camera axis is a decisive factor, since this allows lateral offset estimates and even size and shape classification of the detected obstacles. In comparison to computer vision devices based on conventional video cameras, the range camera brings about the advantage of independence of natural illumination conditions, of context-free distance measurement and of a tremendous reduction in computing power, because signal processing procedures for edge detection and grouping, for pattern-based image object segmentation and for depth triangulation are rendered obsolete. When compared to Laser scanning devices, the range camera features the advantages of a fill factor close to 100%, much faster image repetition rates of 50 to 200Hz, the absence of moving parts, some significantly smaller package volume (~1/10) and some distinctly lower production costs close to those of a conventional CMOS camera. Disadvantages with respect to state-of-the-art Laser scanners are merely given by the shorter detection range and lateral aperture angle (but compensated by considerable faster measurement rates).

Advantages and disadvantages in comparison with Laser scanners reflect to a certain degree the conflicts-of-aims brought about by the limitation of emitted Laser power as given by eye-safety regulations. This will be discussed in more detail in section 3.4.

In comparison with time-of-flight (TOF) cameras based on the principle of modulated light emission such as the so-called photonic mixing device (PMD) and comparable approaches, the ansatz pursued in this project features vast independence of background illumination. This is so, because of the pulse-operated ansatz, where the Laser pulses can be made quite short but nevertheless keeping the amount of energy per pulse at a constant level. Consequently, the background irradiation level is irrelevant as compared to the much greater emitted light intensity. With continuously emitted light, this is not feasible and the range cameras based on that principle suffer from notoriously poor signal-to-noise ratios as well as of insufficient suppression of background illumination.

The present paragraph 3 is organised as follows: the following section 3.2 describes the fundamental principles of the pulse-operated range camera, its basic concepts, and analyses in addition the eye safety requirements. Section 3.3 is devoted to a description of the suppression of background illumination. Section 3.4, finally, describes measures as to the resolution of application-specific conflicts of aims with respect to the covered distance range, aperture angles, angular resolution and image repetition rates.
3.2 Fundamental principles of the pulse-operated range camera

3.2.1 Basic concepts [SAG]

The innovative UseRCams sensor concept calculates the Time of Flight (TOF) indirect from the intensity measurement of single Laser pulses in high-speed shutter windows. Several Laser pulses are on chip averaged to reduce the required Laser power and to increase the measurement accuracy. The approach is called MDSI (Multiple Double Short Time Integration) and will be illustrated by the figure below:

![Figure 3.2.1-1: MDSI (Multiple Double Short Time Integration) measurement principle](image)

The Laser pulse transmitted towards an object will be synchronized with the start of the integration window. The received Laser pulse gives rise to a linear sensor signal U after the light propagation time T0, which is measured at the integration times T1 and T2. Depending on the distance of the object only a certain fraction of the light pulse is detected whilst the integration window is active. Performing two integration measurements with different integration times T1, T2 the position and slope of the integrated intensity signal U can be derived. This allows an exact calculation of the propagation time T0 and hence the distance d according to a simple mathematical relationship. Measurements with two different integration times are necessary to achieve the independence of the method from different surface reflections in a 3D scene. A brighter object with the same distance from the sensor will give rise to an integrated signal with a larger slope but will intersect at the same transition time T0.

A unique feature of the MDSI method is the analogue real-time on–chip accumulation process at each individual CMOS element using multiple pulses for each shutter window. By this means the signal-to-noise ratio increases and leads to an improved distance accuracy. Repetitive integration of Laser pulses will be performed adaptive up to the saturation level at each pixel element. Intelligent procedures can be employed to cover a large dynamic range of different surface reflectivity of targets with this adaptive flash illumination method.
In conclusion the *UseRCams* pulse operated range camera reveals the following technical advantages for solid-state range imaging using TOF technology:

- Pulsed light operation
- Analogue integration of several light pulses on chip
- Strong suppression of background illumination by Correlated Double Sampling (CDS). This feature represents an inevitable prerequisite for out door application especially in automotive environment surveillance
- Participation on future main stream high speed CMOS image sensor developments
- Benefit from future progress in noise reduction and sensitivity enhancement of standard CMOS process technology

**Investigation of competitive TOF technologies and devices:**
Major competitive technologies and producers in this field either determine the propagation time directly by detection of the time delay between emitted and reflected Laser pulses or by methods of intensity modulation techniques. The assessment of these approaches leads to the following results and drawbacks in comparison to the *UseRCams* concept:

- **Laser scanner (several producers):**
  State of the art Laser scanners only allow a distance measurement to one measuring point. Therefore 3D range images of an area require mechanical rotating mirrors, which are slow, bulky, expensive and sensitive to vibration.

- **Range Imaging by continuous wave modulation:**
  PMD technologies GmbH Germany, CSEM Switzerland and Canesta USA are also currently developing solid-state 3D imaging systems
with Time of Flight principle using modulated continuous wave to get the distance information. These approaches have the following disadvantages:

- The technology used is based on a special CMOS process or combined CCD/CMOS process.
- The method is sensitive to background illumination. It will therefore not meet the requirements of the outdoor applications.
- Ambiguity problems may occur due to the continuous wave approach.
- Limitation of dynamic range may occur due to analogue non adaptive integration.

The following chapters describe the preferable technical features of the UseRCams method in more detail and compile the essential specifications and constraints.

### 3.2.2 Eye safety and Laser class

The Laser produces an intense, highly directional beam of light. If directed, reflected, or focused upon an object, Laser light will be partially absorbed, raising the temperature of the surface and/or the interior of the object. In addition to these obvious thermal effects, there can also be photochemical effects when the wavelength of the Laser radiation is sufficiently short, *i.e.*, in the ultraviolet or blue region of the spectrum.

The human body is vulnerable to the output of certain Lasers, and under certain circumstances, exposure can result in damage to the eye and skin. The human eye is almost always more vulnerable to injury than human skin. The cornea (the clear, outer front surface of the eye’s optics), unlike the skin, does not have an external layer of dead cells to protect it from the environment. Laser light in the visible and near infrared spectrum 400 - 1400 nm can cause damage to the retina, while wavelengths outside this region (*i.e.*, ultraviolet and far infrared spectrum) are absorbed by the anterior segment of the eye causing damage to the cornea and/or to the lens. The extent of ocular damage is determined by the Laser irradiance, exposure duration, and beam size. As Laser retinal burns may be painless and the damaging beam sometimes invisible, maximal care should be taken to provide protection for all persons.

#### 3.2.2.1 Maximum Permissible Exposure

The most effective prevention of injury from a Laser beam is to ensure that the Laser beam is encapsulated so that no human exposure can occur. For the case of an exposure to the beam it depends on the level of exposure if injury occurs. The theoretical border between safe and potential harmful is called “Maximum Permissible Exposure” (MPE). The MPE levels are set by the International Commission on Non-Ionizing Radiation Protection and are internationally accepted and adopted by the standardization committees such as IEC TC 76 and ANSI for the respective Laser safety standards IEC 60825-1 and ANSI Z136.1. MPE levels are determined as a function of Laser wavelength, exposure time and pulse repetition. The MPE is usually expressed either in terms of radiant exposure in J/cm² or as irradiance in W/cm² for a given wavelength and exposure duration. The MPE levels are not sharply defined borders between a “hazardous” and a “safe” exposure, therefore, the exposure to a Laser beam must be as small as possible.
3.2.2.2 Laser safety classes

As MPE evaluation is quite complicated, a Laser safety classification scheme has been developed by the international standardization committees according to which Laser products are grouped into classes with similar hazard potentials. In the EU, the new international standard IEC 60825-1 has been adopted by the European standardization organization as EN 60825-1, and is in force since 1. Jan 2001. The manufacturers of Lasers and Laser products are required to certify that the Laser is designated as one of four general classes, or risk categories, and label it accordingly. This allows the use of standardized safety measures to reduce or eliminate accidents depending on the class of the Laser or Laser system being used. The following is a brief description of the primary categories of Lasers:

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>These Lasers are safe under reasonably foreseeable conditions. There may be a more hazardous Laser embedded in the enclosure of a Class 1 product, but no harmful radiation can escape the enclosure.</td>
</tr>
<tr>
<td>Class 1M</td>
<td>These Lasers are safe under reasonably foreseeable conditions provided optical instruments (magnifiers or telescopes / binoculars) are not used. These are likely to be Lasers or LEDs with divergent beams but include products with wide collimated beams.</td>
</tr>
<tr>
<td>Class 2</td>
<td>These Lasers are visible (400 nm to 700 nm). They are safe provided the blink or aversion responses of the human eye operate.</td>
</tr>
<tr>
<td>Class 2M</td>
<td>These Lasers are visible. They are safe provided no optical instruments are used and the blink or aversion responses operate.</td>
</tr>
<tr>
<td>Class 3R</td>
<td>These Lasers have accessible emission exceeding the Maximum Permissible Exposure level for 0.25 s exposure, if they are visible, for 100 s if invisible. Their total output does not exceed the MPE for Class 2 (visible) or Class 1 (invisible) by more than a factor of five.</td>
</tr>
<tr>
<td>Class 3B</td>
<td>These are medium power Lasers and are capable of causing injury when the eye is exposed.</td>
</tr>
<tr>
<td>Class 4</td>
<td>These Lasers are considered “high power”. For constant wave (CW) products, they have an output power exceeding 0.5 W. There is no upper limit to this class.</td>
</tr>
</tbody>
</table>

3.2.2.3 Assessment of Laser safety classes

With each safety class Laser emission limits are associated. The set of maximum allowed power and energy values for each of the classes are called “Accessible Emission Limits” (AEL). For the classification procedure the radiant power and energy has to be measured at a specified distance and with a specified measurement aperture and field of view, and the values are compared to the different AELs. The product is assigned to the next higher class for which the power exceeds the AEL. AELs are directly related to MPEs for the eye by the way of the measurement aperture. The AELs of class 1 are simply derived by multiplication of the respective ocular MPE value with the area of the aperture.

The MPE levels provided in the tables of EN 60825-1 apply for single exposure and a point source. Adjustments of the MPEs are required for multiple pulse exposure and exposure to extended sources.

Multiple pulse exposure, repetitive pulses, pulse train
The MPE levels provided in the tables of EN 60825-1 apply for single exposure. For the evaluation of a pulse train the following criteria have to be considered:

1. Single pulse criterion
   The exposure of every single pulse in the pulse train must be less than the MPE for the pulse (i.e. the MPE for the pulse duration).

2. Average irradiance criterion
   The average irradiance over the considered duration $T$ must be less than the MPE for the exposure duration. For the thermal limits, this criterion relates to a temperature rise, which results from multiple exposures, for photochemical limits this criterion reflects the additivity of individual exposures over time.

3. Reduced pulse criterion
   For wavelength greater than 400 nm the exposure per pulse needs to be less than the MPE for a single pulse reduced by a factor $C_5$, where $C_5 = N^{-1/4}$ and $N$ is the number of pulses within the exposure duration. This criterion reflects the experimental finding that ocular tissue is more sensitive to repeated exposures.

For Laser safety classification the most restrictive criteria is used.

*Extended sources*

The size of the irradiated area on the retina is an important factor for hazard evaluation of optical radiation. The size of the image on the retina is described by the angular subtense $\alpha$, measured in mrad. Due to diffraction, chromatic aberration and scattering the smallest retinal spot size achievable with a well-collimated Laser beam is of the order of 20 $\mu$m, which corresponds to a minimal $\alpha$ of 1.5 mrad. Extended sources that can be achieved for example with an array of Laser diodes will produce a larger retinal image with a larger angular subtense than 1.5 mrad. In this case the angular subtense $\alpha$ will be determined by the beam diameter and the viewing distance.

![Definition of angular subtense $\alpha$](image)

**3.2.2.4 Classification example**

In the following the classification is presented for a pulsed prototype Laser module with a beam characteristic of 2° by 60°.

<table>
<thead>
<tr>
<th>Laser specifications</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>pulse width</td>
<td>30</td>
<td>ns</td>
</tr>
<tr>
<td>pulse power</td>
<td>100</td>
<td>W</td>
</tr>
<tr>
<td>pulse energy</td>
<td>3</td>
<td>$\mu$J</td>
</tr>
<tr>
<td>pulse frequency</td>
<td>5 kHz</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>wavelength</td>
<td>905 nm</td>
<td></td>
</tr>
<tr>
<td>visible source size</td>
<td>55 mm²</td>
<td></td>
</tr>
</tbody>
</table>

Calculation of Accessible Emission Limits for Laser safety class 1

For the given Laser source the following parameters are derived from EN60825-1:

Correction factor $C_4 = 2.57$
Correction factor $C_6 = 50$
Emission duration $T_2 = 55.7$ ns
Angular subtense: $\alpha = 75$ mrad
Aperture size: $A=0.5$ mm²

Since we have a pulse train the 3 criteria described above must be considered:

1. Single pulse criteria
   $$AEL_1 = 2 \cdot 10^{-7} \cdot C_4 \cdot C_6 = 25.7 \, \mu J$$

2. Average irradiance criterion
   $$AEL_2 = 7 \cdot 10^{-4} \cdot \frac{C_4 \cdot C_6}{f} \cdot T_2^{0.25} = 5.7 \, \mu J$$

3. Reduced pulse criterion
   $$AEL_3 = AEL_1 \cdot \left( f \cdot T_2 \right)^{-0.25} = 1.1 \, \mu J$$

The third criteria represent the most restrictive value. It results in an exposure limit of $21 \, \mu J/m^2$ on the averaging aperture.

Estimation of Laser irradiance

The irradiance of the Laser in the minimum eye distance of 100 mm can be estimated to $E=16 \, \mu J/m^2$, assuming homogeneous illumination and no optical losses.

Since the Laser irradiance is below the accessible emission limit this Laser source fulfils the requirements for Laser safety class 1 and cannot cause ocular hazards to humans.

3.3 Suppression of Background Illumination by Utilising short Laser pulses

The 3D distance data acquisition principle relies on the measurement of the travel time of the emitted Laser light pulses to and from the object. The chip typically contains several line sensors, in this case each consisting of 64 pixel circuits. Each pixel circuit (fig. 3.3-1) contains a photodiode PD operating in reverse-bias mode and an associated readout circuitry, i.e. a reset switch $M_1$, 2 source followers (SF1 and SF2), a shutter switch $M_4$, 2 storage capacitors $C_{Sx}$ and $C_{Hx}$, and a select switch $M_3$. The circuit operation relies on a periodical reset of the photodiode capacitance $C_D$ and the storage capacitance $C_{Sx}$ to a fixed reference voltage ($V_{REF1}$) and subsequent discharge due to the photocurrent. The shutter switch $M_3$
controls the integration time of the discharge process at \( C_{Sx} \). Then the remaining voltage stored at \( C_{Sx} \) is read out into a second capacitor bank \( C_{Hx} \) acting as a hold capacitor. The voltage values held at \( C_{Hx} \) are read out using the correlated double sampling (CDS) stage by activating the select switch \( M_3 \). Meanwhile, the acquisition of the next value on \( C_{Sx} \) is performed, thus this architecture yields quasi-continuous light acquisition with minimum dead time. In order to achieve a low power dissipation and high-speed low-noise switching of the S\&H-Stages SF2-C\(_{Hx}\), dynamic bias currents „ipixel\_bias1“ and „ipixel\_bias2“ are required for the source followers. Variation of these bias currents controls the bandwidth \( i.e. \) settling time of the pixel circuitry.

![Figure 3.3-1: 3D pixel circuit with synchronous shutter](image)

This also determines the noise bandwidth. Bias currents „ipixel\_bias1“ and „ipixel\_bias2“ are generated via current mirror circuits using „ipixel\_bias“. Signals „Power\_On\_SF1“ and „Power\_On\_SF2“ are used to switch the source followers between "on" (image acquisition) and "off" (no operation required). During the pauses between 2 consecutive image acquisition cycles the source followers are brought into stand-by-mode by reducing the bias currents. This is very important since it reduces power consumption, chip temperature and, as a consequence of reduced circuit bandwidth, circuit noise. Since these stages are repeated 256 times on the sensor chip the overall power consumption of the chip is significantly reduced (Fig. 3.3-2). According to the selected row of the pixel matrix, a sampling capacitor \( C_{CL} \) is charged to the output pixel voltage \( V_p \) of the selected pixel available at \( C_{H1,2} \) containing the reset and "photo" signals plus all offset and noise voltages (\( \phi_3 \) and \( \phi_5 \) on, \( \phi_4x \) off): this is the "signal sampling" cycle. In the reset phase, \( V_p \) containing the reset voltage of the pixel plus all offset and noise voltages are sampled on \( C_{CL} \), which is the "reset sampling" cycle. The inverting node of the opamp now carries the charge difference between the two cycles, which is being transferred to the corresponding storage capacitor \( C_{FN} \) of the analog memory (\( \phi_3 \) and \( \phi_5 \) off, one out of N \( \phi_4x \) on). This effectively reduces offset and 1/f-noise of the opamp and the source followers. In order to understand the effect of the CDS
technique on distance data acquisition first the time-of-flight measurement with CMOS cameras will be discussed. A few nsec long light pulse generated by an NIR Laser diode and defocused by diffractive optics illuminates an imager field of view defined by a viewing angle. The imager measures the time elapsed between the emission and reception of pulses reflected from an object. The range measurement relies on imager shuttering that is synchronous with pulse emission. The measurement is carried out at two different integration times, i.e. the shutter switch timing is different. This enables the separation of the range information from other factors, such as Laser power, background illumination, and object reflectance. The first measurement is performed by using $T_{\text{shutter}}=T_{\text{pulse}}$, with $T_{\text{shutter}}$ being the active time of $M_3$ and $T_{\text{pulse}}$ the duration of the Laser pulse. Let us assume in the following that $R$ is the sensor responsivity, $r$ the object reflectance, $E_{\text{Laser}}$ the irradiance measured at the sensor, and $T_{\text{travel}}$ is the total travel time of the Laser pulse corresponding with the object.

![Figure 3.3-2: CDS stage and analogue memory](image)

The amount of received light reflected from an object not only depends on the emitted irradiance $E_{\text{Laser},0}$, the reflectance $r$ of the object and its distance, but also on the amount of $E_{\text{back}}$ due to effects of other light sources present. The influence of $E_{\text{back}}$ is eliminated by measuring solely the background irradiance without Laser pulse, i.e. $E_{\text{Laser}}=0$. Thus each measurement must be performed with Laser pulse ON and OFF and the difference being stored on the corresponding capacitance $C_{Fx}$ in the analog memory.

$$V_{p1} = R \cdot r \cdot (E_{\text{back}} \cdot T_{\text{pulse}} + E_{\text{Laser}} \cdot (T_{\text{pulse}} - T_{\text{travel}}))$$

$\wedge$ $V_{p1,\text{back}} = R \cdot r \cdot E_{\text{back}} \cdot T_{\text{pulse}}$ (1)

Thus we have to carry out four measurements in total. The first two measurements yield the pixel output voltages $V_{p1}$, $V_{p1,\text{back}}$, which are given in eq.(1). The difference output voltage at the CDS stage is free of background irradiance and of offset and 1/f-noise.
\[ V_{CL1} \sim R \cdot r \cdot E_{laser} \cdot (T_{pulse} - T_{travel}) \]  

(2)

Eq.(2) applies only if the two measured values of \( E_{back} \) are correlated. This assumption is valid, if \( E_{back} \) does not change within the CDS cycle period. The corresponding control signals of the sensor are shown in Fig.3.3-3. Note that we do not have to carry out an additional reset sampling in this case, we simply measure with the Laser ON and OFF and subtract the measurements, as this corresponds to the CDS operation, too.

Figure 3.3-3: Sensor timing

The voltage \( V_{CL} \) of a certain pixel "x" corresponding with object point no. x in the space plane is being stored in the analog memory at capacitance \( C_{Fx} \) according to:

\[ V_{out1,x} \sim \frac{C_{CL}}{C_{Fx}} \cdot R \cdot r_x \cdot E_{laser,x} \cdot (T_{pulse} - T_{travel,x}) \]  

(3)

The measurement cycle (1)-(3) is repeated by firing a second pulse with \( T_{shutter,long} \) now greatly exceeding \( T_{pulse} \). This means that the complete Laser energy is located within the shutter window. Background suppression and subtraction gives:

\[ V_{p2} = R \cdot r \cdot (E_{laser} \cdot T_{pulse} + E_{back} \cdot T_{shutter,long}) \]

\[ V_{p2,back} = R \cdot r \cdot E_{back} \cdot T_{shutter,long} \]

\[ \Rightarrow V_{CL2} \sim R \cdot r \cdot E_{laser} \cdot T_{pulse} \]  

(4)

This corresponds with a voltage \( V_{out2,x} \) at the CDS stage:

\[ V_{out2,x} \sim \frac{C_{CL}}{C_{Fx}} \cdot R \cdot r_x \cdot E_{laser,x} \cdot T_{pulse} \]  

(5)

Finally, the quotient between \( V_{out1,x} \) (Eq.(3)) and \( V_{out2,x} \) (Eq.(6)) is being computed in the camera system thus yielding a responsivity- and reflectance-free value:

\[ \frac{V_{out1,x}}{V_{out2,x}} = \frac{(T_{pulse} - T_{travel,x})}{T_{pulse}} \]  

(6)

The time \( T_{travel,x} \) elapsed between the emission and reception of the pulse at pixel no. x depends on the travel distance as \( T_{travel,x}=2d_x/v_c \) where \( v_c \) is the velocity of light.
\[ d_x = \frac{v_c}{2} T_{\text{pulse}} \left(1 - \frac{V_{\text{out}1,x}}{V_{\text{out}2,x}} \right) \]  

(7).

The quotient in Eq. (7) now represents the distance of the object point \( d_x \). Note that the non-unity gain of the source followers SF1 and SF2 have been ignored in the calculations. However, all these parameters are cancelled as can be seen in Eqs. (6) and (7). Optionally, each of the two measurement cycles may be repeated \( n \) times using Laser pulse bursts. The resulting voltages are accumulated in the analog memory of the CDS readout circuit operating in accumulation mode. This increases the signal-to-noise ratio by \( \sqrt{n} \) and extends the sensor dynamic range thus increasing the range resolution also by \( \sqrt{n} \).

3.4 Existing conflicts-of-aims between certain camera specs and their resolution

At the end of the preceding section, it was shown how the repeated application of pairs of Laser pulses is suitable to improve the signal-to-noise ratio and increase the range resolution of the distance measurements. Repetition over too long a time interval, on the other hand, lowers the image repetition rate, and thereby decreases the distance precision of objects that exhibit a non-negligible relative velocity. This constitutes a classical example for a conflict of aims, which is resolved in this case by a suitable selection of image frequency rates between 50 and 200 Hz (which can even be run-time adapted by the application). The corresponding time intervals amount to 5 to 20 ms; during such periods of time, an obstacle moving with a relative distance of 20m/s (72km/h) will change its distance by an amount of 10 and 40cm, respectively. This is to be compared with the achievable distance precision of at least 20cm (or less); the choice of image repetition rates of 50 to 200 Hz thereby represent an optimal choice to resolve the relevant conflict.

Because of the limitations of the emitted Laser power, which comes about by eyesafety requirements, there are some further conflicts to be resolved, between the distance range, the longitudinal and vertical fields of view (i.e. the solid angle covered by the camera) and the angular resolution (i.e. the number of pixels). For an isotropic distribution of radiation, the Laser intensity (i.e. the power per area) received by a scattering target is inverse proportional to the square of the distance. For such a scenario, the reduction of both aperture angles to half their values allows an increase of the covered distance range by a factor of 2, since the total emitted Laser power is concentrated in a quarter of the original solid angle. This conflict is partially defused by utilising anisotropic radiation patterns that take advantage of larger emission intensities in the foveal regime of the camera and smaller intensities in the lateral peripheral field of view. As shown in sections 2.1, and 2.3 such a measure is justified by the anisotropic application requirements for front-looking sensors.

A further conflict consists in the choice of the angular resolution (i.e. of the number of pixels per solid angle) as compared to the achievable distance range: twice the angular resolution per linear angle decreases the distance range by a factor of 2. With the requirements derived from present applications, a lateral resolution of the typical width of a pedestrian at a distance of 20 m is intended. At that distance an angular degree corresponds to a width of 34.9 cm. For a lateral field of view of 60 degrees and a horizontal pixel number of 64 this yields to a lateral resolution of
65.5 cm (where the value of 32.73 cm corresponding to the lateral pixel pitch has been doubled to account for Shannon's law). In order to compensate for the Shannon factor, it has been decided to choose an interlaced sensor layout, where adjacent pixel lines are mutually displaced by an amount corresponding to half the horizontal pixel pitch. At a distance of 20 m, this then yields a lateral resolution of 32.7 cm.

In order to ensure some maximised backscattered Laser power per pixel, the vertical resolution (i.e. the resolution with respect to the elevation angle) has been fairly reduced by choosing a pixel matrix of 64*8 pixels, with a pixel pitch of 130*300 µm for the horizontal and vertical dimensions, respectively. This is in addition supported by a pixel fill factor of about 85%, which helps to collect most of the back-scattered light (among other things from retro-reflecting items such as rear reflectors and licence plates which feature almost 100% backscattering rates).
4 Technical Sensor Specifications

4.1 Image sensor chip [FhG/IMS]

4.1.1 Subject of the Specification
Subject of the specification is the complete description of the electrical characteristics of the demonstrator camera described as follows.

4.1.2 Life saving systems / liability
The product is not suited for the use in life saving equipment, systems or devices, where a malfunction or a failure of the product can cause an injury of persons. The usage of the product in such fields of applications is at the users own risk. A liability of the manufacturer and/or the developer of the product and/or third parties is excluded in this context.

Changes in this section require an additional agreement in written form.

4.1.3 Design strategy
During the first project phase, the image sensor concept and its specifications are developed by the application partners of the consortium.

After all consortium partners have agreed on all image sensor specifications the final design steps and final simulations will be carried out by IMS.

The layout will be carried out by IMS.

The whole circuit will be at first checked (layout versus schematic, LVS) by hierarchy. The final check will be done in a flat way.

4.1.4 Device description
The 3D Line sensor will be manufactured in a CMOS technology for the UserRCams consortium. It will be used for the measurement of incident irradiation of Laser light. It is an integrated circuit and consists of:

- 8 x 64 photo diode pixels (customized version, described in the annex)
- a suited readout circuit per column consisting of a CDS stage with analog accumulation capability
- multiplexers for selecting the rows and binning functionality, respectively.
- an analog buffer circuit for each output channel (total 2).

The main application is automotive surveillance. The specification list of the 8x64 pixel line sensor is summarized in the following table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>0.5µm</td>
<td>FhG-IMS Standard CMOS</td>
</tr>
<tr>
<td>Pixel Geometry</td>
<td>130x300µm²</td>
<td></td>
</tr>
<tr>
<td>Pixel Count</td>
<td>512</td>
<td>4x(2x64) = 8x64 pixel</td>
</tr>
<tr>
<td>Line acquisition</td>
<td>multiplexed</td>
<td>2x2 lines are multiplexed for each sensor half,respectively. Possible binning between 2 adjacent lines</td>
</tr>
<tr>
<td>Optical Format</td>
<td>2/3&quot;</td>
<td>Estimation 2x(4x0.3)x64x0.13mm² = 19.968mm² photosensitive chip area</td>
</tr>
<tr>
<td>Die size</td>
<td>12mm x 6mm</td>
<td>2x chip size, Mirrored design (in total: 128 readout circuits for 512 pixels in interlaced mode). Preliminary, dimensions will be fixed during layout finalization.</td>
</tr>
</tbody>
</table>
## Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Principle</td>
<td>Photodiode</td>
<td>Synchronous shutter. Integrating, source follower buffered</td>
</tr>
<tr>
<td>Readout Characteristic</td>
<td>Quasi-linear,</td>
<td>High signal-to-noise ratio. Non-destructive readout, needed by the</td>
</tr>
<tr>
<td></td>
<td>buffered diode</td>
<td>adaptive control mechanism</td>
</tr>
<tr>
<td>Dynamic Range (DR)</td>
<td>69dB</td>
<td>Design goal. Subject of sensor characterization. Distance dynamic:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1:10, reflectivity: 5%...95% (adaptive control). $V_{\text{bias}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>adjustment required</td>
</tr>
<tr>
<td>Noise equivalent exposure</td>
<td>1 W/m²</td>
<td>Design goal. Subject of sensor characterization. 30ns shutter time.</td>
</tr>
<tr>
<td>(NEP)</td>
<td></td>
<td>Binning of 2 lines possible</td>
</tr>
<tr>
<td>Shutter times</td>
<td>min.: 30ns</td>
<td>Programmed by FPGA, $\mu$C</td>
</tr>
<tr>
<td>Output Format</td>
<td>2 x analog</td>
<td>Externally digitized with a 12 bit A/D converter</td>
</tr>
<tr>
<td>Max. Pixel Clock</td>
<td>5 MHz at 20pF</td>
<td>Conversion rate of ADC-Interface</td>
</tr>
<tr>
<td>Pulse/Burst</td>
<td>1...128</td>
<td>Programmable</td>
</tr>
<tr>
<td>Master clock</td>
<td>66MHz</td>
<td>required for shutter</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>$&lt; 3W \at 3.3V$</td>
<td>Dynamic biasing required -&gt; power management</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-40°C...+85°C</td>
<td>Preliminary. Subject of sensor characterization</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>850nm - 910nm</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Acquisition time</td>
<td>50µs...20ms</td>
<td>Determined by the number of pulses required (accuracy)</td>
</tr>
<tr>
<td>Packaging</td>
<td>CQFJ84</td>
<td>Standard ceramic package</td>
</tr>
</tbody>
</table>

Table 4.1.4-1: Specification list 8x64 pixel customized line sensor

The 4x64 line sensor is mirrored on the horizontal mirror axis in order to build up the final 8x64 customized line sensor. Technical details are to be found in the SP-confidential annex.

### 4.2 Laser illumination and optics

A modular concept for the Laser illumination will be developed, which allows the flexible and cost-effective assembly of Laser modules for various applications. The basic element consists of a Laser module with a variable number of Laser diodes bonded directly on a ceramic substrate. Driver electronics is also integrated. Combining several basic modules with appropriate optical lens for beam forming a variety of illumination requirements can be fulfilled.

Target specifications on optics and Laser modules comprise:

**Optics:**
- Precise, application specific Laser beam forming with a high degree of homogeneity
- Low losses for Laser wavelength, typically 905 nm
- Compact design and low cost

**Laser modules:**
- Application specific ray profile within a range of 20 m to 30 m
- Rectangular pulse width with variable length from 100ns to 500ns
- Pulses
- Application dependent assembly of Laser pulse energy up to 150 $\mu$Wsec
- Fulfillment of Laser eye safety regulations (protection class 1)

Prototype devices have been fabricated and first evaluation results confirm the feasibility of the technical requirements.
Figure 4.2-1: Laser pulse module with energy up to 150 µWs

Figure 4.2-2: Typical Laser output of breadboard circuit
4.3 System hardware and hardware interfaces: Specification Table

The requirements of the various types of applications taken into consideration by the four OEMs and SVDO were adapted to the technical chances and constraints provided by the novel technology. The resulting specification figures were collected in a requirement and specification table that serves as a starting point for the camera development task. Some of the specification values given in that table (for instance the illumination and perception aperture values) do only apply to the experimental sensor being developed within SP UseRCams and need to be adapted accordingly, once the sensor is industrialised for the corresponding type of application (in case of such discrepancy, both the experimental as well as final specs are given in the table).

For the sake of better legibility, the table is not reproduced within this document, but is given in a separate file “PR-52300-SPD-041210-v11-RequirementTab.xls”.

As hardware interface for the experimental camera, it was agreed to utilise a 100BaseT Ethernet interface. In contrast to a high speed CAN interface, this ensures sufficient data rates even in the case that the raw images (i.e. pixel information for every image) are to be transferred to the perception computer - as would be required, for instance, for the sake of low-level sensor data fusion. Utilisation of such a standard interface helps to concentrate the project efforts on sensor development and not to dissipate energies with peripheral tasks. The specification and/or choice of a hardware interface suitable for the car industry is the responsibility of vehicle development and sensor industrialisation, but not that of sensor research.

4.4 Data representations and choice of APIs

The software interface for the applications to communicate with the 3D camera will be given by that of a C library that allows the applications to set the adjustable parameters of the 3D camera and also to receive its output data. The output data contains the distance information delivered by the 3D image sensor and the object lists computed by the object detection algorithm.

A preliminary proposal for the software interface is the following:

```
// Create data structures for a maximum number of objects
sl_3DC_Create (T_SLONG sl_MaxObjects)
// Configure the adjustable parameters of the 3D camera
sl_3DC_Init (S_3DC_PARAM s_3DC_Param)
// Start the 3D camera
sl_3DC_Run ()
// Read out the 3D distance image
sl_3DC_GetDistance (T_UWORD *pauw_Distance)
// Read out the distance confidence
sl_3DC_GetConfidence (TUBYTE *paub_Confidence)
// Read out the list of detected objects
sl_3DC_GetObjects (S_3DC_OBJECT *ps_3DC_Objects)
// Stop the 3D camera
sl_3DC_Close ()
// Destroy the reserved data structures
sl_3DC_Destroy ()
```
// Data types
T_SLONG       signed long (32 bits)
T_UWORD       unsigned word (16 bits)
T_UBYTE       unsigned byte
S_3DC_PARAM   tbd (parameter structure)
S_3DC_OBJECT  tbd (object list structure)
5 Future Refinements of the Specifications / Conclusions

5.1 Role of the evaluation prototype camera

Based on existing components, a preliminary prototype will be constructed, for validation of the specification, for fine-tuning of the component development in WP 52.500 and also for the algorithm development in WP 52.700. The resulting prototype camera system will provide 2D/3D images aiming at the extension of the present distance range from 4.5 m to about 20m and will be used for the development of first generation algorithms for the recognition of urban traffic objects.

The know-how and experience accumulated with the deployment and evaluation of this first prototype will then empower the development team to the design of a customised CMOS imager, which aims at the optimal adaptation to pre-crash and blind spot safety applications. In addition, the chip will provide the means for self-testing, in order to meet the safety requirements of automotive applications. The fabricated chip will then be integrated into the final 3D camera system, together with an improved Laser light source and a re-engineered electronic board level design.

5.2 Evolution of the specification process

The specification process of the customized version will proceed in a two-step evolution procedure. Firstly, the experimental results of the already existing 4x64 image sensors will be analysed with respect to noise equivalent exposure, sensitivity and responsivity. The following tables shortly summarize the relevant experimental data.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>FhG-IMS FhG-IMS 0.5µm Standard CMOS 3.3V supply voltage, 1.2W typical power consumption, CQFJ84 package</td>
</tr>
<tr>
<td>Pixel Geometry</td>
<td>130x300µm² Aspect ratio: 1:10, 2/3&quot; C-mount optics</td>
</tr>
<tr>
<td>Pixel Count</td>
<td>256 2x(2x64) = 4x64 lines, 400um scribe line</td>
</tr>
<tr>
<td>Dynamic Range (DR)</td>
<td>80dB distance dynamic: 1:10, reflectivity: 5%...95%, if adaptive control is used</td>
</tr>
<tr>
<td>Noise equivalent exposure (NEP)</td>
<td>4.1 W/m²² 30ns shutter time binning of 2 lines possible, 66MHz master clock</td>
</tr>
<tr>
<td>Distance resolution</td>
<td>5cm 2% of total range. MDSI-FPGA defines number of samples needed to obtain the desired accuracy</td>
</tr>
<tr>
<td>Shutter times</td>
<td>min.: 30ns Programmable by FPGA</td>
</tr>
<tr>
<td>Acquisition time</td>
<td>50µs...20ms Determined by the number of pulses required (=&gt; accuracy), 5 MHz max. pixel clock at 20pF max. Load</td>
</tr>
</tbody>
</table>

Table 5.2-1.: 4x64 pixel line sensor data
As the next step towards enhanced sensor performance, an intermediate test version of the line sensor with 2x64 pixel lines will be developed in order to evaluate the newly introduced current buffer principle concerning improved responsivity and noise behaviour. Simulations on the new pixel principle show an improvement of the NEP (noise equivalent exposure) down to 1-2 W/m². This directly affects the achievable distance resolution of the sensor. After the evaluation phase, finally, a customized version of 8x64 pixel lines will be developed either containing the current buffer principle or an improved version of the pixel principle shown in table 5.2.1. This choice will be taken depending on the measurement results of the test chip.

Important trade-offs on technical constraints that have to be regarded during the design phase are summarized in the following table:

1. With given optics angle the received signal decreases with distance d²:
   - Example: d = 1m...20m    signal variation by factor of 400, i.e. 52dB
2. Further increase of dynamic range DR by reflectance variation (e.g. 1%...100% i.e. 40dB)
3. High DR only possible with adaptive measurement (number of pulses, shutter time)
4. Resolution depends on signal level (SNR) and can be improved by number of pulses, Laser power, smaller viewing angle
5. Laser power / wavelength vs. sensitivity
6. Illuminated area (angle) vs. sensitivity
7. Number of pixels vs. sensitivity, number of pixels vs. chip area (costs)
8. Available Laser power should illuminate only the areas of interest, i.e. illumination of a few lines is more efficient than illuminating a wide area
9. For line(s) sensor the fill factor can be 100%; arrangement of lines possible.
10. Array demands multiplexing which is extremely difficult during acquisition phase (timing, signal &power crosstalk)

5.3 Concluding remarks

Future road safety applications do depend on the development of increasingly intelligent sensor systems well suited for system integration, which meet the requirements of robustness, reliability and perception capability. The UseRCams 3D camera is well suited to meet these challenges by providing a three-dimensional solid state image acquisition concept which in comparison to existing sensor technology reveals distinct advantages for vehicle environment monitoring, capable to classify traffic object like obstacles and pedestrians and to detect their motion. The defined general sensor specification will cover the aims of the various applications planned in the UseRCams sub-project despite of the different functional requirements and detection areas. Furthermore, the results of the sensor and algorithm development should also be most suitable for their integration with the vertical subprojects COMPOSE and APALACI, especially with regard to sensor data fusion, demonstrating the versatile potential and future deployment of the UseRCams technology.
6 Annex: (SP Confidential) Details of Sensor Customisation and Module Requirements

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Keywords

Glossary