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Obstacle detection and avoidance

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1 Executive Summary INRIA

Obstacle detection is a key issue for the deployment of automated vehicles in the urban environment. This deliverable has been elaborated to give some directives to the developpers of such systems. It introduces the state of the art of the various sensors now in the market and those which might soon be and tries to match these sensors with the requirements of the various scenaris which have been elaborated in CityMobil SP2.

Finally, test procedures for the certification of the obstacle detection features of the vehicles are proposed.

2 Introduction INRIA

In sub-project 3 of CityMobil the technological issues of advanced urban transport systems are addressed. The main objective of this sub-project is to remove technological barriers in order to introduce advanced urban transport systems on a large-scale. Advanced vehicle architectures are developed and the basic subsystems for cybercars and advanced city cars are defined to achieve this objective within the sub-project. A dual-mode platform is developed within SP3 and an optimum solutions for human-machine interfaces and information systems are proposed. Furthermore specific obstacle detection systems and navigation techniques, focusing on wireless communication for high throughput are evaluated.

In order to study the described technological issues, working scenarios are developed, which represent different transport areas in modern city life and provide possible solutions for future penetration of innovative transport systems and integration in urban areas under the consideration of the already existing infrastructure. Four scenarios are adressed in Citymobil:

1. Town centre : dual mode vehicles and advanced city cars in a historical town centre
2. E-lanes: high-speed dedicated lanes where vehicles operate in automatic mode
3. Inner city centre: fully automated low-speed vehicles in a pedestrian area
4. Shared traffic: dedicated lanes for automated and classical buses

The scenarios offer a good level of generality and potentiality for the CityMobil sub-project. Functions, such as automatically moving in dedicated lanes, entering and exiting a parking area automatically and joining and leaving a formation of Cybercars, have to be considered within those scenarios.

The selected working scenarios are described in detail to understand the boundary conditions. Considering those scenario descriptions the definition of system requirements are derived for each scenario. The requirements are based on reliable sources such as simulations, experience from previous projects or calculations. Based on the derived requirements, the main technological challenges for the realisation of these scenarios are identified, which allow the subproject to address them in WP3.2 – Human factors, WP 3.3 - Obstacle detection and avoidance and WP3.4 – Cooperative vehicles and navigation. As a result of the deliverable preliminary system definitions are given in form of a description of the vehicles and their components with the necessary additional infrastructure belonging to the system in different scenarios.

This workpackage deals specifically with the technologies and the requirements for obstacle avoidance. Its objective is to give to the developers of the systems, recommandations for the introduction of sensors and software accordingly with the sites selected.

3 State of the art in sensor technologies for obstacle avoidance

3.1 Proximity sensors

3.1.1 Ultrasounds

Ultra sonic (US) sensors are today largely spread in automotive industry for the short distance obstacle detection, most of the time to assist the driver for back maneuvers. Based on a 40-45 kHz sound pressure wavelength, the sensor cover a range of 1 to 3 meters detecting objects in an horizontal beam width of maximum 100° and 60° vertical. They suffer of insufficient information on the objects angular position so that echo cancellation, mainly on the road surface, is impossible to obtain.

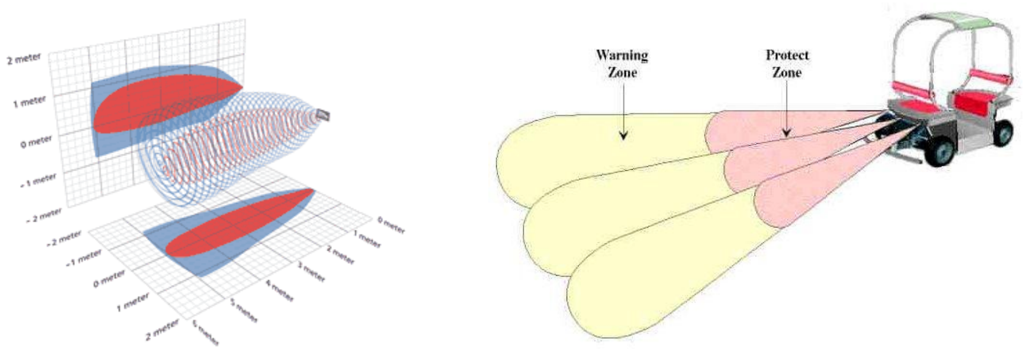
Even if the ultrasonic technology is generally known (e.g. on cars for parking aid), there are some concerns regarding the use of these sensors in an open environment, especially at rather important distances and when a precise measurement of distance or angle is needed.

In this context, Robosoft installed and evaluated on a RobuCab an ultrasonic based anti-collision system.

With ultrasonic detection, the goal was to obtain a good behaviour of the vehicle when an obstacle is detected. In such a case, the vehicle must be able to slow down and stop smoothly. This solution is intended to be cheaper than the laser solution.

In this application the sensors have 2 fields with the possibility to change the distance of detection. The one is a warning zone that makes the vehicle decrease speed, the other is a protect zone that stops the vehicle (Figure 1).

Figure 1: The Ultrasonic shape (left) and the two zones (right)



The two logical outputs of the ultrasonic module are connected to a microcontroller board. The speed modification is made by this board via the control software.

- The range of the zones is 10 to 700 cm (much lower than a laser, but sufficient for vehicles up to 15 km/h); the response time is 240 ms maximum;
- This sensor can be reprogrammed in real-time, meaning that safety distances can be adjusted from one location to another one;
- Several kind of sensors have been mixed (with different shapes) to improve the quality of detection;
- It cannot be used alone because this is not a certified sensor.

3.1.2 Light beams

Light Beams, also known as Photo Eyes have been used in a variety of applications for a number of years. These sensors detect the presence of a person or object that interrupts the light beam by passing through its path. Typically used for threshold safety, entry notification and start-up activation, it has become a mainstay product for many industries from automatic door manufacturers to premises security companies.

Light beams use a transmitter/receiver system to send an invisible or infrared light beam through the air along a desired path (transmitter and receiver are very close the one from the other are both on the vehicle like for ultrasound sensor). When the beam is interrupted, a signal is sent to deliver the distance of the obstacle.

This type of sensor could be used in similar application than ultrasound sensors. However the type of information is different compared to US:

- US detection is made in a cone (3D information) whereas the measure delivered by a light beams is a 1D information. It could be used for wall following application (lateral control), but it exists other type of sensors allowing the type of control with a wider type of information like laser scanner.
- The measure of distance is quicker than US, one can get information every 20/30ms.
- The range of measurement depends on the type of sensor used but can start from 5 cm to 6 m.

3.1.3 Contact

The most common contact sensors are also called smart-bumper. They are usually used as signaling or safety devices for doors on buses, trains and people movers. Designs include electrical and pneumatic edges (airwave pressure) in a wide variety of rubber profile cross sections.

They can be found in robotic application for safety reason (Figure 2) in order to detect collision with obstacles.

This type of detection sensor does not allow any anticipation for obstacle detection. Once the obstacle is detected it is too late to avoid it. It cannot be used in an obstacle avoidance application.

However this technology should be used as an emergency stop in case of collision.

Figure 2: bumper mounted on a roburoc4 robot

3.2 Laser scanners

The laser scanners we present in this chapter are systems allowing the acquisition of 2D representation of the environment.

The strong points of the laser based scanners are:

- Acquisition rate compatible with the speed of vehicle (rates between 5Hz and 100Hz, depending on the resolution of the scanner, which corresponds to a distance of 0.14 m to 2.7 m between 2 acquisition for a vehicle speed of 50km/h)
- Good precision of the measure (around 5 cm – sometimes less depending on the system)
- Possible high range in measurement (up to 250m)

Depending on the type of laser system the weak points of this technology are:

- Their utilization can be limited by the presence of fog when a long distance information is required
- Some problems can occur in case of heavy rain
- These systems give a 2D information about the environment: a pitch movement of the vehicle can bring a big variation of the altitude of the measure. This could be problematic for a long range detection of obstacles.
- The angular resolution can sometimes give problems in the detection of small obstacles.

3.2.1 Sick

Sick is a company proposing several outdoor laser scanner allowing obstacle detection. One can quote the LMS211, LMS221 or LD-LRS.

The LMS211 and LMS221 laser scanner allow a maxium range detection of 80m with an angular resolution of 0.25°, 0.5° or 1°. Depending on the angular resolution selected the acquisition rate can vary from 13ms to 52ms.

The LD-LRS allow a detection up to 250m with an angular resolution varying between 0.125° to 1° and an acquisition period varying between 66.6 ms and 200ms.

The interface of this sensors with ECU is made using a rs232 or rs422 serial line.

The Figure 3 shows these 3 types of Sick laser scanner.

Figure 3: the Sick LMS 211, 221 and LD-LRS

3.2.2 Ibeo

IBEO (now a subsidiary of SICK) proposes also several laser scanner with capabilities comparable with SICK scanner system excepted for one special system, the XT Alasca.

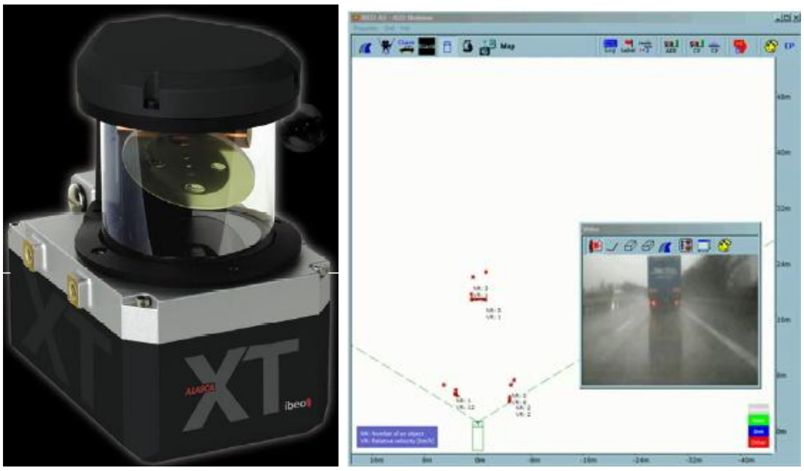
This system was specifically developed for vehicle application. The maximum range of measure is of 250m. The detection of obstacle is made by taking into account not only one echo but 4. This feature allow to this system to be more robust than SICK system to meteorological condition like rain or fog.

Moreover this laser system does get its 2D information not in only one plan but in 4 plans. By this way this system is also more robust to the movement of the vehicle (pitch movement) or road deformation than other existing laser scanners.

This laser scans the environment on 240° with an angular resolution varying between 0.1° and 1° for a rate of 12.5Hz to 25Hz.

IBEO proposes also with this scanner a software package allowing ACC, pre-crash, pedestrian detection, obstacle detection at high speed.

Figure 4: the IBEO XT Alasca and an illustration of this system with rain



3.2.3 Others

SICK and IBEO are the most known (and certainly the most used) laser scanner in vehicle navigation.

One can find also other suppliers for laser scanner, like Hokuyo or Leuze, but these systems do not fit very well with outdoor applications. Indeed these laser systems have a reduced range for measurement. They are then used for safety application or for navigation in indoor applications.

Figure 5: the Leuze and Hokuyo laser scanners

3.3 Radar sensors

Radar systems are active sensors in that they emit or transmit electromagnetic waves and then receive any waves that are reflected back from an object. The distance measurement capability of radar systems is good and velocity measurement can be highly accurate depending on the modulation scheme of the transmitted. To provide good angular detection capability, a range of scanning radars is available or some systems derive angle by processing the returns from two separate antennae.

The automotive industry demands cost effective radar systems for example for Adaptive Cruise Control (ACC) systems. As such nearly all-automotive radar manufacturers are using Gallium Arsenide (GaAs) Monolithic Microwave Integrated Circuit (MMIC) technology rather than military Gunn diode technology. However, GaAs radars are still quite expensive for automotive applications, so manufacturers are now implementing Silicon Germanium (SiGe), particularly in short range radars with the technology likely to transfer to long-range radars around 2010.

Radar functionality on passenger cars is mainly divided into two categories dependent on whether they operate at long or short range.

3.3.1 Long range (76-77 Ghz)

Long-range radars operate at 76 to 77GHz and typically measure target range, relative speed and angular position. The radar’s maximum range is usually between 120 to 200m and the standard azimuth (or horizontal) field of view is around 12 degrees (although manufacturers are now introducing 20 degrees field of view systems). This performance makes long-range radars suitable for:

1. ACC
2. Collision warning
3. Collision mitigation systems.

Different manufacturers have opted to implement different modulation techniques. Some use the traditional Frequency Modulated Carrier Wave (FMCW) concept whilst others use pulse Doppler methods or Frequency shift keying (FSK) techniques. The techniques measure target range and range rate differently (e.g. time of flight or Doppler phase shift) but typically measure angular position of targets using a number of overlapping radar beams. The number of beams typically varies from 2 to 5. However, a current trend is the use of scanning radar techniques to provide a measure of angular target discrimination.

Alternative modulation techniques produce measurements with different measurement specifications. Hence, manufacturers are considering combinations of various modulation techniques so that the radars can derive enhanced information of the road scene that maximises the use of the available bandwidth. The enhanced information, which individual radars in isolation cannot obtain, might include improved accuracy and possibly alternative and increased information.

Radars that operate at 76 to 77 GHz do carry a manufacturing cost penalty compared to lower frequency devices but as they operate at a short wavelength these radars can be made smaller than lower frequency radar.

3.3.2 Short range (24 Ghz)

Short-range radars operate at 24GHz and typically measure target range, range rate and angular position. The radars' maximum range is usually between 0.5 to 50m and they usually provide large azimuth (or horizontal) field of view. This performance makes short-range radars suitable for:

1. Forward facing "Follow to Stop" applications and sensor redundancy for higher authority systems
2. Side facing "lane change assist" or "blind spot monitoring"
3. Rear facing back-over object detection (e.g. when reversing).

The short wave frequency band is considerably more problematic than the 76-77GHz band as it is very crowded with a whole host of neighbouring applications ranging from telecoms to weather forecasting to radio astronomy.

At 24GHz there have been two sub-allocations in frequency. The Industrial, Scientific and Medical (ISM) band from 24.05 to 24.25GHz is available for radars that operate a narrow band modulation scheme. For pulse radars that measure distance to very short range targets a much wider band, in the order of 4GHz is required. The European standard ETSI EN 302 288-2 and the US standard FCC 02-48, Section 15.515 both make provision for low power wideband access centred around 24GHz. However, European legislation does not approve the use of this 24GHz wide band beyond a date of 2013 and does not permit their use within a specified distance of a radio astronomy location.

European authorities have allocated a frequency band from 77 to 81GHz to replace the 24GHz wide band. US authorities have yet to approve this allocation. Furthermore, the microwave devices required to operate at these frequencies are currently more expensive than their 24GHz counterparts and so adoption of this frequency band may be slow.

3.4 Vision Systems

Passive visible light vision systems (passive in the sense that they receive electromagnetic radiation whilst active systems emit and then receive any returns) have the potential to give reliable, high spatial-resolution information about the position of obstacles around a vehicle. Because of this, industry and academia have undertaken vision system research over a number of decades and have developed many successful systems particularly for use in structured or well-defined environments. Fewer successful vision systems exist for obstacle detection in unstructured or poorly defined environments where a more difficult problem exists due to the many different obstacles that the vision system might need to detect.

Vision systems require large data rates (e.g. a need to transfer a 640x480 pixel image with 8-greyscale bits per pixel operating at 25 frames per second (fps) requires 7.32MB/s) and require that this data is processed in real time. This processing may include deriving measurements such as object range that is not directly obtainable from the 2D images (unlike active sensors that determine range data directly through, for example, time-of-flight measurements). These requirements are satisfied using readily available, computationally powerful processors that, with the widespread availability of low cost cameras, enable cost effective object detection systems.

Vision systems are passive and so do not interfere with devices on other vehicles or the infrastructure. However, a disadvantage is that vision systems rely on visible light. Hence, vision systems need to be robust to poor lighting conditions or to partly discernible image features such as may occur in adverse weather conditions. Some systems have achieved this robustness through fusion with alternative sensing technologies (e.g. radar)

3.4.1 Monocular vision

There is no depth data associated with each pixel in a captured image so monocular vision systems are incapable of measuring the distance to an obstacle directly. There are, however, several techniques used by researchers to extract the depth of the scene from a monocular image.

Depth from a Single Still Image

[18] and [21] described a system that can infer scene depth in a single still image from monocular cues (i.e. texture gradients, defocus, colour, and haze) using a multi-scale Markov Random Field (MRF). The system uses images and ground-truth depth maps to train the MRF model. A small remote-control vehicle has used this system to drive autonomously through unstructured environments.

A disadvantage is that the use of a finite set of training images means that the system may not work well in environments that differ significantly from the training set.

Ground Plane Appearance Modelling

Several obstacle detection techniques rely on the segmentation of the image based on the assumption of a flat ground plane and contact between the obstacle and the terrain. [Dahlkamp2006] describes an approach to model the appearance of the terrain ahead of a vehicle. Initially a laserscanner scans the near vicinity ahead of the vehicle for flat, drivable surface areas. This technique assumes that these areas are driveable terrain and uses this data to train the computer vision algorithm. The vision algorithm then classifies the entire field of view of the camera as driveable or unknown. This technique does not actually detect obstacles or classify them but rather detects the regions with no objects that would be significant to the driving task.

This technique has two main disadvantages. Firstly, the detection of the driveable terrain relies on the appearance of obstacles being significantly different from that of the driveable terrain (i.e. this technique may not classify a shadow or flat obstacle as driveable terrain even though it would be drivable and may not detect any obstacle that has the same appearance as the road). Secondly, this technique will overestimate the distance to obstacles that are not in contact with the terrain (e.g. signs hanging from buildings).

Obstacle Appearance Modelling

Some monocular obstacle detection techniques rely on a priori information about the appearance and size of obstacles. [11] describes a system that uses a 3-stage process to determine the presence of vehicles in the scene. First, the system looks for candidate regions within the image that may correspond to vehicles. Second, the system classifies each of these candidate regions by allocating a score that represents the likelihood of the region being a vehicle using several “classification schemes” based on a priori knowledge of the appearance of many vehicles. Finally, each likely vehicle is “approved” over several video frames; effectively using multiple frames makes the vehicle classification robust to the presence of large amounts of clutter and variance in the vehicle appearance with respect to the a-priori knowledge. The range and range rate of the obstacles are then determined using the inverse perspective transform that assumes a flat road plane.

[11] claims the system detects vehicles reliably. However, where a priori information of other vehicle or obstacles is not available then detection of the object, its size, position and speed is less reliable.

Ground Plane "Optical Flow"

Optical flow is a well-known technique to detect the presence of an obstacle moving relative to the background scene. This technique separates obstacles from the background by segmenting the image and then infers the distances to these obstacles. [4] describes a technique that uses odometric measurements to estimate the optical flow of the ground plane. The technique modifies pixels in a frame with the optical flow estimate and then compares them to the pixels in the next frame. Pixels that do not match are either part of an object moving in the ground plane or part of an obstacle above the ground. [4] reports that the technique is robust to inaccurate odometric measurements and unmeasured roll of the host vehicle, however, this technique does fail in the presence of shadows cast by moving objects.

[29] describes a technique that estimates the scene depth from the scaling of image regions. The technique then generates obstacle hypotheses from the depth estimates. The technique then tests the object hypothesis to determine if it corresponds to an obstacle with distance or to a clear roadway. The approach can detect obstacles at distances of 50m.

3D Structure from Motion

Structure from Motion (SfM)[1] is a technique that infers the structure of a static scene and the presence of stationary obstacles through geometric reconstruction over a sequence of images. The recovery of the structure of the scene in this way does not rely on any assumptions about the appearance of an obstacle but does rely on sufficient texture in the scene to be able to "see" the obstacles. The technique determines the camera movement between two frames and then applies epipolar geometry techniques (as used in stereo vision depth mapping). Some solutions that derive structure from motion rely on tracking corresponding features in both images (although [17] presents a correspondence-free approach using the Radon transform). Others resolve the camera motion based on the observed optical flow.

Moving obstacles present a fundamental problem for basic structure from motion approaches because they assume that features are static. An object that may have moved between the capture of the two images could still be located in the same place in the 3D reconstruction and so incorrect depth estimates could result. [31] presents a monocular image- based intersection assistant that detects the motion of obstacles using the difference between the focus of expansion for the background scene and that of the other obstacles. The paper also presents degenerate cases where the technique fails to detect the obstacle.

SfM techniques achieve robust tracking of obstacles in the face of occlusion and incorrect point correspondences by applying techniques such as Random Sampling Consensus (RANSAC) and Particle Filtering.

Temporal Inverse Perspective Mapping (IPM)

[2] extended frame differencing (often used with stationary cameras to detect moving objects) for use with moving cameras in a start-inhibit application. When the vehicle is stationary, a background image is generated which is subtracted from new frames to determine the position of moving obstacles. When the vehicle starts to move, the system switches state and

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[1] Note Simultaneous Localisation And Mapping (SLAM) problem (see [Davison2007]) and SfM are comparable in that they both attempt to reconstruct the movement of the camera. SLAM uses image features to create and update a feature map whilst simultaneously deriving the camera's position (with respect to the map). In SfM a dense set of image features is sought to reconstruct the scene.

uses odometric measurements to determine the motion of the ground plane. The system generates a difference image between the current image mapped onto the ground plane and the previous image mapped onto the ground plane and shifted to keep the ground plane features overlaid. If no obstacles are on the road, the two images are identical (assuming a flat road) and so no significant features appear in the difference image. If there is an obstacle on the road then the system can infer its position from the difference image. The results presented in the paper suggest that this system could be effective for vehicle speeds up to 40km/h but robustness of this technique to vehicle pitching under acceleration and braking is not given.

3.4.2 Stereo vision

In stereovision systems two laterally offset cameras capture images simultaneously. The positions of features in the left and right images differ depending on the separation of the two cameras and the depth of the features (physical distance from the cameras to the features). This so-called disparity is inversely proportional to the depth of the features and is not due to the motion of the features as the images are simultaneous.

Registration is the process of transforming the two images into a common coordinate frame. In the common coordinate frame, a feature in one image will lie on a known line (an epipolar line) in the second image so simplifying the association of features between images. It can be computationally advantageous to arrange the cameras such that the epipolar lines are parallel to the imager rows such that a feature in one image will lie in a horizontal line or row of the other image.

Better processor architectures and more specialised DSP/FPGA platforms are enabling real-time embedded stereovision systems to become feasible. [25] reviews real-time stereo algorithms suitable for intelligent vehicle systems.

Disparity and Correspondence Problem

Stereovision systems traditionally generate a depth map using disparity between the features in the two images. The main challenge when using disparity as a cue to depth is to find corresponding features in both the left and right image in the presence of occlusion and other effects (this is the so-called ‘Correspondence Problem’).

[23] describes a system which uses disparity of “declivity” features (linear features fitted between local image intensity maxima and minima) from each image to determine candidate vertical 3D features for vehicle boundaries. The 3D feature extraction enables the system to more accurately group features that belong to the same vehicle. The system then applies a monocular vision approach to the 3D features (using symmetry and bounding boxes) to find the preceding vehicle.

[16] introduces a technique for developing a histogram of disparities (termed a V-disparity image) along the horizontal rows of the image (when the epipolar lines are parallel to the imager horizontal rows). This provides information about the road profile and road contact points of obstacles.

[19] introduces a technique based on evolutionary optimisation of 3D particles called ‘flies’. Initially, the technique distributes the flies randomly in the space. Flies that lie on the surface of an object have similar local features in both images and so the technique assigns them a high fitness score. If a fly does not lie on the surface of an object then its surroundings in both images will be different and so the technique assigns a low fitness score. The technique employs evolutionary algorithms to the flies such that it takes from 10 to 30 generations for the flies to evolve and to become associated with new objects in the scene.

[8] presents another technique for solving the Correspondence Problem using minimisation of an energy function and graph-cuts.

Inverse Perspective Mapping (IPM)

[5] describes a system that uses Inverse Perspective Mapping (IPM) to map the images from both cameras onto a flat road plane. This technique derives a polar histogram of the absolute value of the difference of the two images. The peaks and spread of values in the histogram are used to assess the presence and position of an obstacle. This technique relies on accurate calibration (i.e. the removal of optical distortion and perspective effects) of the two camera images with respect to the road plane so that features on a flat, empty road surface appear in the same position in each calibrated image.

“6D-Vision” – Temporal Tracking

A reported problem with some stereovision systems is that they incorrectly segment small moving obstacles (i.e. bicycles) in front of a larger (possibly stationary) object. The solution given in [10] is to track both the 3D position and 3D velocity states of each feature in the stereo image (hence “6D-vision”). This allows the use of temporal information to assist in segmentation of moving obstacles and provides a robust detection of obstacles in partial occlusion. [10] apply this method using Kalman Filter Tracking with Interacting Multiple Models (IMM) to support different traffic scenarios. In another paper, [9] demonstrates the fast detection of a child walking behind a stationary vehicle using the temporal tracking technique.

Combination of Different Visual Cues

[12] describes a system which combines a stereo vision system with other visual cues (i.e. shape and texture) to detect pedestrians. The technique does not use sparse stereovision depth data to perform segmentation of pedestrian candidates directly but rather to instantiate shape based detection. The shape detection uses a template matching function to search through thousands of “exemplars” stored in a tree-structure in order to classify the candidates. Texture helps to classify any candidates remaining unclassified as pedestrian or non-pedestrian. A dense stereo depth analysis validates the pedestrians classified. Finally, the pedestrians are tracked using the well-known ‘α-β tracker’. The entire system is “tuned” to give optimum performance.

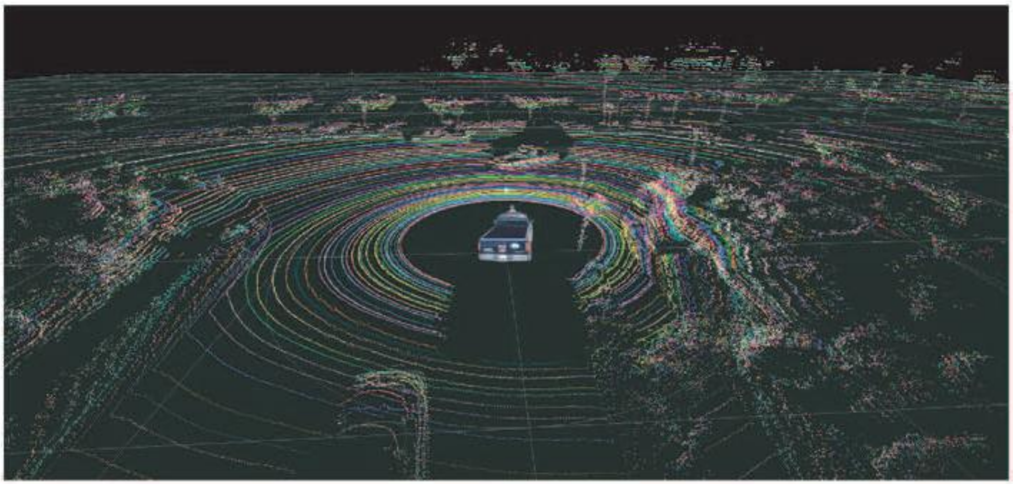
3.5 Solid state 3D sensors

Active sensors such as laser scanners and radar sensors are used to provide measurements in a 2D plane around the vehicle. However in many different scenarios a 2D representation is insufficient. A common solution consist on mounting the sensor on a mobile head in order to add one or more degrees of freedom to the sensor and provide 3D measurements from a set of 2D sensing (just as the lasers scanners provide a 2D sensing using a moving 1D sensor).

This approach has clear drawbacks such as dependency on mechanical pieces and the delay in measures. The different 2D measurements are not taken simultaneously which can cause spurious effects in the measures if the measured objects have relative movement.

One prominent product on this kind is the high definition 360 degrees lidar produced by Velodyne [28] . Using a vertical array of 2D lasers scanners spinning on a rotating head, the sensor is able to produce a 360 horizontal degrees view of the surrounding (see Figure 6). Integrating 64 lasers into one device it provides ~25 vertical degrees of view, between 50 and 100 meters of measurement range with less than 5 [cm] of error and a refresh rate of 5-15 [Hz].

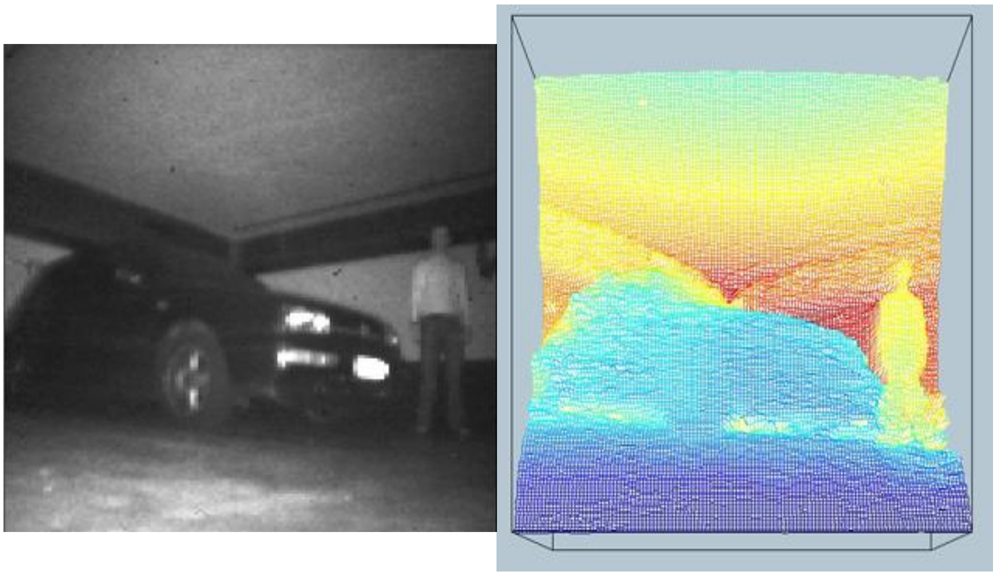
Figure 6: Velodyne high definition 360° lidar output



Recent advances in solid state electronics allows to provide dense arrays of distance sensors, thus creating direct 3D sensing without any moving parts. The physical principle is the same of the 2D lasers canners. Devices of this kind are provided by companies as Swissranger [22] and Advanced Scientific Concepts [1] . These two products represent the two extreme ranges of the possibilities of the technologies.

Swissranger provides a small (around ten centimetre of width, height, length) sensor that provide dense 3D images in the few meters in front of it (depth ~5 meters, field of view ~30°) at 30 Hz (see Figure 7) with a ~150 x 150 pixels resolution and a few centimetres of distance error. This kind of sensor provides adequate 3D data for indoor robotics [30] and can also be used to short range vision in outdoor robotics [3] .

Figure 7: Output of a Swissranger 3D camera

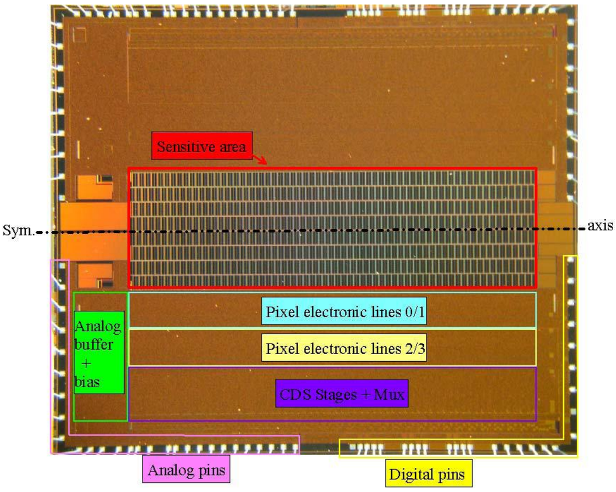


The small size and short range of the Swissranger products are design choices and not limitations of the technology and example of this is the long distance 3D ladar provided by the company Advanced Scientific Concepts. Their product provides dense 3D measurements at a distance of around 1 Km, for exploration application (submarine, military).

The specifications indicate a depth range between 3 meters and 1.5 kilometres, a field of view between 9° and 1° and a depth sensor of 320x240 pixels at 60 [Hz] and a range precision of less than 10 centimetres. Of course to do measurements at such distances the emitted infrared laser is quite powerful (even being eyes safe at the destination distance) so the power consumption of the device is measured in a few hundreds of watts.

Neither the Swissranger short-range miniature sensor nor the Advanced Scientific Concepts oversized system match correctly the need to autonomous vehicles in urban environment. However they can be seen as proofs of concepts for the technology. The European research initiative IP PReVENT has a subproject named UseRCams [15] dedicated to the "development of an affordable active 3D sensor, which is vital in providing improved obstacle detection and classification at short range", this sensor is specifically targeted for automotive systems and the project partners some cars manufacturers. Current prototype provides a measurement range of 25 meters with a 64x8 pixels array and 100 [Hz] refresh rate (see Figure 8).

Figure 8: UserCams electronic sensor



These classes of sensors provide high accuracy, high refresh rate, and robust measurements of the 3D geometry of the surrounding environment. The evolution of electronics will ensure the cost decrease and quality increase of this type of devices. The main remaining drawback is related to the fact that these are active sensors, thus spurious interactions between nearby emitters need to be managed and there is a fix power consumption related to the light emitting part of the device.

3.6 Sensor fusion

Sensor fusion is the process that allows using multiple sensors to provide a single representation of the environment surrounding the vehicle. Multiple sensors are required to enhance the reliability of the sensing, to enlarge the observed area and/or to provide more information about the observed area.

Since multiple sensors fusion relates to integrate multiple observations in order to enhance the current world model estimate, it is closely related to the sequential filtering methods where observations from different time instants are fused.

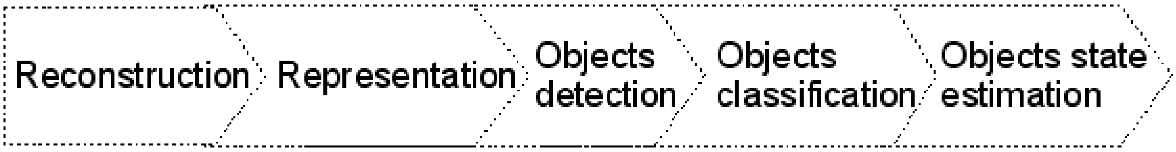
The specific sensor fusion implementations depend on the nature of the sensors used, the sensor models, the world model representation and the mathematical foundation used.

The mathematical foundation commonly used is the Bayesian approach, where the parameters of the world model will be described by a probability distribution. Some works use instead the Dempster-Shafer evidence theory, which instead of computing probabilities provides bounds on discrete probability distributions.

In the context of driverless vehicles the world model will usually consist on a set of obstacle and a prediction of their future positions. In order to enhance the predictions the class of the obstacles should be defined. Thus the sensors will provide information about distance, speed and any data relevant for objects classification.

Figure 9 presents a simple diagram of the usual processing stages (this can vary depending on the specific applications). First the obtained data is reconstructed in the adequate scale and put in the correct reference frame (example: laser scan binary packets are transformed into point in the space). Then the raw points are transformed to match the internal representation (a map of features, or a grid of evidences, for example). This representation is then processed to extract objects (as defined in the world model) that will be classified (assignation of a model for a specific object) and whose state will be estimated (state of the dynamic model selected).

Figure 9: Sensor data processing stages



The fusion of information from multiple sensors can be done at any stage of the data processing. Also the output of multiple algorithms applied over the same sensors measures can be fused; this is lead to the more generic notion of data fusion.

For a discussion on the different sensors fusion architectures the reader should consult the deliverables of the PreVENT IP subprojects ProFusion [13] and ProFusion2 [14] .

4 Requirements for obstacle detection according to scenarios

In the following section the obstacle detection requirements for the various scenarios elaborated in the deliverable D3.1 are discussed. The first scenario deals with partly automated dual mode vehicles/advanced city cars in a historical town centre, the second with a combination of both fully automated cybercars and partly automated dual mode vehicles/advanced city cars (mixed traffic) on dedicated lanes and the third scenario with cybercars in inner city centre. The last scenario describes automated BRT (Bus Rapid Transit) systems on dedicated lanes, which could share with dual mode vehicles and cybercars.

4.1 Town centre

This scenario deals with a historical city centre inside the city structure, which is not well connected to surrounding districts, consists of a network of small roads and limiting vehicle access and parking places. The environment is therefore rather complex. The advanced city vehicles will be parked around the zone and allowed to drive in a dedicated network of roads. The dual mode vehicles provide assisted driving, especially in difficult or narrow passages, in order to follow a fixed trajectory (e.g. in a right angle curve) or to stop at precisely defined places.

Obstacle detection for increased safety of the other road users, especially pedestrians and cyclists is a key element of those vehicles. The capability of use in platoon, where the first vehicle is manually driven and a second one is linked automatically, for instance in order to pick up a vehicle or bring it to users is considered in this scenario.

4.1.1 Obstacle detection main features

Dealing with this scenario, the obstacle detection system has the purpose of:

- Static and moving obstacle detection;
- Obstacle position and velocity estimation;
- Distance keeping from the platoon vehicle ahead.

To achieve an acceptable safety level, the following critical sensor performances must be considered:

- Maximum detection range;
- Horizontal view field angular size;
- Vertical view field angular size;
- Measures resolution and accuracy;
- Refresh rate;
- Data interfacing.

4.1.2 Key requirements for the scenario

General considerations can be made in the light of some specific characteristics of the historical city centre scenario.

Maximum speed allowed

In this scenario, for safety reasons the maximum allowed speed for vehicles is 30 Km/h (≈ 8.3 m/s) due to the particular area peculiarities (presence of narrow transits, short-range curves, sloping roads and causeways) and to the dense presence of pedestrians, including children and elderly people. This value influences obstacle detection requirements, concerning the maximum detection range and the overall reaction time of the vehicle in presence of an obstacle.

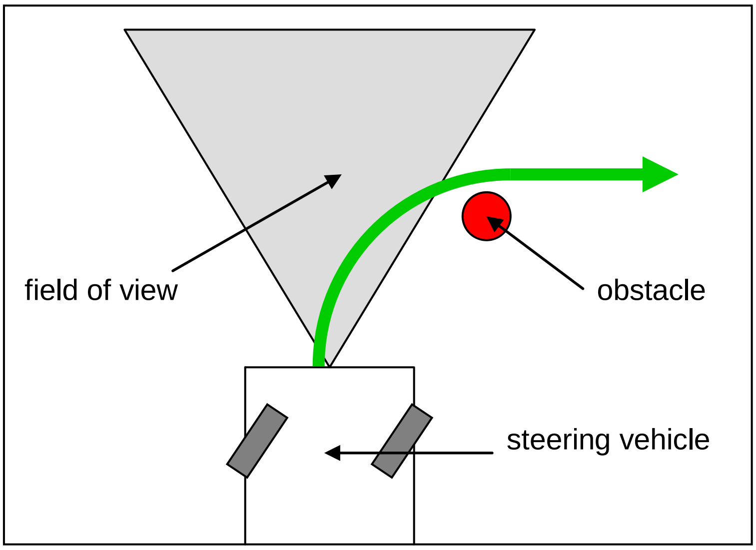
Horizontal and vertical field of view required

With respect to short-range curves, a critical aspect is represented by the angular size of the horizontal front field of view, which must be wide enough to detect not only obstacles standing in front of the vehicle, but also the ones which will be found along the planned path once the turning manoeuvre has been accomplished (see Figure 10). Thus, the wideness of the field of view must be between 150° and 180°.

Vertical field of view must be wide enough to ensure the detection of obstacles with only few centimetres of height. Also reliability in case of pitch dynamics is related to an appropriate vertical field of view size.

Moreover, a maximum size value must be settled, in order to avoid detecting “fake” obstacles placed beyond the vehicle maximum height. Then this value must not exceed 4°, considering the centre of the front bumper as angle vertex.

Figure 10: Obstacle detection during turning manoeuvre



Accuracy and resolution required

Safety requirements are necessary concerning the accuracy and resolution for distance and position estimation of obstacles: especially when vehicles cross the above-mentioned narrow passages (but also in any other unpredictable critical situation), the obstacle detection system must recognize if there is enough room for the vehicle to pass between the sidewalls or any other object or pedestrian standing in front of the vehicle and possibly representing a constriction of the planned pathway. Hence, the maximum allowed uncertainty in obstacle lateral position estimation mustn't exceed 0.3°, corresponding to a position estimation error of 5 cm at a distance of 10 m.

4.1.3 Platooning issues

In this scenario the capability of platooning vehicles must be provided. Hence, from the point of view of obstacle detection, a vehicle operating in platoon modality must keep track of the front distance and position (i.e. front bumper to rear bumper distance and angle) and relative velocity of the ahead platoon vehicle (i.e. ahead vehicle speed with respect to the one behind), in order to follow it, to stop and restart at a safe distance.

Since a minimum safe distance S0 = 2 m and an overall reaction time delay tr = 0.5 s between platoon vehicles must be provided, the ideal safe distance d can be obtained from the equation:

$$d = S_0 + t_r \cdot V$$

where V is the current vehicle velocity.

Being 8.3 m/s the maximum allowed speed, the correspondent maximum safe distance is d_{max} = 6.15 m, that is largely within the detection range of state-of-the-art laser scanners and radar sensors. Also the minimum distance d = 2 m (in case of V = 0) is within sensors detection boundaries. Distance accuracy is not a critical aspect for this purpose, since S_0 and t_r provide a safe and error-tolerant separation between platoon vehicles.

As regards the reaction time t_r, it represents the longitudinal control system overall reaction time, and it consists of the following terms:

- Obstacle detection time and refresh rate;

- Measurements filtering delay;
- Braking actuators delay.

However, being the relative velocity estimated by means of distance-based indirect methods, a propagation of distance measures uncertainty occurs, due to filtering processes; then the distance measure uncertainty shouldn't exceed 5 cm.

In conclusion, for platooning techniques, the obstacle detection system must provide the vehicle longitudinal control system with an almost real-time tracking of the ahead vehicle relative velocity and distance. In order to maintain a safe distance *d*, relative velocity must be always on the range (-0.3 m/s, +0.3 m/s).

4.1.4 Obstacle avoidance issues

As regards obstacle avoidance functionality, the aim is twofold: ensure safety for vehicles and other road city centre users and maintain trip comfort during avoidance manoeuvres; clearly the first target is predominant on the second one.

The obstacle detection system must be able to notice and trace distance and velocity of any object at such a distance that longitudinal system can perform a safe and comfortable stop.

The maximum detection distance for obstacle avoidance required in the city centre scenario, can be easily obtained from the following equation:

$$d = \frac{1}{2}\frac{V_{max}{}^{2}}{a_{max}} + V_{max} \cdot t_r + S_0$$

V_{max} = 8.3 m/s: maximum allowed speed;

a_{max} = -2 m/s2: maximum allowed deceleration for comfortable braking manoeuvre;

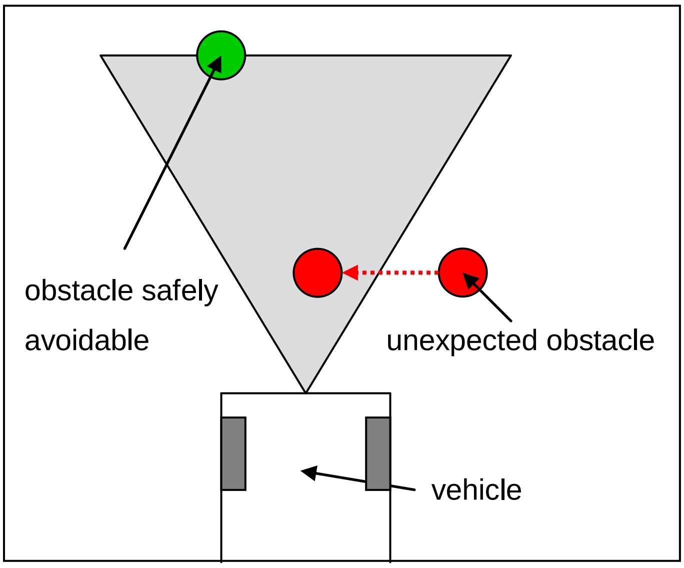
t_r = 0.5 s: vehicle longitudinal control system overall reaction time;

S_0 = 2 m: minimum safe distance.

These scenario parameters set a required maximum detection range of 24 m, which is not critical for state-of-the-art sensors. If vehicle moves at lower speed, also *d* decreases. Concerning the expected measures accuracy, the same accuracy as for platooning is needed.

Being the historical city centre an area also used by pedestrians, such unexpected obstacles could cross the vehicle-planned path moving from roadsides at a distance less than *d*. In this case, safety requirements must overcome braking comfort needs and more deceleration capability must be exploited (eventually the maximum available in extremely critical situations). From the point of view of sensors requirements, to improve unexpected obstacle detection, a wide angle of the front field of view is needed, possibly 180° (see Figure 11). Also refresh rate is a key aspect, to detect any new object as soon as possible. A reliable refresh rate value is 15 Hz (or better): in this way, the front field of view is refreshed every 65 ms, meaning that a vehicle moving at maximum velocity of 30 km/h perform a new scan of the surrounding front area after 54 cm covered.

Figure 11: Obstacle detection for objects moving from road sides



Moving obstacles

In this scenario, different kind of objects must be correctly and safely detected and avoided.

Objects that could be present in the city centre scenario are:

- Road infrastructures;
- Pedestrians;
- Bicycles;
- Other vehicles (AUTS or traditional).

While the first class of objects consists of static road elements, others are likely present in motion. For this reason, obstacle velocity detection is required in order to guarantee the obstacle avoidance reliability. For moving objects the accuracy required is 0.3 m/s (≈ 1 Km/h).

In the borderline case of another vehicle (non AUTS) moving against an AUTS vehicle, at the maximum allowed speed of 8.3 m/s for both vehicles, the detection range required for collision avoidance is 50 m, assuming that also the non AUTS vehicle can perform a deceleration of -2 m/s2.

4.1.5 Data interface

An interface between detection system and central elaboration unit must be defined, in order to communicate obstacle data in a suitable way.

Detection system must process raw sensor data and send output data packets containing the complete list of obstacles for each view. For each obstacle, at least the following features must be provided:

- Spatial coordinates (x-y or polar);
- Speed vector;
- Size and/or type.

A complete list of objects detected in the whole front area must be provided with a refresh rate of 15 Hz; CAN and Ethernet protocols, representing the state-of-the-art for automotive sensors, are suitable solutions for this purpose.

4.1.6 Environment conditions

Obstacle detection performances must be guaranteed also in critical conditions such as poor lighting, sun or lamp dazzling, fog, snow and rain. In these situations, maximum speed could be reduced, in order to decrease limitations for detection range and refresh rate requirements; however, sensors must preserve their reliability for distance and velocity detection, and for platooning management.

4.1.7 Requirements summary

According to scenario characteristics, lateral accuracy and real-time scanning capabilities must be carefully considered (more than distance accuracy and maximum detection range) as fundamental requirements to ensure safety for vehicle users and any other road user or infrastructure.

Table 1: Requirements

Vehicle speed range	0 – 30 Km/h
Horizontal field of view angle	>150°
Vertical field of view angle	< < 4°
Lateral accuracy	< 0.3° cm (5 cm at 10 m)
Distance accuracy	< 5 cm
Maximum range	24 m (50 m for moving obj.)
Refresh rate	>15 Hz
Speed accuracy	< 0.3 m/s
Capability of detection of objects in motion	
Efficiency in critical condition (snow, rain, fog, poor lighting, dazzling)	
Output data interface providing coordinates, speed vector and size/typology for any detected object	

4.2 Principal urban roads with an equipped lane (called “e-lane”)

This scenario deals with a migration step towards autonomous driving by utilising a so-called “e-lane”. Hereby defined roads signposts indicate the possibility of driving autonomously on an e-lane. This e-lane is exclusively reserved for higher automated traffic. With a dual mode vehicle, which is specially equipped and certified, the e-lane can be used. Once the vehicle is on the e-lane the guidance of the vehicle is conducted autonomously.

The driver can focus on other activities (e.g. read newspaper, office work etc.). The driver can intervene and take over the responsibility and leave the e-lane, whenever he wants to. The vehicles drive up to a velocity of 120 km/h on protected lanes, so that there is no interaction with pedestrians, cyclists etc.

In the e_lane scenario the obstacle detection is not so critical since we do not expect any interaction with pedestrian, bicycles or slow moving elements except perhaps at the entrance or exit from the e-lane (where we are back in the town-centre scenario). In the e-lane scenario, the dual-mode vehicles must be able to detect only the vehicle ahead and its relative speed and stop with the minimum deceleration and jerk to avoid it. We might want also to be able to detect a stationary obstacle of significant size, which could damage the operation of the vehicle if we consider that the possibility to have such obstacles (which might have fallen from another vehicle or which might come from vandalism) is real.

Since the ego vehicle is moving at speeds up to 120km/h, we definitely need long distance sensors, which give us the distance, localisation on the track or outside, and relative speed. The sensors must be able in particular to differentiate between an obstacle on the track and some infrastructure, which might be located on the side of the track or above the track (overhead pass for example). The range of the sensor must be around the maximum range needed to perform a comfortable stop behind a stopped vehicle when the speed is 120 km/h, which means about 200M, and the response time must be under one second. The only possibility to do that reliably with today's technologies (and probably excluding the possibility to detect some small obstacles), is to combine a long range radar or lidar with high performance stereo vision. The vision will improve the reliability of the detection through advanced fusion algorithms and will be needed to differentiate between obstacles on the track and those on the infrastructure.

The obstacle detection sensors will also play a key role in the platooning of the vehicles. This will also impose some constraints on the response time and precision of the measure. If we want very tight platoons with gap times under one second, we will need a response time or the relative speed on the order of 100ms if we do not want to rely exclusively on the communication between the vehicles.

4.3 Inner city centre

In the "inner City" scenario a limited fleet of automated vehicles drive fully autonomously in the city centre at low speed. The user can enter the vehicles at defined access points and then has the possibilities to choose the destination on pre-defined tracks. The Cybercars have to interact with pedestrian and cyclists on one side and with other Cybercars and low speed vehicles (cleaning machines etc.) on the other side. For user pick-up and maintenance parking places are reserved. A fleet management system optimises the displacement of the vehicles in real time.

In the Inner city centre scenario the obstacle detection is critical. To allow the obstacles detection the Cybercars vehicles must be able to detect:

- Other cybercars vehicles
- Pedestrians
- Bicycles
- Low-speed vehicles (garbage collector vehicle)
- Small animals
- Inner city infrastructure

For all the type of obstacles we should be able to detect:

- The distance between vehicle and obstacle
- Is the obstacle moving or not
- The direction followed by these vehicles
- Their relative speed

In the case of obstacle detection the Cybercar vehicle must be able to avoid this obstacle. The vehicle should thus be able to:

- Interpret the situation (based on the above information)
- Detect a possible free space
- Adapt the trajectory to the available path

This information about obstacles will be acquired at a relative low speed (around 30km/h max).

All these information should not be obtained with a unique sensor. Even if this information could come from an image analysis there should be redundant information to avoid lack of detection.

Moreover the detection of obstacle must be made to allow obstacle avoidance (which means interpretation of the situation) but also to avoid collision (which means hard real time detection with very tight response time). The vehicle must then be equipped with detection system allowing a very high-speed analysis of the space occupation.

The obstacle detection and avoidance system should then be a multi-sensors system, based on laser range finder, camera and image analysis, ultrasound and all type of sensors which could help in delivering the above information. We could thus quote as a minimum sensors equipment:

- Laser range finder
- Ultrasound sensors
- Stereo camera
- Smart-bumper

4.4 Shared traffic space with automated buses and dual mode vehicles

The fourth scenario consists of dedicated lanes for automated buses and dual mode vehicles/Cybercars. It is based on infrastructure, which is already available in some European cities today. A well-organised, automated public transport system alone can help to alleviate the increasing traffic congestions in European cities. The combination of automated buses and other types of automated vehicles provides an even more efficient saturation of valuable space for traffic on one side and intensifies the deployment of advanced innovative transport systems on the other side, because only minor modifications of the already existing infrastructure are needed.

In this scenario a cooperative control system in form of the traffic management system can improve the handling of traffic and make sure there is no congestion on the dedicated lane. This lane is a priori dedicated to the automated (or assisted) buses with a maximum speed of up to 50 km/h in city centres.

In the shared traffic space with automated buses and dual mode vehicles scenario the obstacle detection addresses a wider scope situation than the e-lane scenario (but lower speed) or the inner city scenario. To allow the obstacles detection, the dual mode vehicles and automated buses must be able to detect:

- Other dual mode vehicles or buses
- Pedestrians
- Bicycles
- Road infrastructure

For all types of obstacles we should be able to detect:

- The distance between vehicle and obstacle
- Is the obstacle moving or not
- The direction followed by these vehicles
- Their relative speed (value and direction)

Vehicle must be able to avoid this obstacle. The vehicle should

In the case of obstacle detection the automated vehicles must thus be able to:

- Interpret the situation (based on the above information)
- Detect a possible free space
- Adapt the trajectory to the available path

Contrary to inner city scenario, this information about obstacles must be obtained at a not so low speed. Also, the distance for getting this information should be longer and the use of radar system is required.

All these information should not be obtained with a unique sensor. Even if this information could come from an image analysis there should be redundant information to avoid lack of detection.

Moreover the detection of obstacle must be made to allow obstacle avoidance (which means interpretation of the situation) but also to avoid collision (which means hard real time detection with very tight response time). The vehicle must then be equipped with detection system allowing a very high-speed analysis of the space occupation.

The obstacle detection and avoidance system should then be a multi-sensors system, based on radar system, laser range finder, camera and image analysis, ultrasound and all type of sensors which could help in delivering the above information. We could thus quote as minimum sensor equipment:

- Laser range finder
- Long range and short range Radar
- Video camera

5 Obstacle detection tests for certification

In the following section a test setup is described, which can be used in the certification process of cybercars and dual mode vehicles. The test setup in this section is aimed at evaluating the obstacle detection function of a vehicle. Within CityMobil D3.4.1 and D3.4.2, test protocols for the functions of respectively navigation and communication will be described. Section 5.1 contains a short summary of the different steps needed to reach certification of a cybercar system. After this a proposal of a test procedure is shown and explained in more detail in section 5.2. Section 5.3 contains links between the test procedure and the different defined CityMobil scenarios.

5.1 Certification procedures

In sub-project 2 of CityMobil future scenarios are addressed. As part of this subproject, WP 2.5 –Legal and administrative issues has made a brief survey of existing legislation, legal traditions and cultural differences in Europe. CityMobil Deliverable 2.5.3 [20] contains the existing standards and guidelines that could be relevant for the future certification of cybercars. The information in that deliverable is primarily based on the work documented in D6.1 [24] and D6.2 [27] of the EU project CyberCars. A short summary:

Traditional vehicles that use public roads have to meet a large number of requirements laid down in standards and regulations. The sheer number of standards limits the car developers in their innovations. But the standards also give the developers guidance on how to create safe and reliable vehicles. When they develop new vehicles the manufacturers know the limits within which they have to stay in order to have their vehicle certified for use on public roads.

In contrast to the extensive set of certification standards for traditional vehicles, there are hardly any rules for vehicles that use private grounds or for vehicles that do not fit into the categories of the European Directive 70/156/EEC. This means on one hand that manufacturers have a large amount of freedom in designing their systems, which creates room for innovative solutions. On the other hand, however, manufacturers and operators run great liability risks in case something goes wrong with their systems. Operators and authorities will be reluctant to introduce innovative systems if there is no objective judgment possible on the safety of such systems. An objective judgment is only possible if it can be proven that a system meets generally accepted standards.

Traditional road vehicles are meant for use on public roads. These public roads represent a system to which a very strict set of rules, that we call traffic regulations applies. When a car is certified the environment in which it is to operate is not explicitly considered. That is not necessary because it is an implicit part of the vehicle design that the vehicle will operate in: the very rigid environment of our public road system. This however is different for Cybernetic Transport Systems.

To reach certification for a cybercar system in a certain environment ideally the following is needed:

- A comprehensive safety assessment of the vehicle in its surrounding. CityMobil deliverable D 2.5.3 contains the theory of both the risk reduction methodology and safety assessment analysis. It is not sufficient to certify the vehicle and vehicle related systems because of the interaction of the vehicles with the environment. The risk reduction methodology is a first step aiming at reducing the safety risks associated with the environment. After that a safety assessment analysis aims at reducing the safety risks associated with the system as a whole.
- A set of standards, which the cybercar system or subsystem or certain functions of the system should meet.

The three main functions that drivers carry out are observing; analysing/deciding and transferring the decision to the vehicle systems. In a cybercar the sensors, the obstacle detection system, the vehicle controller and the different actuators take over these functions. For traditional vehicles standards on component level exist. For these 'new' components such standards do not exist. In the following sections an attempt is therefore made to define a test protocol to evaluate the obstacle detection function of a cybercar or dual mode vehicle. Such a test could become part of future obstacle detection standard.

5.2 Obstacle detection test procedure

The procedure described below is partly based on NEN-EN 125:1997; section 5.9.5 (obstacle detection for backing up of trucks). A short summary:

Vehicles need to be equipped with an obstacle detection to detect dynamic and static obstacles on their path. The obstacle detection needs to comply with the following requirements:

- Detection over the full width of the vehicle (also in curves)
- Vehicle needs to stop for the obstacle without making direct contact or with a maximum bumper force < 250N (in all possible directions)
- Obstacles need to be detected as low as possible and at least test obstacles with the following dimensions and orientation s should be detected:
  - horizontal Ø 200mm L 600mm
  - vertical Ø 70mm L 400mm).
- The reflection characteristic of these objects should correspond to clothes.
- Activating the obstacle detection may not lead to injury.

Next to the requirements from NEN-EN 125:1997, the following requirements are added:

- The obstacle detection should ignore (moving) objects, for example leaves or birds smaller than 7 cm.
- The obstacle detection should ignore static objects besides the track even in curves like parked vehicles, trees, fences, viaducts, etc. or ignore the road surface or

viaduct (if high enough) as an obstacle during pitching or riding on slopes with the vehicle.

- Dynamic objects that move in the direction of the track should be taken into account.

CityMobil deliverable D3.1.1 contains a description of the four different scenarios considered in the project CityMobil. Next to the description some requirements for obstacle detection are stated. These requirements together with the requirement in chapter 4 of the current deliverable are taken into account during the definition of the measurement protocol below. Specific experience with the test setup is gained with the 2nd generation Parkshuttle from Frog navigation systems.

The test procedure contains three parts.

1. Static obstacle detection. This test is to evaluate the detection of static obstacles on the track of the vehicle.
2. Short range obstacle detection. When an object is not detected on time, a bumper-type detection system is a way to stop the vehicle preventing large damage.
3. Dynamic obstacle detection. This test is to evaluate the detection of objects moving towards the track of the vehicle.

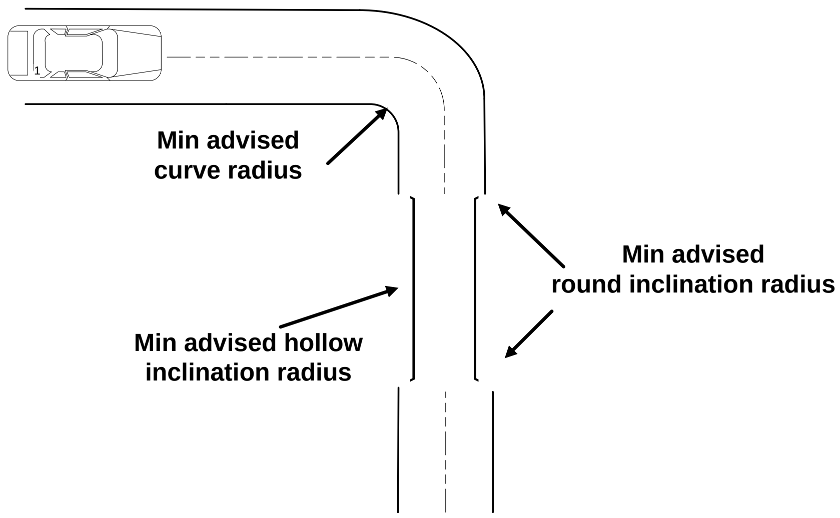
A vehicle has to at least pass part 1 of the test. Whether it has to pass test 2 and 3 depends on the environment the vehicle has to operate in. E.g. an automated bus driving on dedicated lanes on which no pedestrians, cyclists or other vehicles can enter the track, does not have to pass the dynamic obstacle detection test.

5.2.1 Static obstacle detection

The functional test of the obstacle detection and avoidance function should be performed with the subsystem installed in the vehicle that needs to be certified.

The vehicle has to follow a predefined course as shown in the figure below. The speed of the vehicle is set at its maximum speed at which it is allowed to operate in its operational environment. The course consists of a straight track, a curve and a bridge.

Figure 12. Predefined test course



The radius of the inside curve should be the minimal advised curve radius at the defined speed for the vehicle class (car, bus, lorry etc class) at the advised minimal track width. In many countries there are guidelines that specify this radius. An example of the minimal radii for public transport in the Netherlands is given in Table 2. The inclination radius at the entrance, the top and exit of the bridge section should be set at the minimal advised value.

Also for these radii there are guidelines in many countries. An example of the minimal inclination radii in the Netherlands are shown in the Table 2.

Table 2: Velocity versus radius of a road

Velocity [km/h]	Minimal advised curve radius
20	15
30	24
35	35
40	55
50	120
70	290

Velocity [km/h]	Minimal advised round inclination radius	Minimal advised hollow inclination radius
30	175	135
40	375	240
50	675	375
60	1250	550
70	2000	750

The vehicle is not allowed to leave the predefined track. The track width is defined as the width of the vehicle + 0.5 m on both sides. Specific objects will be placed at the track. Since the vehicle is not allowed to leave the track, the only possible solution to avoid the objects on the track is therefore to stop before making contact with the objects. The two criteria at which the vehicle and its obstacle detection and avoidance system are judged, are its ability to stop before all the placed objects on the track and its ability to ignore static objects outside the track.

The following procedural steps should be taken:

The vehicle should drive over the defined test track at the maximum speed. Check the working of the obstacle detection and avoidance system installed in the vehicle by placing test obstacles on the road surface.

The vehicle has to stop without hitting the test obstacle, and the vehicle must ignore the test obstacle when it is placed outside the track.

Perform the tests under the following conditions for the straight part of the track:

1.1 Place the test object (black PVC tube Ø200mm, L 600mm) horizontal in the centre of the track.

1.2 Repeat this test near the borders of the track (both sides of the vehicle). Note the track width is the width of the vehicle + 0.5m on both sides.

1.3 Repeat this test outside the borders of the track (both sides)

- Repeat 1.1-1.3 for the following objects: vertical PVC tube with the same dimension placed at the ground in the colours white, blue, red and yellow.
- Repeat 1.1-1.3 for the following objects: Black bicycle frame in longitudinal direction, bicycle frame in lateral direction.
- Repeat 1.1-1.3 for the following objects: Black aluminium plate 1mx0.6m placed at the ground under a corner of 45 deg with the ground facing the vehicle.

- Repeat 1.1-1.3 with the vehicle at half of the maximum speed.

Perform the tests under the following conditions for the curved part of the track:

- Perform 1.1-1.3, with the object placed halfway the curve and at the end of the curve.

Perform the tests under the following conditions for the bridge section of the track:

- Perform 1.1-1.3, with the object placed halfway the uphill section, at the top of the bridge and halfway the downhill section.

5.2.2 Short range obstacle detection

If the vehicle in its operation environment is operated at relatively low speed and is faced with possible “obstacles” like pedestrians and bicyclists an extra obstacle detection test is prescribed. A bumper-type obstacle detection function has to be present to prevent large damage when an object is not captured through the normal long-range obstacle detection. The vehicle should move at a low speed of about 2m/s in a straight line. Applying a force to the bumper of the vehicle should result in a direct emergency stop of the vehicle. The applied criterion, at which the vehicle and its obstacle detection and avoidance system are judged, is the maximal applied force measured with a force gauge which should not be larger than 250N and the corresponding deceleration of the vehicle should be larger than 6m/s2. The long range longitudinal obstacle detection test does not implicitly state what kind of obstacle detection system has to be installed in the vehicle. The short-range test procedure however implicitly requests a bumper-type obstacle detection system.

The following procedural steps should be taken:

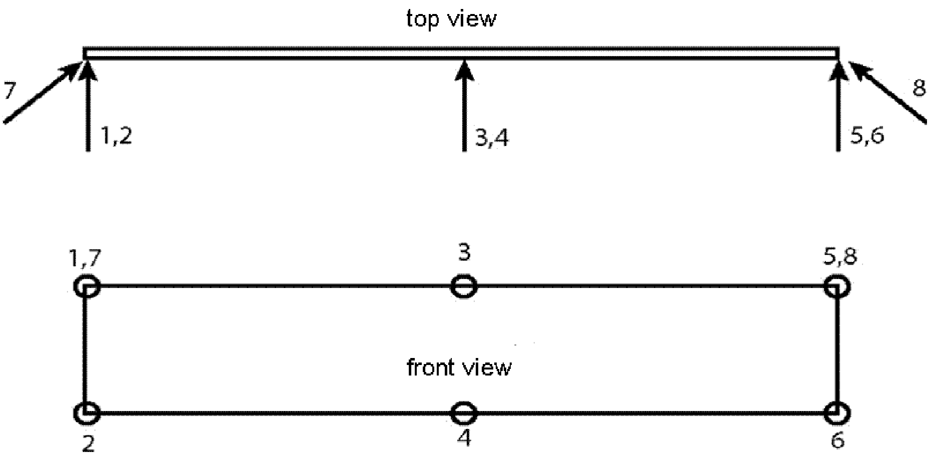
The vehicle should drive over a straight road with a speed of 2m/s. Check the working of the bumper obstacle detection and avoidance function by applying forces to the bumper. The test operator should walk next to the vehicle and apply a force gauge to the bumper. To prevent to dangerous situations the operator may use an elongation arm for the force measurement. The vehicle has to stop at a bumper force lower than 250N and with a deceleration larger than $6 m/s^2$.

Perform the tests under the following conditions for the straight part of the track:

2.1 Apply a force to the bumper at location 1 shown in the figure below. The direction of this force is in the longitudinal direction of the vehicle. Read out the force level that is needed to stop the vehicle. Measure the deceleration of the vehicle.

2.2 Repeat this test for the locations and corresponding directions 2-8.

Figure 13: Predefined measurement locations



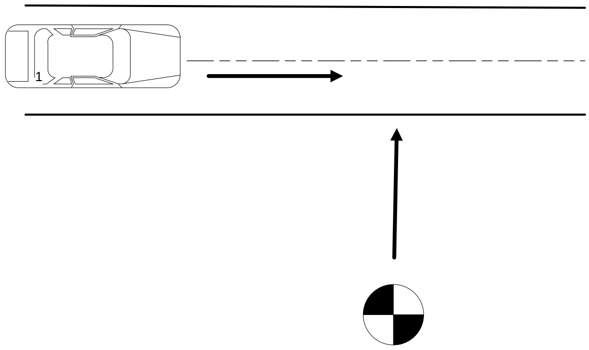
5.2.3 Dynamic obstacle detection

If the vehicle in its operation environment can be faced with obstacles that move towards the track like pedestrians, bicyclists or other vehicles a third obstacle detection and avoidance test is defined. Vehicles that operate in an environment totally surrounded by e.g. fences do not have to comply with this specific test procedure.

The vehicle has to follow a straight predefined course as shown in the figure below. The speed of the vehicle is set at its maximum speed at which it is allowed to operate in its operational environment. The vehicle is not allowed to leave the predefined track. From the side of the track on object is moved towards the straight track. The initial speed of the object is an expected typical speed of a lateral moving object in the operational environment. In this case an initial speed of 30km/h is chosen. The vehicle and the object are initially synchronized in such a way that they will impact each other at a certain point on the track.

The applied criterion, at which the vehicle and its obstacle detection system are judged, is that the vehicle should avoid making contact with the object.

Figure 14: Predefined test course



The following procedural steps should be taken:

The vehicle should drive over a straight test track at the maximum speed. Check the working of the lateral obstacle detection and avoidance by moving a test obstacle with a controlled speed towards the vehicle track.

The vehicle has to prevent a collision with the test obstacle.

Perform the tests under the following conditions for the straight part of the track:

3.1 Synchronize the initial location of the test object (vertical black PVC tube Ø200mm, L 600mm, located at ground level) with the vehicle in such a way that the object will collide with the vehicle when the vehicle does not change speed. The object will move from the right towards the vehicle with an initial speed of 30km/h.

3.2 Repeat this test with the test object coming from the left of the vehicle.

5.3 Obstacle detection test for the different scenarios

The following table contains the four CityMobil scenarios as described in chapter 4. For each scenario the most important characteristics are shown. On base of these characteristics the obstacle detection tests that are most suited to evaluate the obstacle detection performance are marked.

Figure 15: Test protocols for CityMobil scenarios

	1. static obstacle detection	2. short range obstacle detection	3. dynamic obstacle detection
Town centre Dual mode vehicles Obstacle detection of pedestrians / cyclists Platooning of cars	X	X	X
Principal road with an equipped e-lane Dual mode vehicles No pedestrians / cyclists No crossing traffic	X[1]		
Inner city centre Cybercars Obstacle detection of pedestrians / cyclists	X	X	X
Shared traffic space cybercars dual mode vehicles automated high tech buses Pedestrians and cyclists at crossing Traffic management system for crossings	X	X[2]	X[2]

1 In this scenario the level of assistance is limited; the assistance is similar to ACC and LKAS. It is not per definition possible that the vehicles will have the ability to come to an automatic standstill. Therefore the static obstacle test can be performed but possibly the criterion to stop before a placed object, might have to be changed in provide a warning for a placed object.

2 Pedestrians and cyclists are only possible at well-controlled intersections. The traffic management system should manage the vehicles at these intersections. Obstacle detection aimed at pedestrians and cyclists to increase safety might be needed.

5.4 Remarks on test procedures

In the section above an attempt is made to define a test protocol for the function of obstacle detection and avoidance, which could be a base for a future standard. The following is noted:

1. Since a general test protocol is defined, there is no direct link to the CityMobil scenarios, which are described in earlier sections. The test protocol does make distinctions between vehicles, which operate in different environments. Vehicles from different CityMobil scenarios can therefore be tested differently.
2. The test procedure only contains a very limited number of possible test configurations, e.g. a limited number of shapes, colours, weather conditions, number of objects etc. It is clear that this test protocol does not take into account all the specific disadvantages of certain sensor techniques. Like performance in different lighting situations, rain, fog etc. Since a certification test protocol is described which could be used in the standardized certification process of a cybercar vehicle it is not feasible to include a large range of measurements under different environments. These tests should be part of the development of the obstacle detection systems. The risk and the effect of possible mal functioning of the obstacle detection of a particular cybercar under certain (environmental) conditions has to be evaluated in an extended safety assessment of the vehicle in its surrounding.
3. In Chapter 4, requirements at a low level are mentioned for the different CityMobil scenarios. These include: detection of distances, moving or static obstacles, direction and relative speeds. The test protocol evaluates the functioning of an obstacle detection and avoidance system in a controlled vehicle at a higher level: the ability to prevent a collision with an obstacle.
4. The description of the test procedure is not fully determined. I.e. not all dimensions and locations are explicitly mentioned. This would go in to too many details, more than needed at the moment of writing.
5. The test protocol evaluates obstacle detection. Since the vehicle is not allowed to leave the predefined path, active lateral avoidance is not evaluated.
6. Specific and valuable experience with the test setup is gained with the 2nd generation parkshuttle from Frog navigation systems.
7. The specific values for locations, dimensions and velocities are mainly based on experience, but might be subject to change when more test experience is gained.
8. Again it must be noted that to reach certification of an entire automatic guided vehicle system, the certification test of e.g. the function of obstacle detection and avoidance is only part of the process. A comprehensive safety assessment of the vehicle in its surrounding is required. The safety analysis should give indications of the risk of malfunctioning of the obstacle detection function in non-standard situations.

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