Towards "Automated Road": Some projects and new technologies

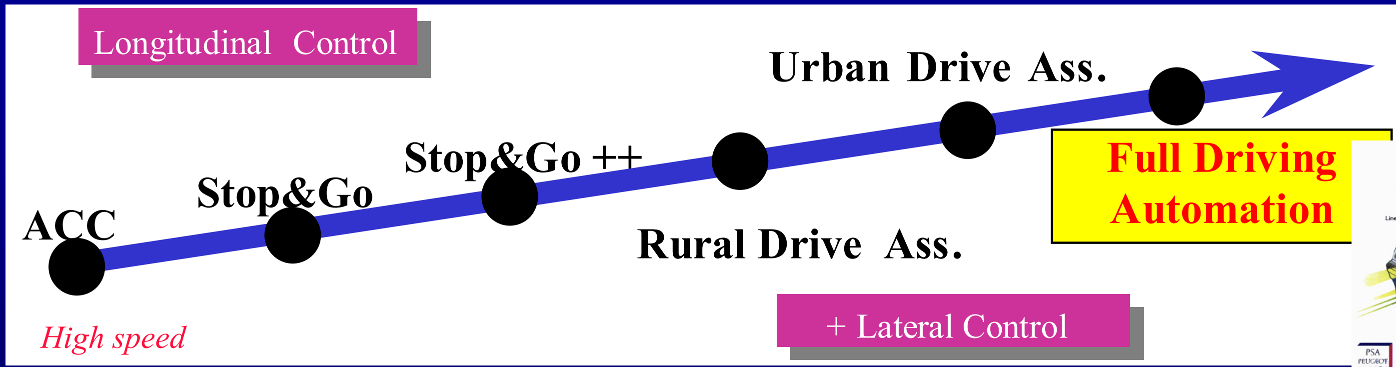
Christian Laugier
INRIA Rhône-Alpes, France

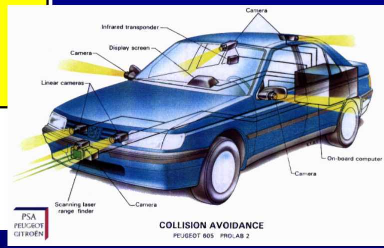
1. General Framework & Main ITS Research Programmes
2. Decisional & Control Architecture for Autonomous Vehicles
3. Obstacle Avoidance in a dynamic environment (V-obstacles & Bayesian Prog)
4. Automatic driving for a Bi-steerable car (Cycab)
5. Conclusion and Future Work

Plenary Speech
ITSC '02 - Singapore, Sept. 3-6, 2002

Automated Road : Two main approaches

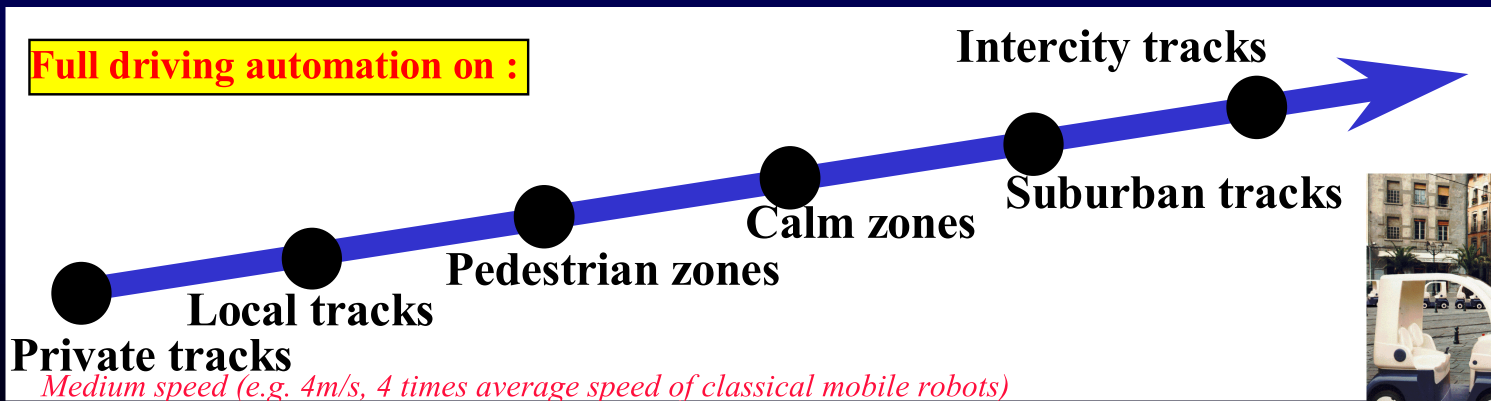
- The Automotive approach (ADASE)





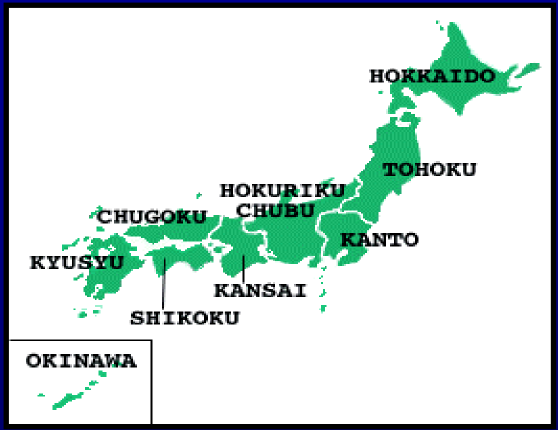
e.g AHS in Japan; Path & IVI in USA; Prometheus, Chauffeur, Carsense in Europe

- The « CyberCars » approach



e.g ICVS in Japan; Praxitele, Parkshuttle, Serpentine, CyberCars in Europe

Main Research Programmes



Japan

- Oriented towards *Automated Vehicle Guidance & Driver Assistance*
- National project widely supported by MLIT
- Large scale demonstrations (1996 & 2000)
- Deployment program for the next 15 years

=> Cf. Talk of Dr. Sadayuki Tsugawa

ITS project in Japan

- *ASHRA consortium & AHS (Advanced Cruise-Assist Hyghway System) project*

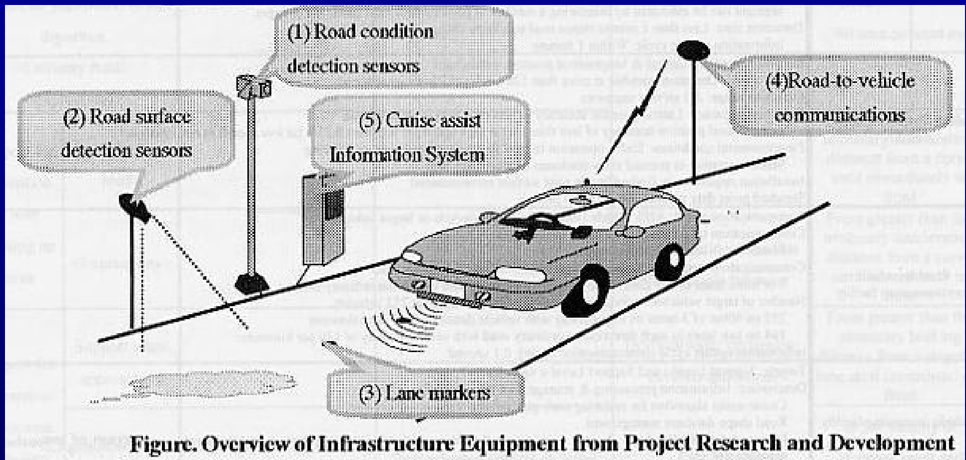
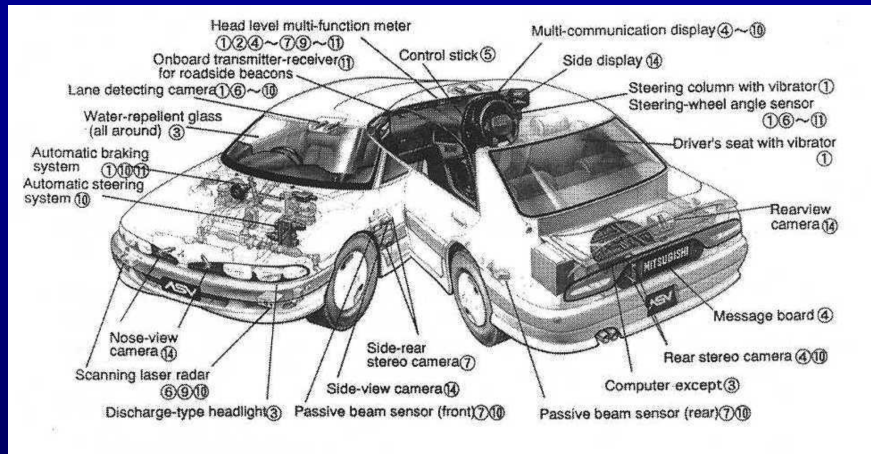


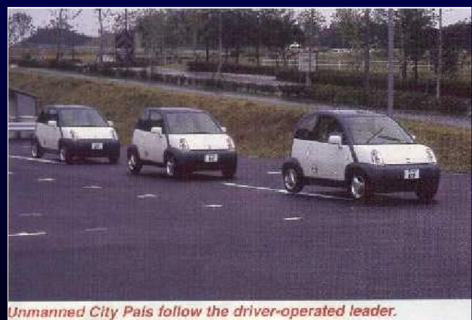
Figure. Overview of Infrastructure Equipment from Project Research and Development



Mitsubishi (Active & passive safety)

- *ICVS & IMTS projects*


Toyota (Crayon system)

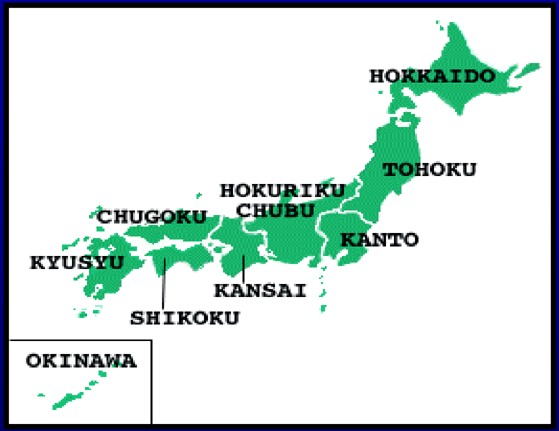


Honda ICVS


Yamaha (Cybercars)


Toyota (IMTS)

Main Research Programmes



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USA

- Oriented towards *Automated Highway Systems*
- National project on AHS (ITS America)
- Large scale demonstration in San Diego (1997)

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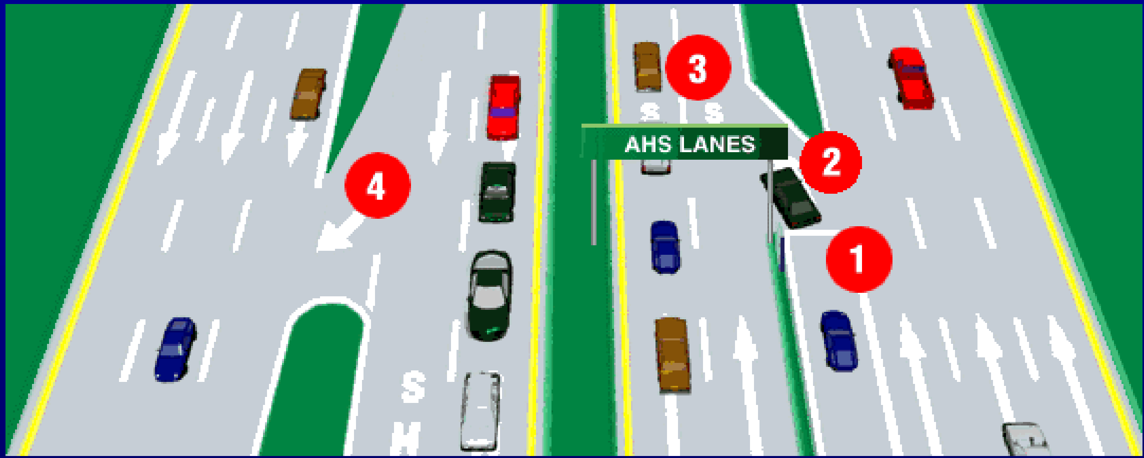
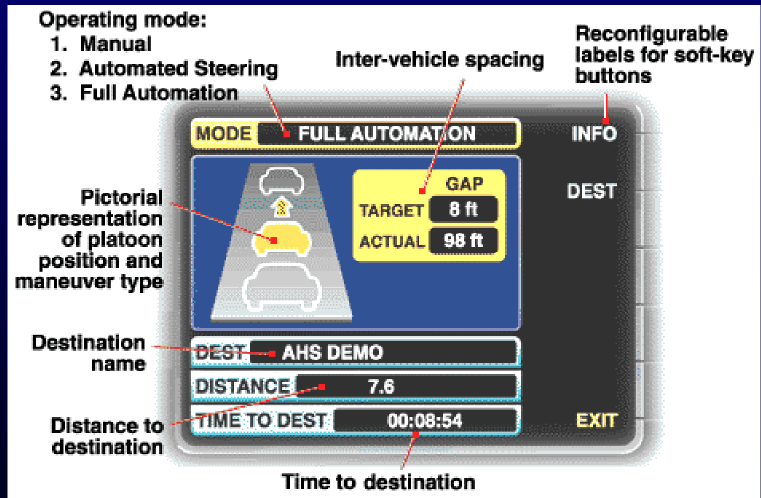
ITS project in USA

Development of fully-automated motorway traffic in USA



San Diego demonstration, August 1997

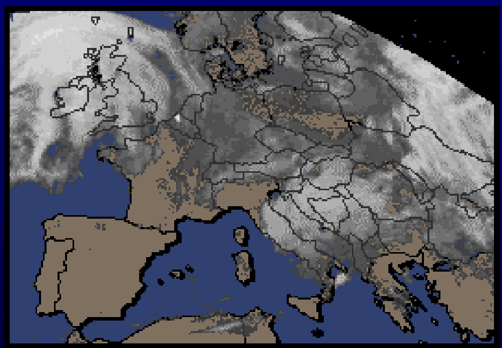


Human interface (Path, California)

Main Research Programmes (C'ed)

Australia, East-Pacific Asia

- Some isolated works, No National projects
- ITS initiative in Singapore *(LTA=> ERP, Traffic control …)*



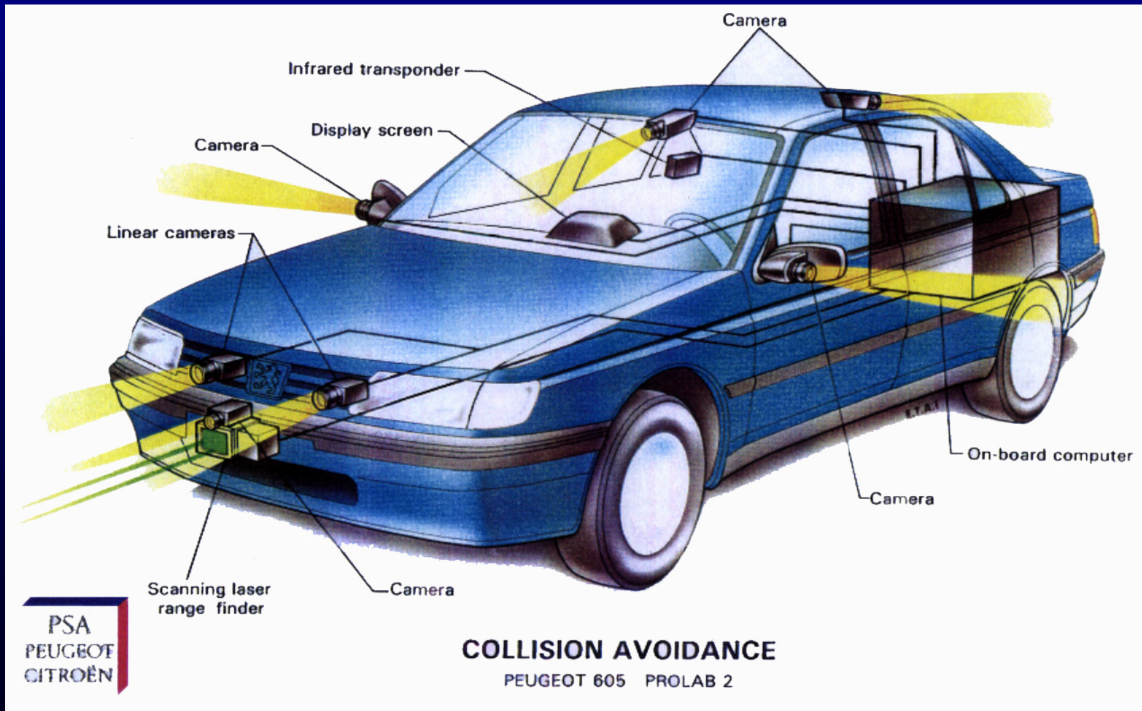
Europe

- Oriented towards ***Driving Assistance & Urban Transport***
  => « Automotive » and « CyberCars » approaches
- Prometheus, Chauffeur, Praxitele, Cybercars ...
- Large scale demonstration (Paris 1994, Rijnwoude 1998, Amsterdam 2002)

Automotive approach: *Prometheus (1986-94)*

« Driving Assistance »

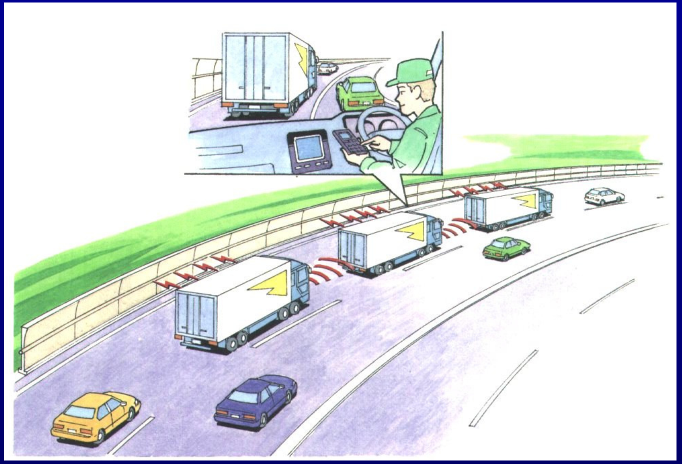
- Smart Cars & Smart highways (for Increasing Safety)
- Demonstration in Paris (Prolab2, Oct. 1994)



French Prolab2 experimental vehicle

Automotive approach: *Chauffeur*

« Automated Road for Trucks »



- **Dedicated Infrastructure (automated lanes)**
- **Increasing Driving Confort and Safety**
- **Reducing Travelling Time (better predictibilty)**

Chauffeur (EU, Daimler Benz/ Iveco)

Automotive approach: *Carsense*

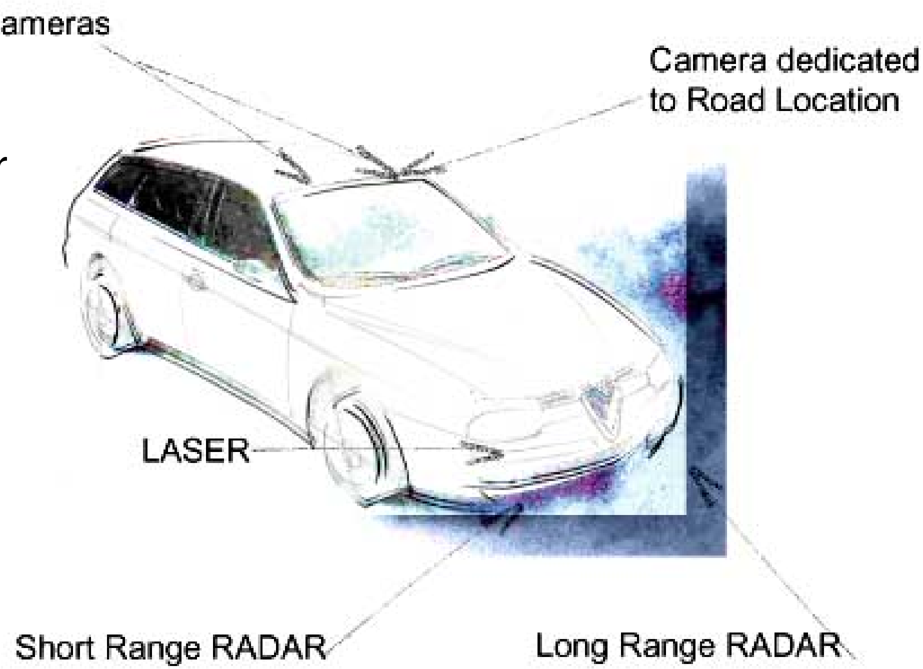
« Sensing of Car Environment at Low Speed Driving »

IST Project 1999-12224 [Jan. 00-Dec. 02]

Partners:
- Car manufacturers: Renault, Fiat, BMW
- Part suppliers: Thomson-CSF, TRW Automotive, Ibeo, Autocruise, Jena-Optonik
- Research Institutes: Inria, Inrets-Leost, Livic, ENSMP

Objectives:
- Develop a sensing system for Advanced Driver Assistance Systems (ADAS) in complex driving situations.
- Based on image processing technology, radar and laser.
- Sensor information is merged in order to achieve a better perception of the environment.

<http://www.carsense.org>



Inria Contributions

- **Obstacle detection using stereo vision** *(Imara/Rocquencourt)*

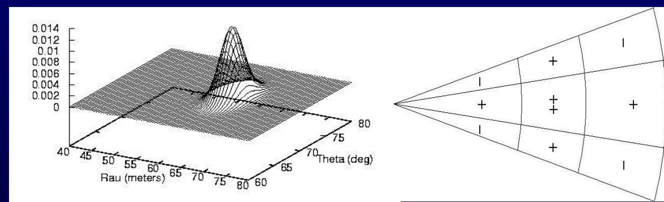
Objectives:
- Detect dangerous obstacles over the road surface
- Real-time execution for slow to moderate speeds
- Parallelizable program architecture

Techniques used:
- Enhanced disparity maps & Wavelet decomposition

- **Multi-sensor data fusion using Bayesian Programming** *(Sharp/Rhône-Alpes)*

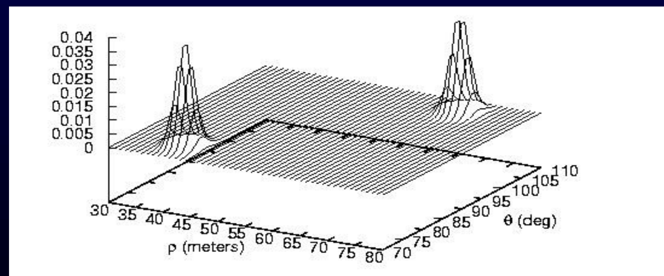
Objectives:
- multiple-target (obstacles) tracking using several sensors (laser, radar, video)

Techniques used:
- Bayesian programming => *formal framework to address uncertainty based on the Probability theory (generic language + inference engine)*



Explicit modeling of the sensors' performance

Example: association and estimation
(m sensors observing n targets)



Result: Multi-modal probability distribution of the targets' presence ($m = n = 2$)

Automotive approach: *Arcos*

« Vehicle-Infrastructure-Driver system for Road Safety »

French precompetitive research project funded by PREDIT [2002-2004]
Predit = French Interrninisterial Land Transport Research & Innovation Programme

Goal : *A decrease of 30% in the number of accidents, once the vehicles and the infrastructure are equipped*

Partners (58):
- Car manufacturers: Renault, PSA
- Private companies: Navtec, Nacam …
- Research Institutes: Inria, Cnrs, Ensmp, Livic …

Technical objectives : safety would be improved based on 4 technical functions :
- managing the inter-distance of vehicles
- warning the driver of the collisions with fixed and slow obstacles
- warning the driver of veering off the road
- informing the cars about an accident ahead

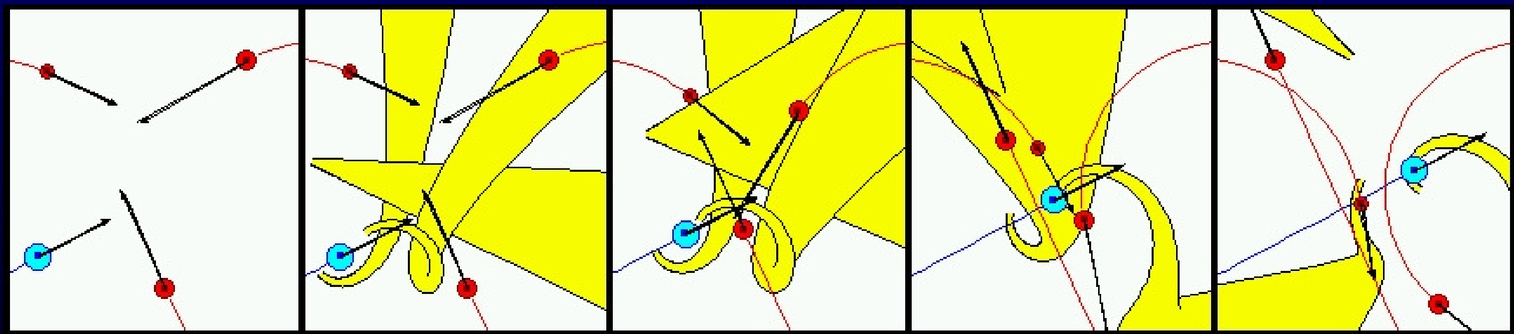
Experimentations :
- 4 experimental platforms
- 3 experimental campaigns (one per year)
- Industrial property on results would protect them and valorize them
  (=> patent, confidentiality, etc)

Inria Contributions

1. Design of the structure of a data base that would be very open and extensible (especially through radio waves)

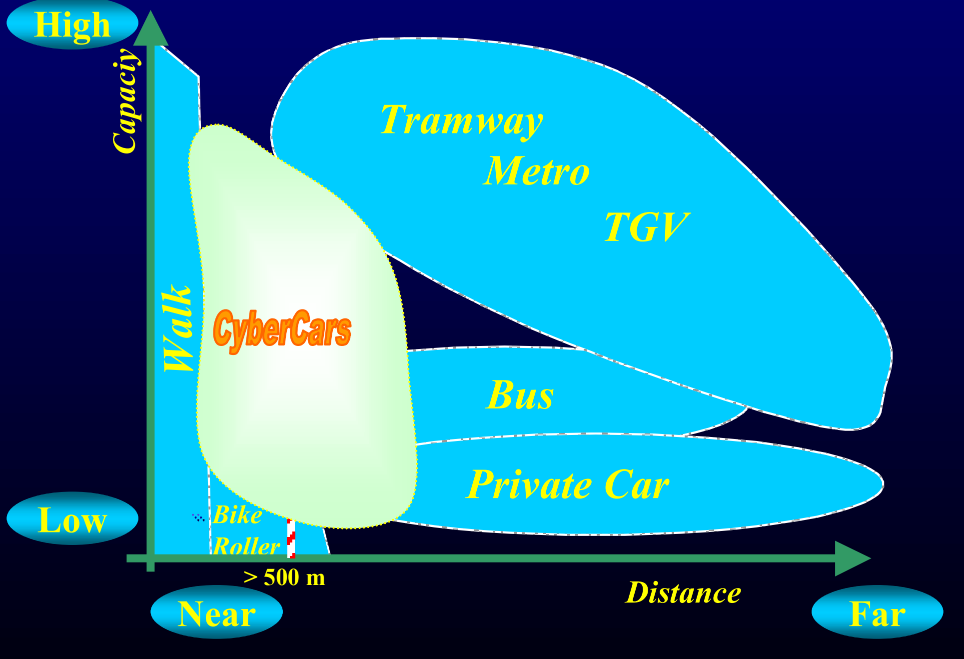
2. Algorithms for planning reachable trajectories and computing admissible bounds on driving parameters

3. Design of a module detecting the danger of collision and evaluating its gravity
=> Concept of "Velocity Obstacle" representing in a synthetic way, at each moment the set of the velocities leading to a collision



The « CyberCars » approach: *Basic idea*

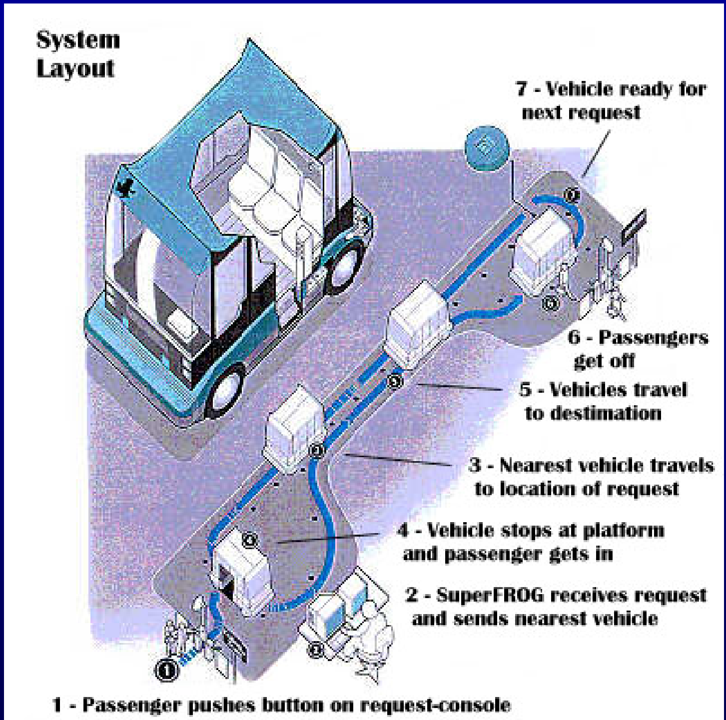
CyberCars are focusing on historical city centres



- Door to door, 24 hours a day
- Small (urban size), silent
- User friendly interface
- Automatic manoeuvres : parking, platooning
  …. up to fully automated

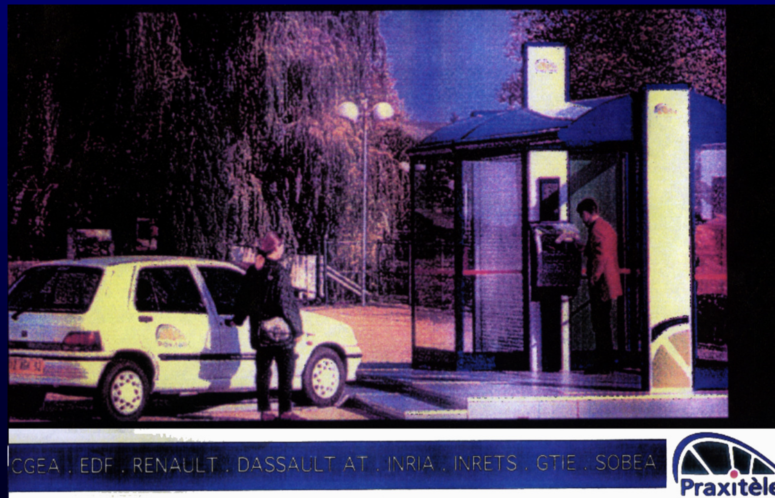
Some CyberCars projects

« Automated Urban/Local Transit »



Serpentine (Switzerland)

ParkShuttle (Frog, Netherlands)



Praxitele (France)

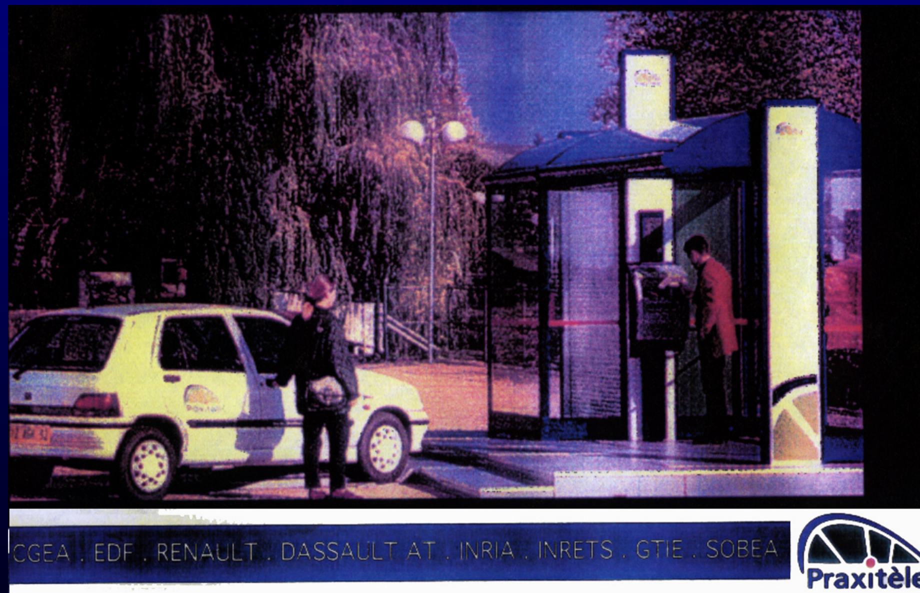
=> Rijnwoude International AGV Demonstration, June 1998

Automated Urban Vehicle - Phase 1

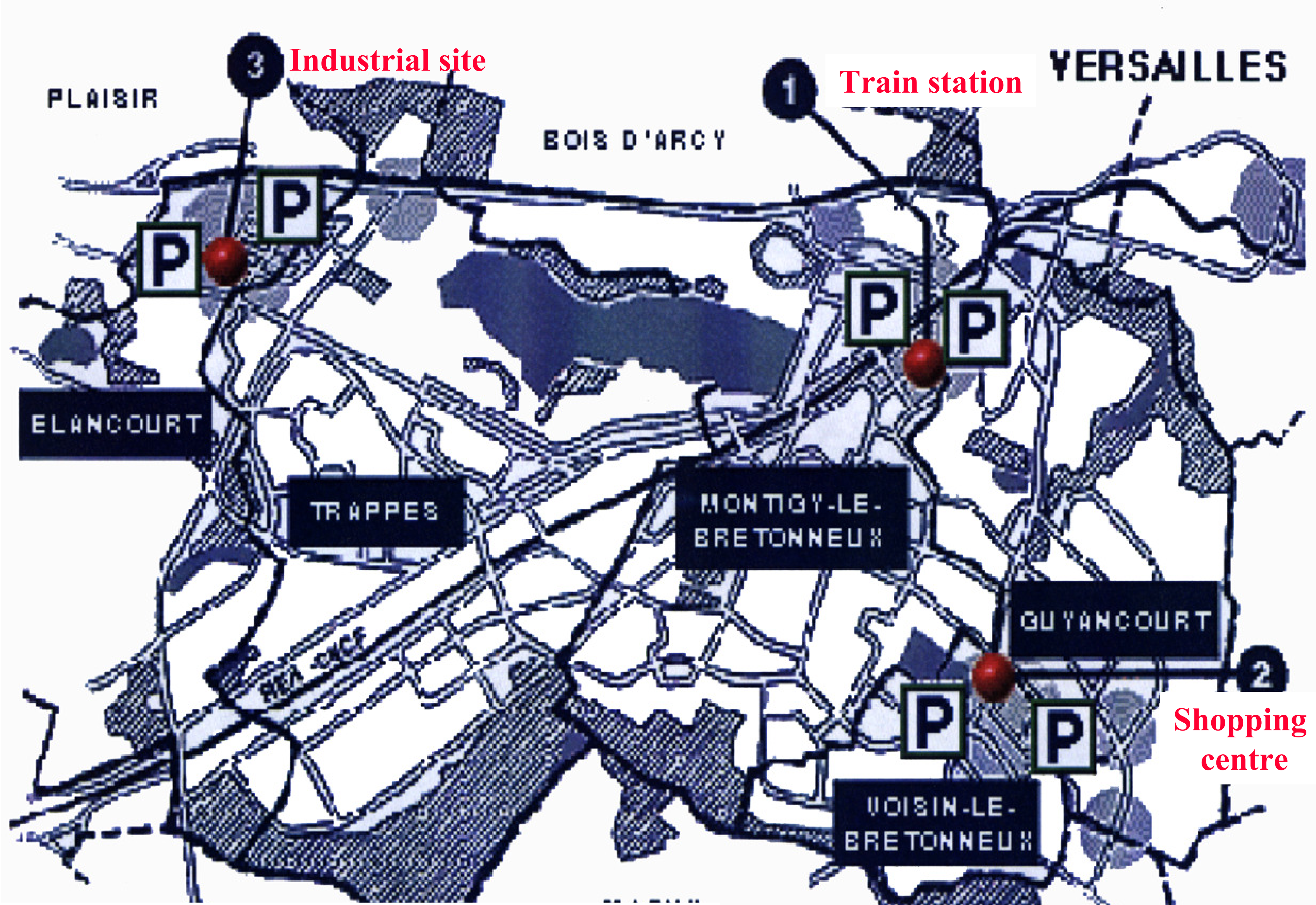
French consortium : Inria, Inrets, Renault, EDF, CGEA, Dassault

- **Inria/Inrets PRAXITELE project (1993-97)**
  - **Public Urban Transit System based on Self-Service Electric Cars**
  - **Large scale experiment in Saint Quentin-en-Yvelines (Oct. 97 - April 99)** *[Blosseville & al 2000]*
  - **No Motion Autonomy in the experimented system at SQY**

Basic idea



Real experiment in SQY



47 vehicles & 9 stations at the end of the experiment *[Blosseville & al 2000]*

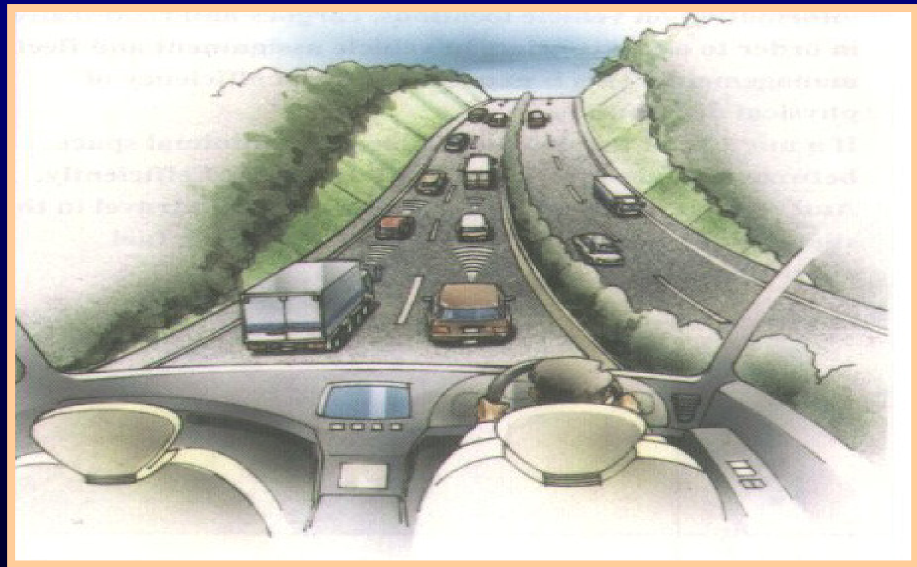
Automated Urban Vehicle - Phase 2

French consortium + EU + Inria/NTU Lab in Singapore

- **CyCab & LaRA (1998-2004)**
  - **Design of an application-oriented Computer Controlled Dual-Mode Vehicle**
  - **Development of the concept of « Motion Autonomy »**

  Platooning & ACC+, Obstacle avoidance, Autonomous maneuvers ...

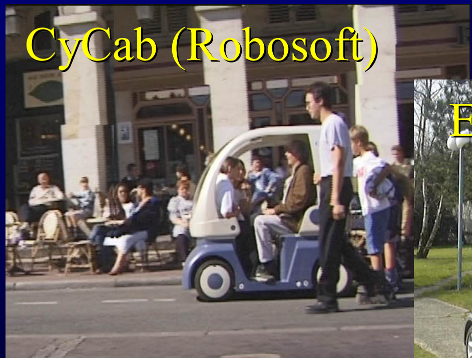
CyCab dual-mode vehicle
=> Commercialized by Robosoft



Concept of « Automated Road »
LaRA Program (leader: M. Parent)
=> 6 research institutes, 30 full-time researchers
Testing grounds at LIVIC, 5 M€ of equipment

Automated Urban Vehicle European project:
Cybercars (2001 -2005)

- **Consortium: 10 industrial partners** *(Fiat, Yamaha, Frog …)*, **7 research institutes** *(Inria, Inrets, Ensmp …)*, **12 cities involved** *(Rome, Rotterdam, Lausanne, Antibes …)*
- **Testing & Evaluation site at Inria Rocquencourt**
- **10 M € for 3 years**



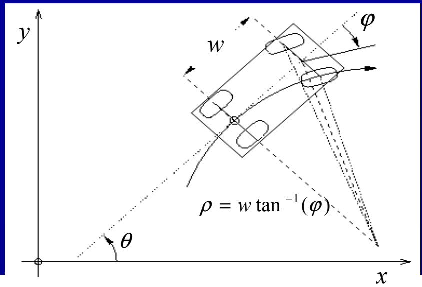
Decisional & Control Architecture

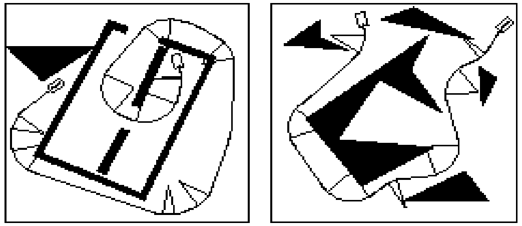
Autonomous Maneuvering

Electric Ligier Dual-mode Car

Cycab

Decisional & Control architecture



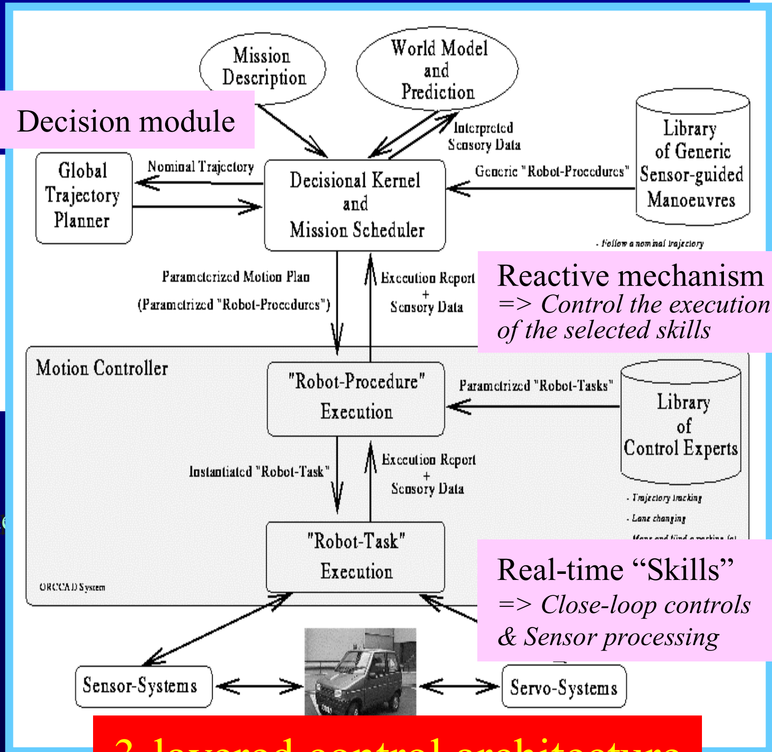


Planning CC-paths

(kinematic constraints ...)

continuous curvature profile + upper-bounded curvature & curvature derivative

[Scheuer & Laugier 98]

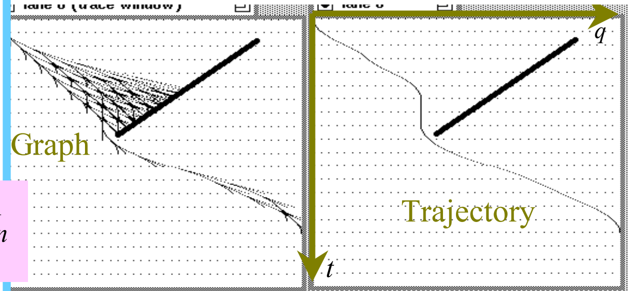


3-layered control architecture

[Laugier et al. 98]

$$\begin{cases} F_{min} \leq F \leq F_{max} & \text{(engine force limit)} \\ \sqrt{R_t^2 + R_n^2} \leq \mu R_b & \text{(no sliding constraint)} \\ 0 \leq \dot{s} \leq \dot{s}_{max} & \text{(speed limit)} \end{cases}$$

$$\begin{cases} 0 \leq \dot{s} \leq \min(\dot{s}_{max}, \sqrt{\frac{\mu g}{|\kappa_s|}}) \\ \max(\frac{F_{min}}{m}, \sqrt{\mu^2 g^2 - \kappa_s^2 \dot{s}^4}) \leq \ddot{s} \leq \min(\frac{F_{max}}{m}, \sqrt{\mu^2 g^2 - \kappa_s^2 \dot{s}^4}) \end{cases}$$



Kinodynamic Motion Planning

(Dynamic constraints ...)

[Fraichard 92]

Platooning [Parent & Daviet 96]

Lane Changing & Obstacle avoidance

[Laugier et al. 98]

Automatic Parallel Parking

[Paromtchik & Laugier 96]

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Platooning

[Parent & Daviet 96]

- **Electronic Tow-Bar**

Platoon of vehicles
(No tele-communication)

CCD Linear camera
(high rate & resolution)

First experimental infrared target

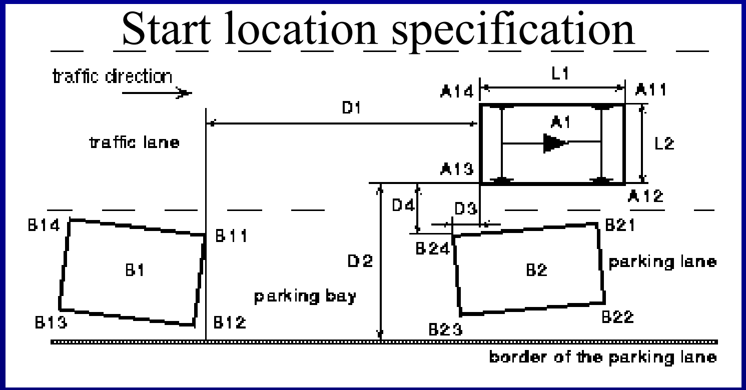
- **Longitudinal control**

$$X_l - X_f = d_{min} + h\,V_f$$
$$A_f = C_v\ \Delta V + C_p\,(\Delta X - h\,V_f - d_{min})$$
$$\text{with } C_v = 1/h \text{ and } C_p = \min(1/h,\ A_{max}/V_f)$$

- **Lateral control** => ***making use of the « tractor model »***
(wheel angle = direction of the leader)

Platooning *[Parent & Daviet 96]*

Automatic Parallel Parking *[Paromtchik & Laugier 96]*



(D1,D2) - Available displacements
F(D1,D2,D3,D4,D5) = 0
where: D5 - a safety distance
D3 - an estimate

1- Obtain available (D1,D2) by range data processing

2- Search for *T* and ϕ_{max} *(control parameters)*

3- Drive the vehicle using sinusoidal controls $\phi(t)$ and $v(t)$

4- Determine the current vehicle's location relatively to the parking bay

If the parked location is reached then stop, else go to step 1

Automatic parking maneuvers *[Paromtchik & Laugier 96]*

Lane Following/Changing *[Laugier et al. 98]*

- **Trajectory Tracking**

$$\dot{\theta} = \dot{\theta}_{ref} + v_{R,ref}\,(k_y y_e + k_\theta \sin\theta_e)$$
$$v_r = v_{R,ref} \cos\theta_e + k_x x_e$$

[kanayama 91]

- **Lane changing & obstacle avoidance**

1- Generate and track a « local trajectory » connecting the nominal trajectory with a collision-free trajectory located in a « parallel free lane »

2- Track the new « safe trajectory » until the obstacle has been overtaken

3- Generate and track a « local trajectory » connecting the « safe trajectory » to the nominal one

- **Generating smooth « local trajectories »**

Maximum allowed curvature

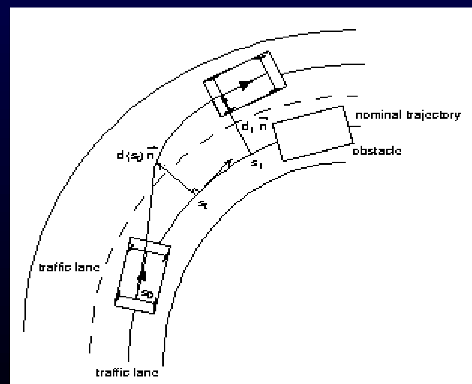
$$C_{max} = \min\left(\frac{\tan(\theta_{max})}{L}, \frac{\gamma_{max}}{v_{R,ref}^2}\right)$$

Minimum distance for lane changing

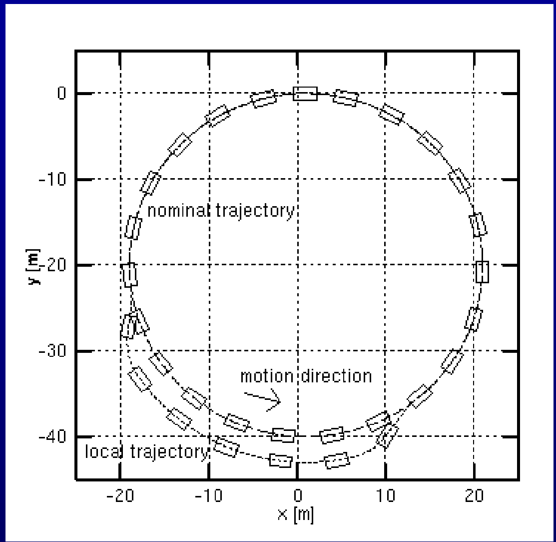
$$s_{T,min} = \frac{\pi\sqrt{k d_T}}{2 C_{max}}$$

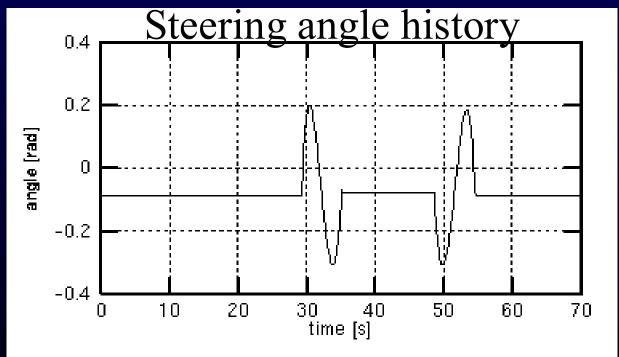
Associated trajectory *[Nelson 89]*

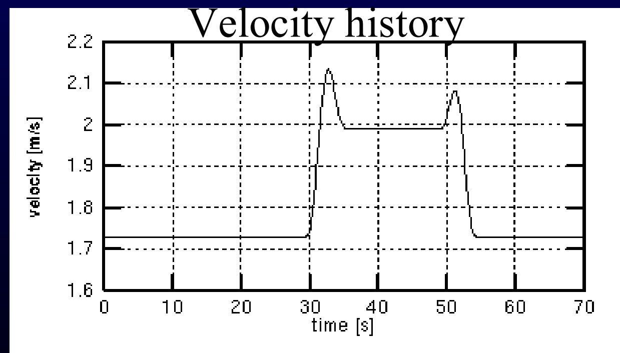
$$d(s) = d_T\left(10\left(\frac{s}{s_{T,min}}\right)^3 - 15\left(\frac{s}{s_{T,min}}\right)^4 + 6\left(\frac{s}{s_{T,min}}\right)^5\right)$$



Lane Following/Changing : *Experimental results*



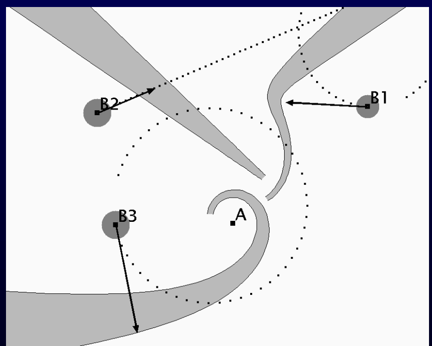


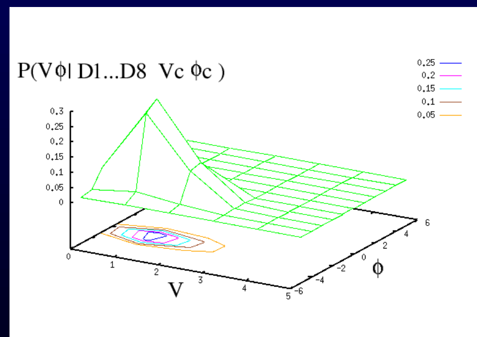


Obstacle avoidance in a Dynamic Environment

V-obstacles & Bayesian Programming

[Shiller & Large & Sekhavat 01] [Bessiere & Lebeltel 00]





Velocity Obstacles : *Basic idea*

- **Main difficulties & motivations**

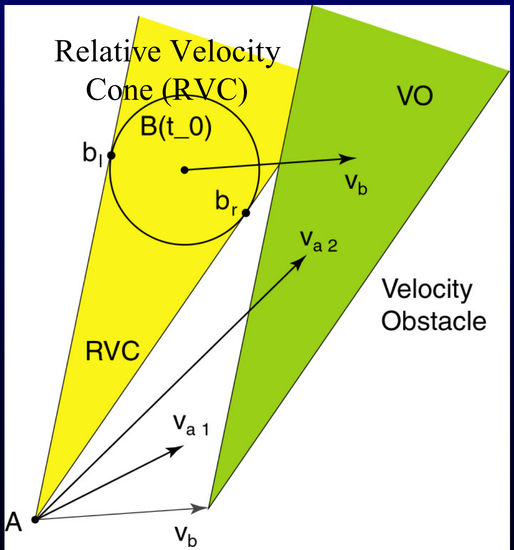
  => On-line Avoidance of obstacles moving along arbitrary trajectories (known or sensed)

  => The traditional state-time approach *(zero order search)* is not tractable (complexity & real-time) … Instead, reason at the "velocity level" *(first order search) !*

- **Initial concept of "Linear V-Obstacle"** *[Fiorini 93 & 98, Goshe 98]*

  => Mobile A and Obstacle B move along straight lines with constant velocities V_a and V_b

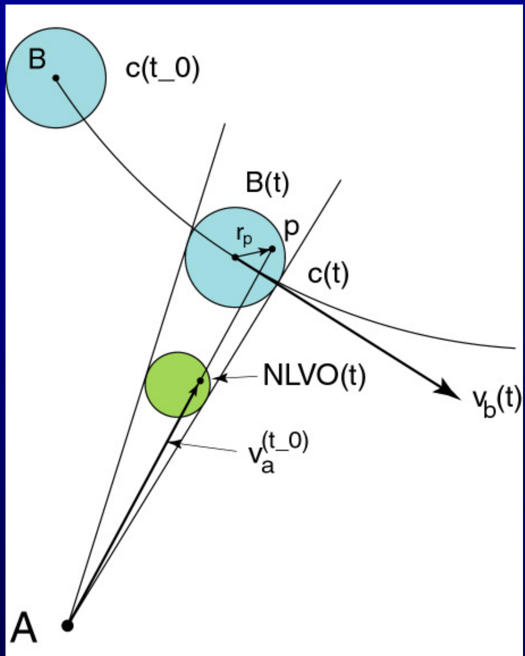
$$RVC = \bigcup A/b, b \in \partial B(t_0)$$
$$VO = v_b + RVC$$



- Any absolute velocity of A, pointing inside VO, would result in collision at some time $t \in (0, \infty)$
- A grazes B at tangency points between RVC and $b(t_0)$.

Non-Linear V-Obstacles

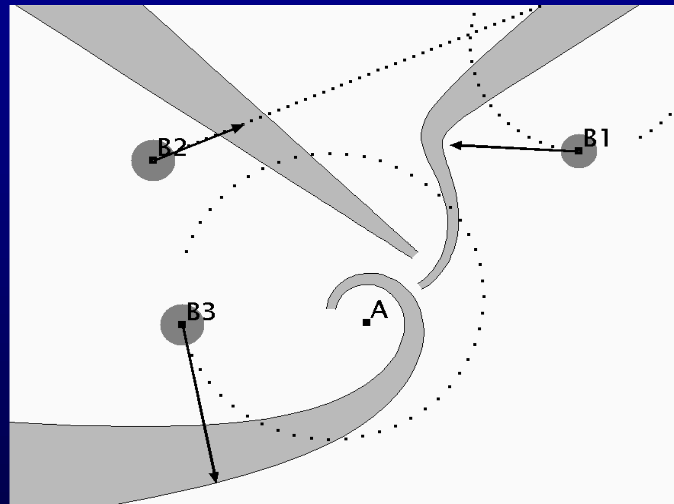
=> Obstacle B moves along trajectory c(t)



NLVO(t) = Absolute velocities of *A* at *t0*
that would collide with B(t)

$$NLVO(t) = \frac{c(t)+B}{t-t_0}$$

$$NLVO_{t_0} = \bigcup_{t>t_0} \frac{c(t)+B}{t-t_0}$$

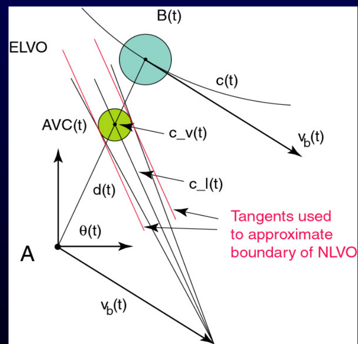


$$Obstacle\ \ trajectory\ \ :\ \ c(t) = d(t)e^{i\theta(t)}$$

$$c_v(t) = \frac{d(t)}{t}e^{i\theta(t)}$$

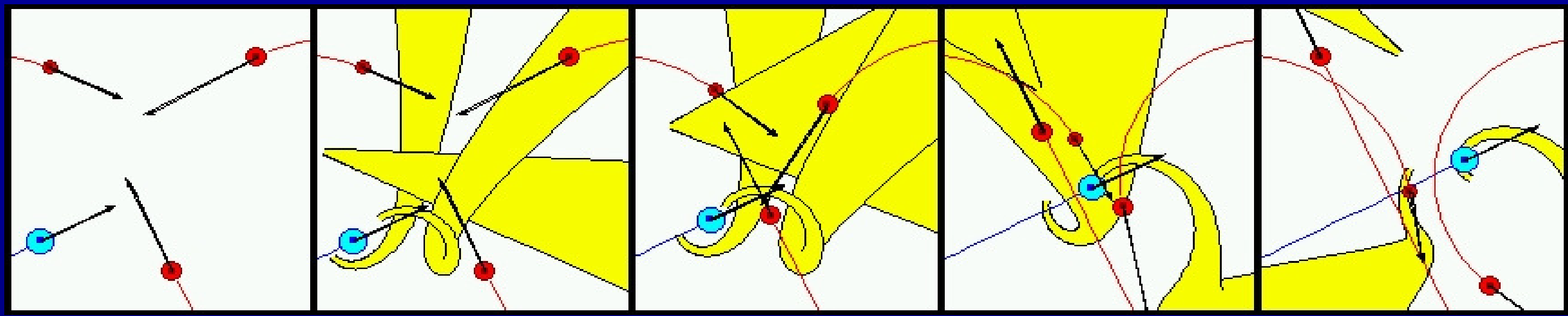
$$vo_r(t) = c_v(t) + i\frac{r}{t}\hat{c}_l(t)$$

$$vo_l(t) = c_v(t) - i\frac{r}{t}\hat{c}_l(t)$$

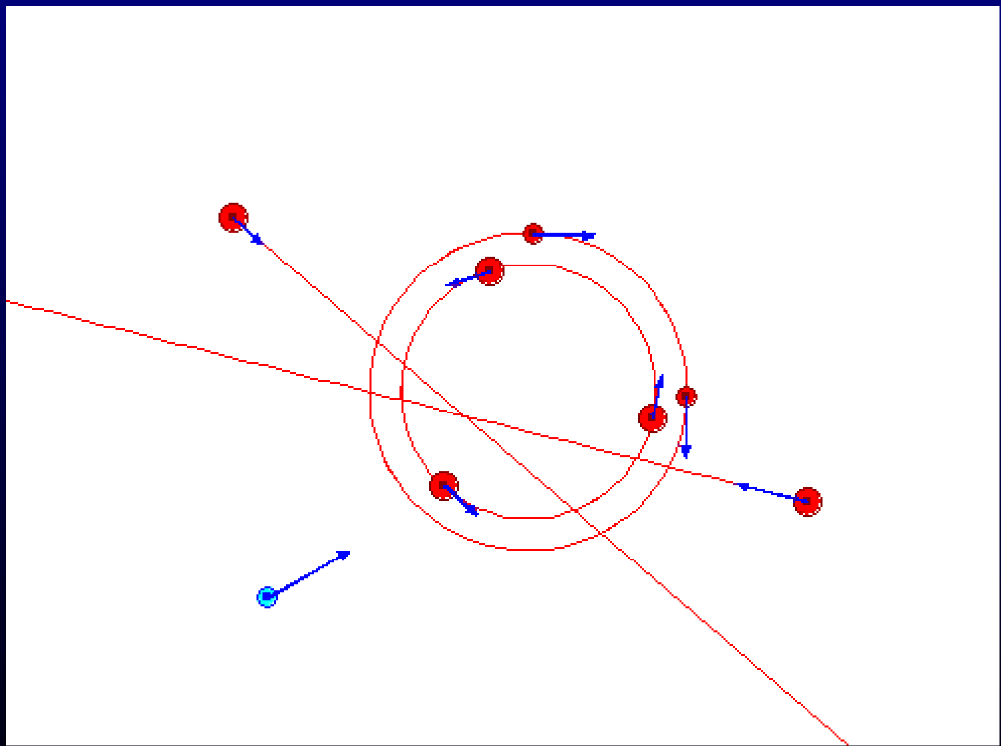


=> Approximate boundaries of NLVO (On-line computation !)

Simulation results (online computation)



A single velocity outside NLVO avoids the obstacle during the time interval for which the v-obstacle was generated



Obstacle avoidance using Bayesian Programming

- **Main difficulties & Motivations**

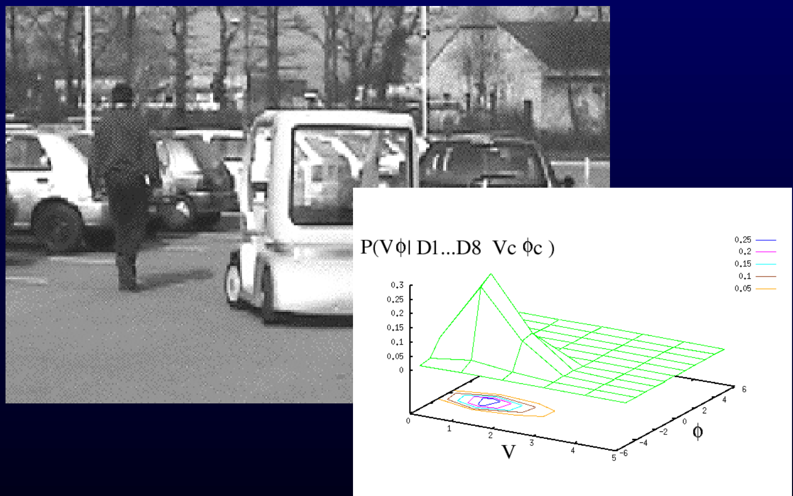
  => *On-line avoidance of sensed stationary or moving obstacles*

  => *Dealing with uncertainty using Preliminary Knowledge & Experimental data*

- **Basic idea**

  => Controlling the vehicle using a probability distribution on (v,ϕ)

  e.g. reducing speed and/or modifying steering angle for avoiding a pedestrian or a car



Incompleteness

Preliminary Knowledge
+
Experimental Data
=
Probabilistic Representation

Maximum Entropy Principle

$$-\sum P_i \log(P_i)$$

Uncertainty

Bayesian Inference
(NP-Hard
Heuristics & Optimization)

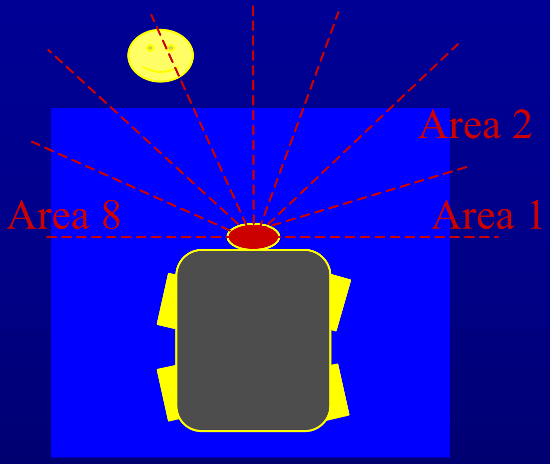
P(AB|C)=P(A|C)P(B|AC)=P(B|C)P(A|BC)

P(A|C)+P(¬A|C) = 1

Decision

=> *Using API « OpenPL », soon commercialized by a start-up*

Programming principle



- V = translational speed; ϕ = steering angle
- Sick laser range finder
- D_i = Distance to the nearest obstacle in area i
- In each area a speed V and a steering angle ϕ are computed, with a given confidence, in order to avoid the sensed obstacle
- Probabilistic Command Fusion weights the values of each area (+ task controls), thanks to the confidence

- **Joint distribution for the fusion**

$$P(V \otimes \phi \otimes D_1 \otimes \ldots \otimes D_8) = P(V \otimes \phi) \prod_{i=1}^{8} P_i(D_i / V \otimes \phi)$$

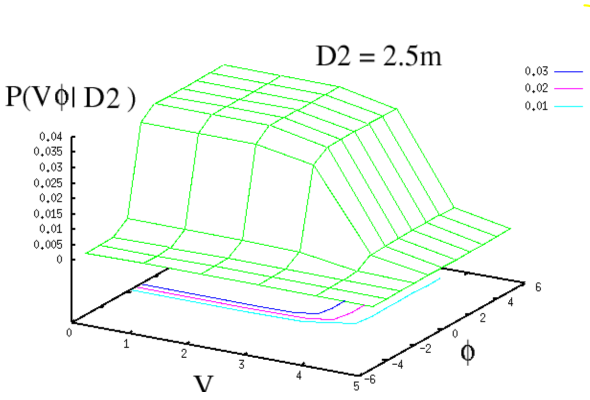
where :
$$P(V \otimes \phi) = \text{Uniform}$$
$$P_i(D_i / V \otimes \phi) = \frac{P_i(D_i) P_i(V / D_i) P_i(\phi / D_i)}{\sum_{D_i} P_i(D_i) P_i(V / D_i) P_i(\phi / D_i)}$$

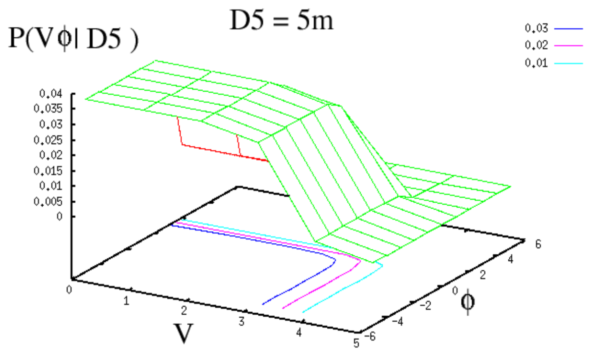
=>Probabilistic joint distribution for area i

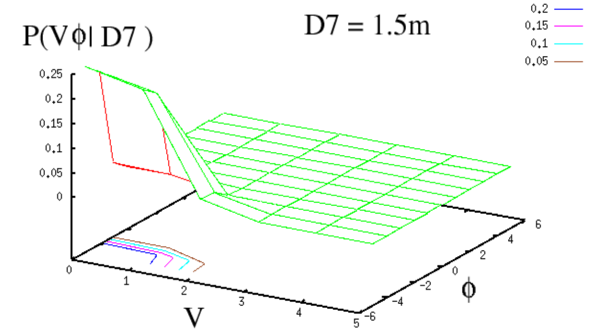
- **Problem solving**

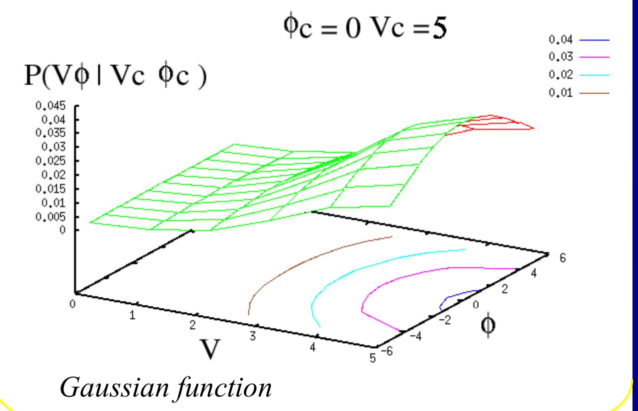
$$P(V \otimes \phi / D_1 \otimes \ldots \otimes D_8) = \frac{P(V \otimes \phi) \prod_{i=1}^{8} P_i(D_i / V \otimes \phi)}{\sum_{V,\phi} P(V \otimes \phi) \prod_{i=1}^{8} P_i(D_i / V \otimes \phi)}$$

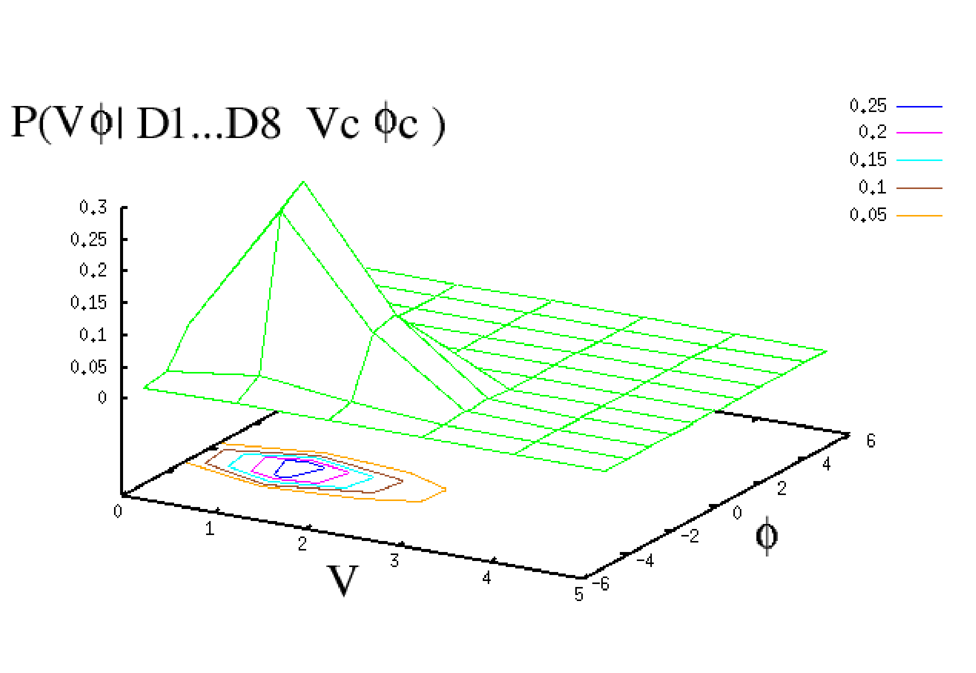
Command fusion







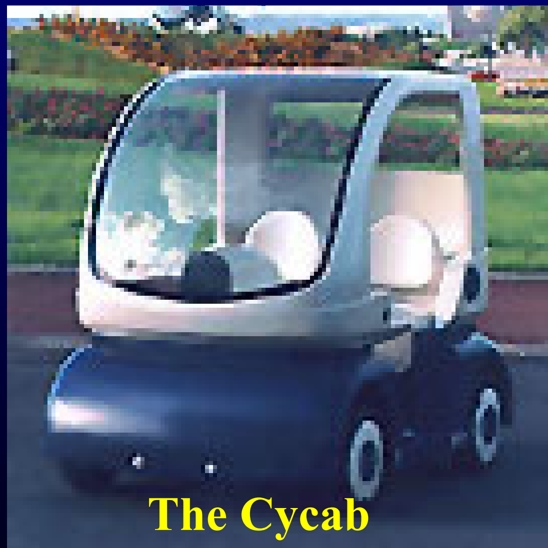




Experimental result

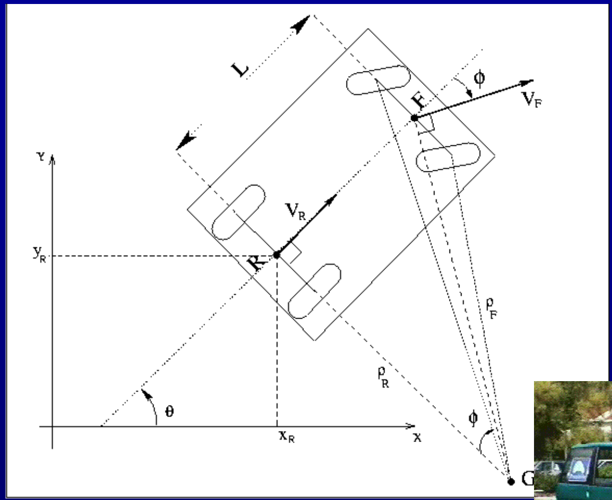
Automatic driving for a Bi-Steerable Car

[Sekhavat & Hermosillo 01]



The Cycab

Standard Car vs. Bi-steerable Car



Standard car

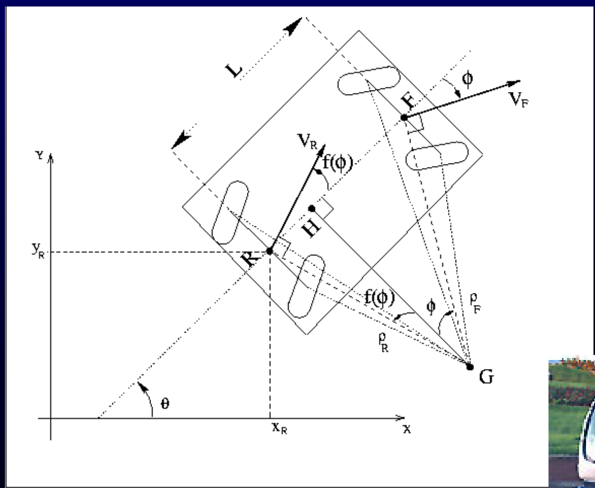
$$\begin{pmatrix} \dot{x}_R \\ \dot{y}_R \\ \dot{\theta} \\ \dot{\phi} \end{pmatrix} = \begin{pmatrix} \cos(\theta) \\ \sin(\theta) \\ \dfrac{\tan(\phi)}{L} \\ 0 \end{pmatrix} u_1 + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} u_2$$

$u_1 = V_R$

$u_2 = \dot{\phi}$

$f(\phi)$: *characteristic function*

$$\begin{pmatrix} \dot{x}_R \\ \dot{y}_R \\ \dot{\theta} \\ \dot{\phi} \end{pmatrix} = \begin{pmatrix} \cos(\theta + f(\phi)) \\ \sin(\theta + f(\phi)) \\ \dfrac{\sin(\phi - f(\phi))}{L\cos(\phi)} \\ 0 \end{pmatrix} u_1 + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} u_2$$



BS-car

=> Smaller turning radius bound & sweeping volume

=> Better maneuverability in cluttered environments

... But Planning & Control much more difficult !

Differential Flatness of the BS-car

- **Flatness property for a BS-car** *[Sekhavat & Hermosillo 00]*

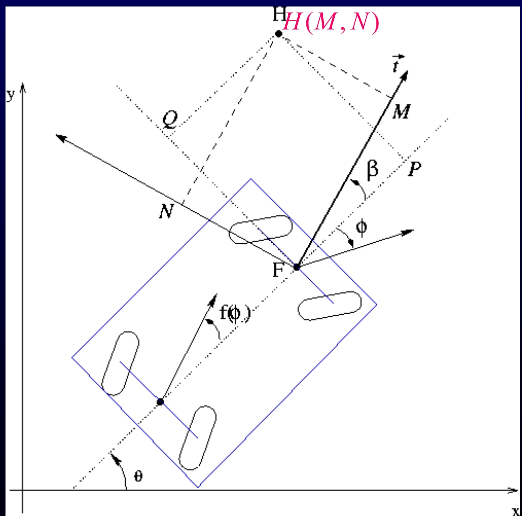
$$X = (x_R, y_R, \theta, \phi) \quad and \quad u = (V_R, \phi)$$

$$Cycab : \quad f(\phi) = k \cdot \phi \quad , \forall k \neq 1$$

$$Flat\ outputs : \quad H = (y_1(\phi), y_2(\phi))$$

$$\Rightarrow \quad \kappa = \frac{\sin((1+k)\phi_0)}{L \cos \phi_0 \cos(k\phi_0)} \quad if\ \phi \in \{0, -\phi_0, \phi_0\}$$

- **Flat outputs for the Cycab** *[Sekhavat & Hermosillo 01]*



$$Turning\ frame : \ (F, \vec{t}, \vec{t}^{\perp}) \quad with \ \beta(\phi) = \tan^{-1} \frac{B(\phi)}{A(\phi)}$$

$$\vec{t} = \cos\phi \, f'(\phi)\, \vec{u}_{\theta+\phi} - \cos f(\phi)\, \vec{u}_{\theta+f(\phi)}$$

$$A(\phi) = \cos^2(\phi) f'(\phi) - \cos^2 f(\phi)$$

$$B(\phi) = \cos(\phi)\sin(\phi) f'(\phi) - \cos(f(\phi))\sin(f(\phi))$$

$$M(\phi) = \frac{L \cos^2(f(\phi))}{\sqrt{A^2(\phi) + B^2(\phi)}}$$

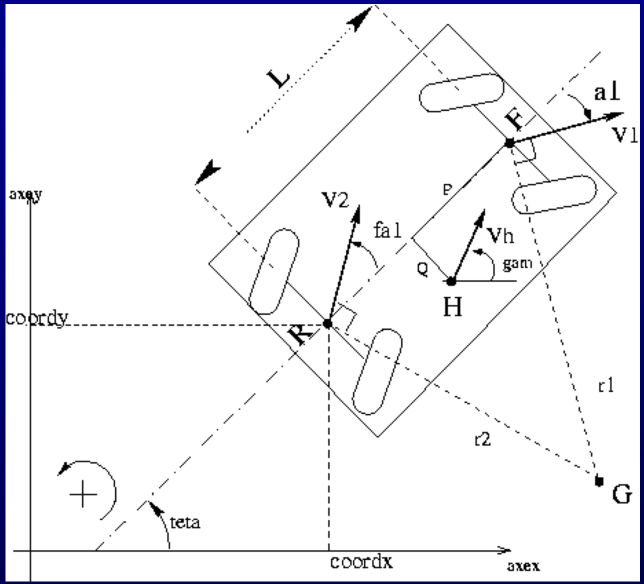
$$N(\phi) = -\int_0^{\phi} \frac{L\cos^2(f(u))(B'(u)A(u) - A'(u)B(u))}{\left(A^2(u) + B^2(u)\right)^{3/2}}$$

Controlling a BS-car

[Hermosillo &Sekhavat 02]

- **Relation between the « *Robot Controls* » and the « *Flat Output* »**

$$\dot{\vec{P}}_H = \upsilon_H \vec{\gamma}$$
$$\upsilon_H = \upsilon_F\left(\cos(\varphi-\beta) - NF\right) + \omega_\varphi\left([\partial M/\partial\varphi] - [\partial\beta/\partial\varphi]N\right)$$



- **Open-loop controls of a BS-car**

$$\omega_\varphi = \upsilon_H\left(\frac{d\kappa}{ds}\right) \Big/ \left(\partial\mathbf{K}/\partial\varphi\right)$$
$$\upsilon_F = \frac{\upsilon_H - \omega_\varphi\left([\partial M/\partial\varphi] - [\partial\beta/\partial\varphi]N\right)}{\cos(\varphi-\beta) - NF}$$

$$\kappa = \mathbf{K}(\varphi) = -\frac{\partial\beta/\partial\varphi}{\partial M/\partial\varphi - \beta N} \qquad F(\varphi) = \frac{\sin(\varphi - f(\varphi))}{L\cos(f(\varphi))}$$

- **Linearizing Feedbacks & Closed-loop controls**

$$\dot{\xi}_2 = (\overline{w}_1 + \kappa^2\xi_1^3)\dot{s}$$
$$\dot{\xi}_1 = \xi_2\dot{s}$$
$$\upsilon_H = \xi_1\dot{s}$$

$$\frac{d\kappa}{ds} = \frac{\overline{w}_2 - 3\kappa\xi_2\xi_1}{\xi_1^3}$$

$$\dot{\chi}_i = \alpha\chi_i + \beta w_i$$
$$\alpha = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \quad \beta = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

$$\chi_1 = \begin{pmatrix} y_1^{(0)} \\ y_1^{(1)} \\ y_1^{(2)} \end{pmatrix} \qquad w_1 = y_1^{(3)}$$

Canonical form for linear systems

Experimental results

SLAM & Motion planning & Control of the Cycab

INRIA RHÔNE-ALPES

Conclusion

- **Some major issues of "Automatic Cars" have been addressed, and it has been shown that large technical progress have been made during the last decade**
- **Three major technical problems have been presented and discussed:** *(1) Autonomous maneuvering, (2) Obstacle avoidance in dynamic environments, (3) Automatic driving for a Bi-steerable car (designed for city centers)*
- **Original solutions have been proposed, implemented, and tested on real vehicles** *(SBM, NLVO, Bayesian Programming, BS-Car Automatic Driving)*
- **However, all these techniques have still to be robustified in order to be really applicable in normal traffic conditions** *(sensing, hazards processing …)*
  => it's the purpose of current work
  Carsense and Cybercars EU projects, Arcos2003 French National project