Human, Dynamic & Open Environments
A new challenge for Robotics

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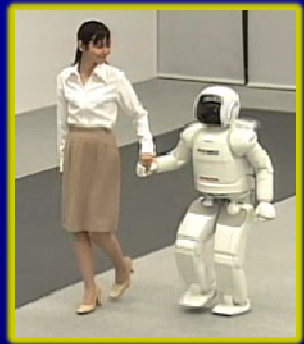
Scientific challenge

- **Overall challenge**

Robots in Human Environments

ITS for improving safety & comfort & efficiency



Personal Assistant & House Keeping & Rehabilitation

- **Main Motivations**

  ✓ Important socio-economic perspectives *=> Transport, Aging society, Medical care & Rehabilitation, Human assistance, Intelligent home …*

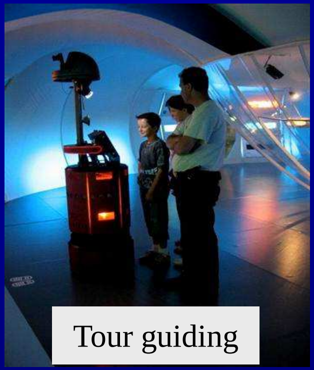
  ✓ Increasing interest of industry *=> Automotive industry, Robots, Health sector, Services …*

  ✓ Challenging research topics *=> Dynamic world, Robust perception, Safety, Human Aware Motion, Complex Human-Robot interactions …*

  ✓ Robotics state-of-the-art + Progress in ICT Technologies *(computers, sensors, micro-nano technologies, energy …)* *=> Challenge potentially reachable*

New problems to be addressed

Introducing Robot in our daily lives brings new challenges to Robotics !



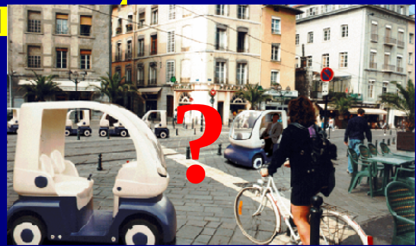
- **Robot & Human have to safely:**
  - ✓ *Cooperate & Accomplish tasks together*
  - ✓ *Communicate & Interact*
  - ✓ *Co-exist*

=> New concept : ***Socially Acceptable Robot Motions & Behaviors***

=> New environments : ***Open & Dynamic & Uncertain***

Required technological breakthroughs

- **Robust Perception & Understanding of Open, Dynamic, Uncertain *(ODU)* environ**



- **Motion Autonomy in *ODU* environments …. with a special emphasis on Safety issue**

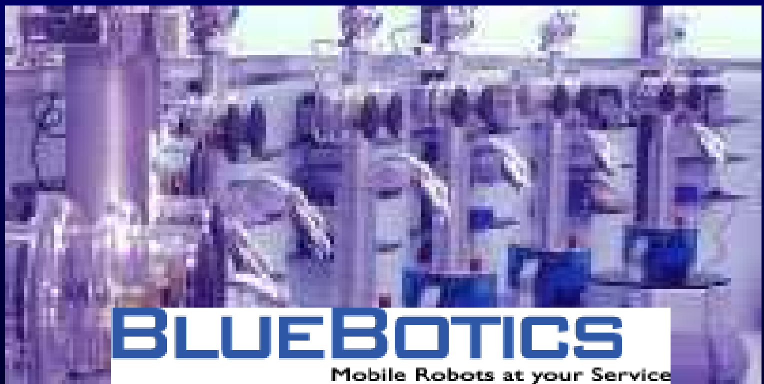
- **Safe & Understandable Human-Robot interactions**

Some previous large experiments (1)

Tour-guide robots (Swiss National Exhibition Expo.02)

BlueBotics SA & Autonomous Systems Lab

- *4 Months, Daily operation, Up to 12h/day, Up to 11 robots simultaneously*
- *13 300 hours Operation time, 3 300 km Traveled distance, 680 000 Visitors*



Some previous large experiments (2)

CyberCars Public Experiments (INRIA & EU Partners)

Antibes

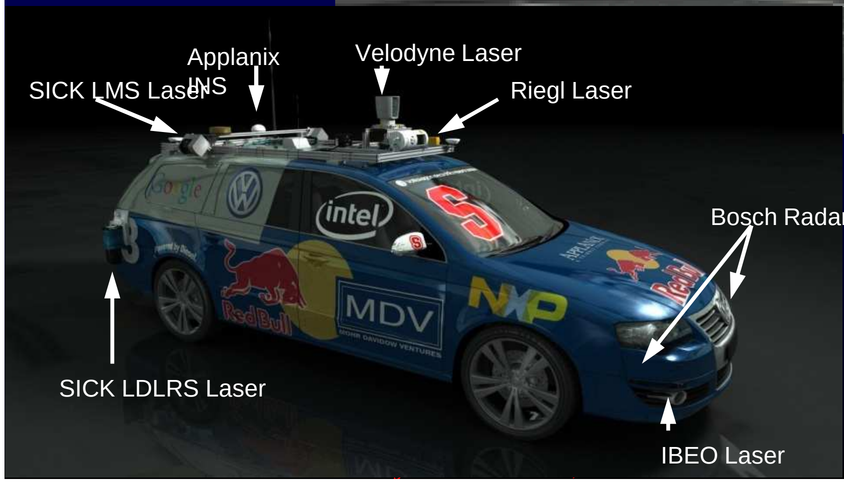
- *Several successful large scale experiments in public areas*
- *Some CyberCars products in commercial use (e.g. Robosoft, Frog …)*

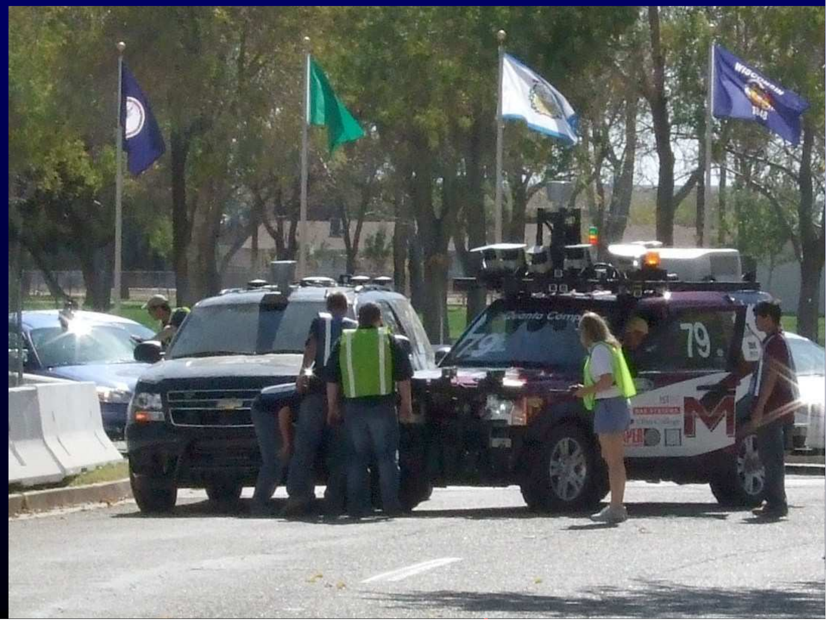
Floriade 2002 (Amsterdam)

Shanghai Public Demo (2007)

Some previous large experiments (3)
Urban Challenge 2007

- 96 km through an urban environment, 50 manned & unmanned vehicles
- 35 teams for qualification (NQE during 8 days), 11 selected teams, 6 vehicles finished the race
- Road map provides a few days before the race, Mission (checkpoints) given 5 mn before the race
- Several incident/accidents during the event





Open research issues

- **Human environment is still an open research issue for Robotics**
  - ✓ *Large experiments in some human environments is a necessary step*
  - ✓*However, major issues such as "Robustness to uncertainty" and "Safety" have to be more deeply addressed*

- **Main problems to solve**
  - ✓ *World & Task complexity => Scalability*
  - ✓*Reactivity & Real-time constraints => Efficiency*
  - ✓*Incompleteness & Uncertainty => Reasoning about uncertainty*
  - ✓*Human in the loop => Human factor in the decisional process & Safety*

General Approach

• Revisit traditional approaches not fully adapted to the processing of *Human environments*

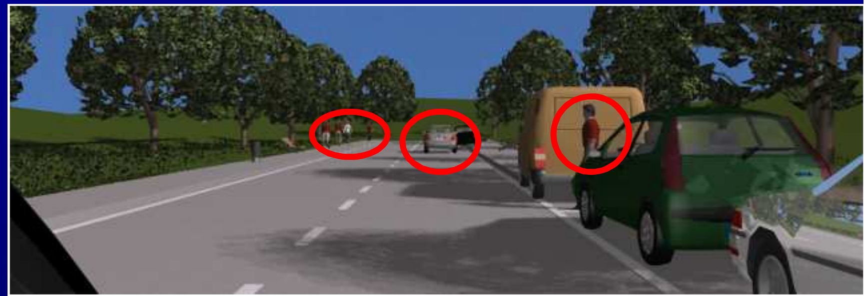
• Design new models & algorithms adapted to *Complex & Highly dynamic & Partly known environments*

• Focus on *Robustness & Efficiency & Safety*

• Uncertainty has to be placed at the heart of the Decisional Process. *Probabilistic models* should probably seen as key tools.

Key related problems for Motion Autonomy

Moving safely amidst Stationary & Moving obstacles (vehicles, pedestrians …)
in Open & Dynamic & Uncertain environments



- **Continuously changing environment**
  - ✓ *Continuous world modeling using sensors*
  - ✓ *Space & Time have to be considered*
  - ✓ *Real-time processing is required*

- **Sensed Stationary & Moving obstacles**
  - ✓ *SLAM + DATMO*
  - ✓ ***Uncertainty** is a key issue (perception, localization, tracking …)*

- **Uncertain & Dynamic environments**
  - ✓ ***World changes PREDICTION is necessary***
  - ✓ ***RISK based navigation decisions (based on world states Estimation & Prediction)***

Main Robotics issues for Open & Dynamic & Uncertain environments

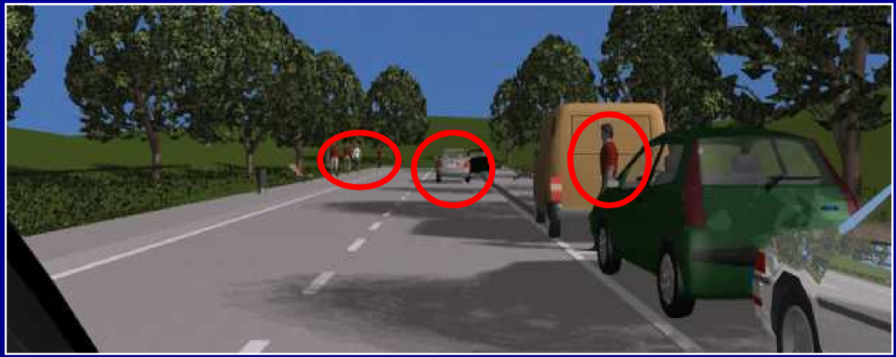
1. **Robust detection & tracking**

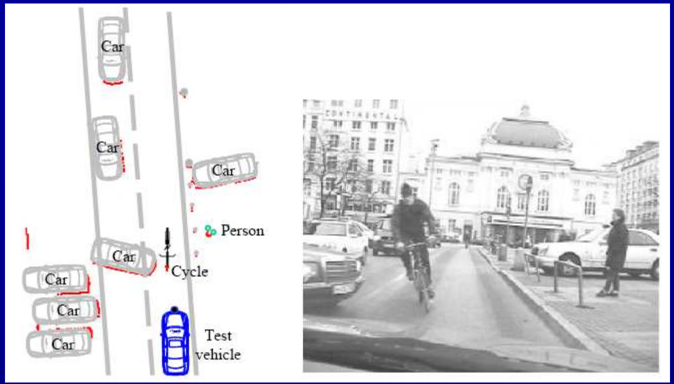
2. **Prediction & Risk assessment**

3. **Safe goal-oriented navigation**

4. **Human-Robot interaction**

Multi-Object Tracking: State-of-the-art (1)





- **Conventional approaches** *[Shalom88][Blackman99]*

Data Association

- **1-Scan :**
  - ✓ *Global Nearest Neighbor (GNN)*
  - ✓ *Joint Probabilistic Data Association (JPDA)*
- **N-Scan :** *Multiple Hypothesis Tracking (MHT)*

Filtering (object dynamic estimation)

- **A single dynamic model :**
  - ✓ *Kalman Filter (KF or EKF)*
  - ✓ *Particle Filter (PF)*
- **N models:** *Interacting Multiple Model (IMM)*

- **Tracking "point" objects (clusters)**
  - ✓ JPDA + PF => Tracking people, indoor *[Schulz et al. 01]*
  - ✓ MHT+IMM => General objects, urban traffics *[Wang04] [Burlet 07]*

  => More robust … but well-known problems with laser-based tracking still hold !
  (objects splitting, Appearing & disappearing targets …)

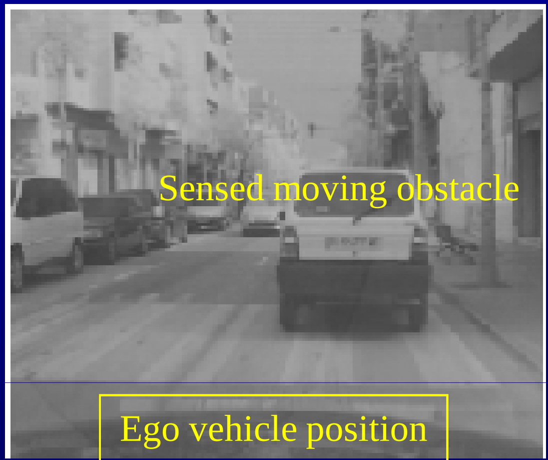
Multi-Object Tracking: State-of-the-art (2)

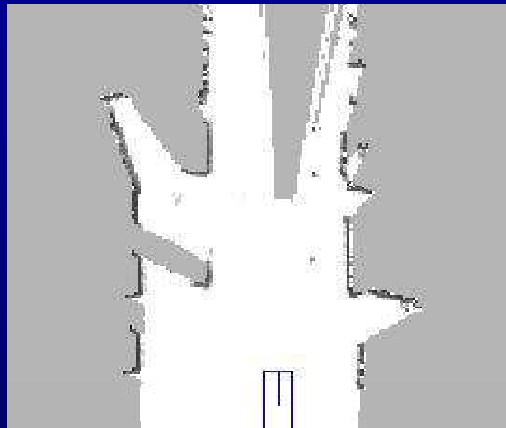
- **Model-based approaches**
  - **Vision** *=> More info for detection & classification, Less accurate distance for tracking*
    - ✓ MCMC (1-Scan) + KF => Vehicles *[Song & Nevatia. 2005]*
    - ✓ MCMC (1-Scan) + KF => People *[Zhao & Nevatia 2008]*
    - ✓ MHT + EKF (stereo vision) => People *[Ess et al 2008]*
  - **Laser** *=> Less informative, Accurate distance , More robust to environment conditions*
    - ✓ GNN + PF (Flexible models) => Vehicles *[Petrovskya &Thrun 08]*
    - ✓ GNN + EKF (fixed models) => Vehicles *[Urmson et al. 08]*
    - ✓ MCMC (N-Scan) + IMM (fixed models) => Vehicles & Peds *[Vu & Aycard 09]*
- **Current work: Improving robustness using Sensor Fusion**
  - ✓ Some promising results for pedestrians detection using *Vision & Laser [Broggi 07]*
  - ✓ An efficient tools Bayesian Occupancy Filter *[Coue & Laugier 05]*

Laser-based Multi-Objects Detection & Tracking

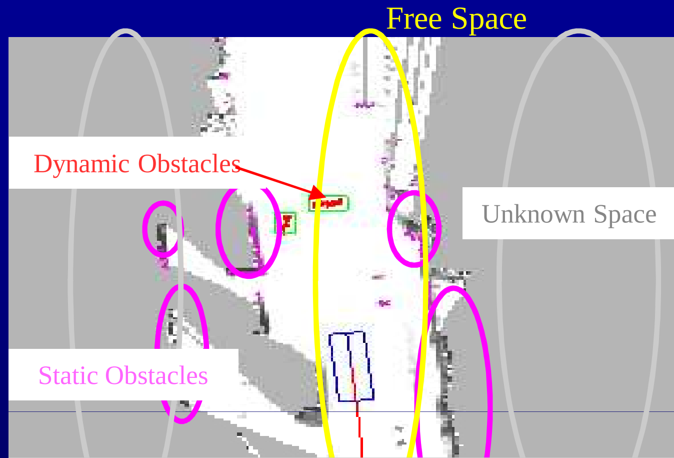
"PreVent" EU project *[Burlet, Vu, Aycard 07-08]*

• Grid-based Obstacles Detection (using Occupancy Grids)





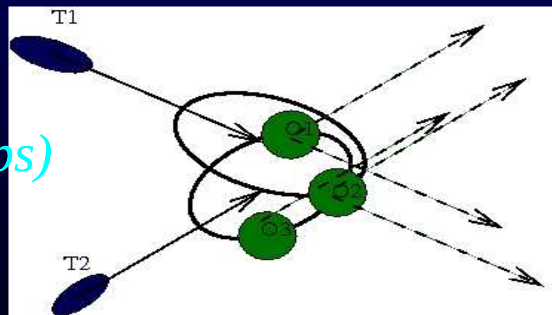
Incremental OG Mapping (sliding window)



Moving Object detection => Check consistency "OG / Raw laser data"

• Multi-Objects Tracking

- ✓ *Mapping & localization: Scan matching*
- ✓ *Data Association: Multiple Hypotheses (for n time steps)*
- ✓ *Filtering : Interacting Multiple Models*



Inspired from [Blakman 98] (radar) & [Wang 04] (laser + ICP)

Multi-objects DATMO – Previous Results

"PreVent" EU project, Versailles demo 2007 (Daimler-Chrysler & Ibeo test vehicle)

Mercedes E-Class 350

Grid-Based approach
Multiple Hypotheses & Interacting Multiple Models

Computational time ~ 10 ms

Application:

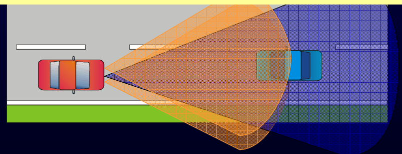
- **Pre-fire & Braking**

Sensors:

- Two short range radars
- A laser scanner ALASCA

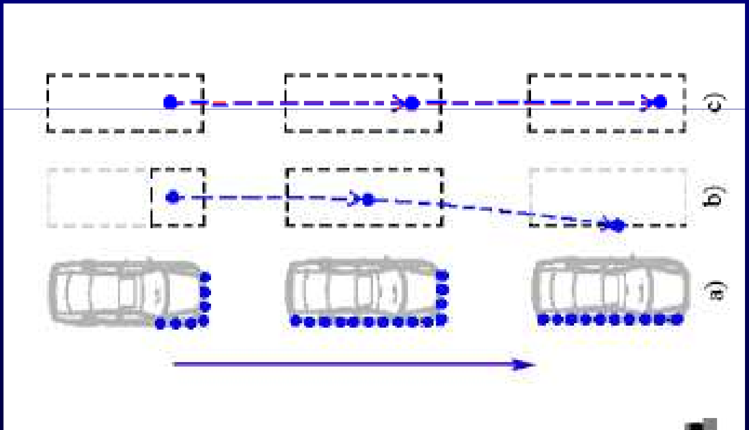
Actuators:

- Electrical belt pre-tensioning
- Automatic braking

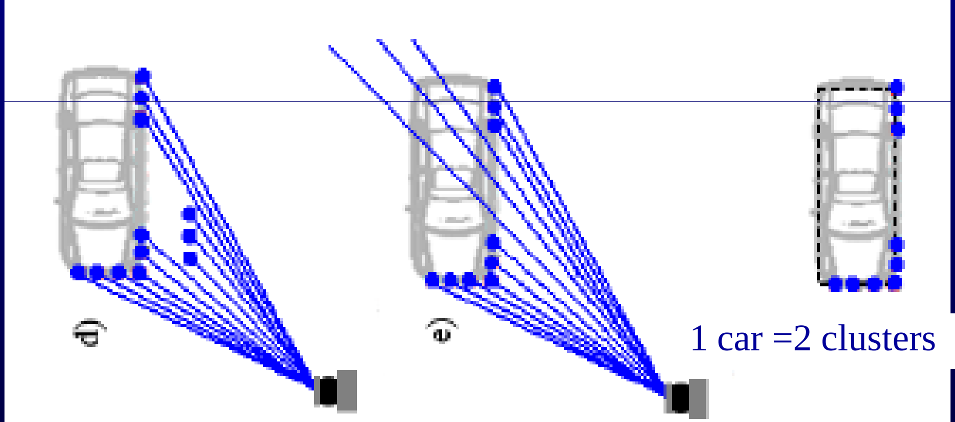


DATMO – Known problems using laser scanner

- Objects are represented by clusters of points
- Tracking clusters leads to a degradation of tracking results
- Object splitting (occlusions, glass-surfaces) makes the tracking harder



Cluster-based tracking errors



Partial occultation Sensor error

=> Using geometric object models can help for overcoming these problems

Stanford Model-based approach

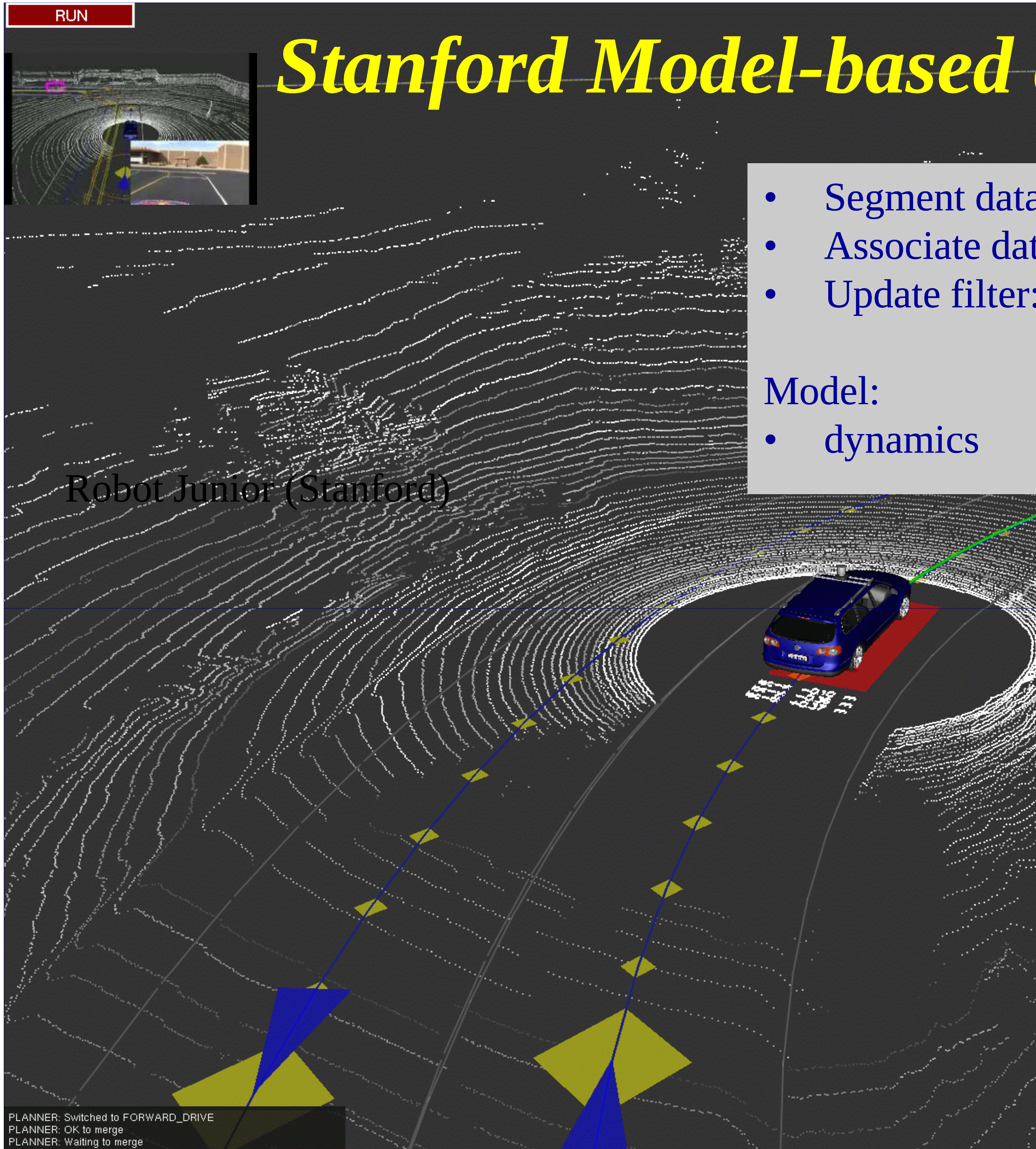
- Segment data
- Associate data: MHT
- Update filter: EKF

} => Bayes filter: RBPF *(1 Scan)*

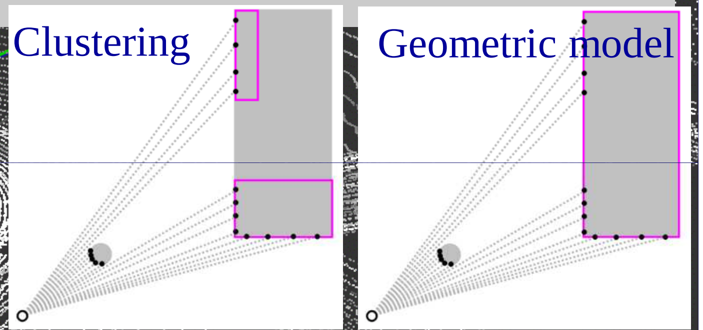
Model:

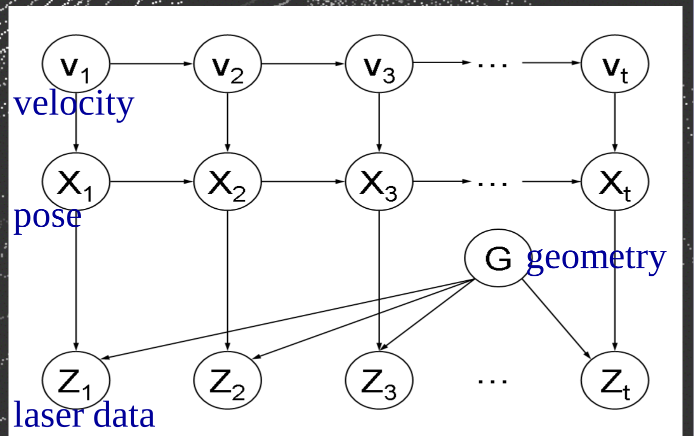
- dynamics

=> { • dynamics • geometry



Robot Junior (Stanford)





Courtesy A. Petrovskaya & S. Thrun

INRIA T-Scans Model-based Approach

Data-Driven Markov-Chain Monte-Carlo *[VU & Aycard 09]*

- Sliding window over *T*-scans *(Time Horizon)* $Z = \{Z_1, ..., Z_T\}$

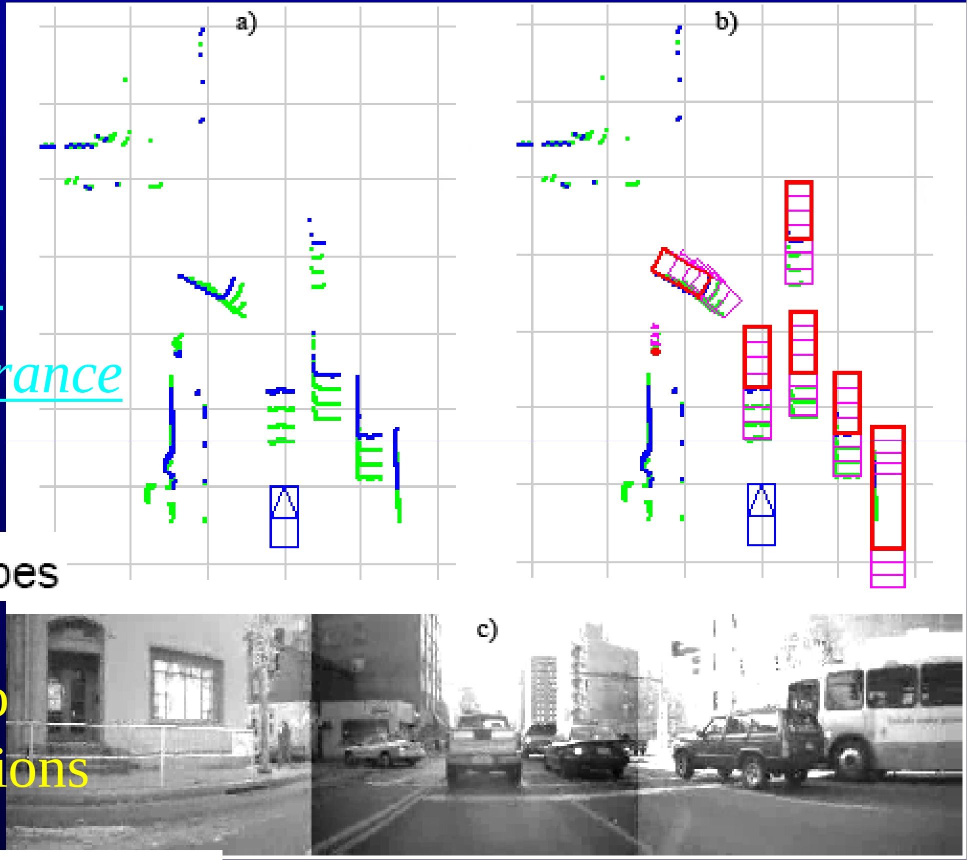
- Find the best explanation of object trajectories (tracks) based on *Spatio-Temporal consistency in both appearance (model) & motion*

- Model Based: τ_k is a sequence of shapes

- Sampling-based method (MCMC) to avoid enumerating all possible solutions

$$\omega^* = \underset{\omega}{\operatorname{argmax}} P(\omega|Z)$$

$$\omega = \{\tau_1, \tau_2, ..., \tau_K\}$$



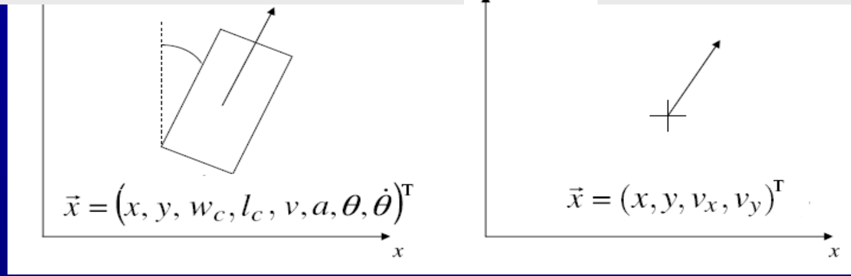
=> Simultaneous Detection, Classification and Tracking

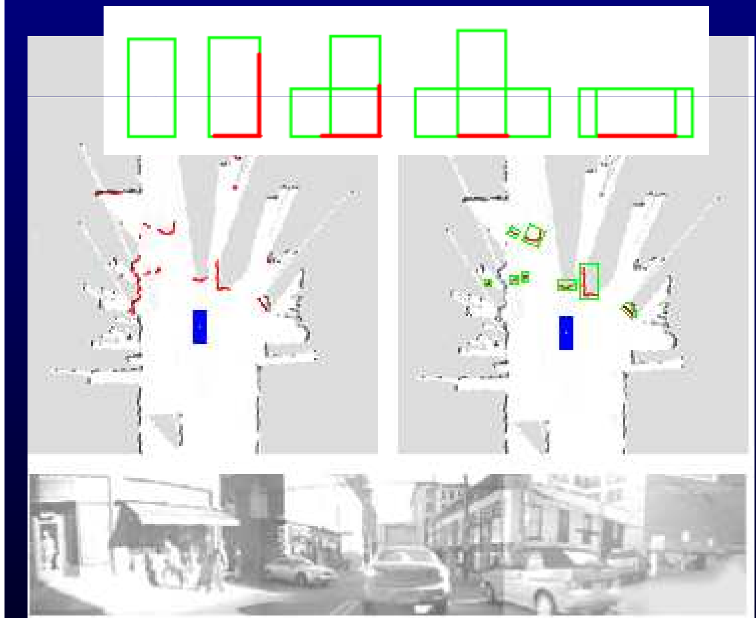
DDMCMC – Models & Hypotheses processing

Results Navlab

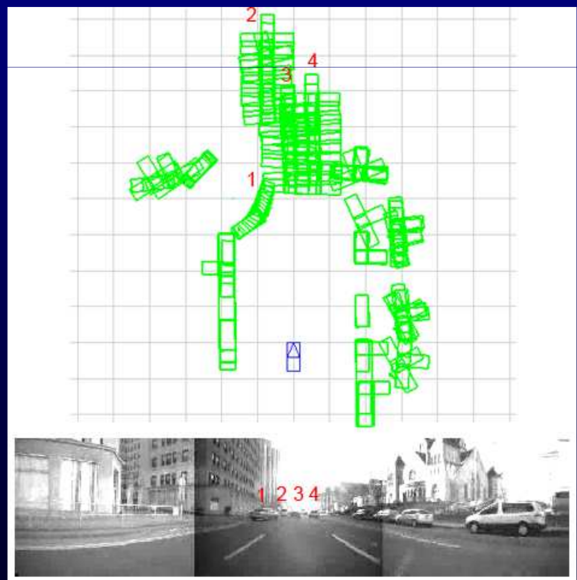
Bus, Truck, Car, Bike
- *Box model (fixed size)*
- *Dynamic model (v, a, turn, stop)*

Pedestrian
- *Point model*
- *Dynamic model (v)*

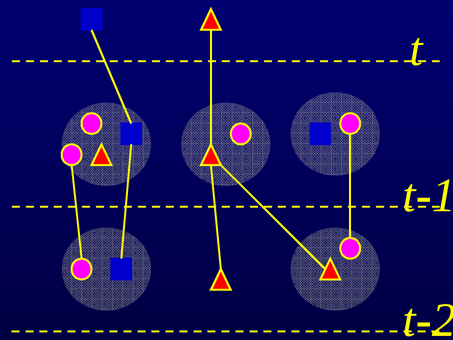




L-shape & I-shape => Box model
Else wise => Point object



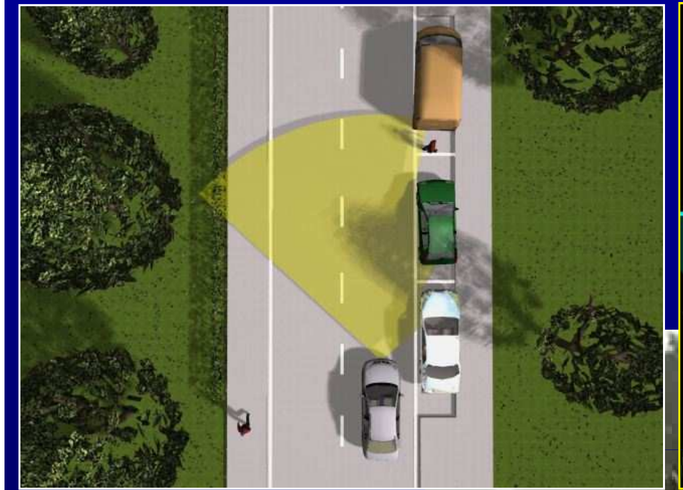
Search of $P(\omega \mid Z)$ over space of moving object hypotheses

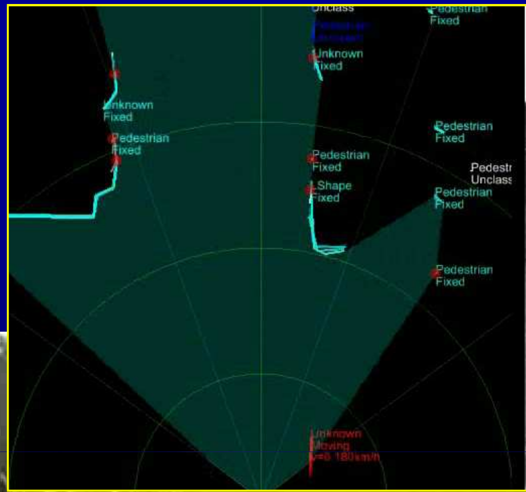


Neighborhood graph
of hypotheses

More Robust Detectors ?

Vision & Laser Fusion for pedestrian detection (Vislab)





Courtesy of A. Broggi (Vislab, Parma University)

Bayesian Sensor Fusion for “Dynamic Perception”

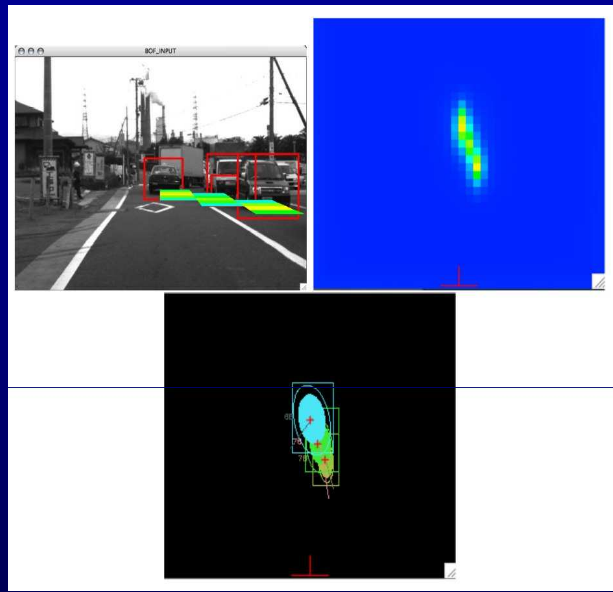
“Bayesian Occupation Filter paradigm (BOF)”

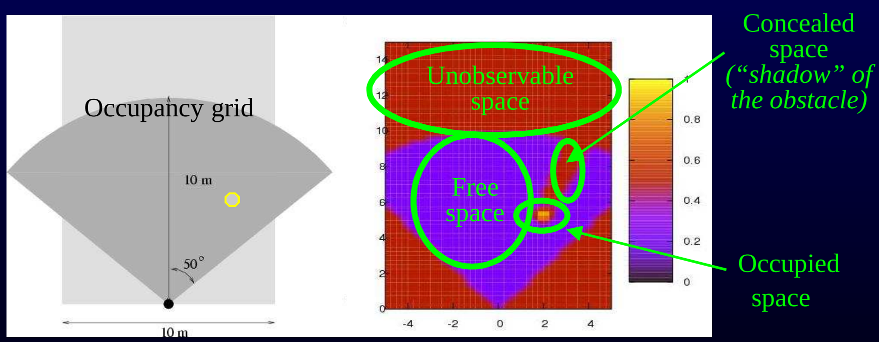
Patented by INRIA & Probayes, Commercialized by Probayes

BOF

- Continuous Dynamic environment modelling
- *Grid* approach based on *Bayesian Filtering*
- Estimates *Probability of Occupation* & *Velocity* of each cell in a 4D-grid
- Application to *Obstacle Detection & Tracking + Dynamic Scene Interpretation*

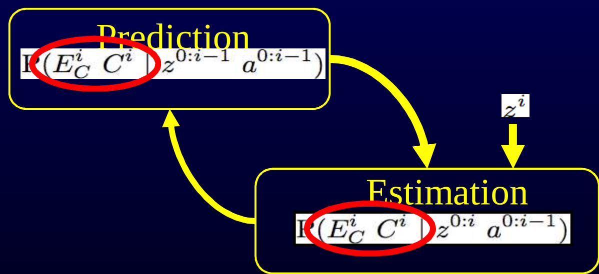
=> More robust to Sensing Errors & Temporary Occultation





Sensed moving obstacle

$P([O_c = occ] \mid z\ c)$
$c = [x, y, 0, 0]$ and $z = (5, 2, 0, 0)$



[Coué & Laugier IJRR 05]

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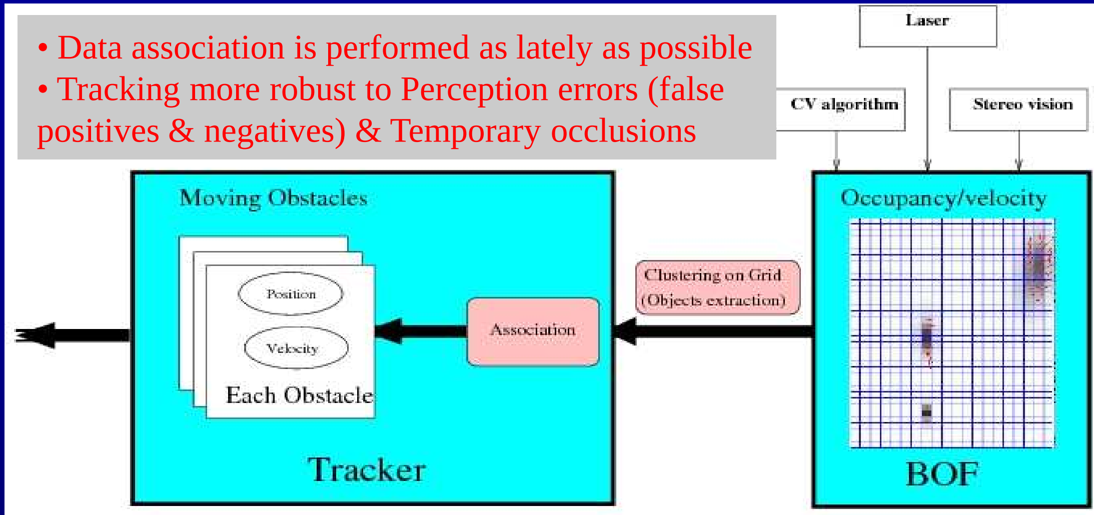
Application to Fusion based Detection & Tracking

- Data association is performed as lately as possible
- Tracking more robust to Perception errors (false positives & negatives) & Temporary occlusions

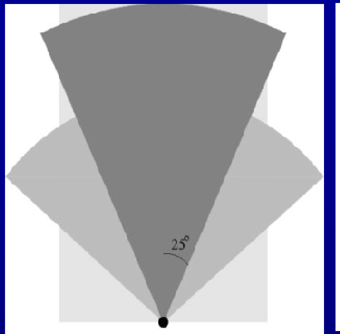


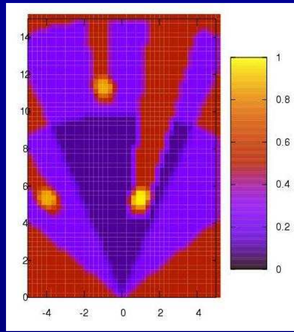
Successfully tested in real traffic conditions on industrial data (e.g. Toyota …)

Denso Data Set

Robustness to Temporary Occultation

Tracking + Conservative anticipation *[Coué & al IJRR 05]*





Description

Specification

- Variables :
  - V^k, V^{k-1} : controlled velocities
  - $Z^{0:k}$: sensor observations
  - G^k : occupancy grid
- $P(Z^{0:k}\ V^k\ V^{k-1}\ G^k) = \begin{pmatrix} P(Z^{0:k})P(V^{k-1}) \\ P(G^k \mid Z^{0:k})P(V^k \mid V^{k-1}\ G^k) \end{pmatrix}$
- Parametric forms :
  - $P(G^k \mid Z^{0:k})$: BOF estimation
  - $P(V^k \mid V^{k-1}\ G^k)$: Given or learned

Question

Inference

$P(V^k \mid z^{0:k}\ v^{k-1})$

Thanks to the prediction capability of the BOF, the Autonomous Vehicle "anticipates" the behavior of the pedestrian and brakes (even if the pedestrian is temporarily hidden by the parked vehicle)

Main Robotics issues for Open & Dynamic & Uncertain environments

1. **Robust detection & tracking**

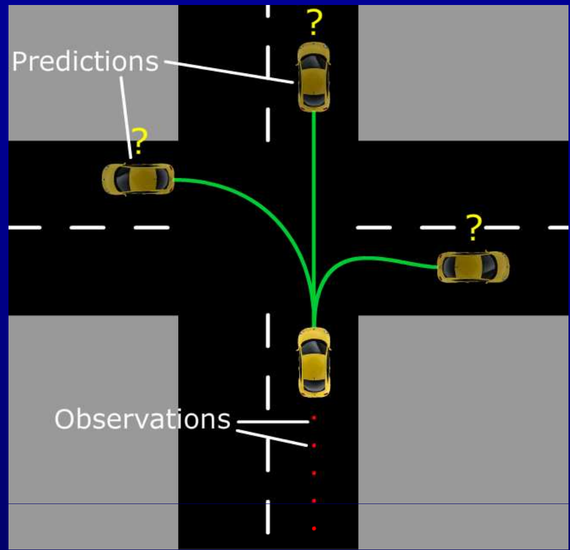
2. **Prediction & Risk assessment**

3. **Safe goal-oriented navigation**

4. **Human-Robot interaction**

Modeling (Predicting) the Future (1)

[Vasquez & Laugier 06-08]

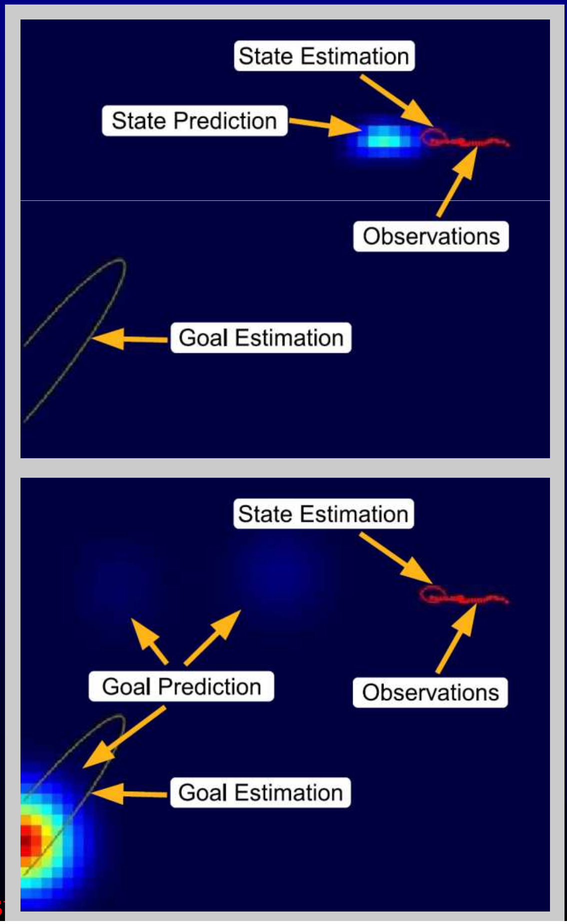


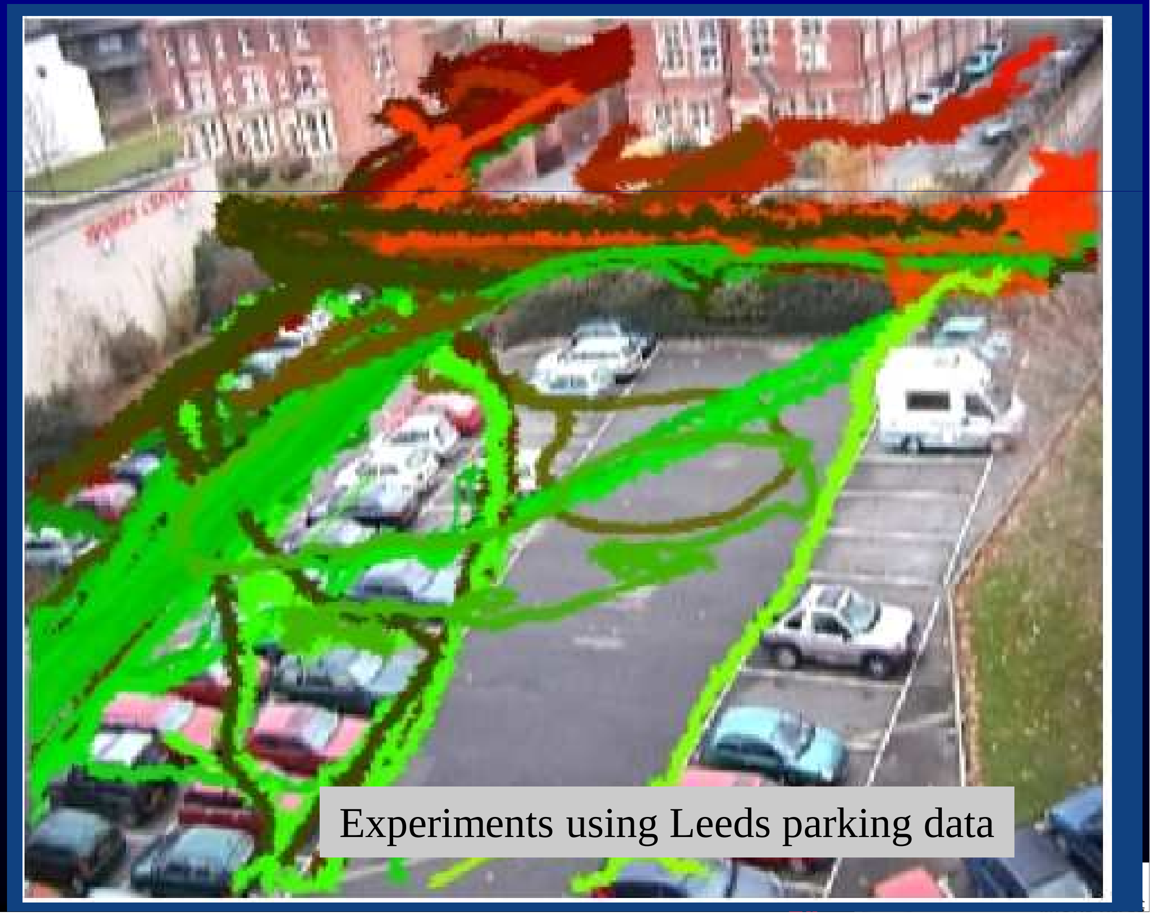
- Risk assessment requires to both *Estimate the current world state* & *Predict the most likely evolution of the dynamic environment*
- Objects motions are driven by *"Intentions"* and *"Dynamic Behaviors"* => *Goal + Motion model*
- Goal & Motion models are not known nor directly observable …. But *"Typical Behaviors & Motion Patterns"* can be learned through observations

Modeling (Predicting) the Future (2)

Our Approach *[Vasquez & Laugier & 06-09]*

- *Observe & Learn "typical motions"*
- *Continuous "Learn & Predict"*
  - ✓ *Learn => GHMM & Topological maps (SON)*
  - ✓ *Predict => Exact inference, linear complexity*

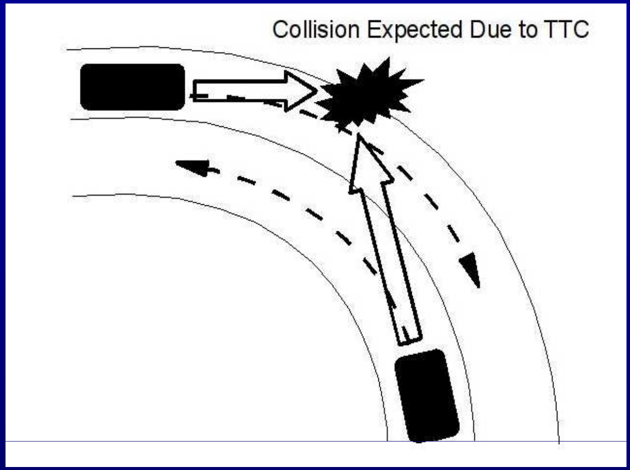



Experiments using Leeds parking data

Collision Risk Assessment (1)

Probabilistic Danger Assessment for Avoiding Future Collisions

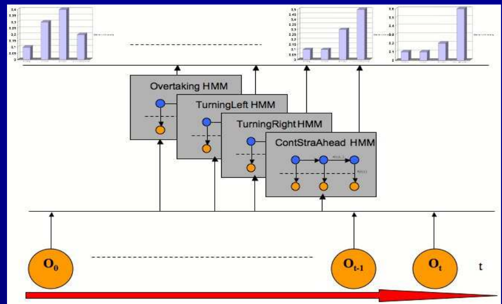
[Tay PhD thesis + Collaboration Toyota]



- Existing TTC-based crash warning assumes that motion is linear
- Simply knowing position & velocity of obstacles at each time instance is not sufficient for risk estimation
- A more accurate description of motion for PREDICTION by *Semantic (turning, overtaking …)* and *Road Geometry (lanes, curves, intersections …)* is necessary !!!!

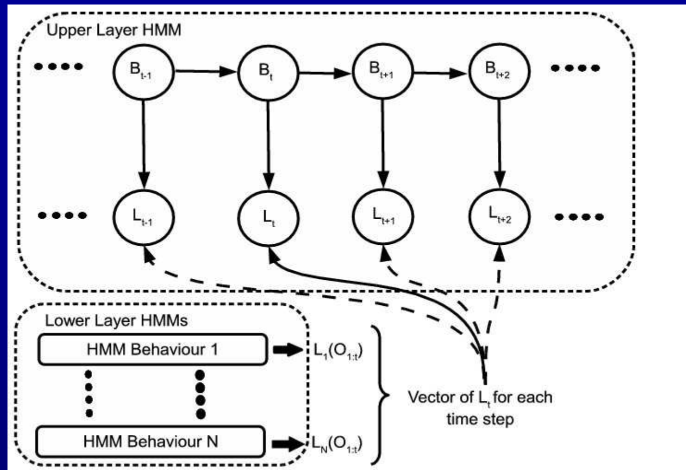
Collision Risk Assessment (2)

- **Behaviors :** *Hierarchical HMM (learned)*



Behavior Prediction

$$P(B_t|O_{1:t}) = L_{B_t}(O_{1:t}) \sum_{B_{t-1}} P(B_{t-1}) P(B_t|B_{t-1})$$



e.g. Overtaking => Lane change, Accelerate …

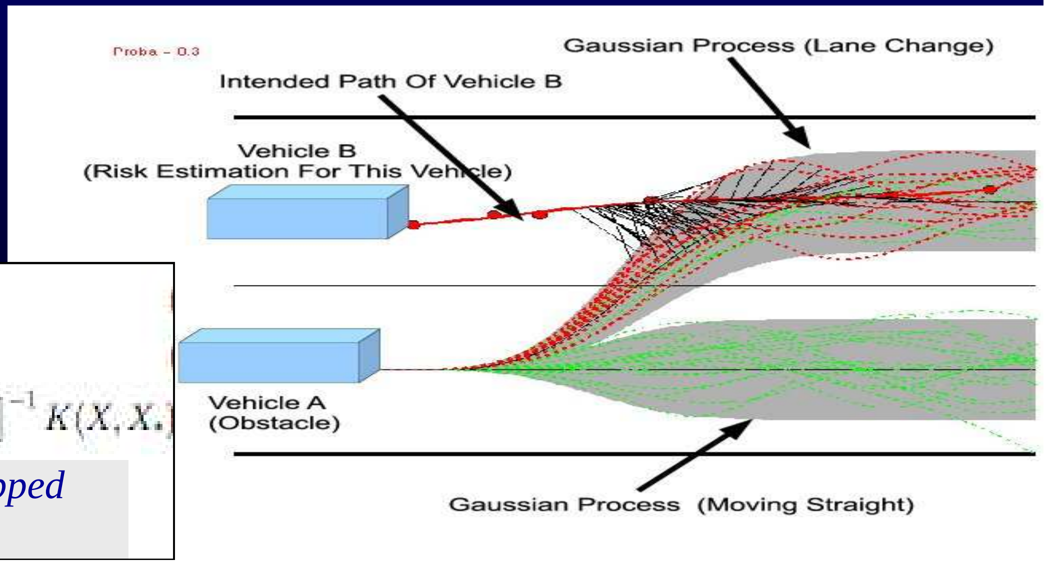
- **Motion Execution & Prediction :** *Gaussian Process*

$$f(x) \sim \mathcal{GP}(m(x), k(x,x'))$$
$$m(x) = E[f(x)]$$
$$k(x,x') = E[(f(x)-m(x))(f(x')-m(x'))]$$

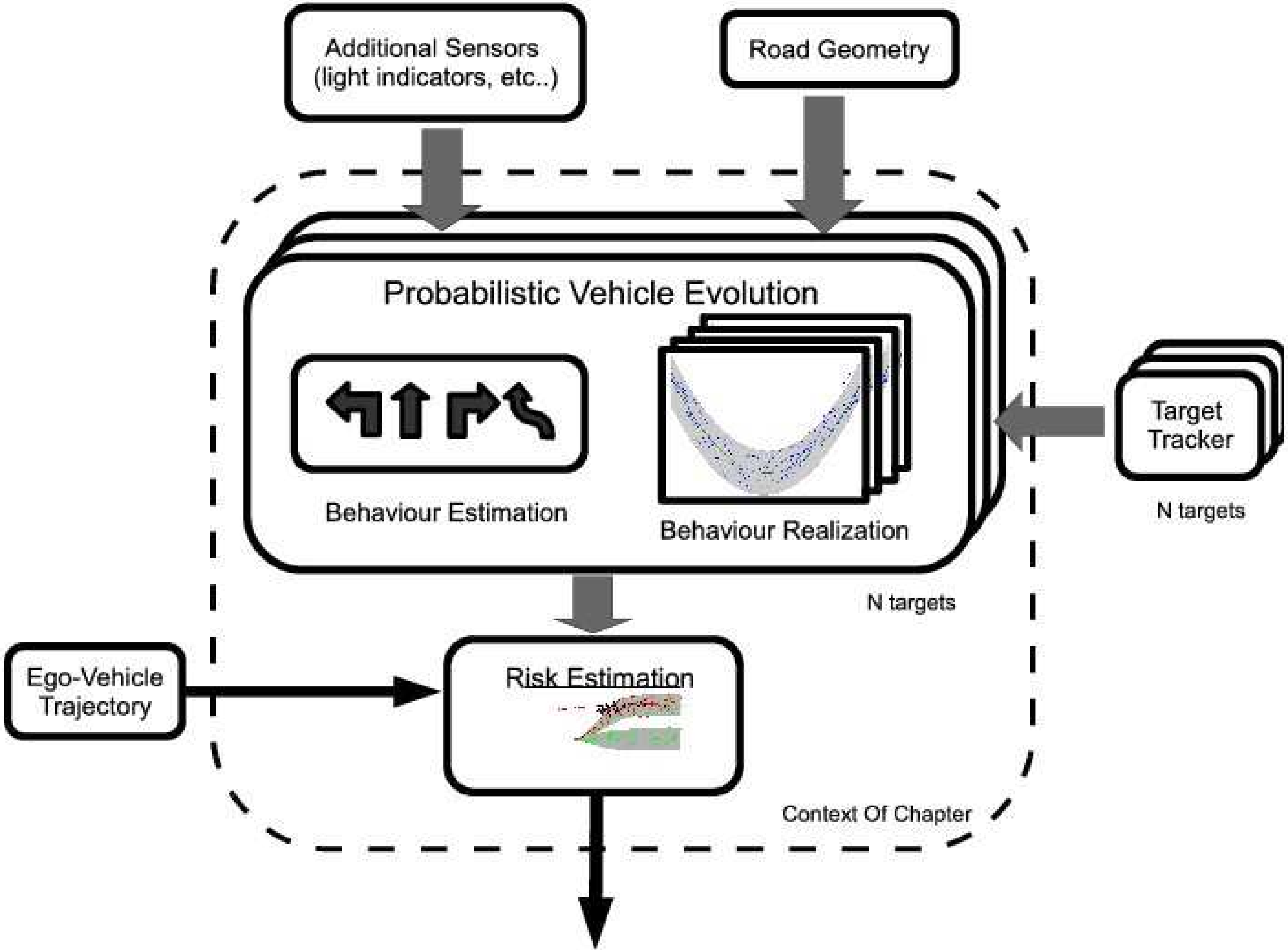
GP: *Gaussian distribution over functions*

$$P(Y_*|X_*,X,Y) = \mathcal{GP}(\mu_{Y_*}, \Sigma_{Y_*})$$
$$\mu_{Y_*} = K(X_*,X)\left[K(X,X)+\sigma^2 \mathbf{I}\right]^{-1} Y$$
$$\Sigma_{Y_*} = K(X_*,X_*) - K(X_*,X)\left[K(X,X)+\sigma^2 \mathbf{I}\right]^{-1} K(X,X_*)$$

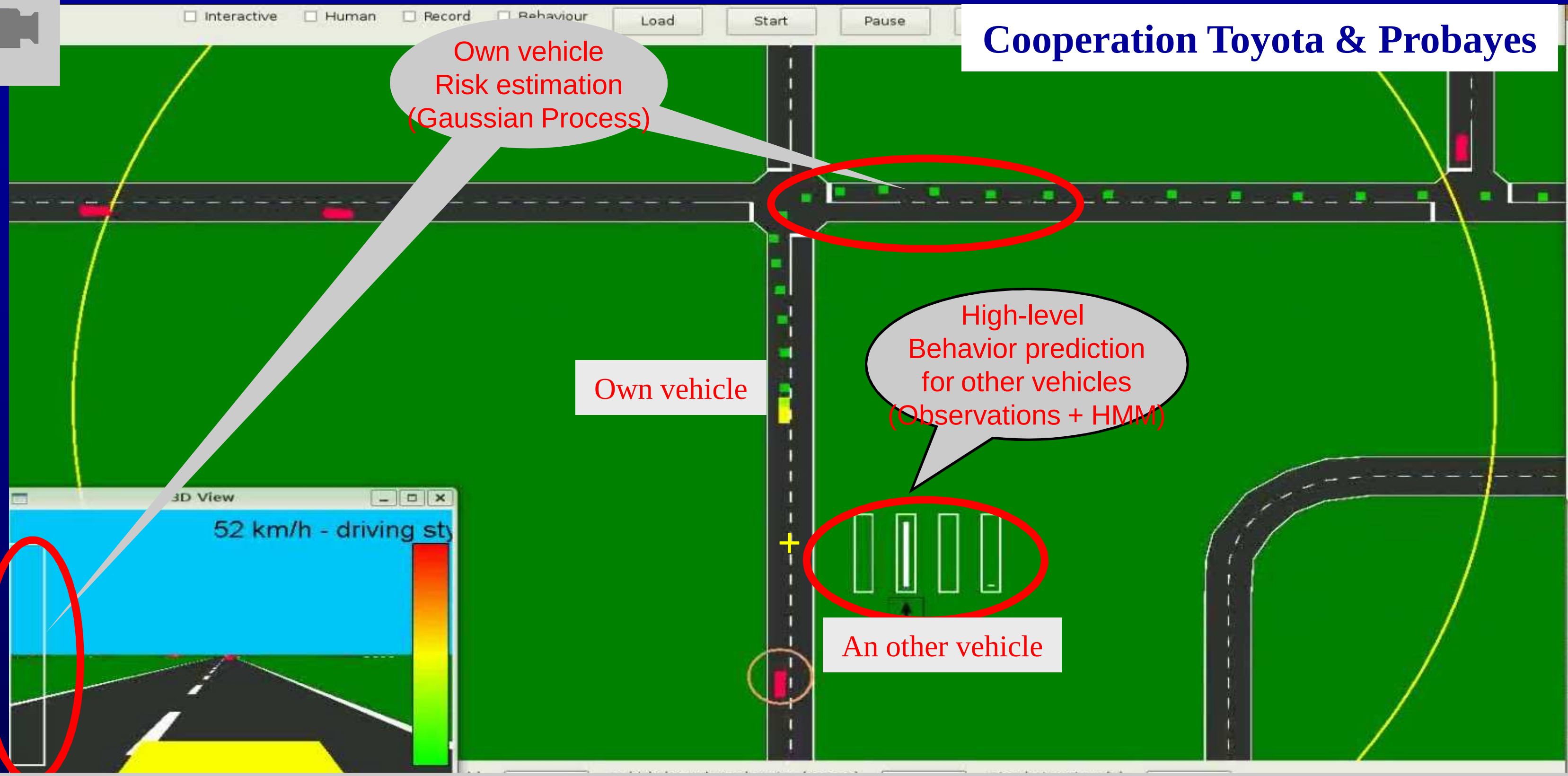
Prediction: *Probability distribution (GP) using mapped past n position observations*



Collision Risk Assessment (3)



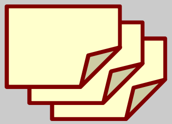
Simulation Results



Behavior Prediction (HMM)

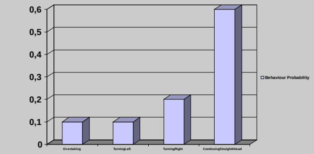
Observations

+



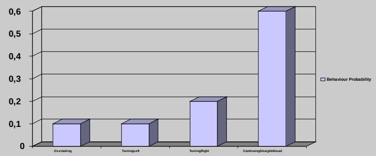
Behavior models

Prediction



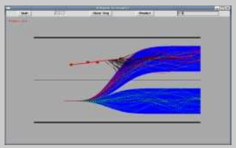
Behavior belief table

Risk Assessment (GP)



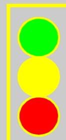
Behavior belief table for each vehicle in the scene

+



Road geometry (GIS) + Own vehicle trajectory to evaluate

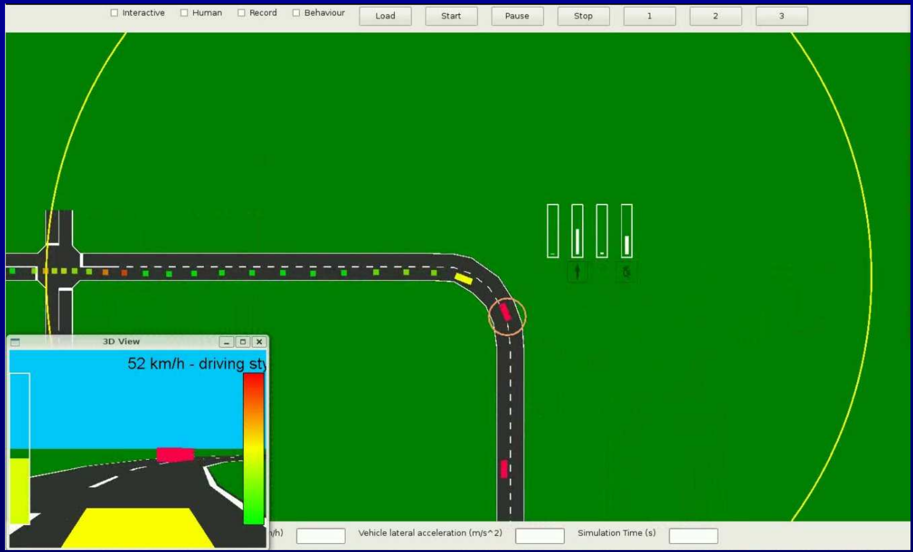
Evaluation

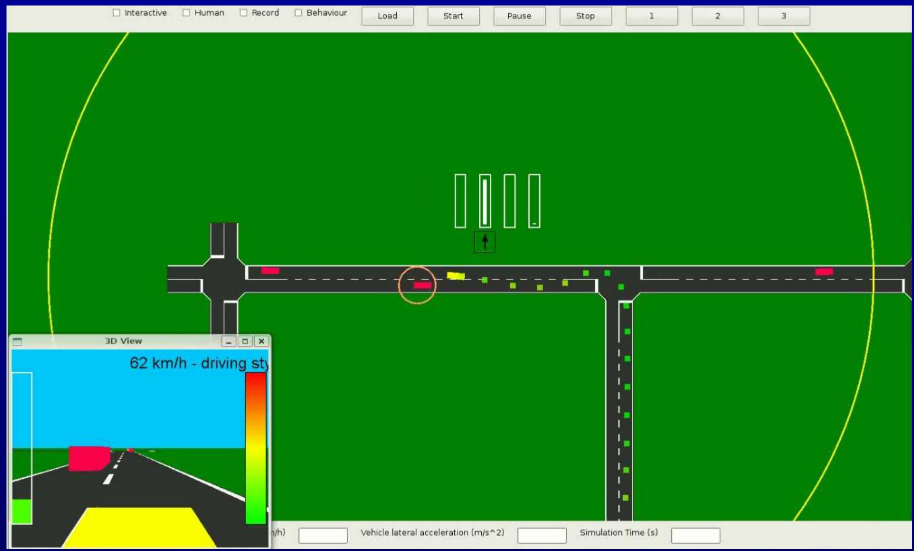


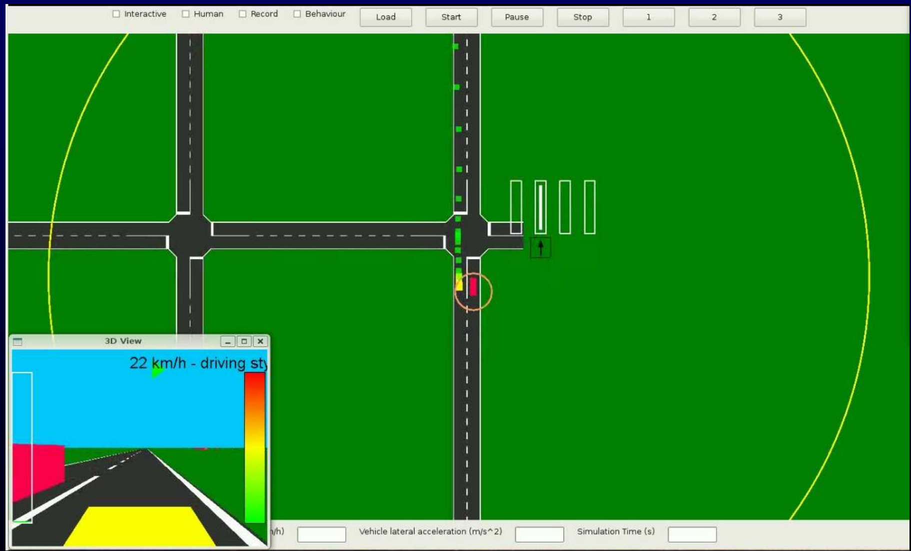
Collision probability for own vehicle

Simulation Results - Intersection

Good sensitivity to risks

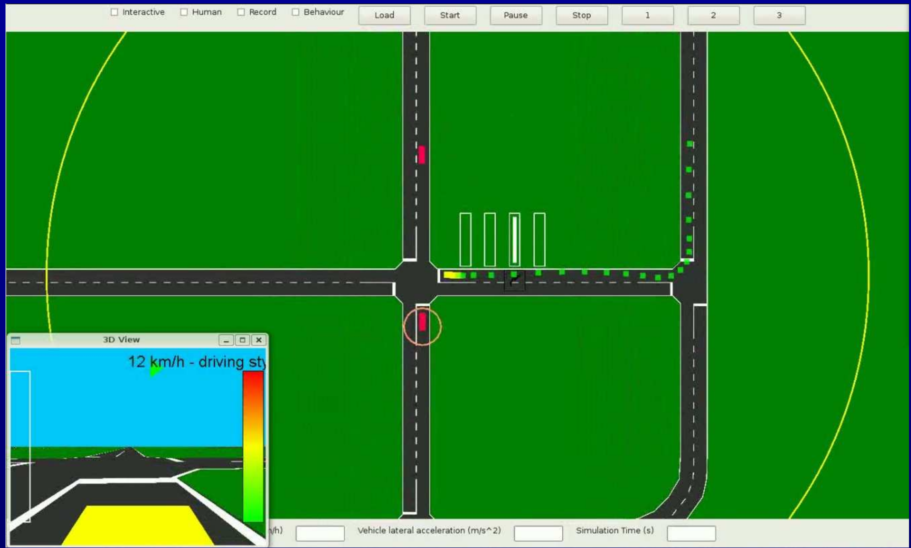


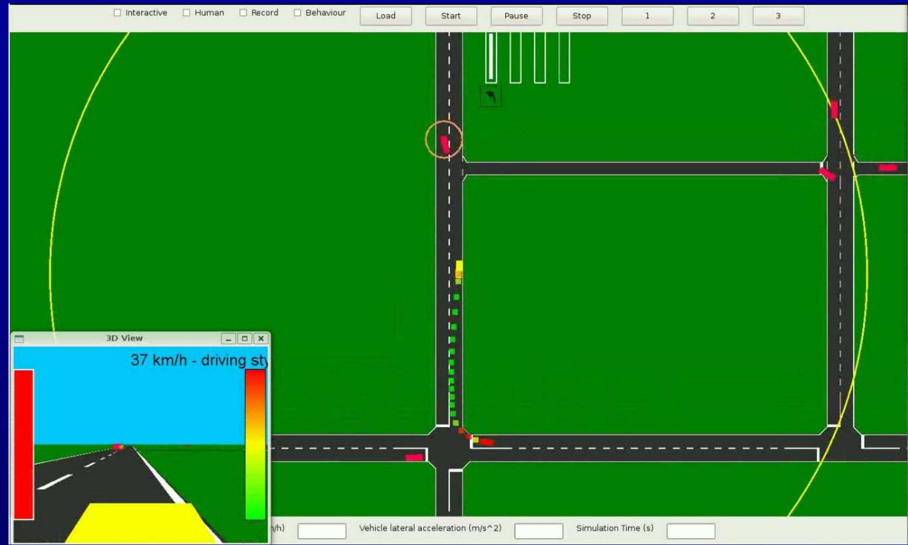


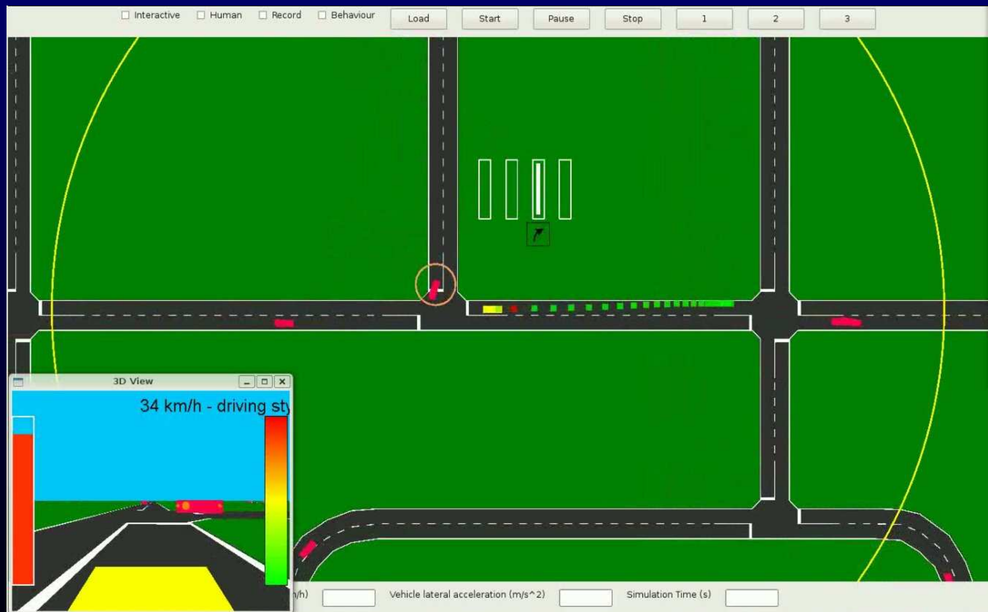


Simulation Results - Intersection

No unnecessary risk panics in intersection







Main Robotics issues for Open & Dynamic & Uncertain environments

1. **Robust detection & tracking**
2. **Prediction & Risk assessment**
3. **Safe goal-oriented navigation**
4. **Human-Robot interaction**

Safe Goal-Oriented Navigation Decision in the Real World

New constraints:

- ✓ *Upper-bounded decision time*
- ✓ *System's dynamics*
- ✓ *Moving Objects' future behavior*
- ✓ *Look-ahead*
- ✓ *Uncertainty*

Positioning:

- ✓ *Few contributions in the literature*
- ✓ *Taking into account all the constraints coming from the Real World*
- ✓ *A new framework based on Iterative safe motion decisions*
- ✓ *Focus on motion Safety*

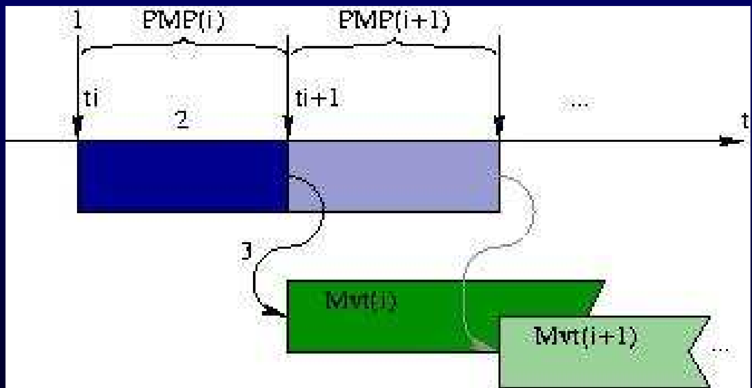
A new framework for Motion Planning in Open & Dynamic environments (1)

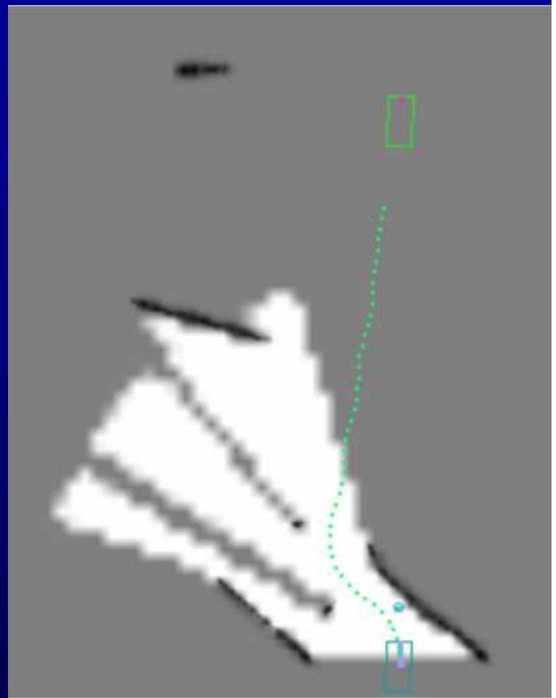
[Fraichard 04] [Petti 06]

• Partial Motion Planning *(PMP)*

Repeat until goal is reached

1. Get model of the future *(Observation & Prediction)*
2. Built tree of partial motions towards the goal
3. When time δ_c is over, Return *" best partial motion " (e.g. closest & safest)*



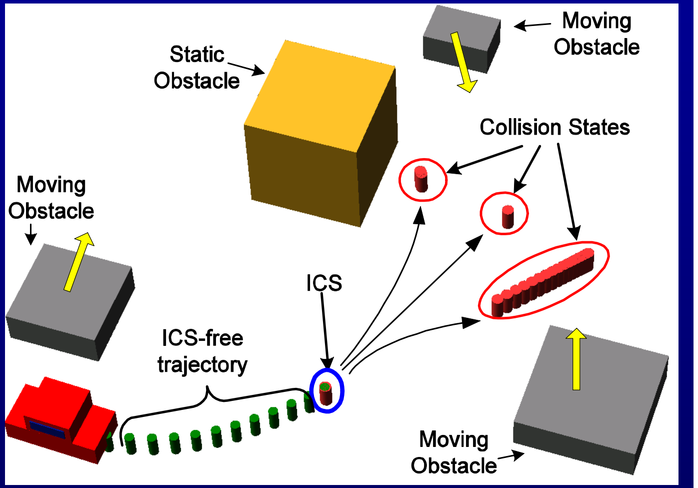


A new framework for Motion Planning in Open & Dynamic environments (2)

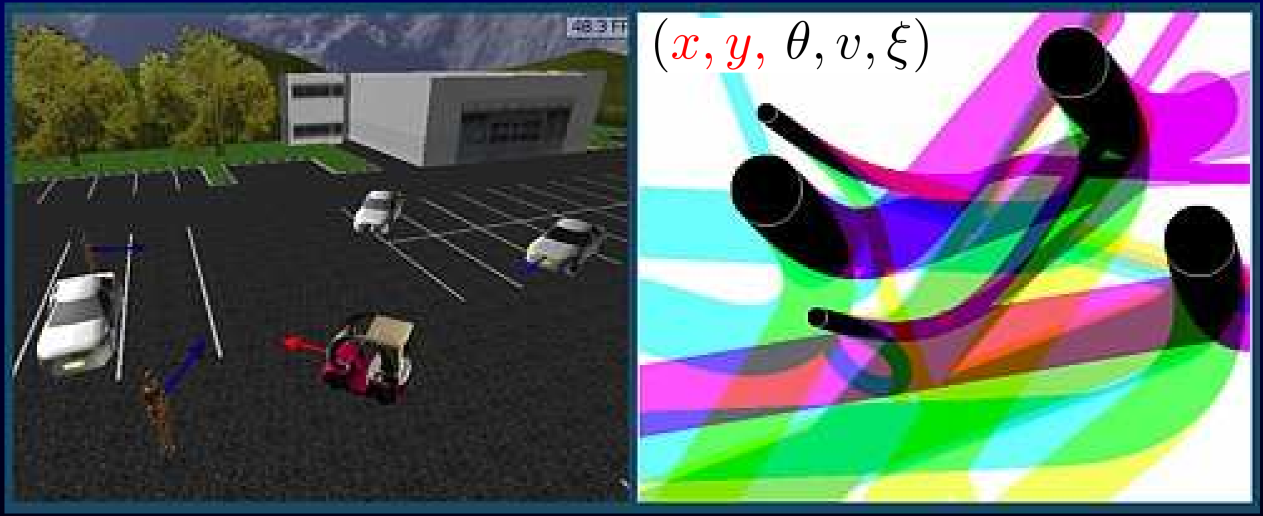
[Fraichard 04] [Martinez 08]

- **Inevitable Collision States** *(ICS)*

  ⇒ Avoiding instantaneous collision is not enough !
  We also have to avoid states leading to "Inevitable Collisions" in the near future
  ⇒ Doing nothing may also be dangerous !



PMP + ICS



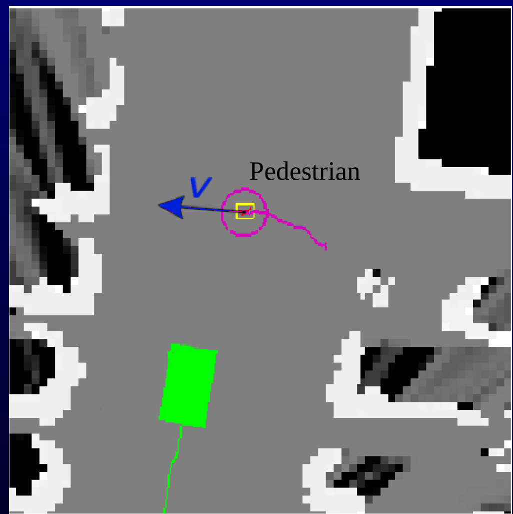
ICS-Check *[Martinez 08]*
ICS-Avoid *[Martinez 09]*
Prob-ICS *[Bautin 09]*

A new framework for Motion Planning in Open & Dynamic environments (3)

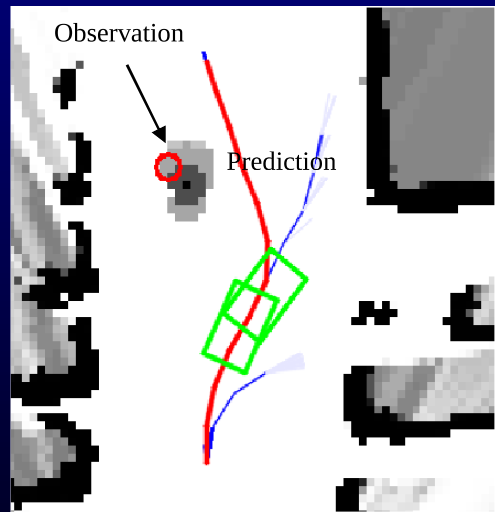
[Fulgenzi & Laugier 07-09]

- **MP using *Probabilistic Collision Risk*** *(PCR-RRT)*
  - ✓ *Integrate Obstacle Detection & Tracking*
  - ✓ *Risk assessment based on Behavior Prediction (HMM & GP)*
  - ✓ *Search function combining RRT and PMP (Previously explored states are updated on-line using new Observations & Predictions)*

Real scene Processing & Recording
(Detection & Tracking)



Reconstructed scene
(Simulator)

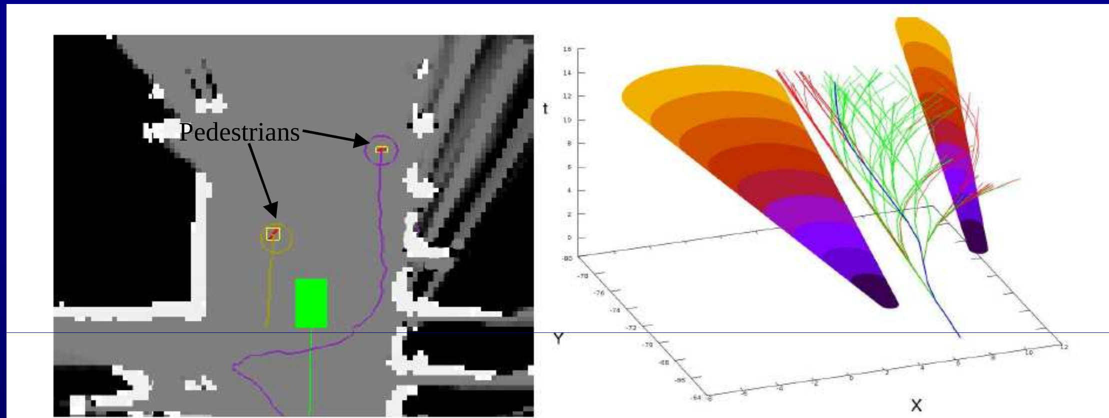


MP & Navigation
(Simulator)

A new framework for Motion Planning in Open & Dynamic environments (4)

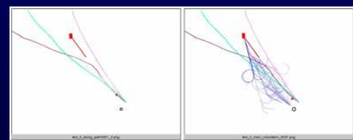
[Fulgenzi & Laugier 07-09]

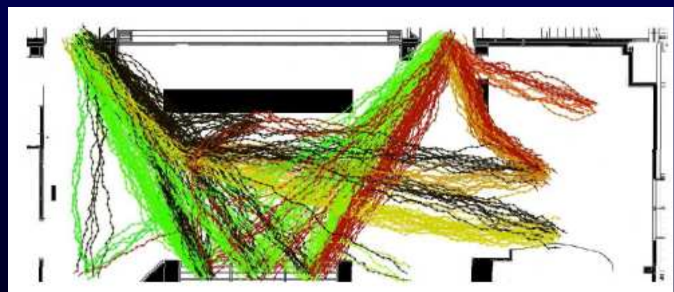
- **PCR-RRT** – *Real data & Simulation results*



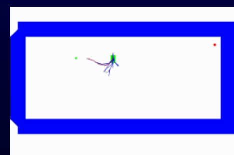
RRT using Mapping & Tracking & "Conservative" Prediction

Navigation principle





Motion Prediction using GP



Moving among peoples

Conclusion

• **Robots in Human Environments :** A new challenge for Robotics, which as recently started to be addressed by the Robotics community

• **Dynamics, Uncertainty, Scalability, Efficiency** are at the heart of the required Models & Algorithms

• Even if impressive live experiments in quite realistic human environments have successfully been achieved in the past few years, **Robustness & Safety** *are major issues to be more deeply addressed in the future*

• **Uncertainty** has to be placed at the heart of the Decisional process. ***Probabilistic models*** should probably seen as key tools.

• **Prediction & Risk Assessment** has to be introduced at several levels of the Decisional process (for achieving ***Consistent & Safe motions***)

Thank You !
Any questions ?

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