The development of machine vision for road vehicles in the last decade

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Abstract

Machine vision for road vehicles started in the mid-80ies. After a very brief review of the initial phase of about half a decade, developments over the last decade are discussed in more detail. The EUREKA-project 'Prometheus' set the stage in Europe and spread activities to all major carmakers and to many universities throughout Europe. The US and some Asian countries soon followed. The basic perceptual and behavioral capabilities for driving and for driver assistance on well-kept high-speed roads have been demonstrated at the end of the Prometheus project. Later developments took two directions: 1. Simple systems for early application in confined domains, and 2. more complex systems with growth potential for performance levels closer to the human one.

In the meantime, first products with machine vision components are on the market; more highly integrated systems have been announced for the second half of this decade. A road map for the development of vision for cars is discussed.

Keywords: Machine vision, road vehicle guidance

1. Introduction

Early predecessors of autonomous ground vehicles like 'Shakey' [1, 2] were designed for mainly indoor use in a benign laboratory environment; because of no alternatives for planetary exploration, studies at JPL in the late 70ies also looked at autonomous wheeled vehicles [3]. At the Mechanical Engineering Laboratory in Tsukuba, Japan, first studies of visual road vehicle guidance along guiding rails have been performed with a pair of vertical stereo cameras [4]; signal processing has been done by conventional means.

Fully on-board autonomous vision systems for vehicle guidance with digital microprocessors started in the early 80ies completely independently in Germany on high-speed roads [5] and in the USA in the framework of the DARPA-initiative 'On Strategic Computing'. In the huge framework of the latter, there was one application area for 'Autonomous Land Vehicles' (ALV) [6]. While in the US emphasis has been placed on developing special computer- and software architectures for vision in the 'Computer Science' and 'Artificial Intelligence' communities, inspired by early knowledge about biological vision systems, in Germany the approach was based on control engineering methods and the developing general-purpose microprocessor technology [7]. Only in 1985, members of the two communities on each side of the Atlantic Ocean became to know of the activities on the other side. Since 1986 a regular exchange on conferences like SPIE 'Mobile Robots', IEEE 'Robotics and Automation' and the International Federation of Automatic Control (IFAC) started.

The year 1987 may be considered a first milestone in the development of road vehicle guidance by machine vision. The UBM[1] test vehicle for autonomous mobility and computer vision **VaMoRs** demonstrated the capability of fully autonomous longitudinal and lateral vehicle guidance by computer vision on a free stretch of Autobahn over more than 20 km at speeds up to 96 km/h (limited only by engine power). This result led to the decision that computer vision for vehicle guidance was included in the European EUREKA-project 'Prometheus'[2]; the previously intended activities for inductive lateral guidance by buried wires have been dropped instead. This step, initiated by the Daimler-Benz company has prepared the ground for a rapid spread of activities in the field, both among European car manufacturers and among universities in many European countries.

At the same time, the concurrent successes in the DARPA-ALV program also triggered new activities in Japan where MITI together with the companies Nissan and Fujitsu started the project 'Personal Vehicle System' [10]. In the US, the car manufacturer General Motors picked up the topic in a special project [11]. The seven-year period of the Prometheus project (87 – 94) may be considered as a period of fast global spread of activities

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[1] Shorthand for **U**niversität der **B**undeswehr **M**unich

[2] **Pro**gra**m**me for a **E**uropean **t**raffic of **h**ighest **e**fficiency and **u**nprecedented **s**afety (see [8, 9])

in the field of computer vision for road vehicle guidance. The main goal of these activities was to show which ones of the many functions required for road vehicle guidance could be automated by computer vision. None of the large car producing companies wanted to loose contact to the cutting edge of technology for road vehicles. This was an extremely favorable situation for advancing the field of computer vision. Interestingly enough it was the mechanical engineering industry, which pushed this development, more than the industry in electrical engineering and computer science. Table 1 gives a survey of the topics investigated in this period. It was soon realized that, in principle, all problems solvable by human vision would be solvable by computer vision also, in the long run.

However, with the price / performance level available in the mid-90ies only a very low percentage would be economically viable; this has led to the split of activities to be discussed in the paper. Over the entire period considered up to here, the basic visual capabilities have been investigated both for developing assistance functions for the human driver in charge (and fully responsible!), and for possibly autonomous functions which do no more need a human driver in the loop directly. In both cases the goal is to reduce accident rates and death toll. The death toll in road traffic on the globe is in the order of magnitude of one hundred thousand persons per year. A large percentage of these accidents are due to human failures.

No matter what the use of machine vision in the long run will be, it will pervade into vehicles of any kind in a similar way as biological vision systems have spread over almost all kind of animal species during the long period of evolution. Being able to look to areas and objects / subjects the system has to cope with in the near future yields so many advantages that those subjects without vision simply will be outperformed and vanish in long run. However, in order to make full use of the advantages offered, these systems have to make use of a knowledge base integrating three-dimensional spatial (3-

Nr.	Topics investigated	Comment
1	Recognition of pairs of lane markings in near front range, horizontal curvature and relative lateral position as well as orientation in lane.	For well marked roads, edge features.
2	Recognition of road boundaries, horizontal road curvature and relative lateral position as well as orientation.	For unmarked roads, additional regional features.
3	Recognition of neighboring lanes in front.	For lane changing
4	Monocular visual detection, tracking and relative state estimation of relatively large stationary obstacles on the road.	Real-time performance with edge features.
5	Detection, tracking and relative state estimation of a moving vehicle in the front hemisphere of own lane.	Real-time performance with edge features.
6	Simultaneous visual determination of pitch angle (of importance on non-smooth ground and during ac- and deceleration).	Improves lateral state estimation.
7	Detection, tracking and relative state estimation for moving vehicles in front and rear hemisphere of own and both neighboring lanes.	Required for autonomous driving on highways.
8	Detection of a crossroad, its width and relative orientation to own road, relative state estimation to center of intersection.	For turning-off or for landmark navigation
9	Recognition of some kinds of traffic signs with color image processing (speed limits, passing prohibited).	Not yet possible in real-time.
10	Recognition of moving humans walking, running, bicycling; relative motion. [Arm waving and gesturing (e.g. with a flag) would be needed too.]	Not yet possible in real-time.
11	Detection of vehicles at a T-junction on the crossroad while standing and preparing to enter the crossroad.	Video-rate not required.
12	Recognition of horizontal and vertical curvature of the road in moderate look-ahead range; self-occlusion at cusps.	Superposition in terms of differential geometry.
13	Checking of neighboring lane (left or right) around own vehicle whether it is free of other vehicles for lane changing: a) by side-looking pairs of stereo cameras b) by (mentally) keeping track of vehicles leaving rear and entering front visual hemisphere (usable for one neighboring lane only!)	Limited range only (< ~ 80 m) VITA_2 VaMoRs
14	Estimation of visual range under foggy conditions	By observing decreasing contrasts

Table 1: Basic visual capabilities investigated in the time frame mid-80ies till the early 90ies

D) and temporal aspects. In biology this has been state of the art for millions of years. In technical systems, the so-called ‘4-D approach’ is based on methods developed by humankind in control engineering only a few decades ago; it has been extended to the interpretation of image sequences from perspective projection in the mid-80ies by the UBM-group [7, 12, 13]. Only with this rich spatio-temporal background can knowledge about motion processes and action schemata of subjects be systematically exploited. Understanding of what is happening around oneself and what may be future actions of other subjects involved in the situation given, is a prerequisite for a desirable defensive style of driving.

2. Two branches of development since the mid-90ies

After the basic feasibility of machine vision had been demonstrated for many tasks in road vehicle guidance (see table 1), the question arose how to proceed in the future. Computing power at moderate volume, power consumption and cost was not yet available for developing large-scale systems aiming directly towards human performance levels. ‘Moore’s law’ for the development of digital microprocessors had proven valid over the last two decades and could be assumed to be valid for another two before reaching physical limits. It states that a factor of 2 in performance can be expected every 18 months, corresponding to one order of magnitude in processing power every 4 to 5 years.

Most of the real-time results in road vehicle guidance up to the early 90ies had been achieved with black/white CCD-cameras and relatively simple edge feature extraction. For handling more complex scenes under difficult lighting and weather conditions more robustly, both color and texture analysis seemed to be desirable. Also, for tight maneuvering and for high speed driving an extended spread of focal lengths and fields of view would be favorable, possibly combined with active control of gaze direction. It has been estimated that an increase of two to three orders of magnitude in computing power would be needed to accommodate the required data processing in real time. According to Moore’ law this corresponds to about one to two decades on the time line; in absolute terms, this performance level could not be expected before about 2010.

This situation has led to a split in developmental efforts. Rather reliable road and lane recognition including relative ego-state could be achieved with conventional general-purpose microprocessors by the mid-90ies (final demo of the Prometheus project in Paris in October 1994, see [14]). Within a few years, this would be possible with a single PC; an additional development step could then bring the solution developed onto specialized hardware as base for a product for the market. In 1997, the first goal has been achieved at several places [16, 17, 18]. Industry with its rather short-range development horizon fully embarked on this line of activities for several applications. This will be discussed in the next section.

When looking at the price / performance ratio for single visual functions it becomes evident that high initial costs occur because of the high data rates in the video stream (~ 10 MB/s for a b/w-image with 400,000 pixel at 25 Hz). For color vision and a spread of focal lengths, unavoidable when human-like performance level is the goal, a factor of about five in data rate will occur. This leads to the conclusion that general-type vision systems seem to be uneconomical for just one function; instead, they will become viable only by exploiting its great flexibility and adaptability, and by having many functions share the same hard- and part of the software resources. Vision is a perception (measurement) process requiring a large knowledge base in the background; only by combining pre-stored knowledge about spatio-temporal processes with the image data stream observed can the 2-D signal be interpreted properly. This huge knowledge base also becomes economically viable only by using it for several or many different purposes as they occur (usually in a sequential manner).

In view of these facts, the other branch of developing vision for vehicles becomes easily understandable. Since computing power finally needed will take a decade or two to develop, why not embark on developing a vision system that integrates all aspects recognized as essential in the long run. Its full deployment may also take a decade or two, in line with the development of the hardware required. However, the overall system architecture and efficient multiple use of components should be designed such that harmonic growth is possible. In the long run, even autonomous learning seems to be essential since not all knowledge should have to be programmed into the system by human developers.

The first generation of vision systems for vehicle guidance developed at UBM (and elsewhere) had only very few completely separate functionalities (in the 80ies). The second-generation transputer systems had several functionalities, more or less uncoupled, which had to be activated by human operators separately according to the task to be performed. There was no internal representation of the perceptual or the behavioral capabilities of the system such that really autonomous decisions could be based upon them. Behavior was rigidly fixed in software code. Representation of the most important environmental objects, however, has been dynamic and could be made available to all distributed agents for perception and control. All of these agents had their own knowledge base, separate from all the others. Coding has been in procedural computer languages in both generations (FORTRAN and C). The new third-generation system has been designed in an object-oriented computer language (C++) with explicit representations of the entire situation perceived and of the own perceptual and behavioral capabilities. This new line of development will be discussed in the next but one section as a candidate for long-term development of the technical sense of vision.

3. Short-range developments for early market application

With the liability question unresolved for autonomous vehicles on the civil market, all car manufacturers devoted their attention for application of machine vision in public traffic to assistance systems. Since in highway-driving getting inattentive or falling asleep and ensuing road run-off is a rather frequent cause of traffic accidents, assistance in lateral vehicle guidance has been one of the first applications investigated [8, 19, 20].

3.1 Assistance in lateral guidance

While in Europe one was hesitant to really offer these systems on the market for cars, in Japan Mitsubishi (optional for 'Galant'-cars in the late 90ies) and Nissan (early this decade) dared this step for the internal Japanese market. DaimlerChrysler (DC) had a system developed by the company 'Odetics' for trucks; it is offered for 'Freightliner' trucks since 00 and for 'Mercedes-Actros' trucks since 01, giving audio warnings (on the left or right side) when the vehicle leaves the center of the lane beyond a certain threshold. Several other carmakers have announced similar assistance systems for their high-end vehicles in the near future. Electronic supply companies like Bosch and Delco among others are also developing know-how in the perception part for these kinds of vision systems; they may team up with carmakers for overall solutions including different human-machine interfaces. Haptic inputs for simultaneous corrections in the proper direction seem to be the favorite means [19]; however, this is rather involved from an implementation point of view. Audio warnings are easy to implement and are the low-key standard.

From the many approaches investigated for road and lane recognition, recursive estimation based on intelligently selected edge features (see figure 1) and differential-geometry (curvature) models seems to have become the standard one [15, 21, 22]. Neural nets have also been investigated [23, 24] but seem to have disappeared in the meantime. This problem set of road and lane recognition including estimation of own lateral state together with the detection and tracking of other vehicles has attracted by far the largest fraction of activities in the field of vision for vehicles (see table 2 below). Most approaches use a single camera fixed to the car body and one focal length of medium range (which is neither sufficient for tight maneuvering nor for high-speed driving).

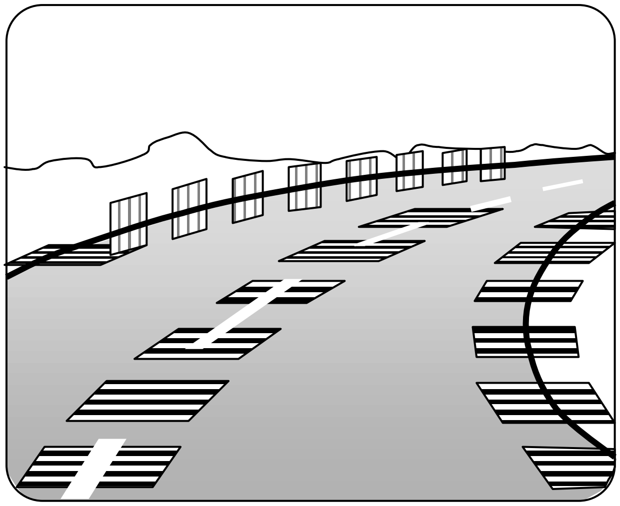

Figure 1: Road recognition with edge features in intelligently selected regions based on spatio-temporal models of continuity (4-D background knowledge).

3.2 Adaptive cruise control

The second most boring task in highway driving besides staying in the middle of the lane is keeping proper distance to the vehicle in front. This longitudinal control task has been investigated for automation with radar sensors for several decades. Because of the tendency for many false alarms due to coarse resolution, multiple reflections and missing capability of road recognition, acceptable solutions had not yet been found till the end of the 80ies. In the early 90ies within the Prometheus project, this problem set has been investigated both with Laser Range Finders (LRF) and with vision exploiting the new generation of digital microprocessors becoming available. Scanning LRF have much improved lateral resolution as compared to radar; single-beam 2-D scanning or multiple beam 1-D scanning solutions have been studied [15]. Eye safety is an important aspect limiting high-power solutions, which would alleviate the data processing part.

In vision, both binocular stereo vision and monocular image sequence analysis have been investigated. For stereo vision in real time, the computing power available was not yet sufficient. Spatio-temporal modeling of own and other vehicle motion in conjunction with odometers for ego-motion turned out to be sufficient for reliable estimation of the relative state of stationary obstacles and other cars. In biological systems this effect is known as motion stereo; in technical systems it is a direct outcome of applying recursive estimation techniques with dynamical models to the vision process from a moving platform. In the early 90ies it could be shown that sufficiently reliable distance estimation to other moving vehicles was indeed possible at distances up to at least about 80 m [25, 26]. During the final demo of the ‘Prometheus’ project on Autoroute 1 near Paris in October 1994, thousands of kilometers have been driven in normal three-lane traffic including convoy driving and transition into this mode from free-lane driving at speeds up to 130 km/h.

This has been achieved with the test vehicles **VITA2** of Daimler-Benz and **VaMP** (of UBM, figure 2), two Mercedes SEL 500 sedan vehicles equipped with dozens of transputers for image processing, for interpretation of the environment, and for vehicle control (**C**ommon **E**uropean **D**emonstrators CED 302 and 303). **VITA2** probably has been the most generously equipped research vehicle for machine vision. Beside the four miniaturized ‘finger’-cameras also used in **VaMP**, two each with different focal lengths (8 and 24 mm) on a single axis platform looking to the front (figure 3) and to the rear, it had an additional 7 pairs of cameras for stereo vision. One pair looked to the front and 3 each to the sides, all with a rather large stereo base (see [27, 28]). Since several university groups contributed to **VITA2**, the multi-processor concept with different types of microprocessors was much more involved than that of **VaMP**, which encompassed a total of about 60 transputers with 16-bit (for image processing and communication) and with 32-bit word length (for number crunching). Typical results of tracking other vehicles both in the front and the rear hemisphere are shown in figure 4. The white markings in the images show the perspective (forward) mapping of lower and side edges of a box encasing the lower part of the vehicle body (up to 1 m height) with the position according to the estimated relative state. The reflecting glass surfaces on the upper part of cars would deteriorate the results when included in the estimation process.

Figure 2: ‘**V**ersuchsfahrzeug für **a**utonome **M**obilität **P**KW’ (**VaMP**) of UBM, twin vehicle to the DB-demonstrator **VITA2** in 1994 near Paris in normal highway traffic.

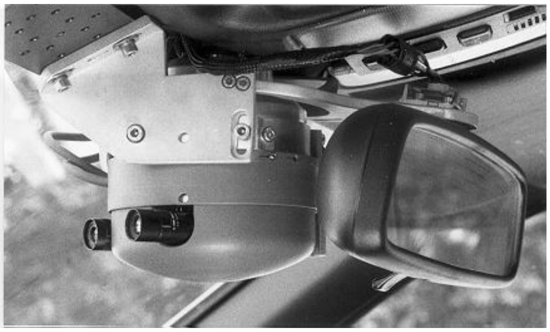

Figure 3: Bifocal arrangement of miniature TV-cameras on a pan platform in front of the rear view mirror of **VaMP** and **VITA 2**, Prometheus, 1994

Next-generation microprocessors (PowerPC 601), used in the mid-90ies in these vehicles, had 10 times the computing power. This has been used for doubling the processing rate to full video rate of 25 Hz (40 ms instead of 80 ms cycle time) and for cutting the number of processors by a factor of five. Reliability and robustness of vehicle recognition under various lighting and weather conditions still was not yet satisfactory for market introduction.

Therefore, the carmakers decided to rely on radar for the first-generation system of **A**daptive **C**ruise **C**ontrol (**ACC**) including more involved signal processing with microprocessors. The actual Mercedes S-class model was the first car on the market to be optionally equipped with such a system, called ‘Distronic’, in 2000. Other electronic suppliers and carmakers have been working on similar systems and followed suit soon. Since radar does not allow recognizing road curvature, this quantity is determined in an approximate manner from other

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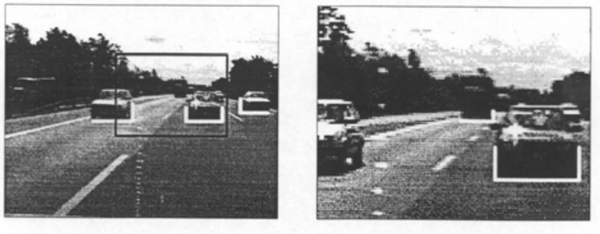

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Figure 4: Simultaneous tracking of multiple vehicles and monocular relative state estimation; top: front-, bottom: rear hemisphere; left wide-angle, right tele-images. Up to 6 vehicles could be tracked in parallel in each hemisphere. Accuracy was in the 2 to 8 % range (depending on distance, max. 100 m).

measurement signals like inertial yaw rate combined with speed driven, or from differences in left/right wheel turn rates. (Both methods rely on the assumption of a quasi-steady driving state and constant curvature).

For large look-ahead distances this assumption is not valid and road curvature changes will have a non-negligible effect. Therefore, developments are under way to complement radar-ACC with a vision component for detecting the actual state of the road in the look-ahead range of the radar [29, 32c]. This additional vision component also considerably improves estimation results for the lateral position of the object detected and allows for localization relative to the lane markings; this is not achievable with a pure radar system. Market introduction of these new hybrid assistance systems can be expected soon.

3.3 Autonomous ‘Stop & Go’-driving

When good and reliable performance of the two vision components discussed above have been demonstrated, the question naturally arises whether combined systems could not be trusted sufficiently for performing relatively non-critical tasks fully autonomously. The boring task of ‘Stop & Go’-driving with an upper limit for speed allowed could be - and is being discussed as - such a case (e.g. speeds less than 30 km/h (or 10 m/s = 36 km/h)). For modern cars the stopping distance from a speed of 10 m/s may be as low as 5 m (under ideal conditions).

In **Stop & Go** traffic, of course, even on highways many kinds of obstacles may occur like humans walking between the vehicles; at low speed, they may enter the driving tube of a vehicle directly from the side nearby. Therefore, obstacle detection can not be confined to a small angular region in driving direction, but a wide field of view has to be monitored. In principle, laser range finders (LRF) or special radar sensors at the front corners of the vehicle as well as wide field of view vision sensors from behind the windshield can be used. LRF have one or a few beams scanning around a vertical axis. Time of flight measurement is the main information input; signal intensity may also be used eventually. Radar systems with a wide aperture for covering a large area nearby will work with a lower frequency than those used for ACC (in the 24 GHz range instead of 77 GHz) [30].

All of these approaches are under study. The demo vehicle VITA(1) of Daimler-Benz (see figure 5) may have been the first vehicle to publicly demonstrate purely vision-based ‘Stop & Go’-capabilities.

Figure 5: ViTA (Vision Technology Application), 1991 first demonstrator of Daimler-Benz for ‘Stop & Go’-capability by vision, Torino, Italy, on secluded roads.

The first systems to hit the market in a few years may be based essentially on radar because this approach has the lowest data processing requirements. Vision, on the contrary, has the highest data rates but also best performance in spatial resolution. In a simple design, cameras with lenses for wide fields of view may be mounted at the upper left and right corners behind the front windshield, looking to the opposite sides of the car body (see figure 6 for a sketch). Together with a third camera looking straight ahead from the center of the windshield, the entire front hemisphere can be covered. However, images with this wide field of view (> 60°) usually need corrections for optical distortions at their sides; in trade-off studies, somewhat larger focal lengths may show to be preferable since a full coverage of 180° does not seem to be mandatory. The disadvantage of this arrangement is that the spatial resolution of the forward-looking camera is not sufficient for long look-ahead distances required at high speeds. The focal length needed for these cases is an order of magnitude larger than the one for a wide field of view nearby. Of course, for standard cameras with less than 800 pixel per row this entails a small field of view. Therefore, either a suite of (about ten) cameras mounted fix to the body, or viewing direction control with an additional tele-camera, or a zoom-lens with gaze control become mandatory in order to be able to track curved roads at larger distances.

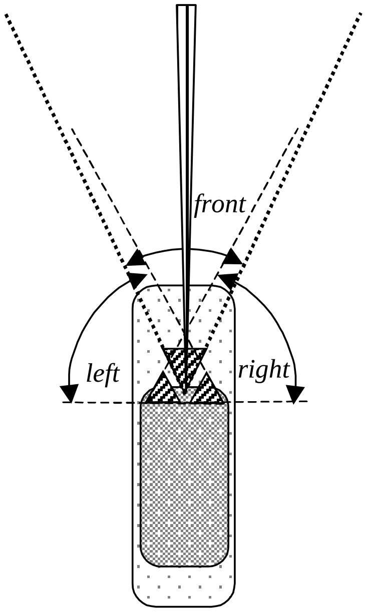

Figure 6: Covering a hemisphere with 3 wide-angle cameras.

Exploiting foveal – peripheral differentiation like in vertebrate eyes allows reducing the data rate by about two orders of magnitude for the same field of view without sacrificing performance. Only a time delay of a fraction of a second for a saccadic shift of attention has to be dealt with when high resolution is required in a peripheral detection area to be analyzed more carefully. This compromise between data rates to be handled and spatial resolution, found in vertebrate vision, has been mimicked with MarVEye and the ‘Expectation-based, Multi-focal, Saccadic’ (EMS-) vision system to be discussed in the next section [31, 32].

A new performance element in ‘Stop & Go’-driving is to laterally follow the car in front when there are no lane markings. In addition, reckless drivers cutting into your lane right in front of you and requesting right of way have to be dealt with. On the other side, changing lane when there are large gaps in a neighboring lane with faster traffic should be possible on explicit demand of the human operator. This type of driver assistance in ‘Stop & Go’ traffic is in the transition region to autonomous driving capabilities. However, a large volume of experience and statistical data with strong indications for the superiority of automatic driving will have to be accumulated and the liability question will have to be resolved before really autonomous driving will be allowed.

3.4 Reading of traffic signs

This topic has been picked up early by a Daimler-Benz research group in the Prometheus project. Understanding speed limitations and ‘Passing prohibited’-signs were the first tasks studied [33, 34]. Many groups around the globe have joined the topic in the meantime as may be seen from [15]. However, reliable recognition of traffic signs in a natural environment along roads with multi-lane traffic is a demanding task since it has to work under any lighting and weather conditions all year round. Up to now, no such system is ready for market introduction at reasonable costs. If available, the actually valid state in traffic regulation could be shown on an internal display on demand by the human driver. It could be a nice add-on on top of other functions; whether it is worth the rather high investment costs for its own merits is rather doubtful.

3.5 Lane change assistance

Just performing lane changes when the neighboring lane is free, is a rather simple task and has been demonstrated early in the development of machine vision [35]. It may be considered a standard capability in visual guidance systems for road vehicles by now. The difficult task is to reliably perceive that the neighboring lane is free; this includes, of course, also faster traffic from behind, even when approaching in the own lane. Since this task is difficult for humans too, an assistance function telling the human driver that it is now absolutely safe to perform a lane change would be appreciated.

For arriving at this statement, the traffic situation both in the front and the rear hemisphere as well as to the side in the neighboring lane has to be evaluated and judged. That this is possible in principle has been demonstrated in the Prometheus project by the UBM-group [36] at the final demonstration on Autoroute 1 near Paris. However, even today the vision community is far from claiming that this task can be solved reliably under *any* lighting and weather conditions. My judgement is that solutions with a mixed sensor set like in ‘Stop & Go’ traffic may solve the task in the long run. But again, the equipment needed on board may be too expensive for just this single task; therefore, maybe towards the end of this decade, integrated systems like the one announced by

DaimlerChrysler will have this capability to offer among several others (see [37]).

3.6 Foreseeable development of vision for road vehicles

Table 2 gives an indication of activities in car industry together with universities and other research institutions around the globe. It has been generated from contributions to the International Symposium on Intelligent Vehicles in four of the years between 1994 and 2000.

Car industry around the globe seems to agree with respect to the steps of development for the next decade. From several sources and communications over the last years, the road map given in figure 7 has been assembled; the time scale may be wrong by a larger percentage, but the sequence of steps is reasonably sure. The last three items on the top are far out into the future; their realization will depend on experience gathered with the previous ones over the years. Recognition of humans has already been picked up by the automotive industry [38, 39]. The question, whether there will be fully autonomous vehicles on the road ever, has distinct proponents and opponents. From my point of view, future statistics on accident rates of vehicles controlled by humans as compared to automatic systems will be the most decisive factor. This question should be left to the next generation for decision. I have no doubt that the average performance level in road vehicle guidance of humans will be achievable in a few decades by technical systems based on vision and some additional signals from more conventional sensors.

4. Towards autonomous driving

Two groups demonstrated long range (partially) autonomous driving on highways in 1995. The Robotics Institute of Carnegie Mellon University (CMU) had its test vehicle NavLab_5 (see fig. 8) run from the East coast (Washington DC) to the West coast of the USA (Los Angeles). It was equipped with a simple vision system for recognition of the horizontal curvature of the road and the lateral position in the lane. Longitudinal control was done by a human driver while lateral control was performed fully autonomously [16]. 98 % of the total distance of more than 5000 km could be driven without intervention of the human safety driver in steer angle control.

A few months later, **VaMP** of UBM demonstrated a fully autonomous long distance drive (both lateral and longitudinal) on the Autobahn over more than 1600 km from Munich to Odense, Denmark [40]. About 95 % of the distance could be driven without intervention of the safety driver. All situations needing an intervention by

Topic of investigation ↓ country →	As	Ja	Fr	Ge	It	Eu	USA	**Total**
Road detection, tracking & rel. state of own vehicle	5	9	7	8	2	5	11	**47**
Vehicle detection and tracking, relative state	2	11	11	11	3	2	15	**55**
Recognition of other objects (traffic signs, humans); relative state	--	4	3	5	2	1	4	**19**
Detection of crossroads, map building, surface state	--	1	2	2	2	1	4	**12**
Longitudinal guidance of vehicles	1	7	5	8	--	2	5	**28**
Lateral guidance of vehicles	1	3	7	7	1	2	5	**32**
Situation assessment and decision making	1	3	8	5	2	1	8	**28**
System components and –integration	1	6	10	10	2	1	10	**40**

Table 2: Number of institutions working on road vehicle guidance by machine vision in the most active countries.
Code: As = Asia without Japan, Ja = Japan; Fr = France; Ge = Germany; It = Italy; Eu = Rest of Europe;
Other subjects treated (**total**) were: Data fusion with other sensor signals (**13**), monitoring of human behavior (**8**), vision for intelligent airbag deployment or headlight control (**7**), detection of objects on crossroads (**6**), tight 2-D maneuvering (**6**), active gaze control (**2**).

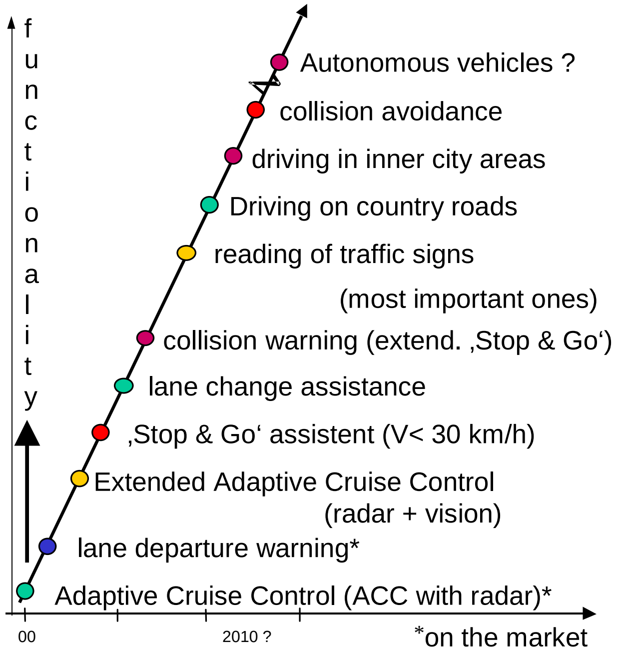

Figure 7: Road map for applications of the sense of vision for road vehicles.

the driver have been monitored carefully in order to see which would be the most urging next steps for closing the gap to 100 % reliable road and lane recognition. The test has been done with black-and-white images and edge detection as shown in figure 1. On construction sites with yellow lane markings overriding the still existing normal white ones, color perception is needed in order to disambiguate recognition. When driving ‘into the sun’ at dusk or dawn (westwards in the evening, eastwards in the morning) careful shielding so that the sun is not mapped directly into the image may help a lot, but cannot always be achieved. In long underpasses or tunnels, lighting conditions may be too low for standard cameras to give usable images. Under bright sunshine with shadows, the dynamic range of the intensity signal is too large for normal cameras; no compromise in parameter setting is possible yielding acceptable results in all image regions. Active control of viewing direction with small fields of view can remedy this situation.

When lane markings are missing or very poor, recognition of the hardened surface of the road can help; region-based image interpretation (homogeneous gray values, shading effects or textured areas) with corresponding background knowledge is needed in these cases. If many other objects are in the scene, color alleviates keeping track of the situation. - Passing vehicles cutting into your lane right in front of the own vehicle caused trouble since range estimation by monocular motion stereo relied on features where the vehicle in front touched the ground. In the near range (up to about 6 m) these are not available in **VaMP** because of occlusion by the own motor hood. Therefore, for detecting these vehicles early, a wide field of view is required; in addition, for fast range estimation nearby, at least binocular stereo vision should be available; trinocular stereo would even be more robust. All these points have been taken into account when designing the third generation vision system at UBM in the mid-90ies.

In 1997 an Italian group also did a long distance test drive ‘Mille Miglia in Automatico’ named after the famous race taking place every year in this country. It could be followed in the internet [41] and also showed that there still was room for improvements.

In the ‘Chauffeur’ project of DaimlerChrysler the second truck in a convoy of two drove fully autonomously on the Autobahn, using beside visual tracking of special markings on the backside of the first truck also several signals communicated from this one by radio link [42].

Figure 8: Navlab 5 of CMU, which performed the demo “Hands-off through America” (automatic lateral control by vision over 98 % of the distance) in 1995.

In a recent project, VW has investigated fully autonomous driving on a secluded test track using vision among other sensor signals [43].

5. Long-range developments with more human-like performance levels

In order to resolve the problems mentioned above, sets of cameras on pointing devices have been studied. In order to keep these ‘vehicle eyes’ simple, the set of 3 to 4 cameras has been mounted fix relative to each other on a platform capable of moving in 1 or 2 rotational degrees of freedom[32]. A large range in yaw (pan) is mandatory for tight maneuvering and for perceiving the local environment in a wide field of view. In pitch (tilt), the required field of view is much smaller for ground vehicles driving on normal terrain or on roads. Only the images of cameras with large focal lengths need inertial stabilization for counteracting perturbations from a non-planar surface or from ac- or deceleration. Figures 9 and 10 show a ‘vehicle eye’ (camera set and platform layout) as a compromise between optical and mechanical requirements.

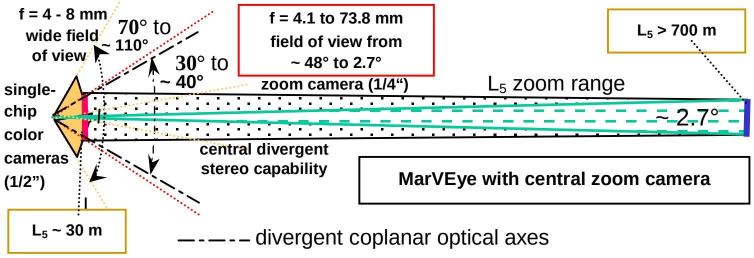

Figure 9: Sketch of ‘MarVEye’ with central zoom-camera with wide zoom range; L_5 = distance at which the size of one pixel corresponds to 5 cm normal to the optical axis.

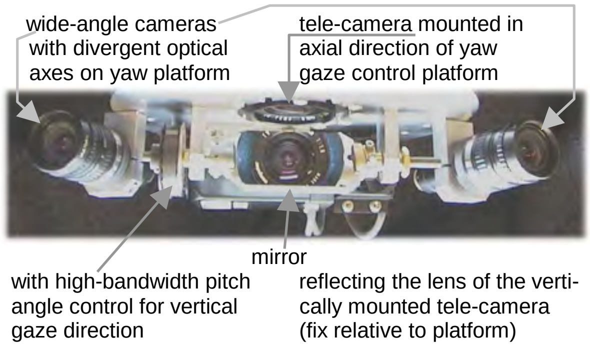

Figure 10: Proposed ‘Multi-focal, active/reactive Vehicle Eye’ **MarVEye** with gaze control in yaw for all, in pitch for the tele-camera only. (View from right-hand side in figure 9)

All cameras turn in conjunction in yaw direction only; the wide-angle cameras are mounted with divergent optical axes in order to increase the simultaneous field of view. They have a central area of overlap allowing binocular stereo interpretation in this region; they map their images directly. The third (zoom) camera is mounted with its optical axis vertical in the yaw axis of the platform; it receives its images through a mirror. This mirror is adjusted in pitch with high bandwidth according to the body motion such that in the image plain the world seems unaffected from the pitching motion of the camera (equal to that of the body). This principle is widely used in weapons technology and has proven to be very advantageous because of the low inertia of the mirror to be moved. Zoom cameras are now on the market with optical zoom ratios of 1 : 18 (f = ~ 4 to ~74 mm) and an additional digital zoom by a factor of four. For most applications this is more than sufficient.

The challenge to be solved with this type of technical eye is the coordinated and consistent interpretation of the various data streams. During fast saccadic motion of the platform for pointing the high-resolution field of view towards the region of interest, no meaningful interpretation is possible due to motion blur. During these short periods of a few video cycles, the system has to rely on its spatio-temporal motion models, which form the basis for recursive state estimation according to the 4-D approach to dynamic vision [7, 13].

With a total effort of about 30 person years over the last 5 years, this third-generation ‘**E**xpectation-based, **M**ulti-focal, **S**accadic vision system’ (EMS-vision) has been developed and proven in both test vehicles **VaMoRs** and **VaMP**. It is integrated in an overall architecture for autonomous mobile robots [32]. Even though there is still a long way to go towards performance levels as shown by biological systems, this approach looks promising since it is easily expandable with more computing power coming along and with experience gained on the basis now available.

The main features are as follows:

- Scene representation is done with object-oriented generic models and explicit homogeneous coordinate transformations (HCT) in a so-called scenetree like in computer graphics. However, since in computer vision the entries into the HCT (parameters of models and state variables) are the unknowns of the problem, a very flexible iteration scheme has been realized [44].
- There are special agents for the visual perception of members of object classes (roads with intersections, obstacles, other vehicles, landmarks). They feed a **D**ynamic **O**bject data**B**ase (DOB) with their best estimates for the states of objects at video rate [45].
- Egostate estimation heavily relies on inertial measurement components in order to bypass difficulties in vision stemming from perturbations while driving on rough ground.
- All perceptual and behavioral capabilities are explicitly represented in the system allowing flexible activation. These maneuver representations may also be used for understanding the motion of other subjects.
- Situation assessment is performed looking at time histories of relevant other objects/subjects in conjunction and by possibly extrapolating maneuvers started into the future (intent recognition). Behavior decision is derived from these results [32e, -g, 47, 50].

A survey on the system architecture is given in [31, 32] and the dissertations [46] (road recognition), [47] (vehicle control), [48] (mission performance). The saccadic vision part for turn-off maneuvers on minor roads (**VaMoRs** with a different, full two-degrees-of freedom gaze platform) has been discussed in [49, 50].

7. Conclusions

Machine vision has made significant progress over the last decade. This is only partially due to increased microprocessor performance according to ‘Moore’s law’ (factor of ~ 100). The number of active groups in the field also has increased strongly. Simple tasks like lane recognition can now be performed by a standard PC. However, reliable and robust performance under any lighting and weather conditions still leaves room for improvements. Upcoming processing power will allow the inclusion of more region-based methods (color, texture recognition) to close the gap. Corresponding knowledge bases are being developed.

This development will also allow to shift object recognition and relative state estimation to a larger extent to vision, thereby reducing the need for active range sensing methods (radar, laser). From the very nature of the components involved in high-performance (human-like) vision it pays off to go for integrated flexible vision systems which exploit the same hardware and software for a multitude of functions as they are needed during mission performance. This will become possible over the next decade or two. One candidate has been briefly touched upon.

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