NEW TECHNOLOGIES FOR VEHICLES
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Abstract:
Developments in vehicle technologies for control, navigation, obstacle detection and platooning are described. The aim of these activities, in conjunction with the parallel work on infrastructure technologies, has been to improve the basic functionalities of cybercars, especially in term of controllability, safety, cost and operation domain.

Keyword List:
Cybernetic Transport Systems, Vehicle, Control, Sensors, Actuators, Navigation, Obstacle detection, Obstacle avoidance, Platooning

CONTENTS

1. Introduction

A major task of the CyberCars project is to **improve basic technologies for the operation of cybercars, also called Automated Guided Vehicles (AGV).**

The definition of the cybercar was agreed upon during the first phase of the project :

Cybercar Definition

Cybercars are road vehicles with fully automated driving capabilities. A fleet of such vehicles forms a transportation system, for passengers or goods, on a network of roads with on-demand and door-to-door capability. The fleet of cars is under control of a central management system in order to meet particular demands in a particular environment. At the initial stages, cybercars are designed for short trips at low speed in an urban environment or in private grounds.

In the long term, cybercars could also run autonomously at high speed on dedicated tracks. With the development of the cybercar infrastructures, private cars with fully autonomous driving capabilities could also be allowed on these infrastructures while maintaining their manual mode on standard roads.

Cybercars are members of the general family of people movers and close to PRT (Personal Rapid Transit) but they offer the advantage of being able to run on any ground infrastructure which means they are cheaper and more flexible.

Cybercars have to satisfy challenging requirements, like **following a complex path** with high accuracy, assuring complete **safety with no control from a driver**, and realising new functions for road vehicles like **a platoon of vehicles** where the first one is controlled manually and the other ones follow in automated mode.

The analysis performed in the first phase of the project (Workpackage WP1) has shown that state-of-the-art technologies, mostly derived from robotics, still have a number of limitations or inefficiencies regarding the requirements of AGV's .
From one side, some existing technologies have to be improved in term of performance. From the other side, there is an opportunity to identify new concepts, allowing to simplify the operation of cybercars and reduce the cost of equipment.
This aspect is linked to the aim of extending step by step the application of cybercars from the present experiences on private and controlled areas to some more open environments, possibly shared by other road users: a major issue to be investigated is therefore how to obtain this extended operation, balancing the interventions on vehicle technologies, infrastructure equipment and operation procedures.

In this context, activities in Workpackage 2 for new **vehicle technologies** have been focused on the following **areas**, identified as most impacting:

- Vehicle controls;
- Navigation and guidance;
- Obstacle detection and avoidance;
- Vehicle platooning.

The present report describes these activities and the related results obtained:

- Chapter 2 introduces the main objectives, the role of partners, and a list of major results.

- Chapters from 3 to 6 refer to the specific developments in the four areas; a first section in each chapter introduces the state of the art, the challenges for development and summarises the main findings.
- Chapter 7 gives a first series of conclusions and comments, in view of the evaluation phase planned in workpackage WP4 of the project.

2. Workpackage framework

2.1 Objectives

Main objective within Workpackage 2 of the CyberCars project is to improve existing technologies for automatic **navigation**, **obstacle detection** and **platooning**, identifying new solutions which are more performing and cheaper than the existing techniques.
A second important goal is to improve the **control architectures** for vehicles, in term of hardware (HW) and software (SW) : to this respect, a major issue is to assure the necessary safety and reliability for all the basic functions, starting from engine management, braking and steering.

The focus of these activities is on technologies mounted **on board**; they are therefore complementary – and must be integrated – with the developments in Workpackage 3 regarding infrastructure technologies, to obtain effective solutions for the operation of cybercars.

Four **types of vehicles** are considered for the implementation of technologies: a People Mover assuring a comparatively larger capacity of 20 passengers (FROG), a smaller four seats AGV applied at present to transport visitors in show areas (Yamaha-AGV), an even smaller two passenger vehicle developed by INRIA and now sold by Robosoft (the CyCab), and two general purpose platforms, which can be used for different applications depending on the specific equipment mounted on-board (Robosoft).

For all these Cyber cars a limited range of speeds (up to 30-50 km/h) is taken as a constraint, suitable for the first types of application envisaged, and affecting the requirements for the technical solutions under study.
Two other vehicles are studied in the project addressing system design aspects: a dual-mode vehicle running on roads (manually) and automatically on rails (RUF), and a small city car where the focus is on the architecture for dual mode driving (either manual and automatic) starting from standard automotive concepts and technologies (CRF).

More specifically, in relationship with the existing knowledge derived basically from robotics, the workpackage objectives involve the following main aspects:

- a **modular distributed approach** for the control architectures, allowing to adapt the on-board modules, depending on the application environment (network, lanes, infrastructure, possible obstacles, etc.);
- CAN based solutions for the communication network, assuring **reliability** for safety critical functions;
- a SW tool for the **easy design and simulation** of the architectures;
- a deeper understanding of sensor requirements for obstacle detection, with emphasis on **safety for users** in all conditions: this will lead to identify the most promising sensor technologies, based on either vision, laser or radar, and to develop suitable systems;
- Techniques for the **precise localisation** of vehicles, which allow a **limited investment in the infrastructure**, particularly based on GPS, vision and inertial sensors;
- A demonstration of **platooning schemes**, especially testing the use of **on board sensors** like cameras or lasers to detect the preceding vehicle.

To reach the expected results, design studies must be performed and specific **prototypes and software modules** must be developed and integrated on vehicles, testing the basic performances.
A subsequent and complete experimentation is planned in Workpackage 4, with a technical evaluation of the most promising solutions in a test site, focusing the functional level.

The general frame for these developments is **to extend the application domain** of Cyber cars, according to the roadmap defined at the beginning of the project [see: Technical Annex and Figure 1]. In fact, driving automation is expected to enlarge its operation from private grounds, where most of the applications are now exploited, to local tracks, pedestrian zones or specific city areas, aiming progressively to more complex environments and road networks, with a greater interaction with other road users and traffic.
The improvement of navigation, obstacle detection and platooning techniques intends to contribute to this general goal, increasing the potentiality of these new ecological and efficient transportation means.

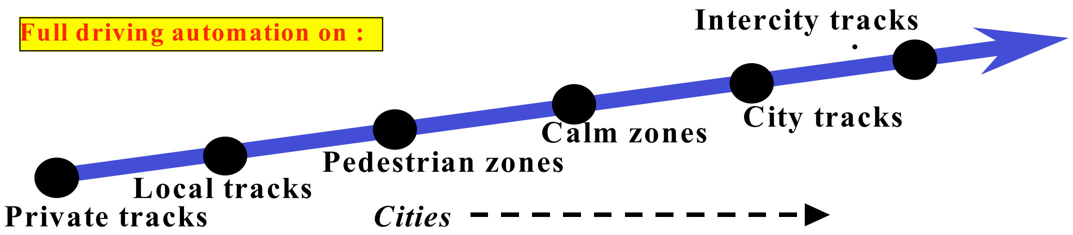


Figure 1 Evolutionary approach for cybercars

2.2 Role of partners

Eight partners have contributed to the workpackage, including two car manufacturers (CRF, YME), three suppliers (FROG, Robosoft, RUF) and three research institutes (INRIA, University of Bristol, University of Coimbra). The following table shows their main roles in the workpackage.

Partner	Short name and country		Main role in WP2
Centro Ricerche Fiat	CRF	I	WP coordinator; study of dual mode vehicle; investigation on automotive radar.
Yamaha Motor Europe	YME	NL	Controls. Regenerative brake.
Frog Navigation Systems	FROG	NL	New platform for People Mover; architecture and controls, improved obstacle detection, magnetic rulers.
Robosoft	Robo	F	New RobuCab platform; wire guidance; camera and laser based techniques; platooning.
RUF International	RUF	DK	Guidance for large collective vehicles by magnetic probes. Platooning.
Institut National de Recherche en Informatique et Automatique	INRIA	F	SW tools; vision based localization; stereo vision; platooning; study of complex maneuvers.
University of Bristol	UB	UK	General study for platooning schemes.
University of Coimbra	ISR	PT	Experimental platform: path tracking; integration of inertial navigation and GPS; development of stereo vision.

3. Vehicle controls

3.1 Baseline and project results

Cybercars by definition are under full control of computers and/or microcontrollers.
These controls have to operate in particular on the three elements of a vehicle for its motion: acceleration, deceleration (and stopping) and finally steering.
These controls are well known in the field of industrial robotics; however, up to now their installation on a road vehicle running in an external and less controlled path has been far from easy.

In fact the first computer controlled vehicles, derived from existing robotic solutions, were not well fitted to this more difficult environment, often with poor control performances and especially poor reliability.
Now, thanks to recent advances in drive-by-wire technologies from the automotive sector, the control of fully automatic vehicles becomes a bit easier, in particular with the availability of hardware components such as computer controlled actuators for braking or steering.
However, the design, development and validation of such computer controlled systems is far from easy and, for a low volume production, the cost can be high and the reliability not certain.

The focus of the work on controls in CyberCars is therefore to develop new hardware products as well as software production and validation technologies, to simplify the development phase.
The following aspects characterise this approach:

- **Improved integration** for different functions (traction, braking, steering) under full computer control;
- **Reliability**, especially for safety critical controls;
- **Distributed system approach**, allowing a flexibility of implementation for the different applications;
- **Methods for easy design** and validation.

At the end of the workpackage, it can be said that consistent improvements in distributed and safe architectures, as well as the HW subsystems have been obtained and implemented on various vehicles. SW packages, in part already existing, have been improved and tested on various platforms. Moreover, a solution for a longer term application of cybercars has been investigated, addressing the architecture of a dual mode vehicle which can be manually driven on ordinary roads and automatically controlled in a more dedicated infrastructure.

The main results in the area of vehicle controls, are therefore as follows:

- *The development and application of the **software tool** SynDEx, for optimising distributed real-time embedded systems (INRIA - paragraph 3.2); the SW has been used by project partners for several applications; to create, implement and certify the control systems; rapid prototyping has been demonstrated.*
- *Advanced **architecture and components** for the second version of the Park Shuttle, with double CAN network for improved reliability (FROG NT - see paragraph 3.3) : in particular the system provides redundancy for safety critical applications and three different levels of braking (normal, fast and emergency);*
- ***A CAN based architecture** implemented in RobuCar, CyCab and Yamaha vehicles (INRIA) and in the test platform prototype (ISR); (this aspect can be found in several descriptions throughout the present report);*

- ***A new braking system** offering improved comfort (low jerk) and enhanced vehicle range by energy regeneration (YME – see paragraph 3.4); the system has been tested at the Floriade show on 25 vehicles running for 5000 Km each;*
- *The definition of a **vehicle solution for dual mode driving** (manual + automatic) on a city car (CRF- paragraph 3.5); the vehicle is based on a small and clean thermal engine plus an electric traction, and uses standard automotive components for steering and braking.*

3.2 Software tools for distributed architecture (Inria)

It has often been accepted that a distributed hardware/software architecture for complex machines should be simpler to realise on the hardware side, at least to simplify the wiring problems. On the other hand, the development of the software in these distributed environments is much more difficult due to the numerous synchronisation problems and the difficulty to debug such systems. To solve these difficulties, INRIA has developed a software tool which is now distributed in aerospace and automotive sectors, called SynDEx (www-rocq.inria.fr/syndex).

SynDEx is a system-level CAD software, based on the "Algorithm Architecture Adequation" (AAA) methodology, for rapid prototyping and for optimising distributed real-time embedded applications.

The first major application of this software tool has been on the CyCab platform which is a small electric vehicle specifically designed to transport 2 persons in restricted areas as downtown areas, pedestrian malls, etc. It has been designed by INRIA and is now manufactured by the Robosoft Company. Robosoft is now using SynDEx as its development tool for all its robotics applications.

3.2.1 Objective

- To propose software tools to allow users to create/implement/test/certify applications for safe AGV control.

3.2.2 Operational goals

- Specification and verification of an application algorithm as a directed acyclic graph (DAG) of operations,
- Specification and verification of a multicomponent architecture as a graph of programmable components (processors) and/or non programmable components (ASIC, FPGA, sensors),
- Specification of the algorithm characteristics relative to the hardware components (execution and transfer time, period, memory, etc),
- Optimisation of the algorithm implementation (distribution and scheduling) onto the multicomponent, and visualization of a timing diagram simulating the real behaviour,
- Generation of dedicated distributed real-time executives, deadlock free and mainly static, with optional real-time performance measurement.
- Or generation of the configuration of a standard real-time system as RTLinux, RTAI, Osek, etc.

The goal is to provide an architecture that maintains the essential predictability features found in centralized approaches like master/slave configurations but works in an event-based control system in a completely dynamic, decentralized way.

3.2.3 Baseline reference

Standard real-time software tools.

3.2.4 Deliverables

SynDEx is available for free download at www.syndex.org. Executive kernels are provided for MPC555 Motorola microcontroller, RTAI/Linux, etc.

3.2.5 Description

Although new monoprocessor architectures (workstations), provide ever increasing computation power, they cannot cope with the ever increasing complexity of some control, signal and image processing applications. Parallel architectures are needed, as well to satisfy real-time constraints (computation load balancing), as to take into account the distributed nature of the resources (sensor/actuator, computation, memory) of real-time applications.

These heterogeneous architectures, built from different types of programmed components (RISC, CISC, DSP processors) and/or of non-programmed components (ASIC, FPGA, full-custom integrated circuits), all together connected through a network of different types of communication components (point-to-point serial or parallel links, multipoint shared serial or parallel buses, with or without memory capacity), are called multicomponent.

AAA METHODOLOGY

AAA means Algorithm Architecture Adequation. The goal of the AAA methodology is to find the best matching between an algorithm and an architecture, while satisfying constraints. Adequation means an efficient matching; note that it is different from the word "adequacy" which involves a sufficient matching.

The AAA methodology is based on graphs models to exhibit both the potential parallelism of the algorithm and the available parallelism of the multicomponent. The implementation consists in distributing and scheduling the algorithm graph on the multicomponent graph while satisfying real-time constraints. This is formalized in terms of graphs transformations. Heuristics taking into account execution time durations of computations and inter-component communications, are used to optimize real-time performances and resources allocation of embedded real-time applications. For the purpose of co-design, resources may be of processor type when a program must be allocated on it (i.e. a sequence of operations executed by a processor and a sequence of communications), or may be of integrated circuit type when only a unique operation must be allocated on it (a net-list of interconnected logical blocks, CLBs).

The result of graphs transformations is an optimised Synchronized Distributed Executive (SynDEx), automatically built from a library of architecture dependent executive primitives composing the executive kernel. There is one executive kernel for each supported processor. These primitives support boot-loading, memory allocation, inter-component communications, sequentialization of user supplied computation functions and of inter-component communications, and inter-sequences synchronization.

On the vehicles delivered by Robosoft to various research laboratories, two CAN buses interconnect the subsystems of the vehicles: "Internal CAN" and "External CAN". The first one is used in the control motion of the vehicle; it interconnects the motor controllers (Motorola micro-controller MPC555) and the central computer. On the other hand, the "External CAN" is used to interconnect different smart sensors and the central computer.

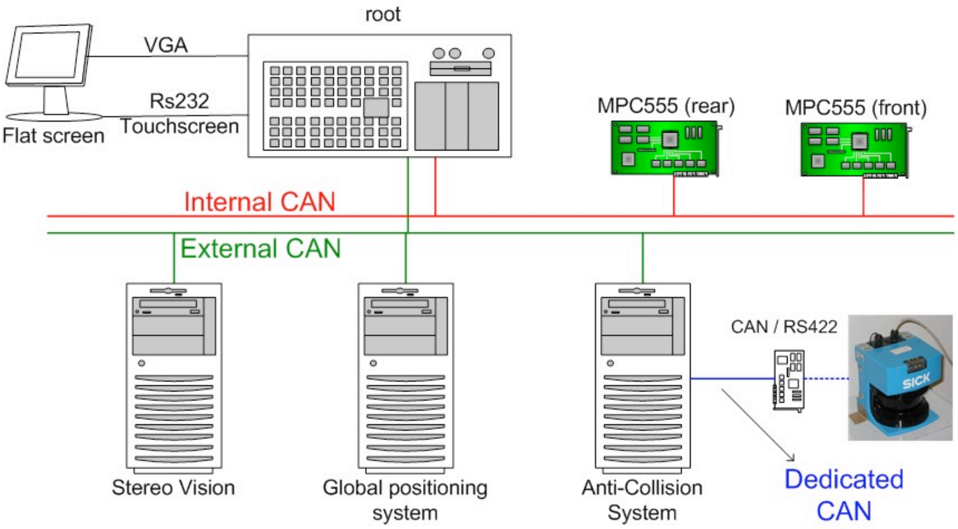


Figure 2 CAN Network Architecture

This modular architecture enables an easy integration of new sensors and modules (see **Erreur ! Source du renvoi introuvable.**). Systems such as a global positioning system, stereovision-based obstacle detection and anti-collision system are being integrated in the navigation system.

The original communication between the PC and the Sick Laser Measurement System (LMS) can be done either by RS232 or RS422. Since the first has a low baud rate, we were forced to use the RS422 communication, with this protocol we can set the system to work with a baud rate up to 500Kbps, enabling a complete scan acquisition to be made in less than 20 milliseconds. To give flexibility to the system, a RS422 to CAN-bus converter was developed. This converter is based on a PIC microcontroller, which has a CAN-bus controller integrated. Even with the CAN-bus setup at 1 Mbps baud rate, the data from the LMS almost consumes the available resources of the CAN-bus due to the overhead superimposed by the CAN protocol. The real-time communication couldn't be guaranteed with the high rate used to transfer the LMS data, therefore a dedicated bus is used to do this link.

SYNDEX CAD SOFTWARE

SynDEx is a graphical interactive software with on-line documentation, implementing the AAA methodology. It offers the following functionalities:

- Specification and verification of an application algorithm as a directed acyclic graph (DAG) of operations where edges are dependences between operations, or interface with specification languages such as the Synchronous languages providing formal verifications, AIL a language for automobile, Scicos a Simulink-like language, AVS for image processing, CamlFlow a functional data-flow language, etc,
- Specification and verification of a multicomponent architecture as a graph composed of programmable components (processors) and/or specific non programmable components (ASIC, FPGA), all interconnected through communication medias (shared memory, message passing),

- Specification of the algorithm characteristics relatively to the hardware components or vice versa (execution time of operations and data transfers, memory, etc), specification of the real-time constraints to satisfy (presently total execution time of the algorithm), and specification of distribution and scheduling constraints,
- Optimization of the algorithm implementation (distribution and scheduling) onto the multicomponent, and visualization of a timing diagram simulating the real-time behaviour,
- Generation of dedicated distributed real-time executives, or configuration of general purpose distributed real-time executives: RTlinux, Osek, etc.

These executives are deadlock free and based on off-line scheduling policies. Dedicated executives which induce minimal over-head are built from processor-dependent executive kernels. Presently executives' kernels are provided for: ADSP21060, TMS320C40, TMS320C60, i80386, MC68332, MPC555, i80C196 and Unix/Linux workstations. Executive kernels for other processors can be easily ported from the existing ones.

The distribution and scheduling heuristics, as well as the timing diagram, help the user to parallelize his algorithm and to size the hardware while satisfying real-time constraints. Since SynDEx provides a seamless framework from the specification to the distributed real-time execution, formal verifications obtained during the early stage of the specification, are maintained along the whole development cycle. Moreover, since the executives are automatically generated, part of tests and low level hand coding is eliminated, decreasing the development cycle duration.

The CyCab is controlled by a distributed embedded computer system based on a CAN network, providing features such as, secured manual driving (using an embedded analogue joystick) or autonomous driving and route planning. Two MPC555 based nodes are used on the standard vehicle, one for each driving axle. These nodes can be connected to one host PC for man-machine interface (Figure 3).

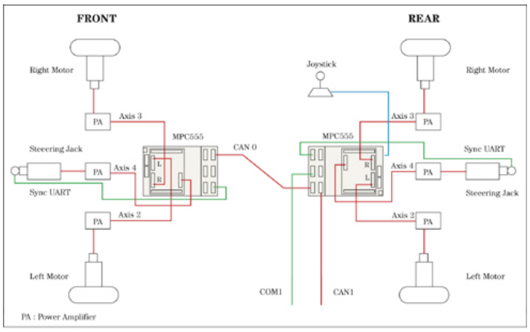


Figure 3 Scheme of the distributed computer system

SECURED MANUAL DRIVING OF THE CYCAB

The Figure 4 shows a snapshot of the architecture graph of our application implemented using SynDEx. This actual hardware architecture, is composed of two MPC555 microcontrollers (F555, R555) and one i586 (root) all linked through a CAN bus.

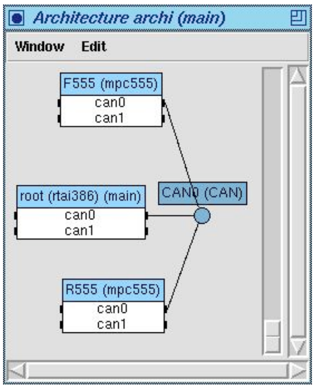


Figure 4 Architecture graph

The Figure 5 presents a snapshot of the data-flow graph of the ``manual driving" application algorithm. The vertices are the operations to be executed on the data. The edges are data dependencies between operations. This graph is composed of 3 kinds of vertices: the input ones only produce data, the processing ones produce and consume data, and the output are the ones which only consume data.

Typically the input vertices [most left boxes] are associated to the sensors and the output vertices [most right boxes] to the actuators. That is why they must be constrained to be assigned to the components attached to the sensors and actuators. The graph is cyclically executed; data flow from left to right. The execution time of one graph is the real-time loop period.

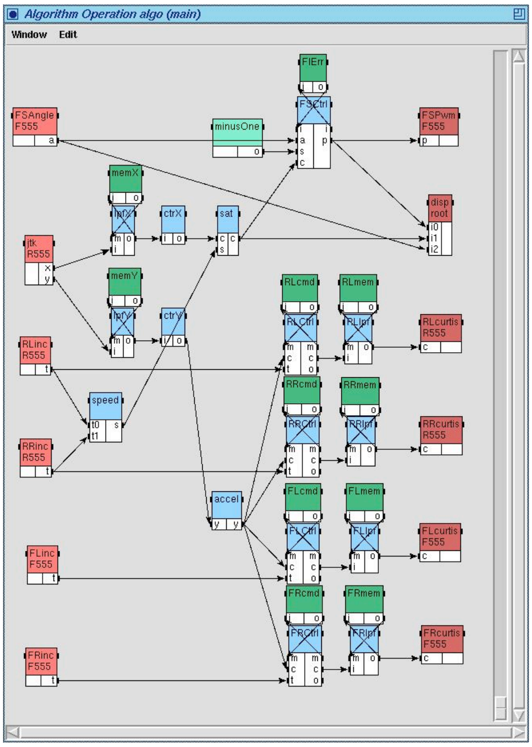


Figure 5 Data flow graph

The Figure 6 presents the predicted execution time given by SynDEx after the Adequation was completed. It shows only one execution of the graph. Each column represents the sequence of operations assigned to each processor, the Y-axis showing the time progress from top to bottom. The edges represent processor communications. More precisely, the origin of an edge is the date when the data is ready to be sent, and the ending of the edge is the date when this data is available on the destination processor.

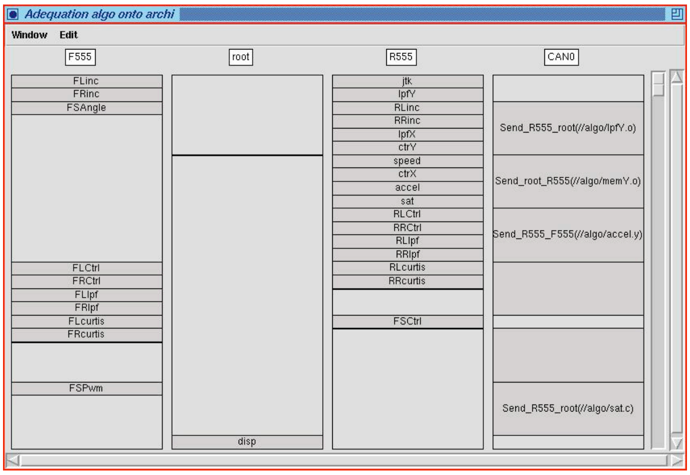


Figure 6 Predicted execution time for a sequence of operations

On each processor the optimized macro-code generated by SynDEx is expanded by the M4 (Gnu) macro-processor to produce an assembly and/or C code. A makefile is also generated. It performs the compilation and the link, calling Gnu GCC, and loads executables on the processors through the CAN bus. On each MPC555, thanks to this optimized macro-code the complete executable code is less than 15Ko.

Each communication medium, i.e. here each CAN bus, is a sequential resource where interprocessor data transfers must be ordered. Rather than a dynamic ordering, done at run time by the CAN arbitration on transfers contents, and which requires identification information to be transferred and decoded, a static ordering is chosen at compile time, where each transfer is uniquely identified simply by its position in the communication sequence. As the CAN bus has no centralized communication sequencer, the communication sequence must be distributed and synchronized on all the processors sharing the bus: at each communication step, all processors know the transfer type and size, the transmitting processor knows its source buffer address, each receiving processor knows its destination buffer address, and each remaining processor is synchronizing, i.e. waits for data as if it were receiving, but does not store the data. Moreover, to avoid dynamic buffer allocation and overruns, the transmitting processor does not start transmitting data before it has received, from each receiving processor, an empty synchronizing frame meaning that the destination buffer is available for reception.

3.3 Drive, Steer & Brake controls and architecture (Frog)

Through the use of electric drive and electrically driven brakes and steering (now becoming available on production automobiles), the cybercars are effectively “wire-driven”. However, the controls for all these actuators are still in their infancy, both at the hardware level and at the software level. The purpose of this task is to arrive at simple but efficient controllers and at software tools which can ensure the safety and reliability of the computer systems and hence of the vehicle. The approach proposed is based on a distributed system around a double CAN network in order to implement redundancy in safety critical systems. At the software level, we will use the latest techniques for real time programming in a distributed environment which have already been tested in laboratory conditions. The objective is to demonstrate the effectiveness and the safety of these tool and to make them available to all the industrial partners for integration into the vehicles through programming of the applications.

The new developed systems for driving, brake and steering are software controlled by the so-called FrogBOX (Figure 7)

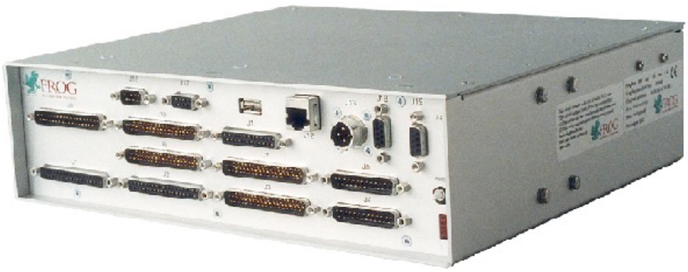


Figure 7 ‘FrogBOX’ for vehicle control

The FrogBOX includes an industrial processor onboard. The software (FROG Navigation Controller) for controlling the system (vehicle) are installed on the FrogBOX . The system is divided in three parts: brake, steer and driving system (Figure 8):

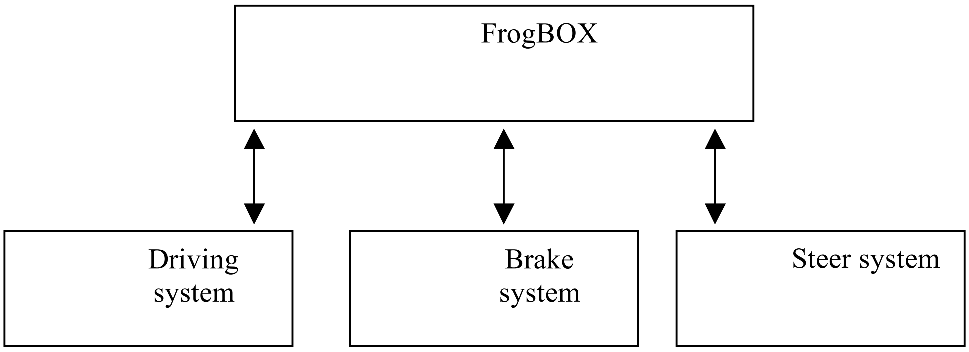


Figure 8 Scheme of the control system

3.3.1 Driving system

This chapter describes the functional interface between the Traction System and the FROG Navigation Controller as used for the People Mover Generation 2.

The Traction System exists of a Motor Controller, a Traction Motor and Parking Brakes. The Frog Navigation Software will control this Traction System in such a way that the required accelerating and decelerating of the vehicle is met. An overview of the traction system is given in Figure 9.

REQUIREMENTS

Hardware set-up

The torque generated by the traction motor is transmitted via a differential gear to the rear wheels of the vehicle. The final torque on the wheels will control the acceleration and deceleration of the vehicle. At standstill the Parking Brake on the rear wheels holds the vehicle at the required position, in case of an emergency stop or major Traction Fault the same is used as failsafe brake.

The Proportional Brakes (fitted on all four wheels) in combination with the Electrodynamic Brake (Traction Motor on rear wheels) will decelerate the vehicle in case of a normal stop. During a Fast-stop or emergency stop the Traction Motor Controller is switched off, now the vehicle will decelerate by use of the Proportional Brakes and/or the Fail Safe Parking Brake.

Holding and Positioning brakes

At standstill the Parking Brakes holds the vehicle at the required position. As soon the Navigation Controller decides to move, the Motor Controller puts the requested torque on the output shaft. With an adjustable delay the signal LIFT PARKING BRAKES becomes high and the brakes will be released, now the vehicle is able to move. This delay prevents that the vehicle rollback on an incline.

As soon the brakes are lifted the feedback signal PARKING BRAKES LIFTED becomes high. The time between the LIFT PARKING BRAKES command and the signal PARKING BRAKES LIFTED feedback is monitored by the Navigation Software, if this time is to long (1 a 2 sec) the motor controller is switched off. While the vehicle moves the Paring Brakes are always lifted and the signal PARKING BRAKES LIFTED is always high, if not the system shuts down.

When the vehicle approaches the final destination the speed is reduced to the positioning speed. The vehicle keeps this very low speed till the final destination is reached and the parking brakes are dropped.

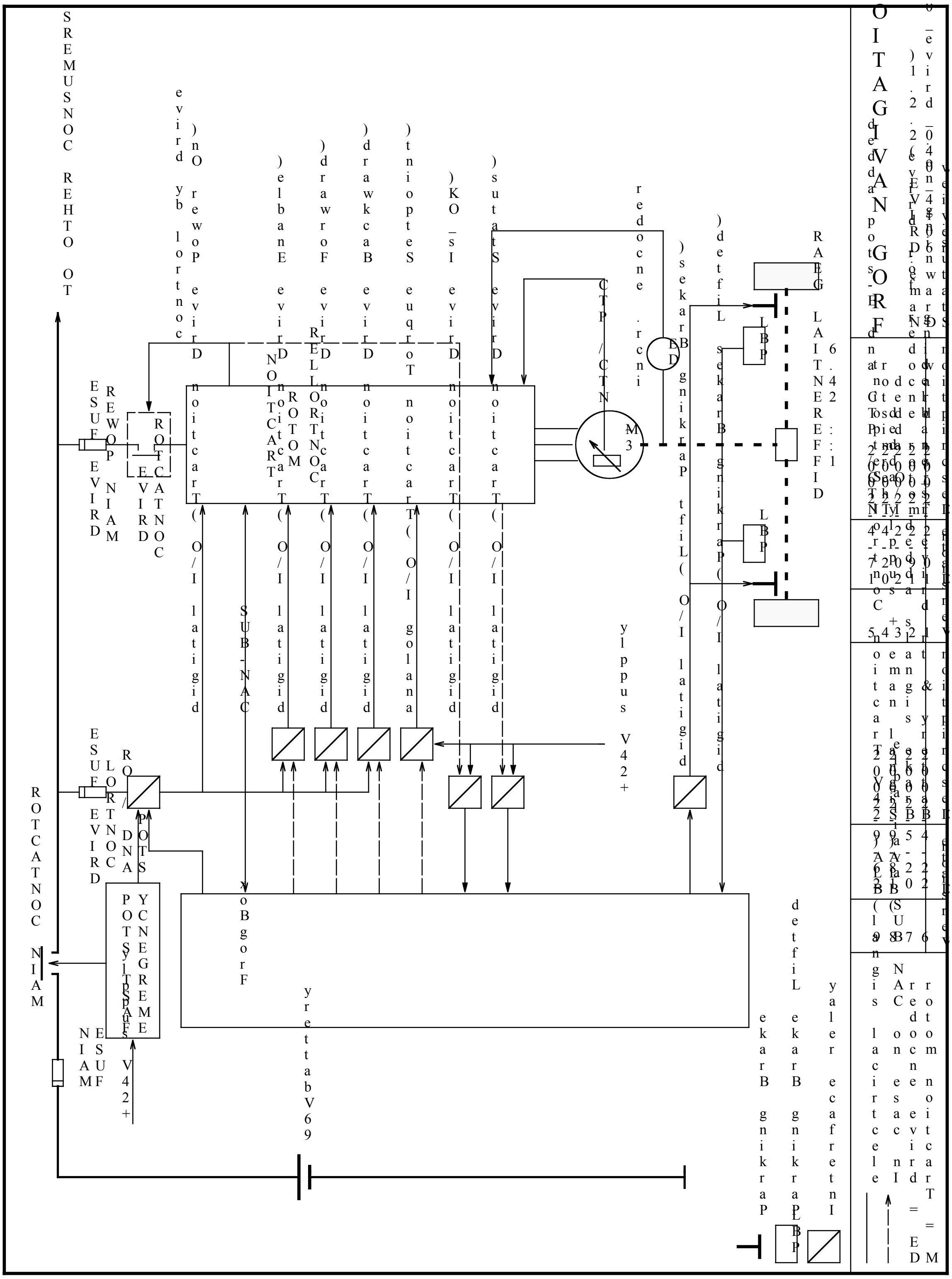

TO OTHER CONSUMERS
control by drive
digital I/O (Traction Drive Power On)
digital I/O (Traction Drive Enable)
digital I/O (Traction Drive Forward)
digital I/O (Traction Drive Backward)
analog I/O (Traction Torque Setpoint)
digital I/O (Traction Drive Is_OK)
digital I/O (Traction Drive Status)
TRACTION MOTOR CONTROLLER
DRIVE POWER FUSE
MAIN DRIVE CONTACTOR
DRIVE CONTROL FUSE
CAN-BUS
EMERGENCY STOP SWITCH
MAIN FUSE
+24V
MAIN CONTACTOR
FrogBo
96V battery
+24V supply
NTC/PTC
M 3
incr. encoder
digital I/O (Lift Parking Brakes)
digital I/O (Parking Brakes Lifted)
DIFFERENTIAL GEAR 1:24.6
Parking Brake
Interface relay
M = Traction motor
FROG NAVIGATION

Figure 9 Scheme of the traction system

Normal Operation

For this application the Motor Controller operates as torque controller/amplifier. This means that the TRACTION TORQUE SETPOINT from the FROG Navigation Controller will be realised as output torque on the motor shaft, this over the full speedrange of the Traction Motor. The following requirements are applicable for the Traction System:

- The transition between the TRACTION TORQUE SETPOINT and the output torque on the motor shaft is linear. A not linearity of 5% is permissible
- The step response over the full range of the TRACTION TORQUE SETPOINT is defined in Figure 10 , t4 - t5. The torque on the output shaft will reach the TRACTION TORQUE SETPOINT within 100ms; an error of 10% in the torque is permissible.
- On a step response the overshoot in torque is less than 10% (worst condition) and the output torque will be settled in less than 200ms.
- If the TRACTION TORQUE SETPOINT is kept constant the steady state error in the actual motor torque is less than 3% of the setpoint. Ripple in the output torque of the Traction Motor is minimal and will not damage the differential gear.
- The TRACTION TORQUE SETPOINT can be freely changed and is only ramped in the motor controller where this is required for protecting the motor and/or controller against failure, but the acceleration/ deceleration adjusted in the motorcontroller is never less than 1750 rpm/s2 (2,5 m/s2 acceleration of the vehicle).
- Changing from positive to negative motor torque is without any additional delay, deadband and/or jerk.
- Good controllability of the output torque especially at low speeds is required; this with the same performance as described above.
- The extra delay introduced by the motor controller at a start from standstill is < 50ms (deadband t0 - t1, see figure 10)
- The controller will protect itself and the motor (by use of a temperature sensor) against overload and faults; in such a case the controller will switch off or continue with reduced performance.

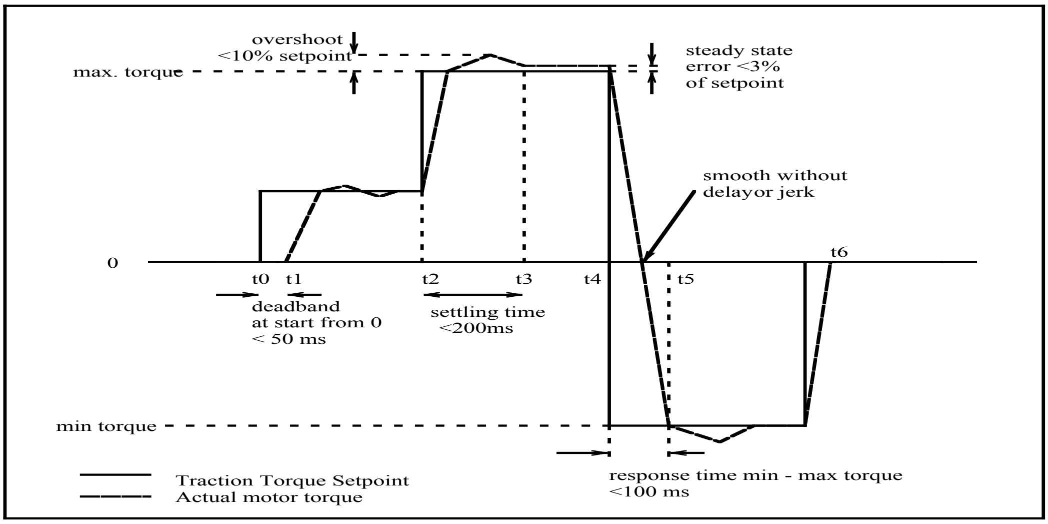


Figure 10 Signal forms for a start from standstill

Emergency stop

In case of an Emergency Stop the main contactor will be opened by the Navigation Controller, for safety this will happen without any delay. Instantaneously the main batteries are disconnected from Motor Controller; this could happen at any motor speed and torque. At the same time the mechanical Parking Brakes are activated. Such an emergency stop may never result in any damage to the motor or controller.

Communication via CAN bus

The interface with the motor controller is performed via a CAN bus using CAN open protocol with the following specifications:

- 250kbit/sec
- optical isolated
- Device profile for drives and motion control, DS 3.01 & DSP 4.02 compliant

Every 50 to 100 ms the navigation controller software will generate a SYNC to initiate the data exchanged between the motor controller and the navigation controller. In case of a CAN BUS error or cable failure the power stage of the motor controller will be disabled.
The system is also available for the brake and steer system.

3.3.2 Steering system

INTRODUCTION

This chapter describes the functional interface between the Steer Motor Controller and the FROG navigation controller.
The battery supplied motor controller will be used for position of the steering wheels of the People Mover Generation 2. The steer wheel position setpoints are generated by the FROG Navigation software and send to the steer motor controller via a CAN open bus system. An overview of this steering system is given in Figure 11.

REQUIREMENTS

General

The steering system of the People Mover Generation 2 consists of a closed loop servo system, a power steering box including a hydro pump, two steering wheels and several sensors.
After the servo system receives a steering setpoint of the navigation software the actuator will rotate the input shaft of the power steering box to the required position. The output lever of the power steering box will follow on which the steering wheels moves to the new position. The Navigation Software measures this steering wheel position by means of an encoder mounted on each steering wheel. Based on that information a new steering setpoint is calculated and send to the servo system.

Hardware Requirements

If one of the limit switches mounted on the left and right end of the power steering unit is activated, the servo system reduces the steering force. This prevents overheating of the servo motor. To prevent any mechanical damage mechanical end stops are mounted.
The angle measuring device must be mounted in such a way, that it measures the wheel angle relative to the vehicle’s centre line with a maximum inaccuracy of 0.1°, under all load conditions.
The resolution of the steering system is characterised by the largest distance between two setpoint levels, that do not lead to a movement of the steering wheel. The resolution should be better then 0.1 °.

The linearity of the steering system is characterised by the largest deviation between setpoint and actual steering angle at any point from maximum counter clockwise angle to maximum clockwise angle, under the assumption that no force remains in the system, and the systems is granted sufficient settling time. The non-linearity should be less than 0.1 °.
An optional*) holding brake is mounted on the servomotor to keep the steering wheels in a fixed position in case of an emergency stop.

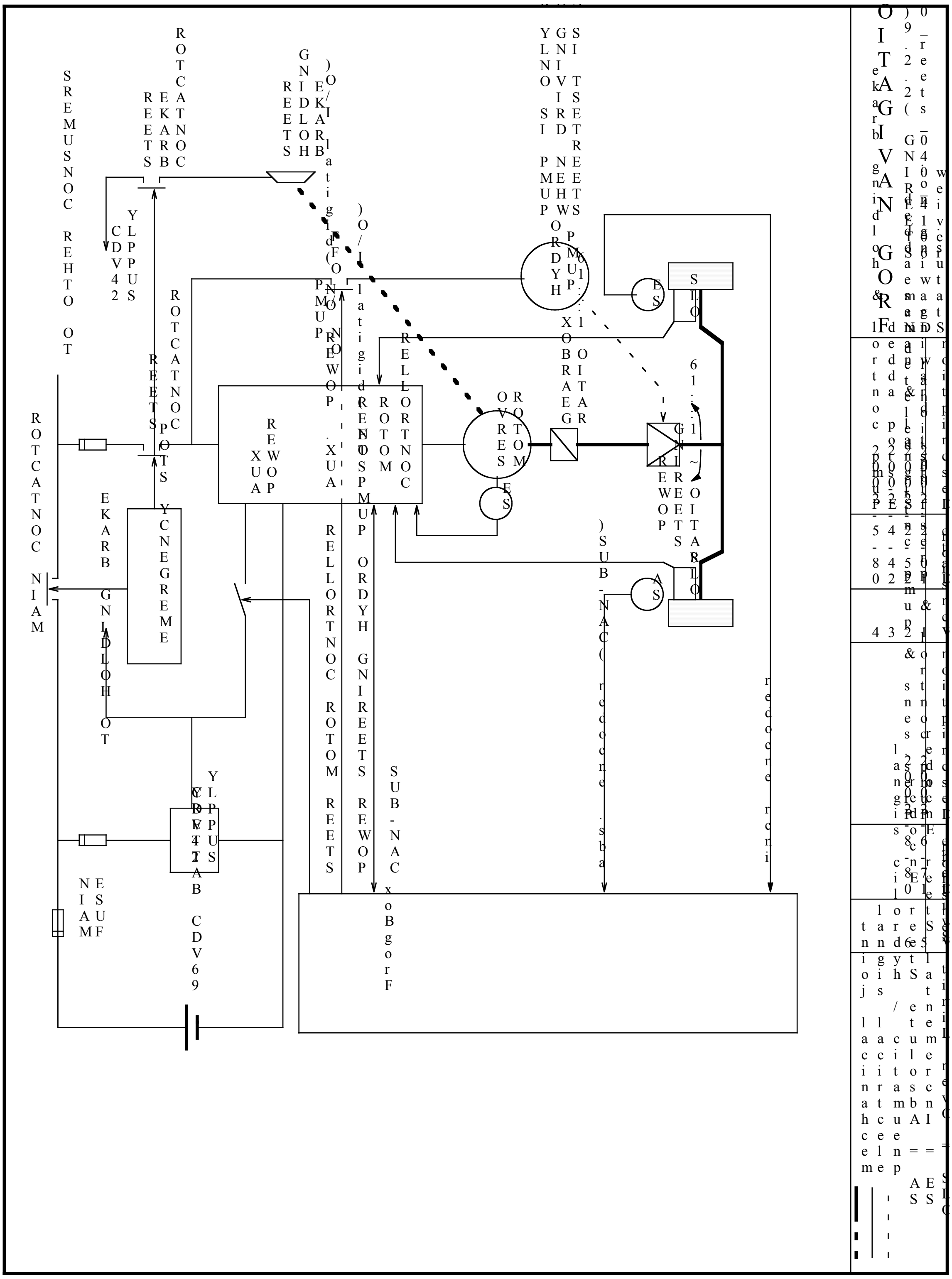


Figure 11 Scheme of the steering system

CONTROL SYSTEM

General

The setpoint from the Navigation Software to the steering controller falls within the kinematic and dynamic possibilities of the steering system. The steering wheels must follow the commanded setpoints within the specifications mentioned below. The steering setpoint from the Navigation Software obliges to the following criteria:

- The maximum change rate of the angle setpoint is such that the resulting steering wheel rotation rate for any wheel ($\omega_{s, max}$) is less than 25 °/second.
- The change rate of $\omega_{s, max}$ is unlimited.
- The absolute value of the maximum steering angle setpoint is such that the real wheels would not steer beyond their mechanical end stops.

The angle setpoint is defined relative to the vehicle's centre line.

Step response

The specification of the performance of the steering servo for steering wheel angles between –1.0° and +1.0° is based on the step response of the system. The *setpoint* is a step from 0° to 1°. The *response* of the steering system is characterised by the response time, the overshoot and the steady state error. (Figure 12)

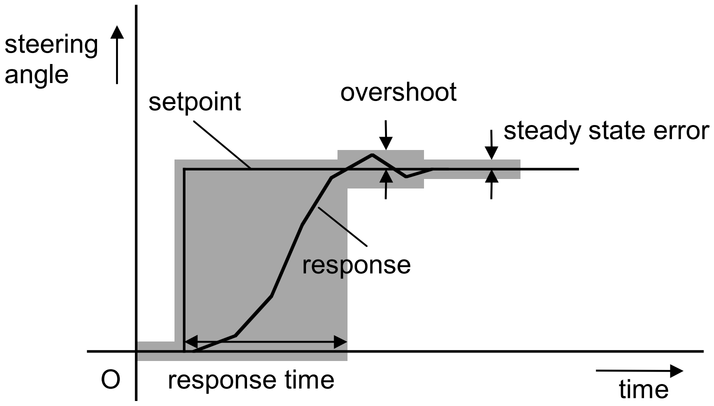


Figure 12 Step response requirements for steering system

The *response time* is the time between setpoint step and the moment that the steering angle comes within 10% of the end value. This time includes communication delay, actuator delay and dynamics. The response time must be better than 100 milliseconds.

The *overshoot* is the largest angle of the response as a percentage of the setpoint value. The overshoot of the step response must be less than 10%.

The *steady state error* is the remaining difference between setpoint and response while the wheels rolls on a perfect floor. The response is measured at the absolute steering encoder. The steady state error must be less than 0.1 °.

Ramp response

The specification of the performance of the steering servo for steering angles larger than ±1.0° is based on the response on a setpoint ramp as indicated in the figure below. The *setpoint* is a ramp with maximum steering speed (25 °/s) to a steady value. The *response* of the steering system is characterised by the response time, the overshoot, the steady state error and the settling time. (Figure 13)

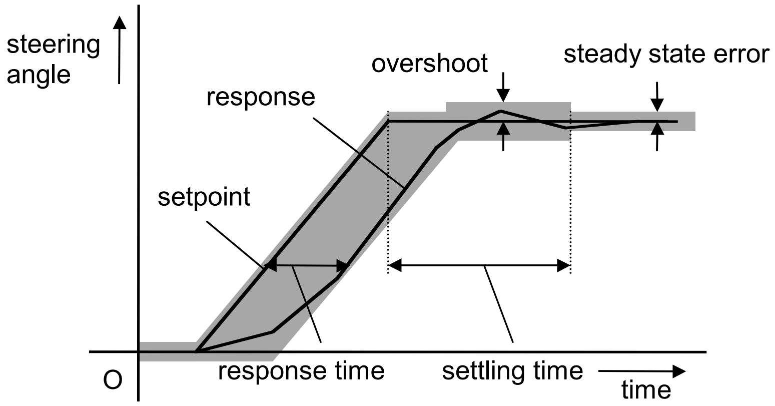


Figure 13 Ramp response requirements for steering system

The *response time* is the largest time lag between setpoint and response in the first half of the ramp. This time includes communication delay, actuator delay and dynamics. The response time must be better than 100 milliseconds.
The *absolute overshoot* is the difference between the largest angle of the response and the steady state setpoint value. The absolute overshoot must be less than 0.3°.
The requirement for the *steady state error* on a ramp setpoint is of course equal to the requirement for a step response: less than 0.1 °.
The response must be bounded to the setpoint plus or minus the steady state error within the *settling time*, which is measured from the moment that the setpoint reaches its end value. The settling time must be less than 300 milliseconds.

OPERATION

Start-up procedure

At each "cold" start-up the navigation controller measures the absolute steering wheel position and calculates the absolute servo motor shaft position. This calculated position is sent via the CAN interface to the steer controller. After this value is loaded as absolute position, the steer controller becomes active and will use the incremental encoder fitted on the motorshaft for absolute positioning.

Power Steering Hydro Pump

The hydro pump is controlled by the Navigation Software and is required for proper operation of the steering system. Just before the vehicle starts to move this pump switches on and continuous operation as long as the vehicle is in motion. If the vehicle stops the pump is switched off after an adjustable delay.
In Manual Mode the pump is always running. In case of a fast stop the pump continues operation but when an emergency stop is activated the pump is switched off immediately.

Normal operation

For this application the steer motor controller operates as closed loop position-time controller: the absolute position setpoint from the navigation controller will be realised as actual position on the motorshaft.
During normal operation every 50 to 100ms a new position setpoint is generated by the navigation software. On a SYNC the steer controller updates the setpoint and moves the motorshaft to the new position. The time to reach the new position is limited by the maximum speed, acceleration, deceleration and motor current/torque as adjusted in the steer motor controller. Other ramping in the steer controller is not active.
At least the ramping, speed, acceleration, deceleration and gain of the controller are adjustable. In case of overcurrent, I2t or overtemperature the controller will reduce or limit the output current. If

this results in a position error the steer controller may never switches off but will continue operation and moves to the best reachable position. Via the CAN bus the steer controller will inform the navigation software about the position error. Nevertheless, in case of a major fault (e.g. runaway of the servo system) the steering system is shut down and the STEER DRIVE STATUS bit is set low without any delay.
During normal operation the optional [1] holding brake on the steer motor is always lifted, this means that the electrical motor torque keeps the motor at the required position.

Fast Stop

In case of a fast stop the complete steering system continues operation, only after the Fast Stop Time Delay has passed the system shuts down.

Emergency Stop

In case of an emergency stop the steer motor controller and the power steering hydro pump will be disconnected (without any delay) from the main battery, this could happen at any motor speed and torque. An emergency stop may never result in any damage to the motor or controller. At the same time the optional holding brake will hold the steering motor in the actual position.

Controlled by hardware I/O

Steer Motor Controller Auxiliary Power On [From FNS to Steer Drive]
If this input on the Steer Motor Controller is supplied with 24VDC the control electronics including the CAN bus becomes active. This input can also be used to reset the controller in case of a CAN bus error.
Power Steering Hydro Pump On [From FNS to Hydro Pump]
If this output is set high the Power Steering Hydro Pump start to run. While the vehicle is in motion this output is always high. Five seconds after the vehicle comes to a standstill this output is set low and the power steering unit is deactivated. Just before departing of the vehicle the output is set high. In manual mode this output is always high.
Steer Limit Switch Left/Right [From Power Steering Unit to Steer Motor Controller]
If the left or right limit switch on the power steering unit is reached the motor controller reduces the steering force. This reduced force prevents overheating of the steeringmotor but keeps the motor in the maximum steering position.

3.3.3 Braking system

INTRODUCTION

This chapter describes the functional interface between the brake system and the FROG navigation controller. The brake system for the People Mover Generation 2 has three different sub-systems:

- The parking brake
- The proportional brake with ABS
- The electrodynamic (ED) brake

Activation of one or more of these brake systems will result in the required deceleration of the vehicle. The FROG navigation software will control these brake systems, an overview of the system is given in Figure 14.

DESCRIPTION OF THE BRAKE SYSTEMS

Parking Brake

If the signal 'LIFT PARKING BRAKES' is set high the parking brake valve will be energised and the brakes will be lifted. The parking brake is a fail-safe system; in case of power and/or air pressure loss the mechanical brakes on the rear wheels will drop and stop the vehicle within the required braking distance.

In case of a major failure the parking brakes can be lifted manually by use of nuts on the brake cylinders. In this RESCUE mode electrical and/or mechanical interlocks prevents that the vehicle can operate in MANUAL or AUTOMATIC mode.

Proportional Brake with ABS

The proportional air brake is controlled by the FROG navigation software and is not fail-safe. The PROPORTIONAL BRAKING TORQUE calculated by the Navigation system is divided over the front an rear wheels by use of two analogue controlled proportional valves. One valve activates the disc brakes on the front wheels and the other valve the drum brakes on the rear wheels. The transition from this analogue setpoint into the torque on the brake shoes is linear and reproducible. The requested torque will be realised within <100ms.

If the signal 'ABS SYSTEM ERROR' is low the ABS system is operational and able to reduce slipping of the wheels by use of the ABS valves. These valves are only activated in case the braking force is too high and the wheels start to slip. At the same time the signal "NO ABS INTERVENTION" becomes low to inform the FROG navigation software that the requested braking force is not realised on the wheels. Now the FROG navigation software will adapt the deceleration of the vehicle to the circumstances.

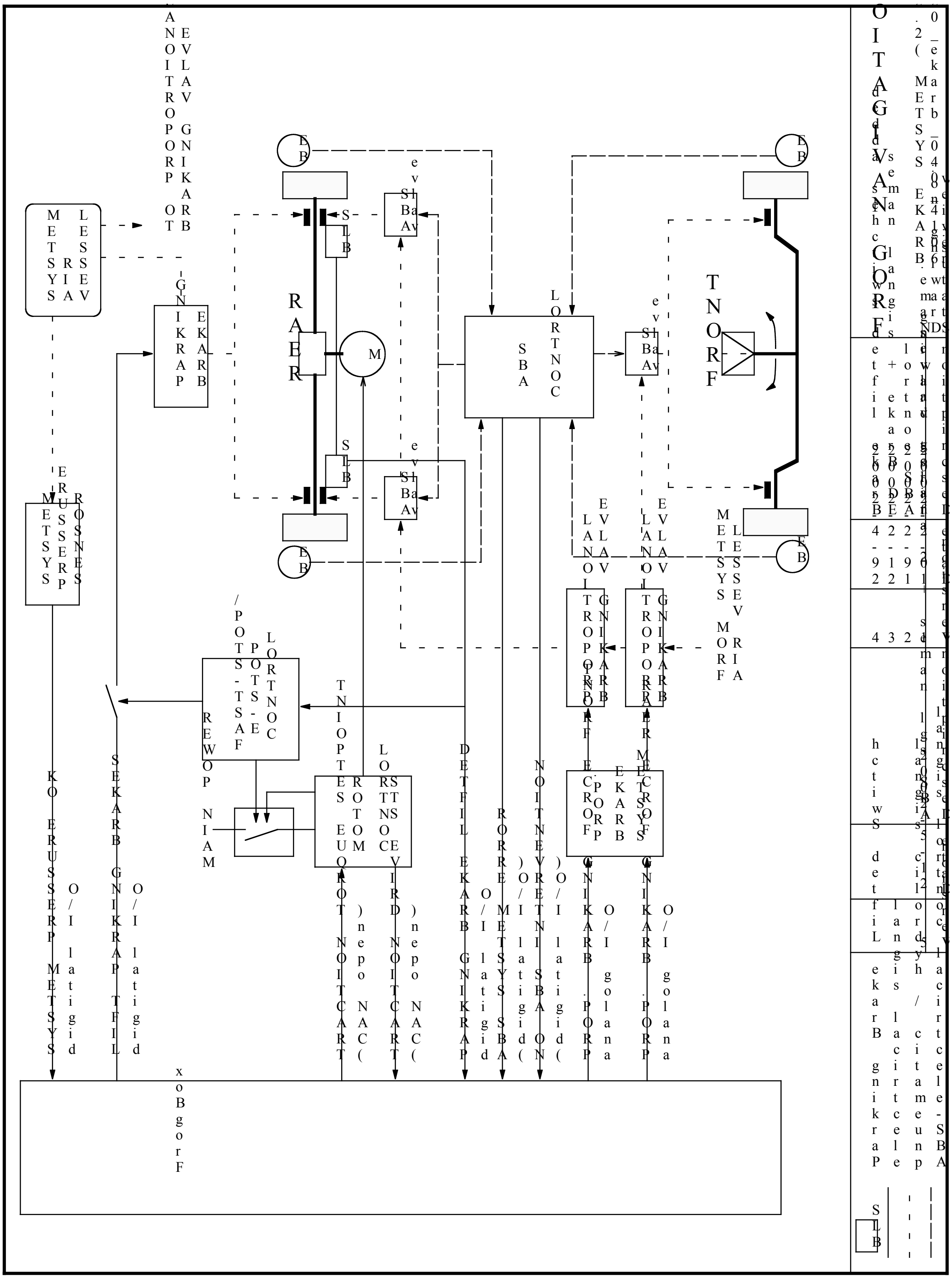


Figure 14 Scheme of the braking system

Electrodynamic (ED) brake

The electrodynamic braking force is realised by the traction motor and controlled by the motor controller, this ED brake is not fail-safe. The Frog Navigation software calculates the required braking force and sent a negative TRACTION TORQUE SETPOINT to the motor controller via a CAN bus. The motor controller will control the traction motor in such a way that the torque on the motorshaft becomes negative.

In case the motor controller is not operational the status of the "TRACTION CONTROLLER STATUS" will change and the ED brake is not active. Now the torque realised by the ED brake is zero. For more details see functional description of the drive system.

CONTROL OF THE BRAKE SYSTEMS

Starting conditions

When the vehicle is energised the air compressor will run and supply the pneumatic systems. The pneumatic sub-systems will be supplied one by one in the following fixed sequence:

- Air vessel for discbrakes front
- Air vessel for drumbrakes rear
- Air vessel for parking brake
- Air vessel for suspension

If the pressure for parking brake is reached the signal 'SYSTEM PRESSURE OK' becomes high, now the brake system is ready for operation. Please note that the air pressure for the suspension is not required for MANUAL operation of the vehicle. The suspension is a comfort function and not required for safety.

The signal 'PARKING BRAKE LIFTED' should be low to indicate that the parking brakes are not manual lifted by use of the nuts on the brake cylinders. If high the emergency stop circuit is locked and can't be reset by the Navigation Software.

At power-up of the ABS brake system the signal 'ABS SYSTEM ERROR' must be high. After the speed of each sensed wheel has reached 7 km/h this signal 'ABS SYSTEM ERROR' becomes low. If not the ABS system is not operational and the Navigation Software will reduce the vehicle speed to 10km/h.

Parking Brake

The parking brakes are only used to hold the vehicle at its position at stand still or to decelerate the vehicle in case of an emergency stop. During normal operation the parking brakes are lifted while the vehicle is in motion and will be dropped at standstill. The parking brakes are never used for 'normal' deceleration.

The 'PARKING BRAKE LIFTED' feedback gives the actual condition of the parkingbrakes. Each time the brake is activated this brake condition is monitored by the Navigation Software, in case of malfunction the emergency stop circuit is activated.

Normal Operation Brake

As long as the following conditions are true:

- the FROG navigation software is operational,
- the signal 'SYSTEM PRESSURE OK' is high
- and the signal 'PARKING BRAKE LIFTED' is high

The normal operation braking system is active. The normal operation brake is a combination of braking torque realised by the ED brake and/or the proportional mechanical brake. The required braking torque to meet the requested vehicle deceleration is controlled by the FROG navigation software and divided over both brake systems. During braking the proportional brake becomes only then active when the maximal permissible force for the ED brake is reached. The stand-alone ABS system prevents slip and slide on the wheels as result of the mechanical brakes.

Emergency Stop Brake

In case of an emergency stop the safety relay interrupts the LIFT PARKING BRAKE signal to the parking brake valve. This results in an uncontrolled braking action by use of the fail-safe parking brake and the proportional brakes. During an emergency stop the ED brake is deactivated.

Rescue Mode

In the RESCUE mode the brakes are lifted manually by use of nuts on the braking cylinders. For safety reason the electrical control of the vehicle is disabled by use of the PARKING BRAKE LIFTED signal. This is realised by mechanical interlock and/or an electrical contact in the emergency stop circuit.

SPECIFICATIONS

As soon as the vehicle has reached its destination and the velocity is approximately 0 m/s the parking brake will be dropped.

- positioning deceleration:	max 1.0 m/s²
- acceleration:	1 m/s²
- normal stop:	1.0 – 3.0 m/s²
- fast stop:	3.0 – 5.4 m/s²
- emergency stop:	5.6 m/s²
- steer angle	48 degrees.

IMPLEMENTATION

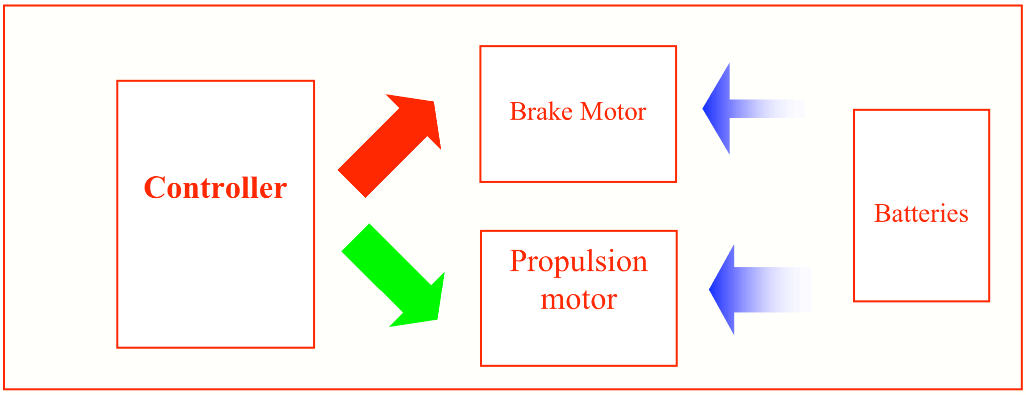
Implementation of the steer, brake and driving module is done on the prototype of the ParkShuttle, the CTS for Rivium2.

3.4 Regenerative brake (Yme)

3.4.1 Regenerative Braking

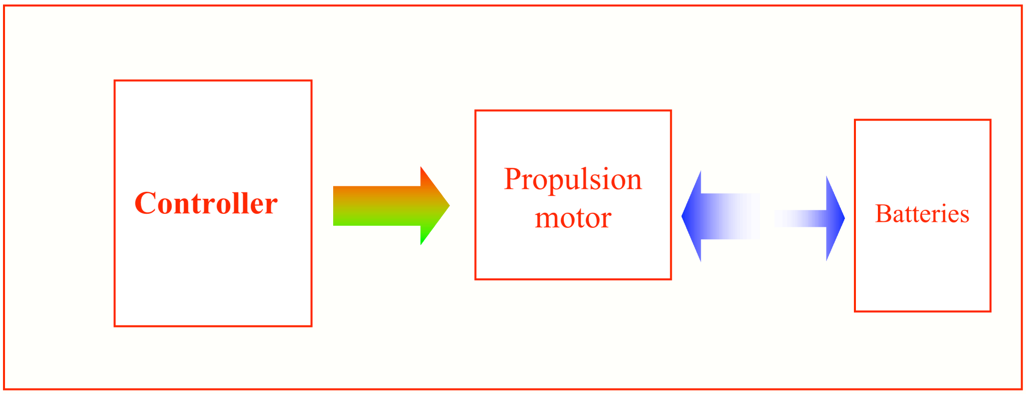
Regenerative braking is the process by which some of the kinetic energy stored in the vehicle's translating mass is stored in the vehicle during decelerations. In most electric and hybrid electric vehicles on the road today, this is accomplished by operating the traction motor as a generator, providing braking torque to the wheels and recharging the traction batteries. The energy provided by regenerative braking can then be used for propulsion or to power vehicle accessories.

OLD SITUATION



In the old situation if the set speed was higher than the actual speed the controller gave the order to accelerate. In other words the power flowed from the batteries to the propulsion motor to gain speed. When the set speed was lower than the actual speed the controller gave the order to decelerate. This means that the controller applied the brakes.
So during driving the controller was applying brake-motor and propulsion motor to keep its speed. The result is that by braking a lot of energy is converted into heat.

NEW SITUATION



In the new situation the vehicle brakes by using the 3,5kW propulsion motor as generator. When accelerating the energy flows from the batteries to the propulsion motor. When the vehicle decelerates the propulsion motor will be used as a generator and the energy that has been gained flows back to the batteries.

3.4.2 Results

The results tested on a hill are shown in the graph (Figure 15). The test was performed on driving with a vehicle uphill. That is represented as the light gray area. When driving downhill the motor starts to act as generator and the power gained at the same trajectory is shown as the dark gray area.

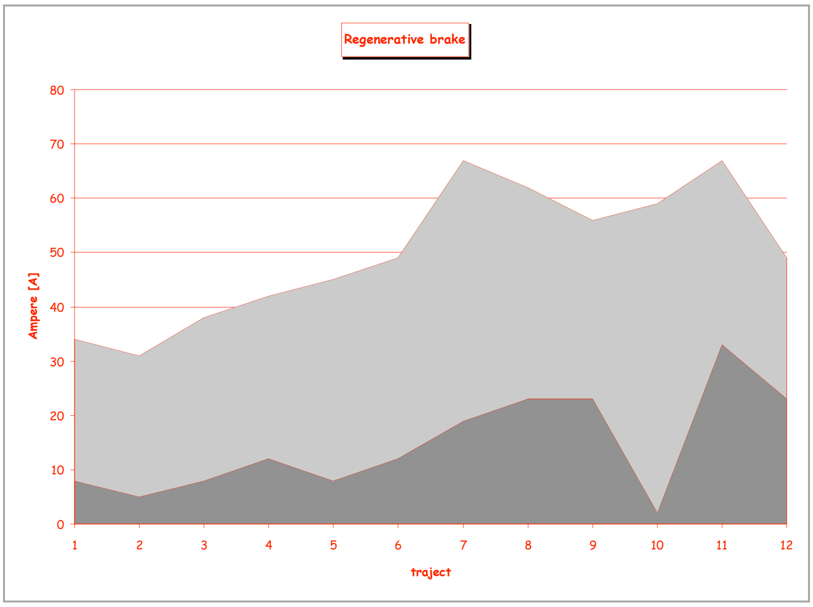


Figure 15 Current flow in the regenerative brake for a representative test uphill

3.5 Vehicle controls for dual-mode vehicles (Crf)

3.5.1 Dual-mode vehicle

The CyberCars project is focused on new forms of vehicle-sharing, exploiting the opportunities offered by automated vehicles in specific infrastructures.

A related possibility, which increases the domain of operation, is to consider also a traditional manual driving for running in normal traffic.
With such "dual-mode" capability, vehicles can be offered to drivers on ordinary roads, but their automated mode allows them to be collected and distributed, for instance by platooning or by remote control. These cars would certainly run on "clean" energy when needed in restricted urban areas; in addition, they can be controlled in speed and in parking, and could be automatically moved according to demand, or parked when not in use.

As a part of activities on vehicle and control architectures, a dual mode vehicle has been investigated, based on the following main characteristics:

- a use in urban scenarios with large possibilities for the origins and destinations,
- a modular layout with a solution for two passengers and a solution for two plus two passengers (50% percentile in rear seats),
- emission levels at least 50% of Euro IV regulations on the ECE cycle,
- a communication system linking the vehicle to the control center foreseen for the management of Cyber Cars,
- the capability of being transferred by automated mode or by platooning in specific lanes.

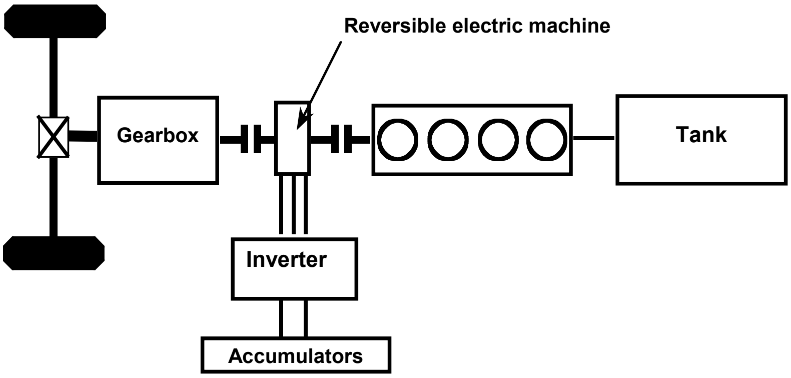


Figure 16 Scheme of the architecture for a parallel hybrid vehicle

The general scheme which has been defined according to such characteristics is a parallel hybrid solution (Figure 16) where a small and clean thermal engine (e.g. a new generation gasoline engine of 400cc) is supported during transients by an electric motor with a set of accumulators with rather reduced weight. This scheme is able to accept an energy input during regenerative braking, and provides autonomy with the electric traction alone, up to a level essentially related to the choice of the accumulators. With respect to the pure electric approach, the hybrid architecture offers a cost effective solution when considering applications with larger volumes and reduced weights (or autonomy in the manual mode of operation).
It also offers considerable flexibility for the Cyber Cars application, providing an easy management of "Start and Stop" situations, comfortable driving in the city traffic and very low overall emission levels and fuel consumption (around 100g CO_2 per km).

The corresponding layout, which is based on standard industrial components, and main characteristics are reported in Figure 17.

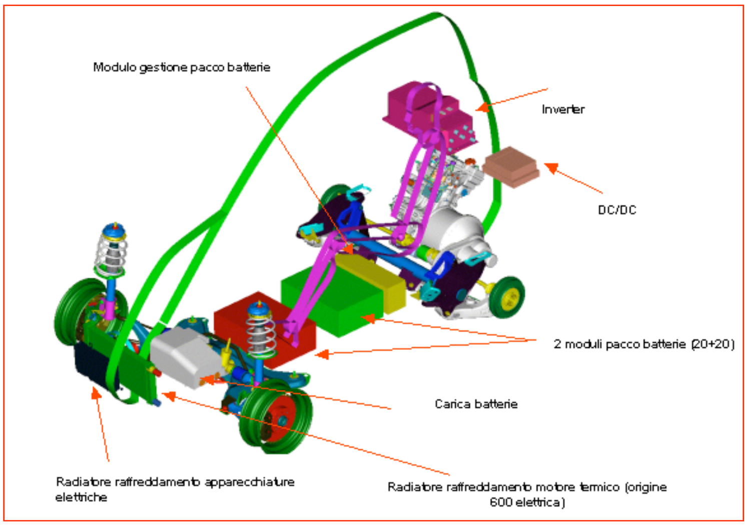

Modulo gestione pacco batterie
Inverter
DC/DC
2 moduli pacco batterie (20+20)
Carica batterie
Radiatore raffreddamento apparecchiature elettriche
Radiatore raffreddamento motore termico (origine 600 elettrica)

Figure 17 System layout

3.5.2 Control System Architecture

The basic aspect to be considered when defining the control system is the innovative function of driving in the platooning or the automated mode. Therefore the control is strictly linked to the obstacle detection sensors.
A general scheme is outlined in the following.

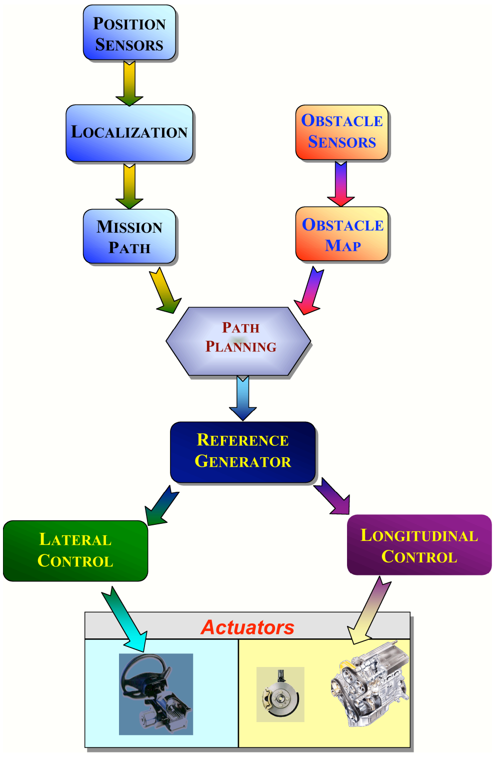


Figure 18 Control System Architecture

A block diagram for the control system, including the obstacle detection sensors is shown in Figure 18. A description of the final blocks, which are more specific, is given as follows:
Reference generator: according to the data on local path, it generates a reference for both the longitudinal and lateral control, assuring requirements of comfort and safety.
Lateral control: generates the input to the actuator for lateral vehicle dynamics: steering system
Longitudinal control: generates the input to the actuators for the longitudinal vehicle dynamics (engine and brakes)

<u>ACTUATORS:</u>

<u>Steering system</u>

The electric power steering system is composed of a DC Brushless motor that applies an assistance torque to the steering shaft, an electronic control unit that produces the requested torque for the lateral movement and a torque-steering wheel sensor.
The steering system can work on the basis of torque generated by control strategies and on the basis of the driver torque (dual-mode operation).
This steering system, in order to work in dual-mode operation, needs the following inputs:

- vehicle speed signal
- electrical connection to the vehicle alternator
- electrical connection to the vehicle ignition switch
- control torque request
- control status information

The standard EPS system is equipped with purpose-built software to interface with the lateral control system. Therefore the interface can be divided into two distinct parts: the standard EPS interface to the vehicle, and the elements required specifically for the lateral control.
The new interface elements required for lateral control take the form of digital communications between the EPS unit and the lateral control unit over a high speed CAN data-bus.

The messages transmitted from the lateral control unit to the EPS system are updated and posted on the CAN network at a nominal 100 Hz rate.

Engine Control Unit

Engine control unit executes the acceleration command requested by driver or, in case of automated mode, by longitudinal control (dual-mode operation).
The throttle opening angle is transformed into an engine torque request through an engine map and an internal control loop guarantees the execution of the acceleration requested.
During the automated drive, the engine control unit interface expects the Receive Message from the longitudinal control system to be updated at 100 Hz.

Electronic Braking System (EBS)

The EBS is able to manage both a driver request and an automated request.
The applied pressure is precisely controlled by a Brake Electronic Control Unit that supervises and pilots all braking operations.
The brake request can be made by the user pressing the brake pedal (manual actuation) or can be requested by a CAN shared ECU to perform high level of vehicle dynamic control (automatic actuation).
A pressure sensor measures the pressure in the master cylinder (pressure actuated) and communicates it to the Brake ECU which uses it as actuation feedback.
When the Braking System is ready to operate, it advises the external world sending an appropriate message. In case an automatic braking request is present, the longitudinal control unit which requires the brake service, sends a message containing the pressure demand information.
The message transmitted from the longitudinal control unit to the EBS is updated at a nominal 100 Hz rate.
The Braking System lets the driver the possibility to deactivate automatic braking request by pressing the brake pedal.
For safety reasons automated decelerations greater than 5 m/s^2 are not allowed.

3.5.3 Lateral and Longitudinal Control Architecture

A scheme for the architecture of the lateral control is shown in Figure 19.

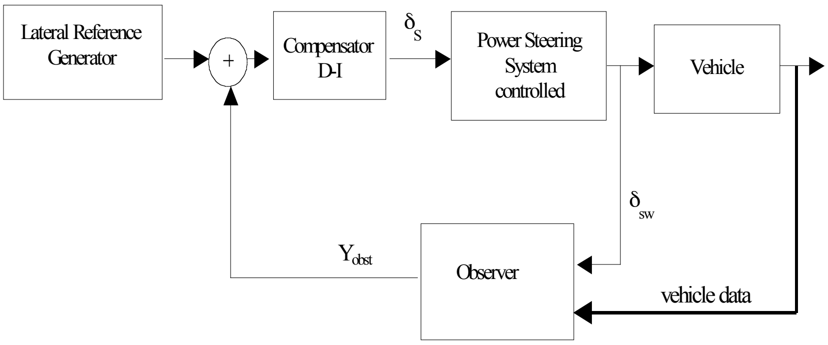


Figure 19 Lateral Control Architecture

The control has the aim to minimize the error between the lateral position of the vehicle and a reference trajectory.
This trajectory can vary as a function of the vehicle speed, and is computed from the data of the sensor system. An additional aspect is the definition of a path which the vehicle should be able to follow: therefore the reference path should be defined according to the vehicle dynamics, and therefore following a “model-based” approach.

The observer is deputed to the reconstruction of the lateral position within the lane, using the data from the position sensor, the measurement of steer angle at the wheels, and information from the lateral acceleration sensor. The observer feedback gain matrix must be chosen with a good compromise between the response time and the sensitivity to disturbances.
The compensator receives the lateral error as an input, and computes the control demand to the steering system.

The corresponding scheme for longitudinal control is shown in Figure 20.

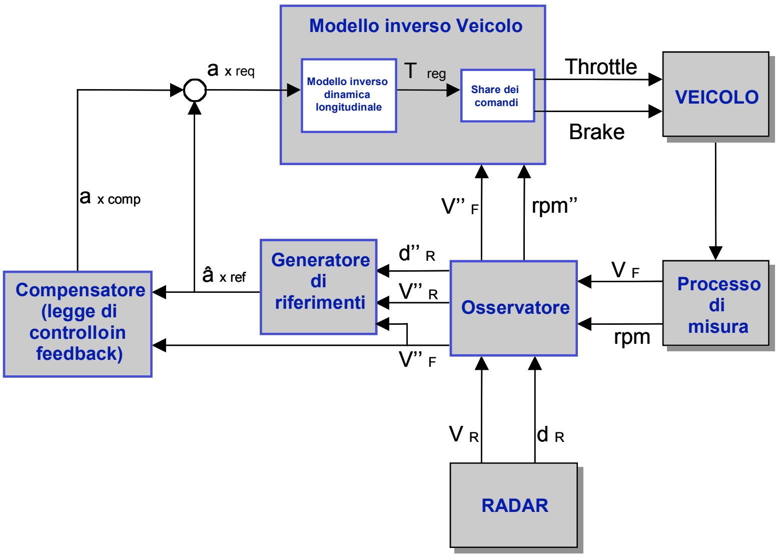


Figure 20 Longitudinal Control Architecture

The main purpose of this system is to drive the actuators so that the vehicle can follow the acceleration profile given by the reference generator.
The system provides two outputs:

- A request for engine torque (or throttle angle) sent to the engine control unit
- A request for braking pressure (related to deceleration) to the braking system
- Two operation modes are foreseen for the controller:

- A speed control, where the objective is to reach and maintain the desired speed
- A distance control, where the objective is to reach and maintain a given distance to the preceding vehicle.

Starting from the data given by the obstacle detection system, and according to the specific control logics, the controller generates essentially a request for a torque, either to the engine or to the brakes. Consequently, the vehicle will accelerate or decelerate up to the planned speed or to the required distance from the vehicle in front.

The structure of the controller is the same for both operation modes, and includes the following parts:
Observer: allowing to reconstruct the real parameters, from the measurements which can be corrupted or delayed. (e.g. filtering the distance and speed signals given by the obstacle detection sensor)
Reference generator and direct control action: generates the reference acceleration, starting from the actual speed and the required speed (in the speed control mode) or starting from the true and planned distances (in the distance control mode).
Feedback control: designed so that the control objective can be reached when all the parameters of the system are known. The closed-loop control algorithm is designed respecting control specifications and is also related to the vehicle longitudinal dynamic. This closed-loop correction allows to compensate possible errors due for instance to a wrong inverse vehicle model, or to external disturbances like a variation or irregularity in the road slope.
Inverse vehicle model: manages the actuators generating the reference values for the engine control unit and the braking system.

4. Navigation technologies

4.1 Baseline and technology improvements

Up to now, the few existing cyber cars are non-flexible vehicles, based on proprietary navigation systems which are developed for very focused applications, like People Movers.
In the existing applications, several techniques for localisation and navigation are employed, like wire guidance, transponders, magnetic sensors, and GPS. All of these have some advantages but also some drawbacks, as described in deliverable D1 and summarised in the following table.

In particular, wire guidance and transponders still present problems especially with installation procedures, maintenance and cost. The GPS system appears as a very flexible approach (considering the differential and real time kinematics methods, which offer suitable accuracy), but could present difficulties in a city area with the satellites can be obscured. The inertial sensors and micro-gyros can be installed on cars, providing an interesting measurement technique, which however should be integrated with other techniques (like odometer data and or GPS), since accuracy is not sufficient at the present stage.

Technology	Control requirements	Application in urban environment	Opearation reliability	Global evaluation for R&D in CyberCars	Notes
Wire guidance	1 (2 to be examined)	1	1	in part	Complex installation and maintainence
Magnet localisation	2	2	to be examined	yes	Good accuracy and robustness
Transponder	1	2	1	no	Limits of speed and accuracy
Scan laser with reflectors	2	0	1	no	limited robustness; problems for infrastructure
Vision systems	1 (2 to be examined)	2	2	yes	promising; new schemes to be investigated
dGPS localisation	2	0	1	no	Difficult contact with satellites may result in urban areas
Inertial navigation	0	2	2	in part	To be intergrated with other methods

Comparison of techniques for navigation of Cyber cars
2 = suitable
1 = suitable only in part
0 = NOT suitable or raising problems

Such a situation suggested to concentrate efforts regarding navigation technologies on the following points:

- Improvement of some known and simple solutions, particularly the **magnetic localisation**, in term of cost, accuracy and easy installation on board;
- Study of solutions allowing a **limited investment in the infrastructure:** emphasis has been given on autonomous vision or laser systems based on landmarks;
- Effort to implement a modular architecture, allowing the **flexible adaptation** of different techniques on vehicle platforms, depending on application requirements;

A standard on-board computer, a localisation and guiding system, and an anti-collision system, constitute the key subsystems for such a modular approach; their features will depend on the characteristics of the application, such as the environment, the vehicle speed, the network structure.

In this way, it is possible to customise the design and the integration process for new vehicles and for specific uses. This approach may also contribute to specify standardized interfaces (hardware and software) for cyber cars.

The results of these activities are a significant improvement of two vehicle platforms (Park shuttle and Robucab) and the availability of several research prototypes ready for extended testing.

Going to more technical details, the following major results can be highlighted:

- *The **magnetic ruler technique** on the Park Shuttle has been improved with new signal processing schemes: this resulted in halving the density of sensors, increasing the distance from the antenna to the magnets (20 cm), and obtained better accuracy of 0,1 m at 20 Km/h (FROG NT – see paragraph 4.2);*
- *In another configuration (Ruf vehicle and elevated rail infrastructure) a **magnetic probe** based on induction has been studied and realised; the very compact device is able to control the path of a collective Cyber car when choosing among different tracks . (RIF – paragraph 4.3);*
- *A **vision system** on the CyCab platform allows to reconstruct the left and right borders of the road, being well adapted to capture the dynamic features of the scene; it has been tested in urban areas (city centre and harbour of Antibes) at 36 km/h and 25 frames per second; (Inria – paragraph 4.4)*
- *A **modular architecture** has been implemented in different platform; a particular example is the RobuCab, where different composition of modules allows to implement various applications such as vehicles for public or for individual urban transport, teleoperated vehicles, outdoor platforms for research.*

Other additional results concern the setting–up and evaluation of some more traditional techniques, like the wire guidance (paragraph 4.5) and the scan laser with reflecting beacons (paragraph 4.6). Regarding autonomous techniques, other prototype systems have been realised and tested in this workpackage, like a vision system able to track a painted line, which for the moment operates at low speed (paragraph 4.7), and a GPS receiver coupled with inertial sensors (paragraph 4.9).

All these activities have confirmed the basic role of navigation technologies for the correct operation of Cyber cars.
In particular, the improved magnetic rulers are considered a fundamental option for short term applications on local tracks, with a combination of straight parts and curves. In a longer time perspective, computer vision could offer interesting possibilities with a lower impact on the infrastructure. Inertial sensors are a relevant technology to follow for future developments, even if they do not provide today the necessary performance; however improved characteristics and lower costs are anticipated, due to the on-going trends of Microsystems technologies for automotive products.

4.2 Navigation scheme with magnetic ruler (Frog)

4.2.1 Software and grid navigation

Although one of the main advantages of the cybercars is to use non-mechanical guidance, the cost of the electronic guidance could still be lowered. The existing techniques rely nowadays on wires in the ground, magnets or transponders also in the ground. These techniques costs from 10,000 to

600,000 Euros per kilometre and are not easily changed for new courses. Research and development work has been carried out in cooperation between the research institutes and the technological enterprises in order to develop and test new techniques based on a combination of DGPS, vision and inertial navigation. These techniques need to be integrated in the vehicles, evaluated and tested in real environments. The experimental test site will be used for the performance evaluation of these new techniques.

4.2.2 Design considerations

MAGNET ORIENTATION

The earth magnetic field has a constant vertical component and a direction horizontal component aimed at the North. Since the measurements need to be independent of the vehicle's orientation the magnets and the grid sensor should be lined up for measurements of the vertical component only. In that case the Earth magnetic field is a constant background offset to the measurements independent of vehicle orientation.

DETECTION MECHANISMS

For the dipole field that holds for the magnets used the strength of the vertical component is proportional with l/r3

Previously : low detection heights (4 cm)
Suppose a simple check is used to detect the magnets position: peak detection that is considered to be reliable when the magnetic field has decreased to 50% of the maximum value. At 4 cm detection height the field reduces to half after only 2 cm distance. So 2 cm after passing the magnet it's position becomes available to the navigation software. During this small distance the vehicle's movement can be treated as quasi-static and a simple interpolation back to the timestamp of the peak will suffice.

Needed: high detection heights (20 cm)

SIMPLE APPROACH

Now investigate what will happen if this method is used at detection heights of 20 cm. At this height the forward distance to 50% drop will be 10 cm. Vehicle movement cannot be treated as constant in the grid sensor software. Furthermore the magnetic field at 20 cm is 125 times weaker than at 4 cm and therefore more prone to noise or interference. This calls for more robust data processing.
These considerations call for some synchronization mechanism with positional information between navigation software and grid sensor and more noise immune data handling.

ADVANCED APPROACH

To cope with the increased noise and interference the preferred method of detection would a 'maximum likelihood estimator'. This method is adopted in MMS. The physical model for a magnetic dipole is matched with the measurements to find the most likely position of the magnet. This result is send to the navigation computer. The properties of the noise distribution in the measurements are exploited to give information about accuracy of the estimated position. Due to the theoretical model of the magnetic dipole and the normally distributed measurement noise the resulting equations are similar to the more widely known 'non-linear least square method' but with the promise of the more preferable features of a maximum likelihood estimator applying.

TIMING

With the maximum likelihood estimator used typical calculation times when using representative sets of data take about 20 ms, worst case 10 ms typical. Assuming a 4 meter pitch in magnet grid and a scanning range of 40 cm this would leave 3.6 meter for calculations between magnets. This limits the speed to 180 m/s or 648 km/h.

Since the vehicle will build up an additional route deviation over this distance of 3.6 meter a more realistic limit would be a maximum travelled distance during calculation. A maximum accepted travelled distance during calculation of 1 meter would limit the maximum speed to 50 m/s or 180 km/hrs.

4.2.3 Magnetic Measurement System

FrogMMS is a new developed magnetic-sensor. The idea is patented by Frog Navigation System. The base idea is that the magnetic field will be measured by a sensor-array during the drive over the magnets. The position of the magnets related to the sensor-array will be calculated by comparing the measured data with the model of the magnetic field.

TWO METHODS OF MAGNETIC LOCALISATION.

The position of the magnets will be done by calculation in the software. The sensor can be used in different ways. In all cases the measured data are different points (x,y,z) in space. Two possibilities are available:

- All measured data will be combined to calculate the position of the magnets related to the measure-system.
- A selection of measure-data will be used o calculate of one or more magnets-coordinates

Using as much as possible of space information for calculating the position is an advantage of the first method. A disadvantage is that it is not always possible to calculate the relative position. The system does not know the path over the magnet.
The second assumption method will calculate the position of the magnets on a particularly time without the moving information. This method is less depending of the navigation system. Disadvantage is that not all measurements can be combined, the "rrruis--onderdrukking, is less strong. These let to a minor accuracy.
On the other hand the higher accuracy of the first method will be in practice not so high, because the space "mapping" of the measurements are difficult to realize.

The two methods are useful. If the space mapping can be done in a practical way, the first method will be favourable.

Method 1 - Direct magnet localisation from all available measurements.

Important is that the relative position of the measurements (x,y,z) relative to each other as well as possible are known. Is that the case the measurements together are a good model of the magnetic field. With this outcome the position of the magnets to the sensor array can be calculated..
The mapping of the measurements can be done in two ways:

- the navigation system will give the magnet-system with the movement information (example 20 time/second).
- the magnet system will calculate the moving parameters from the speed and the curve-angle from the measurements.

The second method is only possible if the movements during passing the magnets as "stationary" can be interpreted; the calculated steer-angle, speed and measure-high are constant. Advantage of this calculation is that the measure-system is less depending of the navigation computer.
If possible the first method will be used, where the navigation computer will feed the measure-system with detailed information of the movement. The movement information can be given in the ""form"" of 2 dimensional translation speed vector and a rotation speed. Beside the movement-information the only information needed are the sensor number (related to the position of the sensor element in the lineal) and the time of the relative position of the measurement.
In Figure 21 the scanning of a magnet in the (x,y) surface is indicated..

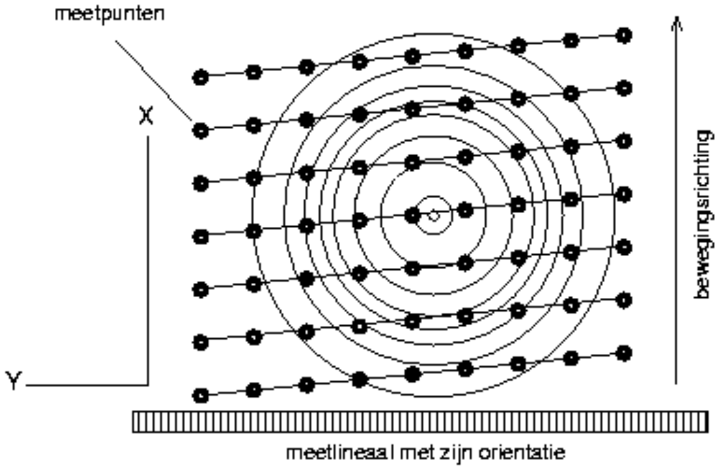


Figure 21 Top view of measurements for localisation of the magnet.

This is an example of a magnet measurement, wherewith the vehicle drives straight forward, with a constant velocity and the measures are done with equal time interval.
The constant speed and constant measure-interval give a constant equally spaced patron and the movement straight forward gives a scan area which is perpendicular on the magnetic-ruler.
The following Figure 22 shows the picture of the magnet passage, in which the vehicle makes a turn with a constant curve-speed, with also the speed of the vehicle and the measure time-interval is constant.

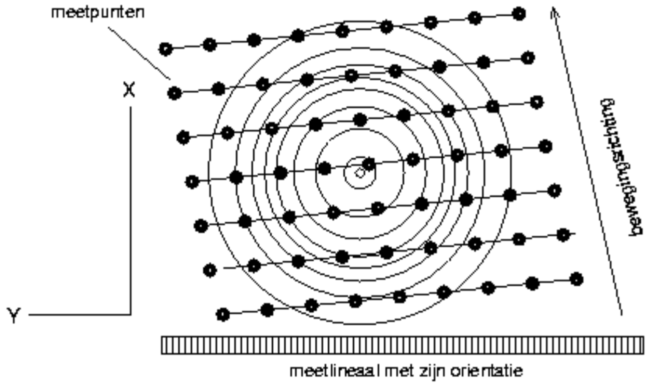


Figure 22 Top view of measurements for localisation of the magnet in a curved path.

In practice the orientation of the vehicle during driving will change, so also the magnetic ruler. This means that the successively scans will not be on parallel lines, but it will be a slightly curve. The last scan will show a rotation compare with the first one. This effect will be less than the translation-effect. (distortion of the movement of the drive direction).

The real scan will be not measured with identical time interval. This is not necessary because the measure time will be notice very accurately (milli-seconds). If the movement-information during the magnet passage with enough frequency (10 times a second) will be done, it will be possible to reconstruct with enough accuracy the position of the magnets.

The movement-information is in general in one layer. Also the height of the ruler to the magnet has to be calculated in the model. If the height is constant it will be no problem. Changes in height will result in a lower position accuracy in the movement-direction. The field-symmetry particularly of the movement direction will be the same

.

Method 2 – selective use of data

Using the measure data on a selective way can be done in different ways.
The goal is the same. Locate the magnets accordingly the measure system, without using the knowledge of the movement.
This can be realizing by taking a snapshot of the magnetic field.

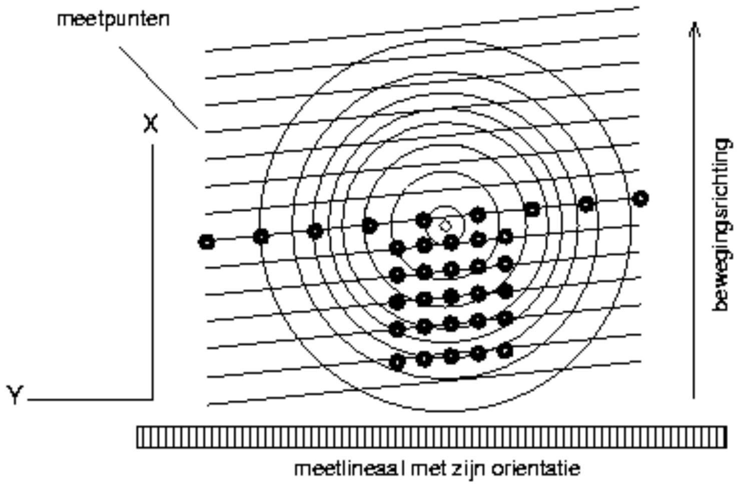


Figure 23 magnetic measurements using method 2

One of the possibilities is:

- Read continuously the magnetic-ruler and look to the average value of the measurement.
- Store the average value of the measurements if a (manual) drempelvalue will be overschreiden.
- Scan a couple of sensors who have a maximum value and store the measurements.
- Do a bigger scan if the values has reach a maximum value and use the values to determine the position of the magnets to the ruler.

This method can lead to better result in the cases where the vehicle has a strong steer-movement. Also strong veermovements (other height distance) has no height influences on the position calculation of the magnets. Especially in out-door toepassingen with light vehicles, with a low velocity of the vehicle this method will be in favour.

Also with very low speed, in cases of positioning the vehicle and with a sharp steer movement will the snapshot method will give a result with a higher accuracy, especially if the movement-information will be taken in account.

With the low speed there will be enough time to do more measurements and the result can be calculated in a better way.

Also the result of the measurement will be available earlier comparing with the first method. In the snapshot method the result is already available at the top of the measurement. In the first method the result will be available after the total measurement. The snapshot method is better to manoeuvre the vehicle.

Combined method.

With the software data acquisition and calculation it is possible to use the best method depending on the movements of the vehicle. Also comparing the two methods to obtain the best result is possible.
An example if the vehicle (by road or veer karakteristieken) will differ in height movement with a high frequency (example a light vehicle in an outdoor application) it will be useful to do the calculation not for the total data in once, but calculate the data in section, which results in less failures for the different height.

VEHICLE MOVEMENT AND ACCURACY

The asked accuracy will be opposite everedig with the speed of the vehicle. Higher speed will mend bigger distances and broader lanes. This means that the requirement for measure-accuracy in the movement-direction will be less: it is not so important on a particularly moment if the position is plus or minus 10 centimetre farther if the vehicle drives with 20 km/hrs.
This is also the case for the lateral accuracy.

The highest accuracy will be asked, for longitudinal and lateral, if the vehicle has to stop. In this case more time is available for the magnet passage. A measure accuracy of less than 15 mm in both directions is reachable.

4.2.4 Implementation

Implementation of the magnetic-ruler is done on the prototype of the ParkShuttle, the CTS for Rivium2.

4.3 Magnetic probe for collective vehicles (RUF)

4.3.1 Objective

The aim of this task is to improve the current magnetic probe system for RUF

4.3.2 Operational goals

It is intended to develop an improved magnetic probe which can be used with several frequencies of the magnetic field in order to allow for multiple directions in the RUF switch.

4.3.3 Baseline reference

The current status is that the switch is based upon a magnetic probe as a separate unit and a electronic circuit which is able to handle only 2 frequencies (Figure 24).

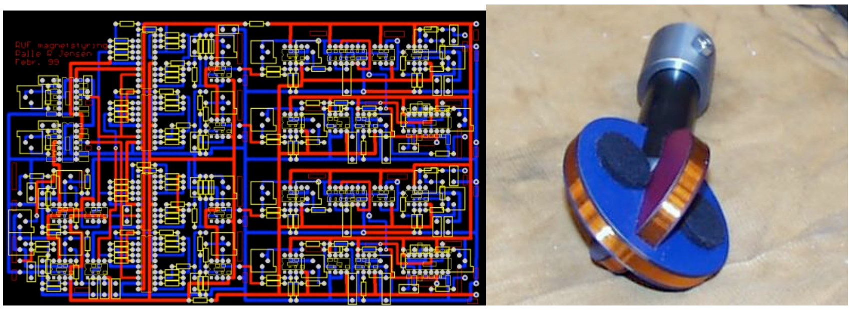


Figure 24 present system for the magnetic probe

4.3.4 Deliverables

An electronic circuit which is able to handle many frequencies of the magnetic field and where the probe is an integrated part of the circuit.

4.3.5 Description

It is important for the proper function of the RUF system that a switch can handle multiple directions, as shown in Figure 25. This will ensure that the junction in a RUF system will be as small as possible. Visual impact is of vital importance for any elevated system so the size of the switch is important even if there typically only is a junction for every 5 km of monorail.

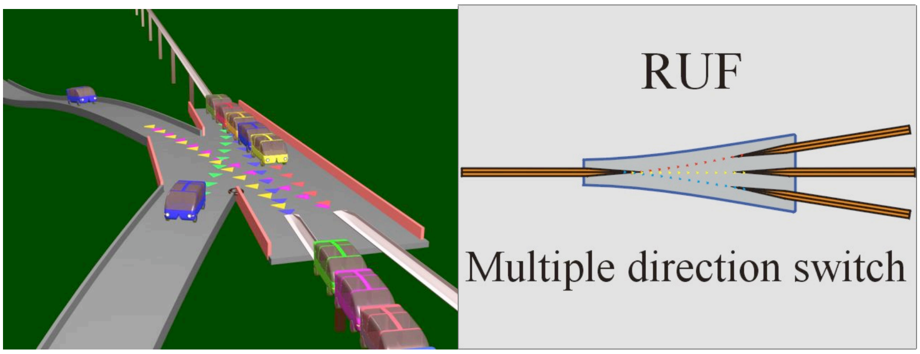


Figure 25 RUF Multiple direction switch

The magnetic guidance principle used in RUF is based upon a two wire system. The current through the wires is a sine wave with a frequency in the range of 8 – 15 kHz.

The probe is sensing the field (Figure 26) with a horizontal pick-up coil and a vertical coil is sensing the lateral position by measuring the horizontal field through the coil.
If the vertical coil is exactly in the middle plane between the two wires, the coil will not pick up any signal, so the position signal is zero.

If the vertical coil is offset from the center, a signal is collected and the magnitude is approximately proportional with the offset.

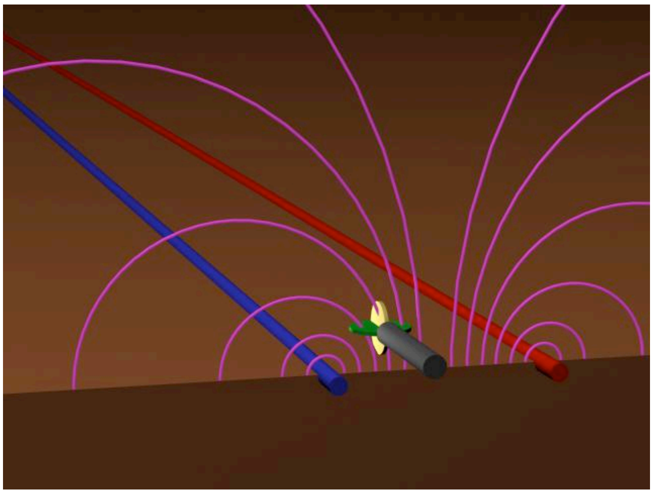


Figure 26 Plot of the magnetic field

A typical two wire configuration consists of two wires with a separation of 30 cm and the probe is typically placed 30 cm above ground in the front of the vehicle.

This configuration will have a reasonable linear function for an offset of +/- 10 cm. The function area can be expanded if the wires are placed further apart. This could be relevant at the access point where the driver has to “hit the field” before being able to enter the monorail.

The access to the rail has to be accurate to within +/- 5 cm. There is a passive device making sure that the vehicle will enter the rail correctly even if the guidance system should fail just before a vehicle tries to access the monorail.
The new circuit is based upon a sample and hold principle.

The pick-up signal is filtered through an 8th order bandpass filter using switched-capacitor technology
The LTC1264 chip uses a 20 times higher clock frequency than the bandpass frequency. This means that the bandpass frequency can be changed simply by changing the clock frequency.

The circuit function is as follows:
The filtered FIELD signal is fed to a zero cross detector which will enable a counter to count the clock frequency (20 times higher than the bandpass frequency). When the counter has reached the number 5, the counter is disabled until the FIELD crosses zero in the same direction next time. A reset pulse is generated when the counter reach the number 5 and this pulse will both reset the counter and disable it. The same reset pulse will now pick a sample of the PHASE signal and store it until next period of the FIELD signal. The sample is a DC signal which can be in the range of -3 to +3 Volt and it can be used to control the steering of the vehicle when it tries to follow the magnetic field.

The lateral position is measured once every 100 microseconds if the FIELD frequency is 10 kHz.
A print layout for the circuit has been made and testing of the circuit ready to start.

4.4 Vision-based Localization into Urban-like Area (Inria)

4.4.1 Introduction

Our study deals with the reliable localization of an autonomous vehicle in an urban environment. For some years, the GPS system assert itself as the main localization system develop on mobile robots for outdoor applications. However, most of the area of the cities do not receive any GPS signals due to the urban structures like buildings and streets. Indeed, the GPS receptors require the reception of 4 different satellites to locate correctly their poses on earth. We then purpose a vision-based algorithm to estimate a mobile robot motion in the urban environment using the projective invariants of a planar scene, viewed from a pair of stereo cameras.

The vision approach has furthermore two main advantages : it is environmental free and is particularly well adapted to capture dynamic parts of the urban dynamical environment like pedestrians and cars. Nevertheless, the detection of the principal characteristics are often occluded by the usual drawbacks of a vision sensors like brightness and shadow effects depend on the meteorological conditions.

4.4.2 Overview

We assume that the urban structures, which decrease the signal-noise ratio of the GPS emission, can be used to rapidly segment the image of the static scene as a driving hallway. We hence develop a two-stage algorithm in order to increase robustness. The first stage detects the borders of the road using a contour-based approach and primarily allows us to estimate the Dominant Vanishing Point (DVP). The DVP and the borders of the road are then used to limit the region where the feature points (FPs), corresponding to the road lane markers, can be extracted. The second stage uses a robust technique based on projective invariant to match the lines and points between two images. Finally, the FPs and the VLs lying on the road in the two images allow the homography computation.

4.4.3 Method

Classically, a Canny operator is used to detect the edges and after polygonal approximation, to obtain the segments of lines. Due to the bad quality of the images, the edge detection data are particularly inaccurate. According to our experiments, the midpoint location seems to be the only reliable characteristic of each segment. The length and the orientation of extracted segments are noisy. However, we note that the longer the segment is, the more correctly located it is. We then merge the segments into cluster of potential VLs which converge to the location of the DVP in the previous image. We also consider the high frame rate reduce the DVP motion in images.

We then achieve to segment the limits of the road plane in image whatever the type of road : straight or curved [1]. We indeed assume that the road is locally plane and limited by at least 2 parallel borders but can be unstructured. We compensate this lack of constraints by taking account a priori knowledge of the scene. We consider the static environment contains sets of ortho-parallel edges which allow us to robustify the DVP location. If we track a minimum of 4 VLs, we match them robustly between 2 images by considering the unicity of the cross-ratio. The cross-ratio is indeed the second projective invariant with the order constraint.

A homography is described by a 3*3 matrix H, which has 8 entries: 9-1 of scale factor. Therefore, H is uniquely determined by solving a linear system of equations containing at least a set of 4 correspondences lying on the same plane. The homography contains the translation and rotation motions, up to a scale factor, between two camera frames. Now, the pencil of VLs is also not sufficient, due to the link (DVP) between the coordinates of VLs, to verify this last condition.

We then detect some feature points with an Harris filter in the image region delimited by the first and the last VL which verify the unicity of the cross-ratio. Only the points which have an Harris score higher than 95% of the best score are considered correctly detected. The matching method we use is based on singular value decomposition of an appropriate correspondence strength matrix.

4.4.4 Experimentations

We validate our approach using video sequences recorded in the streets of the old city of Antibes and in the harbour neighbourhood. We use an uncalibrated stereo vision system. The speed of the vehicle was about 10 m/s and the frame rate was 25 Hz. The sequences contain more than 1000 black and white images of size 728*440 pixels.

The Figure 27 shows samples of our video sequence test. The experimental vehicle runs on a straight road, slows down then stops before an obstacle (parked vehicule) to finally overtakes it and pursues its displacement. The borders of the road are correctly detected. Some VLs on the road plane are not used to compute the homography estimation because the corresponding VLs are misdetected and do not converge to the DVP. On the contrary, some VLs out of the road plane verify the unicity of the cross-ratio due to the tolerance criteria we fix. In the same way, we do not have any method to discriminate robustly what are the correctly matched couples of FPs lying on the road plane.
The results of the homography estimation between two views are hence sometimes not so efficient as we expect by solving recursively the weighted mean squares solution of the linear system formed with the DVPs, the FPs and the VLs estimation [2]. The resolution of a such system requires taking into consideration some projection errors. Therefore the computation sometimes drift to some unreliable estimations, particularly when all the detected charateristics locate on a reduced region of image.

The next figure presents the chronogram of the corresponding DVP location in images left and right during all the test sequence. Some discontinuities of the DVP location appear when the vehicle ends the first part of its overtaking. The field of view is also reduced and the algorithm detects some VLs which all have the same orientation. Furthermore, the edges detected with the Canny filter are particularly inaccurate although the algorithm correct most of the misdetections by considering a priori constraints of the urban scenes. Concurrently, we can highlight the pitch angle of the vehicle that is its acceleration motion by focusing the mean joint variations of the DVP ordinates. The vehicle runs on a horizontal road plane, the ordinate had to be stationary. The misdetections errors hence appear as insignificant.

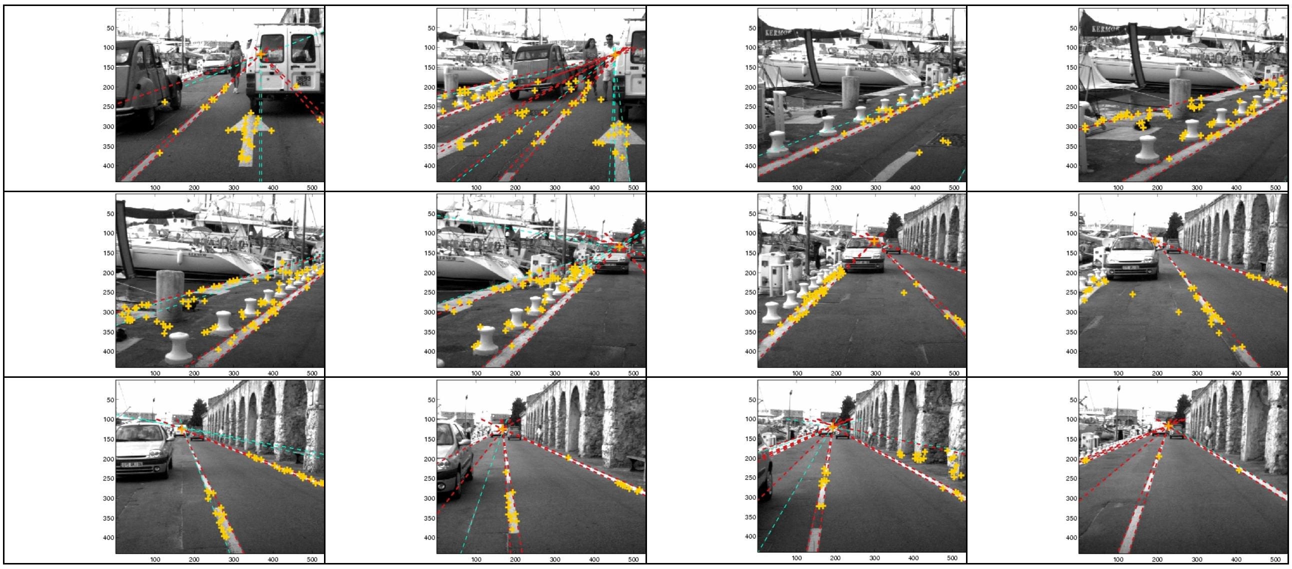


Figure 27 From top left to bottom right : samples (910 to 1020) every 10 images of the detected characteristics on the road plane. We compute the DVP location (orange '+') as the best estimation of the intersection of the VLS (cyan dashed lines). The highligthed red VLs and the yellow FPs are matched between the 2 views of the stereo pair to estimate the road plane homography.

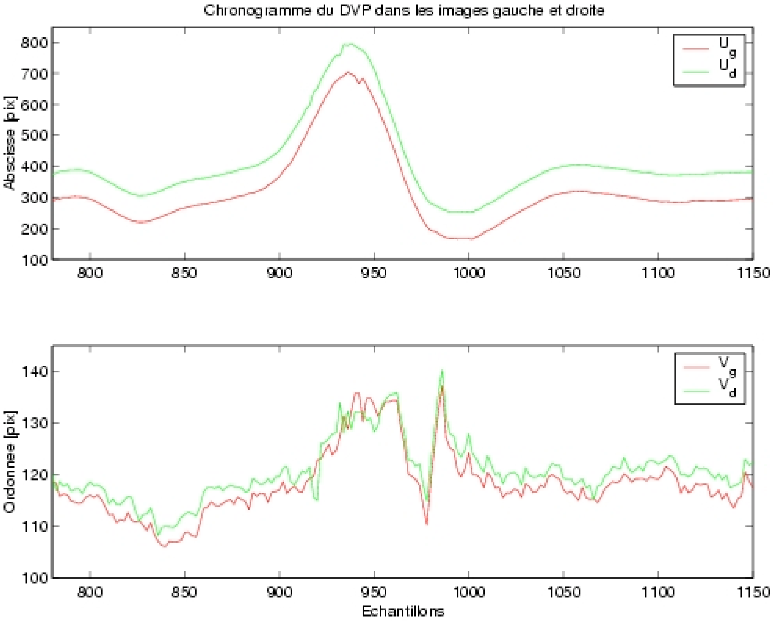


Figure 28 Abscisses (top) and ordinates (bottom) of the DVP location in images left (red) and right (green)

4.5 Wire guidance (Robosoft)

4.5.1 Objectives

Wire guidance is a standard solution in robotics to provide a continuous localisation of an automated vehicle. It has some disadvantages related to the difficulty and cost of installation, as well as the reliability. Robosoft has investigated this technique with the purpose to evaluate the performance of different available sensors and to check the implications of using this technology on its RobuCab platform.

4.5.2 Description

The wire is an inductive loop powered by a generator (Figure 29). Inductive track guidance with inductive loops has been proven as a very reliable system. The system is not influenced by dirt, colour, concrete, ice and snow etc. Nevertheless guide wires have to be installed carefully so that the wires do not break and influences caused by metal within the track can be avoided.

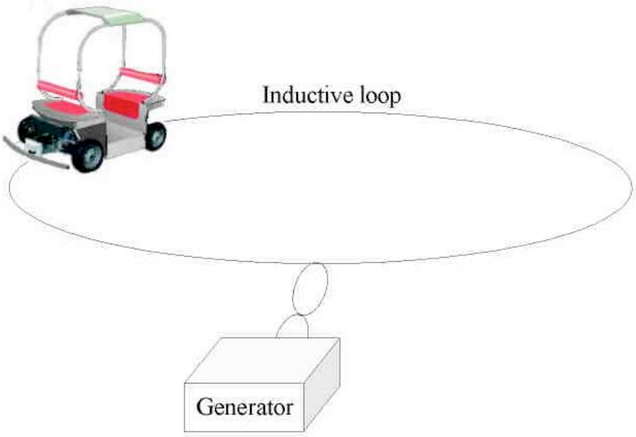


Figure 29 The wire guidance system

Three inductive sensors are used to follow the wire. The sensors give a voltage depending on the distance with the wire. Modifying the steering, the vehicle tries to "keep the wire" in the middle of the right and the left sensor.
At first, we made the tests with the Yamaha sensors. Other tests have also been carried out with the Goetting sensor, in which all antennas are installed in the same box (Figure 30).

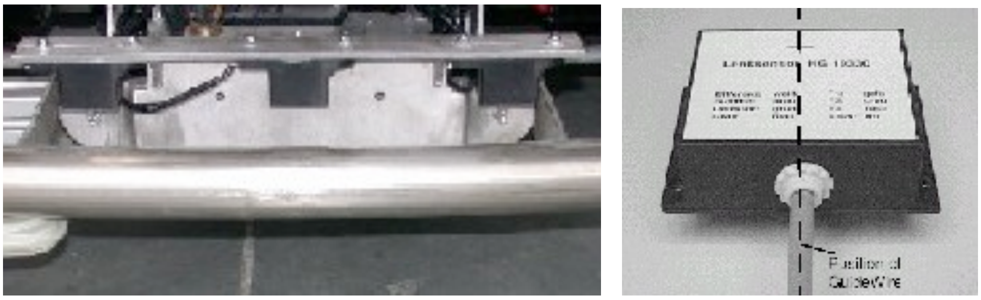


Figure 30 The Yamaha sensors(Left) and the Goetting sensor(Right)

As shown on Figure 26, the difference of voltage between the right and left sensor is used to compute the front wheels steering angles (Ud). Getting the real angle (Y), we obtain an error that is used in a PI controller to compute the servo amplifier command (U).

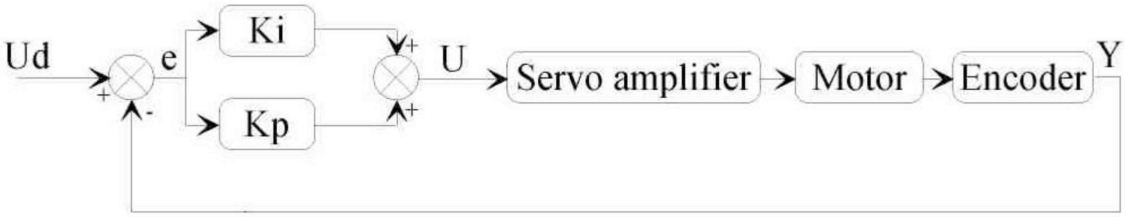


Figure 31 Control of the front steering angle with Yamaha sensors.

To change the velocity of the RobuCab we use transponders that are sending a value (new velocity) to the vehicle. The control of the speed is a PI, like in the steering control but Ud is the desired speed, U the speed command computed by the PI and sent to the servo amplifier. Instead of an absolute encoder, an incremental encoder is used to know the real velocity.

4.5.3 Results

Our tests were made with the Yamaha sensors, then with Goetting sensors.
The current velocity we reached is 2,5 m/s. We are now improving the tuning of the controller and the quality of the generator, and we plan to reach the velocity of 5,0 m/s very soon.
In good conditions (wire correctly installed, generator with a good adjustment), the lateral control has an error lower than 1 cm (see Figure 32).

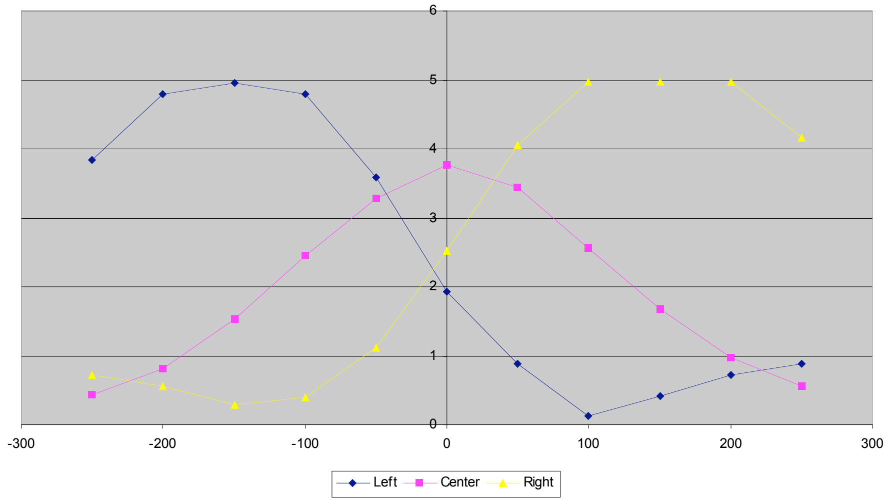


Figure 32 Values of the 3 sensors, are changing with the distance to the wire

We also developed a new generation of oscillator. With this new device (Figure 33), the vehicle is much more stable up to.5 m/s. This new oscillator allows longer wire (almost 1 km).

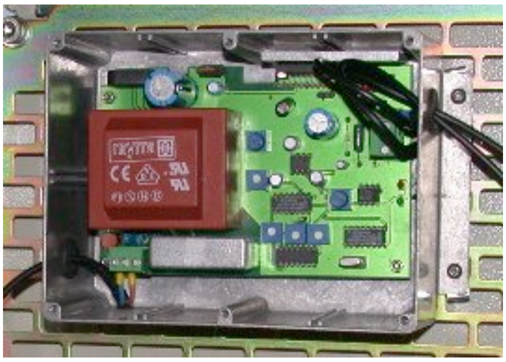


Figure 33 Generator used to power the wire

To improve again the quality of the wire guidance, we plan to modify the position of the sensors : As shown in Figure 34, the sensors have to follow the kinematics of the steering wheels in order to know if the steering correction is good (the centre of sensor is on the wire) or not.
This will nevertheless require mechanical changes in the steering system.

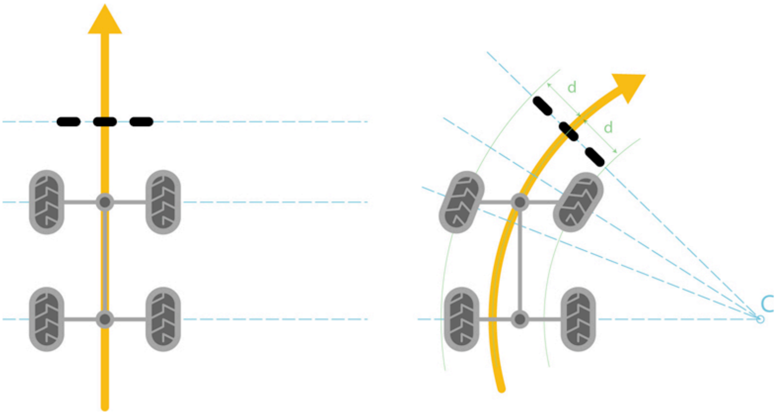


Figure 34 Scheme of wheels kinematics

The final result is an operational system, while before the CyberCars project only a mock-up was available.

4.6 Virtual line following (Robosoft)

4.6.1 Objectives

The purpose of the virtual wire guidance is to develop an easy-to-implement system for the RobuCab having the same features than wire guiding, but with a simpler installation procedure. Some reflective beacons are positioned in the environment, and the path of the RobuCab is defined using the teaching-by-showing method (Figure 35).
With such a system, it is very easy to modify a path comparing to the wire guiding system.

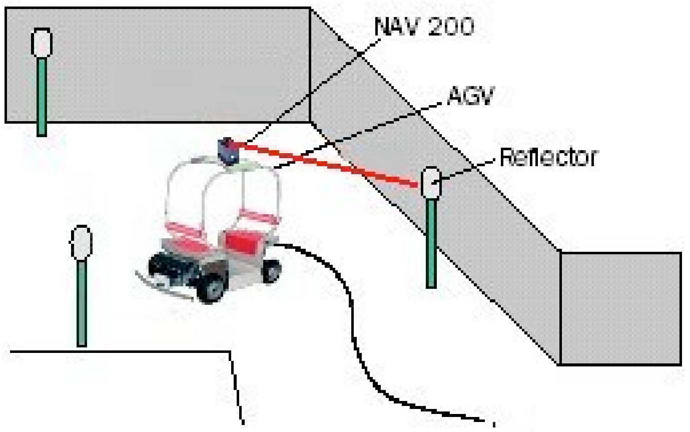


Figure 35 The vehicle uses some beacons to follow a virtual line

4.6.2 Description

The rotating laser and reflectors allow the vehicle to know its position and orientation.
The virtual path is defined over control points. These points can be learnt (driving the vehicle in joystick mode and “dropping some control points”) or defined on a map generator software.
The path is built using straight lines and arc of circles passing through the control points (see Figure 36).

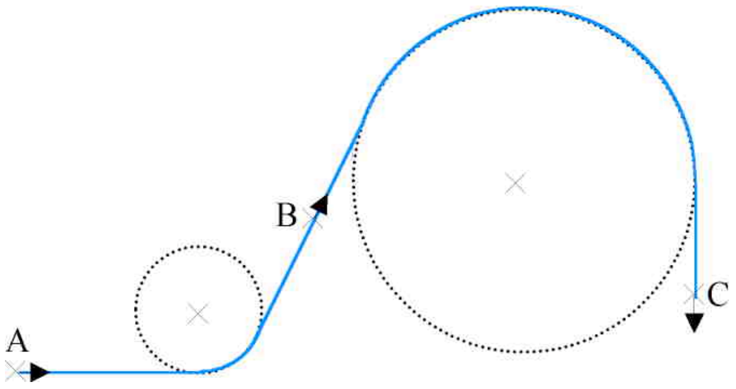


Figure 36 A path can be defined using a few control points

The rotating laser is connected to the RobuCab’s computer through a serial line. The acquisition of data and the computation of the speed and the steering of the vehicle are done in C language in the RobuCab’s onboard PC. Using a shared memory, this velocity and this steering angle are sent to the low level control (the SynDEx application on the RSMPC555 boards).

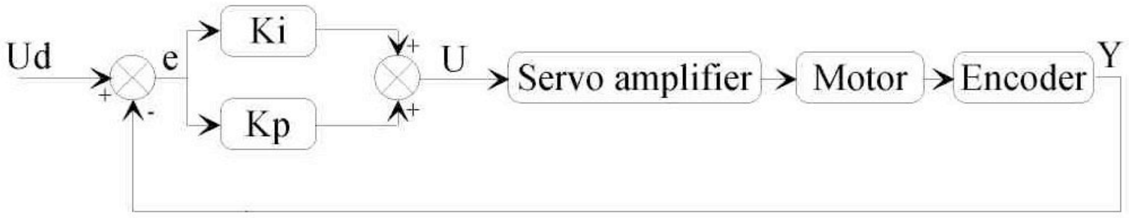


Figure 37 The PI controller of the virtual line tracker

To control the speed (respectively the steering angle), we use a PI controller (Figure 37), getting real speed (respectively the real steering angle) from a incremental (respectively absolute) encoder.

4.6.3 Results

The partner is at the beginning of this development, which was started in the project from only basic ideas. The following aspects can be outlined:

- The virtual line tracker is still under development. Our final goal is to go faster than the present 2m/s reached by SICK by introducing into the algorithms an estimated velocity of the RobuCab leading to a more accurate position estimation..
- The virtual line following is a solution for sites that cannot support an heavy installation such as wire following need.

4.7 Video camera for lane guidance (Robosoft)

4.7.1 Objectives

The purpose of the lane guidance is to develop a white line tracking system for RobuCab and supply an easy way to define a path that will be followed by the vehicle (Figure 38).
This system, which is very cheap because based on a simple webcam, can be installed very quickly comparing to wire and virtual wire guidance. At the beginning of CyberCar, the RobuCab did not have any automatic guiding system.

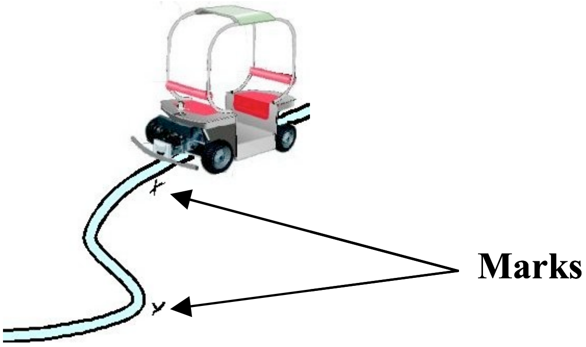


Figure 38 The line guidance

4.7.2 Description

A digital camera is used to follow a line drawn on the floor. Modifying the steering, the vehicle tries to keep the centre of the digital camera in the centre of the line (cancel the distance d and the angle a, see Figure 39).

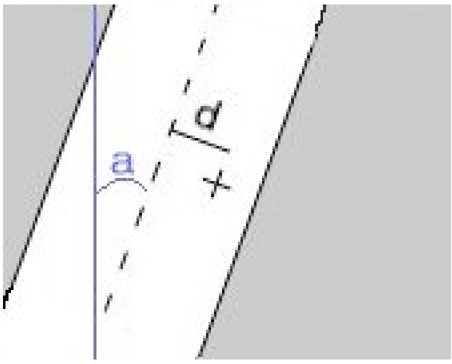


Figure 39 The camera’s view

The webCam is plugged to the RobuCAB’s computer by a Fire Wire link. The acquisition of data and the computation of the speed and the steering of the vehicle will be done in C language in the RobuCab’s computer. Using a shared memory, this velocity and this steering angle will be sent to the low level control (the SynDEx application on the RSMPC555 boards).

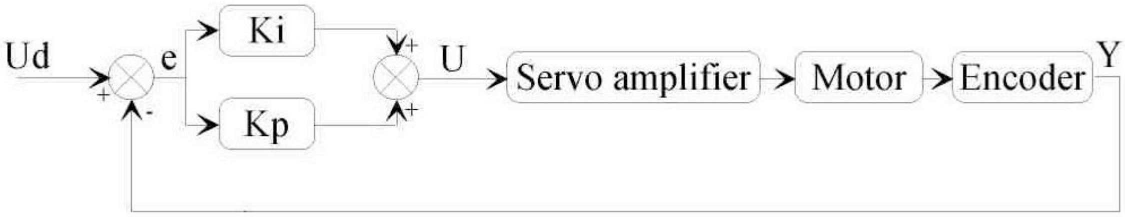


Figure 40 The controller of the white line tracker

To control the speed (respectively the steering angle), we use a PI controller (Figure 40), getting real speed (respectively the real steering angle) from a incremental (respectively absolute) encoder.

4.7.3 Results

A good stage of operation for low speeds with a real site has been reached.
The current velocity is 1 m/s. We have only made tests on short distance (5 m) so the max velocity is not reached yet. We plan to install a longer line and improve the tuning of the control to reach the velocity of 5,0 m/s. At 1 m/s, the lateral control has an error lower of 1 cm.

4.8 Navigation technique using laser and odometry (Inria)

4.8.1 Objective

In the frame of the development of navigation techniques, a specific purpose at Inria has been to develop a software system embedded in a vehicle, equipped with a laser telemeter, to perform the navigation task. Such a system allows to demonstrate the potential of a navigation technique based on laser and odometry for cybercars. The main aspect, compared to standard solutions, is the use of on-board equipment only. Such a feature can be exploited in term of flexibility and easier implementation of applications.

4.8.2 Description

We developed a technique to localize and guide outdoors vehicles by both vehicle odometry and landmark localization. We use reflective poles spaced out about 50 m apart and located on each side of the trajectory of the vehicle. The ladar detects distances, angles, speed, and the position of obstacles within 20 m. Odometry is performed by a steering sensor and encoder attached at the vehicle differential. Using this information, the embedded system matches the vehicle's computed position with the location of the poles.

The ladar, a laser scanner from IBEO, transmits a pulsed laser beam which uses a rotating mirror to scan an area in front of the vehicle. Within this area of 20 m x 20 m, distances and angles to poles are measured such that position and speed are available to the vehicle computer via a CAN bus at the frequency of 10 Hz. The distance measurement resolution of the ladar is 3.9 mm with an accuracy of +/- 5 cm. The angle increment is 0.25° so that one reflective pole of ∅ 5 cm can be detected from up to a distance of 12 m.

The ladar provides dead-reckoning feedback by measuring the vehicle location with respect to reflective poles spaced throughout the vehicle course. Poles are easily identified by the ladar up to a range of 12 m away. The ladar detects the nearest pole and tracks its positions until the vehicle passes the pole. The measurement provides the position and orientation of pole in the vehicle frame. The vehicle updates its position if a pole is detected by the ladar and identified in the GIS database (Geographical Information System) of vehicle.

Next (Figure 41) is the experimental result by trajectory following (points of the trajectory to follow are circles) with matching of poles (positions of poles detected by ladar are crosses). Blue line is the estimated position of vehicle using laser and odometry technique. Each time the vehicle identifies the pole, the estimated position of vehicle is updated.

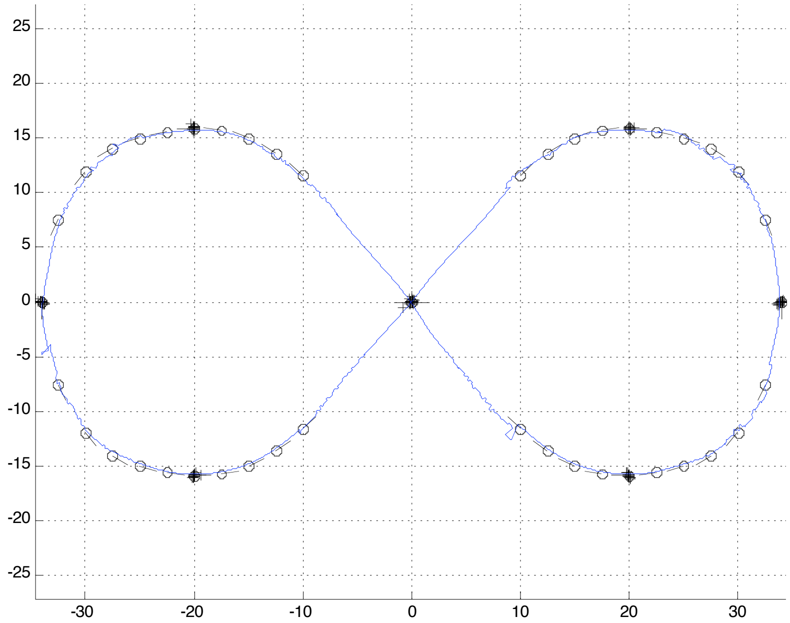


Figure 41 Experimental data on path following

The testing vehicle was an outdoor electrical car made by Yamaha based on a golf car frame, equipped with sensors and an embedded PC. For this experiment, we used the vehicle in the automatic mode i.e. speed and steering controls are managed by our algorithms. The vehicle travelled from starting point [-32 m; 0 m] of the loop and finished at the same point with an position accuracy of +/- 0.5 m.

4.9 Integration of inertial navigation and GPS (ISR)

The aim of this module is to obtain a navigation system using only the information from inertial sensors and a GPS receiver in order to achieve a better positioning performance than with any of the individual systems. To improve the performance of the GPS system at a low-cost, a DGPS configuration is to be used.

This type of navigation system allows for a high degree of flexibility since it doesn't need any change on the infrastructures or the environment in order to function properly.

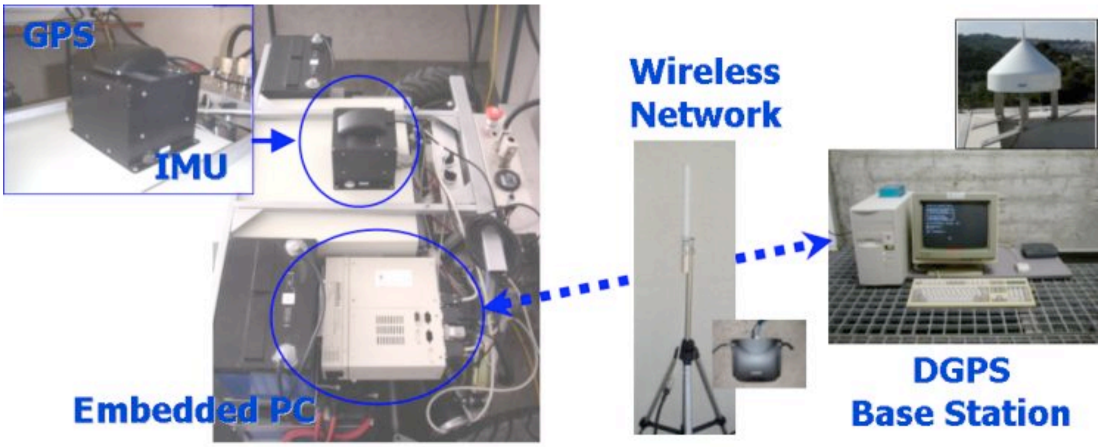


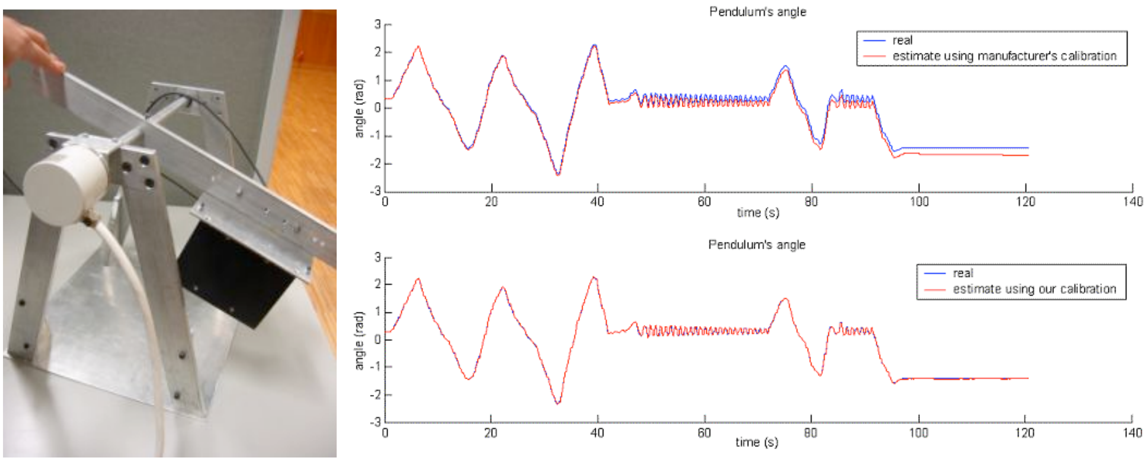
Figure 42 Navigation system developed by ISR

The system used, illustrated in Figure 42 consists of a Garmin® GPS receiver: model GPS35-HVS, capable of accepting differential corrections, an Inertial Measuring Unit (IMU) from Crossbow®: model DMU-FOG, with three silicon accelerometers and three fibre-optic rate gyros, and an embedded system from Advantech®: model PCM-9577F-00A1, with an Intel→ Pentium III processor, where the navigation algorithm is performed. The DGPS base station consists of an Allstar DGPS base station from CMC Electronics®, connected to a desktop PC in charge of broadcasting the DGPS corrections through (wireless) TCP/IP connections to all of the client GPS receivers.

4.9.1 Inertial Sensors Calibration

Since the inertial sensors measure first and second order derivatives of the parameters that should be reported by the positioning system, any small error in the measured quantities will be accumulated over time due to the needed integration process. In order to minimise the error build-up, the inertial sensors need to be properly calibrated. With this in mind, a procedure for calibrating the inertial sensors was developed.

For the calibration procedure, a pendulum was constructed. The calibration system, illustrated in Figure 43a), consists of the pendulum with a high-resolution absolute encoder attached to its shaft. Resorting to the encoder's readings, the real quantities that should be measured by the IMU can be determined and the inertial sensors can then be calibrated by the developed procedure.



a) b)

Figure 43 a) Simple device for calibration of the inertial sensors.
b) Comparison of results for estimation of the pendulum's pose.

A test was performed in which the pendulum was moved with periods of forced motion and periods of oscillation with no human intervention, and the inertial data was recorded. The inertial data was integrated over time in order to obtain the pendulum's pose. Figure 43b) shows a comparison of results for the pendulum's angle estimation using the recorded inertial data after being calibrated. The difference between both estimates is that in the upper graph it was used the manufacturer supplied calibration sheet to calibrate the inertial data, and in the lower graph the used calibration data was the one obtained by our calibration procedure. As can be seen the estimation based on the manufacturer's calibration data has a much higher error build-up than the one based on our calibration data, what validates our calibration procure.

4.9.2 Performance Evaluation

The main characteristic that needs to be evaluated in a positioning system is how accurately the system reports the vehicle's position.
The procedure used to evaluate this most important criteria needs to have knowledge of both the real trajectory followed by the vehicle, and the trajectory reported by the positioning system. The procedure used for evaluation was the following:

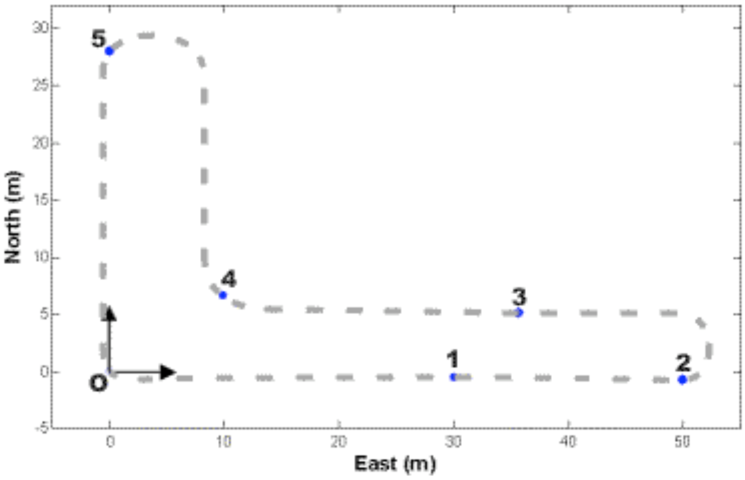


Figure 44 Plot of the measurement course and calibration points

Five measurement points were defined in our test course, as can be seen in Figure 44. Three of these measurement points were placed in three different turning places, one at the beginning, one in the middle and the other at the end of the curve. The other two measurement points were placed in positions where the vehicle was moving in a straight line. A map of the measurement points was obtained by traditional measurement techniques.

The vehicle went nine times through each of the five measurement points, but following slightly different trajectories in the space in-between the measurement points, since the vehicle was driven manually. The speed of the vehicle was also different for each try.

Since it was not guaranteed that the vehicle passed exactly through each of these measurement points, a calibrated video camera was attached to the vehicle and recorded the passing through each of the measurement points. The camera was oriented so as to be able to view the measurement points when the vehicle passes close to them. A *posteriori*, the real vehicle position near each of the measurement points was obtained by the knowledge of the real position of the measurement points and the position error measured by the calibrated video camera.

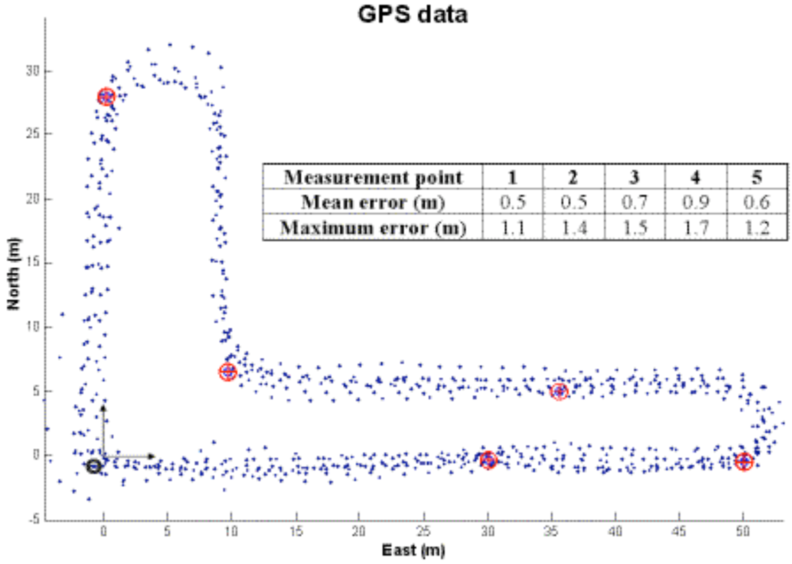
Since it was not practical for the logger of the positioning system to also record the video, neither are the delays of both systems (the positioning system and the video camera) similar, the adopted solution for synchronization between the positioning system and the video camera was based on a visual aid, in our case a L.E.D. in front of the camera which blinks once when the data logging starts, and once again when it stops. After that, the real trajectory for the vehicle was obtained in the image processing stage, where the synchronization between the positioning system and the video was performed.

A steady state performance was also evaluated by placing the vehicle over two distinct measurement points for five minutes in each of these points.

4.9.3 Results

For evaluating the performance of the navigation algorithm, the above procedure was followed and the sensorial data was logged in order to use the navigation algorithm offline.

The test was performed in a fairly clear area in order to have good visibility of GPS satellites. The DGPS station was placed nearby (baseline around 100 meters) so that the DGPS corrections improve the GPS solution as well as possible. The vehicle was driven manually along the course, and for that reason, the real trajectory followed between the measurement points differs in each turn.

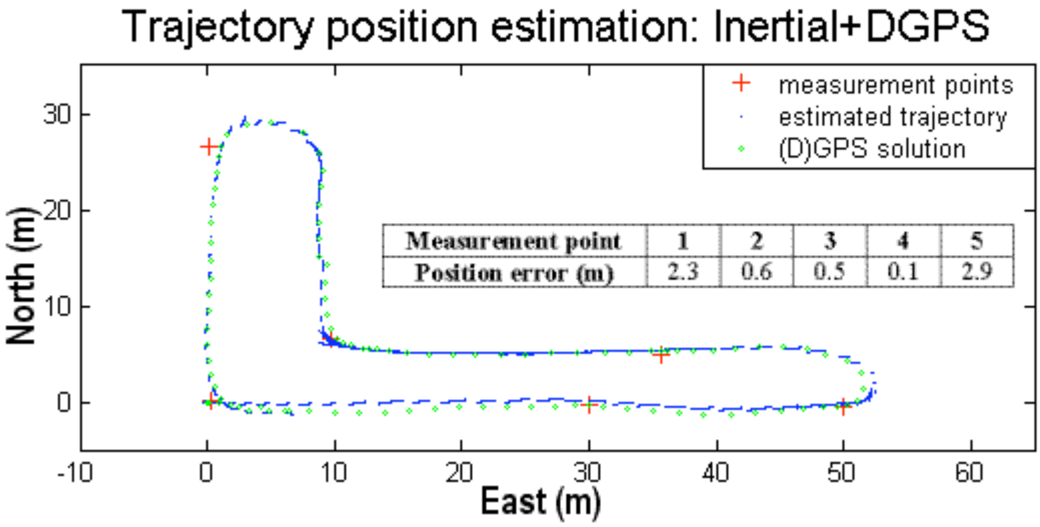


Measurement point	1	2	3	4	5
Mean error (m)	0.5	0.5	0.7	0.9	0.6
Maximum error (m)	1.1	1.4	1.5	1.7	1.2

Figure 45 Results of the GPS as a stand-alone solution

Figure 45 shows the trajectory followed as reported by the GPS receiver in the complete nine turns of the test. The five measurement points defined in the evaluation procedure are also illustrated with red marks, along with the error for the GPS data at each of those measurement points. The GPS data presented in the figure has already been filtered to eliminate bad GPS fixes which would corrupt the position estimate.

It should be noted that although the errors were acceptable for a simple DGPS configuration, it was due to a clear view of the sky and the automatic filtering of anomalous data caused by temporary signal blocking, multipath reflections and other GPS error sources.



Measurement point	1	2	3	4	5
Position error (m)	2.3	0.6	0.5	0.1	2.9

Figure 46 Results of the navigation system integrating GPS with inertial data

Fusing this DGPS information with the inertial data, we obtained the results illustrated in Figure 46 for the first turn in the experiment. Comparing these results with the results for the stand-alone GPS solution, we can see that the error of the navigation system relying on data fusion increases greatly at trajectory curves. This is suspected to be due to the need to integrate the noisy accelerometers data, which after some time leads the vehicle velocity to drift away from the real velocity, and at the trajectory curves, the inertial system will still 'think' the vehicle is moving in the direction it was moving before. Some more inspection of these results has to be performed, probably followed by a change in the inertial unit used. The navigation algorithm has also to be revised in order to achieve the performance required for an autonomous vehicle.

4.9.4 System Characteristics

The developed navigation system relies on a Kalman filter to integrate both measurements accounting for their uncertainties. The Kalman filter's state variables consist of the vehicle's three-dimensional position, velocity and acceleration in the ENU (East-North-Up) coordinate frame, along with the vehicle's attitude and three-dimensional angular velocity in the same coordinate frame. The measurement vector consists of the GPS outputs, specifically three-dimensional position and velocity, and the inertial sensors outputs, namely three-dimensional linear acceleration and angular velocity, with all these measurements expressed in the ENU coordinate frame. The system model considers the vehicle's motion during a sample period to be modelled as constant linear acceleration and angular velocity, since those are the higher order derivatives of pose information that are directly measured from the set of used sensors.

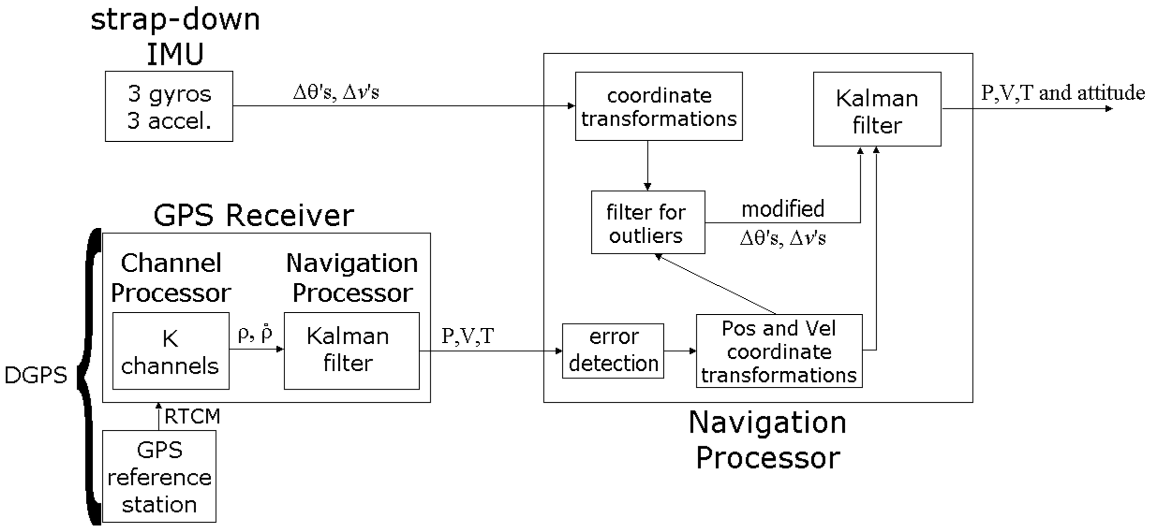


Figure 47 ISR's Navigation system architecture

Figure 47 presents the architecture of the navigation system integrating information from GPS and inertial sensors.

The inertial sensors are sampled at a rate of about 100 Hz, and the GPS receiver outputs position information at a rate of 1 Hz. The navigation system's output frequency is 10 Hz.

The vehicle's pose is expressed and determined in terms of unit quaternions in order to have a robust and computationally efficient form of performing rotations. Another characteristic of the system worth mentioning is its ability to automatically filter out erroneous GPS measurements in order to achieve a high integrity navigation system.

4.10 Complex maneuvers (Inria)

We consider the problem of tracking a vehicle with a nonholonomic unicycle-like robot by using vision data acquired with an on-board camera. A distinctive feature of the present study is that no assumption is made on the target motion so that, due to nonholonomic constraints on the robot which forbid instantaneous lateral motion, perfect tracking of the target is generically impossible. A practical situation which illustrates this problem arises when one is interested in making a robotic car automatically follow another car. This corresponds to a typical car-platooning application except that tracking has to be continued when the leader performs maneuvers that involve changes in the sign of its longitudinal velocity. To our knowledge, this type of problem has seldom been addressed in the literature. As a matter of fact, finding an adequate formulation of the control problem is not even straightforward in this case. Indeed, while following a leading vehicle with positive longitudinal velocity can be solved with classical control techniques, and is well documented in the robotics/automotive literature, what does tracking mean when the leader moves backward? A possible scenario consists in imagining a virtual frame attached behind the vehicle. The problem at hand then basically amounts to controlling the posture error between this frame and the robotic car's body. Zeroing this error all the time would correspond to perfect tracking. Stated in these terms, the control problem looks alike trajectory tracking, another much studied problem. There is however an important difference. In the trajectory tracking case, it is assumed that the reference trajectory is feasible, i.e. compatible with the kinematics of the controlled vehicle. In our case, this assumption does not hold because the velocity of the virtual frame has a lateral component which vanishes only when the vehicle moves along a straight line. Since nonholonomy forbids such a lateral motion for the robotic car, perfect tracking of the virtual frame is usually not possible. Instead, some type of practical stabilization yielding, for instance, uniform ultimate boundedness of the tracking errors (in both position and orientation) has to be considered.

4.10.1 Control Strategy

The control strategy here considered is based on the transverse function control approach, developed by Morin and Samson [1,2], which provides a general framework for the design of control laws yielding practical stabilization for nonlinear controllable driftless systems submitted to additive perturbations. The key point of this control strategy is to relax the objective of perfect tracking, the realization of which is usually not possible with a maneuvering target. Using the transverse function approach, we can specify a neighborhood of the target posture - which can be as small as desired -, and design a nonlinear feedback which ensures the convergence of the robot to this neighborhood, independently of the target motion.

4.10.2 Practical issues

To implement the control approach, various issues related to the experimental setup have been addressed. For instance, a camera mounted on the robot allows to observe the target and reconstruct the posture of the robot with respect to the observed target by using standard geometrical computation. The knowledge of the target velocity is understandably useful for tracking purposes and improving the performance of the control scheme. In our application no sensor measuring this velocity directly is available. We have thus designed a velocity estimator, based on the visual data provided by the on-board camera and the odometry measurements. This estimator also provides filtered values of the relative position of the robot with respect to the target. This is useful to reduce the effects of noise in visual data.

4.10.3 Simulation result

The simulation result shown below illustrates a few features of the approach. On this figure, the posture of the unicycle-like robot is represented in blue, and that of the omnidirectional target in green. The target velocity is estimated. The control parameters are chosen so as to ensure that, after the initial transient phase, the posture error of the robot with respect to the target is less than 0.5 meter in position and 1.0 radian in orientation. The whole simulation implements a single feedback controller and does not involve any trajectory planification algorithm.

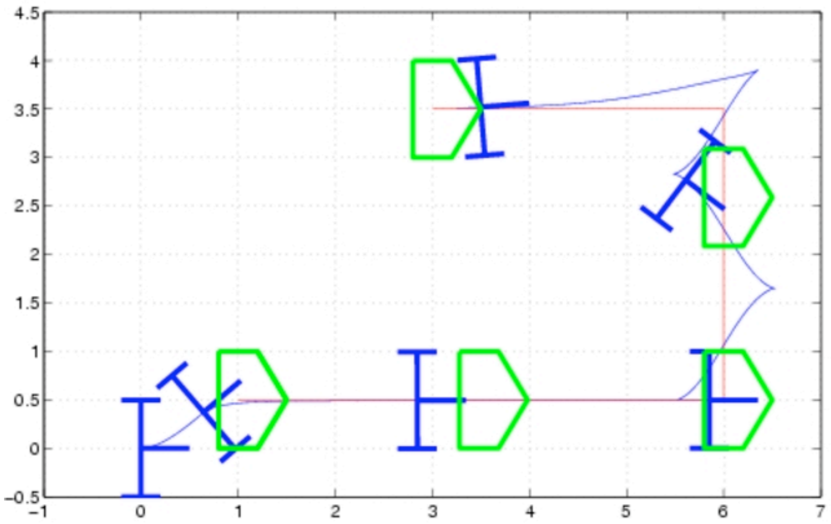


Figure 48 Target tracking 1

The target motion involves four phases. In the first phase, the target, at the bottom left corner, is motionless. The robot approaches the target in order to enter a pre-specified domain. Its final position, before the target starts moving, is shown on the figure. This phase already illustrates the concept of practical stabilization: convergence to the target is not enforced strictly, posture errors are maintained within pre-defined bounds.
The second phase of the simulation illustrates the behaviour of the controlled robot when the target moves along a straight line. During this motion, the robot stays behind the target with relative orientation and lateral position errors tending to zero.
Lateral motion of the target is shown in the third phase. Such a motion is not feasible by the robot, which instead performs manoeuvres to follow the target. During this motion, the relative posture errors remain within the same pre-defined bounds.
During the last phase, the target moves again along a straight line, but with negative longitudinal velocity.

4.10.4 Experimental results

The control law has been tested experimentally on our unicycle-like mobile robot. In the absence of sensors capable of providing measurements of the target absolute position and orientation, only experimental results showing a motionless target and the way it is rallied when the robot is initially located far away from the target are reported. They illustrate in particular how different choices of pre-defined tracking error upper bounds can induce significantly different rallying trajectories for the controlled robot.

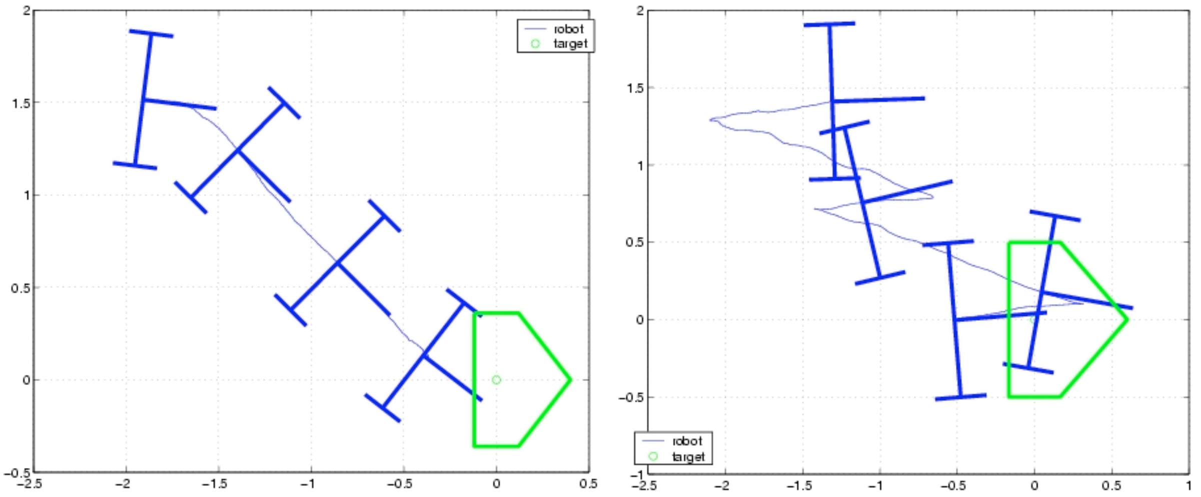


Figure 49 On the left-hand side figure, the maximum authorized orientation error is 1.0 radian. This allows the robot to rally the target without manoeuvres. On the right-hand side, the maximum authorized orientation error is reduce to 0.3 radian. Due to more stringent constraint on the robot's orientation, the rallying motion involves several manoeuvres.

5. Obstacle Detection Technologies

5.1 Baseline and technology improvements

One of the most challenging problems of cybercars is safety on the roads, in particular the avoidance of obstacles while preserving a reasonable commercial speed. This is a basic requirement for the evolution of cybercars, according to the evolutionary roadmap. In fact, even in the first steps, when vehicles are operated on a dedicated lane with some type of barriers, the presence of somebody crossing the path or the interaction with an obstacle cannot be excluded.

The existing technologies for safety rely on expensive laser systems, typically with a scanned beam, detecting objects in the front area and on tactile bumpers, switching off the traction in case of a contact.
Regarding vision systems, a certain experience on road vehicles already exists, but consolidated applications are based on simple processing tasks (not directly related, on present products, to obstacle detection): an example is the recognition of white marks on the road for lane keeping. In robotics, most of the systems are based on stereo cameras and an inverse perspective mapping, with the assumption of a flat road. These solutions operate correctly only when calibration and installation are accurate, and also when the assumption of road flatness is not significantly violated.

In this context, besides trying to reduce the cost of a laser system, it is important to develop new detection technologies offering additional flexibility, more precise information on the environment, and simplified procedures. In the area of computer vision, the work has been concentrated on stereo systems, with solutions offering simplified calibration and avoiding the assumption of a flat road.

Therefore, the following approaches have been considered:

- **Techniques to improve safety** for both road users and cybercars users, in several operational conditions, mostly based on improved processing of laser signals;
- Improvement of **image processing for stereo vision**, focusing the modelling of the environment, the calibration methods and the path tracking;
- The evaluation of **automotive radar systems** (devices, processing), which could provide a low cost and reliable solution due to the high volume productions;
- The testing of well known **ultrasound sensors**, offering an economic device with however some environmental limitations.

The results obtained are described in the subsequent paragraphs, and are here summarized:

- ***Automotive radar sensors** and systems have been evaluated in two configurations (CRF - paragraph 5.2); suitable performances have been demonstrated in a platooning scenario and when braking behind a stopped vehicle; the angular field of view now offered has been found insufficient;*
- *Some advanced solutions for **stereo vision** have been implemented, including:*
  - > *a technique with simplified calibration and applicability on non-flat roads (ISR – paragraph 5.3)*
  - > *a technique based on 3D models with an 'evolutionary' approach allowing pattern recognition (INRIA – paragraph 5.7)*
- *New data processing has been developed for a **dual laser scanner** on the Park Shuttle (FROG – paragraph 5.4), with measurements performed at two heights for increased safety; the system provides a recognition of on-path and near-path obstacles, an easy*

and automatic configuration of the area of interest from the route plan, and enhanced comfort due to strategies for a gradual stopping;

- *Other more* ***standard solutions*** *have been tested for the purpose of understanding the domain of operation, particularly a certified laser scanner (ROBO, ISR – paragraph 5.5) and a device with low cost ultrasonic sensors (ROBO – paragraph 5.6);*
- *A new approach for* ***path tracking*** *based on fuzzy logic has been studied (ISR – paragraph 5.8)*

From the experience gained in the work, it can be concluded that the scan laser remains at the moment the preferred option, with significant improvements now obtained in the data processing. For this technology, it is now known that suppliers are developing second generation devices for application on vehicles, with smaller dimensions and a reduced cost.
The automotive radar has shown an interesting potential for cybercars, when systems with a larger field of view will be available, as expected from the present trends.
Finally, vision systems maintain a great interest for the variety of functionalities they provide, also considering the integration of obstacle detection and navigation. In this area, significant progress has been obtained, but further experimentation and setting-up appears necessary for cybercars.

5.2 Evaluation of automotive radar technologies (Crf)

5.2.1 Objective

- The aim of this study is to evaluate the use of Obstacle Detection and Collision Avoidance technologies available in the automotive field for Cyber Cars applications. The focus in on microwave radar sensors, considering benefits which could derive from the market introduction, in large volumes, of sensors for advanced driver assistance systems, particularly in term of availability at a low cost, architectures and standards.

5.2.2 Operational goals

- Detection at short range and large field of view, to satisfy requirements for cybercars;
- Sensor performance with different categories of objects, particularly pedestrians, cycles, standing objects;
- Processing for scene analysis in an urban environment.

5.2.3 Description

REQUIREMENTS

The Cyber Cars are expected to move in a *dedicated lane*, inside an ordinary urban environment with frequent Stop&Go conditions; moreover, these lanes could be crossed by other road users (pedestrians, cyclists, vehicles), either accidentally or even on suitable infrastructures, like crossings or traffic lights. The general environment includes all the structures present in urban roads.
In this context, the main requirements impacting on obstacle detection are defined below:

- Max velocity = 13.9 m/s (50 km/h)
- Max longitudinal deceleration value = - 5 m/s^2
- Max lateral acceleration in curves = 2 m/s^2

- Minimum curvature radius = 5 m
- Obstacles to be detected ⇒ vehicles, pedestrians, bicycles, generic objects

From these considerations, the features of the sensors to be used for a cybercars application are presented below in terms of the following features: range, velocity, Field of View (both horizontal and vertical), refresh time.

Angular measurements:

Figure 50 shows some possible effects related to angular accuracy (the sensor ability to correctly provide a measure) and resolution (the ability to distinguish two objects close together).

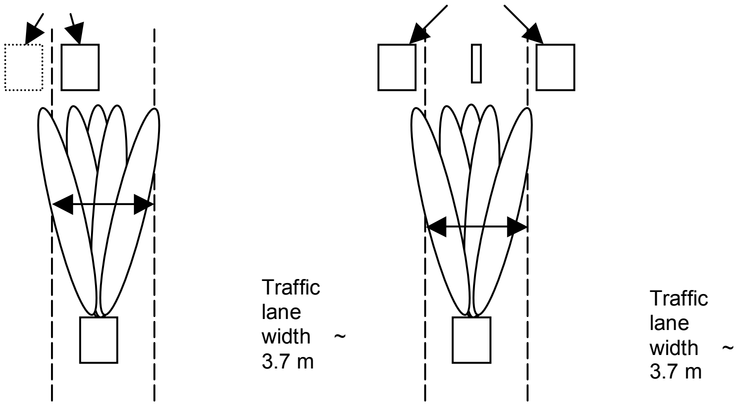


Figure 50 Effects of angular accuracy (a) and angular resolution (b)

In the left part of the figure the effect of sensor angular accuracy is described. If the lateral position of the obstacle is measured non correctly, than a side obstacle staying outside of the vehicle path could be perceived as inside the vehicle path. This would generate a false braking of the vehicle in order to avoid a collision with the obstacle supposed to be inside the vehicle path.

In the right part of the figure the effect of angular resolution is shown. If two objects, located on the two sides of the vehicle path, are not resolved, then a false obstacle could be detected.

Distance

Regarding the **sensor range**, important considerations are the maximum speed envisaged for the Cyber Cars vehicles and their maximum deceleration value. Considering that the vehicle has to stop before an accidental stationary obstacle present in its path, the equation to be considered is:

$$d = \frac{1}{2}\frac{v^2}{a} + v \cdot T_{reaz} + d_0$$

where:

- d is the sensor range
- v and a are respectively the velocity and acceleration of the vehicle
- T_{reaz} is the reaction time of the system (since cybercars are driven automatically). This time includes the detection and processing time for the sensor system and the reaction time for the vehicle control and actuation. We can assume a total reaction time of about 1 s.
- d_0 is the stop-distance, that is the distance at which the vehicle should stop with respect to the obstacle. At the moment, the value is chosen equal to 3 m.

With these assumptions, the safety braking distance is d = 36.2 m, corresponding to the maximum range for obstacle detection, in order to stop the vehicle moving at the maximum speed and with maximum deceleration. Of course this is a minimum requirement, but for safety reasons, a longer range could be useful to make the system well accepted by the users and to improve the evaluation of obstacle parameters.

Regarding the **range accuracy**, starting from typical values for automotive applications, an interval of ±1 m has been chosen, which can be considered precise enough for the control strategies relating to car following, automatic braking and collision avoidance manoeuvres. Better performances could be considered in a future perspective, taking into account technology developments.

Concerning the **resolution** item, it is defined as the minimum distance at which two objects with the same angular position and velocity should be distinguished. For the scenarios in which the CyberCars system shall operate, the possibility to separate two vehicles at a distance of 4 m is regarded as a good value.

Horizontal and Vertical Field of View

The sensor system has to cover a wide area in front of the vehicle and also laterally (at least partially); in fact, due to the characteristics of urban traffic, it is extremely important to detect cut-in (and cut-off) vehicles or other road users before they become really an obstacle in the vehicle path.
Another important feature is to detect obstacles in curves, with advance time to allow a braking manoeuvre and a stop at safety distance behind the target. This feature has to be guaranteed for all possible speeds and curvature radii.

In order to compute the necessary horizontal field of view, we can consider the most demanding situation, that is the minimum curve of 5 m radius. In this case, the maximum vehicle speed is limited by the value of maximum lateral acceleration, following the formula:

$$a = \frac{v^2}{R}$$

At the allowed maximum speed (3.2 m/s) we obtain a detection distance of 7.2 m to be provided by the sensor.

Starting from the minimum curvature radius R and the detection distance for that curve d, (Figure 51) it is possible to derive the maximum field of view using the formula:

$d = 2\ R \sin(\alpha)$

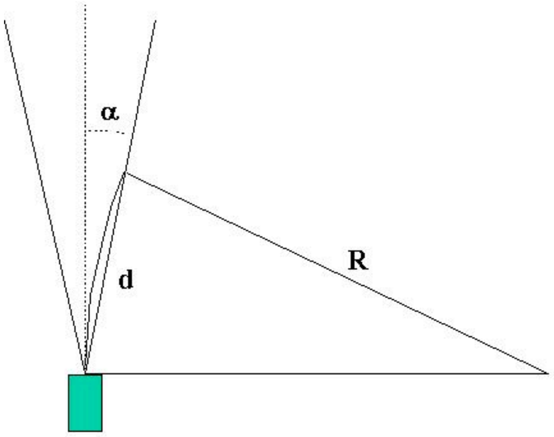
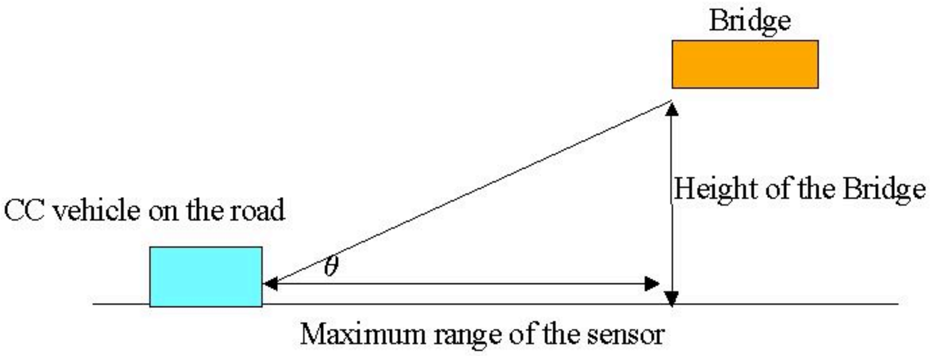


Figure 51 Relationship between curvature radius, detection distance and field of view

The final requested value for the horizontal field of view is therefore ±46° .

Concerning the **vertical angular field of view**, this parameter is connected to the possible detection of suspended objects (signals, bridges, tree branches, etc.), which could be confused with an obstacle on the road. On the other side, obstacles that constitute a danger for the vehicle have to be detected also on the vertical dimension. For the case of a bridge, the Figure 52 shows the situation; most sensors used at present, including devices based on a scanned laser, do not provide a measure of the **vertical angle**.



The angle θ is the vertical FOV

Figure 52 Scheme of a possible false alarms caused by a bridge.

As pictured in Figure 52, the ϑ angle gives the maximum value for the beam width of a radar sensor. Considering 5 m as a minimum height for the bridge (in accordance with Italian law) and a maximum range of 36.2 m, the value is 7.6 degrees. This value is to be considered as the maximum value that can be accepted for vertical field of view. Lower values can be accepted depending of the kind of obstacles that can be found on the road travelled by the vehicle.

The necessary **angular resolution** can be derived considering the possibility to distinguish two obstacles separated by a lateral distance of about 1.5 m (corresponding roughly to the width of the vehicle) at the maximum range of the specific sensor considered, as shown in Figure 50b. In fact, it is fundamental to understand if the Cyber Car can pass between, for example, two vehicles in adjacent lanes. With the aforementioned range value, the angular resolution is 2.37°.

About the **angular accuracy**, the requirement is to have a lateral accuracy of 0.5 m at 36.2 m, which corresponds to an angle of 0.79°. This value is necessary in order to evaluate if an object is inside the vehicle path or not (see Figure 50a).
Note that no accuracy and resolution for the vertical angle are provided; because on the vertical dimension it is mainly useful to understand if the obstacle is a potential danger, with no need to measure its height.

Other parameters

Considering the other parameters, their requested values are as follows:

- **relative velocity:** taking into account the requirements of the system and the technical constraints of sensor technology, the range is *± 50 km/h (± 13.9 m/s)*
- **refresh time** / **update frequency** : for an emergency braking and a collision avoidance manoeuvre, the sensor system should be able to give a new objects with an update frequency of at least *10 Hz*

Focusing on the relative speed, its **accuracy** and **resolution** have been chosen equal to 0.28 m/s and 1.39 m/s respectively; these values are based on previous experimental tests in scenarios relevant for a CyberCars operation, and on the current performances of sensors already available on the market.

Summary Table

The following table sums up the values range of aforementioned parameters with their own accuracies and resolutions:

Parameters	Range	Accuracy	Resolution
Distance	(0 ÷ 36.2) m	± 1 m	4 m
Relative speed	±13.9 m/s ± 50 km/h	± 0.3 m/s ± 1 km/h	1.4 m/s 5 km/h
Horizontal Angular Position	± 46°	0.8°	2.4°
Vertical Angular Value	(0 ÷ 7.9) °	---	---
Refresh Time	100 ms	---	---
Update Frequency	10 Hz	---	---

EVALUATION OF RADAR SYSTEMS

The most common technology for automotive obstacle detection and ranging is now the microwave radar. For advanced driver assistance systems (ADAS), the microwave components ordinarily used are based either on 77 GHz frequency for long range applications or on 24 GHz for short range. However, while the 76-77 GHz band has been allocated for this kind of automotive applications, the use of 24 GHz band is still not allowed in Europe with the spectrum required from some of these applications (this band is regulated in the US).

Both single beam and multi beam sensors, providing improved angular information, are available on commercial products, while scanning devices are applied at present on research prototypes.
The output from a radar sensor is generally a map of objects in the field of view, with data on their distance, angle and relative velocity. By processing these data, the situations of potential danger are identified.

Two prototype radar systems have been considered for the purpose of evaluating situations of interest for Cyber Cars:

- a configuration combining long and short range sensors
- a configuration with a long range sensor, covering a larger field by mechanical scanning.

The systems have been installed on two prototype vehicles based on a normal production passenger car platform, Alfa Romeo 156 (Figure 53). These cars are equipped with a Stop&Go function, which is - among ADAS functionalities - the one more similar to the Cyber Cars applications. However, the horizontal field of view required by the specified application cannot be covered by existing automotive radars.

The Stop&Go system is intended to give support to the driver in queue situations, at low speed. Upon driver request, the longitudinal control of the vehicle is taken by the system that operates on the brake and the throttle in order to keep a set speed or to follow the vehicle in front at a proper distance. When the front vehicle stops, the equipped vehicle is also brought to stop, thus realising an extension of the ACC (Adaptive Cruise Control) function to low speeds, down to zero. The maximum operating speed for the Stop&Go function is usually set to 50 km/h.

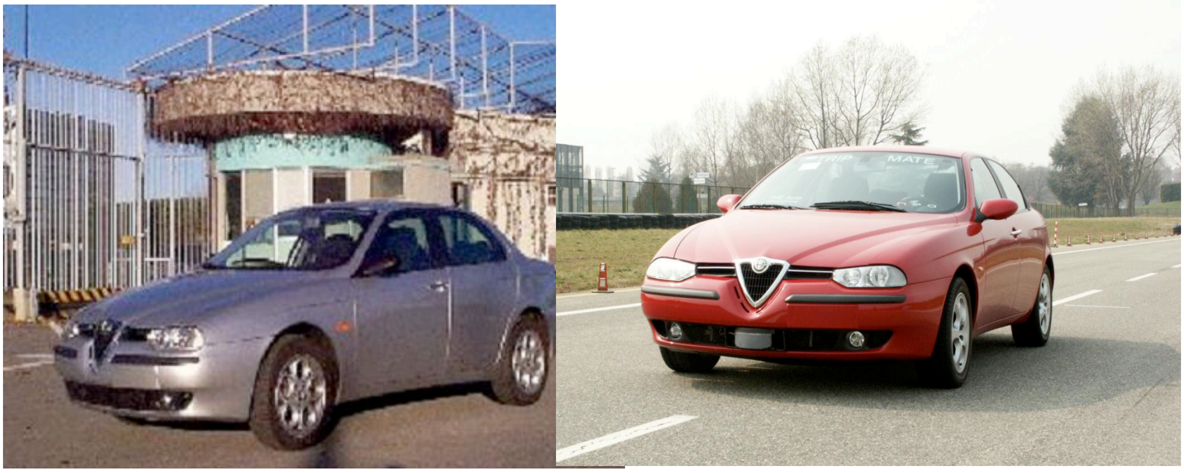


Figure 53 prototype vehicles with the obstacle detection sensors

The first prototype vehicle is equipped with a mono-pulse (multibeam) long range radar (LR1) and two short range radars (SR); the first device covers the frontal area, while the short range sensors are intended to support the detection of side and near obstacles. A scheme of the system architecture is given in Figure 54.

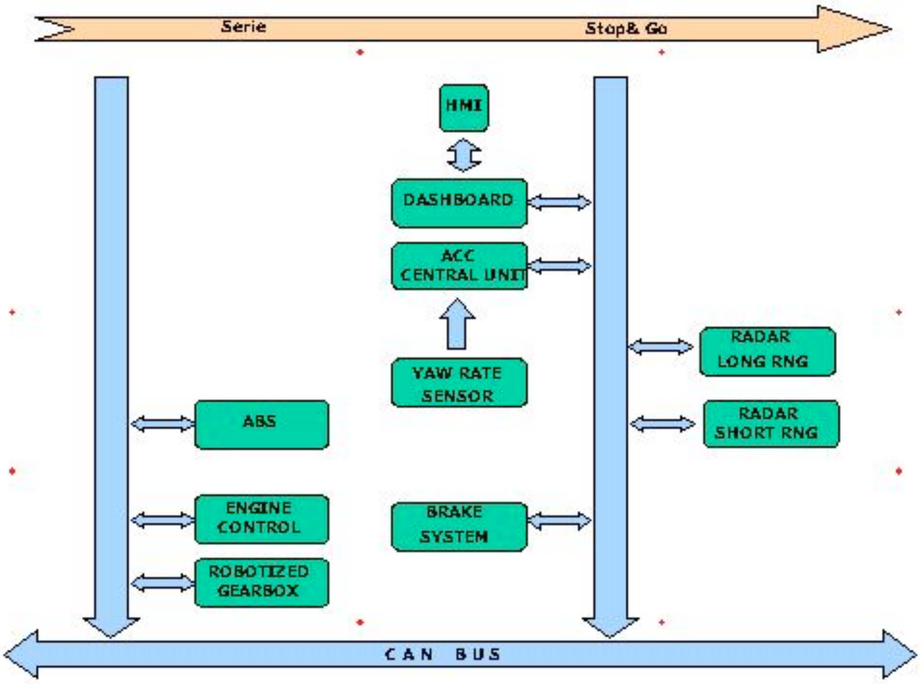


Figure 54 System Architecture

The characteristics of the sensors are reported in the following tables

Long Range Radar (LR1)			
Parameters	Range	Accuracy	Resolution
Operative Frequency	76.5 GHz	---	---
Antenna	Mono-pulse	---	---
Modulation	FSK	---	---
Distance	(1 ÷ 150) m	Max (± 1 m, 5 %)	4 m
Relative Velocity	(-180 ÷ 180) km/h	0.5 km/h	Not given
Horizontal Angular Position	± 5 ° for distance < 40m ± 4 ° for distance > 40m	0.5°	---
Vertical Angular Value	0 ÷ 5 °	---	---
Refresh Time	40 ms	---	---
Update Frequency	25 Hz	---	---

Short Range Radar (SR)			
Parameters	Range	Accuracy	Resolution
Operative Frequency	24 GHz	---	---
Antenna	Single beam	---	---
Distance	(0.3 ÷ 15) m	± 30 mm	not given
Relative Velocity	0-250 km/h	not given	---
Horizontal Angular Position	± 40°	---	---
Vertical Angular Value	0 ÷ 14 °	---	---
Refresh Time	20 ms	---	---
Update Frequency	50 Hz	---	---

The LR1 radar requires in input information about the vehicle speed and yaw-rate (in order to reconstruct the trajectory followed by the car), and gives in output information about longitudinal and angular position, in addition to the relative speed of the relevant obstacles. The short range radar requires in input information about the vehicle speed and gives in output the longitudinal position and the relative speed of the obstacles.

The radar (LR2) on the second prototype vehicle can cover a 50% larger field of view by scanning the beam with an oscillating antenna. Its characteristics are as follows:

Long Range Radar (LR2)			
Parameters	Range	Accuracy	Resolution
Operative Frequency	76-77 GHz	---	---
Antenna	Horizontal mechanical scanning	---	---
Modulation	FMCW	---	---
Distance	(2 ÷ 200) m	2 m	5 m
Velocity	(-360 ÷ 360) km/h	1 km/h	5 km/h
Horizontal Angular Position	± 7.5 °	< 0.1°	1.3 °
Vertical Angular Value	± 3 °	---	---
Refresh Time	100 ms	---	---
Update Frequency	10 Hz	---	---

Like LR1, also LR2 radar requires in input information about the vehicle speed and yaw-rate, and gives in output information about longitudinal, angular position and relative speed of the relevant obstacles.

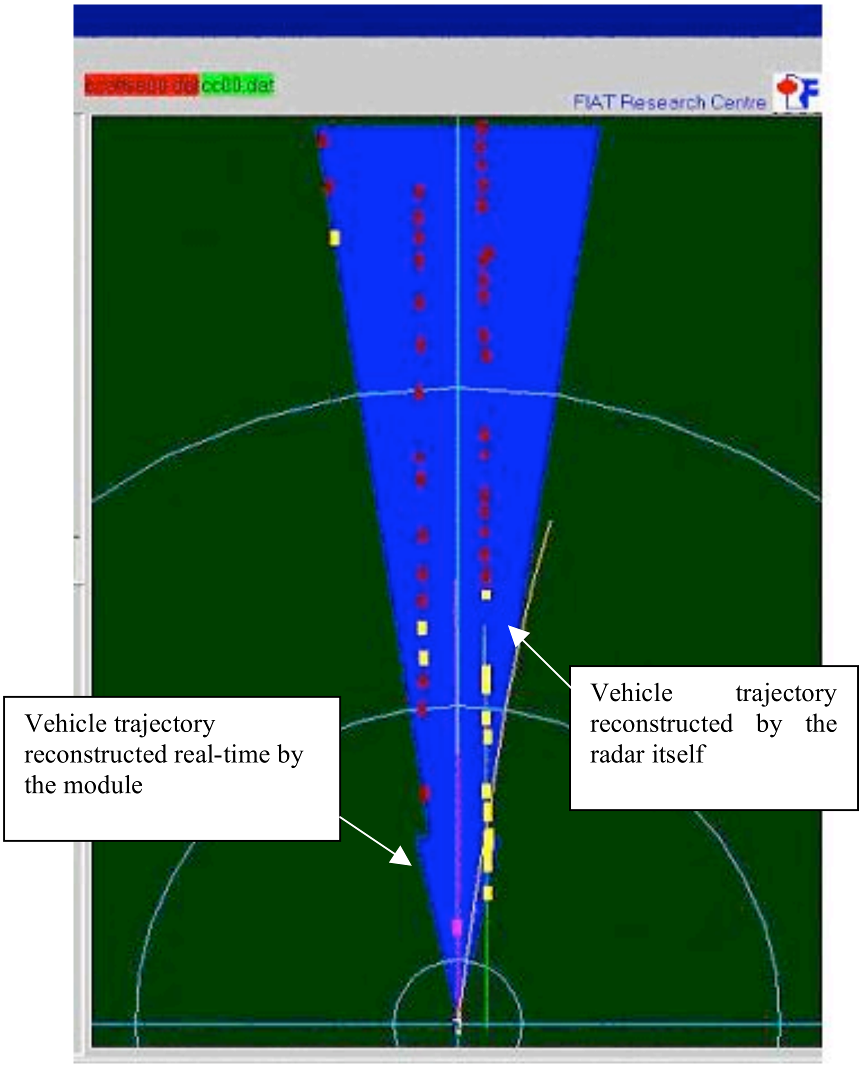
Object data processing

All the data acquired by both long and short range radars, related to objects that are moving or lying in front of the vehicle, are transmitted to the module of data processing. This module is set in order to select the data related to the object on the vehicle trajectory: therefore only these data are transmitted to the control system for the adequate longitudinal and lateral support.

In particular, first of all, the object data processing acquires the measurements of the "n" obstacles in front of the vehicle and creates an "obstacles map" of the objects detected by all the sensors implemented on the prototype vehicle.
Simultaneously, based on the vehicle speed, yaw-rate and steering angle, this module reconstructs the vehicle trajectory and selects the possible "dangerous obstacle" lying on the vehicle path.

The following Figure 55 shows an example of real-time elaboration of the object data processing.

Take note that for simplicity the obstacles are represented as rectangles. The updating of the analysis is based on the sensors refresh time, that is 40 ms or 100 ms, considering the selected sensors for these prototype vehicles.



Vehicle trajectory reconstructed real-time by the module

Vehicle trajectory reconstructed by the radar itself

Figure 55 Example of real-time elaboration of the object data processing

Graphically, the colour of the rectangle changes depending on the relative obstacle speed and on the risk of collision. In particular, the colour brown indicates stop obstacles (that means with relative speed equal to the vehicle one), the colour yellow is related to obstacles with low risk of collision (that means outside the vehicle path) and the colour fuxia the object with the highest risk of collision (that means inside the vehicle path).

If the number of obstacles on the vehicle path is more than one, the nearest is to be considered as the principal target.

The lines in the Figure 55 indicate respectively:

- the vehicle trajectory provided in real-time by the module, based on the steering angle, yaw rate and vehicle speed;
- the vehicle trajectory reconstructed by the radar itself;
- circular lines drawn at fixed distance from the vehicle barycentre, at 10 –50 –100 m.

Summarising, the principal input and output of the object data processing are:

Input – The module collects the information of "n" obstacles in front of the vehicle coming from all the sensor implemented on the vehicle.

Output – The module, after computing the vehicle trajectory, gives information about the presence of the principal obstacle on the vehicle path, providing distance, angular position and relative speed measurements to the control module.

IMPLEMENTATION

The evaluation will be based on track tests with the two prototype vehicles, and different types of obstacles, like other vehicles and pedestrians.
The following test scenarios are considered, according to the procedures defined in the CyberCars project:

- Standing obstacle on the vehicle path at various offsets
- Pass-by situation
- Platooning performance in following a moving obstacle and in braking behind a stopping vehicle

Change of slope

An example of data obtained by the LR2 radar is shown in Figure 56: the scenario is a braking situation in front of a standing car and the final distance is 3.2 m.

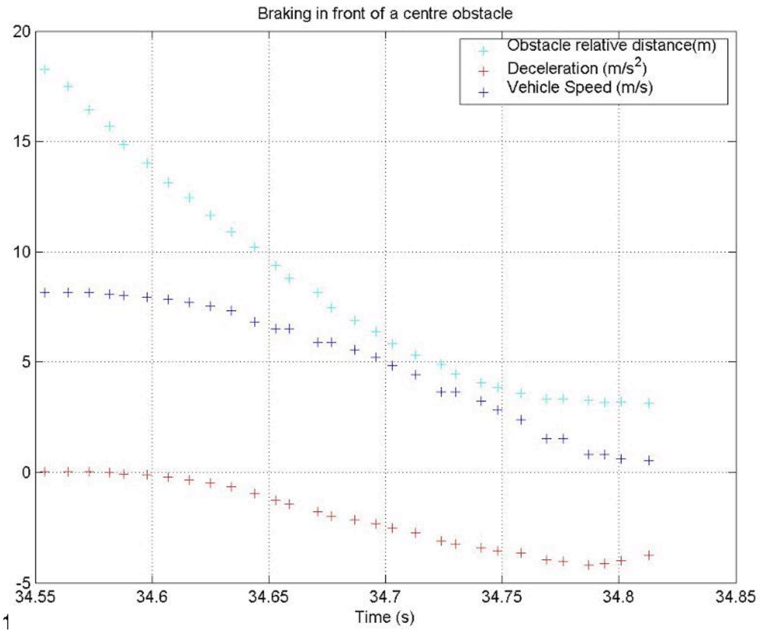


Figure 56 Signals detected in a braking situation with radar LR2.

5.3 Stereo vision (Isr)

5.3.1 Design considerations

The goal of the obstacle detection using stereo vision was the detection of obstacles even if the road was slightly tilted or slanted. Therefore instead of using a inverse perspective mapping approach a quasi-planar model for the road was developed.

The global structure of the algorithm can be represented in Figure 57.

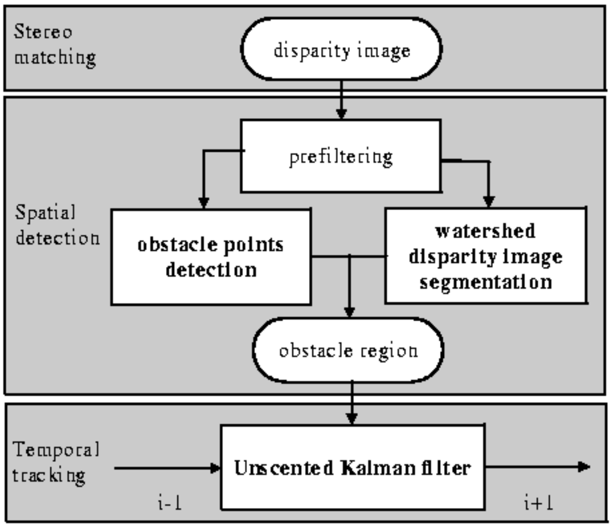


Figure 57 Structure of the stereo vision system

In this model the road is a plane whose normal vector is constrained within a range around the normal of the base plane (Figure 58).

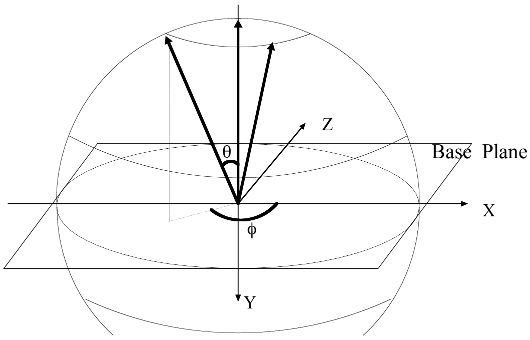


Figure 58 The range of variation of the normal vector

Under this assumption, we define obstacles as objects above the road surface, whose normal vector is almost perpendicular to that of local road surface. According to the quasi-planar scene assumption, the unit normal vector of the road surface *(a_w, b_w, c_w)* can be represented in spherical coordinates as follows (see Figure 58):

$$\{N(R,\theta,\phi) \mid R = 1, 0 < \theta < \theta_0\}$$

where θ is the latitude angle relative to the negative Y axis. The unit normal vector of the obstacle surface can be represented as follows:

$$\{N(R,\theta,\phi) \mid R = 1, \frac{\pi}{2} - \theta_1 < \theta < \frac{\pi}{2} + \theta_1\}$$

where θ_0 and θ_1 are the predetermined thresholds for the road surface and for the obstacle surface, which depend on the road conditions.

Since a plane in 3D is also a plane in the disparity space of the stereo system, a scaled version of the normal vector can be estimated directly in the disparity space. Let us consider the following coordinate systems (Figure 59):

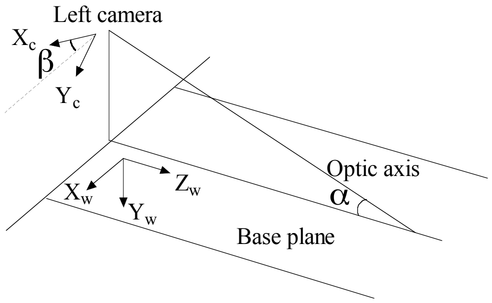
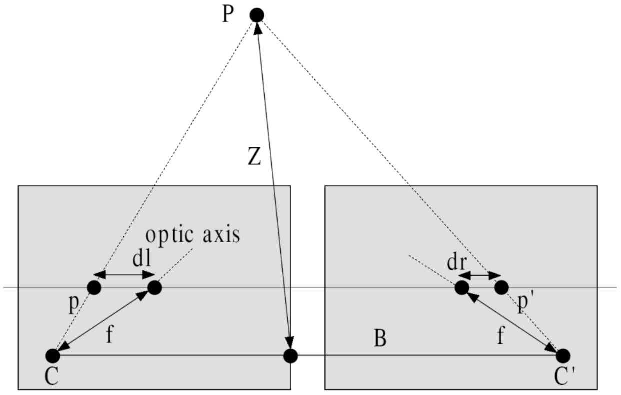


Figure 59 Coordinates used for the stereo system

where R_w is the world coordinate system and R_c is the left camera coordinate system.The angle between the optic axis and the road plane is α and the angle between the X_c axis (which coincides with the baseline) and the X_w axis is β. In the left camera coordinate system, the image coordinates (using a pinhole camera model) can be expressed as in Eq.1. In a stereo system, we can make the approximation that the pixels are square and therefore the scale factors t_u and t_v are equal: $t = t_u = t_v$ Then if f is the focal length in pixels: $f = f_0=t$, where f_0 is focal length in metric units, we have

$$u = f\frac{X}{Z}, v = f\frac{Y}{Z},$$

In a fronto-parallel stereo system we have the following geometrical relationships:



And therefore,

$$Z = \frac{Bf}{d},$$

where Z is the depth, B the baseline, f the focal length and $d = dl - dr$ the disparity. If a plane equation in world coordinates is

$$aX + bY + cZ = 1$$

then its equation in the disparity space *(d, u, v)* is,

$$d = B(au + bv) + Bfc$$

As a result the first two components of the plane normal *(a, b)* can be computed as the partial derivatives of the disparity *d* with respect to *u* and *v*. We obtain:

$$(\frac{\partial d}{\partial u}, \frac{\partial d}{\partial v}) = B(a, b)$$

To classify obstacle points the components of the plane normal are multiplied by a factor that is a depth ratio, which is a function of the points.

5.3.2 Results

At the present development stage a prototype has been realized, with the following characteristics: The processing is implemented in C++ on a commercial Pentium IV 1.4 GHz. The images of 320x240 resolution are grabbed with an IEEE 1394 interface card by a DCAM var-baseline digital stereo head, with 20cm baseline. The whole process for detecting obstacle points and segmentation of isolated obstacles is performed within 40ms.

A summary of the performances is shown in the following table:

	Time (ms)
Stereo analysis	<15
Pre-filtering	<2
Obstacle detection	<5
Watershed segmentation	<15
Tracking	<1

A first example, consisting of an image of the stereo pair, the corresponding disparity image and the detected free space is shown in Figure 60.

A road with non-constant slope, and the obstacles detected using the planar and the non-planar assumption is represented in Figure 61.

The capability to detect obstacle boundaries is indicated by Figure 62.

Finally Figure 63 shows the obstacle detection and tracking obtained with the Unscented Kalman Filter chosen for this application.

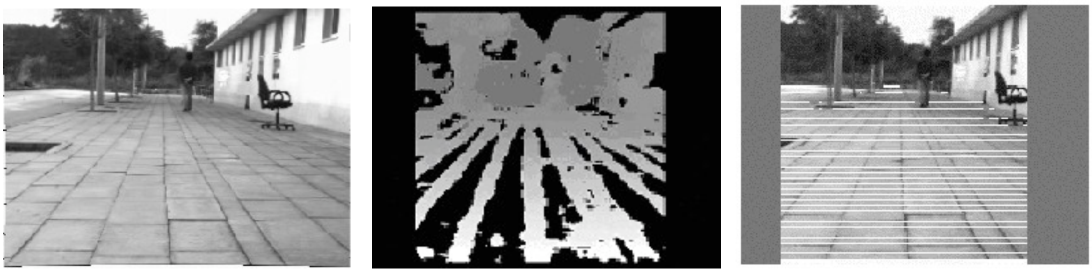


Figure 60 Detection of free space

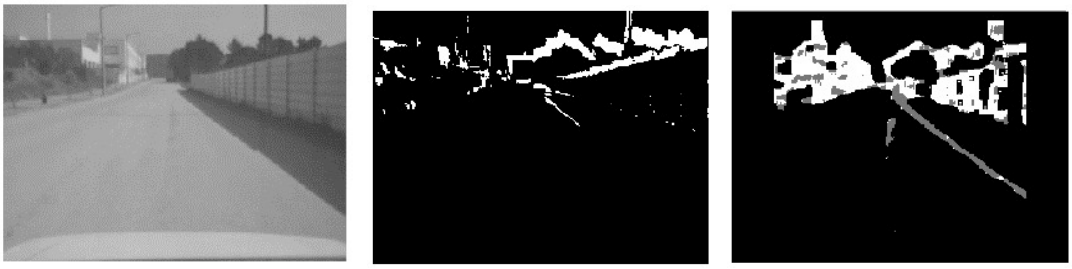


Figure 61 Obstacle detection in a road with non constant slope

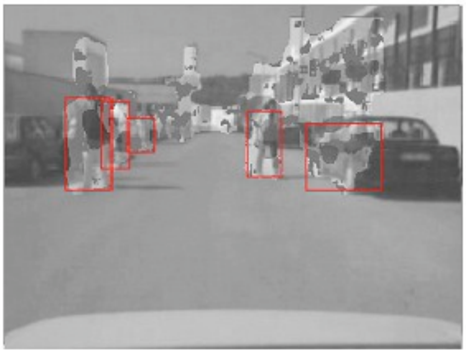


Figure 62 Detection of obstacle boundaries

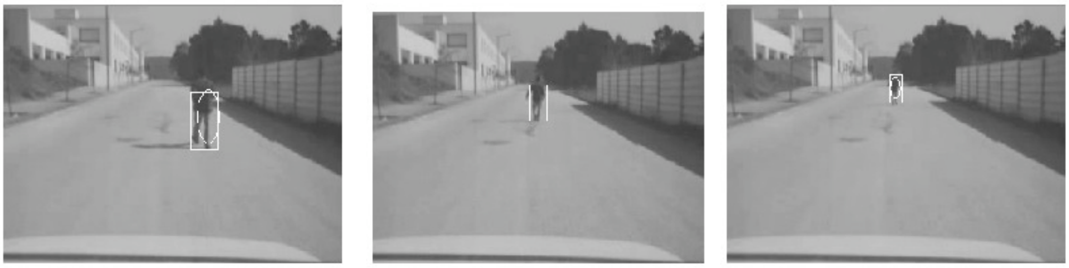


Figure 63 Tracking of an obstacle

5.4 Improved scan laser system (Frog)

This section describes the developments made by Frog for the collision avoidance on their new vehicle, the ParkShuttleII.

5.4.1 Hardware

For obstacle avoidance the Sick laser scanner is used. The Sick laser scanner is (at this moment) the only scanner with an approved regulation certification. The scanner is not suitable for fast data-transfer to a computer. This is necessary for doing the calculation for obstacle detection to determine the position of the obstacle in the field of interest. A special interface was developed to have a data transfer of 300 kbyte/second (sick has standard 30 kbytes/second). With this transfer-rate it is possible to detect an obstacle and do save operations with redundancy. The obstacle detection is also use to determine the brake-behaviour.

5.4.2 Software: Collision Avoidance Module

INTRODUCTION

The collision avoidance controller is an implementation of a reaction module. It is responsible for the detection of obstacles and taking appropriate measures. These include, stopping the vehicle before a collision will occur and slowing down the vehicle for objects that are close to the path of the vehicle. The controller is integrated with the other guidance control modules as shown in Figure 64.

Module Applicability

The main task of the collision avoidance controller is to check if obstacles are on or near the planned path and to take appropriate measures based on that. Note that this differs from guarding the path actually driven by the vehicle. This would require some compromising solution that tries to combine the actually driven path with the anticipated path as we have seen in earlier implementations.

The followed approach separates the overall problem of preventing collisions into two different tasks: guard the planned path (task of the collision avoidance controller) and make sure that the vehicle does not deviate from the planned path (task of the tracking controller).

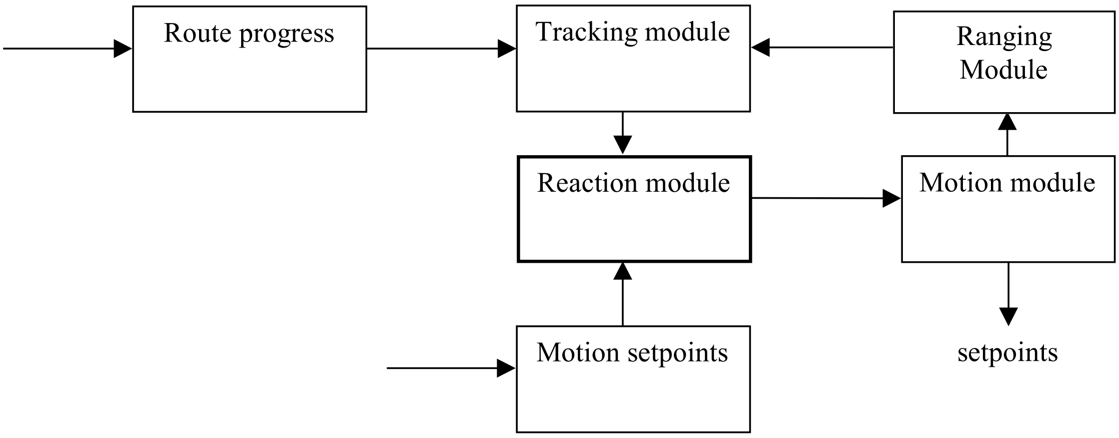


Figure 64 The reaction module and its neighbours

5.4.3 Summary of Features

Easy configuration:

There is no need to define which area should be guarded since this is automatically derived from the commanded route. Required configuration concerns mainly the required reactions for on-path and near-path objects (if a non-default approach is required) and configuring the scanner control strategy. Further, defining reference objects and known objects that should be ignored are optional parts of the configuration

Enhanced reliability:

Since the area that needs to be guarded doesn't have to be specified, no mistakes or inaccuracies can be introduced by giving inaccurate definitions. This has been a major problem of earlier implementations causing the vehicle either to make unnecessary stops for objects outside its path or not to stop at all for objects that actually were on its path.

Statistical obstacle detection framework:

Instead of stopping immediately for every detected obstacle, a three-stage approach is followed. First, an obstacle probability number is derived from observed object characteristics such as object size and distance. This probability is combined with earlier measurements for the same area, which can be either done by the same scanner or by other scanners. Next, based on the combined probability number some required reaction is defined for each detected obstacle, including a maximum driving velocity. Finally, all reactions are combined into a set of reaction requirements that are used to generate a velocity profile and a route progress value limit. This statistical approach provides some level of ghost object filtering and also enables to combine measurements from different scanners

Measurement ageing:

A measurement ageing mechanism models the fact that object measurements have a limited relevant lifetime. The obstacle probability for areas which have not been scanned for some time will converge to some defined obstacle probability number. For these areas, reactions requirements will be computed which are combined with other required reactions based on scanned areas to compute the final set of required reactions

On-path and near-path objects recognition:

A distinction is made between objects detected outside the vehicle's path and those that are on its path. For those two groups of objects, different reactions can be configured in the so-called reaction strategy. The default configuration is that the vehicle will slow down while passing an object that is outside its path and stop for obstacles that are on its path.

Extended reaction computing:

The computed reaction for the set of detected on-path and off-path objects is not limited to just stopping in time with some fixed deceleration as was the case in earlier designs. A reaction is computed frequently based on the current set of computed reaction requirements. These reaction requirements are defined as an ordered sequence of velocity restrictions, each of which is valid during a defined driving interval (partly in the past, mainly in the future). From these requirements, comfortable speed profiles are generated and used for limiting the driving set points during each cycle. Apart from this a maximum route progress value is computed and output. External controllers must ensure that the vehicle will not drive beyond this point.

Control strategy:

A strategy is used to configure the activation of the available scanners. Since this is likely to be application specific, this has been designed as a separate sub-module.

Range scanner test based on reference objects:

Optionally, the configuration may include the definition of reference objects, which then will be used to test associated range scanners. Such tests are done on the fly when the vehicle passes these reference objects. From the measured information metrics such as scanning range and beam height and direction are computed and checked

Dealing with defined objects:

Optionally, a set of objects can be defined, which will be ignored when being detected. The intended use for this is, for example, to ignore nearby walls, stations, and so on. This mechanism is designed to be safe in the sense that only off-path parts of such defined objects are actually taken into account.

World simulation and Range Scanner simulation:

Apart from the collision avoidance controller, a mechanism is provided enabling to define a simulated environment in which obstacles can be defined. Also, a simulator is available enabling to simulate the behaviour of range scanners. Together, this enables to drive the vehicle through the simulated world in which simulated scanners detect simulated obstacles

Integrity:

The collision avoidance controller provides a number of hooks that can be connected to an integrity mechanism, being:

- Integrity condition of the controller itself, representing correct functioning
- Integrity conditions associated with the test result for each range scanner for which reference objects have been defined
- Integrity conditions of each range scanner
- Scan age of scans of each range scanner

Logging and visualization support:

The main flow of information inside the controller goes through variables and therefore can be logged. This is:

- Raw scan data
- Range scan data
- Clockwise ordered scan data
- Recognized objects
- Reaction requirements

Tools are provided to plot or display this information. Besides, additional tools are available to make snapshots of relevant information and to plot this.

5.4.4 Design description

Figure 65 provides an overview of the main submodules of the collision avoider. The base actions and flow of information is as follows:

Whenever a range scanner has a new range scan available, the data collector gets that information
The data collector generates a clockwise ordered scan from the range scan and outputs that information
The main con
troller receives clockwise scans from the data collector and instructs the object detector to update the object memory according to that information

Asynchronously or synchronized with receiving scans, the main controller instructs the object detector to produce a set of reaction requirements based on the current state of the object memory. The main controller then outputs these requirements. The exact moment at which reaction requirements are computed is determined by the installed reaction strategy. Different strategies can be for example to simply do the computation at a fixed rate or to do that after scans have been made by a specific group of scanners.

When a new set of reaction requirements have become available, the reaction processing module computes a new progress limit (rp-lim) and a schedule for limiting the motion setpoints
The following subsections describe each of the submodules in more detail.

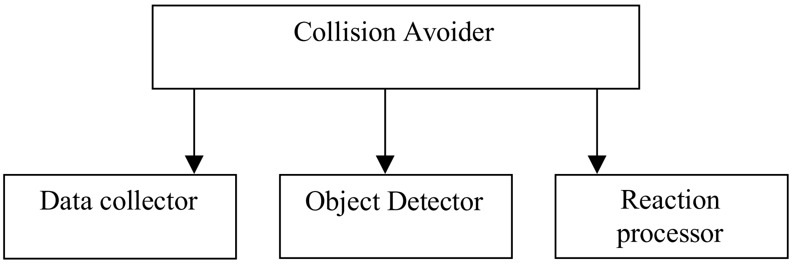


Figure 65 Scheme of the collision avoider

Data collector module

The data collector module searches the assembly tree for range scanners. It handles range scans from each of these scanners and outputs such information after having it converted into clockwise ordered range scans. This module uses a control strategy to determine if and when specific range scanners have to be enabled or disabled.

Object detector module

This module is responsible for the detection and classification of objects based on collected clockwise scans. Also, it is responsible for computing a set of reaction requirements based on earlier detected objects that have been classified as obstacles.
To perform these tasks, this module keeps an object memory consisting of a square grid of cells of roughly 0.5 x 0.5 meter. In this memory, the information from the scans is represented as probabilities that obstacles are present in each of these cells.

Area of interest and ignoring defined objects

In the coming subsections, the main tasks of this module will be described in detail. For each subtask, a common set of information is needed that is be used to determine where the geographical area of interest exist that has to be considered in the computations.
The area of interest (Figure 66) is computed based on two hull curves specifying the path that the vehicle will follow. These hulls are based on the route for the vehicle and are derived from the position of the corners of the vehicle when the control point is moving along the route. Currently, the use of only one control point is supported.
The first hull (base hull) is simply the hull of the vehicle, extended laterally with the expected lateral uncertainty. The second hull (extended hull) is derived from the base hull by widening it in lateral direction. At any moment, only a section of the hulls from the beginning up to the end of the route is used. This is, the section beginning immediately behind the vehicle and up to some maximum distance in front of the vehicle.
The idea behind using two hulls is that whenever some object is found within the base hull, it is considered to be an obstacle for which the vehicle ultimately will have to stop. If an object is found outside the base hull but within the extended hull, it is considered as an object for which the vehicle may have to slow down (while passing it) but not as an obstacle for which the vehicle has to stop.

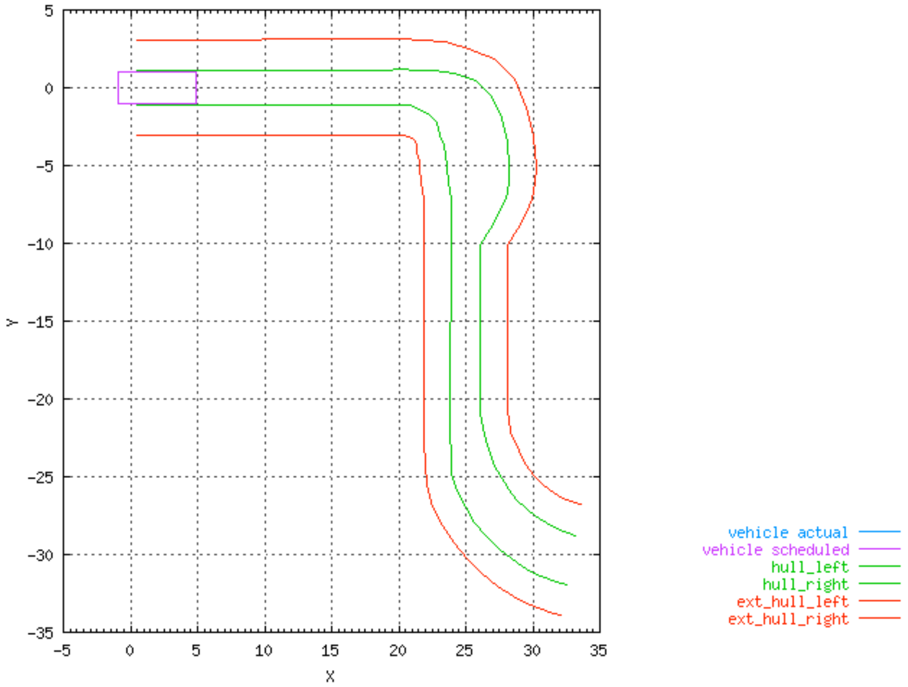


Figure 66 Area of interest specified by hull curves

When the vehicle moves, the hulls are extended at one side and cut off at the other side. At any time, the area that is covered by the extended hull is defined to be the current area of interest. Object detection and reaction processing is done only for that area.
Whenever the hull is extended, the area defined by the new hull section is compared with optionally defined objects that have to be ignored. If the two overlap, the object memory cells that are within the area of interest but outside the base hull are marked as 'ignored'. This will be used at a later stage during computing reaction requirements based on the state of the object memory to ignore those cells associated with the defined objects.

Object detection and classification

Following the scan in clockwise direction, each point of the scan is checked to lay within the extended hull. If not, the detected object is ignored. If it is inside, it is considered to be a relevant object measurement. A sequence of detected relevant object measurements are taken together and considered to belong to a single object as long as the measured distance to the scanner does not change too much. If object measurements are found with a significant change of distance to the scanner, they are considered to belong to a different object. From the scan points belonging to a single object, the object size (as seen from the point of view of the scanner) is computed. This is the sum of the distances between each adjacent object point plus some extra size based on the scanning angle resolution (see Figure 67).

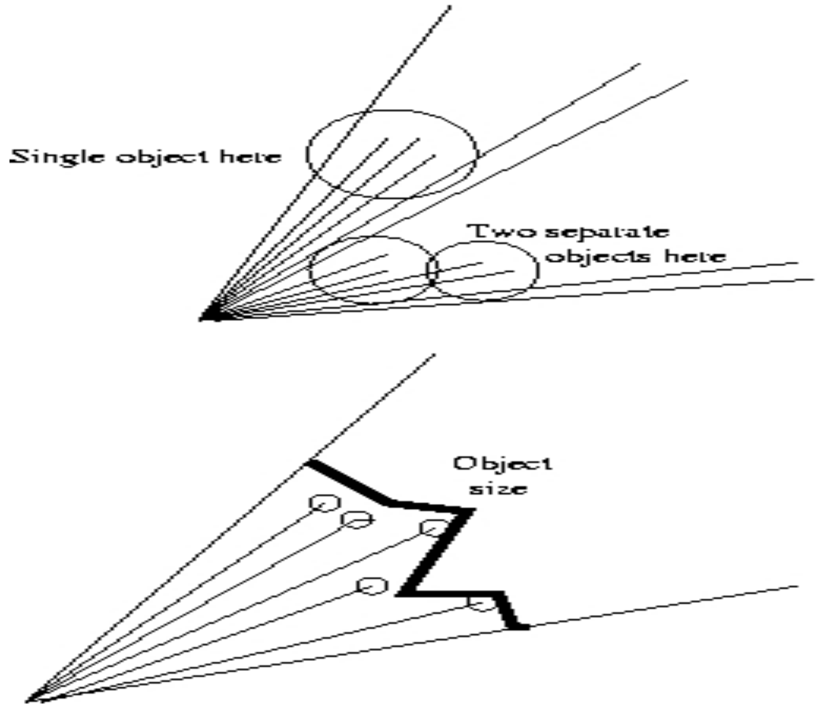


Figure 67 Computation of the size of a detected object

From the object size, a probability update number is derived that represents the level of certainty that the detected object is really an obstacle. The detection strategy is used to obtain that probability number. Very small objects are almost certainly not obstacles, but merely measurement noise or detected rain and alike. Very big objects are almost certainly real obstacles. The probability update number is used to update the obstacle probability figure as stored in the object memory.

Object memory updating based on scans

The object memory is implemented as a square matrix of cells big enough to hold the maximum hull length that needs to be considered at a given time (roughly 120 x 120 meter). The memory is moved when the vehicle has moved, such that the centre of the object memory always corresponds with the current vehicle. Cells that are added to the object memory after a move are initialized with a specified initial obstacle probability. This number can be used to express an element of the required strategy: must areas be scanned free before the vehicle moves in or do we want to drive everywhere unless an obstacle has been actively found in that area.

A subset of the object memory cells are updated for each beam of the processed scan. Only object memory cells that lay within the area of interest are updated. For each updated cell, the obstacle probability and the update time are updated. Cells that lay behind an area that is outside the area of interest as seen from the point of view of the scanner are not updated. This is, only areas that have line of sight from the scanner and for which the beams from the scanner to those areas lay completely above the area of interest will be processed.

The actual updating of object memory cells is done as follows:

- For each scan ray that hits an object within the extended hull: update the object memory cell priority as occupied for each cell that is crossed by the line section starting at the detected object and ending at the maximum scan distance in the scan direction. The exact probability update value is the value that was computed based on the object's size. Note that object memory cells they lay behind the found object are also updated with the same obstacle update probability number. This is, since the 'depth' of the obstacle is unknown, the obstacle is assumed to stretch as far as the length of the scanned area.

- For each scan: consider updating the object memory cells that are intersected by the line section starting at the scanner center position and ending at the scanned free distance. But, update only those cells that have not yet been updated in step 1. If reference objects have been defined for the associated scanner, only update memory cells that are within the verified reliable scanning range for the related sensor group

Since the object memory is updated for each collected scan, the information of different scanners that wholly or partly cover the same area are combined over time. The configuration of probability update numbers determine what the combined obstacle probability for each cell will be.

Object memory updating for measurement ageing

The obstacle probabilities associated with cells of the object memory that lay within the area of interest are continuously updated as an effect of ageing of the information that was used to compute the obstacle probability for those cells.

The final obstacle probability that the ageing process will converge to and the ageing rate are parameters of this mechanism. This final obstacle probability can be seen as an parameter of the strategy that is required to be followed: only recently scanned areas can ever be assumed to be obstacle free or, found obstacles may no longer be there after some time after which they were found and will therefore evaporate. A reasonable approach might be to let the probability converge to one if enough scanners are available so that every part of the entire area of interest is scanned. If less scanners are available, a compromising approach may be to let the probability converge to some value for which only driving at a low speed is required. In such case, additional sensors may be required to obtain a safe overall solution.

Reaction processor

A reaction processing strategy determines when reaction computing is done. By default, this is done at a fixed rate. The strategy enables, for example to compute reactions only when specific scanners or groups of scanners have produced scans, which can be useful if multiple scanners are scanning overlapping areas.

Computing reactions is conceptually done for each cell that lies within the current area of interest. However, cells that have been marked 'ignored' (as done for defined objects that have to be ignored) and cells that lay under or after the current vehicle position (those are marked to be 'passed') are no longer considered.

Reactions are computed for two slightly different cases:

- Slowing down or stopping for obstacles detected within the base hull, and
- Slowing down objects detected outside the base hull but within the extended hull

Computing these reactions is done by using the object detection strategy, which specifies maximum velocity for found obstacles and objects. To account for uncertainty in the orientation of the vehicle, the check whether a found obstacle or object is within the base hull is made dependent on that uncertainty. This has as effect that objects far away are sooner found to be inside the base hull than objects closer to the vehicle. At very large distances, the extra margin is reduced again. This is done to prevent extraordinary large margins, whereas obstacles at these distances and at the border of the vehicle path are not really of much interest.

The min/max progress values are based on the location of the obstacle, a required stopping margin, and the dimensions of the vehicle.

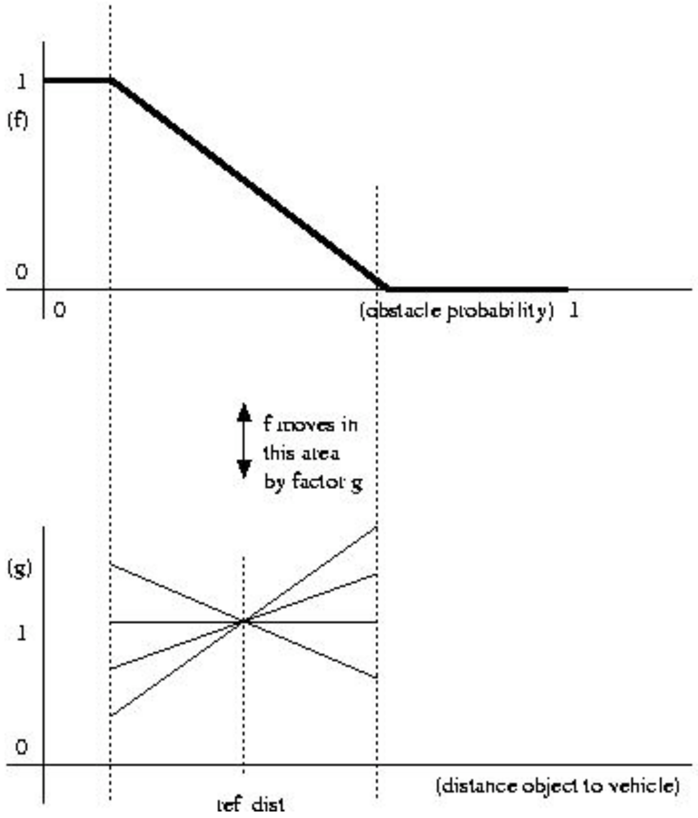


Figure 68 Snapshot of the object memory state (obstacle probability values)

The default strategy implementation uses the following method to compute the maximum velocity:

- a factor f is computed that is used later to scale the maximum driving velocity (see Figure 68) This value is 1 for small obstacle probabilities and 0 for high obstacle probabilities. In between, it may vary from 1 to 0.
- a second function g is used to scale the value of f for in-between obstacle probabilities. This scaling is done based on the relative distance to a reference distance
- if the object is found to be within the base hull (taking into account the orientation uncertainty) f * g * unconstrained velocity is returned. If the object is outside the base hull, the passing velocity is computed as Vmin + a * lateral_distance_outside_curve, with a = a_min + f * g * (a_max – a_min).
- the result of reaction requirement computing is a sequence of {minimum progress, maximum progress, maximum velocity} requirements. These progress ranges are non overlapping and the maximum velocity constraint is lower for each successive requirement.
- The potentially many reaction restrictions (remember that they are computed for each object memory cell within thearea of interest) are combined into a much smaller set. This is done by the following methods:
- By classifying the maximum velocity value
- By classifying the distance from obstacle to vehicle
- By generating a new requirement for higher progress values only if that requirement specifies a lower maximum velocity than its predecessor
- By a hard limit on the number of requirements that may be generated. This is done since the high processing power needed to process even a rather small number of reaction requirements.

Note that, despite the limited resolution of the object memory cells, the final accuracy with which objects are found to be within or outside a hull is only determined by the accuracy of that hull itself.

5.4.5 Implementation

Implementation of the avoidance module is done on the prototype of the ParkShuttle, the CTS for Rivium2.

5.5 Laser based system for obstacle detection (Robosoft)

5.5.1 Objectives

The main goal is to validate a certified (related to the machinery directive) anti-collision system for the RobuCab.

With the laser detection, we want the vehicle to have a good behaviour with obstacles. Detecting them, the vehicle must be able to slow down and stop.

5.5.2 Description

One of the few available certified devices is the laser PLS (SICK) that is a on shelf component with Machine Directive 98/37 EU certification.
This laser has two fields which shapes can be changed (Figure 69). The one is a warning zone that makes the vehicle decrease speed, the other is a protect zone that stops the vehicle.

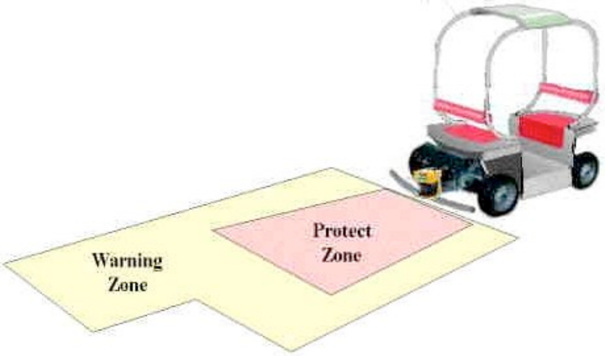


Figure 69 The two zones of the PLS

The two logical outputs of the detection module are connected to a MPC555 board, shown in Figure 70. The speed modification is made by the microcontroller in a SynDEx application.

Figure 70 The MPC555 board

5.5.3 Results

The project activities allowed to reach an operational stage starting from a simple mock-up. For indoor applications, with a correct definition of the warning and stop zones, this system has shown its effectiveness on a real Cybercar in operation.
Some basic aspects are as follows:

- For a velocity of 12 km/h we set the protective field range to 2 m, and the warning field range to 20 m.
- The Response time is 80 ms minimum, depending on the accuracy needed
- This system is sensitive to direct lights. For outdoor application, we encounter problems with strong rain and condensation due to a transition between a cold and a hot area. We had to increase the response time to 480 ms to filter some objects like falling leaves or rain drops.

5.6 New Applications of ultrasonic detection (Robosoft)

5.6.1 Objectives

The objective is to install on the RobuCab an ultrasonic based anticollision system and compare it with the laser system.
With the ultrasonic detection, we want the vehicle to have a good behaviour with obstacles. Detecting them, the vehicle must be able to slow down and stop. This solution is intended to be cheaper than the laser solution.

5.6.2 Description

We use the Trans O Prox module (Microsonic) with WMS800 (Microsonic) sensors which is an on shelf component but does not have the Machine Directive certification.
The sensors have 2 fields which shapes cannot be changed (Figure 71), only 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.

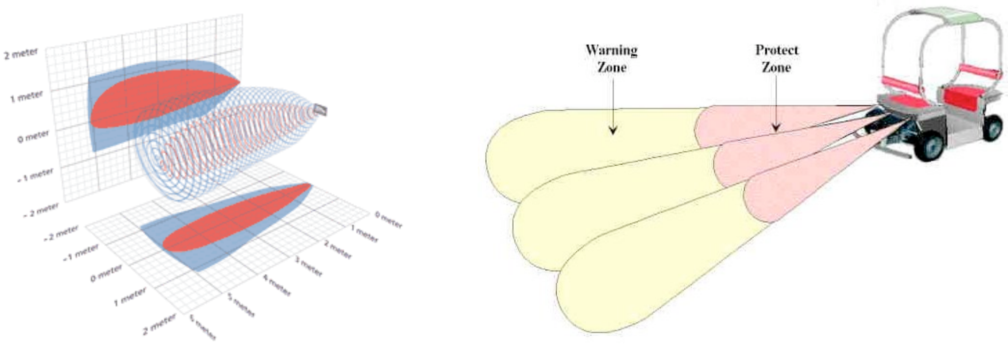


Figure 71 The Ultrasonic shape (left) and the two zones (right),

The two logical outputs of the ultrasonic module are connected to a MPC555 board (Figure 72). The speed modification is made by the microcontroller in a SynDEx application.

Figure 72 The MPC555 board

5.6.3 Results

- 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 (this feature is much more difficult to implement on the laser);
- We have to mix several kind of sensors (with different shapes) to improve the quality of detection;
- It cannot be used alone because this is not a certified sensor.

5.7 Stereo Vision Using the Fly Algorithm (Inria)

In this work we present a novel technique for fast stereo reconstruction based on artificial evolutionary algorithms. The ``fly algorithm'' is a fast artificial evolution-based technique devised for the exploration of parameter space in pattern recognition applications. In the application described here , we evolve a population of individuals which constitutes a particle-based three-dimensional representation of the scene. Each individual represents a three-dimensional point in the scene. Evolution is controlled by a fitness function which contains all pixel-level calculations and uses classical evolutionary operators (sharing, mutation, crossover). Test results on real road scene are presented.

5.7.1 Introduction.

Most stereo-vision algorithms used in robot vision use an image-oriented approach: after an initial image segmentation step, they exploit the epipolar constraint to find the best match between image segments given by two or more cameras. Depth information is derived from the disparities detected.

In our approach we view stereo-vision as an optimisation problem. It is translated into a search in the space of all possible 3-D models that represent the scene; however stated thus the problem becomes easily intractable, special care should be taken in the choice of the 3-D models. In order to reduce the size of the search space, our 3-D models consist of a set of 3-D points in space that represent sparsely the scene. This representation is obviously not adequate in applications where a complete scene description is required, however it can be very useful when the task to be solved does not need a complete scene description. Unlike classical stereo-vision algorithms which analyse the images for a solution to the 3-D reconstruction problem, our approach can be viewed as a space-based approach, in which we propose a candidate solution in 3-D space and verify its validity in the images (2-D space).

The Fly algorithm[1] described here is an evolutionary algorithm devised for parameter space exploration in computer vision applications, which has been applied to stereo-vision. It is based on the Parisian paradigm[2] which treats each individual as a part of the solution of the problem rather than as a complete solution. Its basic principle is to evolve a population of 3-D points (the `flies') in order to optimize an objective function such that the flies concentrate onto the surfaces of the objects in the scene.

5.7.2 Previous work.

Artificial evolutionary algorithms have become widely used optimization techniques and we are starting to see many application of evolutionary algorithms in computer vision problems. We can cite for example Roth et al. [3] and Lutton et al. [4] who developed genetic algorithms for primitive extraction, Fan [5] and Bhanu et al. [6] for their work on image segmentation. In pattern recognition applications, Hill et al. [7] employed genetic algorithms in medical images interpretation; Bebis et al. [8] worked on 3-D shape recognition in multiple images. Fujiwara [9] and Sawai [9] worked on 3-D face reconstruction with 3-D mesh optimization. In this work we describe a new 3-D reconstruction technique based on evolutionary computation.

5.7.3 Evolutionary 3D reconstruction.

A fly is defined as a 3-D point with coordinates . We suppose that the cameras' calibration parameters are known, hence the coordinates and of a fly's projections on the left and right images of the stereo pair can be easily calculated using projective geometry. If the fly is on the surface of an opaque object, then the corresponding pixels in the two images will normally have highly similar neighborhoods (Figure 73). Conversely, if the fly is not on the surface of an object, their close neighborhoods will be poorly correlated. Figure 73 illustrates this idea.

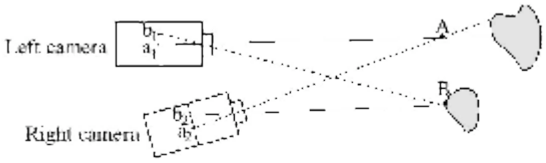


Figure 73 Pixels and projections fly have identical grey levels, while pixels and projections of fly which receive their illumination from two different physical points on the object's surface, have different grey levels.

The role of the genetic operators is to evolve a population of flies, first initialised without any reference to the scene, toward a spatial distribution such that their local average density gives a good representation of the probability of presence of an obstacle within the field of view. To this end, we defined a fitness function [1] which exploits the above property by evaluating the degree of similarity of the fly's image projections, giving higher fitness values to flies lying on objects surfaces.

The gradient intensity in the numerator is used to reduce the fitness of the flies which project onto uniform regions and are therefore less significant. Best experimental results are obtained when is defined as the norm of the gradient calculated with a Sobel operator. Additionally, we modified the denominator of the fitness function to reduce its sensitivity to the constant component of the image, which strongly depends on camera sensitivity adjustments.

Evolutionary Operators.

Our aim is to evolve the flies' positions so that they concentrate where fitness is highest, corresponding to space regions with high obstacle probability. Evolutionary Strategies provide a powerful tool for such collective optimisation, using biologically-inspired Darwinian evolution operators.

At each generation, evolution and selection operators are applied, in order to evolve the population's individuals toward better solutions. However, classical artificial evolution aims at optimizing a single individual in a population. Here, unlike in most optimization problems, our aim is not to find one optimal solution but use the whole population to represent the potential solution, following the Parisian Evolution scheme.

The population is initialized randomly inside the intersection of the cameras' fields of view. The initial statistical distribution is chosen in order to obtain a uniformly distributed projections in the left image.

5.7.4 Experimental results.

In this section we show a few results on real road scenes treated off-line. Undergoing work aims at implementing an on-line version on a CyCab vehicle equipped with a stereo camera system and an on-board PC. Additionally the vehicle has a IBEO lidar [16] which gives additional depth information that our algorithm fuses with visual data to build a representation of the scene. Figure 74 shows typical reconstruction results. The results were obtained after 30 to 40 generations of 5000 flies after 1.05s to 1.4s of computation time on a standard commercial PC with a 2GHz CPU. Figure 75 shows a typical fitness profile.

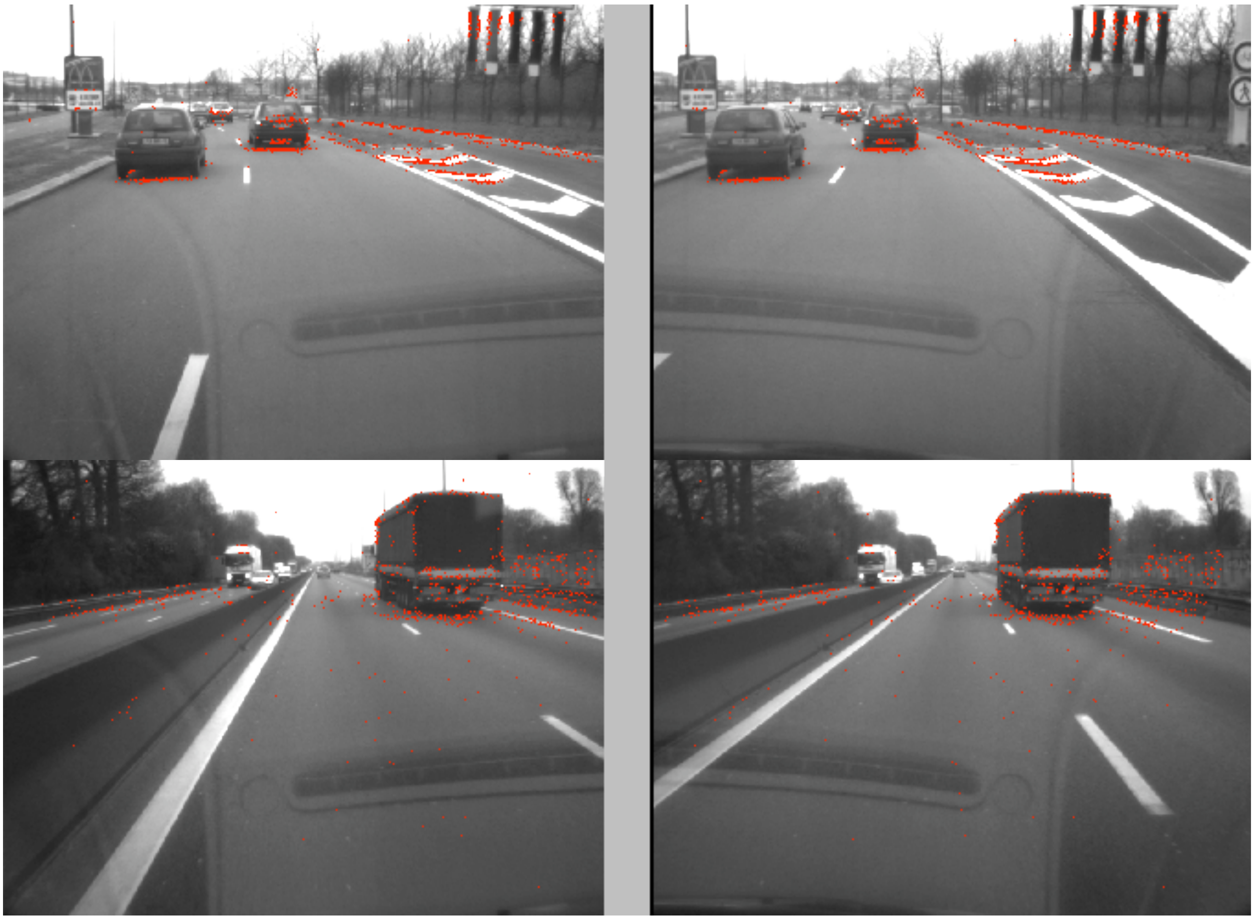


Figure 74 : Reconstruction results (red points), shown on the left and the right images.

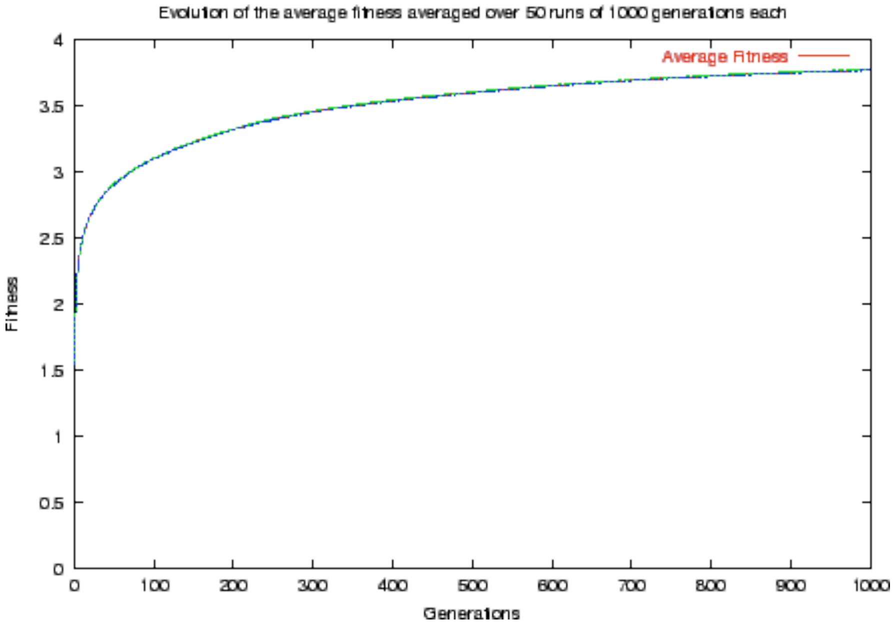


Figure 75 : Fitness evolution over time.

5.7.5 Conclusion.

In this paper, we show that Parisian Evolution Strategies are able to provide an efficient, lightweight alternative to classical techniques used in mobile robot stereo-vision, sensor data fusion and trajectory planning.

One interesting property of the Fly algorithm is its ability to deliver progressive results and not needing any costly image segmentation. CMOS camera technology is particularly well adapted to this technique as it is able to deliver asynchronous up-to-date pixel data upon request from the algorithm. Perception results are continuously refined and readily available for the trajectory planner. The robot is thus able to react to new external events almost immediately, without the usual delays found in classical systems due to image delivery rate and the classical need to terminate with image processing before engaging into further computations.

The fly algorithm will not provide an accurate scene reconstruction comparable to image segmentation-based techniques. On the other hand its ``anytime algorithm'' [17] properties and efficient exploitation of state-of-the-art image sensors allow faster response to external events than any classical method subject to image refresh rate, with reduced computing power. This may be a choice for embedded applications where both low production cost and fast response are critical.

5.8 Path-Tracking Controller with an Anti-collision Behaviour of a Cybercar (Isr)

5.8.1 Objective

This aim of this research is to develop a path-tracking controller of a bi-steerable cybernetic car with an anti-collision behaviour. The velocity planner and the anti-collision system are fundamental modules in the architecture. The path tracking implementation uses fuzzy logic. The smoothness of the acceleration profile was one of requirements taken into account in the controller design. The anti-collision system based on Laser Range Data consists of estimating the trajectories and behaviour of surrounding objects. Simulation and experimental results are presented showing the effectiveness of the overall navigation control system.

5.8.2 Navigation System

CONTROL ARCHITECTURE

The control architecture is made up of two main modules: the Velocity Planner Module (VPM) and the Path Tracking Controller (PTC). The VPM provides the desired trajectory, and computes the maximum velocity and the comfortable velocity based on the *curvature*, external factors, and the passenger's comfortable acceleration. External factors are tyre characteristics, road slope and weather conditions. In order to follow the trajectory, the actual position computed by odometry (with some re-calibration procedure using landmarks) is fed as input. The next desired position and the reference velocity are fed to PTC.

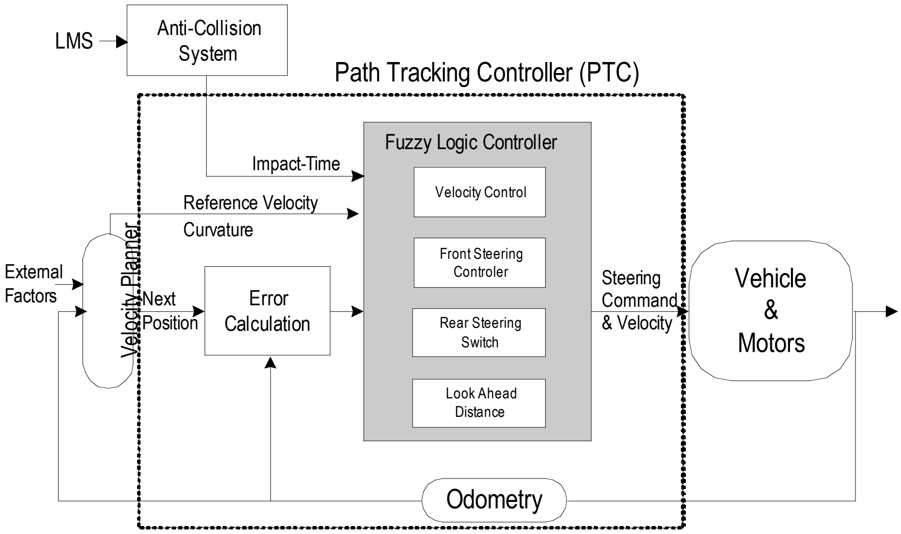


Figure 76 Navigation system architecture, with an anti-collision behaviour.

In the PTC the errors between the desired pose and actual pose are used as inputs to the Fuzzy Logic module that converts them to desired commands. Additionally the impact-time computed in the anti-collision system is provided to the PTC. The collision avoidance is made by controlling the vehicle reference velocity, this means reducing or even stopping the vehicle in situations of eminent danger. A position error and a heading error are measured for every new iteration.

KINEMATIC MODEL OF THE CAR

The car has the ability to steer both the rear and the front pair of wheels. The classical model, which considers an imaginary wheel at the mid point of the wheels axles so that it is oriented in the direction of the steering command is used. Wheels rolling without slipping assumption were made in simulations.
The vehicle kinematics, motors and odometry models were considered in the simulations. They are vehicle dependent and their relevant parameters are described in this section.

VELOCITY PLANNER MODULE

The VPM estimates the linear reference velocity in which the vehicle should travel (which can be the maximum value allowed or not), as well as determines the next reference trajectory point. One main objective taken into account was to make the travel as comfortable as possible, i.e. to give the system the capability of fully control the smoothness of the acceleration profile either lateral, or longitudinal.

PATH-TRACKING CONTROLLER

The PTC is divided in four independent modules: Steering, Rear Steering Switch, Velocity Control and Look-ahead Distance. The anti-collision system provides the impact-time as input to the PTC. In order to properly avoid collision with obstacles the impact-time is integrated in the velocity control module.

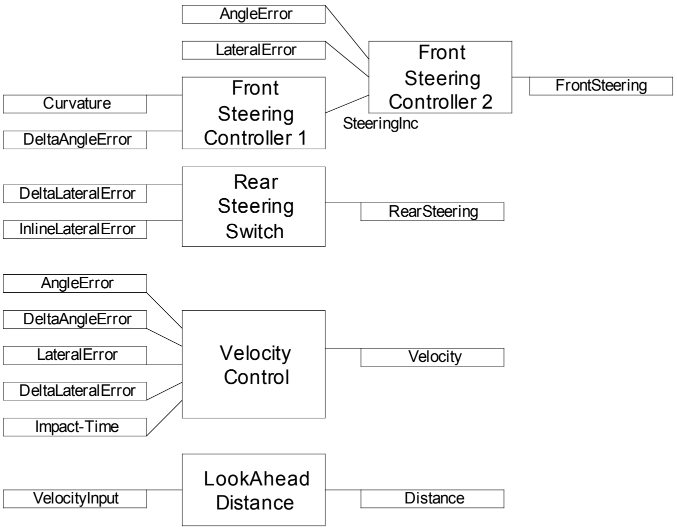


Figure 77 PTC Structure.

The Front Steering module (composed by controller 1 and 2) computes the steering command. The purpose is to minimize both the orientation error, and the lateral error. Additionally a Steering Increment *SteeringInc* fuzzy variable is computed in order to achieve a faster recovery from an undesired pose. The variable *SteeringInc* is the output of a fuzzy module which has as inputs the *curvature* and the *Delta Angle Error*. This module ensures a geometrical convergence towards the path to be followed.

The Rear Steering Switch module decides whether the rear axle should steer to opposite direction of the front axle (Dual Mode) or in the same direction (Park Mode). The inputs for this module are the Delta Lateral Error and the Inline Lateral Error (ILE). This module steers the rear wheels in the same direction as the front wheels; the result is a decreasing of the vehicle yaw motion. The yaw motion is necessary for executing a manoeuvre but is undesired for the stability of the vehicle.

The Velocity Control module computes a weight factor assigning a level of significance to the reference velocity, i.e. if the errors have a high magnitude or the impact-time as a low magnitude then the velocity must be decreased, otherwise the reference velocity is applied. This module is of extreme importance since the collision avoidance is decided here, i.e. if the impact-time is small, then the vehicle velocity is reduced or null, otherwise if the impact-time is high the vehicle velocity (weight factor) is not affected by this variable.

The Lookahead module computes a distance D to a point in front of the vehicle called the VP. This distance is function of the vehicle velocity.

5.8.3 Anti-Collision System

The following block diagram describes the dataflow between the modules, which constitute the anti-collision system: Segmentation, Object Tracking, Obstacle Classification and Impact-time Computation.

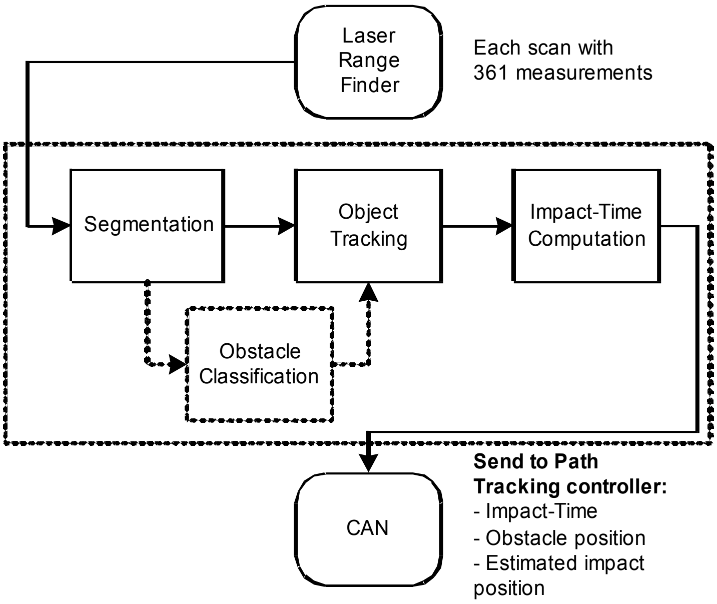


Figure 78 Anti-collision system architecture.

SEGMENTATION

The goal here is to identify the limits of possible existing objects detected by the LMS and if so, to filter and provide additional information about the object in analysis. The readings are subdivided into small sets of neighbour points (segments), taking into account the proximity between two consecutive points of the scan. A segment is, hence, a set of measurement values (points of the scan) close enough to each other, which due to their proximity probably belong to the same object.

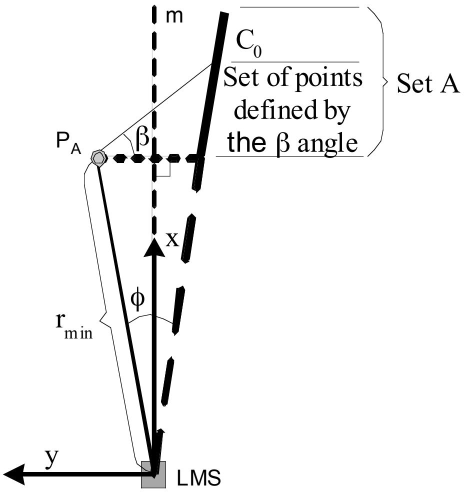


Figure 79 Illustration of the segmentation algorithm. Set A - Set of values that the farthest point can take to belong to the same segment as the nearest point PA.

After the subdivision of each scan in segments, a selection of several points of the segment and the computation of the visible dimensions of the object take place.

OBJECT TRACKING

It is necessary to identify the segment-object pair in an unquestionable fashion. For that purpose, the reference point of the detected segments is compared with the reference point estimated with a Kalman filter for each tracked object. For each detected segment, an interest region is defined, in which the search of existing objects is performed. Since the LMS is carried by vehicles it is necessary to consider the movement of the LMS in the tracking of the objects. When performing the Kalman filtering update cycle all the variables involved (including actual and previous state) are expressed in the same reference frame.

IMPACT-TIME COMPUTATION

The Impact-Time Computation module uses the results of all previous ones to estimate the impact-time and position, for each one of all detected objects. The method used is based on the projection of all possible points of impact in the direction of the object's velocity, and for each instant it is assumed a constant object velocity relative to the vehicle. As we can see in the following Figure, these points are the edges of the car (*d, e, and f*) and of the object (*a, b, c*). So, from the projection lines starting on the object, defined by the starting points and velocity vector, we select the shortest line that intercepts a line segment of the boundary of the vehicle. Applying the same method for the projection lines that start on the car, we finish the process and achieve the colliding shortest distance. The object velocity is assumed to be constant *V.*

6. Platooning technologies

6.1 Baseline and technology improvements

Platooning techniques are needed for cybercars for two different reasons :

- for offering the possibility to move empty vehicles from one location to another one, using a single driver;
- for increasing the throughput of cybercars on a given infrastructure, by reducing the headway to a strict minimum.

In both cases, the following vehicles should follow the preceding vehicles as close as possible, on the same tracks and without collision, even in case of hard accelerations and decelerations and in tight curves.

Only a limited experience is available on this topic.
A certain similarity exists with present-day commercial techniques, used in Adaptive Cruise Control (ACC) for automobiles, which are based on ranging systems, such as lasers or radars, and concern only the longitudinal guidance.
New improvements are under way at research level, which consider longitudinal and lateral guidance using vision and targets (Chauffeur Project from the EC and ICVS system from Honda) or radar and markers on the road (IMTS from Toyota). Inria has patented a platooning technique with a more advanced vision sensor, which does not require a communication link between the vehicles, nor markers on the infrastructure. This technique required additional developments in order to obtain a reliable sensor at low cost.

Based on the above picture, the project activities on platooning have been focused on the sensor issues, taking into account the coupling of longitudinal and lateral guidance, and aiming to avoid the use of equipment in the infrastructure.

Three techniques have been addressed, and demonstrated in simple scenarios in a test area.
The first approach uses a ***camera based technique extracting features*** *from the image of the preceding vehicle (INRIA – paragraph 6.3): the method proved to be a basic building block for a fleet of homogeneous vehicles, which is adaptable to different vehicles by simple SW modifications;*

The second approach applies a ***laser scanner with reflective beacons*** *(ROBO – see paragraph 6.4); this is a simple method which could provide distance and orientation of the preceding vehicle between 2 and 15 m; it has the advantage of adding practically no cost if the same laser sensor is used for collision avoidance.*

The third approach is a ***camera based technique with IR lights*** *(INRIA, ROBO – paragraph 6.5), according to the patent previously mentioned. Progress has been made in the use of low cost vision sensors and the coupling between image processing and control.*

In addition, ***general aspects of platooning*** *have been considered, to provide guidelines for the implementation of techniques. (Univ. Bristol – Annex to chapter 6).*

From the above developments, a ***preliminary feasibility of platooning schemes at low speeds has been demonstrated*** *and the* ***approaches for possible applications*** *have been identified.*
Additional work remains to be done to consolidate these techniques and to define details of the solutions for a demonstration site. A specific challenge to be addressed in future work concerns the issue of string stability and the robust control for such a train of vehicles.

6.2 Vision based platooning system (Inria)

6.2.1 Objective

- The objective of this activity is the development of a vision based technique for platoon driving of a fleet of homogeneous electric cars.

6.2.2 Operational goals

- Develop a system based on a single camera
- No active target needed on the front vehicle
- Only special features on the vehicle chassis are used as references

6.2.3 Description

<u>**PLATOONING FOR SMALL PUBLIC URBAN VEHICLES**</u>

We wish to be able to drive a "train" of empty public cars with only one driver in the front car (see Figure 80). This function is needed to pick up cars which have been abandoned in various locations and to redistribute them to appropriate locations. Trains could be up to six cars long and the distance between cars will vary between 0 and 5 meters depending of the speed (maximal speed of the CyCab vehicle is around 30 km/h).

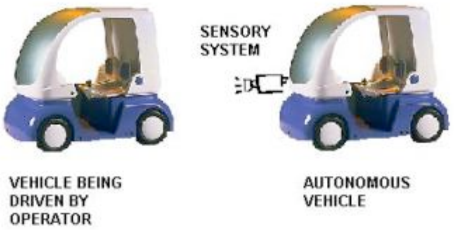


Figure 80 Scheme of the first and second vehicle in a platoon

SYSTEM DESCRIPTION

A single colour camera is needed and only special features of the chassis of the CyCab platform are used to identify it; no active target is needed.
The following is a short description of the way the algorithm works:

1. Low-level image filtering and enhancement
2. Detection of the horizontal segments that characterise the chassis of the vehicle. The high contrast between the different parts of the CyCab chassis permit to well-distinguish these lines in the image
3. Projective invariant formula between horizontal line positions is used to identify the chassis of the front vehicle from the environment perturbation
4. Finally, colour information is used to finish characterising the vehicle chassis

5. To improve the speed of the algorithm an estimator is used to anticipate the position of the CyCab in the future image. By doing this, we reduce the size of the area of interest in the image, and then reduce the number of operations on the image.
6. By using scale factor on chassis dimension, we are able to know the exact distance between the front and the following vehicle. And, by tracking the CyCab in successive images, we are able to compute the relative speed of the vehicle.

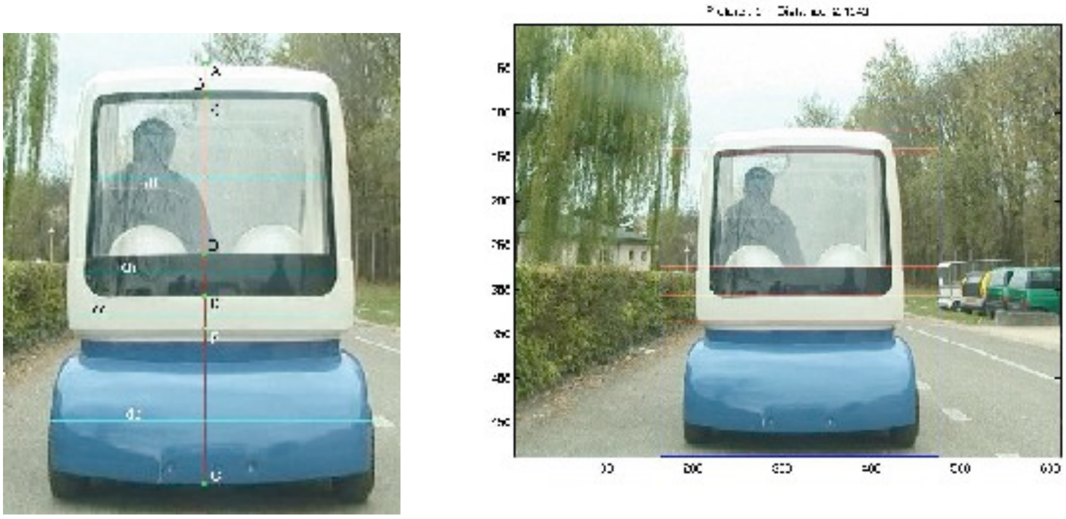


Figure 81 Features of the Cycab used for vehicle localisation

6.3 Laser based system (Robosoft)

6.3.1 Objectives

The objective is to use an off-the-shelf sensor to implement platooning (Figure 82). The laser LMS221 (SICK) is used to know the distance and the orientation with the leader vehicle.
With such a system, we can for example use only one vehicle to collect all the other vehicles all around the city.

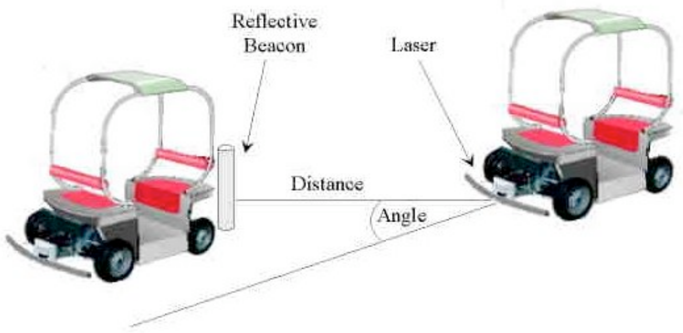


Figure 82 The vehicle follows the leader

6.3.2 Description

The on-board system tries to cancel the angle between the two vehicles and also tries to keep the same distance by modifying the speed of the following vehicle.

The laser is plugged to the RobuCab's computer through a Serial line. The acquisition of data and the computation of the speed and the steering of the vehicle are made in C language in the RobuCab's on-board computer. Using a shared memory, this velocity and this steering angle are sent to the low level control (the SynDEx application on the RSMPC555 boards).

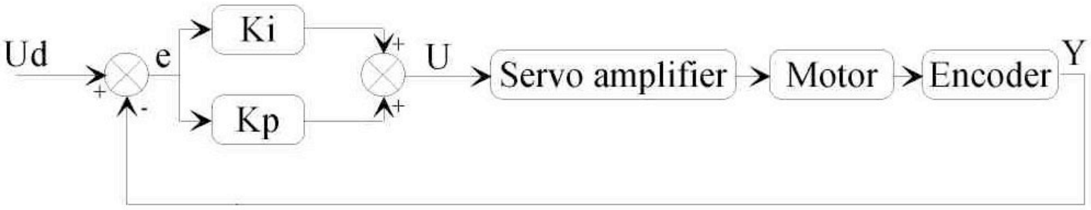


Figure 83 The PI controller of the platooning system

To control the speed (respectively the steering angle), we use a PI controller, shown in Figure 83, getting real speed (respectively the real steering angle) from a incremental (respectively absolute) encoder.

6.3.3 Results

- The catching distance is 2m. The vehicle is "loosing the target" at 15m. The laser covers an angle of 180°;
- Our current velocity is 10 km/h in a parking. We plan to perform tests on the road to reach the velocity of 18 km/h;
- The robustness of the platooning has been demonstrated, even if there are some unexpected reflections appearing in some cases.

6.4 Linear camera based system (Inria-Robosoft)

6.4.1 Objective

- A low cost linear camera based technique, for platoon driving is developed and basic performances are tested. Three working prototypes, mounted on three Cycab, are realized.

6.4.2 Operational goals

- Develop a system based on a low cost linear camera.
- Use of CAN bus for data communication.
- Use of infrared target made of three or five sets of LED organized in vertical lines and non co-linear.

- Cooperative driving in a platoon at speeds up to 50kmph and a distance between 75cm and 5m depending of the speed (and up to 15m for the rendez-vous phase between a single car and a passing platoon).

6.4.3 Description

We are building a linear camera, based on low cost components to have robust platooning using modulated infrared targets.

For that, we made our first prototype based on a 150 MHz DSP, from Texas Instruments, and on a linear CCD sensor, from Sony Corporation.

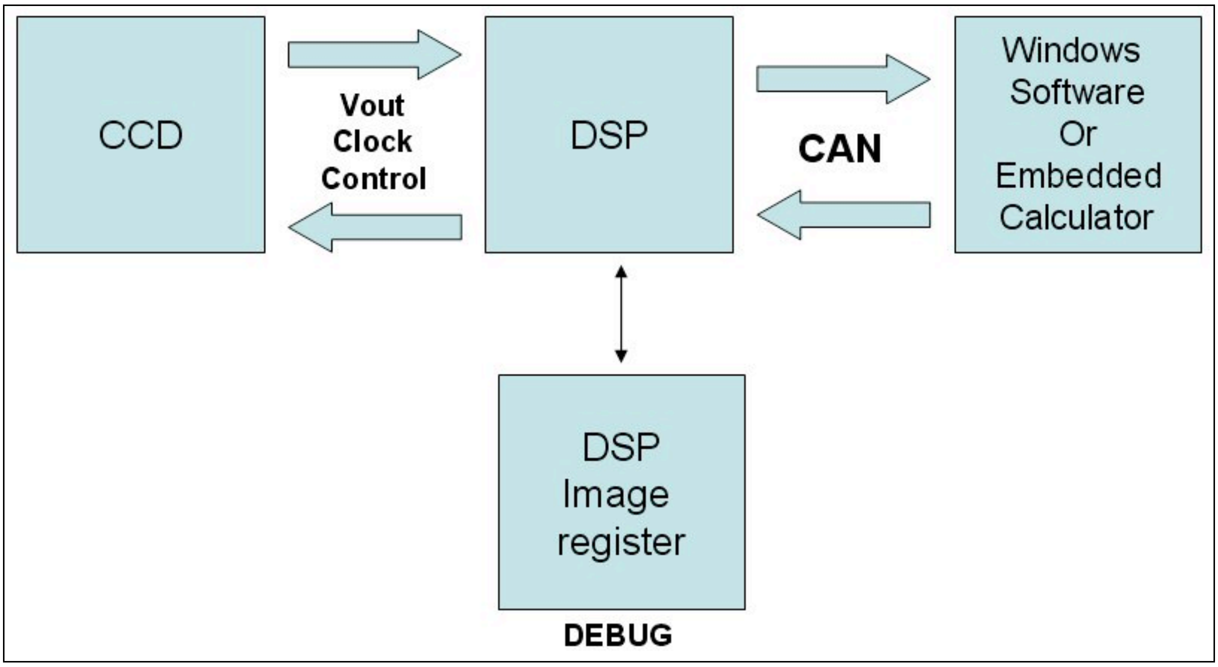


Figure 84 : Global architecture

The target is made of three or five sets of infrared LED (880nm), organized in vertical lines and non co-linear.

The targets are located at the rear of each vehicle.

The CCD sensor has 2048 pixels and we can acquire the data at rates of 1000Hz.

The optical part is equipped with a 24mm photo objective and a cylindrical lens in order to adjust to the changes of the relative angle between the two cars in the vertical plane, and an infrared band pass filter.

To have a robust acquisition, we modulate the target, and we synchronize the camera with the target by using an optical phase-locked loop.

After getting the position of each target on the CCD surface, we are able to calculate the distance, the deportation and the angle of the vehicle (DX, DY and DΨ [Fig3]).

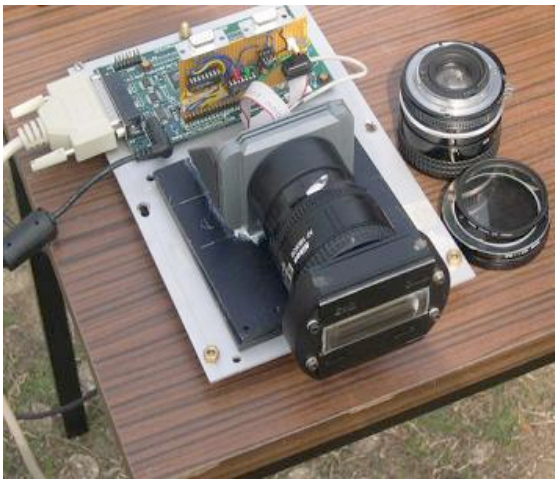


Figure 85 Linear camera prototype

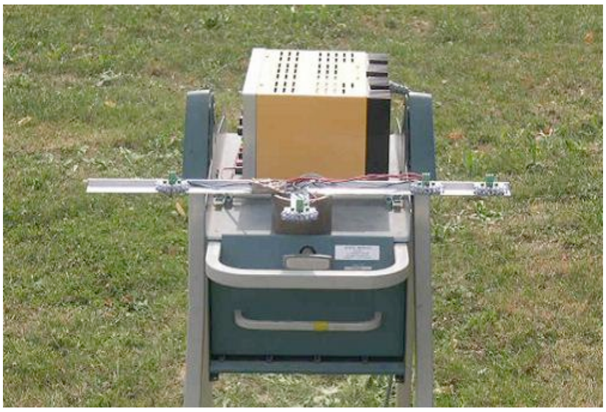


Figure 86 Infrared targets

The platooning will be made by using this three data and specific controllers. [Platooning for Small Public Urban Vehicles P Daviet M Parent 1995].

6.5 Annex to chapter 6: Modelling for platooning strategies (UB)

6.5.1 General considerations

The capacity of a conventional highway is directly related to the average separation, ie the average distance between successive cars. On present roads the separation and thus the overall capacity is governed by the sum of the judgements of all drivers on the separation distance which can be reasonably accepted.

There are a wide variety of well recognised issues in this situation

1. Every driver will make an individual decision on what they regard as a safe separation distance.
2. Acceptable separation distances vary strongly with speed.

3. Data shows that the separations accepted are typically between 1 and 2 seconds at motorway speeds.
4. The separations are found to relate to the combination of the time judged by a following driver to be necessary to start reacting together with the drivers judgement on the maximum deceleration rate which can be anticipated by the vehicle in front.
5. These separations fail to meet the “brick wall” stopping distances which are accepted as safe in other applications, in particular railways, which imply instantaneous stopping of the vehicle in front (see further discussion below).
6. There is also wide evidence that drivers judgements formed in good weather conditions are mismatched to the reality of poor weather conditions. This includes rain, poor visibility, and snow/ice.
7. It is well established that the natural response of human drivers leads to traffic flow instabilities, including “shock waves” which propagate local congestion within the traffic flow. These waves cause serious limitations in highway capacity.

In all countries the physical expansion of the road network is now severely limited, but demand continues to increase. Thus there has been wide consideration of the use of technological means to improve capacity. Platooning is one of these approaches.

It has been observed that in natural traffic flows there is a strong tendency for traffic to form “platoons” ie groups of vehicles travelling together with a space before the next group.

It has been proposed that, by using sensing devices, platoons of cars could be formed automatically. The key benefit claimed from this process is the ability to operate a series of vehicles at far shorter headways. Sufficient gap is normally planned between platoons in to allow any platoon to meet “brick wall” criteria in relation to the platoon in front. However within the platoon, rather than the 1-2 second separation typical in current motorway experience, it is normally planned to operate at within platoon separation of 0.1-0.5 seconds. These are very small spacings. It is claimed that these are safe because in the event of a problem within a platoon, a following vehicle is so close behind its leading vehicle that vehicle to vehicle contact will only occur at low relative speed and not result in major crash problems. This claim has not yet been subject to full clearance by the appropriate regulatory authorities.

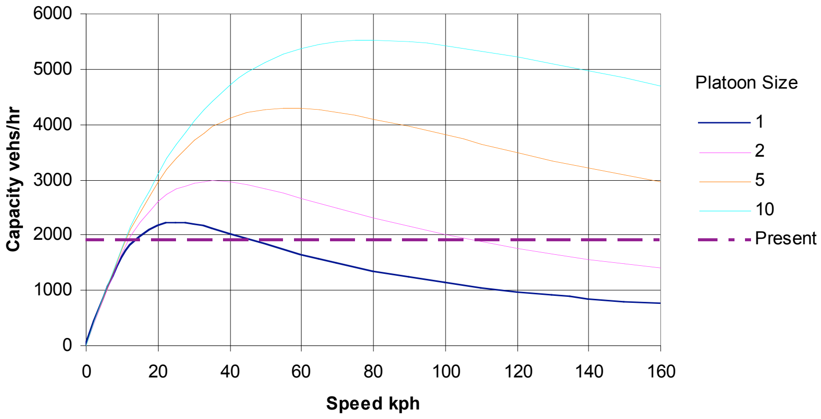


Figure 87 Lane Capacity with Platooning; (assumptions are: 5m vehicle, 0.5g emergency deceleration, 0.2 second vehicle separation and response delay).

The ability to operate vehicles in platoons would add significant levels of capacity to typical freeways. The benefits are quantified in Figure 87. The graph for a platoon of 1 vehicle gives the capacity limit which would apply if brick wall stopping criteria were applied to individual cars. Typical present lane capacities are 1800-2000 vehicles per hour. (In practice this limit is also a function of speed with a maximum capacity at around 80 kph). Comparison of the “1” and “present” curves demonstrates the point that current capacities accepted on motorway lanes do not meet key brick wall stopping criteria at higher speeds.

However it can also be seen that any platooning at short headways provides major benefits in lane capacity, especially at higher speeds. If it were accepted that, even in worst case situations, individual platoons would subject to a maximum deceleration rather than an instant “brick wall” stop then platoons could be formed at reduced separations and even higher levels of capacity could be realised.

These substantial advantages have been widely recognised and platooning approaches have been evaluated in depth by authorities in Europe the US and Japan. In both the US and Japan full practical tests have been run of the operation on actual freeways of platoons of cars fully equipped with sensors and control equipment. In both countries magnetic markers installed into the freeway provided the lateral guidance. Although the tests were technically entirely successful, it has been reported that the passenger’s response to the very close separation used in the tests was very negative.

In principle there are a wide range of sensors which can be used to provide longitudinal control of the vehicles. These include radar, ultrasonic, laser and optical techniques. All of these have been used in practice. It seems likely that a final system would require the use of multiple sensors combined with sensor data fusion to provide safety via dissimilar redundancy.

It should be recognised that the provision of sensors on vehicles to detect vehicle to vehicle separation provides a wide range of other potential benefits for the driver. In essence a sensor suite would allow mitigation of many of the issues listed in the introduction to this section.

1. The safe separation distance could be set, or at least advised to each driver
2. The recommended separations could be set to vary appropriately with speed
3. The separations recommended could be set to reflect road and weather conditions.
4. Suitable response processes built into the separation could eliminate the congestion wave problem and potentially lead to major improvements in highway capacity.

For cybercars there is an additional use of platooning techniques. This is the use of linked trains of empty cybercar vehicles to achieve empty vehicle management. This was demonstrated by Parent ten years ago.

The key question on the use of platooning techniques is how these techniques can be made fully safe. In essence the position of all the major manufacturers is that any sensor controlled process can only be used as a driver aid, ie simply to provide advice to the driver. Particularly in the US the legal aspects of passing control to an autonomous device are almost certainly too demanding to allow any serious prospect of full automation from this approach. Unfortunately this would eliminate much of the benefit.

A second possible issue is that there has been no examination of the efficiency of the platooning process under real trip demand. On any real road planned trip lengths of individual vehicles vary considerably. Thus there will be vehicles wishing to join or leave platoons regularly. A number of studies have been undertaken on the technical issues associated with the formation and dispersal of platoons. However, it is not clear to what extent this platoon forming and reforming process under real demand patterns will compromise the ability of platooning to deliver the full benefits in capacity claimed. This issue is the subject of one task during the Cybercar program.

6.5.2 Effects of Real Trip Demand

In any real situation vehicles will join and leave the motorway. Under platooning this requires that vehicles join and leave platoons. It seems that this could be a frequent occurrence. For example if the average trip length on the motorway were 20 km and the average separation between exits were 5 km then 25% of vehicles will both join and leave at each exit.

There have been a number of studies of joining and leaving platoons. There are essentially two issues

1. Maintaining acceleration and jerk within comfort limits
2. Establishing acceptable safety

Most studies appear to have concentrated on the comfort issue. However it is clear that acceptable safety is by far the more important point. The acceptability of various approaches to the regulatory authorities is not clear. For rail and related systems "brick wall" criteria are the m norm. On the assumption that the leading vehicle instantly stops following vehicles must be able to brake safely to a stop without impact. Although extreme, this situation is not out of the question since there is the possibility of the leading vehicle to impact for example a fallen tree or other substantial stationary object. In automotive practice, as discussed earlier vehicles on motorways do not normally retain a separation which allows brick wall stopping criteria to be met. This has been accepted both by the public and by the regulatory authorities. Thus it might be reasonable to assume that a platooning process which gave an overall increase in safety, albeit not to full train levels could be acceptable.

However it must also be recognised that acceptance criteria for automated systems will certainly be far more demanding than those which are customary for driver controlled systems. It is far from clear what safety rules would finally apply. However it is possible to speculate

For the purposes of this discussion it will be assumed that the basic argument that vehicles in close proximity in platoons are "safe" can be accepted. But is it should be noted that this is not an established position and there are a series of issues which remain unresolved.

The usual arrangement is that successive platoons of vehicles are separated by a larger spacing. The general process is shown in the top half of Figure 88, although this understates the actual separation between platoons.

The key further issue is that of joining and leaving platoons. As noted above this is a frequent occurrence. Thus it is necessary to consider platoon formation and dissolution procedures in some depth.

There are a variety of approaches
<u>A On line</u>
In the RUF system it is assumed that at each exit the platoons will dissolve into individual vehicles operating at lower speed which can then exit from the through lane in the usual way. New vehicles join at this location and all vehicles are then reformed into platoons for passage towards the next exit.

<u>B Off-line</u>
It is inevitable that vehicles in the middle of a platoon will require to leave. The process suggested by most authors is for the leaving vehicle to pull out laterally from the platoon into an adjoining lane within which that vehicle can undergo the necessary deceleration. The remaining vehicles in the platoon will then go through an internal adjustment recompression process to fill the gap left by the leaving vehicle.

This requires a leaving lane to be added to any through lane, as suggested in Figure 88.

It is normally assumed that vehicles joining a platoon join at the rear. However, the argument that vehicles are safe within platoons necessarily implies that vehicles joining platoons are, at least for some part of the process not safe. It could be argued that if the period of reduced safety is sufficiently short then the process as a whole could be accepted.

From this point of view it is difficult to believe that vehicles can join the rear of a full speed platoon within the platoon lane without passing through an unacceptable period of lack of safety during the final closure process to the platoon. Both the on-line and off-line platoon approaches offer possible solutions. In the on-line case platoon formation occurs at low speed so that safety requirements can be satisfied. In the off line case it is natural to undertake the principal acceleration process in the adjoining lane. Once speeds have been matched the vehicle can move laterally to join with the rear of the platoon. This is shown in the figure.

It is only necessary to have the additional joining and leading lanes close to the exits, so the additional infrastructure costs are limited.

The above solutions will apply satisfactorily when platooning is confined to a single lane. However most heavily used roads are multilane. It appears to be difficult to arrange multilane platooning satisfactorily.
An ideal solution would be to arrange that outer lanes were restricted to vehicles for which no immediate leaving or joining was planned. To achieve this requires a lane change process. One method would be to arrange that immediately after an exit the outer lane platoons run slightly ahead of the inner lane platoons to allow for vehicles to leave inner lane platoons and join outer lane platoons. Towards the exit the inner lane platoons would run ahead of the outer so that the lane change process could be accomplished from outer to inner, and finally to the exit lane. This description shows that, although possible, actual realisation of such a system in practice would be very complex.

In principle the online process provides opportunities for lane change towards the exit, but if capacity is not to be compromised this will probably require the construction of temporary mini-platoons to accommodate the vehicles moving from lane to lane. Again although possible it is clear that the process will be complex and difficult to realise safely and effectively.
Nevertheless the overall potential benefits of platooning suggest that further in-depth study of the issues is justified.

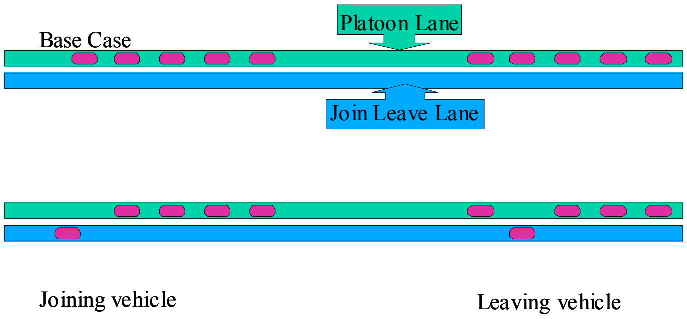


Figure 88 Diagram of Platooning Process

7. Conclusive remarks

A synthesis of the main activities in the four areas covered by the workpackage is given by the table at page 109. It shows, for each technology object of investigation:
- the main sensors or actuators involved,
- the basic feature,
- the vehicle platforms used for the specific development.

Those platforms which will be used for subsequent tests are indicated. The table also indicates if the activity is focused on the development of a new concept, or vice versa on the adaptation and assessment of existing techniques.

Looking to all these developments on new technologies for vehicles, it appears that they have generated a number of **important steps for the effective operation of cyber cars**, contributing to a progress from the present applications on private areas as assistive devices, to a use on tracks or zones with fully automatic vehicles where some interaction with other road users is expected.

In particular, the following conclusive remarks, summarising some considerations given in the previous chapters, can be applied to the four categories of technologies.

Regarding **vehicle controls,** the use of advanced architectural solutions is facilitating in general terms the development of vehicles, where traction, braking and steering are integrated and reliability is improved with respect to previous solutions.
A consistent progress has been realised in the definition of a modular approach. Moreover, basic HW components (such as generic microcontrollers or regenerative braking system) have been developed.

The application of SW tools in the design phase has shown good performance and positive impacts on the quality and on the speed of the development process. These tools have been applied by partners for several platforms considered in the project.
An additional remark is that automotive controls and actuators are definitely finding their way into cybercars; besides using such technologies on the different physical platforms, they have also been considered at design level, conceiving a city car which allows both automated and manual driving, for improved flexibility in the setting-up of transportation systems based on cybercars.

In the area of **navigation,** different prototypes have been implemented, with major improvements in two areas: magnetic localisation and computer vision.
Magnetic sensors, thanks to the new processing schemes and logics, provide a very significant accuracy, and reduce the danger of hitting the antenna, due to the larger distance from the ground now allowed. They are considered a basic solution for short term applications.
Vision systems have a great potential due to the large amount of information they can provide, and the possibility to avoid expensive installations on the road. Moreover, they can be used for different purposes such as navigation, obstacle detection and platooning.
Dedicated image processing have been developed to extract relevant features from the scene. Preliminary tests have given positive results for a navigation at low to medium speed in a characteristic environment for Cyber cars. Vision systems are considered especially in a longer time perspective, since further R&D work is needed for this topic.

The area of **obstacle detection** has also seen significant results. The laser scanner remains the more developed technology, and progress has been made here for a safer operation, based on improved signal processing (adaptation of the area of interest, recognition of objects in the path or out, different levels of braking).

The automotive radar has proven to be a good and less expensive alternative, once the angular field of views will be increased, which is an expected technological trend. Finally different concepts of obstacle detection from stereo vision could be implemented, with first experiments demonstrating a good potentiality. Further tests are planned for the next phases of the project.

Finally, regarding **platooning,** the feasibility of simple schemes has been demonstrated in complex paths, at least with low speeds, and even using only on-board sensors. Techniques based on a scan laser or a camera have been able to give the distance and the orientation of the preceding vehicle.
Another relevant development is the use of a simple colour camera to extract data of the preceding vehicle looking to specific geometric features. This method can be a basic building block for a fleet of homogeneous vehicles and is adaptable for different vehicles by simple SW modifications.
Since very limited experience was available on this topic, the results obtained are encouraging.
The Platooning functions are not planned for the first steps of the Road map of Cyber cars, but for future implementations they will certainly facilitate the operation of systems with more capacity, when high throughput and logistic aspects will play a basic role.

SUMMARY OF DEVELOPMENTS ON NEW TECHNOLOGIES FOR VEHICLES

AREA	**SENSORS ACTUATORS**	**TECHNIQUE & FEATURES**	**PLATFORM FOR IMPLEMENTATION**						TECHNOLOGY (FOCUS OF WORK)
			PARK SHUTTLE	YAMAHA	CYCAB	ROBU CAB	EXPERIM. PLATF.	DESIGN LEVEL	
CONTROLS		SW FOR DESIGN		O	O	O		X	1
	DRIVE STEER BRAKE	AUTOMATED DRIVING	X→	O	O	O	O		2
	BRAKE	ENERGY REGENERAT.		X→					2
	DRIVE STEER BRAKE	DUAL-MODE DRIVING						X (CAR)	2
NAVIGATION	MAGNETS	MEASUR. OF MAGNETIC FIELD	X→						1
	MAGNETIC PROBE	HANDLING OF MULTIPLE DIRECTIONS						X(RUF)	2
	STEREO CAMERA	ROAD GEOMETRY EXTRACTION			X→				2
	WIRES	INDUCTIVE TRACK GUIDANCE		O	O	X	O		1
	SCAN LASER	REFLECTION FROM BEACONS ON ROAD		X	O	X			1
	CAMERA	TRACKING OF PAINTED LINE ON ROAD		X →	X→	X→			1
	SCAN LASER	ROAD FEATURES EXTRACT., +ODOMETRY		X	X				1
	D GPS	LOCALISATION + ODOMETRY				X→		X	1
	CAMERA	TRACKING OF TARGET			X→				2
OBSTACLE DETECTION	RADAR (AUTOMOTIVE)	OBSTACLE DETECTION					X→		1
	STEREO CAMERA	SIMPLE CALIBRATION & NON-FLAT ROADS					X		2
	SCAN LASER	DUAL SCAN AND ADVANC. PROCESSING	X→						2
	SCAN LASER	OBSTACLE DETECTION	O	O	O	X→	O		1
	ULTRASOUNDS	OBSTACLE RANGING AT SHORT DISTANCE				X→			1
	STEREO CAMERA	OBSTACLE RECONSTR. FLY ALGORITHM			X→				2
	SCAN LASER	PATH & OBJECT TRACKING					X→		2
PLATOONING	COLOUR CAMERA	VEHICLE FEATURES EXTRACTION			X→				2
	SCAN LASER	REFLECTION FROM BEACONS ON VEHICLE				X→			2
	LINEAR CAMERA	COOPERATIVE LED'S ON VEHICLE			X→				2

SYMBOLS IN THE TABLE

A) PLATFORM (IMPLEMENTATION)

X: VEHICLE PLATFORM USED FOR SPECIFIC DEVELOPMENT DESCRIBED IN THE REPORT

O: VEHICLE PLATFORM WHERE TECHNIQUE IS ALSO AVAILABLE (DUE TO INTERNAL DEVELOPMENTS OR EXCHANC BETWEEN PARTNERS)

→: TO BE TESTED IN FOLLOWING PHASES OF CYBERCARS PROJECT

B) TECHNOLOGY (FOCUS OF WORK)

1: ADAPTATION OF AVAILABLE DEVICES

2: NEW CONCEPTS DEVELOPED

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