

# Embedded Bayesian Perception & Risk Assessment for ADAS & Autonomous Cars

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## *Keynote*

*Workshop PPNIV-7, IEEE/RSJ IROS 2015, September 28<sup>th</sup> 2015, Hamburg*

# *Content of the talk*

- Socio-economic context & Addressed problem
- Bayesian Perception (*Key Technology 1*)
- Bayesian Risk Assessment & Decision-making (*Key Technology 2*)
- Conclusion & Perspectives

# *Automobile plays a big role in our human society*

## *A Social & Industrial revolution in the 20<sup>th</sup> century*

### *The car ?*

**A technological machine designed for enhancing individual Mobility ?**



**For most of cars owners it's more than that !**

- ✓ **Synonymous to motion freedom**
- ✓ **Often considered as a Precious Personal Goods & showing a particular Social position**
- ✓ **Often synonymous to Driving Pleasure (including speed feeling)... but this is progressively changing because of rules enforcements**
- ✓ **Look / Performances & Comfort / Safety are more and more considered as important criteria ....**

# *But the reality is somewhat different !*

*in particular in cities*



# ***Intelligent Mobility & Next Cars Generation***

## ***A drastic change of the Societal & Economic context***

- ❑ Huge expected growth of the number of **Vehicles** (*~3 billions in 2050*) & of **People in cities** (*~75% of population in 2050*)
- ❑ Human Society is **no more accepting** all the **nuisances** & the incredible socio-economic cost of traffic **accidents** => *50 millions injuries & 1.3 million fatalities/Year in the world [1]*  
*... 93% of road accidents are caused by human errors !*
- ❑ **Driving Safety & Efficiency** are now becoming **major issues** for both **governments** (*regulations & supporting plans*) and the **automotive industry** (*technology & commercial issues*)
- ❑ **Growth of ADAS market:** *\$16 billions at the end of 2012 ... \$261 billions by 2020 [2]*
- ❑ **New Technologies can strongly help for** (*e.g. for ADAS & Autonomous Driving*)
  - ✓ *Constructing Cleaner & more Intelligent cars => Next cars generation*
  - ✓ *Developing Sustainable Mobility solutions for smart cities => Cybercars*

[1] G.Yeomans. Autonomous Vehicles, Handling Over Control: Opportunities and Risks for Insurance. Lloyd's 2014

[2] ABI Research on Intelligent Transportation Systems and Automotive Technologies Research Services

# The good news

- Thanks to the last decades advances in the fields of *ICT & Robotics, Smart Cars & ITS* are **gradually becoming a reality**
  - => *Driving assistance & Autonomous driving, Passive & Active Safety systems, V2X communications, Green technologies for reducing fuel consumption & pollution ... and also significant advances in Embedded Perception & Decision-making systems*
  
- **Legal issue** is also progressively addressed by governmental authorities
  - => *June 22, 2011: Law Authorizing Driverless Cars on Nevada roads ... and this law has also been adopted later on by California and some other states in USA*
  
  - => *Several other countries (including Europe, France, Japan ...) are also currently analyzing the way to adapt the legislation to this new generation of cars*

# Automotive industry

## Expected evolution from ADAS to Driverless Cars?

Horizon 2020-30 ?

Nissan promises a driverless car for 2020

LE FIGARO

Date : 29/08/2013



Autonomous car: An industrial challenge for tomorrow !  
French Minister of Industry & Carlos Ghosn (CEO Renault-Nissan)



Google Car 2011  
=> 140 000 miles covered



Toyota  
Automated Highway Driving Assist  
=> Demo Tokyo 2013, Product 2020

But also most of the major  
Automotive Constructors !  
e.g.

Tesla (90% Autonomous in 2016)

Volvo, Mercedes Class S, BMW

....

Still some open questions: *Why driverless cars ? Intelligent co-Pilot v/s Full Autonomy ? Acceptability ? Legal issue ? Driver / Co-Pilot Control transitions ?*

# Today talk: Addressed Problem & Challenges

## Safe & Socially Compliant Vehicle Navigation in Open & Dynamic Human Environments

### *Focus on Perception & Risk Assessment & Decision-making*

Place Charles de Gaulle (Paris), every day



**Situation Awareness & Decision-making  
in complex situations**



Road Safety campaign, France 2014



**Anticipation & Prediction**

### Main features

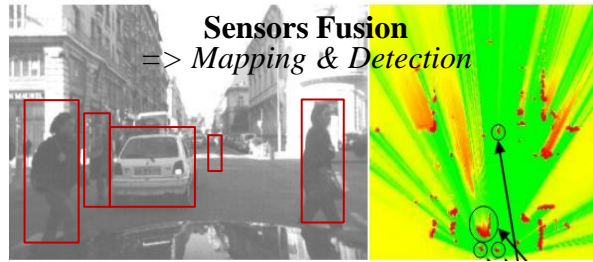
- ✓ Dynamic & Open Environments
- ✓ Incompleteness & Uncertainty (*Model & Perception*)
- ✓ Human in the loop (*Social & Interaction Constraints*)



# Key Technology 1: Bayesian Perception



**Embedded Perception**  
=> *Continuous monitoring the dynamic environment*



## ❑ Main difficulties

*Noisy data, Incompleteness, Dynamicity, Discrete measurements + Real time !*

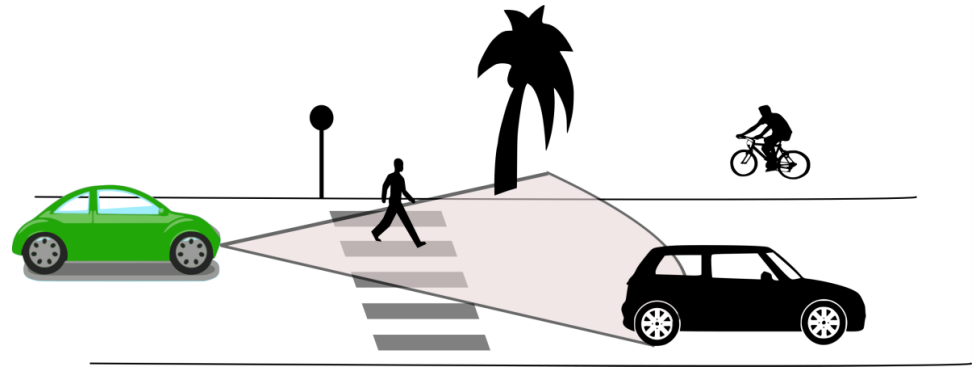
## ❑ Approach: Bayesian Perception

- *Reasoning about Uncertainty & Time window (Past & Future events)*
- *Improving robustness using Bayesian Sensors Fusion*
- *Interpreting the dynamic scene using Semantic & Contextual information*

# Bayesian Perception : Basic idea

## Sensors Observations




*Lidar, Stereo camera, IMU ...*

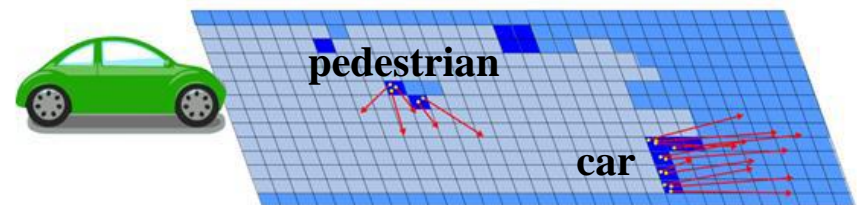


Bayesian  
Perception

## Environment Model

- *Sensor Fusion*
- *Occupancy grid integrating uncertainty*
- *Velocities representations*
- *Prediction models*

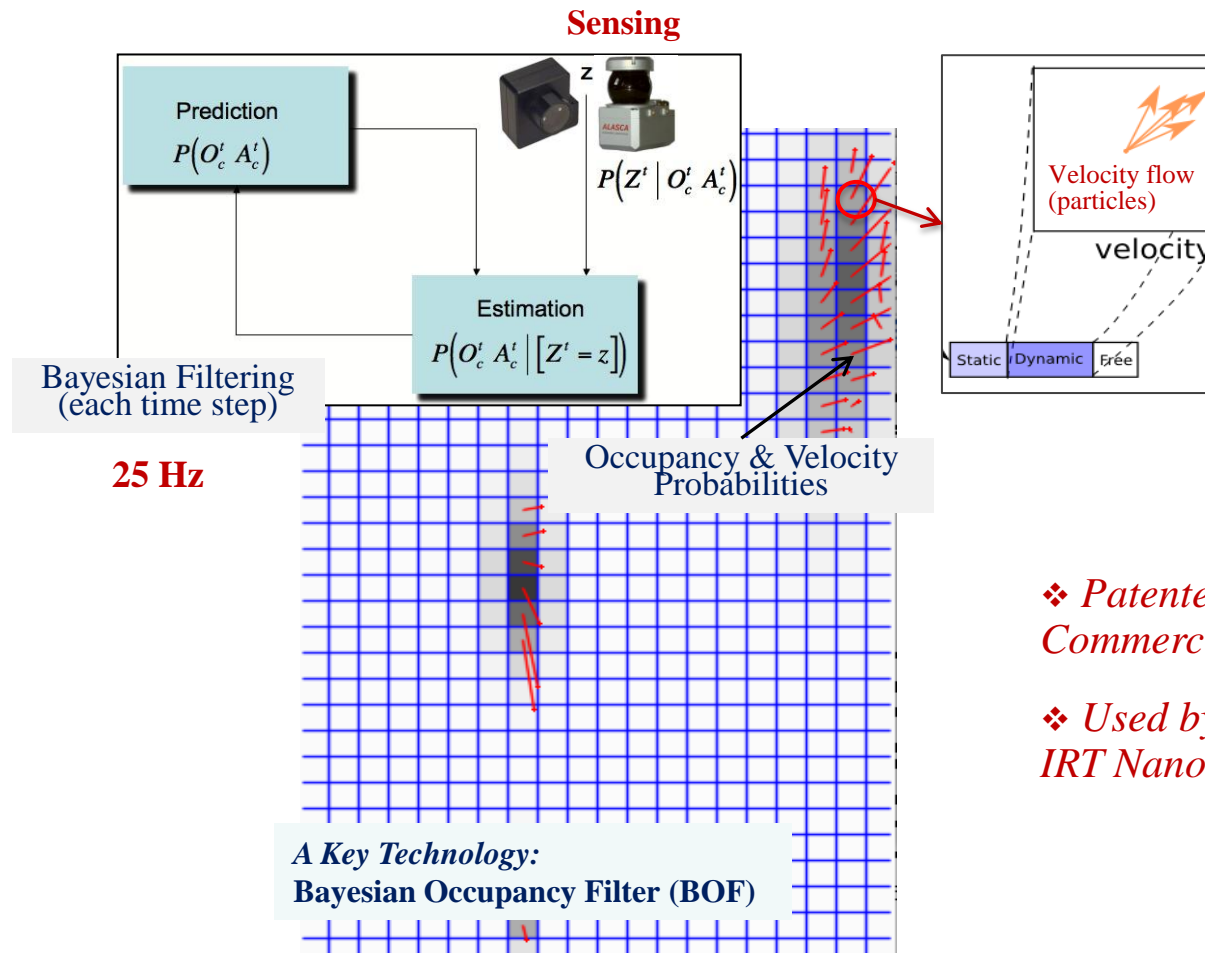
$P[o|Z,C]$  :      $\approx 0$       $\approx 0.5$       $\approx 1$



Occupancy probability + Velocity probability  
+ Motion prediction model

# A new framework: *Dynamic Probabilistic Grid*

## *A clear distinction between Static & Dynamic parts*



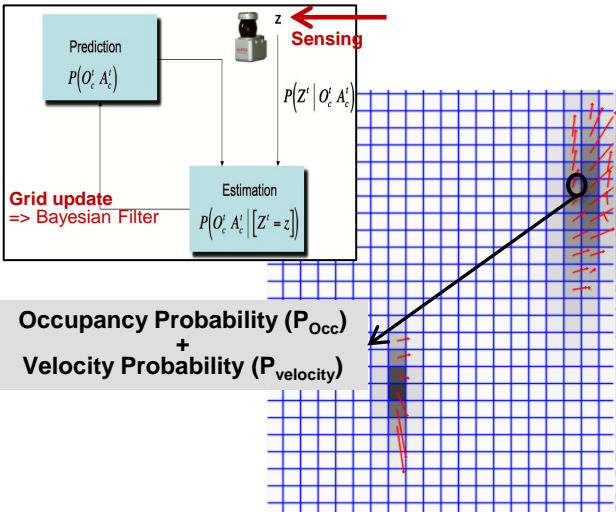
- ❖ *Patented by Inria & Probayes, Commercialized by Probayes*
- ❖ *Used by: Toyota, Denso, Probayes, IRT Nanoelec / CEA*

- ❖ Processing Dynamic Environments using **DP-Grids** (*Occupation & Velocity Probabilities*)
- ❖ Bayesian Inference + Probabilistic Sensor & Dynamic Models (*Robust to sensing errors & occultation*)
- ❖ **Highly parallel processing** (*Hardware implementation : GPU, Many-core architecture, SoC*)

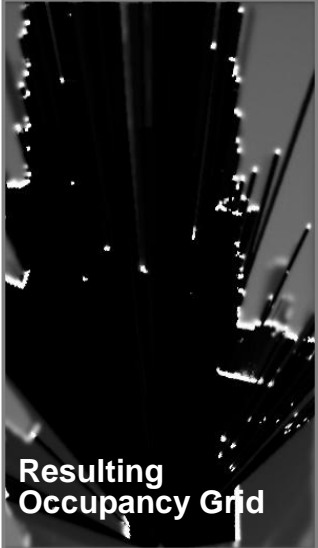
# Bayesian Occupancy Filter (BOF): *Outline*

## Main features:

- Estimate **Spatial occupancy**
- Analyze **Motion Field** (*using Bayesian filtering*)
- **Reason at the Grid level** (*i.e. no object segmentation at this level*)

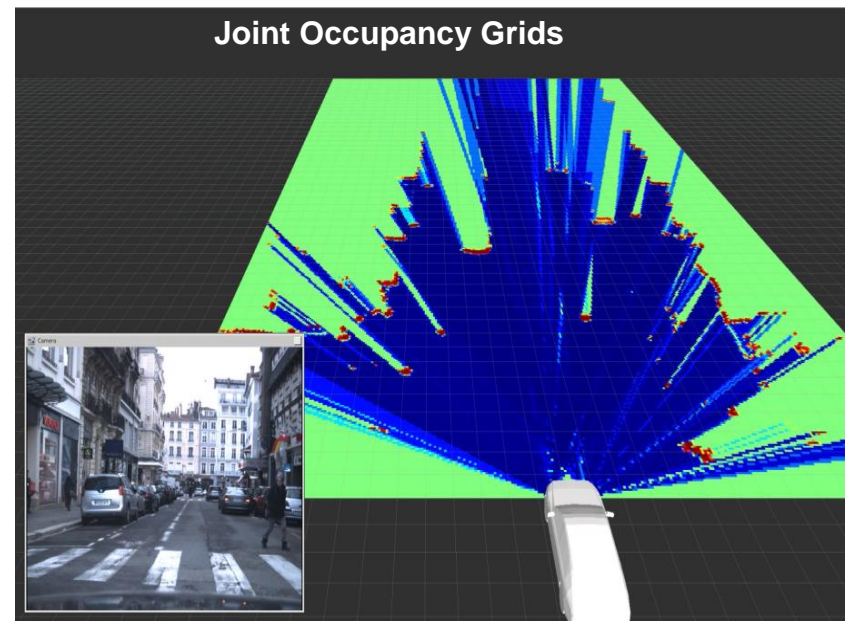
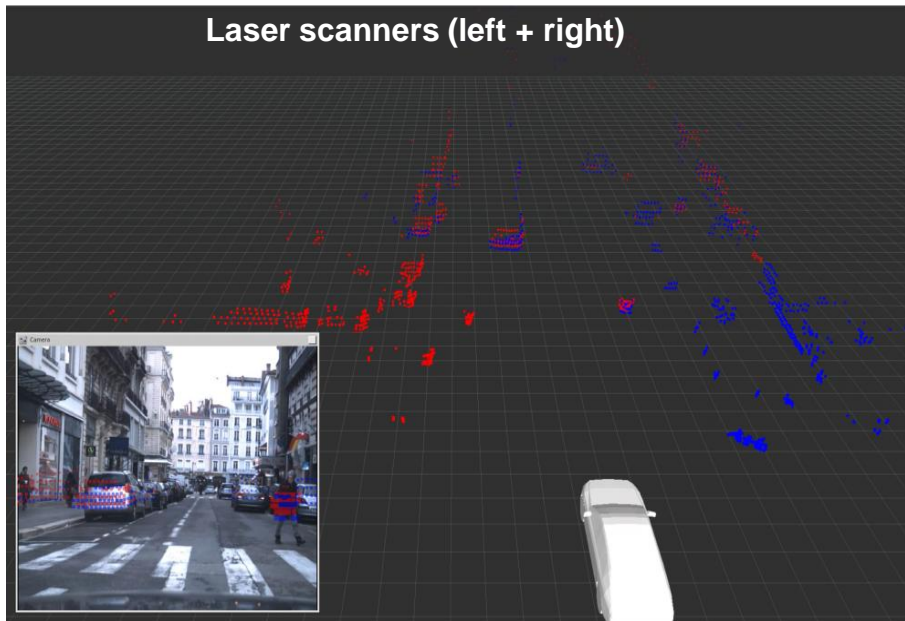


Sensors data fusion + Bayesian Filtering



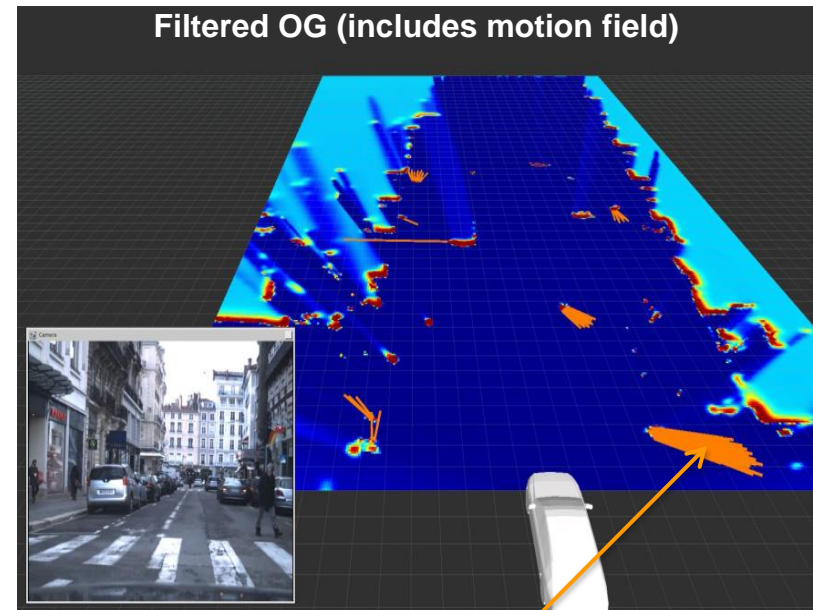
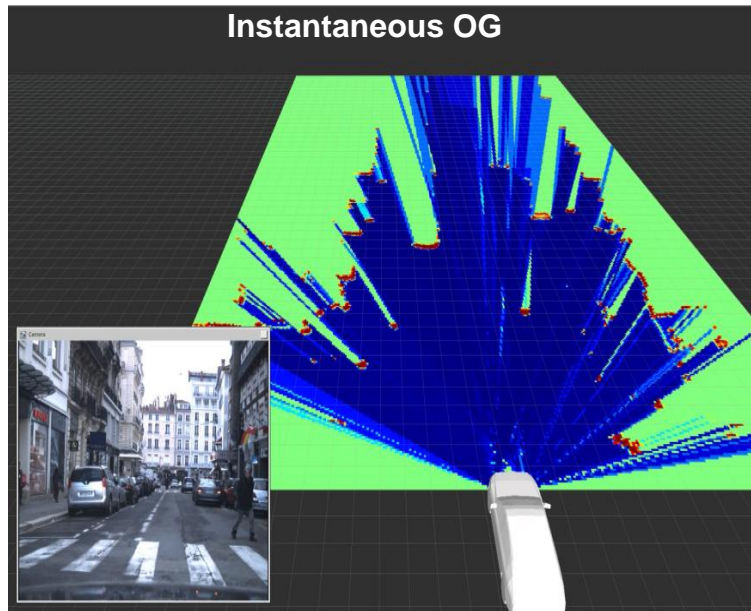
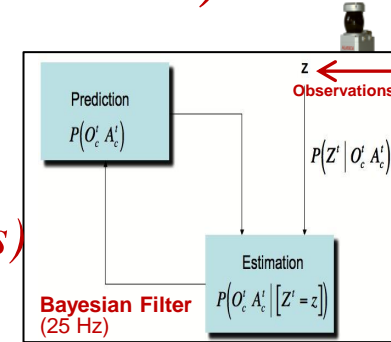
# Data fusion: *The joint Occupancy Grid*

- Observations  $Z_i$  are given by each sensor  $i$  (*Lidars, cameras, etc*)
- For each set of observation  $Z_i$ , Occupancy Grids are computed:  $P(O | Z_i)$
- Individual grids are merged into a single one:  $P(O | Z)$



# Taking into account dynamicity: *Filtered Occupancy Grid (Bayesian filtering)*

- Filtering is achieved through the *prediction/correction loop (Bayesian Filter)*.  
*It allows to take into account grid changes over time*
- Observations are used to update the environment model
- Update is performed in each cell in parallel (*using BOF equations*)
- **Motion field** is constructed from the resulting filtered data



**Motion field is represented in orange color**

# Bayesian Occupancy Filter – Formalism

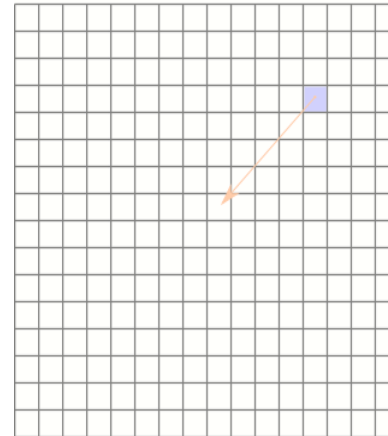
## Variables:

- $C$  : current cell
- $A$  : antecedent cell, i.e. the cell from which the occupancy of the current cell comes from
- $O$  : occupancy of the current cell  $C$
- $O^{-1}$  : previous occupancy in the antecedent cell
- $V$  : current velocity
- $V^{-1}$  : previous velocity in the antecedent
- $Z$  : observations (sensor data)

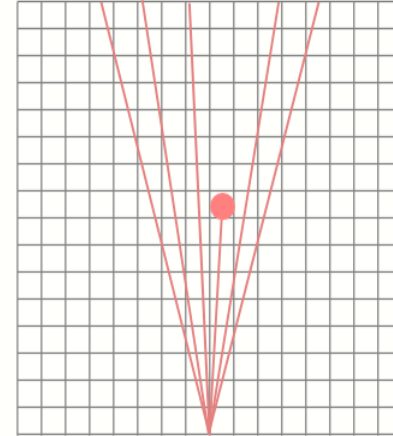
## Objective:

**Evaluate  $P(O \ V \ | \ Z \ C)$  : Probability of Occupancy & Velocity for each cell  $C$ , Knowing the **observations  $Z$**  and the cell **location  $C$**  in the grid**

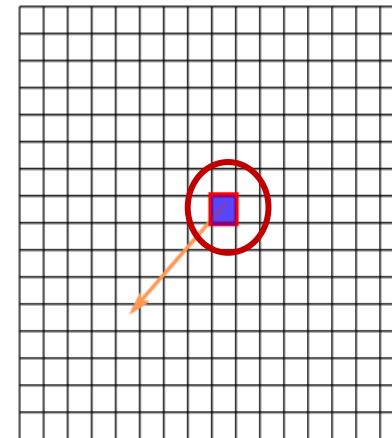
Previous Model (t-1)



Observations (t)



Current Model (t)



# Bayesian Occupancy Filter

*How to theoretically compute  $P(O V | Z C)$  ?*

$$P(O V | Z C) = \lambda \sum_{A O^{-1} V^{-1}} P(C A O O^{-1} V V^{-1} Z)$$

Sum over the possible antecedents  $A$  and their states  $(O^{-1} V^{-1})$

The joint probability term can be re-written as follows:

$$P(C A O O^{-1} V V^{-1} Z) = P(A) P(O^{-1} V^{-1} | A) P(O V | O^{-1} V^{-1}) P(C | A V) P(Z | O C)$$

**Joint probability**  $\Rightarrow$  used for the update of  $P(O V | Z C)$

**$P(A)$**  : Selected as **uniform** (every cell can a priori be an antecedent)

**$P(O^{-1} V^{-1} | A)$**  : Result from the previous iteration

**$P(O V | O^{-1} V^{-1})$**  : Dynamic model

**$P(C | A V)$**  : **Indicator function** of the cell **C** corresponding to the “**projection**” in the grid of the antecedent **A** at a given velocity **V**

**$P(Z | O C)$**  : Sensor model

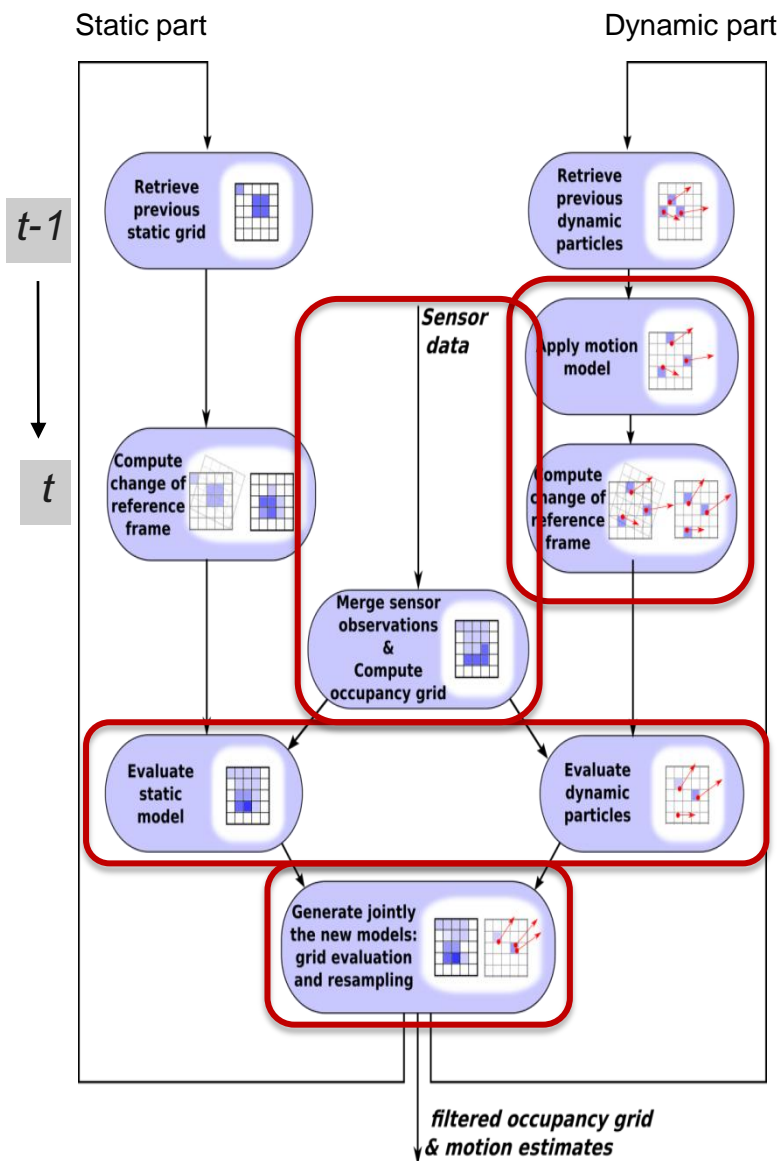


# Bayesian Occupancy Filter

How to compute  $P(O \ V \ | \ Z \ C)$  in practice (HSBOF process)

## Main steps in the updating process

- Dynamic part (particles) is “projected” in the grid using motion model (*motion prediction*)
- Both Dynamic & Static parts are expressed in the new reference frame (*moving vehicle frame*)
- The two resulting representations are confronted to the observations (*estimation step*)
- New representations (static & dynamic) are jointly evaluated and particles re-sampled



# *Underlying Conservative Prediction Capability*

*=> Application to Conservative Collision Anticipation*

Autonomous  
Vehicle (Cycab)



Parked Vehicle  
(occultation)

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

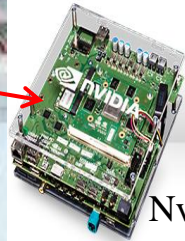
# Implementation & Experimentation



**Toyota Lexus**



**Manycore  
SThorm**

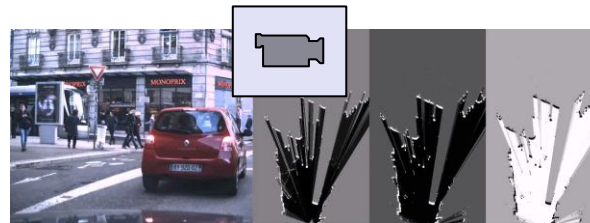


**GPU  
Nvidia Jetson**

**Miniaturization**



**Renault Zoé**



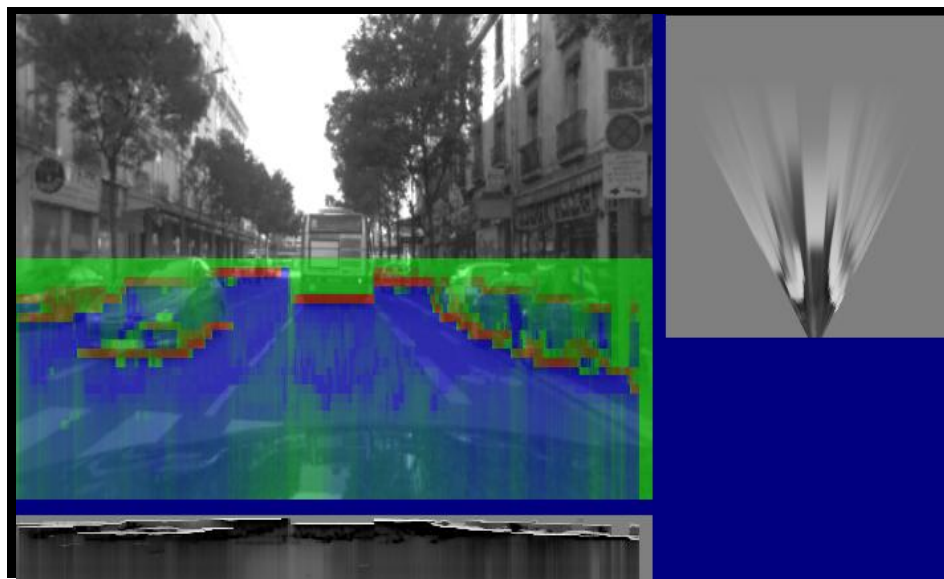
**HSBOF & 2 Lidars**

# Bayesian Sensor Fusion (Inria / Toyota Lexus)

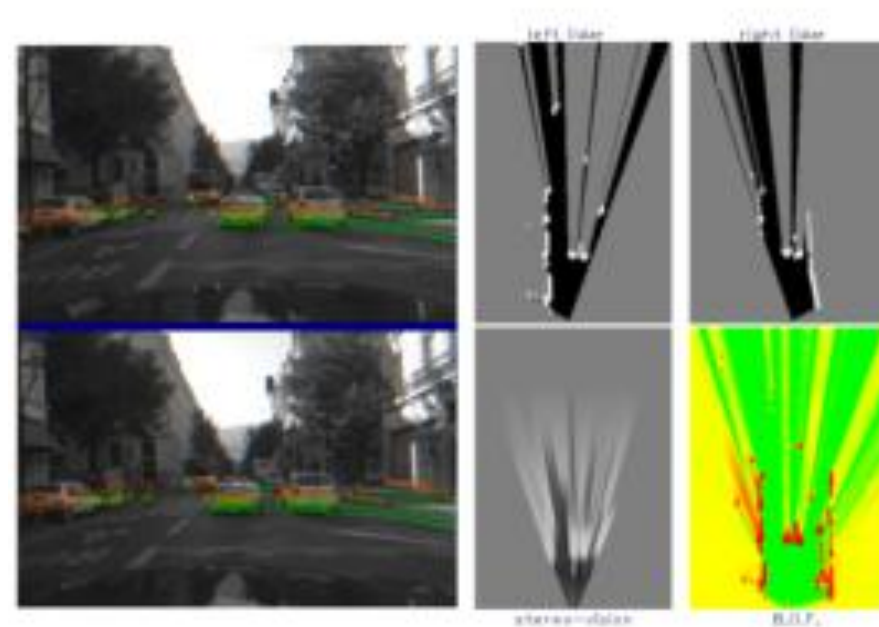
CPU+GPU+ROS / Stereo + 2 Lidars + GPS + IMU



[Perrollaz et al 10] [Laugier et al ITSM 11]  
IROS Harashima Award 2012



*Stereo Vision*



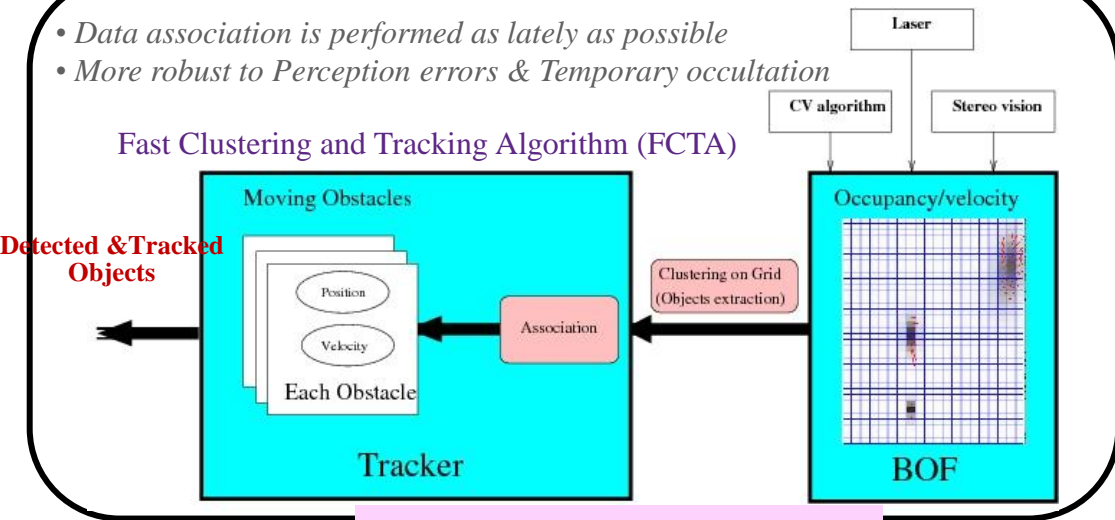
*Bayesian Sensor Fusion*

# Grid & Object level processing architecture

## Bayesian Sensor Fusion + Detection & Tracking

- Data association is performed as lately as possible
- More robust to Perception errors & Temporary occultation

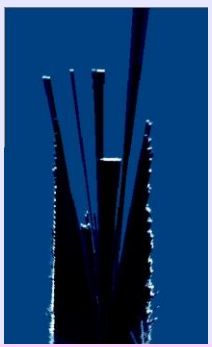
### Fast Clustering and Tracking Algorithm (FCTA)



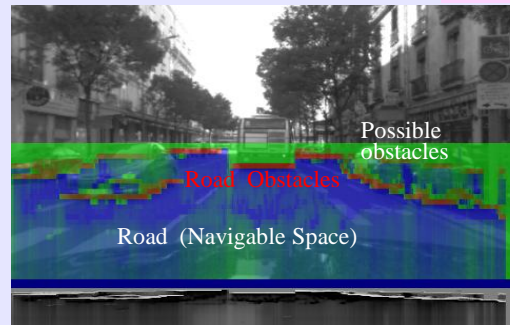
[Mekhnacha 09, Laugier et al ITSM'11]



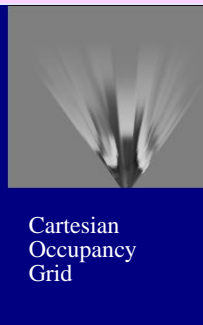
Laser Fusion (8 layers, 2 lasers)



[Perrollaz et al 10-12]



Stereo-vision (U-disparity OG+ Road/obstacle classif.)



Cartesian Occupancy Grid

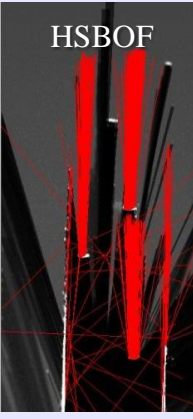
[Qadeer et al 12, Negre et al 14]



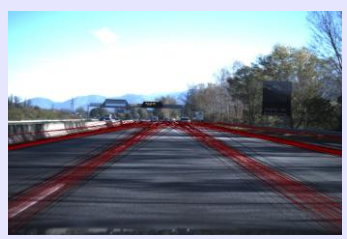
Reducing false detections

### Motion Detection

=> Dynamic grid filtering using Motion data (IMU + Odometry)



HSBOF



Multi-Lane tracker

### Intensity Features



Depth Features

### Objects classification



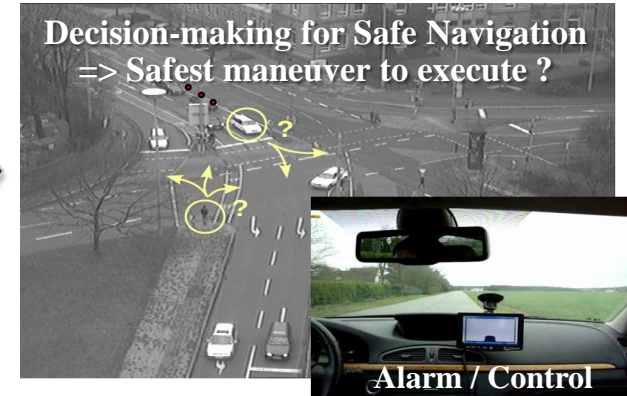
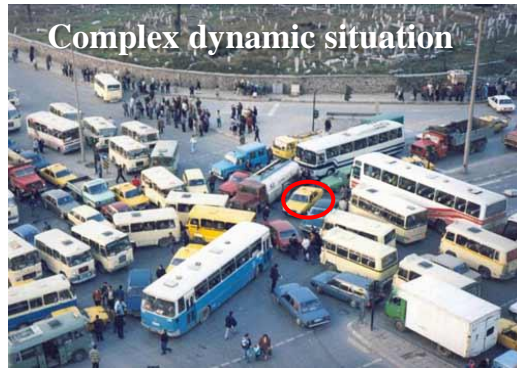
Codebook Matching

Detections

[Makris et al 12]

# Key Technology 2: Risk Assessment & Decision

=> Decision-making for avoiding Pending & Future Collisions



## □ Main difficulties

*Uncertainty, Partial Knowledge, World changes, Human in the loop + Real time*

## □ Approach: Prediction + Risk Assessment + Bayesian Decision

- Reasoning about *Uncertainty & Contextual Knowledge (History & Prediction)*
- *Avoiding Pending & Future collisions (Probabilistic Collision Risk at  $t+\delta$ )*
- *Decision-making by taking into account the Predicted behavior of the observed mobile agents (cars, cycles, pedestrians ...) & the Social / Traffic rules*

# Short-term collision risk (*Grid level, Conservative*)

## Objective:

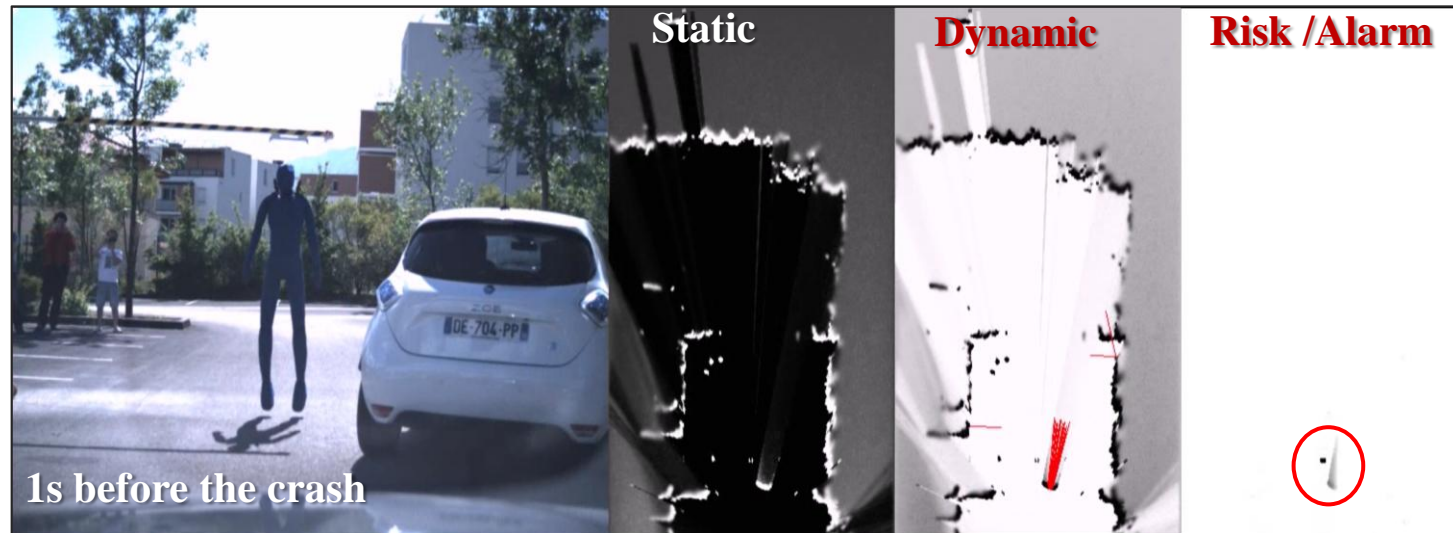
- Detect “Risky Situations” a few seconds ahead ( $0.5 - 3 s$ )
- Risky situations are localized in Space & Time
- Conservative motion prediction in the grid (Particles & Occupancy)
- Collision checking with Car model (shape & velocity) for every future time steps (*horizon  $t + \delta$* )

$\delta = 0.5 s \Rightarrow$  Precrash

$\delta = 1 s \Rightarrow$  Collision mitigation

$\delta = 1.5 s \Rightarrow$  Warning / Braking

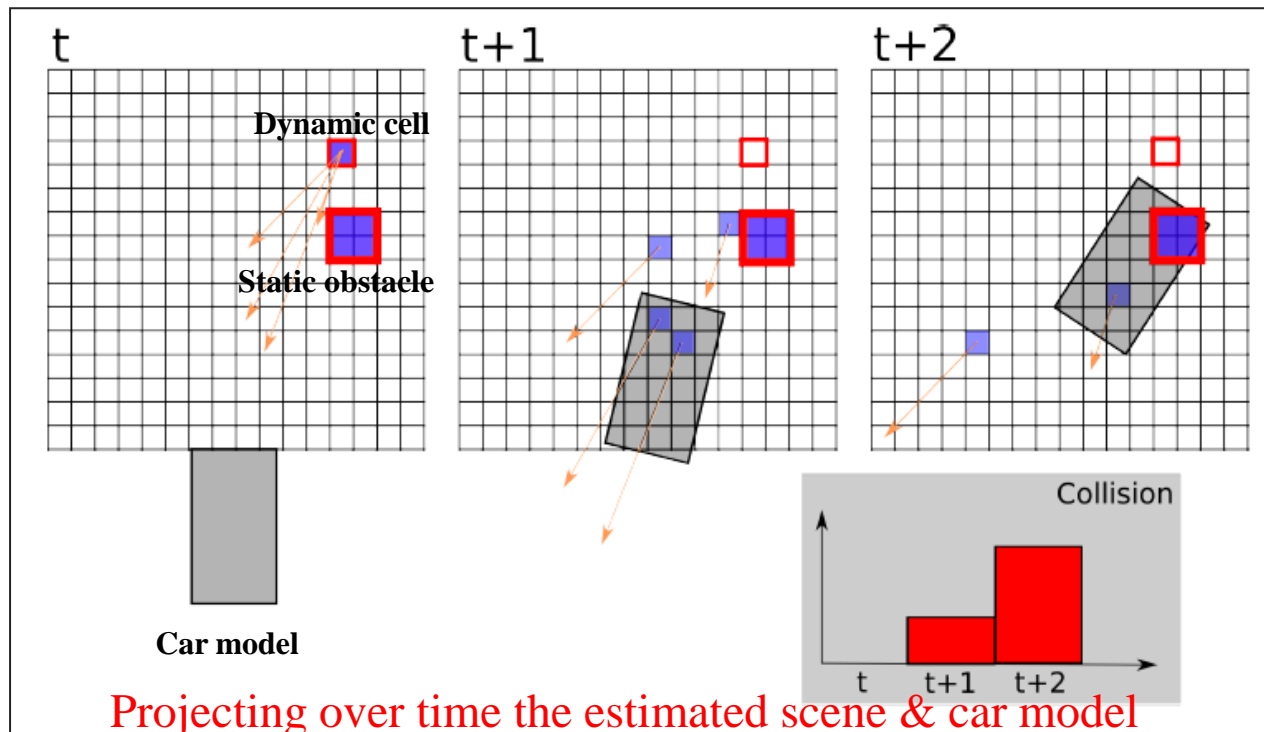
## System outputs:



# Short-term collision risk (*Grid level, Conservative*)

## Approach (*using conservative prediction*)

- ✓ Projecting over time the Estimated scene (*Particles & Occupancy*) & Car model (*Shape & Velocity*) => *Apply a conservative motion model (using current car motion data)*
- ✓ Collision assessment for every next time step
- ✓ **Integration of Risk** over a time range  $[t \ t+\delta]$





# Short-term collision risk – *Experimental results*



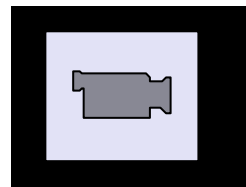
## Urban street experiments

*=> Almost no false alarm (car, pedestrians...)*



## Crash scenario on test tracks

*=> Almost all collisions predicted before the crash (0.5 – 2 s before)*



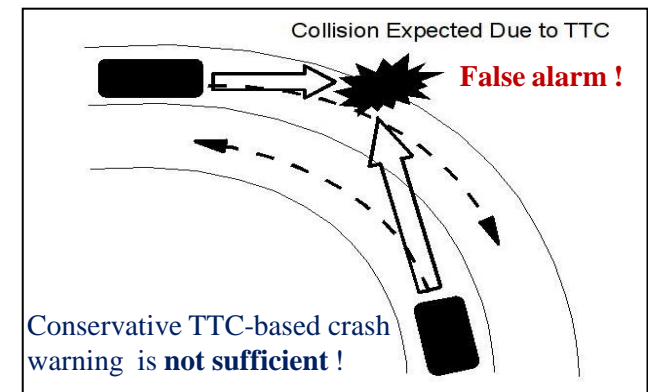
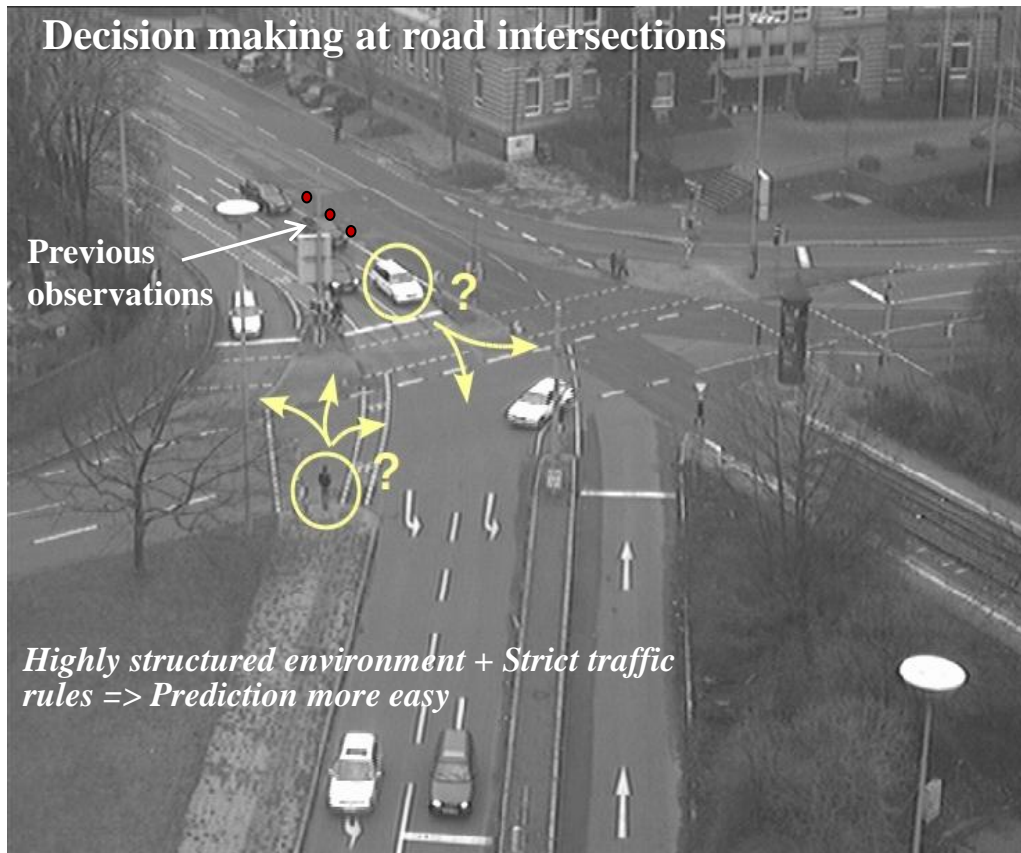
video

# Generalized Risk Assessment (Object level)

=> Increasing time horizon & complexity using semantics

- ⇒ Understand the **Current Situation** & its likely **Evolution**
- ⇒ Evaluate the **Risk** of future Collision for **Safe Navigation Decision**
- ⇒ Highly structured environment & Traffic rules make prediction more easy

## Decision making at road intersections



## Context & Semantics

(History & Space geometry & Traffic rules)

+

## Behavior Prediction

(For all surrounding traffic participants)

+

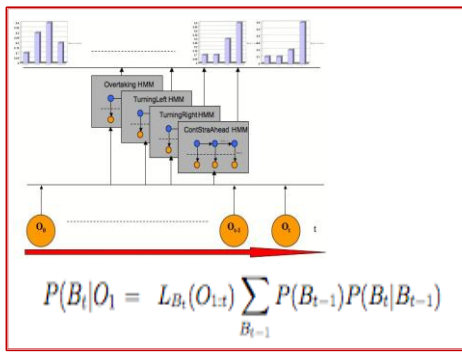
## Probabilistic Risk Assessment

# Behavior-based Collision risk (*Object level*)

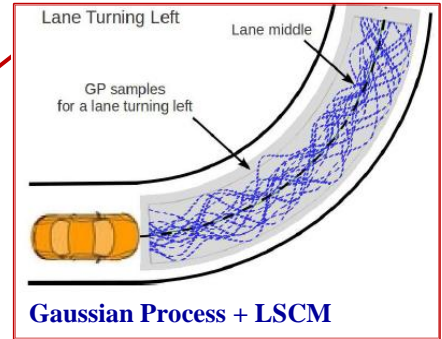
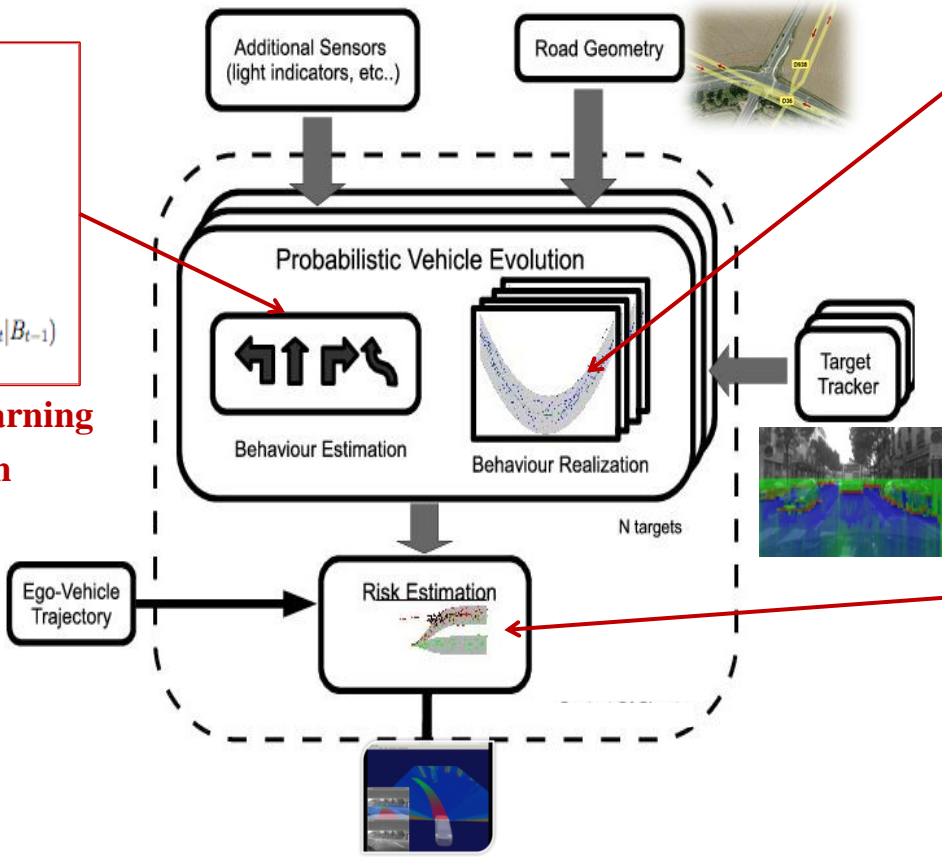
## Trajectory prediction & Collision Risk Assessment

[Tay thesis 09] [Laugier et al 11]

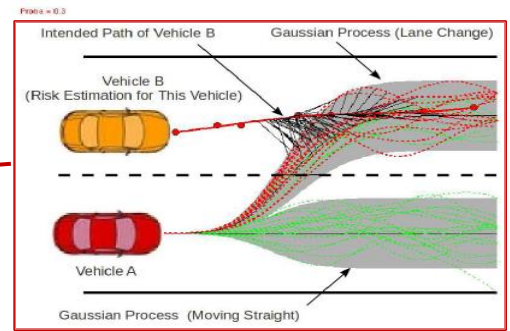
Patent Inria & Toyota & Probayes 2010



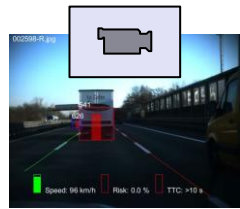
**Behavior modeling & learning**  
+  
**Behavior Prediction**



**From behaviors to trajectories**



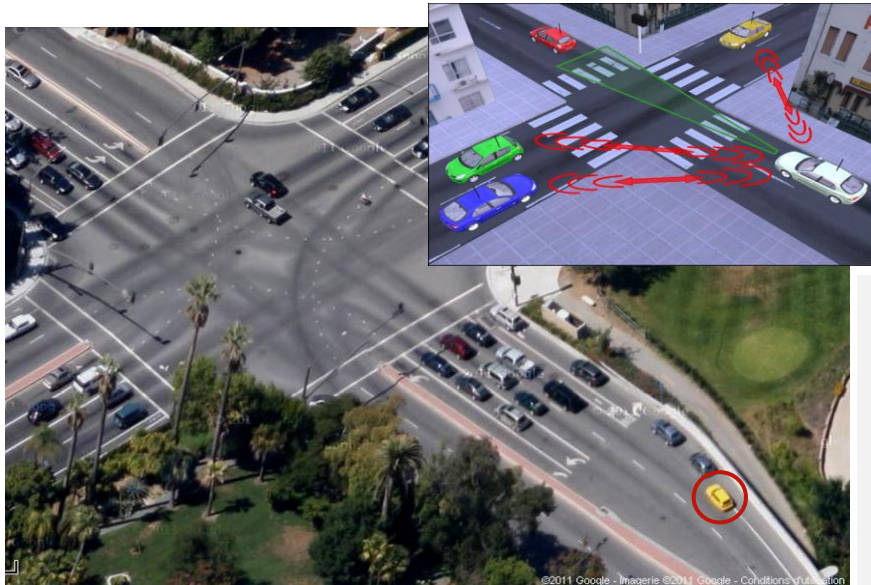
*Behavior prediction & Risk*  
*Probayes & Inria & Toyota*



**Video**

# Behavior-based Collision risk (*Object level*)

## *Intention & Expectation approach*



### Intersection:

- ✓ *Complex Geometry & Traffic context*
- ✓ *Large number of Vehicles & Possible Maneuvers*
- ✓ *Vehicle behaviors are **Interdependent***
- ✓ ***Human Drivers are in the loop !***

## Human in the loop & Interdependent behaviors

- ⇒ Detect drivers errors & Colliding behaviors
- ⇒ **Risk** = Comparing maneuvers Intention & Expectations (using DBN)

# Behavior-based Collision risk (*Object level*)

## Intention & Expectation approach

Patent Inria & Renault 2012 (intersections) + Patent Inria & Berkeley 2013 (generalization)

[Lefevre thesis 13] [Lefevre & Laugier IV'12, Best student paper]

**A Human-like reasoning paradigm** => *detect Drivers Errors & Colliding behaviors*

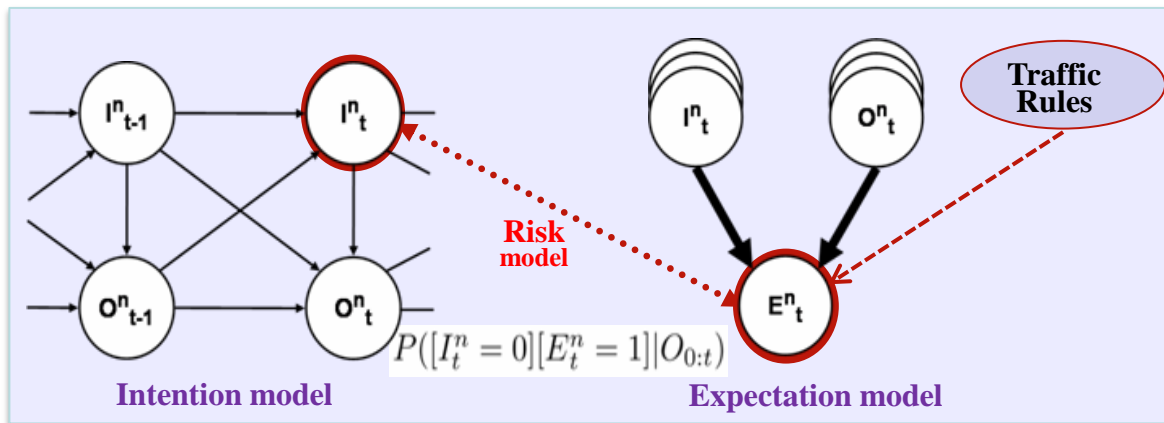
✓ *Estimating “Drivers Intentions” from Vehicles States Observations ( $X Y \theta S TS$ )*  
=> *Perception or V2V communication*

✓ *Inferring “Behaviors Expectations” from Drivers Intentions & Traffic rules*

✓ *Risk = Comparing Maneuvers Intention & Expectation using a “Dynamic Bayesian Network”*  $P([I_t^n = 0][E_t^n = 1]|O_{0:t})$

=> *Taking traffic context into account (Topology, Geometry, Priority rules, Vehicles states)*

=> *Digital map obtained using “Open Street Map”*

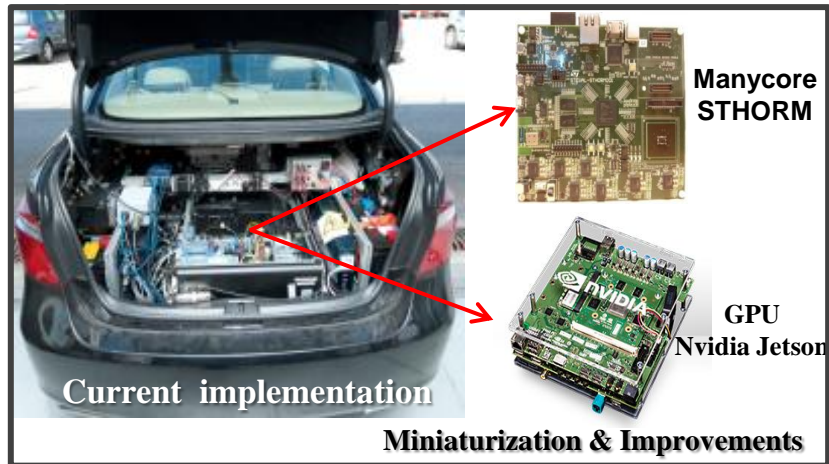


Dynamic Bayesian Network

# Current & Future work

## □ Approaches for Software & Hardware integration (*Embedded Perception*)

=> Reduce drastically Size, Weight, Energy consumption, Cost ... while improving Efficiency



CPU (2006) GPU (2010) Manycore & GPU low power (2014)



Dedicated Hardware & Software integration (2017)

SoC (2018-20)



=> *Coop. CEA LETI (common projects & PhD student)*

## □ Technologies for Autonomous Driving (*Perception + Decision + Control + Learning*)

✓ PhD on “*Driving Decisional Process*” => *Coop. Berkeley & Renault*

✓ PhD on “*Models & Algorithms for Autonomous Driving*” => *Toyota*

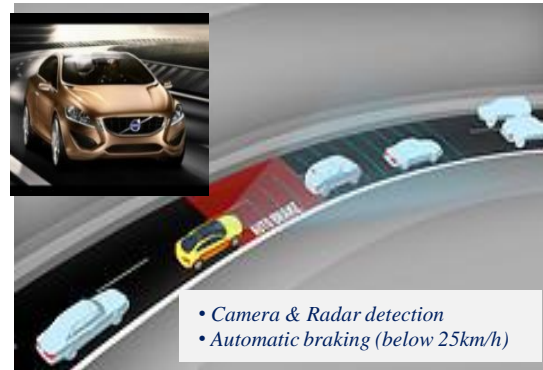


# Conclusion & Perspectives

- ❑ **Intelligent Cars (ADAS & Future Driverless Cars)** are gradually becoming a reality



Parking Assistant (2004)



Volvo Pedestrian avoidance system (2011)



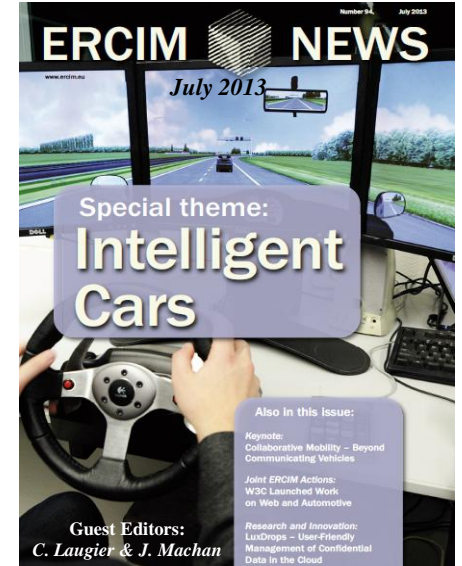
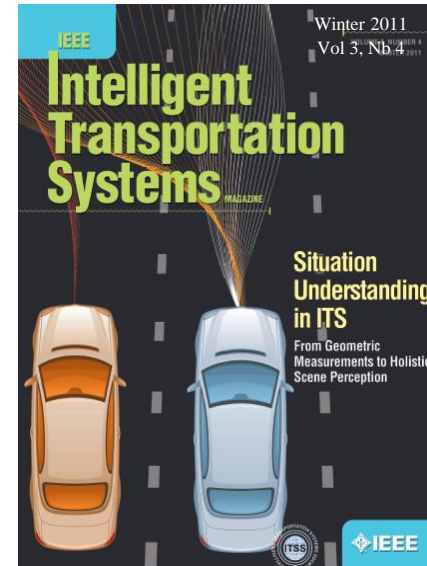
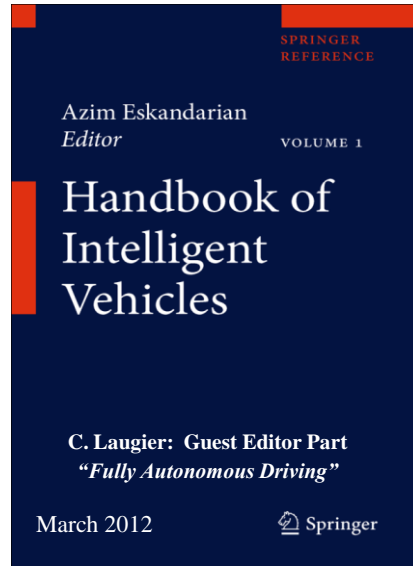
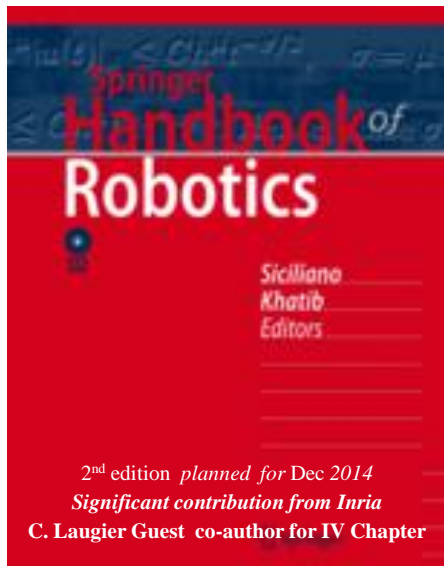
Fully Autonomous Driving (2025-30 ?)



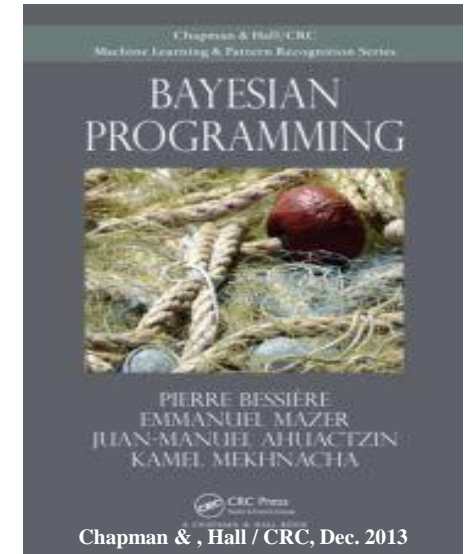
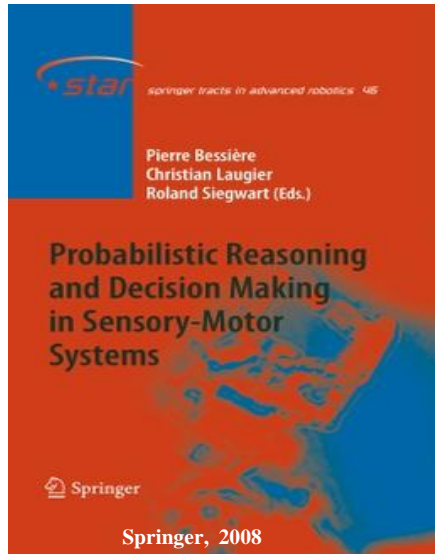
- ❑ **Bayesian Perception & Situation Awareness & Bayesian Decision** are *key Technologies for dealing with uncertainty & addressing the Challenge of Autonomous Vehicles*

- ❑ **Several implementations on commercial cars & Tests in realistic traffic situations** have successfully been performed

.... However system **Robustness & Efficiency** have still to be improved, in particular when **human is in the loop (Share control & Interaction)**



**Thank You  Any questions ?**



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