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# Topological navigation using sensory memory: SLAN versus SLAM

Philippe Martinet, J. Courbon, Y. Mezouar, B. Thuilot

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**Topological navigation using sensory memory**  
*SLAN versus SLAM*  
 Dassault Aviation, Saint-Cloud, France, December 16<sup>th</sup> 2009

**Professor Philippe Martinet**  
 J. Courbon, Y. Mezouar, B. Thuiot



**LASMEA Laboratory**  
 Blaise Pascal University

[martinet@lasmea.univ-bpclermont.fr](mailto:martinet@lasmea.univ-bpclermont.fr)  
<http://www.lasmea.univ-bpclermont.fr/Control/>  
<http://robots.lasmea.univ-bpclermont.fr>



*Program of the journey*

10H	Accueil et présentation de la journée	B. Patin	Dassault Aviation
10H15	Les enjeux et problématiques du SLAM (Survey)	P. Rives	Inria-Sophia Antipolis
11H	Initialisation immédiate d-amers en SLAM monoculaire. Points et lignes	Juan Sola	LAAS
12H	<b>Navigation topologique par mémoire sensorielle: SLAN vs SLAM</b>	<b>P. Martinet</b>	<b>LASMEA</b>
14H	Outils et méthodes d'estimation pour le SLAM - Application au Slam visuel	P. Rives	Inria-Sophia Antipolis
15H	Détection visuelle de fermeture de boucle et applications au SLAM métrique et topologique	D. Filliat	ENSTA ParisTech/UEI Lab
16H		N. Paparoditis	IGN/MATIS
17H	Cloture du séminaire	B. Patin	Dassault Aviation



*Outline of the presentation*

**Introduction**

- LASMEA
- Sensor based Control
- Navigation
- SLAN vs SLAM

**A generic model**

- A unified model for camera
- Case of fisheye cameras
- Partial euclidian reconstruction

**Topological navigation system**

- Global system
- Case of vision
- Differents Modules
- SOVIN

**Illustrations**

- Indoor applications
- Outdoor applications

**Discussion**

- Learning process
- Updating process
- Closing the loop problem



➔ **Introduction**    A generic model    Topological navigation system    Illustrations    Discussion

**Lasmea**       Director : Michel Dhome

400km south of Paris  
200km West of Lyon       CNRS/UBP  
Mixed Unit 6602   

France    Clermont-Ferrand    University Campus    LASMEA

➔ **Introduction**    A generic model    Topological navigation system    Illustrations    Discussion

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Mixed Unit 6602   

**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,  
49 Phd, 2 post-doc

➔ **Introduction**    A generic model    Topological navigation system    Illustrations    Discussion

**Lasmea : GRAVIR-PERSYST**

**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

Lasmea : GRAVIR-COMSEE

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

Lasmea : GRAVIR-ROSACE

ROSACE

P. Martinet & Y. Mezouar

Robotics and Autonomous Complex systems

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

VISIR

Visual Servoing of Robots

AGV

Automatic Guided Vehicles

MICMAC

Modeling, Identification and Control of Complex Machines

Omnidirectional visual servoing 15 to 60Hz

Topological navigation through sensory memory

Multi-sensor-based control

Control design under uncertain dynamics

Hybrid control architecture 15 to 60Hz

Multi-robot-system control ...

Vision-Based Control of Parallel Robots 400Hz

Control of redundant robots 1kHz

Control of High Dynamics System ...

Lasmea : GRAVIR

People involved in SLAM or near SLAM problems

PERSYST

F. Berry, R. Chapuis, F. Chausse, P. Checchin, J.P. Derutin, L. Trassoudaine (IMPALA/CITYVIP)

(CITYHOME/EURIPIDE/BRI)

COMSEE

M. Dhome, M. Lhuillier, E. Royer

(MOBIVIP/CITYVIP/BODEGA)

(FACT/CITYHOME/EURIPIDE/BRI)

ROSACE

Y. Mezouar, P. Martinet, B. Thuilot

(MOBIVIP/CITYVIP/BODEGA/R-DISCOVER/ARMEN)

(SAFEMOVE, FACT/CITYHOME/EURIPIDE/BRI)

Applications

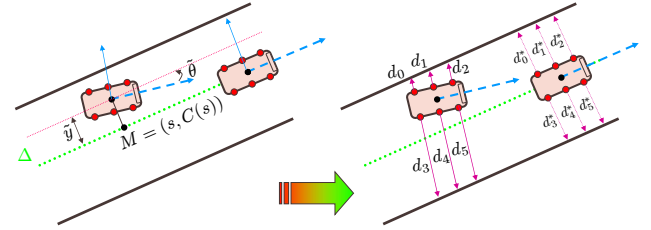
Autonomous navigation (RTK-GPS, Vision, Multi-sensor)

Platoon: Autonomous leader (RTK-GPS, Vision, Multi-sensor)

Platoon: Leader manually driven (RTK-GPS, Vision)

2D/3D maps building (vision, Radar, Range finder, Multi-sensor)

Sensor based control: History [ESPIAU87]



Lateral control in cartesian space:

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

Explicite declaration of  $\Delta$  and required cartesian localization

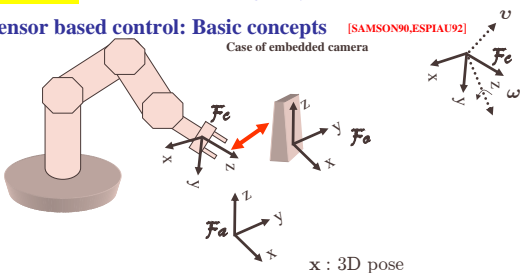
Lateral control in sensor space:

Bringing  $d$  to  $d^*$

No explicite declaration of  $\Delta$  and do not required cartesian localization

Sensor based control: Basic concepts [SAMSON90,ESPIAU92]

Case of embedded camera



$$s = s(x, t)$$

$$\dot{s} = \frac{\partial s}{\partial x} \frac{dx}{dt} + \frac{\partial s}{\partial t}$$

$$\dot{s} = \frac{\partial s}{\partial x} v + \frac{\partial s}{\partial t}$$

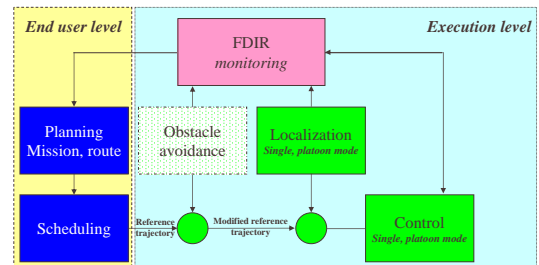
Interaction matrix If (fixed object)  $\frac{\partial s}{\partial t} = 0$

$$\dot{s} = L_s v + \frac{\partial s}{\partial t}$$

$$\dot{s} = L_s v$$

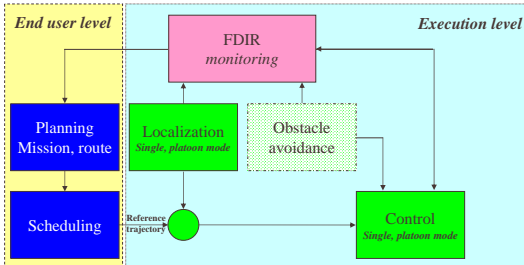
Navigation

Navigation scheme



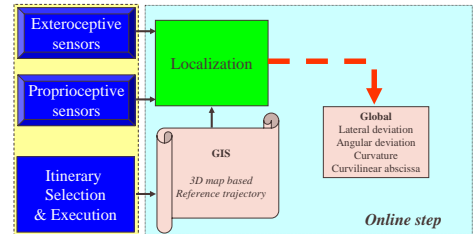
Navigation

Navigation scheme



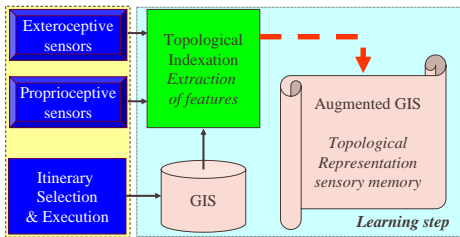
Navigation

3D Map based navigation (absolute navigation)



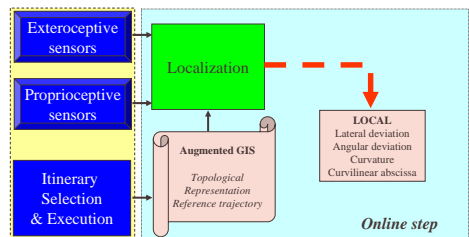
Navigation

Memory based navigation (relative navigation)



Navigation

Memory based navigation (relative navigation)



SLAN vs SLAM

	SLAM	SLAN
MAPS	Metric 2D/3D	Topological Semi-Metric
Localization	Absolute	Relative
Control space	Cartesian	Sensor space Cartesian (relative)

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- Different Modules
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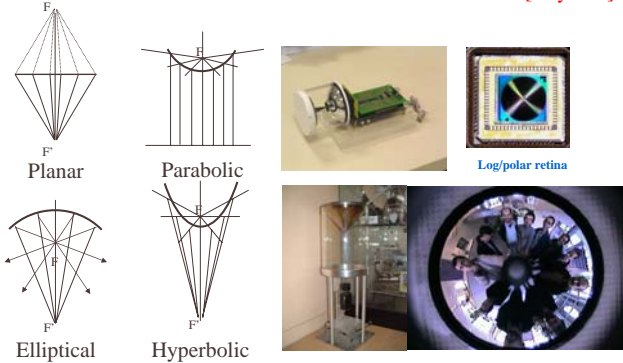
Illustrations

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**A unified model for camera** *Single view point system : Classification [Geyer00]*



**A unified model for camera** *Single view point system : Classification [Geyer00]*

$\varphi$  and  $\xi$  : Mirror parameters

Mirror type	$\xi$	$\varphi$
Parabolic	1	1+2p
Hyperbolic	$\frac{d}{\sqrt{d^2+4p^2}}$	$\frac{d+2p}{\sqrt{d^2+4p^2}}$
Elliptical	$\frac{d}{\sqrt{d^2+4p^2}}$	$\frac{d-2p}{\sqrt{d^2+4p^2}}$
Planar	0	1
Conventional	0	1

**A unified model for camera** *Single view point system : case of point*

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

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

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

$$\mathbf{m}_p = \mathbf{K}_M \mathbf{m}_n$$

Mirror : unitary sphere

**A unified model for camera** *Single view point system : case of point*

$\varphi$  and  $\xi$  : Mirror parameters

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

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

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

Special cases :  
 $\epsilon = 1$  and  $\xi = 0 \rightarrow$  perspective projection  
 $\epsilon = 0$  and  $\xi = 1 \rightarrow$  spherical projection

**Generic Projection function**  
 $\mathbf{m}_p = \frac{\mathbf{K}_M \mathbf{M} \mathbf{f}(\mathbf{m}_{3D})}{\mathbf{K}_M}$

**Case of fisheye camera** *Fisheye camera model : definition*  $\star \mathcal{F}_m$  : camera frame  $\star \mathcal{F}_i$  : image frame

- $\star r$  = distance between  $X$  and the image point
- $\star \theta$  = angle between the incoming ray and the principal axis

Pinhole camera  $\mathbf{x}_p = (x_p \ y_p)^T$   $\mathbf{x} = (X \ Y \ Z)^T$  Fisheye camera  $\mathbf{x}_f = (x_f \ y_f)^T$

$$r_p(\theta) = f \tan \theta$$

radial distortions

Constraint 1 : the ray arriving along the distortion axis is not deformed:  $r_f(0) = 0$ .

Constraint 2 : the radius  $r_f(k)$  is monotonically increasing for  $k > 0$ .

**Case of fisheye camera** *Fisheye camera model : Pinhole based models*

Mapping :  $r_p \xrightarrow{T_1} r_f$

$$L(r_p, n) = 1 + k_1 r_p^2 + k_2 r_p^4 + \dots + k_n r_p^{2n}$$

n parameters

- $\star r_f^1(r_p) = r_p L(r_p, n)$  used for perspective cameras [T. Pajdla97, Hartley00, Zhang98, Ma2006...]
- $\star r_f^2(r_p) = \frac{r_p}{L(r_p, n)}$  handle high distortion [Fitzgibbon01]
- $\star r_f^3(r_p) = \frac{r_p}{1 + k_1 r_p^2}$  one parameter [Fitzgibbon01]

**Case of fisheye camera** *Fisheye camera model : Pinhole based models*

Mapping :  
 $r_p \xrightarrow{T_1} r_f$

★  $r_f^4(r_p) = r_p \frac{L_1(r_p, n_1)}{L_2(r_p, n_2)}$  rational model n1+n2 parameters [Li05]

★  $r_f^5(r_p) = s \log(1 + \lambda r_p)$  logarithmic mapping [Basu95]  
 s is a scaling factor and λ a gain to control the amount of distortion

★  $r_f^6(r_p) = \frac{1}{\omega} \arctan(2r_p \tan \frac{\omega}{2})$  Field-of-view (FOV) model [Devenay01]

★  $r_f(r_p) = \lambda r_p$  [Hartley07]

The "distortion function"  $\lambda = \{\lambda_1, \lambda_2, \dots, \lambda_n\}$  can be then fitted by a parametric model

**Case of fisheye camera** *Fisheye camera model : Captured rays based models*

Mapping :  
 $\theta \xrightarrow{T_2} r_f$

★  $r_f^1(\theta) = f\theta$  cameras with limited distortions [Kingslake89]

★  $r_f^2(\theta) = 2f \tan(\frac{\theta}{2})$  stereographic projection preserves circularity and thus project 3D local symmetries onto 2D local symmetries [Fleck94,Stevenson95]

★  $r_f^3(\theta) = f \sin \theta$  orthogonal or sine law projection [Ray94]

★  $r_f^4(\theta) = f \sin(\frac{\theta}{2})$  equisolid angle projection [Smith92]

**Case of fisheye camera** *Fisheye camera model : Captured rays based models*

Mapping :  
 $\theta \xrightarrow{T_2} r_f$

★  $r_f^5(\theta) = f(k_1\theta + k_2\theta^3 + \dots + k_n\theta^{2(n-1)+1})$   
 Improvement of the polynomial model accuracy [xiong97,kannala04,schwalbe05,Scaramuzza06]

★  $r_f^6(\theta) = \alpha \sin(\beta\theta)$  ★  $\alpha$  : scale factor  
 ★  $\beta$  : radial mapping parameter [Kumler00]

★  $r_f^7(\theta) = a \tan(\theta/b) + c \sin(\theta/d)$   
 Combination of  
 - stereographic projection (with parameters a, b)  
 - equisolid angle projection (with parameters c, d) [Bakstein02]

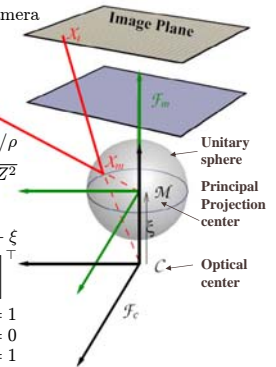
**Case of fisheye camera** *Generic camera model : Unified Spherical Model*

- ★  $F_c$  : frame attached to the conventional camera
- ★  $F_m$  : frame attached to the unitary sphere

$X = [X Y Z]^T \quad \underline{x} = [x y 1]^T$   
**Step 1 : Projection on the unitary sphere**  
 sphere  $X_m \text{ in } F_m: X_m = X/\rho$   
 where  $\rho = \|X\| = \sqrt{X^2 + Y^2 + Z^2}$

**Step 2 : Perspective projection**

on the normalized image plane  $Z = 1 - \xi$   
 $\underline{x}' = f(X) = \begin{bmatrix} X & Y \\ \varepsilon_s Z + \xi\rho & \varepsilon_s Z + \xi\rho & 1 \end{bmatrix}^T$   
 spherical projection :  $\varepsilon_s = 0$  and  $\xi = 1$   
 pinhole model :  $\varepsilon_s = 1$  and  $\xi = 0$   
 Catadioptric model :  $\varepsilon_s = 1$  and  $\xi = 1$



**Case of fisheye camera** *Generic camera model : Unified Spherical Model*

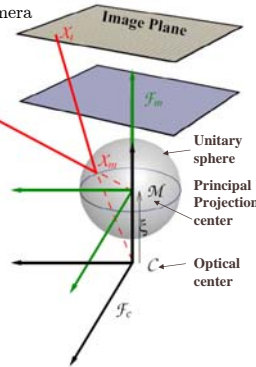
- ★  $F_c$  : frame attached to the conventional camera
- ★  $F_m$  : frame attached to the unitary sphere

$X = [X Y Z]^T \quad \underline{x} = [x y 1]^T$

**Step 3 : Projection onto image plane**

$\underline{x} = M \underline{x}'$   
 $M = \begin{pmatrix} f\kappa & 0 & 0 \\ 0 & \delta f\kappa & 0 \\ 0 & 0 & 1 \end{pmatrix}$  f : focal length  
 δ is equal to ±1  
 κ > 0

catadioptric cameras :  $\delta = -1$   
 perspective camera :  $\kappa = 1$  and  $\delta = +1$



**Case of fisheye camera** *Generic camera model : Unified Spherical Model*

- ★  $F_c$  : frame attached to the conventional camera
- ★  $F_m$  : frame attached to the unitary sphere

$X = [X Y Z]^T \quad \underline{x} = [x y 1]^T$

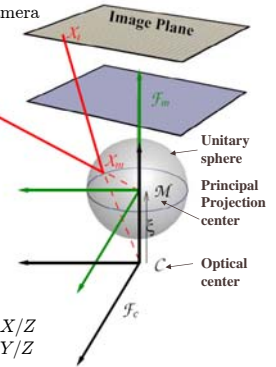
**Step 4 : Pixel transformation**

$m = K \underline{x}$  plane-to-plane collineation K

$K = \begin{pmatrix} k_u & s_{uv} & u_0 \\ 0 & k_v & v_0 \\ 0 & 0 & 1 \end{pmatrix}$

$(u_0, v_0)^T$  : position of the optical center  
 $k_u$  and  $k_v$  : scaling along the x and y axes  
 $s_{uv}$  : skew

Pinhole camera setting  $\xi = 0, \kappa = 1$  and  $\delta = +1$   $\begin{cases} x_p = f_p X/Z \\ y_p = f_p Y/Z \end{cases}$



**Case of fisheye camera** *Generic camera model : Unified Spherical Model*

**For fisheye camera**

$r_f = r_f(r_p) = \frac{f_f r_p}{1 + \xi \sqrt{\frac{r_p^2}{f_f^2} + 1}}$  is a  $T_1$ -mapping linking the perspective Radius  $r_p$  and the fisheye radius  $r_f$

Constraint 1 : easily verified ( $r_f(0) = 0$ )  
 Constraint 2 :  $r_f(k)$  is monotonically increasing for  $k > 0$

$r_f = r_f(\theta) = \frac{f_f \tan \theta}{1 + \xi \sqrt{\tan^2 \theta + 1}}$  is a  $T_2$ -mapping linking the radius  $r_f$  and the incidence angle  $\theta$

**The generic camera model is candidate for fisheye camera modeling**

**Case of fisheye camera** *Validation with calibration toolbox [MEI07]*

Computation of  $f_f$  and  $\xi$  (Producers data)  
 Model fitting for all existing fisheye cameras  
 Calibration

**List of fisheye cameras considered**

Coastal Optical 4.88mm f/5.2  
 Nikon MF 6mm f/2.8  
 Coastal Optical 7.45mm f/2.8  
 Sigma 8mm f/4.0 < 1998  
 Peleng 8mm f/3.5  
 Nikkor 10.5mm f/2.8  
 ORIFL 190-3

**List of models considered**

Polynomial model using perspective projection  
 $r_f(r_p) = r_p(1 + a_1 r_p^2 + \dots + a_3 r_p^6)$   
 Polynomial model using unified model projection  
 $r_f(r_u) = r_u(1 + a_1 r_u^2 + \dots + a_3 r_u^6)$   
 Proposed unified model  
 $r_f = r_u$

**The generic camera model is validated with an average of 0.2 pixels reprojection error for fisheye camera modeling**  
**Only one parameter required**

**Partial euclidian reconstruction** Unified model - Case of points

Introducing  $\eta = s \frac{\rho}{|z|} = \sqrt{1 + X^2/Z^2 + Y^2/Z^2} > 0$   $s = \text{sign}(Z)$

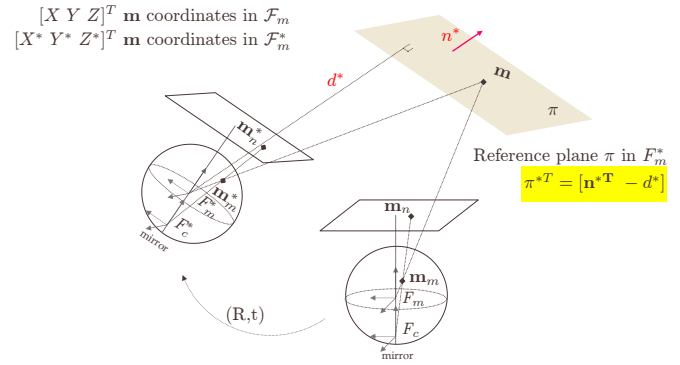
$\begin{cases} x = \frac{X/Z}{1 + \xi \eta} \\ y = \frac{Y/Z}{1 + \xi \eta} \end{cases} \begin{cases} (1 + \xi \eta) x = \frac{X}{Z} \\ (1 + \xi \eta) y = \frac{Y}{Z} \end{cases} \begin{cases} \eta^2 - (x^2 + y^2)(1 + \xi \eta)^2 - 1 = 0 \end{cases}$

$\eta = \frac{\pm \gamma_x + \xi(x^2 + y^2)}{1 - \xi^2(x^2 + y^2)}$   $\eta$  computed without ambiguity

where  $\gamma_x = \sqrt{1 + (1 - \xi^2)(x^2 + y^2)}$

$\mathbf{m}_m = (\eta^{-1} + \xi) \bar{\mathbf{m}}$  with  $\bar{\mathbf{m}} = [x \ y \ \frac{1}{1 + \xi \eta}]^T$   
 $\mathbf{m}_n$

**Partial euclidian reconstruction** Unified model - Case of points



**Partial euclidian reconstruction** Unified model - Case of points

$\mathbf{m}_m = (\eta^{-1} + \xi) \bar{\mathbf{m}} = \frac{1}{\rho} [X \ Y \ Z]^T$   $\bar{\mathbf{m}} = [x \ y \ \frac{1}{1 + \xi \eta}]^T$   
 $\mathbf{m}_m^* = (\eta^{*-1} + \xi) \bar{\mathbf{m}}^* = \frac{1}{\rho^*} [X^* \ Y^* \ Z^*]^T$   $\bar{\mathbf{m}}^* = [x^* \ y^* \ \frac{1}{1 + \xi \eta^*}]^T$

Homogeneous coordinates:

$\underline{\mathbf{m}} = [X \ Y \ Z \ H]^T$  and  $\underline{\mathbf{m}}^* = [X^* \ Y^* \ Z^* \ H^*]^T$

$\rho(\eta^{-1} + \xi) \bar{\mathbf{m}} = [I_3 \ 0] \underline{\mathbf{m}} = [R \ t] \underline{\mathbf{m}}^*$

**The distance from the world point  $m$  to the plane ( $\pi$ )**

$d(m, \pi) = \pi^{*T} \cdot \underline{\mathbf{m}}^* = [n^{*T} \ -d^*] [X^* \ Y^* \ Z^* \ H^*]^T = \rho^*(\eta^{*-1} + \xi) n^{*T} \bar{\mathbf{m}}^* - d^* H^*$

**Partial euclidian reconstruction** Unified model - Case of points

$\Rightarrow H^* = \rho^* \frac{(\eta^{*-1} + \xi)}{d^*} n^{*T} \bar{\mathbf{m}}^* - \frac{d(m, \pi)}{d^*}$   
 $\rho^*(\eta^{*-1} + \xi) \bar{\mathbf{m}}^* = [X^* \ Y^* \ Z^*]^T$

$\underline{\mathbf{m}}^* = \rho^*(\eta^{*-1} + \xi) \mathbf{A}_\pi^* \bar{\mathbf{m}}^* + \mathbf{b}_\pi^*$  where  $\begin{cases} \mathbf{A}_\pi^* = [I_3 \ \frac{n^*}{d^*}]^T \\ \mathbf{b}_\pi^* = [0_{1 \times 3} \ -\frac{d(m, \pi)}{d^*}] \end{cases}$

$\rho(\eta^{-1} + \xi) \bar{\mathbf{m}} = [R \ t] \underline{\mathbf{m}}^*$   
 $\rho(\eta^{-1} + \xi) \bar{\mathbf{m}} = \rho^*(\eta^{*-1} + \xi) \mathbf{H}_\pi \bar{\mathbf{m}}^* + \alpha t$   
 with  $\mathbf{H}_\pi = R + \frac{t}{d^*} n^{*T}$  and  $\alpha = -\frac{d(m, \pi)}{d^*}$

Euclidian Homography

**Partial euclidian reconstruction** Unified model - Case of points

$m \in \pi$

$\bar{m} = \beta_{x,x^*} H_\pi \bar{m}^*$

where  $\beta_{x,x^*} = \frac{\eta^{*-1} + \xi}{\eta^{-1} + \xi} \frac{\rho^*}{\rho}$

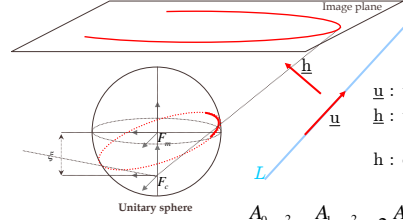
**Linear form**

$\bar{m} \times H_\pi \bar{m}^* = 0 \rightarrow H_\pi \rightarrow R \text{ and } t_{d^*} = \frac{t}{d^*}$

$\sigma = \frac{\rho}{\rho^*} = (1 + \mathbf{n}^* T \mathbf{R}^T t_{d^*}) \frac{(\eta^{*-1} + \xi) \mathbf{n}^{*T} \bar{m}^*}{(\eta^{-1} + \xi) \mathbf{n}^T \bar{m}}$

**Partial euclidian reconstruction** Unified model - Case of lines

Similar results are obtained from lines (using polar lines)



**Plücker coordinates**

$L = (\underline{u}, \underline{h}, h)^T$

- $\underline{u}$  : unitary vector along the line  $L$
- $\underline{h}$  : unitary vector orthogonal to the interpretation plane
- $h$  : distance between the origin of the frame and the line

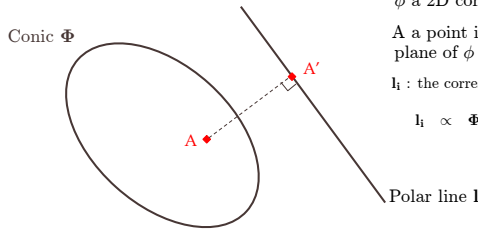
$\frac{A_0}{A_5} x^2 + \frac{A_1}{A_5} y^2 + 2 \frac{A_2}{A_5} xy + 2 \frac{A_3}{A_5} x + 2 \frac{A_4}{A_5} y + 1 = 0$

$B_i(h, \xi, K_M) = \frac{A_i}{A_5}$

**Partial euclidian reconstruction** Unified model - Case of lines

Similar results are obtained from lines (using polar lines)

**Polar lines**



$\phi$  a 2D conic curve

A a point in the definition plane of  $\phi$

$l_i$  : the corresponding polar line

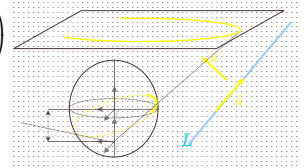
$l_i \propto \Phi A$

**Partial euclidian reconstruction** Unified model - Case of lines

Similar results are obtained from lines (using polar lines)

**Polar lines**

$\Omega = \begin{pmatrix} h_x^2 - \xi^2(1 - h_y^2) & h_x h_y(1 - \xi^2) & h_x h_z \\ h_x h_y(1 - \xi^2) & h_y^2 - \xi^2(1 - h_x^2) & h_y h_z \\ h_x h_z & h_y h_z & h_z^2 \end{pmatrix}$



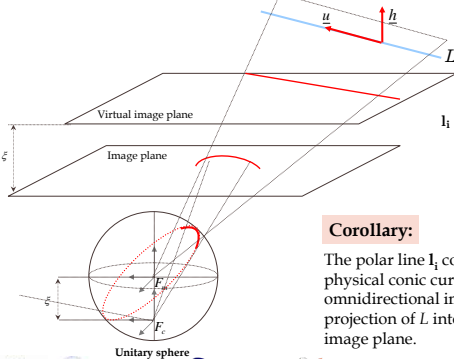
$\underline{x}_i^T \underbrace{K^{-T} \Omega K^{-1}}_{\Omega_i} \underline{x}_i = 0$

The polar line of the optical center with respect to the conic  $\Omega_i$  is given by:

$l_i \propto \Omega_i O_i$  principal point  $O_i = [u_0 \ v_0 \ 1]^T = K[0 \ 0 \ 1]^T$

**Partial euclidian reconstruction** Unified model - Case of lines

Similar results are obtained from lines (using polar lines)



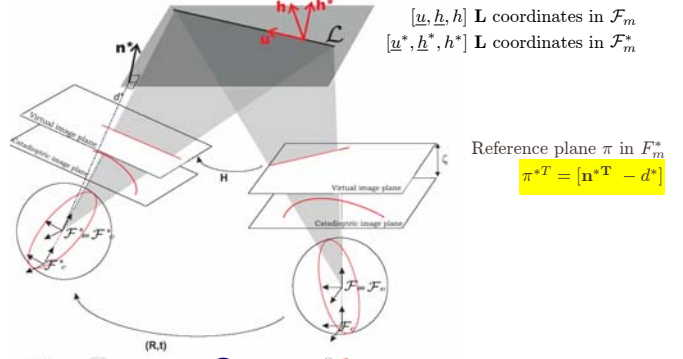
$l_i \propto K^{-T} \Omega K^{-1} O_i$   
 $\propto K^{-T} \Omega K^{-1} K \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$   
 $\propto K^{-T} \begin{pmatrix} h_x \\ h_y \\ h_z \end{pmatrix}$

**Corollary:**

The polar line  $l_i$  computed from the physical conic curve projection of  $L$  in the omnidirectional image is the perspective projection of  $L$  into the virtual camera image plane.

**Partial euclidian reconstruction** Unified model - Case of lines

Similar results are obtained from lines (using polar lines)



$[\underline{u}, \underline{h}, h]$  L coordinates in  $\mathcal{F}_m$   
 $[\underline{u}^*, \underline{h}^*, h^*]$  L coordinates in  $\mathcal{F}_m^*$

Reference plane  $\pi$  in  $\mathcal{F}_m^*$   
 $\pi^{*T} = [\mathbf{n}^{*T} \ -d^*]$



**Partial euclidian reconstruction** Unified model - Case of lines

Similar results are obtained from lines (using polar lines)

$\mathcal{X}_1$  and  $\mathcal{X}_2$  are two points in the 3D space lying on the line  $\mathcal{L}$

$$\begin{aligned} \mathbf{h} &\propto \mathbf{H}^{-T} \mathbf{h}^* & \mathbf{l}_i &\propto \mathbf{K}^{-T} \mathbf{h} & \rightarrow & \mathbf{l}_i \propto \mathbf{K}^{-T} \mathbf{H}^{-T} \mathbf{h}^* \\ \mathbf{l}_i^* &\propto \mathbf{K}^{-T} \mathbf{h}^* & & & \rightarrow & \mathbf{l}_i \propto \mathbf{K}^{-T} \mathbf{H}^{-T} \mathbf{K}^T \mathbf{l}_i^* \\ & & & & & \mathbf{l}_i \propto \mathbf{G}^{-T} \mathbf{l}_i^* \end{aligned}$$

$$\mathbf{G} = \mathbf{K} \mathbf{H} \mathbf{K}^{-1}$$

Linear form

$$\mathbf{l}_i \times \mathbf{G}^{-T} \mathbf{l}_i^* = 0 \quad \text{with 4 couples } (\mathbf{l}_i, \mathbf{l}_i^*) \quad \rightarrow \quad \mathbf{H} \quad \rightarrow \quad \mathbf{R} \text{ and } \mathbf{t}_d = \frac{\mathbf{t}}{d^*}$$

$$\mathbf{H} = \mathbf{R} + \frac{\mathbf{t}}{d^*} \mathbf{n}^* T$$

$$r = \frac{h}{h^*} = (1 + \mathbf{t}_d^* T \mathbf{R}^T \mathbf{n}^*) \frac{\|\mathbf{n}^* \times \mathbf{K}^T \mathbf{l}_i^*\|}{\|\mathbf{R} \mathbf{n}^* \times \mathbf{K}^T \mathbf{l}_i^*\|}$$

# Outline of the presentation

## Introduction

- LASMEA
- Sensor based Control
- Navigation
- SLAM vs SLAM

## A generic model

- A unified model for camera
- Case of fisheye cameras
- Partial euclidian reconstruction

## Topological navigation system

- Global system
- Case of vision
- Different Modules
- SOVIN

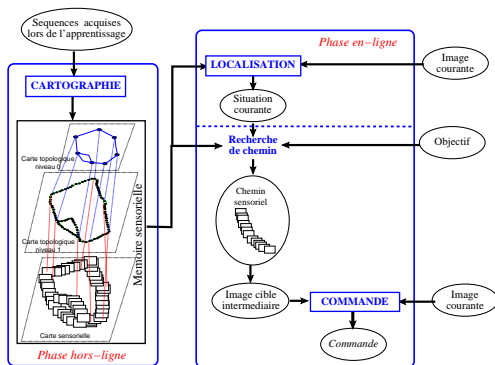
## Illustrations

- Indoor applications
- Outdoor applications

## Discussion

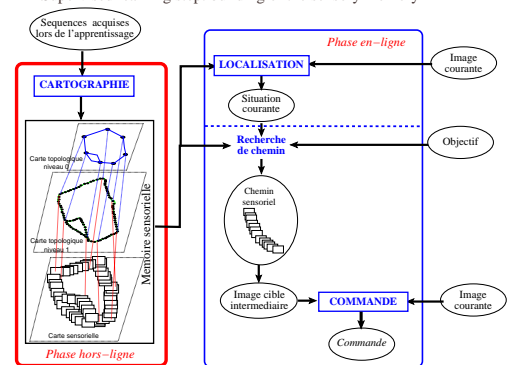
- Learning process
- Updating process
- Closing the loop problem

## Global system



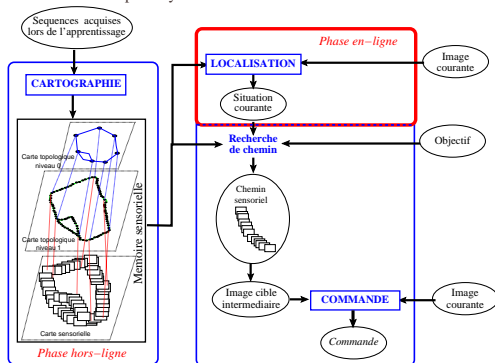
## Global system

Supervised learning step: building of the sensory memory



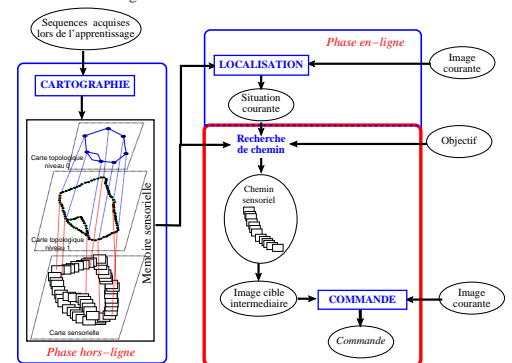
## Global system

Initialization: primary localization

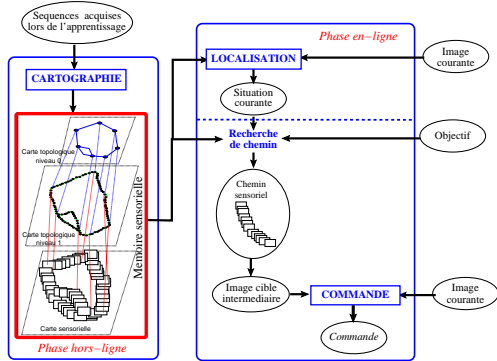


## Global system

One line navigation and control

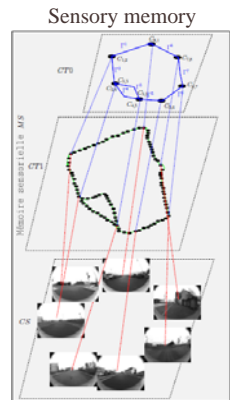


**Case of vision**



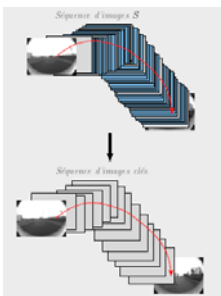
**Case of vision**

- Topological map level 0 (CT0)**
  - ✓ High level representation : corridor, routes, ..
- Topological map level 1 (CT1)**
  - ✓ Image network representation
  - ✓ Navigability
  - ✓ Commandability
  - ✓ Plannification
- Sensory map (CS)**
  - ✓ Initial localization
  - ✓ Sensor based control
  - ✓ Visualization of the environment
  - ✓ Human interface

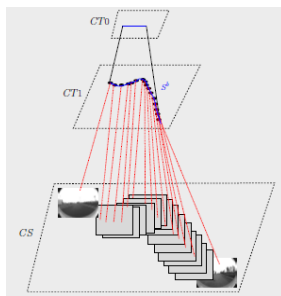


**Different modules** Learning step (first arc, first two nodes)

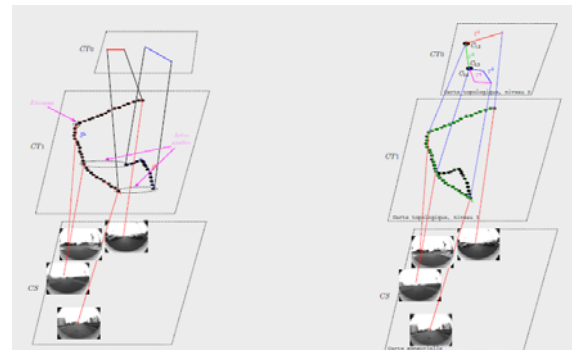
**Key images selection**



**Building the sensory memory**

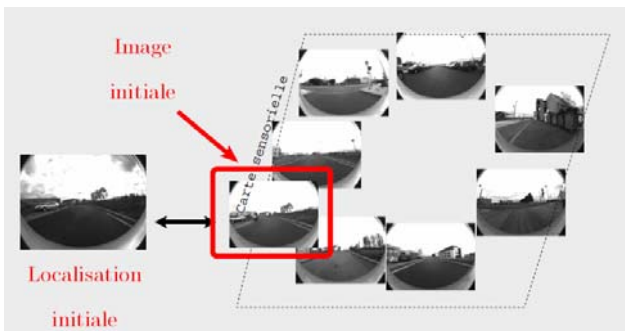


**Different modules** Learning step (expanding the process...)



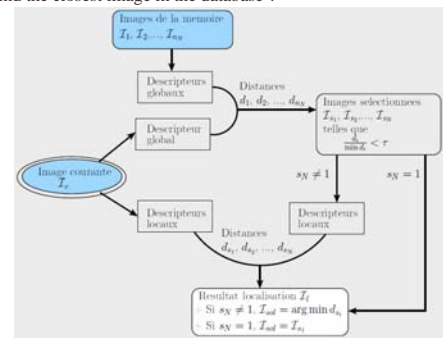
**Differents modules** Initial localization

How to find the closest image in the database ?



**Differents modules** Initial localization

How to find the closest image in the database ?

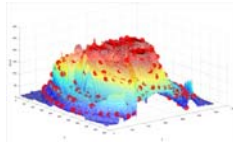
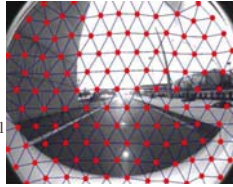


### Differents modules Initial localization

How to find the closest image in the database ?

Use of a regular mesh [PERSSON04]  
Cubic interpolation of the image surface

**Global descriptor** : vector of the interpolated grey level pixels at the position of the control point



Control point distribution (one example)

### Differents modules Initial localization

How to find the closest image in the database ?

**Local descriptor** : interest points detected by Harris Stephen detector

Use of patches 11x11



Matching done by using the centered cross correlation score ZNCC

Use of the number of matched point to compute the similarity between 2 images

### Differents modules Initial localization

How to find the closest image in the database ?

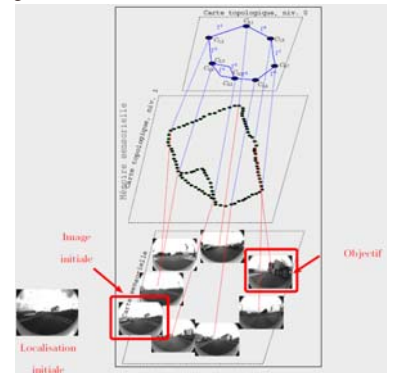
**Evaluation of the approach [ICRA08]** using three image databases regarding 3 main criteria:  
Used memory size, percentage of success, computation time for localization

Camera	Taille image	Nb images	Images
Catadioptrique	1024 x 768	978	
Fisheye 110 deg	384 x 288	188	
Fisheye 190 deg	640 x 480	445	

Several approaches were compared : GONZ [GONZALES02], PHLAC [LINAKER04], CUB, SURF, SIFT, HARRIS, **CUBHAR**

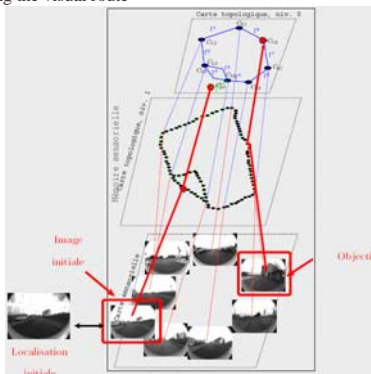
### Differents modules Planifying the visual route

How to find the optimal path ?



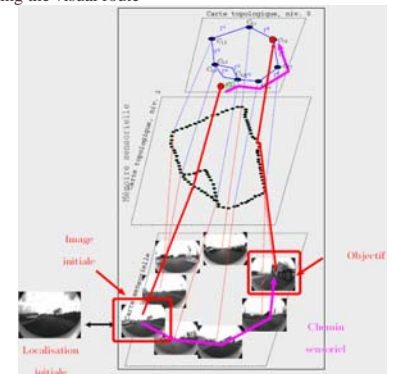
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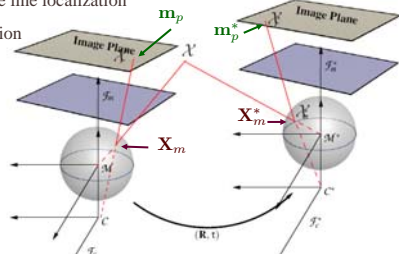
### Differents modules Planifying the visual route

How to find the optimal path ?



**Differents modules** One line localization

Scaled euclidian reconstruction



Epipolar constraint can be expressed by:

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

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

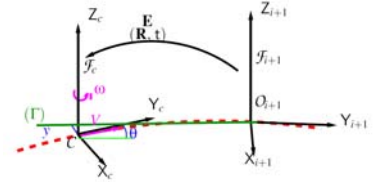
From five couples of points E can be estimated

Outliers are rejected by using RANSAC

**Differents modules** State estimation and control (one example)

State model of the mobile robot

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



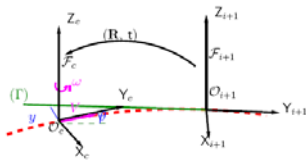
$$F_i = (O_i, X_i, Y_i, Z_i)$$

$F_{i+1} = (O_{i+1}, X_{i+1}, Y_{i+1}, Z_{i+1})$  the frames attached to the robot when  $T_i$

Kinematic model of the mobile robot  $\begin{cases} \dot{s} = v \frac{\cos \theta}{1 - c(s)y} \\ \dot{y} = v \sin \theta \\ \dot{\theta} = \omega \left( \frac{\tan \delta}{l} - \frac{c(s) \cos \theta}{1 - c(s)y} \right) \end{cases} \Rightarrow$  Chained System theory [IAV04]

**Differents modules** State estimation and control (one example)

Path following approach

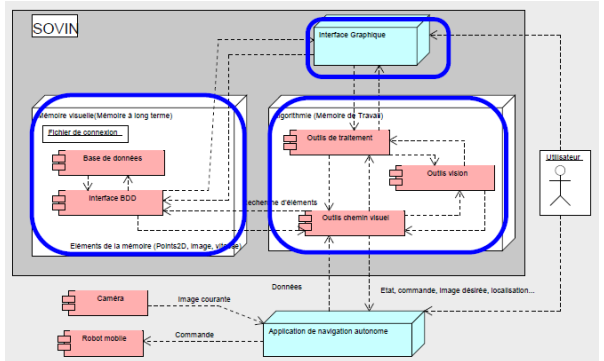


Goal:  $y \rightarrow 0, \theta \rightarrow 0$  before  $F_c$  reaches  $F_{i+1}$

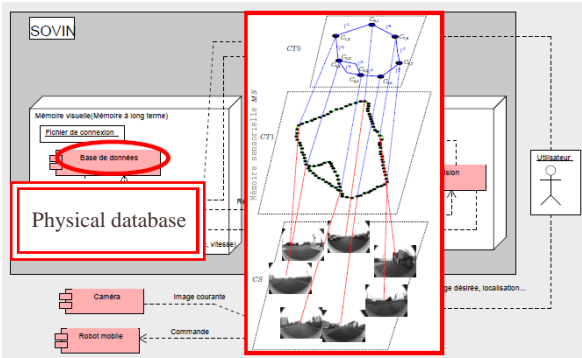
Asymptotically stable guidance control law based on the chain system approach:

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

**SOVIN** A global software environment for topological navigation in wide spaces

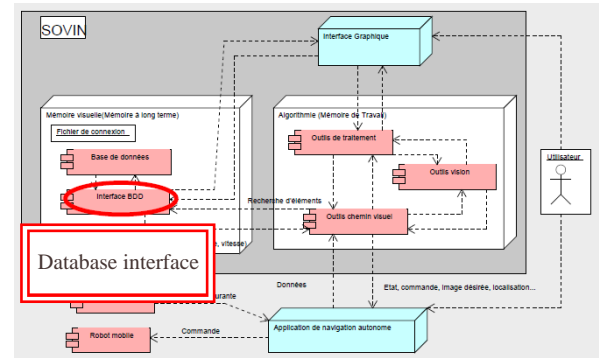


**SOVIN** A physical database organized in three levels



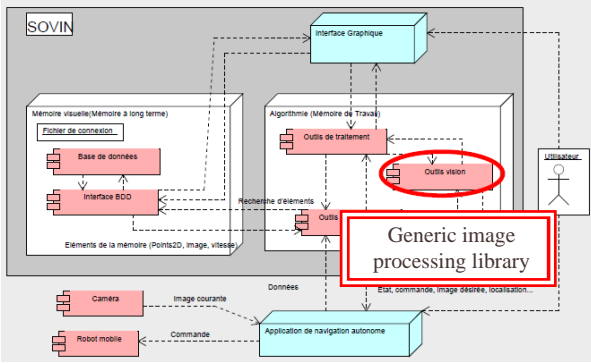
Physical database

**SOVIN** An efficient database interface for on line and real time applications

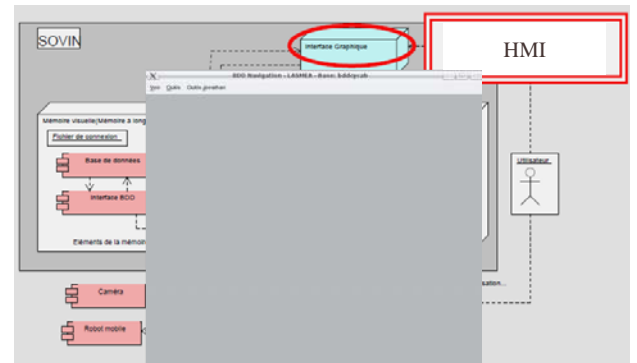


Database interface

**SOVIN** A generic library (generic visual sensor) for visual algorithm processing



**SOVIN** An efficient Human Machine Interface for managing applications



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- Differents Modules
- SOVIN

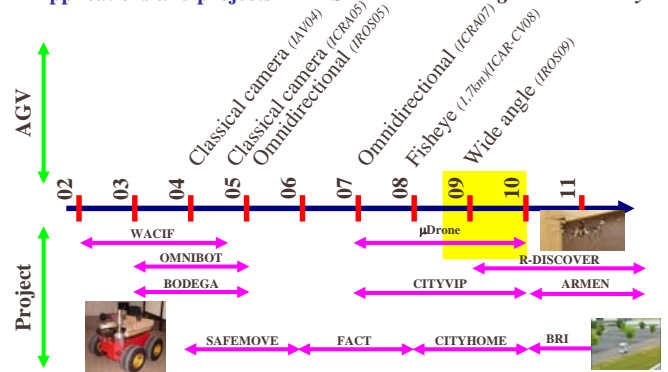
### Illustrations

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- Closing the loop problem

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



### Indoor applications : WACIF project (2002-2005)

Autonomous Robot for Telepresence navigation, localization, learning, warning and communication capabilities



> Study and development of a demonstrator like a personal robot fully integrated in the context of « wireless home »



> An innovant domotic HMI dedicated for software useful for human, family and home applications



➔ **Wireless communication and services**



> Telepresence and telesurveillance tasks  
home supervision through any wireless point, abnormal event detection in family environment (intrusion, noise, ...)



➔ **Autonomous navigation strategy**

### Indoor applications : WACIF project (2002-2005)

#### Global navigation strategy

##### Topological representation

Predefined trajectory

Graph representation

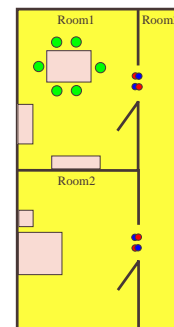
Visual memory concept

Hypothesis : knowledge

HS = HOME Space

RS<sub>i</sub> = Room Space *i*

HS = ∑<sub>i</sub> RS<sub>i</sub>



- Starting point
- Ending point

Topological representation step is a part of the knowledge we get from the HOME environment

### Indoor applications : WACIF project (2002-2005)

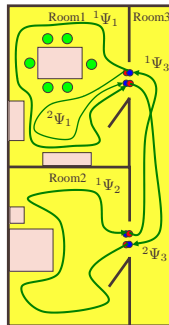
#### Global navigation strategy

##### Topological representation

##### Predefined trajectory

##### Graph representation

##### Visual memory concept



Predefined trajectory step is totally supervised using robot teleoperation

### Indoor applications : WACIF project (2002-2005)

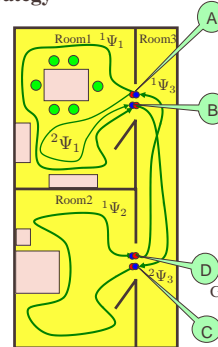
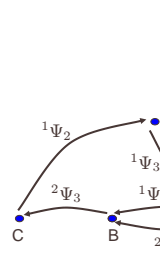
#### Global navigation strategy

##### Topological representation

##### Predefined trajectory

##### Graph representation

##### Visual memory concept



Graph representation step is deduced from the previous step

### Indoor applications : WACIF project (2002-2005)

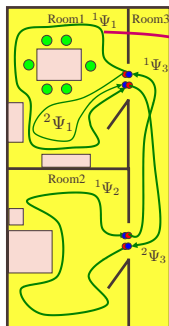
#### Global navigation strategy

##### Topological representation

##### Predefined trajectory

##### Graph representation

##### Visual memory concept



Along the teleoperated trajectories a set of key images is selected. Visual memory concept is used for navigation

### Indoor applications : WACIF project (2002-2005)

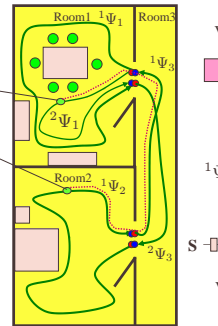
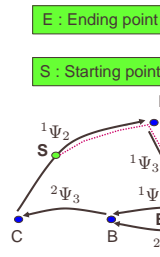
#### Global navigation strategy

##### Topological representation

##### Predefined trajectory

##### Graph representation

##### Visual memory concept



From the graph a Visual route is generated. Visual memory concept is used for navigation

### Indoor applications : WACIF project (2002-2005)

#### Global navigation strategy

##### Functional decomposition

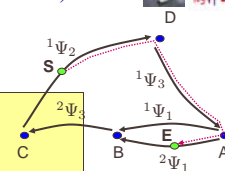
##### Learning Off line

Define each  ${}^i\Psi_j$  : learn the trajectory

- ★ Robot teleoperation
- ★ Models features extraction and selection
- ★ Mosaic construction

##### Re-run of trajectory : On line

- ★ Extract the reference model from the visual route
- ★ Select and track models in current images
- ★ Localization in the mosaic
- ★ Lateral control of the non holonomous robot



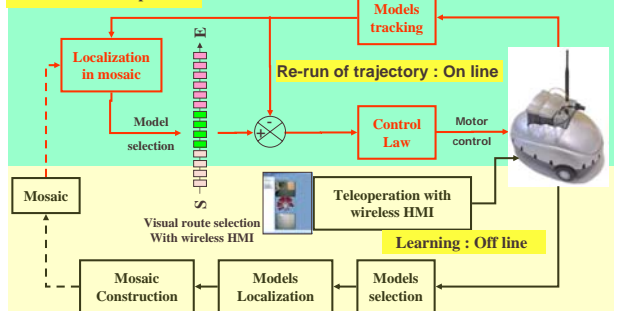
Ait Ader [04]  
Blanc [04]  
Blanc [05]

### Indoor applications : WACIF project (2002-2005)

#### Global navigation strategy

Ceiling images are used

##### Functional decomposition



**Indoor applications : WACIF project (2002-2005)**  
 Navigation using visual memory

Topological map of the environment showing a grid of nodes and edges. A robot is shown at a specific node. A sequence of images shows the robot's path through the environment, with corresponding nodes highlighted on the map.

**Indoor applications : OMNIBOT project** **ROBEA** **onnitot**  
 From omnidirectional vision to mobile robot control  
 Development of a complete perception and control approach for mobile robot using omnidirectional vision

The diagram shows a control loop: 'Consigne visuelle' (visual command) is processed by '4 - Commande' (control) to produce a 'Loi de commande' (control law). This law is used to drive a 'Torseur cinématique' (kinematic wrench) which controls the robot. Simultaneously, the robot provides an 'Image' (image) which is processed by '3 - Image' (image processing) to produce 'Image' (image) data. This data is fed back into the control loop.

**Indoor applications : OMNIBOT project** **ROBEA** **onnitot**  
 From omnidirectional vision to mobile robot control

Development of a complete perception and control approach for mobile robot using omnidirectional vision :

- ✓ Sensor design and Calibration,
- ✓ Image processing and Visual servoing

The diagram shows 'Desired features (s\*)' and 'Current features (s)' being compared. The error signal  $\Delta s$  is processed by a 'Control law' to produce a displacement  $\Delta r$ , which is used to move the robot. The robot's camera captures an 'Image', which is processed by 'Image processing' to extract 'Current features (s)'.

**Indoor applications : OMNIBOT project** **ROBEA** **onnitot**  
 H. Hadj Abdelkader [05]  
 Navigation with omnidirectional visual memory : [ICRA07]

The diagram shows a robot's path in a room. Key images are taken at various points along the path, labeled with  $\psi_1$  and  $\psi_2$ . A 'Starting point' is marked, and a 'Last key image of the visual route' is indicated.

**Indoor applications : OMNIBOT project** **ROBEA** **onnitot**

**Omnidirectional Visual Servoing from Polar Lines**  
 [Hadj 06]

The image shows a robot in a room and a close-up of a camera lens with green lines overlaid, representing the polar lines used for visual servoing.

**Indoor applications : ROSACE project** Using a fisheye camera

**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

The flowchart shows the process: 'Visual memory building: database building' (Offline step) leads to 'Localization in the memory: Visual route extraction' (Offline step). This is followed by 'Visual path following' (Online step) which leads to 'Control input'.

**Indoor applications : ROSACE project**

Using a fisheye camera

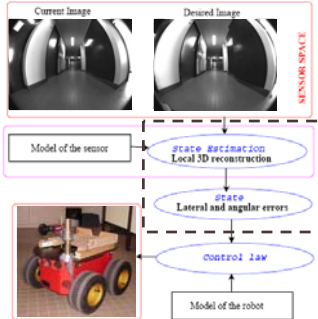
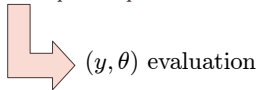


**Localization**

Vision based memory navigation strategy :

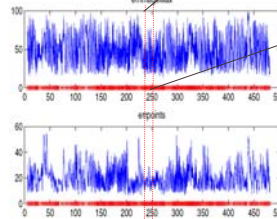
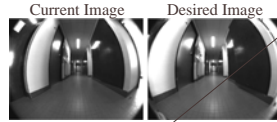
Localization into the visual memory

- a- Global localization
- b- Selection of key images
- c- Relative pose computation



**Indoor applications : ROSACE project**

Using a fisheye camera



Global localisation (6.5s) 306 matchings  
 Visual route (280 key images) – Matching mean=108  
 - ErrImageMax: longest distance between an image point and its position in desired image  
 - Errpoints: Mean distance between those points

When errImageMax reaches 20 we decide to change key image

**Indoor applications : ROSACE project**

Using a fisheye camera



[Courbon08]

**Indoor applications : ROSACE project**

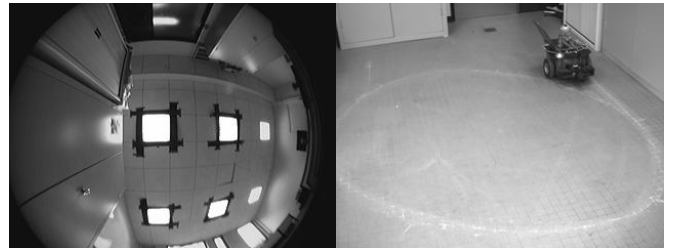
Using a fisheye camera



J. Courbon [07]

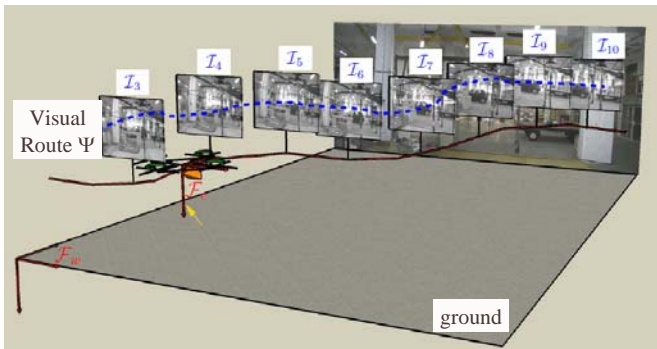
Automatic Guided Vehicles robot control using a fisheye lens

Autonomous navigation using a visual memory



**Indoor applications : µdrone project**

Flying robot [IROS09]



**Indoor applications : µdrone project**

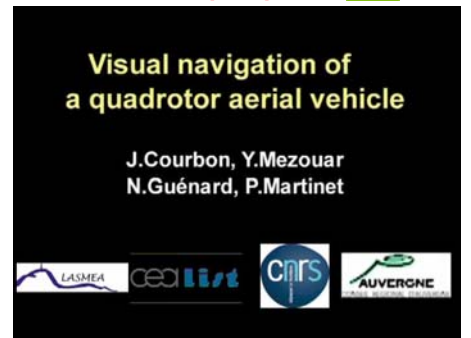
Flying robot [IROS09]



Topological navigation using visual memory

CEA 2009 Fontenay-aux-Roses

Using vision only Clermont-Ferrand LASMEA-GRAVIR





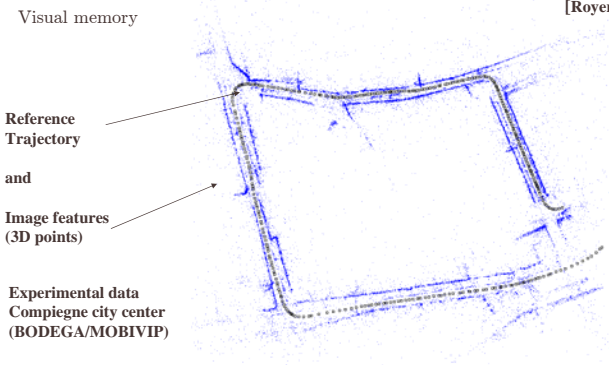
Outdoor applications : MOBIVIP project

urban context [Royer04]

Visual memory

Reference Trajectory and Image features (3D points)

Experimental data Compiegne city center (BODEGA/MOBIVIP)

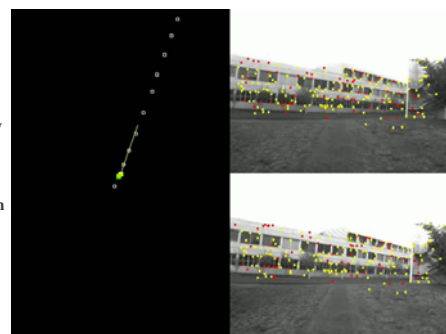


Outdoor applications : MOBIVIP project

urban context [Royer04]

Perception Localization using monocular camera

Reference Trajectory and localization



Key images And features

Current images and features

Outdoor applications : MOBIVIP project

urban context [Royer06]

Perception and control



2006: Les Cezeaux Campus CFd

2006: Inner city of Clermont-Fd

Outdoor applications : CITYVIP project [ICRA09]

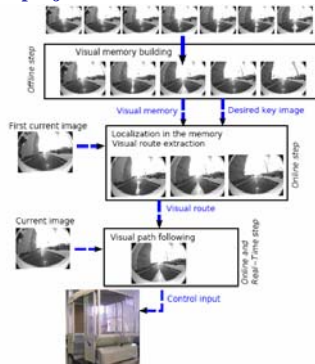
urban context

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



Outdoor applications : CITYVIP project [ICRA09]

urban context

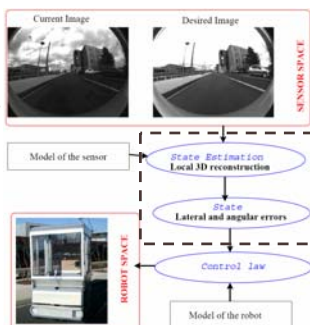
Localization

Vision based memory navigation strategy :

Localization into the visual memory

- a- Global localization
- b- Selection of key images
- c- Relative pose computation

(y, θ) evaluation



Outdoor applications : CITYVIP project [ICRA09]

urban context

Testbed

Experimental robot is a Robucab from Robotoc

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

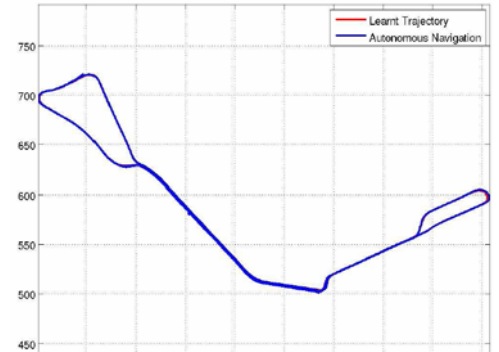
Longitudinal velocity  $V$  has been fixed to  $1\text{ m s}^{-1}$   
 $K_p$  and  $K_d$  are tuned regarding a double pole located at value 0.3



**Outdoor applications : CITYVIP project** [ICRA09] urban context  
 Experiment Loop 1200 m – 35 edges  
 Navigation 1700m (26 minutes, 1400 keys images, 54 edges)



**Outdoor applications : CITYVIP project** [ICRA09] urban context  
 Experiment



Lateral error:  
 - mean: 23 cm  
 - standard deviation: 30 cm.  
 Navigation stops after 1700m for security reasons (small number of matched points)

**Outdoor applications : CITYVIP project** [ICRA09] urban context  
 Video

Topological navigation using visual memory  
 Cityvip  
 Clermont-Fd 2008

Using vision only  
 Clermont-Ferrand  
 LASMEA-GRAVIR



## Outline of the presentation

### Introduction

- LASMEA
- Sensor based Control
- Navigation
- SLAN vs SLAM

### A generic model

- A unified model for camera
- Case of fisheye cameras
- Partial euclidian reconstruction

### Topological navigation system

- Global system
- Case of vision
- Differents Modules
- SOVIN

### Illustrations

- Indoor applications
- Outdoor applications

### Discussion

- Learning process
- Updating process
- Closing the loop problem

### Learning process

Part of the next step: R-DISCOVER project  
 Automatic discovering & learning the environment

### Updating process

Part of the next step: R-DISCOVER project  
 Automatic updating the environment

### Closing the loop problem

No a priori needs for closing the loop.  
 Can be useful for improving topological maps



*Thanks for your attention*  
*Any questions*



<http://www.lasmea.univ-bpclermont.fr/Control>  
<http://www.lasmea.univ-bpclermont.fr/Personnel/Philippe.Martinet>

[martinet@lasmea.univ-bpclermont.fr](mailto:martinet@lasmea.univ-bpclermont.fr)

