"I can't define a robot,
but I know one when I see one"
by- Joseph Engelberger

Université Blaise Pascal

LASMEA

Towards an Urban Cooperative and Autonomous Navigation System

Risky Interventions and Environmental Surveillance-Maintenance (RISE 2010) IARP workshop

Sheffield Hallam University, Sheffield, England, January 20-21th 2010

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http://robots.lasmea.univ-bpclermont.fr

Outline of the presentation

Introduction
- ***LASMEA***
- ***Motivation***
- ***Navigation strategies***

Automous navigation
- ***Modeling***
- ***Control***
- ***Applications***

Cooperative navigation
- ***Modeling***
- ***Control***
- ***Applications***

Perspectives
- ***Autonomous navigation***
- ***Cooperative navigation***

LASMEA: Presentation

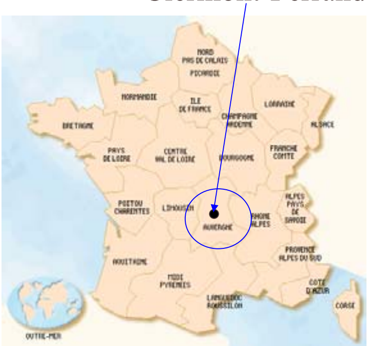
LASMEA

Director : Michel Dhome

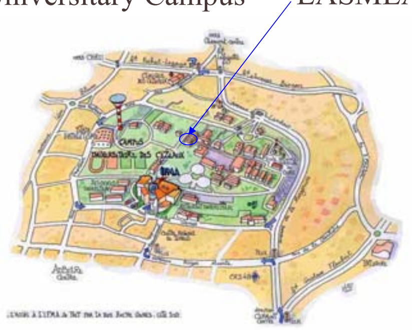
400km south of Paris
200km West of Lyon

CNRS/UBP
Mixed Unit 6602

France Clermont-Ferrand



Universitary Campus LASMEA



LASMEA: Presentation

LASMEA

Director : Michel Dhome

http://wwwlasmea.univ-bpclermont.fr

2 research groups

MATELEC

- *Optoelectronics, microelectronics*
- *Electromagnetism*
- *Gaz sensor*

33 teacher/researcher
1 research scientist
25 Phd

GRAVIR

- *Perception System*
- *Computer that See*
- *ROSACE*

25 teacher/researcher
2 research scientist,
51 Phd, 2 post-doc

LASMEA: GRAVIR

Main objective: « Development of theoretical concepts and methodology for systems perception and control, and their validation on real demonstrators ».

Current organisation :

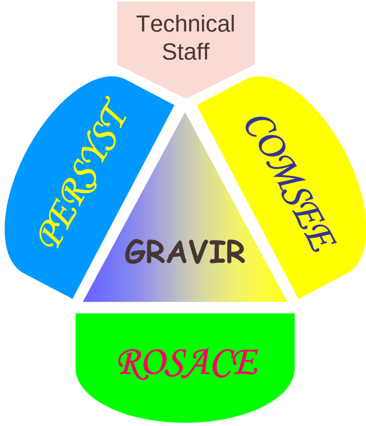
group leaders
J.P. Derutin, T. Chateau, Y. Mezouar

3 scientific themes
J.P. Derutin, T. Chateau, P. Martinet & Y. Mezouar

1 scientific comitee

Technical staff and secretary

1 general assembly and 1 group seminary per year



GRAVIR *(over 100 persons)*
Permanents : *2 CNRS, 10PU, 13MCF*
Temporary : *1 PAST, 3 post-doc, 12 CDD*
Students : *51 PhD, 3 MASTERs, 2 CNAM*
Technical Staff and secretary : 5.5

Introdution | Autonomous navigation | Cooperative navigation | Perspectives | Conclusion

LASMEA: GRAVIR

Perception System

PERception SYSTems — *J.P. Derutin*

Multisensor Perception
- Data fusion
- Scene understanding
- SLAM

Smart Sensors
- Algorithm Architecture Adequation
- Cognitive Vision

Architecture and methods
- Parallelism in vision
- High speed prototyping tools
- Tools for embedded applications


Towards an Urban Cooperative and Autonomous Navigation System
RISE10, IARP workshop on Risky Interventions and Environmental Surveillance-Maintenance
Sheffield Hallam University, Sheffield, England, January 20th 2010

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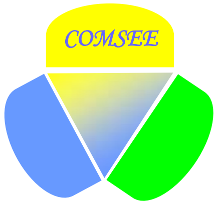
LASMEA: GRAVIR



Artificial Vision

COMputer that SEE — *T. Chateau*

http://comsee.univ-bpclermont.fr

Geometry for visual perception
- Metrology by vision
- Automatic rigid scene reconstruction

Vision in Deformable Environments
- Modeling and algorithm for deformable environment

Visual Recognition
- Real time object tracking
- Object recognition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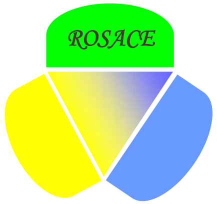
LASMEA: GRAVIR



ROSACE

P. Martinet & Y. Mezouar

ROboticS and Autonomous Complex systEms

http://wwwlasmea.univ-bpclermont.fr/Control

VISIR — *VIsual ServoIng of Robots*
- Omnidirectional visual servoing
- Topological navigation through sensory memory
- Multi-sensor-based control

AGV — *Automatic Guided Vehicles*
- Control design under uncertain dynamics
- Hybrid control architecture
- Multi-robot-system control

MICMAC — *Modeling, Identification and Control of Complex Machines*
- Vision-Based Identification of Parallel Robots
- Vision-Based Control of Parallel Robots
- Control of High Dynamics System


Towards an Urban Cooperative and Autonomous Navigation System
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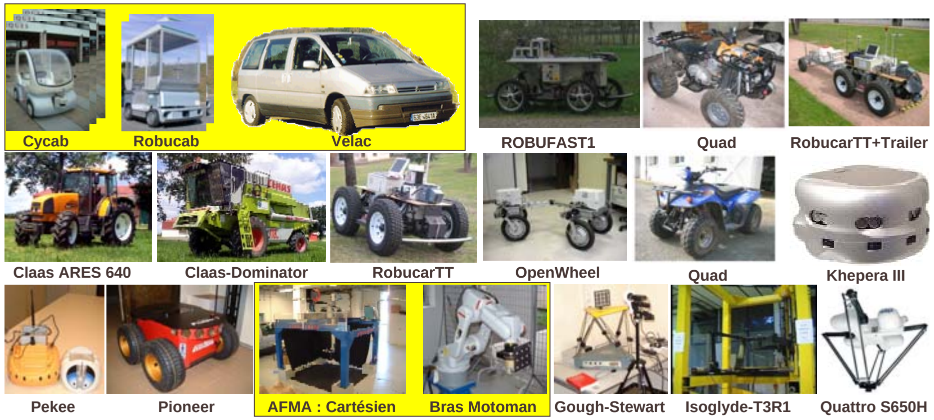
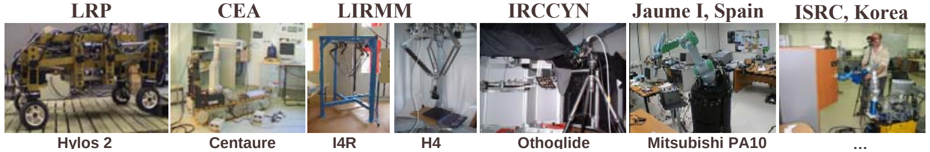
GRAVIR : Robotic Platforms



Collaborations

LRP | CEA | LIRMM | IRCCYN | Jaume I, Spain | ISRC, Korea

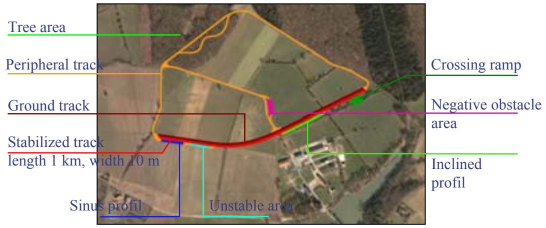


GRAVIR : experimental site

- Available: **PAVIN** urban area

Urban area : 2500 m² – 320 m of streets / rural area : 1900 m² – 260 m of tracks

- Future: **PAVIN** in natural environment



Motivation: Urban Transportation Systems Concept

http://www.lara.prd.fr/en/

http://imara.inria.fr/

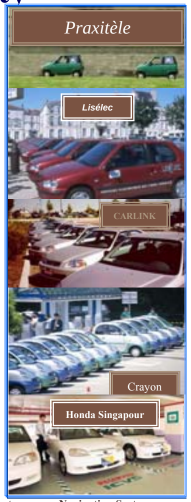
Motivation : Inner-cities congestion

Motivation: Urban Transportation Systems Concept

Their attractiveness depends mainly on their flexibility

"they have to answer to various public needs"

Car sharing concept



appears as a suitable answer in specific areas
(inner-cities pedestrian zones, airport terminals, ...)

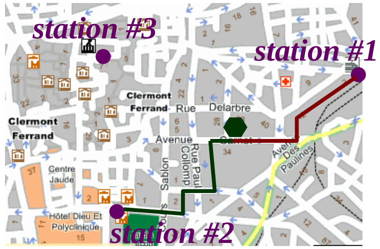
Such systems have been developed since the mid-90's :
Praxitèle in France, CarLink in USA, Crayon in Japan…

Motivation: Autonomous navigation

Car sharing concept demands for

automatic guidance capabilities

To transport passengers in an entire automatic way



To bring back empty vehicles to stations for refilling and reuse

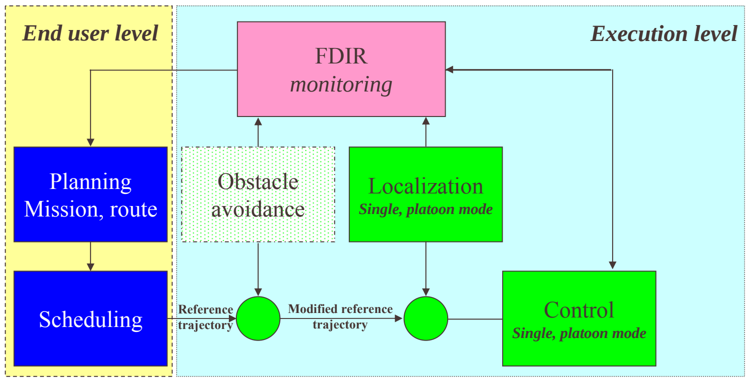
Autonomous vehicle

To deliver free vehicles for customer use

Platoon capability

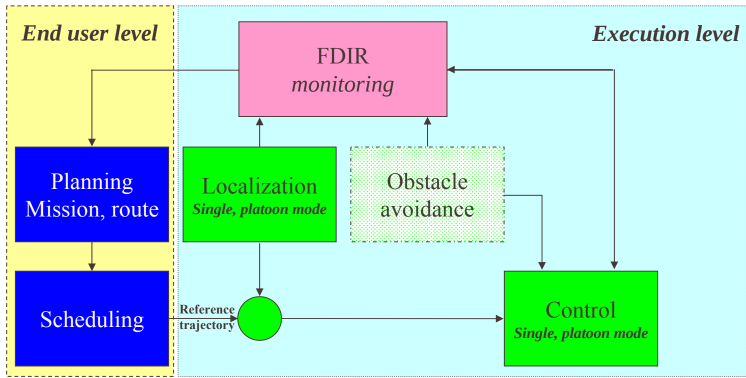
Navigation strategies

Navigation scheme



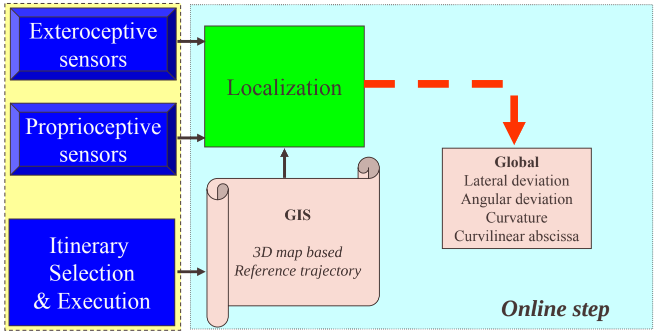
Navigation strategies

Navigation scheme



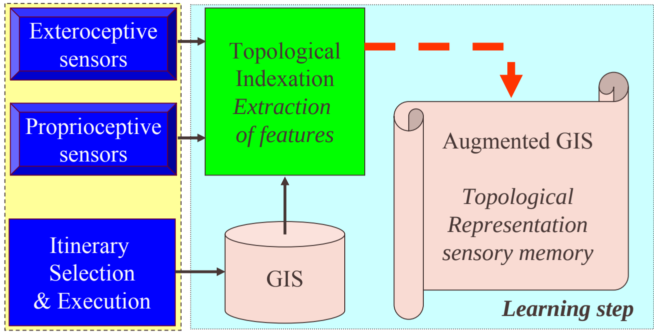
Navigation strategies

3D Map based navigation (absolute navigation)



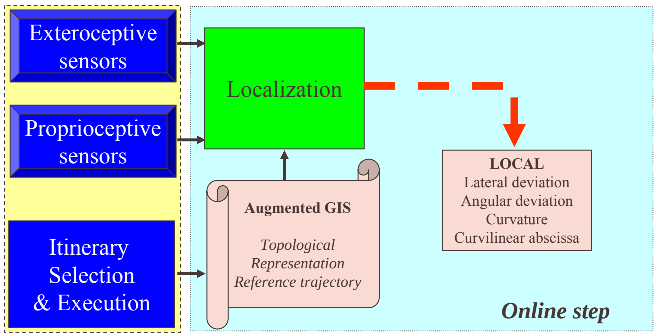
Navigation strategies

Memory based navigation (relative navigation)



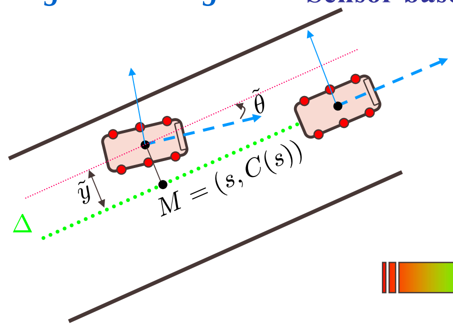
Navigation strategies

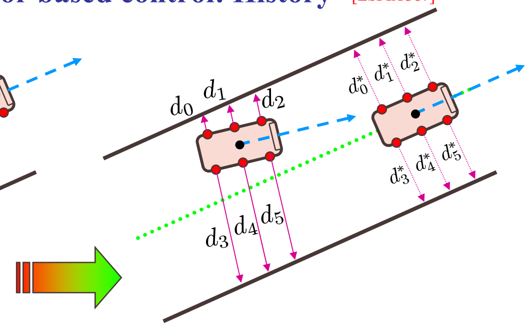
Memory based navigation (relative navigation)



Navigation strategies

Sensor based control: History [ESPIAU87]





$$d = (d_0, d_1, d_2, d_3, d_4, d_5)^T$$

Lateral control in cartesian space:

Bringing $(\tilde{y}, \tilde{\theta})$ to $(0,0)$

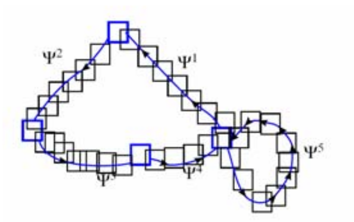
Explicite declaration of Δ and required cartesian localization

Lateral control in sensor space:

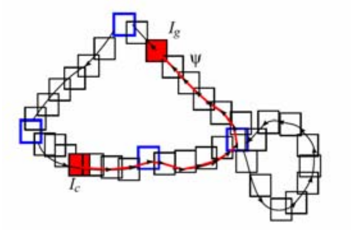
Bringing d to d^*

No explicite declaration of Δ and do not required cartesian localization

Navigation strategies Using a topological description of the environment



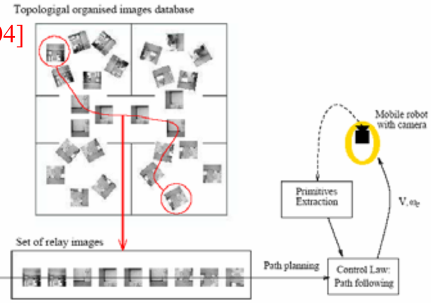
Topological representation of the environment

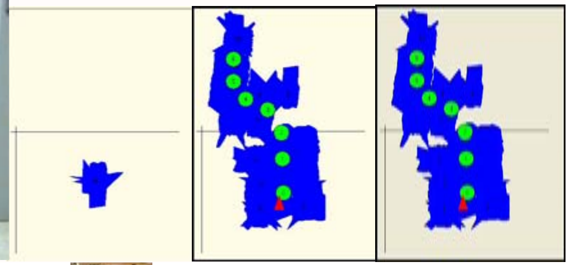


Performing navigation as a visual route to follow

Previous Work Blanc [04] Ait Ader[04]

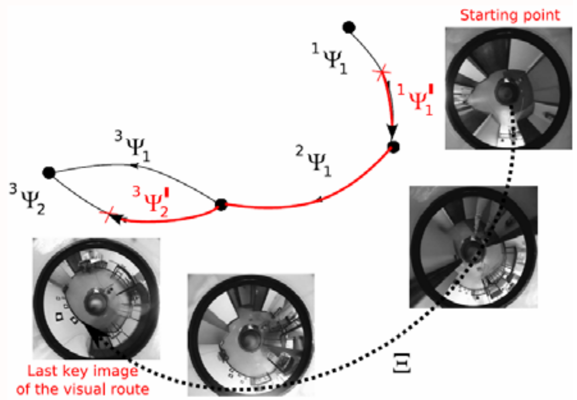
Navigation using visual memory





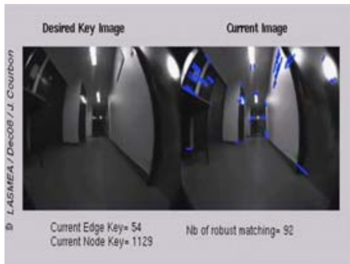
Previous Work H. Hadj Abdelkader [05]

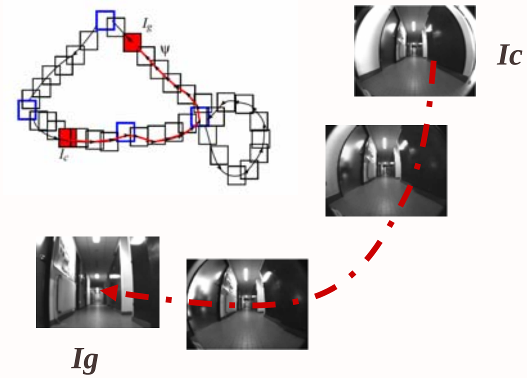
Navigation with omnidirectional visual memory : [ICRA07]



Other application fields J. Courbon [08]

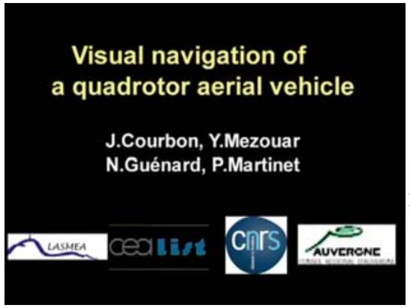
Navigation with fisheye visual memory : [ICARCV08]

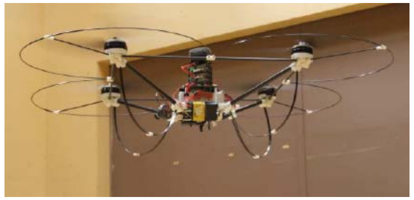




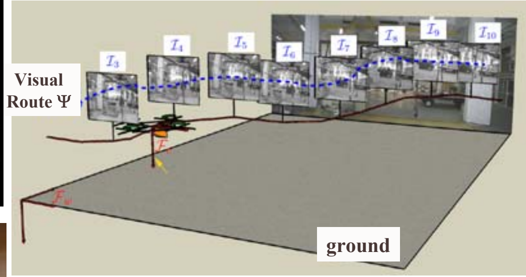
Other application fields

J. Courbon [09]





Navigation with fisheye visual memory : [IROS09]



Outline of the presentation

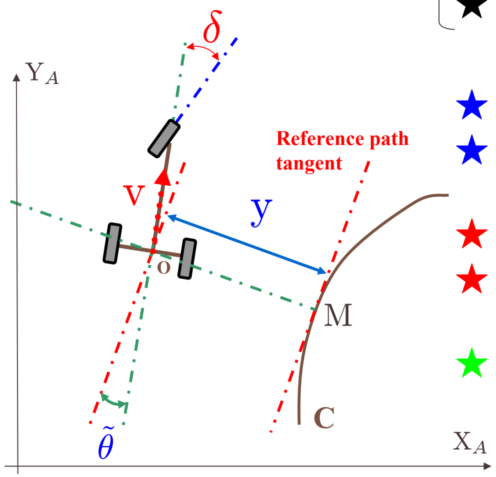
Introduction
- LASMEA
- Motivation
- Navigation strategies

Automous navigation
- Modeling
- Control
- Applications

Cooperative navigation
- Modeling
- Control
- Applications

Perspectives
- Autonomous navigation
- Cooperative navigation

Modelling: Notations



M:
- ★ s : curvilinear coordinate
- ★ $c(s)$: curvature

- ★ $\tilde{\theta}$: angular deviation
- ★ y : lateral deviation

- ★ δ : wheel angle
- ★ v : vehicle linear velocity

- ★ l : wheel base length

Modelling: State model

The vector $(s_i, y_i, \tilde{\theta}_i)$ describes the state of the i^{th} vehicle

Modelling is derived under non-slipping assumptions (tricyle model) [Samson95, Daviet95, Thuilot04]

→ relies on a kinematic model
→ designed with respect to the reference path

$$\begin{cases} \dot{s}_i = v_i \frac{\cos\tilde{\theta}_i}{1-y_i c(s_i)} \\ \dot{y}_i = v_i \sin\tilde{\theta}_i \\ \dot{\tilde{\theta}}_i = v_i \left(\frac{\tan\delta_i}{l} - \frac{c(s_i)\ \cos\tilde{\theta}_i}{1-y_i\ c(s_i)} \right) \end{cases}$$

Syst Ia

Control objectives

y_{i+1} and $\tilde{\theta}_{i+1}$ to 0

δ_{i+1}

Control: Lateral control in curved path following

[Thuilot04]

Chained state vector $A = (a_{1i}, a_{2i}, a_{3i})^T = \Theta(s_i, y_i, \tilde{\theta}_i) \begin{cases} a_{1i} = s_i \\ a_{2i} = y_{1i} \\ a_{3i} = \tan\tilde{\theta}_i \,(1 - y_i\, c(s_i)) \end{cases}$

Chained Control vector $M = (m_{1i}, m_{2i})^T = \Upsilon(v_i, \delta_i)$

Chained System [Samson95]
Exact linearization

$(*)' = \frac{d}{ds}(*)$

Chained model driven by s

$$\text{Syst Ia} \Rightarrow \begin{cases} \dot{a}_{1i} = m_{1i} \\ \dot{a}_{2i} = a_{3i} m_{1i} \\ \dot{a}_{3i} = m_{2i} \end{cases} \Rightarrow \text{Syst IIa} \begin{cases} a'_{2i} = a_{3i} \\ a'_{3i} = m_{3i} \end{cases}$$

→ linear system structure
→ full lateral / longitudinal decoupling

PD control law

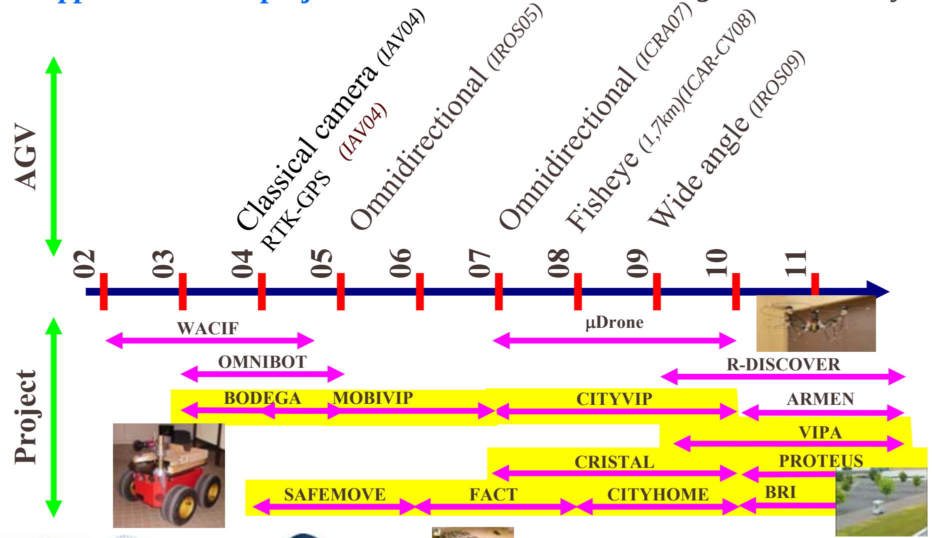
$$m_{3i} = -k_d\, a_{3i} - k_p\, a_{2i}$$

(k_d, k_p) tuning specifies a settling distance

$$a''_{2i} + k_d\, a'_{2i} + k_p\, a_{2i} = 0 \Rightarrow (a_{3i}, a_{2i}) \to (0,0) \Rightarrow \left(y_i, \tilde{\theta}_i\right) \to (0,0)$$

Vehicle trajectories are velocity independent

Applications and projects in LASMEA — *AGV using visual memory*



Applications and projects: MOBIVIP — *AGV using RTK-GPS*

Mobivip : Clermont-Fd 2004

Navigation using RTK-GPS
Clermont-Ferrand : LASMEA-GRAVIR

Applications and projects: MOBIVIP — *AGV using vision only*

urban context
[Royer04]

Visual memory

Reference Trajectory

and

Image features (3D points)

Experimental data
Compiegne city center
(BODEGA/MOBIVIP)

Applications and projects: BODEGA *AGV using vision only*

BODEGA : Clermont-Fd 2005

Navigation using vision only
Clermont-Ferrand : LASMEA-GRAVIR

Applications and projects: MOBIVIP *AGV using vision only*

MOBIVIP : Clermont-Fd 2006

Navigation using vision only
Clermont-Ferrand : LASMEA-GRAVIR

Applications and projects: CITYVIP *AGV using visual memory*
General framework :

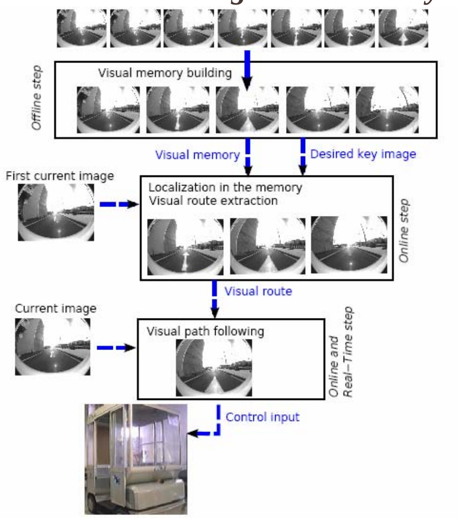
Vision based memory navigation strategy :

3 steps :

1. Visual memory building

2. Localization into the visual memory

3. Navigation into the visual memory



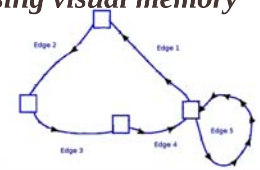
Applications and projects: CITYVIP *AGV using visual memory*
Graph based representation

Vision based memory navigation strategy :

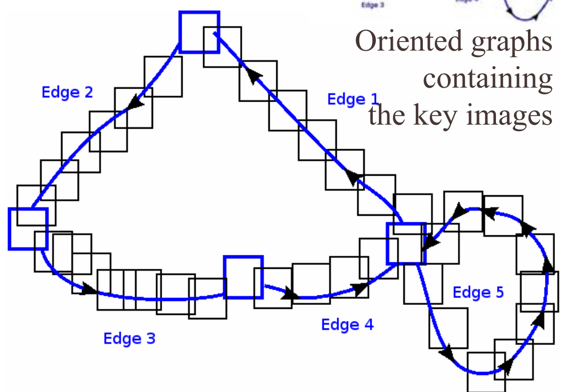
Visual memory building

a-Topological description
b-Learning the environment
c-Extraction of interesting features

Can be
•Harris points
•Sift features
•…



Oriented graphs containing the key images



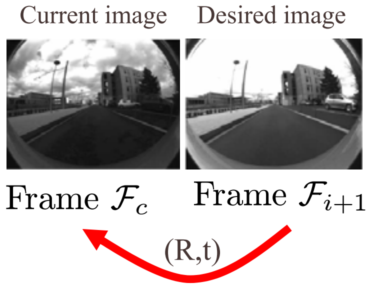
Applications and projects: CITYVIP *AGV using visual memory*

Localization

Vision based memory navigation strategy :

Localization into the visual memory

a- Global localization *[ICRA08]*
b- Selection of key images
c- Relative pose computation



Applications and projects: CITYVIP *AGV using visual memory*

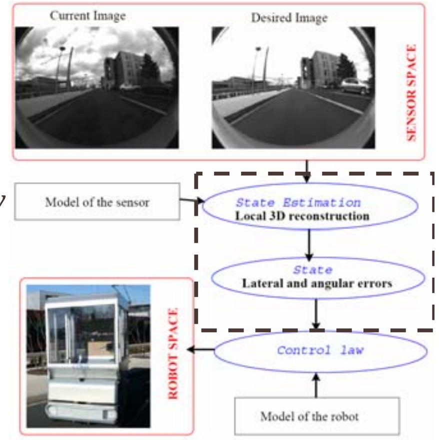
Localization

Vision based memory navigation strategy :

Localization into the visual memory

a- Global localization *[ICRA08]*
b- Selection of key images
c- Relative pose computation

(y, θ) evaluation



Applications and projects: CITYVIP *AGV using visual memory*

Unified model

Use of unified camera model for fisheye camera

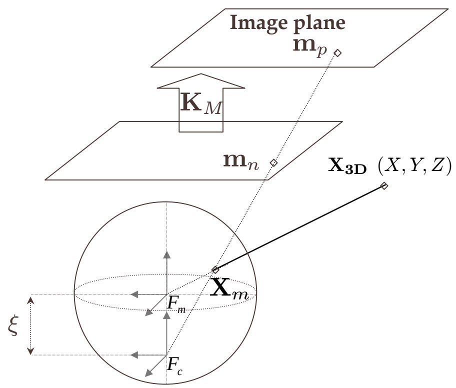
[GEYER00] [IROS07]

$$\mathbf{X_m} = \frac{1}{\rho}\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$\rho = \|\mathbf{X}\| = \sqrt{X^2+Y^2+Z^2}$$

$$\mathbf{m_n} = [\mathbf{x}^T \beta]^T = \begin{bmatrix} \dfrac{X}{Z+\xi\rho} \\ \dfrac{Y}{Z+\xi\rho} \\ \beta \end{bmatrix}$$

$$\mathbf{m_p} = \mathbf{K_M m_n}$$



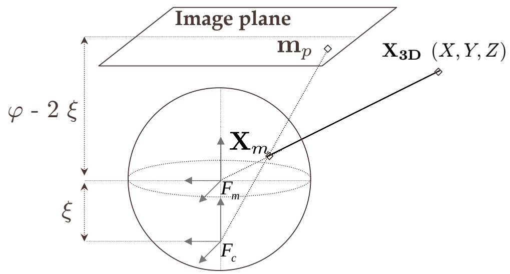
Mirror : unitary sphere

Applications and projects: CITYVIP *AGV using visual memory*

Unified model

Single-viewpoint systems

Case of points φ and ξ : Mirror parameters



$$\mathbf{M} = \begin{bmatrix} \varphi-\xi & 0 & 0 \\ 0 & \varphi-\xi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{K} = \begin{bmatrix} f & fs & u_0 \\ 0 & fr & v_0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{f}(\mathbf{X_{3D}}) = \begin{bmatrix} \frac{X}{\epsilon Z+\xi\sqrt{X^2+Y^2+Z^2}} \\ \frac{Y}{\epsilon Z+\xi\sqrt{X^2+Y^2+Z^2}} \\ 1 \end{bmatrix}$$

Special cases :

$\epsilon = 1$ and $\xi = 0$ ➔ perspective projection
$\epsilon = 0$ and $\xi = 1$ ➔ spherical projection

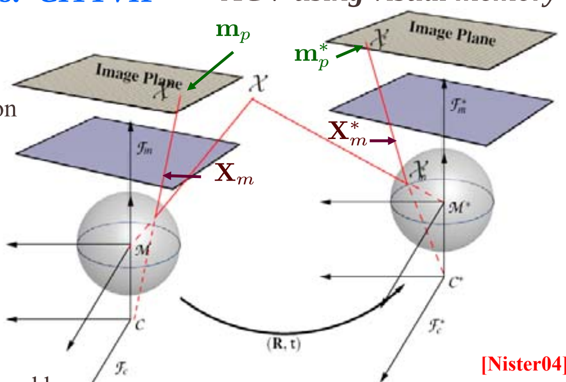
Generic Projection function

$$m_p = \underbrace{\mathbf{K}\ \mathbf{M}}_{\mathbf{K}_M}\ \mathrm{f}(\mathbf{X_{3D}})$$

Applications and projects: CITYVIP — *AGV using visual memory*

Localization

Scaled euclidian reconstruction



[Nister04]

Epipolar constraint can be expressed by :

$$\mathrm{X_m}^T\mathbf{R}(\mathrm{t}\times \mathrm{X_m}^{*T}) = \mathrm{X_m}^T\mathbf{R}\,[\mathrm{t}]_\times\, \mathrm{X_m}^{*T} = 0$$

For pinhole model $\mathrm{X_m}^T\mathbf{E}\mathrm{X_m}^{*T} = 0$

From five couples of points E can be estimated

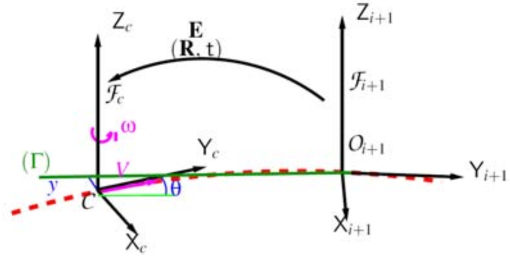
Outliers are rejected by using RANSAC

Applications and projects: CITYVIP — *AGV using visual memory*

Control

State model of the mobile robot

$$(s, y, \theta)$$



- $\mathcal{F}_i = (O_i, \mathbf{X_i}, \mathbf{Y_i}, \mathbf{Z_i})$
- $\mathcal{F}_{i+1} = (O_{i+1}, \mathbf{X_{i+1}}, \mathbf{Y_{i+1}}, \mathbf{Z_{i+1}})$ the frames attached to the robot when $\mathcal{I}_i$

Kinematic model of the mobile robot

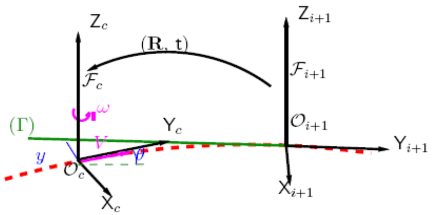
$$\begin{cases} \dot{s} = V\dfrac{\cos\theta}{1-c(s)y} \\ \dot{y} = V\sin\theta \\ \dot{\theta} = V\left(\dfrac{\tan\delta}{l} - \dfrac{c(s)\cos\theta}{1-c(s)y}\right) \end{cases}$$

⇒ Chained System theory [IAV04]

Applications and projects: CITYVIP — *AGV using visual memory*

Control

Path following approach



Goal: $y \longrightarrow 0$, $\theta \longrightarrow 0$ before $\mathcal{F}_c$ reaches $\mathcal{F}_{i+1}$

Asymptotically stable guidance control law based on the chain system approach:

$$\delta(y,\theta) = \arctan\left(-l\left[\cos^3\theta\left(-K_d\tan\theta - K_p y\right)\right]\right)$$

Applications and projects: CITYVIP — *AGV using visual memory*

Testbed

Experimental robot is a Robucab from Robosoft

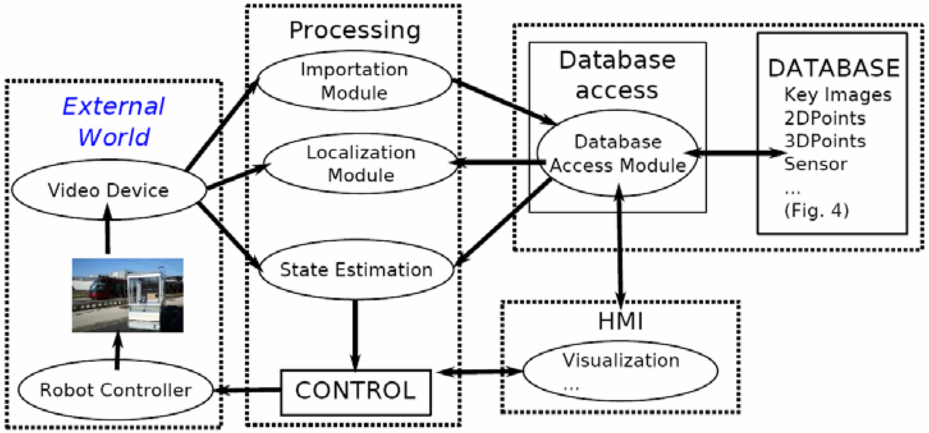
Algorithms are implemented in C^{++} language on a laptop using RTAI-Linux OS with a 2GHz Centrino processor

Fujinon fisheye lens, mounted onto a Marlin F131B camera
Field-of-view of 185 deg
Image resolution in the experiments was 800 × 600 pixels
Frame rate of 15fps

Longitudinal velocity V has been fixed to $1\,ms^{-1}$
K_p and K_d are tuned regarding a double pole located at value 0.3

Applications and projects: CITYVIP *AGV using visual memory*

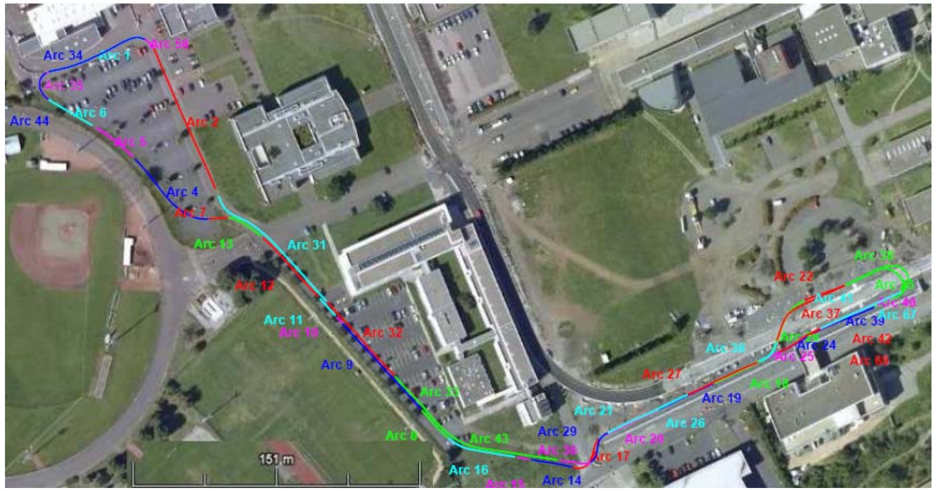
Testbed : SOVIN Architecture



Applications and projects: CITYVIP *AGV using visual memory*

Experiment

Loop 1200 m – 35 edges
Navigation 1700m (26 minutes, 1400 keys images, 54 edges)

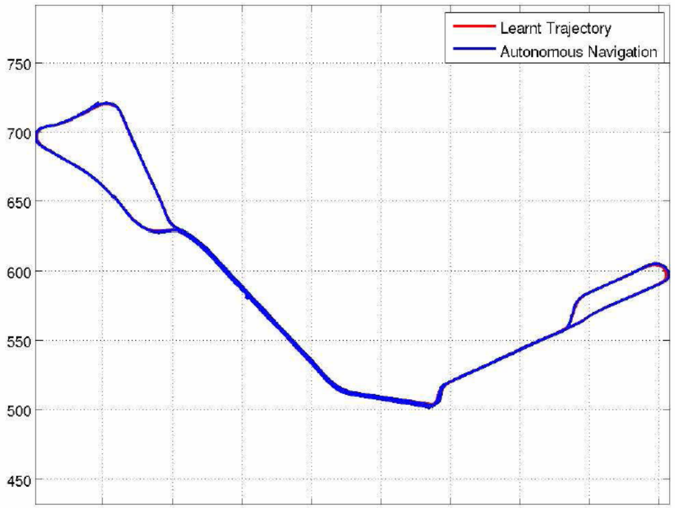


Applications and projects: CITYVIP *AGV using visual memory*

Experiment

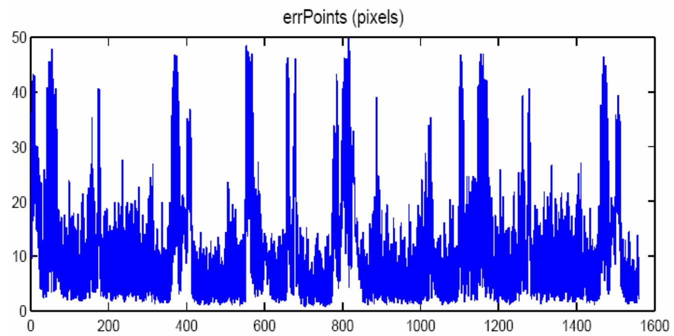
Lateral error:
- mean: 23 cm
-standard deviation: 30 cm.

Navigation stops after 1700m for security reasons (small number of matched points)



Applications and projects: CITYVIP *AGV using visual memory*

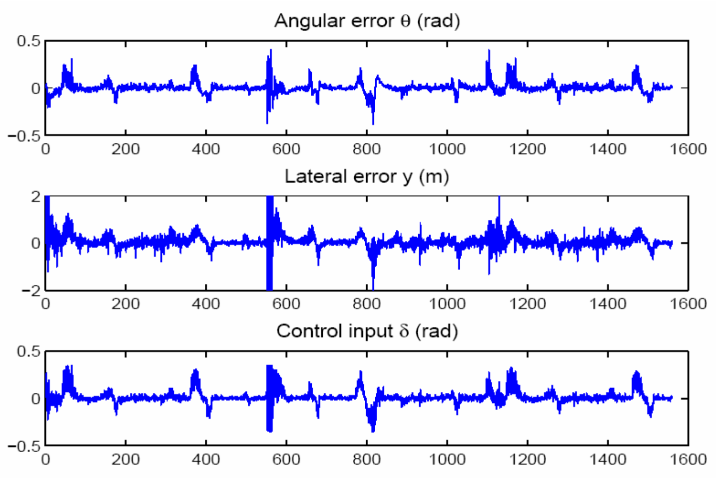
Experiment



Errpoints:Mean distance between an image point and its position in desired image

Applications and projects: CITYVIP *AGV using visual memory*

Experiment



Applications and projects: CITYVIP *AGV using visual memory*

Video

Topological navigation using visual memory

Cityvip
Clermont-Fd 2008

Using vision only
Clermont-Ferrand
LASMEA-GRAVIR

Outline of the presentation

Introduction
- ***LASMEA***
- ***Motivation***
- ***Navigation strategies***

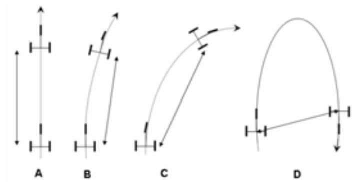
Automous navigation
- ***Modeling***
- ***Control***
- ***Applications***

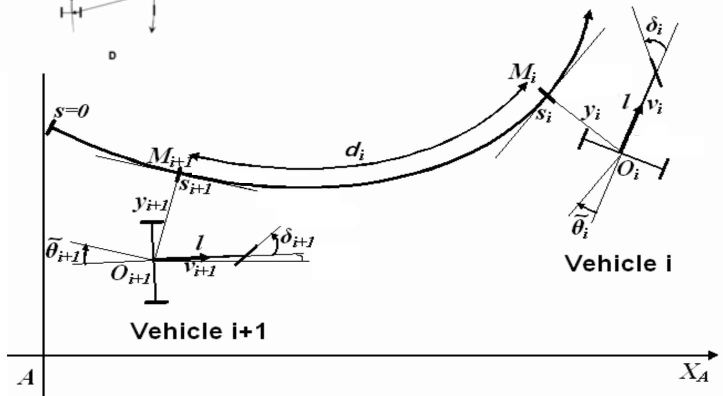
Cooperative navigation
- ***Modeling***
- ***Control***
- ***Applications***

Perspectives
- ***Autonomous navigation***
- ***Cooperative navigation***

Modelling: platoon

★ d_i : curvilinear distance





Modelling: State model

The vector $(s_i, y_i, \tilde{\theta}_i)$ describes the state of the i^{th} vehicle

Modelling is derived under non-slipping assumptions (tricyle model)
[Samson95, Daviet95, Thuilot04]

→ relies on a kinematic model
→ designed with respect to the reference path

$$\begin{cases} \dot{s}_i &= v_i \frac{\cos\tilde{\theta}_i}{1-y_i c(s_i)} \\ \dot{y}_i &= v_i \sin\tilde{\theta}_i \\ \dot{\tilde{\theta}}_i &= v_i \left(\frac{\tan\delta_i}{l} - \frac{c(s_i)\ \cos\tilde{\theta}_i}{1-y_i\ c(s_i)}\right) \end{cases}$$

Longitudinal Modelling

$$d_i = s_i - s_{i+1}$$

$$\begin{cases} \dot{d}_i &= \dot{s}_i - \dot{s}_{i+1} \quad \textit{Syst Ib} \\ \dot{d}_i &= v_i \frac{\cos\tilde{\theta}_i}{1-y_i c(s_i)} - v_{i+1}\frac{\cos\tilde{\theta}_{i+1}}{1-y_{i+1}c(s_{i+1})} \end{cases}$$

$(s_i - s_{i+1})$ to d

V_{i+1}

Control: Longitudinal control in curved path following [Bom05]

Kinematic model $\quad d_i = s_i - s_{i+1} \qquad e_i = d_i - d$

Syst Ib $\quad \dot{e}_i = v_i \frac{\cos\tilde{\theta}_i}{1 - y_i c(s_i)} - v_{i+1}\frac{\cos\tilde{\theta}_{i+1}}{1 - y_{i+1}c(s_{i+1})}$

Exact linearization

Syst IIb $\quad v_{i+1} = \frac{1 - y_{i+1}\ c(s_{i+1})}{\cos\tilde{\theta}_{i+1}}\left(\frac{v_i\cos\tilde{\theta}_i}{1 - y_i\ c(s_i)} - u_{i+1}\right)$

$u_{i+1} = \dot{e}_i$ **auxiliary control law**

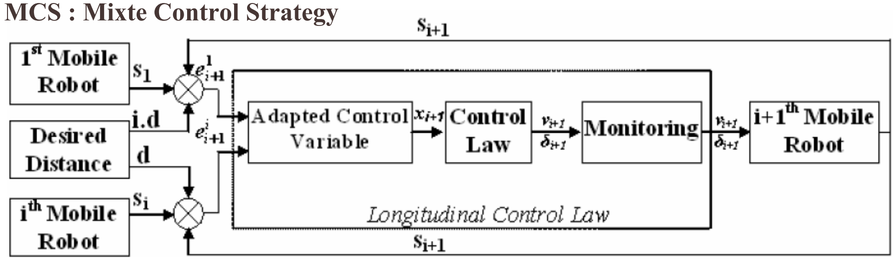
Proportional control law

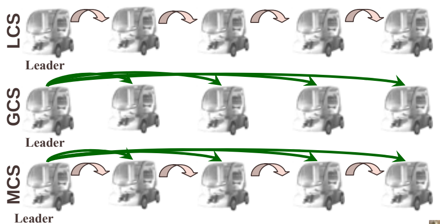
$u_{i+1} = -k\, e_i \qquad k > 0 \qquad v_{i+1} = \frac{1 - y_{i+1}\ c(s_{i+1})}{\cos\tilde{\theta}_{i+1}}\left(\frac{v_i\cos\tilde{\theta}_i}{1 - y_i\ c(s_i)} + k e_i\right)$

$\dot{e}_i = -k\, e_i$ → $d_i \to d$ *Standard longitudinal control mode*

Control: Longitudinal control in curved path following [Bom05]

MCS : Mixte Control Strategy





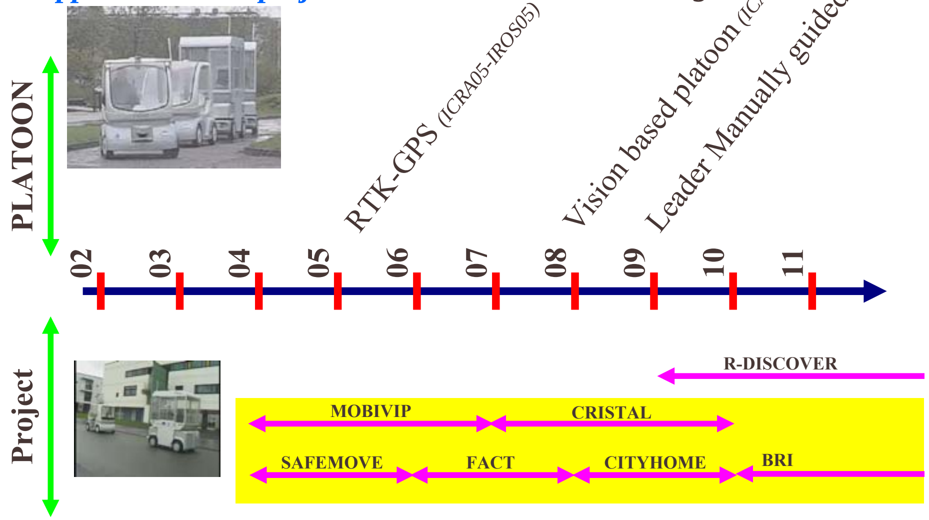
LCS $\quad x_{i+1} = e^i_{i+1} \qquad e^i_{i+1} = s_i - s_{i+1} - d$

GCS $\quad x_{i+1} = e^1_{i+1} \qquad e^1_{i+1} = s_1 - s_{i+1} - i.d$

MCS $\quad x_{i+1} = \sigma_{i+1}e^1_{i+1} + (1-\sigma_{i+1})e^i_{i+1}$

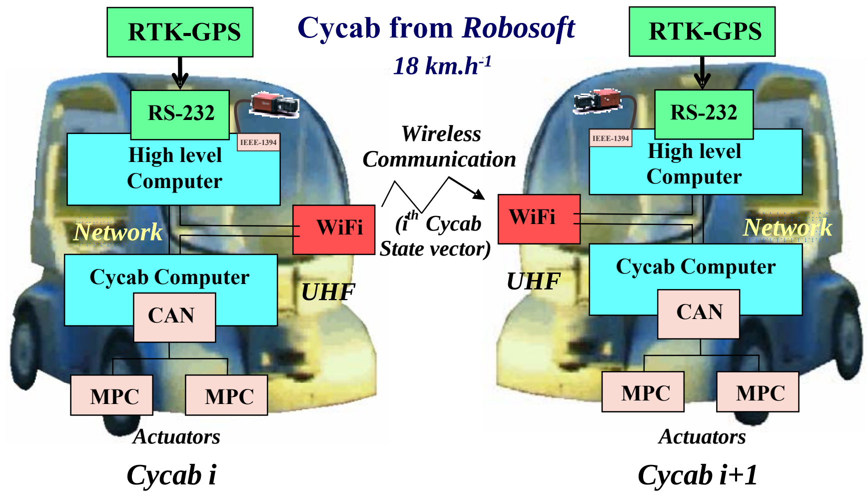
Applications and projects in LASMEA

Platooning



Applications and projects : testbed

Thales Navigation **'Aquarius 5002'**
Position (2cm), velocity, at 10Hz



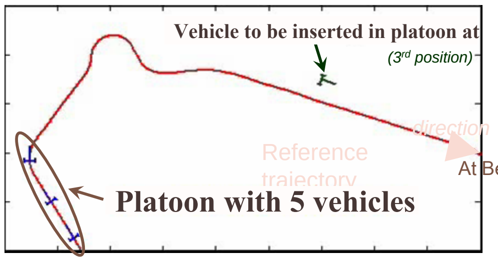
Applications and projects : MOBIVIP *Platooning*

Mobivip
Clermont-Fd 2006

Using RTK-GPS only
Clermont-Ferrand
LASMEA-GRAVIR

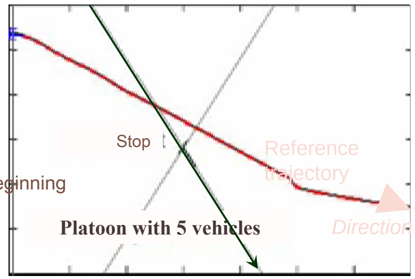
Applications and projects : MOBIVIP *Platooning*

Mobivip : Clermont-Fd 2006



Platoon using RTK-GPS
Insertion
Clermont-Ferrand : LASMEA-GRAVIR

Mobivip : Clermont-Fd 2006



Platoon using RTK-GPS
Joining
Clermont-Ferrand LASMEA-GRAVIR

Applications and projects : MOBIVIP *Platooning*

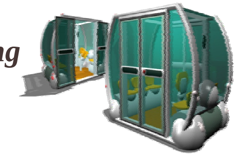
Mobivip : Clermont-Fd 2006

Platoon using RTK-GPS
Insertion
Clermont-Ferrand : LASMEA-GRAVIR

Mobivip : Clermont-Fd 2006

Platoon using RTK-GPS
Joining
Clermont-Ferrand LASMEA-GRAVIR

Applications and projects : CRISTAL — *Platooning*



Cristal : Montbelliard 2008

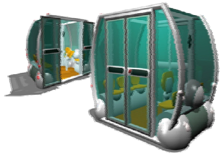
Platoon using RTK-GPS
Manually driven leader
Clermont-Ferrand : LASMEA-GRAVIR

Cristal : Clermont-Fd PAVIN 2009

Platoon using RTK-GPS
Manually driven leader
Clermont-Ferrand LASMEA-GRAVIR

Applications and projects : CRISTAL — *Platooning*

Cristal : Clermont-Fd 2008



Platoon using vision/ranger finder
Clermont-Ferrand LASMEA-GRAVIR

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Autonomous navigation

Topological navigation using sensory memory
- Improving robustness of vision algorithms
- Developing new site characterization algorithms (for nodes)
- Using metric in topological maps
- Using a sensory memory using multiple sensors
- Developing a redundancy approach
- Learning & registering the free space in the sensory memory
- Extending this concept to any kind of robotics tasks
- …

Moving to SLAN application (unknown environment)
- Automatic learning of the sensory memory
- Bio-inspired behavior
- Developing the concept of dynamic memory
- …

Cooperative navigation

Topological navigation using sensory memory
- Validating the sensory memory in a platoon/formation of robots
- How one sensory memory can be shared and used ?
- Multi topological maps fusion
- …

Moving to SLAN application (unknown environment)
- Cooperative learning of the sensory memory
- Strategy for spatial covering (R-DISCOVER project)
- …

Developing new architecture for control and navigation
- Hybrid architecture
- Multi objective controller design
- …

Exploring new application fields
- Off road environment

Thanks for your attention

Any questions

http://wwwlasmea.univ-bpclermont.fr/Control

http://wwwlasmea.univ-bpclermont.fr/Personnel/Philippe.Martinet

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