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Lecture on Bayesian Perception & Decision-making for Autonomous Vehicles and Mobile Robots

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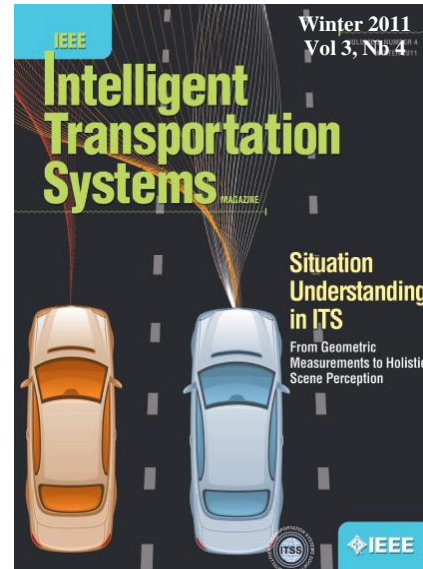
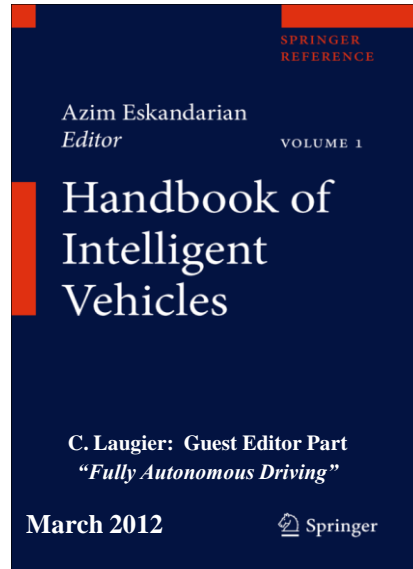
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Lecture on Bayesian Perception & Decision-making for Autonomous Vehicles and Mobile Robots

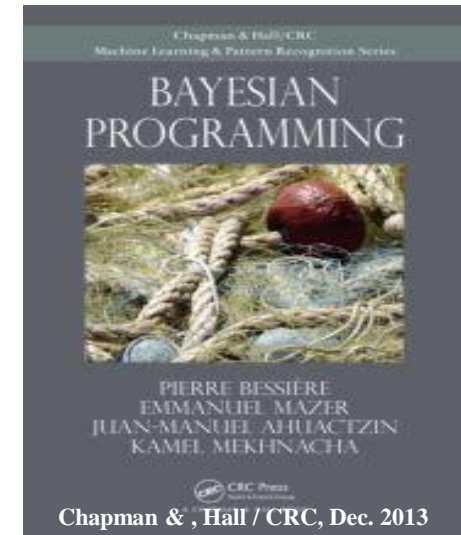
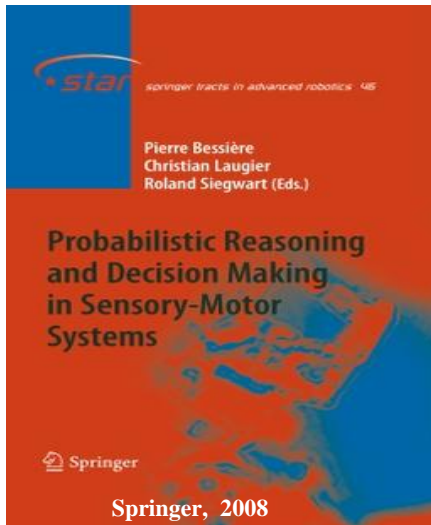
Dr. HDR Christian LAUGIER, Research Director at Inria
INRIA Grenoble Rhône-Alpes, Chroma team
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Lecture at Beijing Institute of Technology
Intelligent Vehicle Research Center, School of Mechanical Engineering
May 8th 2017



Relevant Literature on Robotics & IV & ITS



Content of the Lecture

- ❑ **Socio-economic & Technological Context**
- ❑ **Decisional & Control Architecture: Outline => Not presented !**
- ❑ Bayesian Perception (*Key Technology 1*)
- ❑ Embedded Perception & Experimental results
- ❑ Bayesian Risk Assessment & Decision-making (*Key Technology 2*)
- ❑ Conclusion & Perspectives

Cars & Human Mobility

A Psychological & Technological evolution

A quick on-going change of the role & concept of **private car** in human society !



Ownership & Feeling of Freedom
Affective behaviors & Shown Social position
Driving pleasure ... but less and less true !



Next cars generation => Focus on Technologies for
Safety & Comfort & Reduced Pollution
Driving Assistance v/s Autonomous Driving

❖ Context

- => Expected 3 Billions vehicles & 75% population in cities in 2050 (current model not scalable !!!)*
- => Accidents: ~1.2 Million fatalities/Year in the world*
- => Driving safety & Nuisance issues (pollution, noise, traffic jam, parking ...) are becoming a major issue for both Human Society & Governments & Industry*

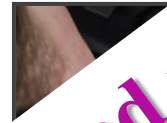
Cars & Human Mobility

A Psychological & Technological evolution

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Ownership & Feeling of Freedom
Affective behaviors & Shown Sociability
Driving pleasure ... but less efficiency



Automation => Focus on Technologies for
Safety & Comfort & Reduced Pollution
Driving Assistance v/s Autonomous Driving

❖ Technology & ... change de **mobility habits** of people
=> Share ... pooling, more ADAS & Autonomy (e.g. Tesla autopilot)
New ... Car, Robot Taxis (Uber, Nutonomy)...

❖ ... Market for Automotive Industry
... in 2012 & Expected \$261 billions in 2020 (f)

(f) Forecasted Global Market for ADAS Systems by 2020. ABI Research. 2013.

Autonomous Vehicles: 30 years R&D

Pioneer work at INRIA in the 90's : *Autonomous parking, Platooning in cities, People mover (Cycab)*



1986 VaMors (Dickmann Munich U)
First autonomous vehicle on a road,
Followed by EU project Prometheus



2004 Darpa Grand Challenge
*Significant step towards Motion Autonomy
... But still some uncontrolled behaviors !!!*



2007 Darpa Urban Challenge
*97 km, 50 manned & unmanned
vehicles, 35 teams*



2011 Google Car project
Fleet of 6 automated Toyota Prius
140 000 miles covered on California roads
with occasional human interventions

Sustainable Mobility – *Cybercar technologies*

□ An EU driven concept since the 90's: “Cybercars”

- ✓ *Autonomous Self Service Urban & Green Vehicles moving at low speed*
- ✓ *Numerous R&D projects in Europe during the past 25 years (Several European cities involved)*
- ✓ *Some Start-ups & Commercial products for semi-protected areas (e.g. airports, industrial areas, amusement parks ...), e.g. Robosoft & Easymile, 2GetThere, Induct & Neavia...*

□ Several early large scale public experiments in Europe



Floriade 2002, Amsterdam
(2GetThere & Inria)



Cybus experiment, La Rochelle 2012
(CityMobil Project & Inria)

Autonomous Cars & Driverless Vehicles

- Strong involvement of Car Industry & Large media coverage
- An expected market of 500 B€ in 2035
- Numerous recent & on-going real-life experiments for validating the technologies



Tesla Autopilot based on Radar & Mobileye



Costly 3D Lidar & Dense 3D mapping



Cybus experiment, La Rochelle 2012 (CityMobil Project & Inria)



Drive Me trials
 • 100 Test Vehicles in Göteborg, 80 km, 70km/h
 • No pedestrians & Plenty of separations between lanes



Driverless Taxi testing in Pittsburgh (Uber) & Singapore (nuTonomy)
 => Mobility Service, Numerous Sensors ... Engineer in the car during testing



Several design & serious accidents in past few months (Tesla, Google, Uber ..)
Safety is still not guaranteed!

Safety issues: *Example of the Tesla accident*

❑ **Safety is still insufficient** (*a false sense of Safety for users ?*)

=> Still some Perception & Situation Awareness errors (even with commercial systems)

=> On May 7th 2016, Tesla driver killed in crash with Autopilot active

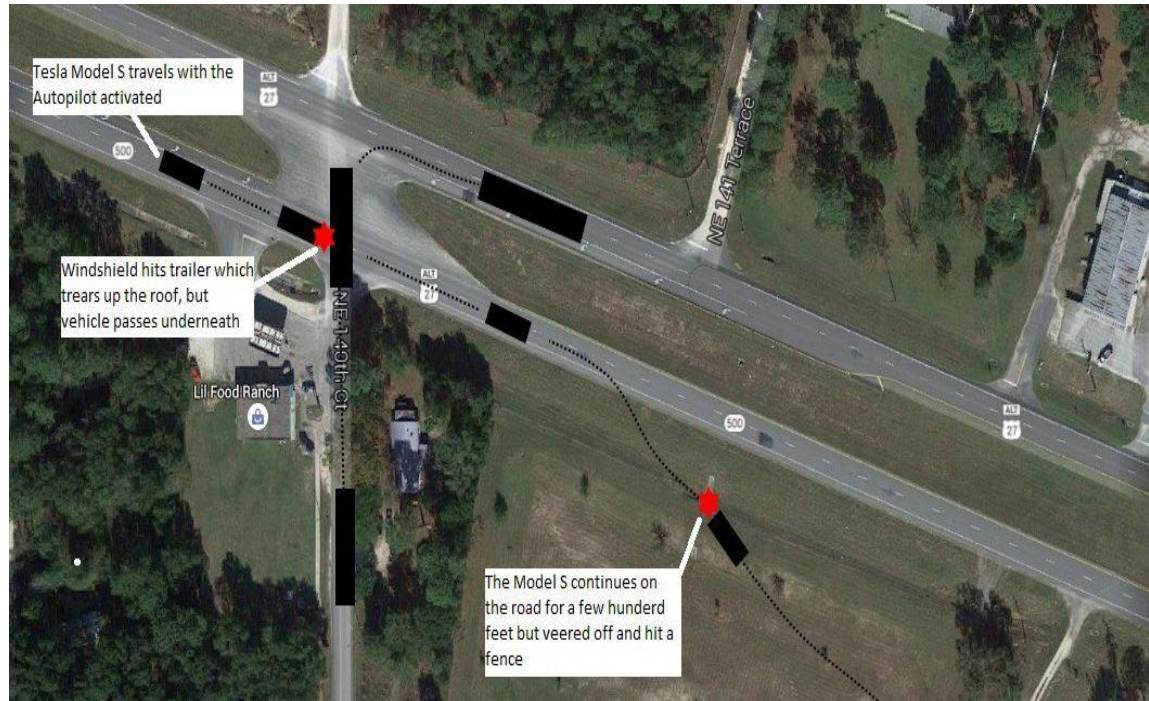


Displayed information

Tesla Model S – Autopilot

Front perception:

Camera (Mobileye) + Radar + US sensors



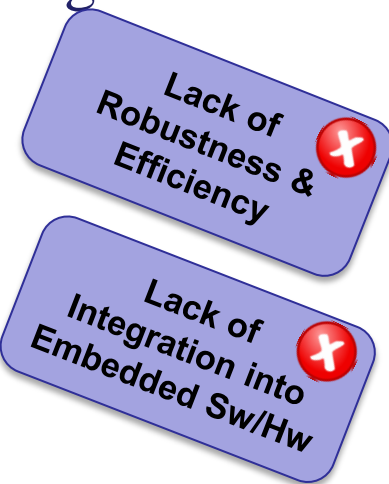
=> The Autopilot didn't detected the trailer as an obstacle (*see internet for available comments on NHTSA investigation & Tesla conjecture*)

Perception: State of the Art & Today's Limitations

- ❑ Despite significant improvements during the last decade of both Sensors & Algorithms, **Embedded Perception** is still one of the major bottleneck for Motion Autonomy
=> Obstacles detection & classification errors, incomplete processing of mobile obstacles, collision risk weakly address, scene understanding partly solved...
- ❑ **Lack of Robustness & Efficiency & Embedded integration** is still a significant obstacle to a full deployment of these technologies



*Trunk still full of electronics & computers & processor units
High computational capabilities are still required*



Perception: Required system capabilities

Understanding Complex Dynamic Scenes



Situation Awareness & Decision-making



Dealing with unexpected events e.g. Road Safety Campaign, France 2014



Anticipation & Prediction for avoiding upcoming accidents

Main features

- ✓ Dynamic & Open Environments => *Real-time processing*
- ✓ Incompleteness & Uncertainty => *Appropriate Model & Algorithms (probabilistic approaches)*
- ✓ Sensors limitations => *Multi-Sensors Fusion*
- ✓ Human in the loop => *Interaction & Social Constraints (including traffic rules)*
- ✓ Hardware / Software integration => *Satisfying Embedded constraints*

Content of the Lecture

□ Socio-economic & Technological Context

□ **Decisional & Control Architecture : Outline**

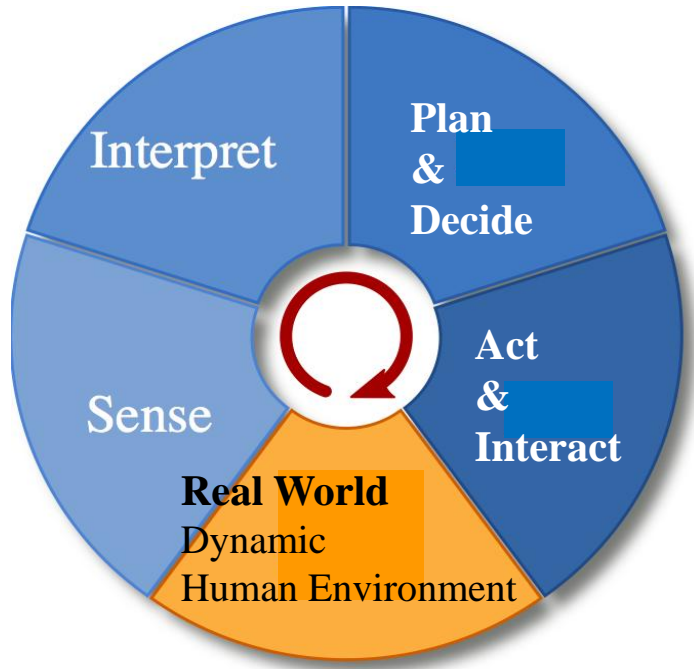
□ Bayesian Perception (*Key Technology 1*)

□ Embedded Perception & Experimental results

□ Bayesian Risk Assessment & Decision-making (*Key Technology 2*)

□ Conclusion & Perspectives

Decisional & Control Architecture (1)

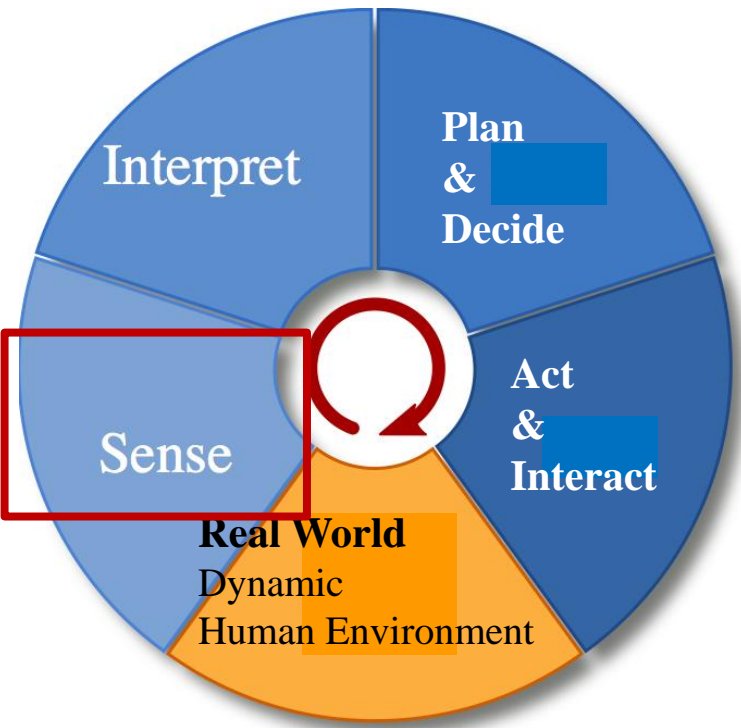


❑ **How to control Robot actions in a Dynamic world populated by Human Beings ?**

❑ **Combining & Adapting interdependent functions for:**

- ✓ Sensing the environment using various sensors
- ✓ Interpreting the dynamic scene (Semantics)
- ✓ Planning Robot motions & Deciding of the most appropriate action to be executed
- ✓ Acting & Interacting in the real world (Safety & Acceptability)

Decisional & Control Architecture (2)



❑ Objective

Perceive what is happening in the Dynamic Scene using various sensors

❑ Main Difficulty

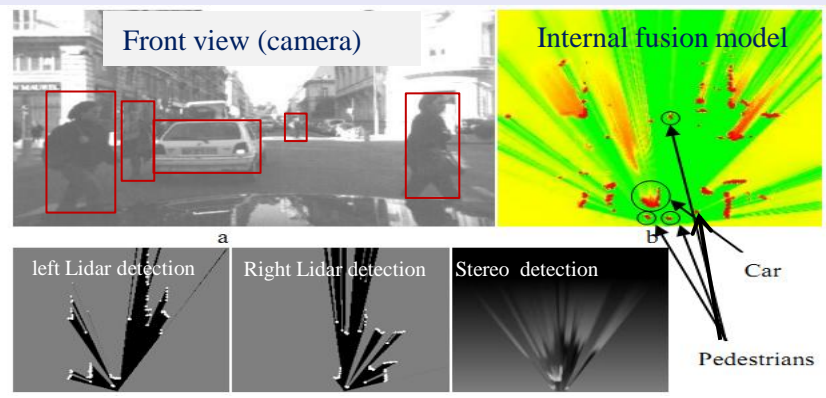
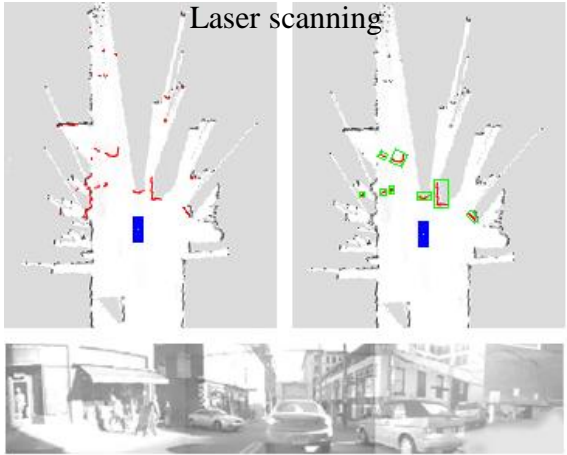
- ✓ Huge heterogeneous sensory data
- ✓ Sensing errors & Uncertainty
- ✓ Real-time processing

❑ Main Functions

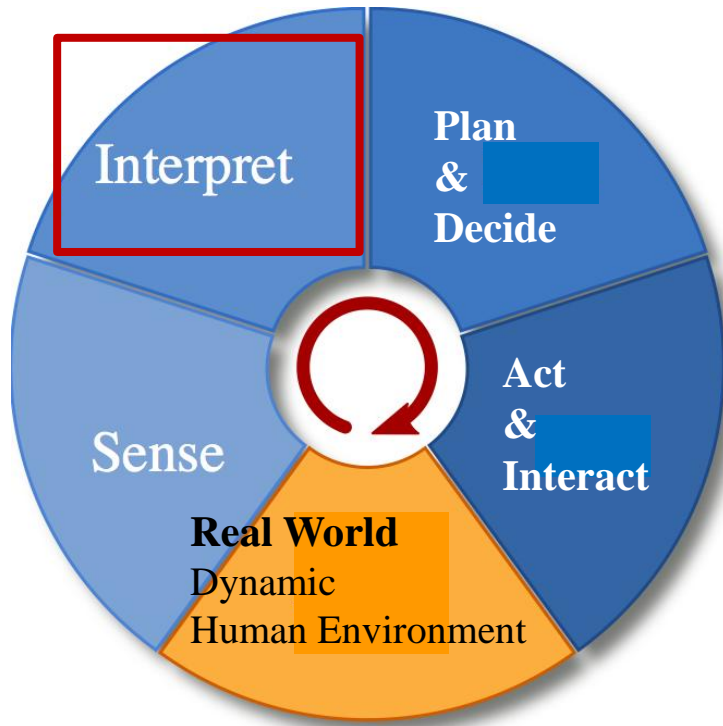
- ✓ Localization & Mapping (SLAM)
- ✓ Static & Mobile Objects Detection

❑ Main Models & Algorithms

- ✓ Bayesian Filtering
- ✓ Feature based & Grid based approaches



Decisional & Control Architecture (3)

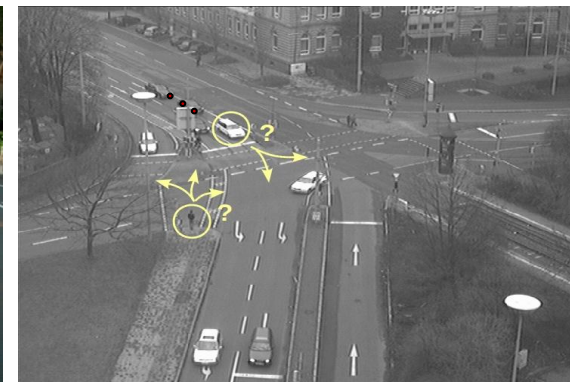
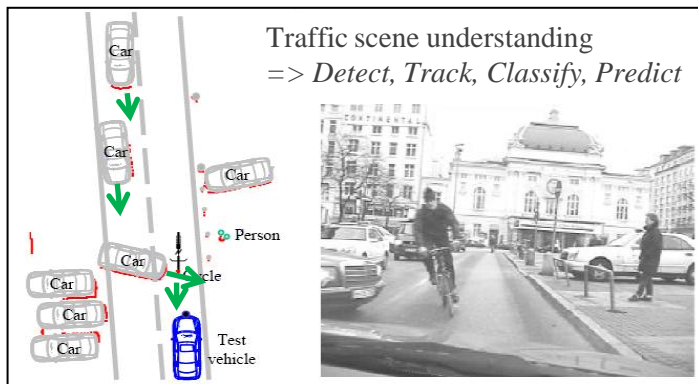


❑ Objective

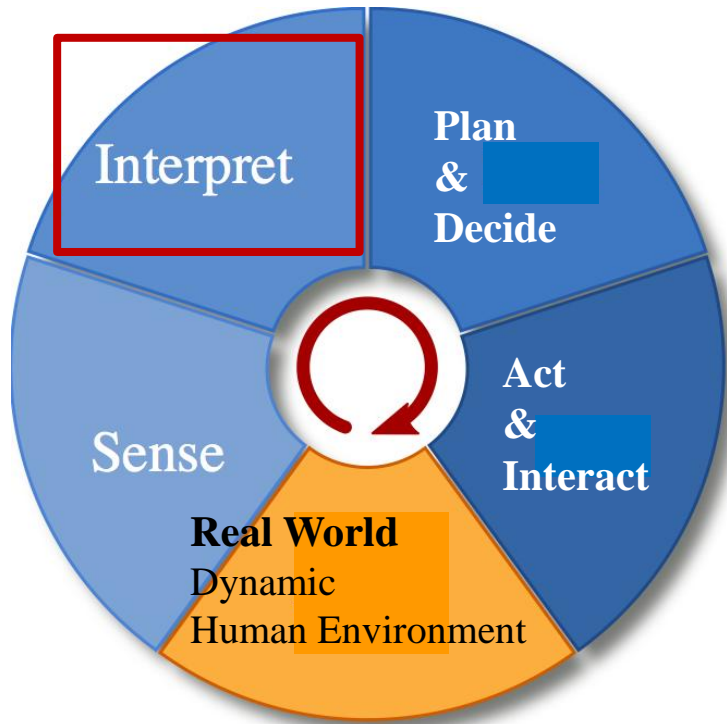
Understand the content of the Dynamic Scene using **Contextual & Semantic knowledge**

❑ Main Difficulty

- ✓ Uncertainty
- ✓ Real-time processing
- ✓ Reasoning about various knowledge (history, context, semantics, prediction)



Decisional & Control Architecture (3 bis)

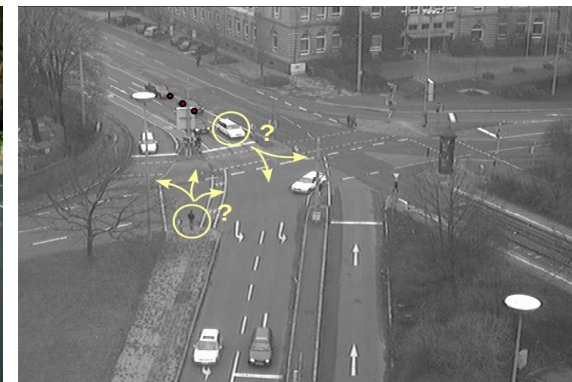
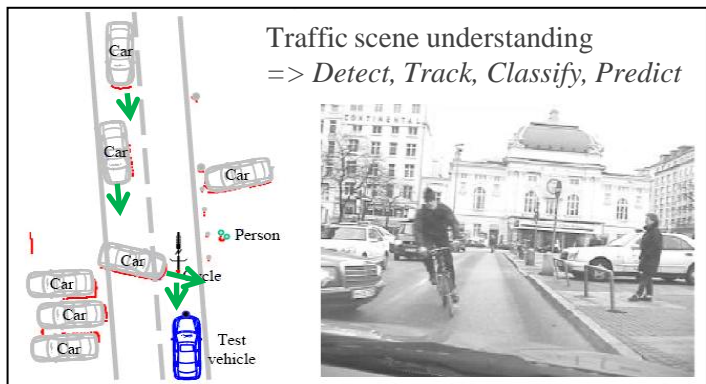


□ Main Functions

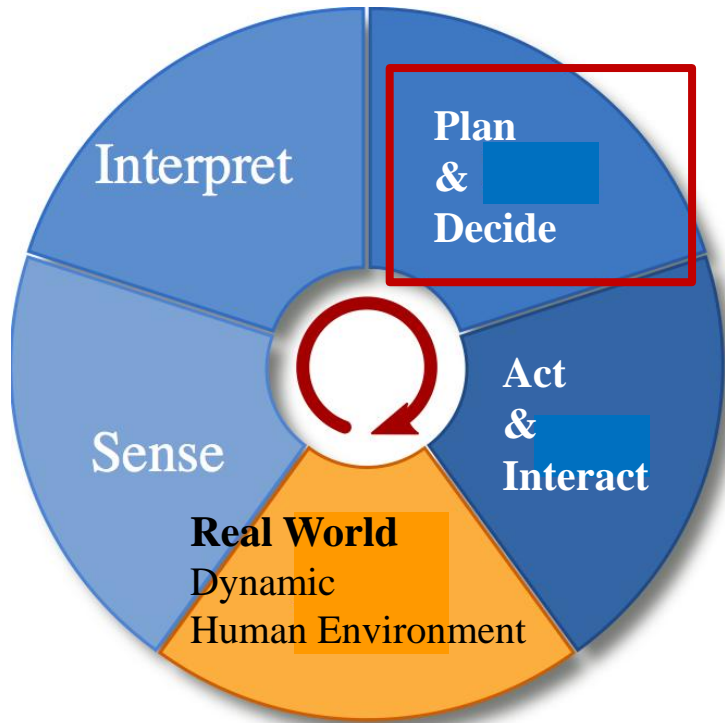
- ✓ Detection & Tracking of Mobile Objects (DATMO)
- ✓ Objects classification (recognition)
- ✓ Prediction & Risk Assessment (avoiding future collisions)

□ Main Models & Algorithms

- ✓ Bayesian Perception Paradigm
- ✓ Behaviors modeling & learning
- ✓ Bayesian approaches for Prediction & Risk Assessment



Decisional & Control Architecture (4)



❑ Objective

Planning robot motions & Deciding of the most appropriate action to be executed by the robot (Goal & Context & Risk)

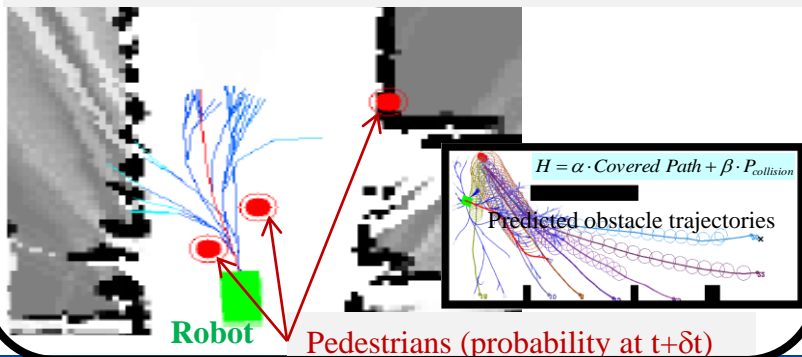
❑ Main Difficulty & Functions

- ✓ On-line Motion Planning under various constraints (time, kinematic, dynamic, uncertainty, collision risk, social)
- ✓ Decision making under uncertainty using contextual data (history, semantics, prediction)

❑ Main Models & Algorithms

- ✓ Iterative Risk-based Motion Planning (e.g. Risk-RRT)
- ✓ Decision making using Contextual data & Bayesian networks

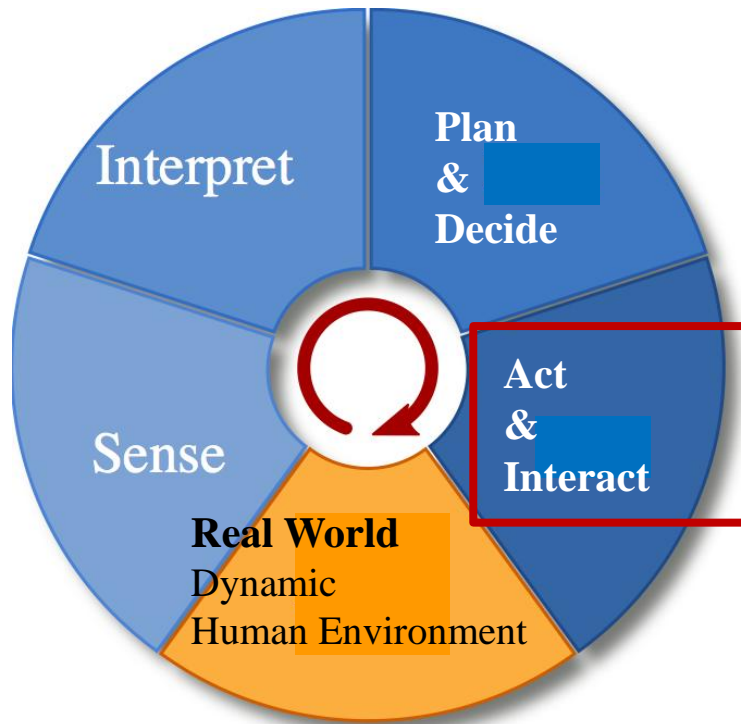
Iterative Motion Planning under Time & Risk constraints



Decision making (avoiding collision)



Decisional & Control Architecture (5)



❑ Objective

Controlling the robot for executing **Safe & Socially Acceptable robot actions**, while taking into account the related **Human – Robot Interactions**

❑ Main Difficulty & Functions

- ✓ Robot navigation while taking into account both Safety & Social constraints
- ✓ **Human in the loop**

❑ Main Models & Algorithms

- ✓ Human-Aware Navigation paradigm (safety & social filters)
- ✓ Intuitive Human-Robot Interaction



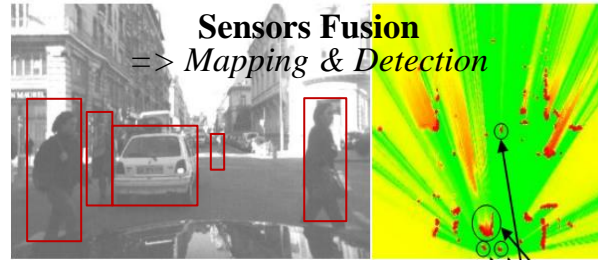
Content of the Lecture

- Socio-economic & Technological Context
- Decisional & Control Architecture : Outline
- **Bayesian Perception (*Key Technology 1*)**
- Embedded Perception & Experimental results
- Bayesian Risk Assessment & Decision-making (*Key Technology 2*)
- Conclusion & Perspectives

Key Technology 1: Embedded Bayesian Perception



Embedded Multi-Sensors Perception
⇒ *Continuous monitoring of the dynamic environment*



❑ Main challenges

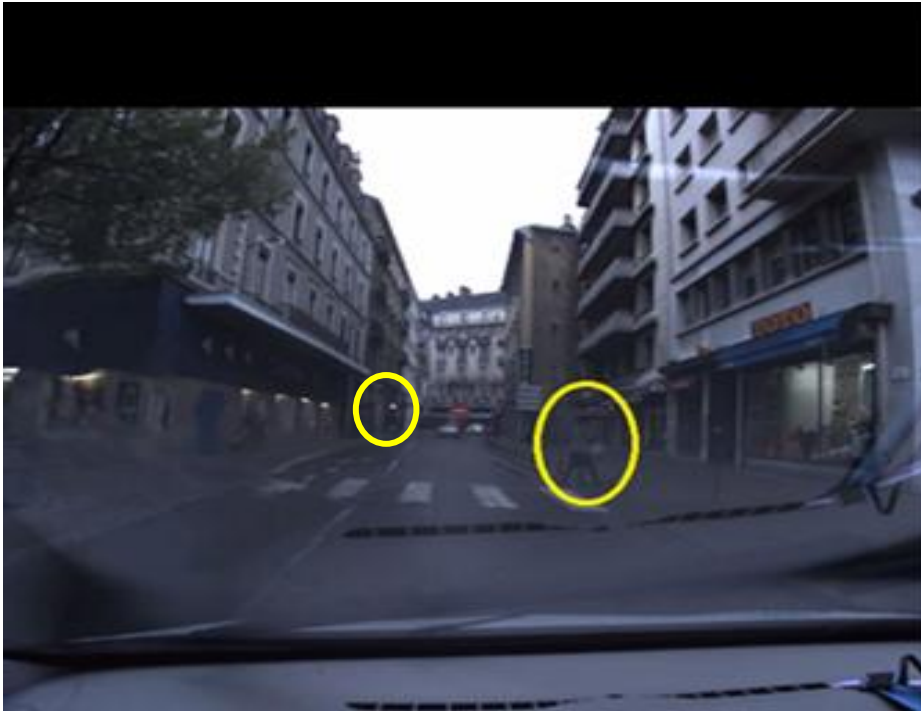
- ✓ *Noisy data, Incompleteness, Dynamicity, Discrete measurements*
- ✓ *Strong Embedded & Real time constraints*

❑ Approach: Embedded Bayesian Perception

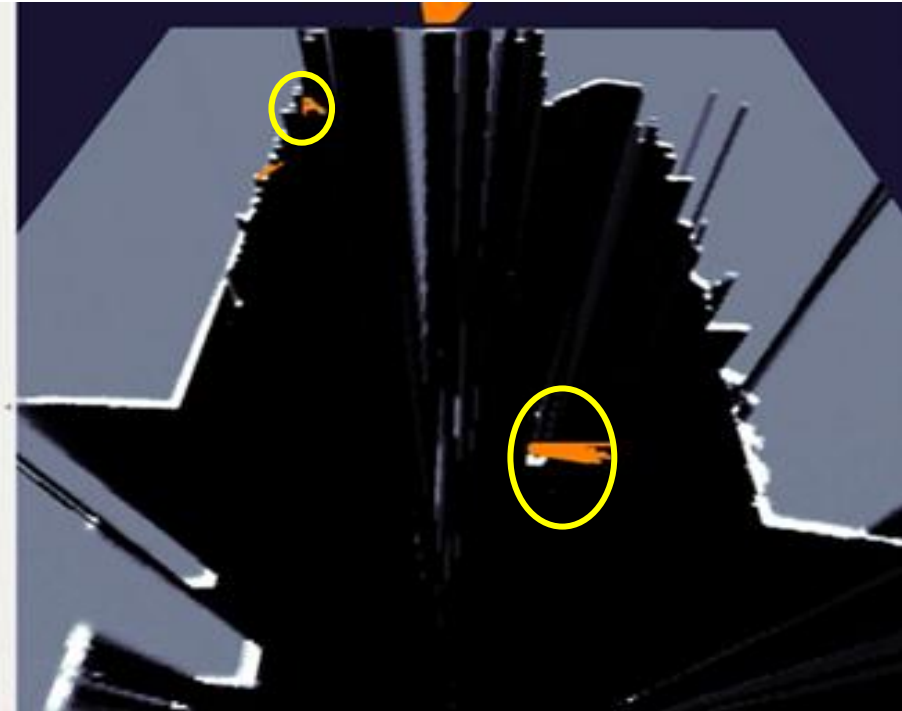
- ✓ *Reasoning about Uncertainty & Time window (Past & Future events)*
- ✓ *Improving robustness using Bayesian Sensors Fusion*
- ✓ *Interpreting the dynamic scene using Contextual & Semantic information*
- ✓ *Software & Hardware integration using GPU, Multicore, Microcontrollers...*

Improving robustness using Multi-modality sensing

Camera Image at Dusk (Pedestrians not detected)



Processed Lidar data (Pedestrians detected)



Camera output depends on lighting conditions
Cheap & Rich information & Good for classification

Lidar more accurate & can work at night
Good for fine detection of objects ... but still Expensive

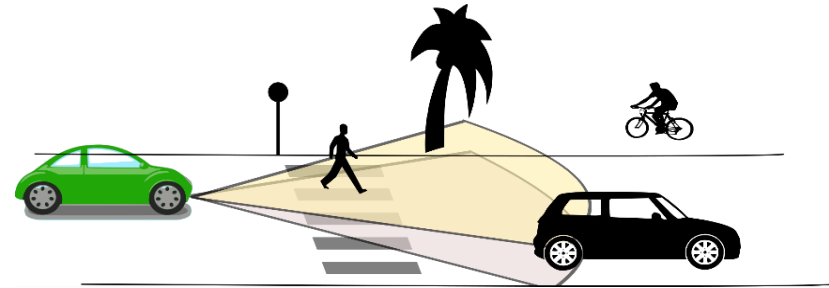
- Develop **Robust & Efficient Multi-Sensor Fusion** approaches using probabilistic models
- **Good news:** A new generation of **affordable “Solid State Lidars”** will arrive soon on the market !
 - => No mechanical component & Expected cost less than 1000 US\$ (before mass production)
 - => Numerous announcements since Spring 2016



Bayesian Perception : Basic idea




□ Multi-Sensors Observations

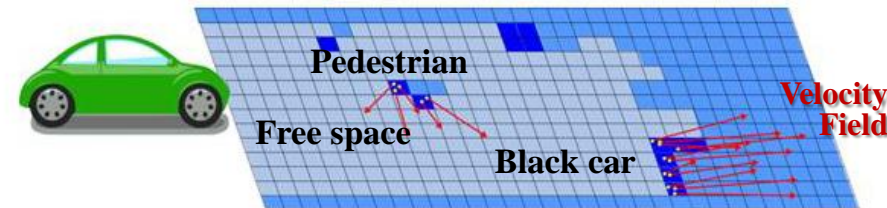
Lidar, Radar, Stereo camera, IMU ...



□ Probabilistic Environment Model

- ✓ *Sensor Fusion*
- ✓ *Occupancy grid integrating uncertainty*
- ✓ *Probabilistic representation of Velocities*
- ✓ *Prediction models*

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



Concept of Dynamic Probabilistic Grid
⇒ Occupancy & Velocity probabilities
⇒ Embedded models for Motion Prediction

□ Main philosophy

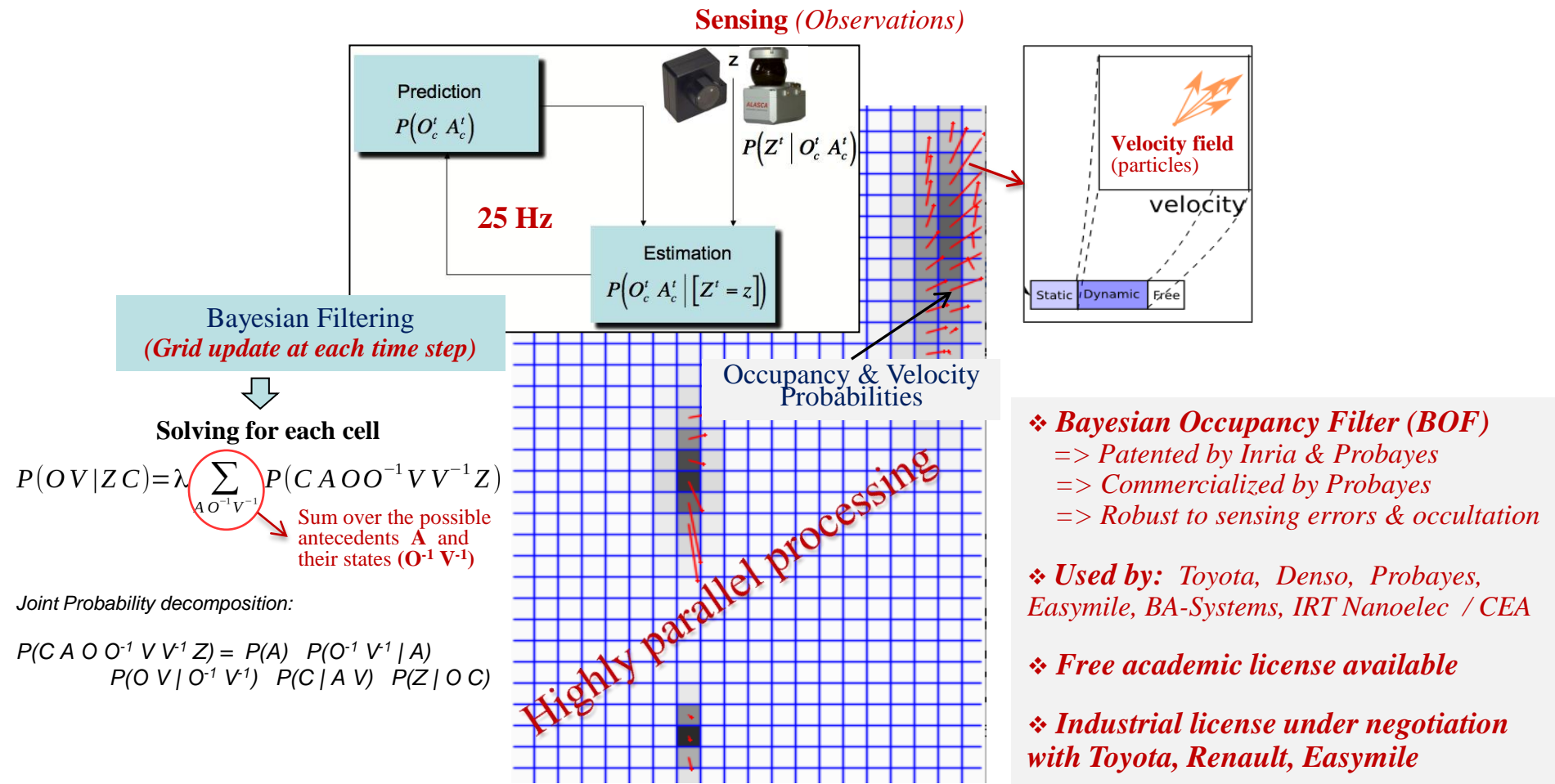
Reasoning at the grid level as far as possible for both :

- **Improving efficiency** (highly parallel processing)
- **Avoiding traditional object level processing problems** (e.g. detection errors, wrong data association...)

A new framework: Dynamic Probabilistic Grids

=> A clear distinction between Static & Dynamic & Free components

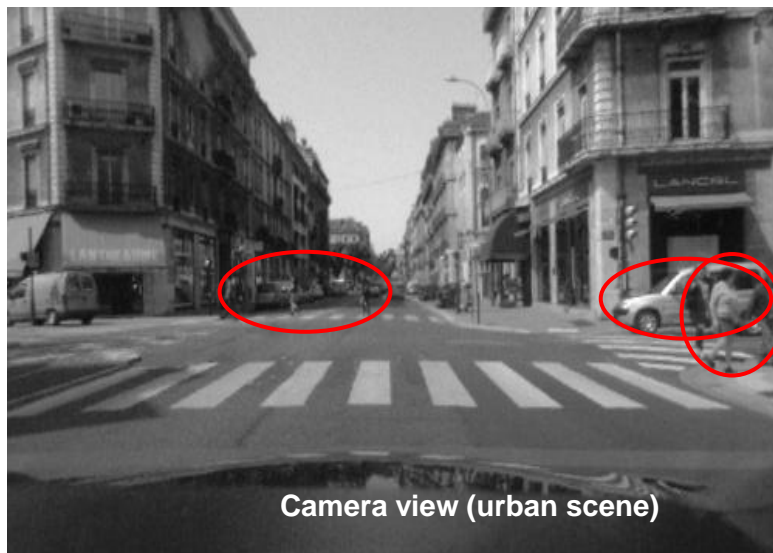
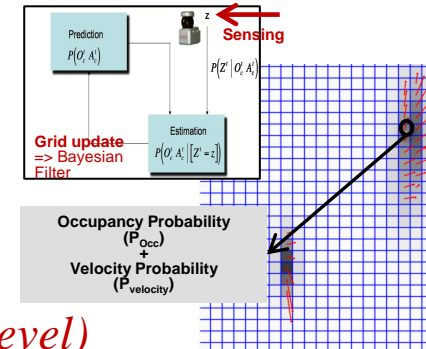
[Coué & Laugier IJRR 05] [Laugier et al ITSM 2011] [Laugier, Vasquez, Martinelli Mooc uTOP 2015]



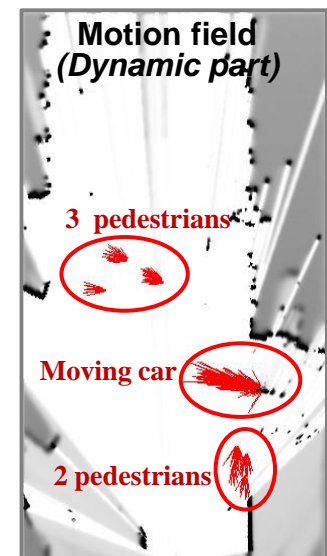
- ❖ **Bayesian Occupancy Filter (BOF)**
 - => Patented by Inria & Probayes
 - => Commercialized by Probayes
 - => Robust to sensing errors & occultation
- ❖ **Used by:** Toyota, Denso, Probayes, Easymile, BA-Systems, IRT Nanoelec / CEA
- ❖ **Free academic license available**
- ❖ **Industrial license under negotiation with Toyota, Renault, Easymile**

Bayesian Occupancy Filter (BOF) – Main Features

- Estimate **Spatial occupancy** for each cell of the grid $P(O | Z)$
- **Grid update** is performed in each cell in parallel (using *BOF equations*)
- **Extract Motion Field** (using *Bayesian filtering & Fused Sensor data*)
- **Reason at the Grid level** (i.e. *no object segmentation at this reasoning level*)



Sensors data fusion
+
Bayesian Filtering

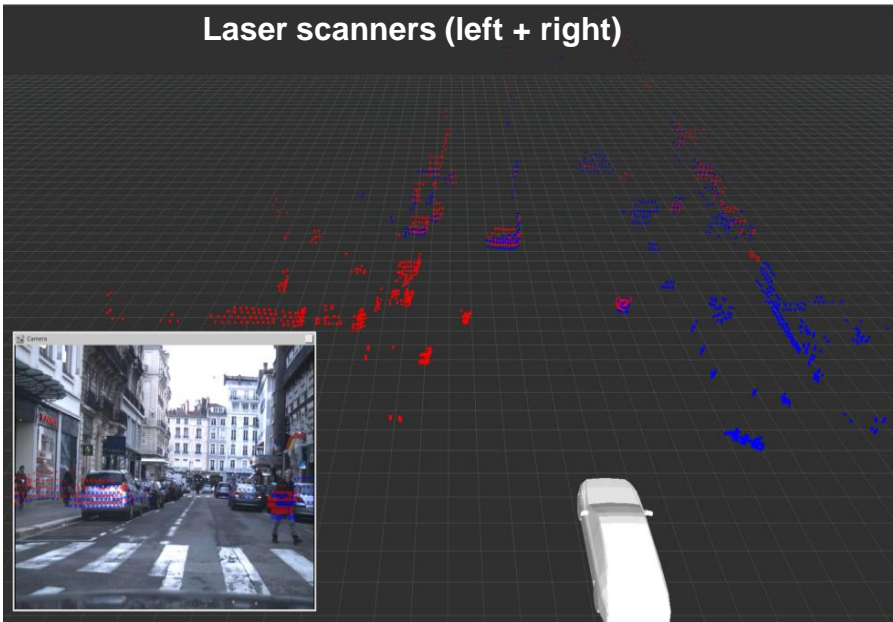


Exploiting the Dynamic information for improving Scene Understanding !!

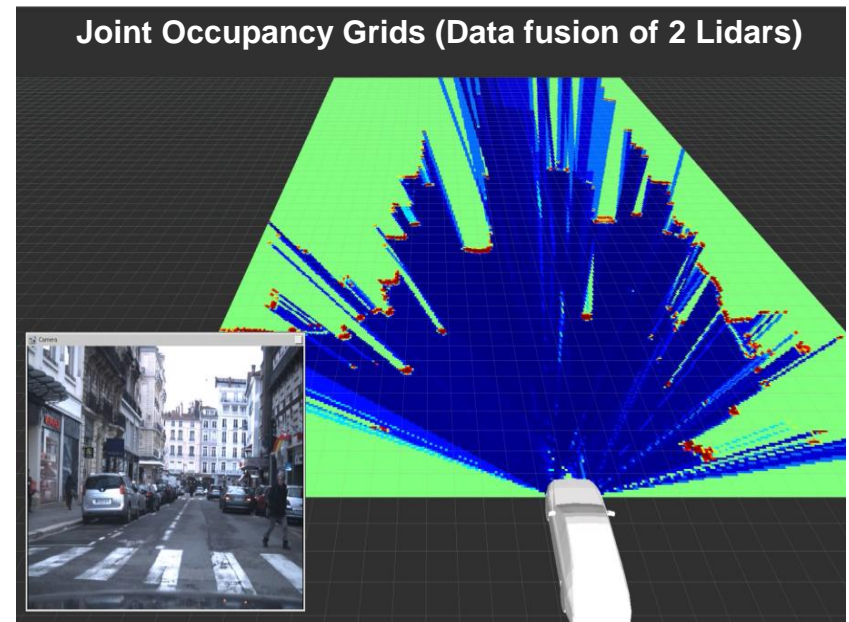
Bayesian data fusion: *The joint Occupancy Grid*

- 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: $P(O | Z)$

Laser scanners (left + right)

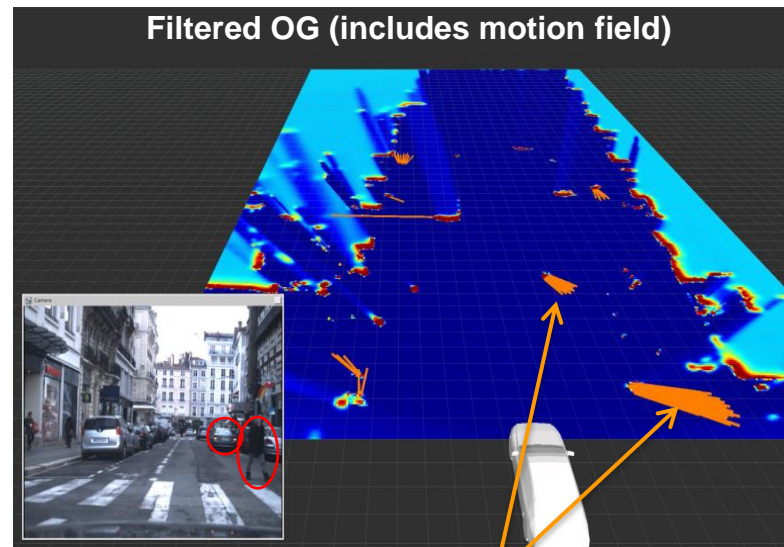
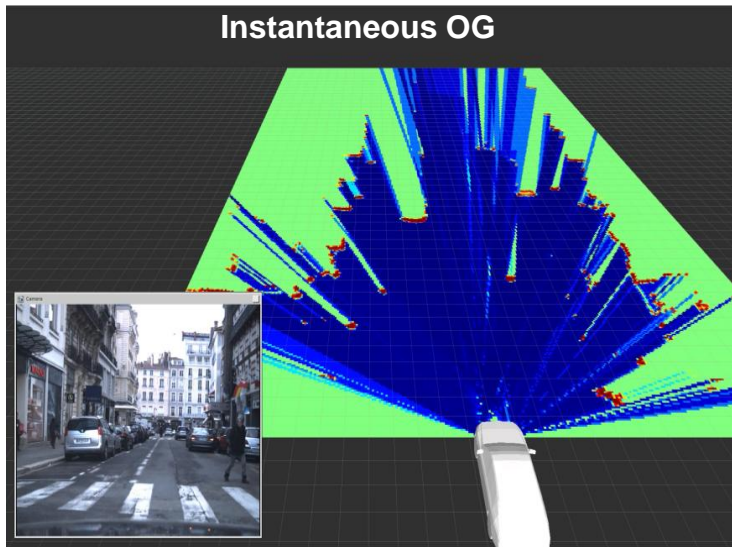
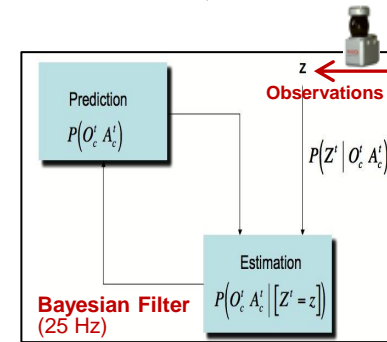


Joint Occupancy Grids (Data fusion of 2 Lidars)



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



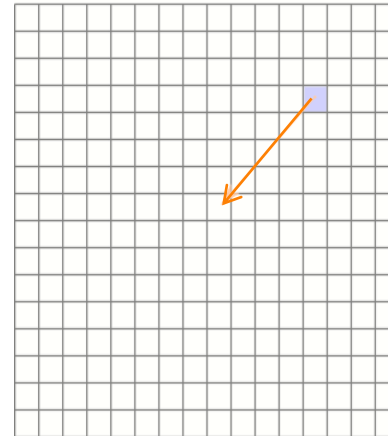
Motion fields are displayed in orange color

Bayesian Occupancy Filter – *Formalism*

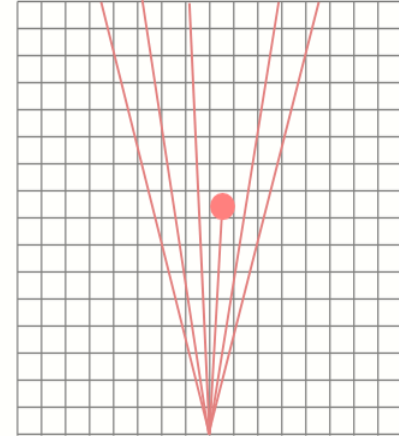
Variables:

- 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)

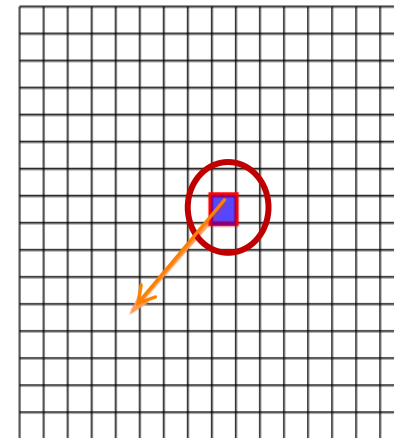
Previous Model (t-1)



Observations (t)



Current Model (t)



Objective:

Evaluate $P(O \ V \ | \ Z \ C)$

*=> Probability of Occupancy & Velocity for each cell C ,
Knowing the observations Z & the cell location C in the grid*

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**) at time t-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 => 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 theoretically compute $P(O V | Z C)$?

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But, computing this expression is difficult in practice

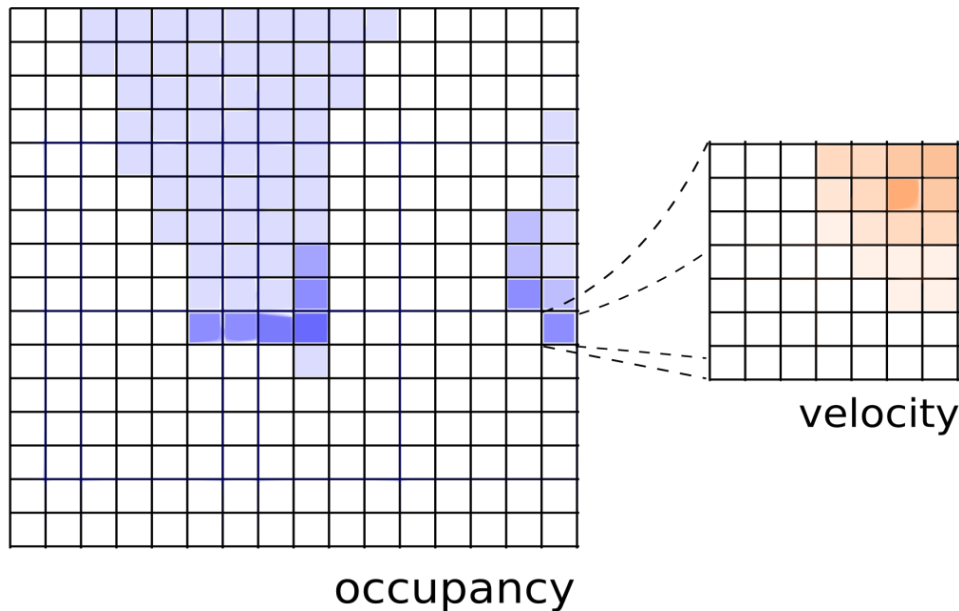
=> Huge range of possible antecedents

=> Strongly depends on Grid size & Velocity range

How to compute $P(OV | Z C)$ in practice?

Initial approach: The classic BOF process

- **Regular grid**
- **Transition histograms** for every cell (for representing velocities)



How to compute $P(OV | Z C)$ in practice?

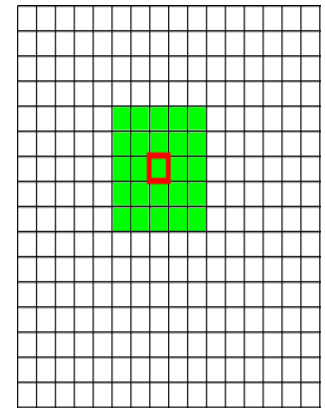
Initial approach: The classic BOF process

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

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

Practical computation:

→ Sum over the **neighborhood**, with a **single possible velocity per antecedent A** of equation:

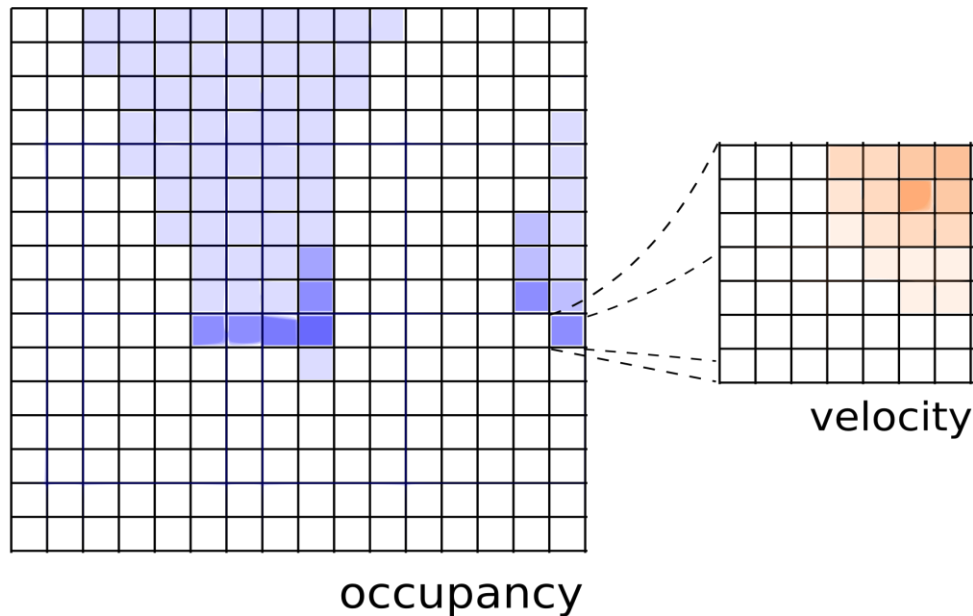


$$P(C A O O^{-1} V V^{-1} Z) = P(A) P(O^{-1} V^{-1} | A) P(O V | O^{-1} V^{-1}) \\ P(C | A V) P(Z | O C)$$

How to compute $P(OV | Z C)$ in practice?

Initial approach: Drawbacks (1)

- **Velocity histogram** needs to be accurate on both **low & high velocities**
 - ⇒ *Its resolution has to be high, while being mostly empty !*
 - ⇒ *It requires a large memory size (but in practice the accuracy is still weak) !*

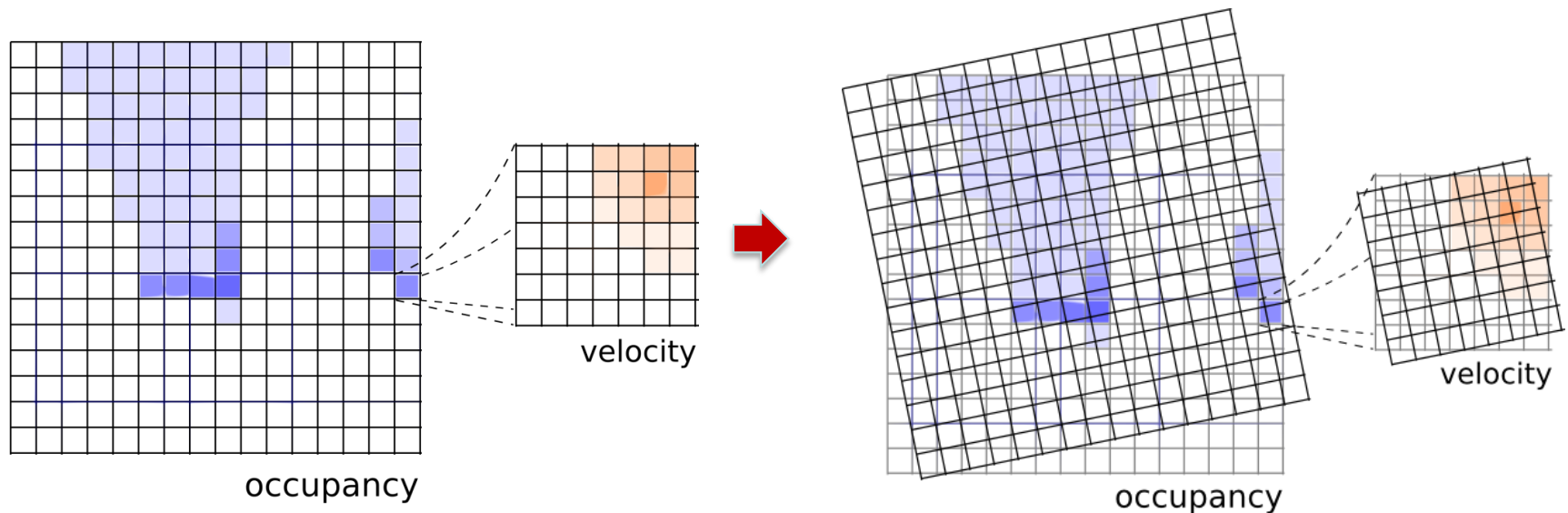


⇒ Large memory size required
⇒ Weak accuracy

How to compute $P(OV | Z C)$ in practice?

Initial approach: Drawbacks (2)

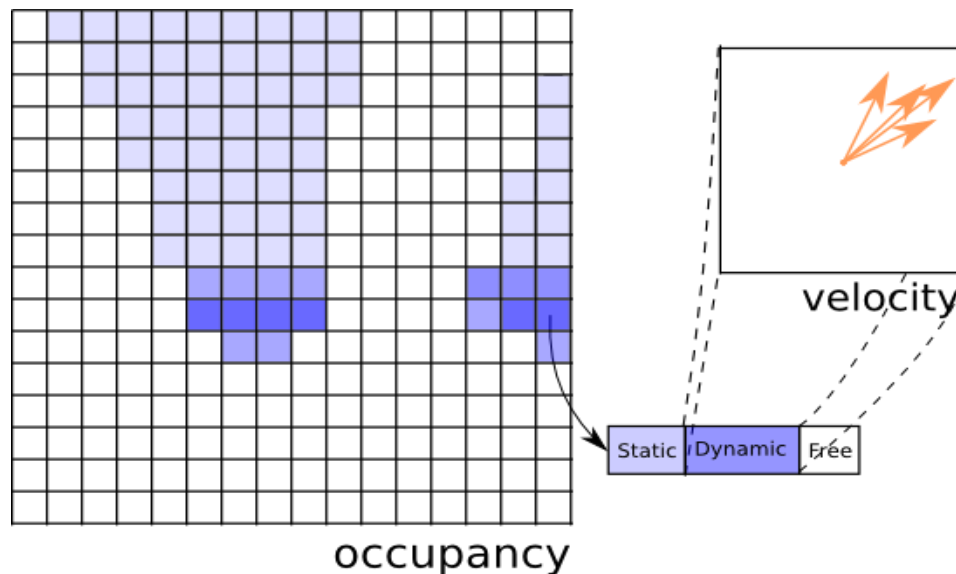
- **Temporal aliasing** \Rightarrow *Due to update & real frequencies synchronization*
- **Spatial aliasing** (moving grid) \Rightarrow *High complexity due to 4-dimension interpolation*
 \Rightarrow *Approximations required in practice*



How to compute $P(OV | Z C)$ in practice?

HSBOF updating process (principle)

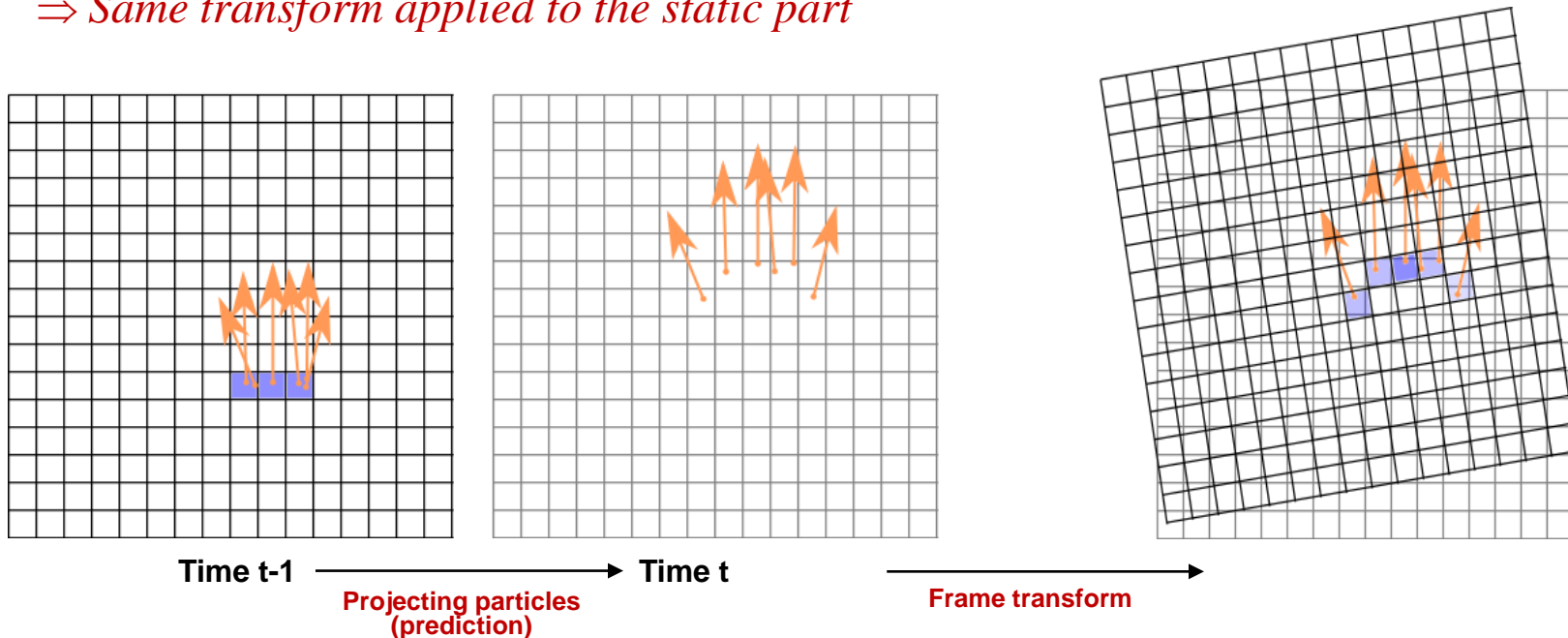
- **Basic idea:** *Modify the representation structure to avoid the previous computational problems*
 - ✓ Making a clear distinction between **Static & Dynamic & Free** components
 - ✓ Modeling velocity using **Particles** (*instead of histogram*)
 - ✓ Making an **adaptive repartition** of those particles in the grid



How to compute $P(OV | Z C)$ in practice?

HSBOF updating process (principle)

- Introducing a Dynamic model for “projecting” particles in the grid ($S_{t-1} \rightarrow S_t$)
 - ⇒ *Immediate antecedent association*
 - ⇒ *Simplified velocity prediction to the cells*
- Updating Grid Reference Frame
 - ⇒ *Translation & Rotation values **provided by sensors** (Odometry + IMU)*
 - ⇒ *Same transform applied to the static part*

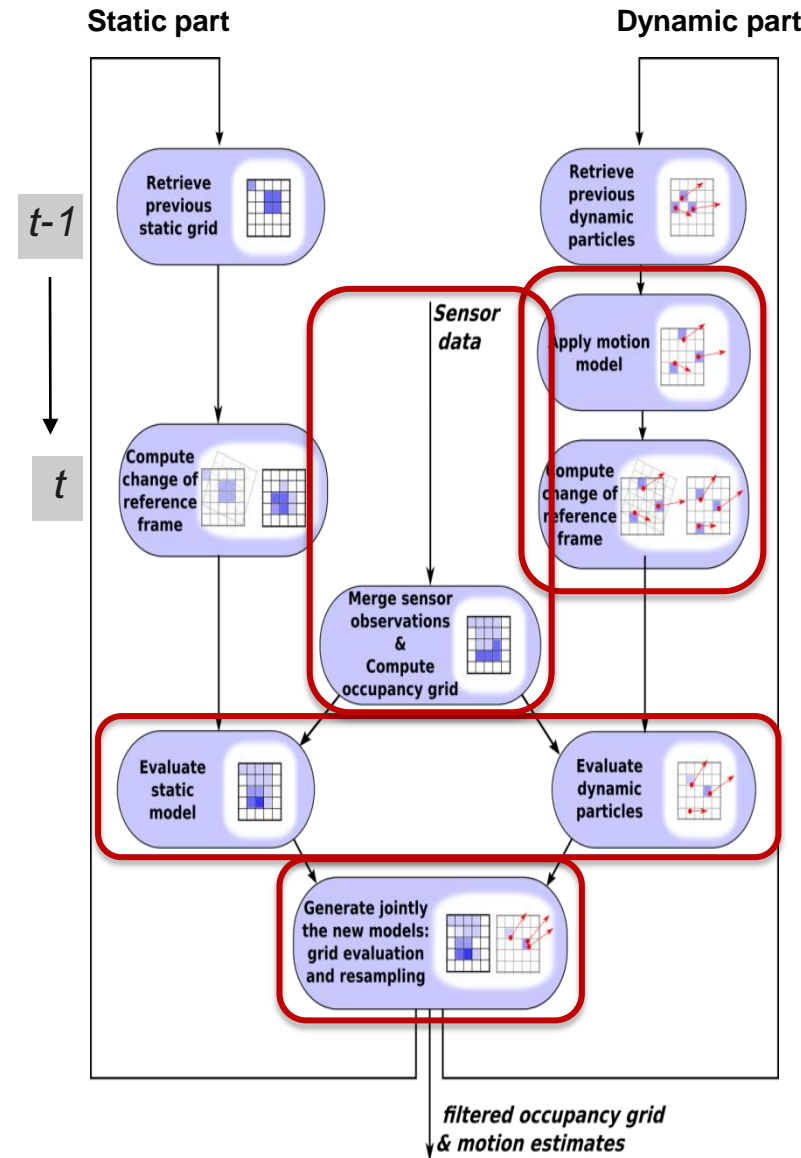


How to compute $P(OV | Z C)$ in practice?

HSBOF updating process (outline of the algorithm)

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



How to compute $P(OV | Z C)$ in practice ?

HSBOF filtering calculation

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

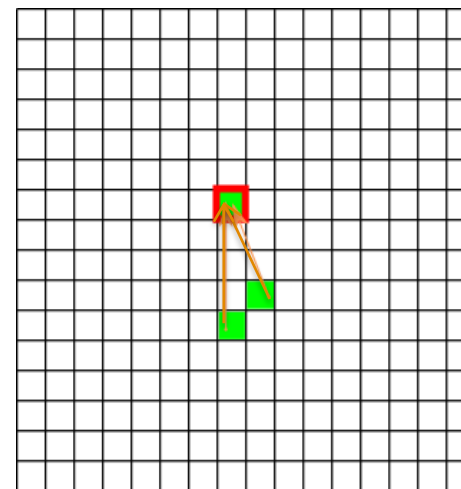
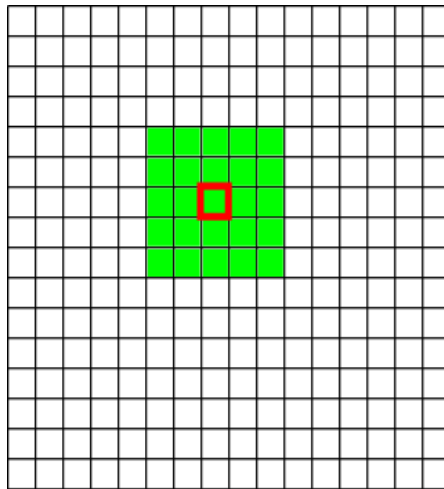
Sum over the neighborhood, with a single velocity per antecedent

A more efficient computation approach :

=> Sum over the particles projected in the cell & their related static parts

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

Previous
computation approach
(histograms)



New
computation approach
(particles)

HSBOF: *Main Features (summary)*

- Empty & Static components => **Occupancy Grid**
- Dynamic components => **Sets of Particles (Motion field)**
 - ✓ Smooth integration of the ego-motion (IMU & Odometry)
 - ✓ Propagation of sets of particles in the Grid (using dynamic models)
 - ✓ Joint estimation of distributions
- More efficient (computation & memory) & Better estimation of velocities (more accurate)

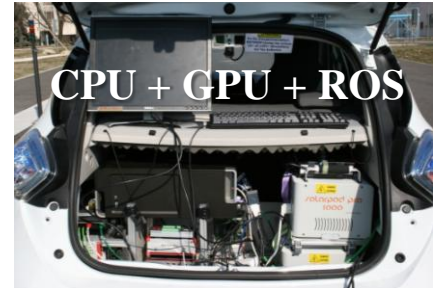
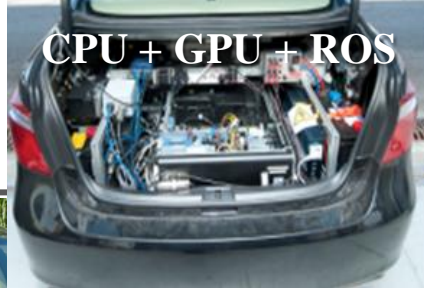
Content of the Lecture

- Socio-economic & Technological Context
- Decisional & Control Architecture: Outline
- Bayesian Perception (*Key Technology 1*)
- **Embedded Perception & Experimental results**
- Bayesian Risk Assessment & Decision-making (*Key Technology 2*)
- Conclusion & Perspectives

Experimental Vehicles & Embedded Perception Units

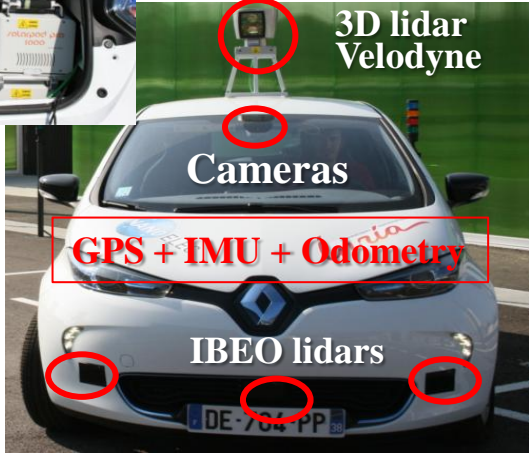


Toyota Lexus 2010



ROS

Renault Zoé 2014



Connected Perception Unit



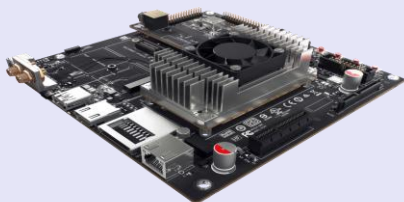
Nvidia GTX Titan X
Generation Maxwell



Nvidia GTX Jetson TK1
Generation Maxwell



Nvidia GTX Jetson TX1
Generation Maxwell



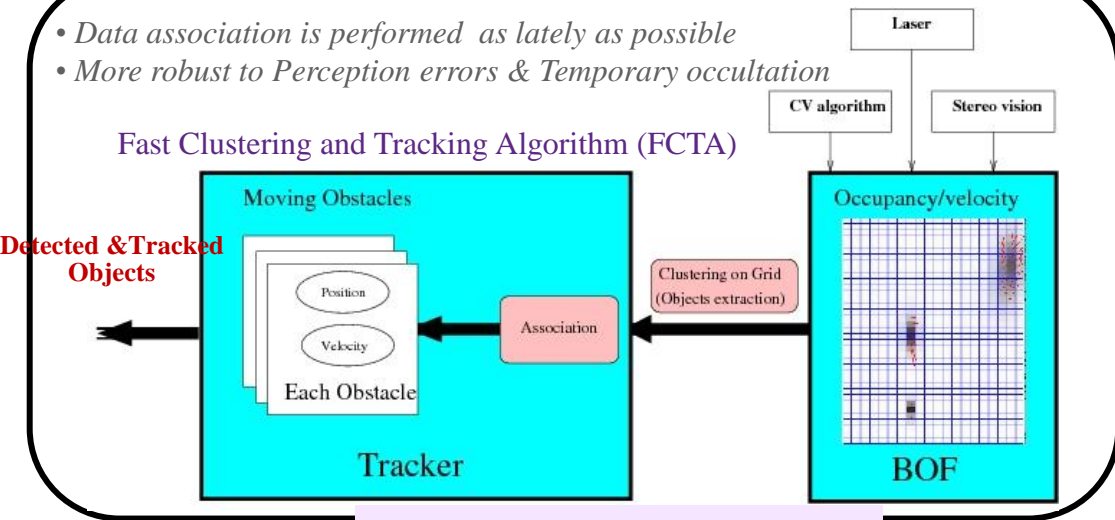
Embedded Perception Units & Hardware

Former Bayesian Perception Architecture (outline)

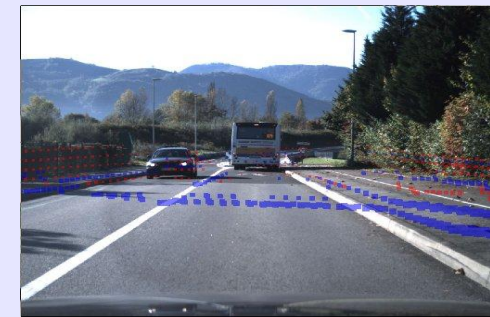
Bayesian Sensor Fusion + Detection & Tracking

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

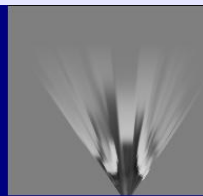
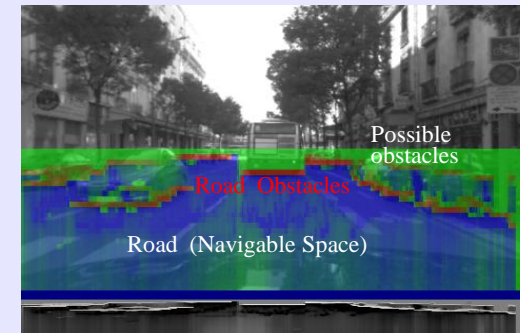
Fast Clustering and Tracking Algorithm (FCTA)



[Mekhnacha 09, Laugier et al ITSM'11]

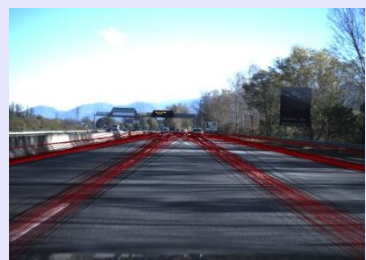


Laser Fusion (8 layers, 2 lasers)



Cartesian Occupancy Grid

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

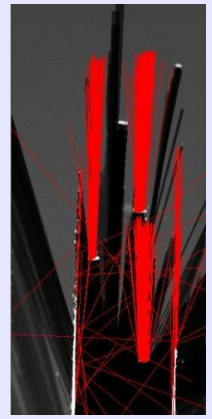


Multi-Lane tracker



Motion Detection

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



Intensity Features



Objects classification



Codebook Matching

Detections

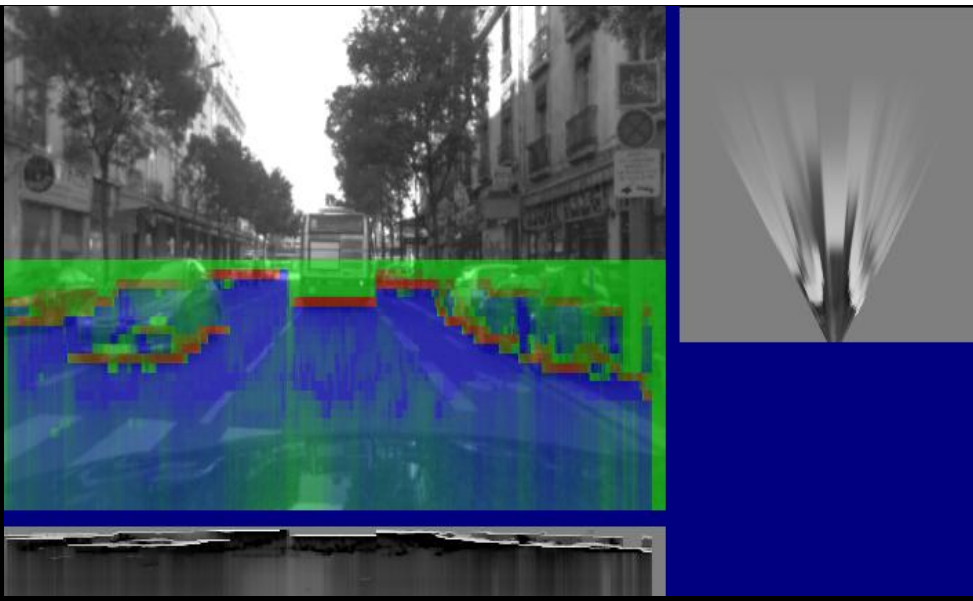
Depth Features

Former experimental results (*Inria – Toyota Lexus*)

Multiple sensors Fusion (Stereo vision & Lidars)

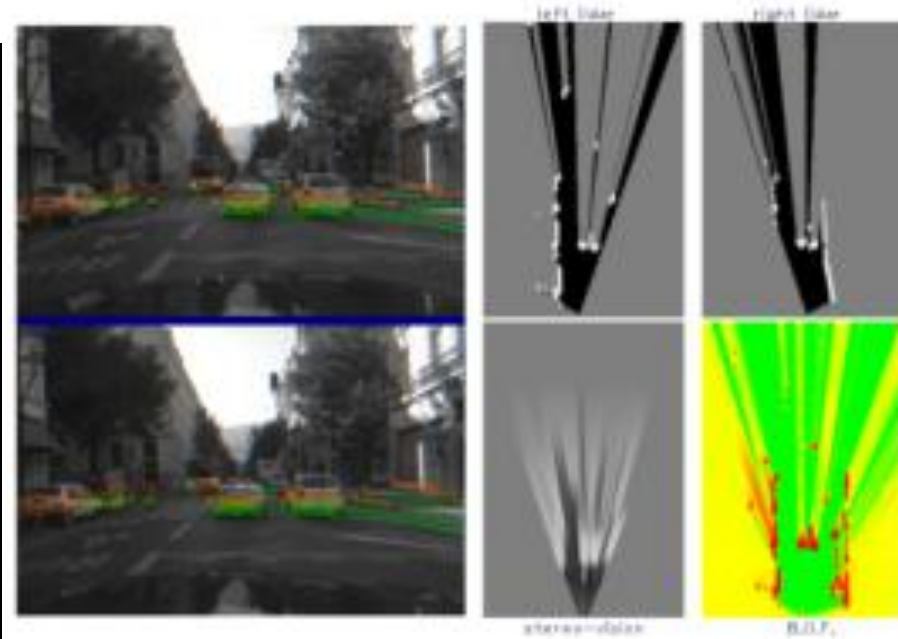


[Perrollaz et al 10] [Laugier et al ITSM 11]
IROS Harashima Award 2012



Stereo Vision

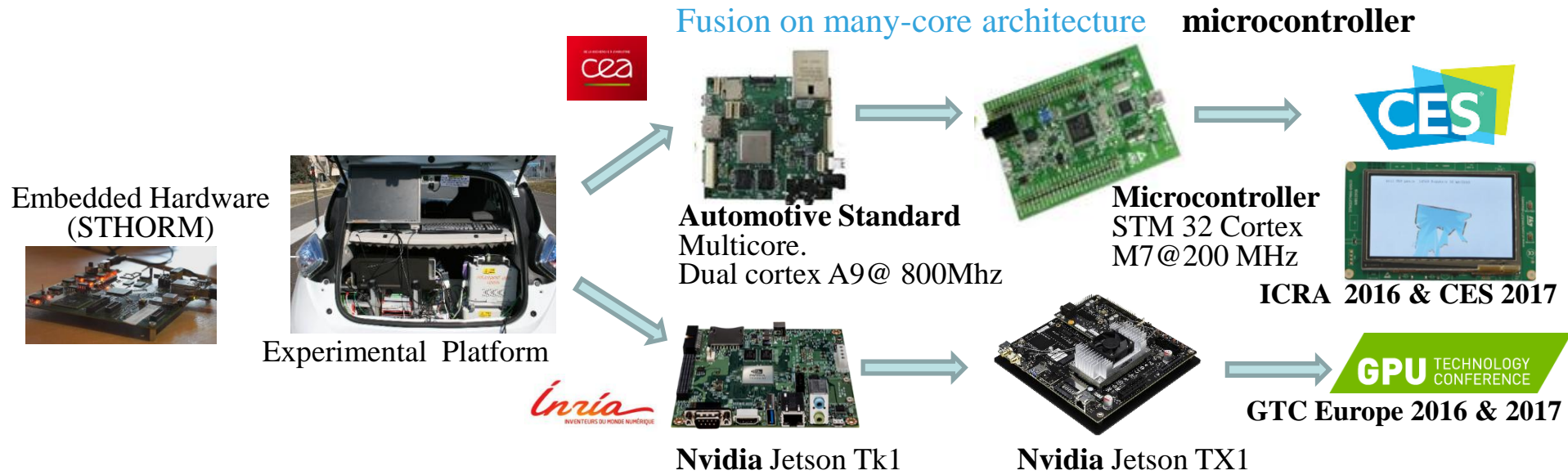
(U-disparity OG + Road / Obstacles classification)



Bayesian Sensor Fusion (Stereo Vision + Lidars)

Embedded Perception

Objectives & Achievements 2013 -17



BOF

HSBOF

CMCDOT

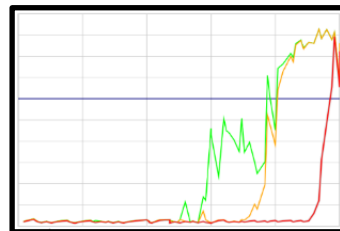
CMCDOT *Cuda Optimization on Tegra*

2013

2014

2015

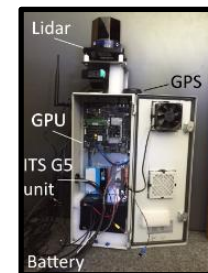
2016 - 17



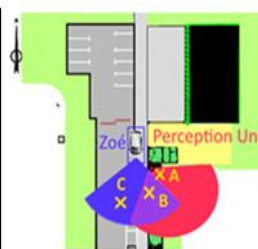
Risk assessment system



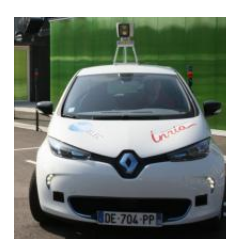
Experimental scenario (crash-test equipment)



Connected Perception Unit



Distributed Perception (V2X)



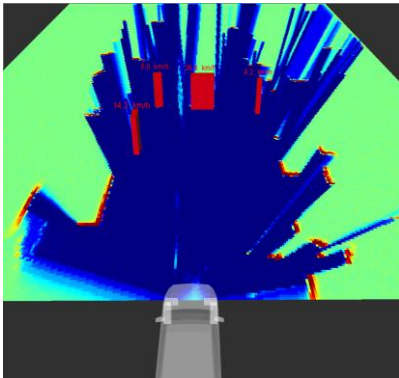
Zoe Automatization

DP-Grids: *Recent implementations & Improvements*

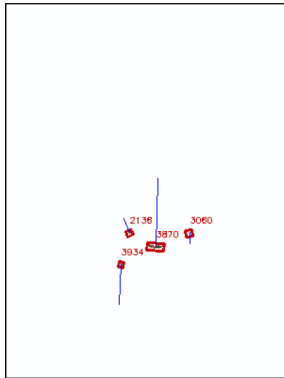


*Several implementations (models & algorithms) more and more adapted to **Embedded constraints & Scene complexity***

- ❖ Hybrid Sampling Bayesian Occupancy Filter (HSBOF, 2014) [Negre et al 14] [Rummelhard et al 14]
=> *Drastic **memory size reduction** (factor 100) + Increased **efficiency** (complex scenes) + More accurate **Velocity estimation** (using Particles & Motion data from ego-vehicle)*
- ❖ Conditional Monte-Carlo Dense Occupancy Tracker (CMCDOT, 2015) [Rummelhard et al 15]
=> *Increased **efficiency** using “state data” (Static, Dynamic, Empty, **Unknown**) + Integration of a “**Dense Occupancy Tracker**” (Object level, Using particles propagation & ID)*
- ❖ CMCDOT + Ground Estimator (under Patenting, 2017) [Rummelhard et al 17]
=> *Ground shape estimation & Improve obstacle detection (avoid false detections on the ground)*



Grid & Pseudo-objects



Tracked Objects



Classification (using Deep Learning)

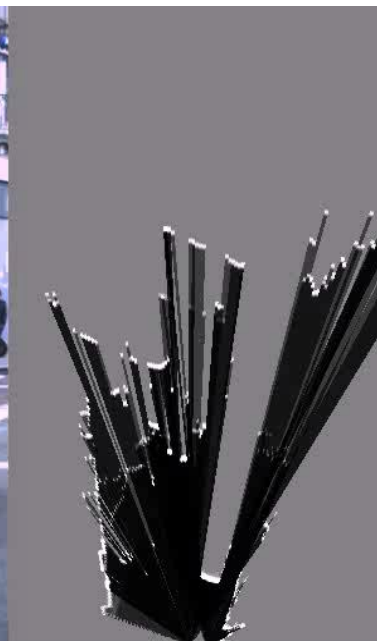
Detection & Tracking
& Classification

Experimental Results in dense Urban Environments

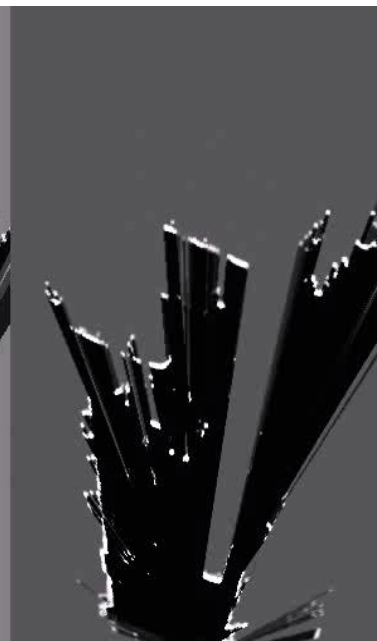
Observed Urban Traffic scene



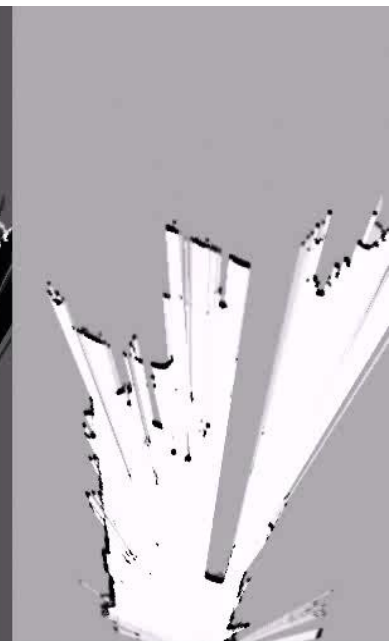
Ego Vehicle (*not visible on the video*)



OG Left Lidar



OG Right Lidar



OG Fusion
+
Velocity Fields



Detection & Tracking & Classification results



Moving Object Classification

Pedestrian

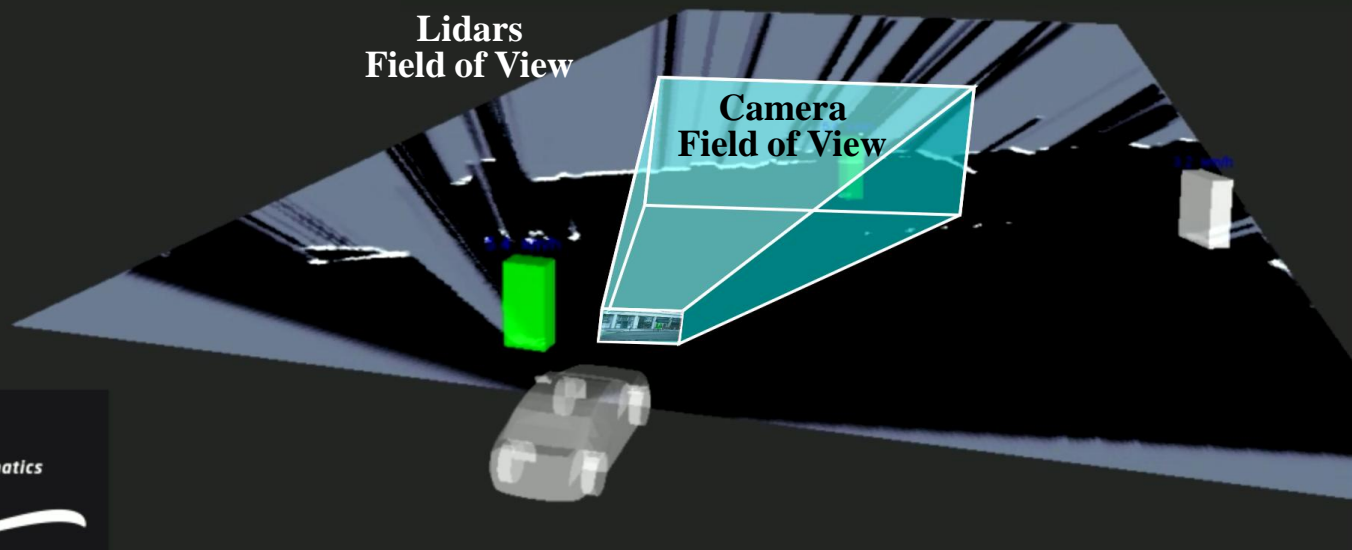
Bicycle

Vehicle

Other

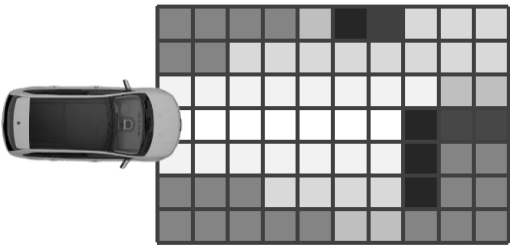
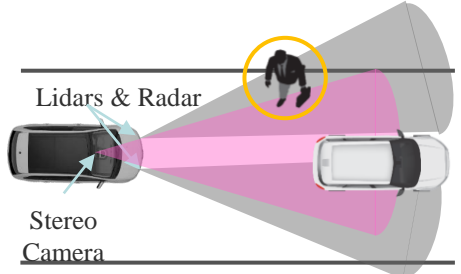
Lidars
Field of View

Camera
Field of View



Software / Hardware Integration – Motivation

PhD Tiana Rakotovao



~ Billions Floating-point operations per sec

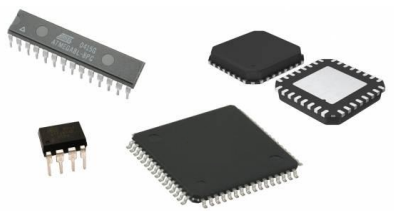
- OGs in practice:
- High number of cells
 - Several sensors

Not adapted for automotive industry



High-end GPUs & CPUs

Electronic Control Units
Microcontroller, FPGA ...



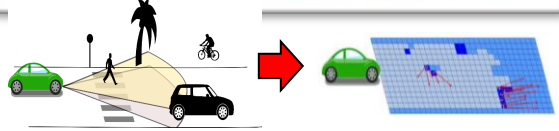
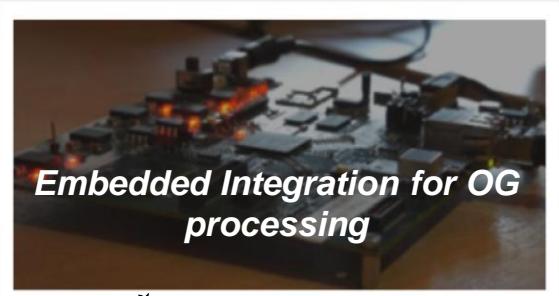
How to integrate computing requirements of OGs into embedded ECUs ?

Software / Hardware Integration – Main Features

PhD Tiana Rakotovao

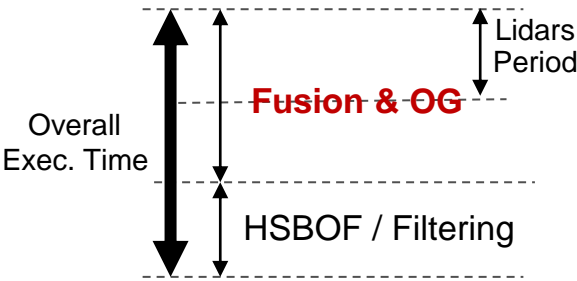
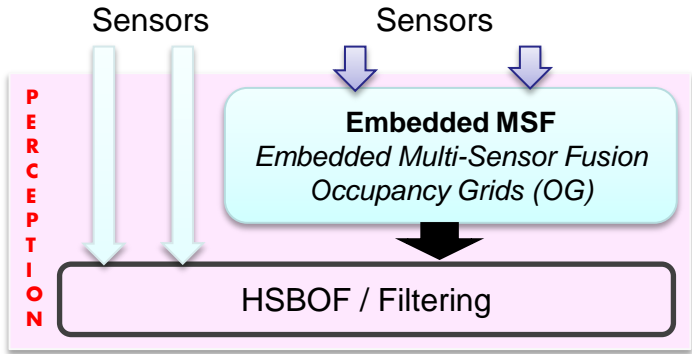


The challenge: How to cope with contradictory requirements & constraints ?



- **Embedded characteristics:** *Low computing power, Low memory space, Low bandwidth*
- **Embedded constraints:** *Low purchase cost, Low energy consumption, Small physical size*
- **Algorithmic constraints:** *High computing requirement, High memory space & bandwidth requirement*

Time Performance Analysis



HW Accelerator
 => Focus on Embedded Multi-Sensor Fusion

Software / Hardware Integration – GPU



- Highly parallelizable framework, **27 kernels** over cells and particles
 => Occupancy, speed estimation, re-sampling, sorting, prediction
- Real-time implementation (20 Hz), optimized using Nvidia profiling tools

Results:

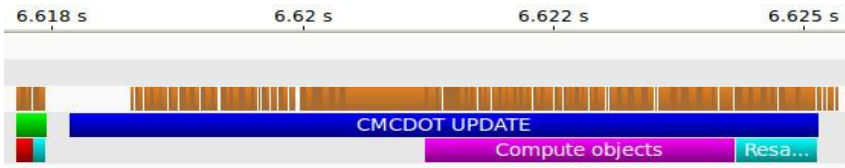
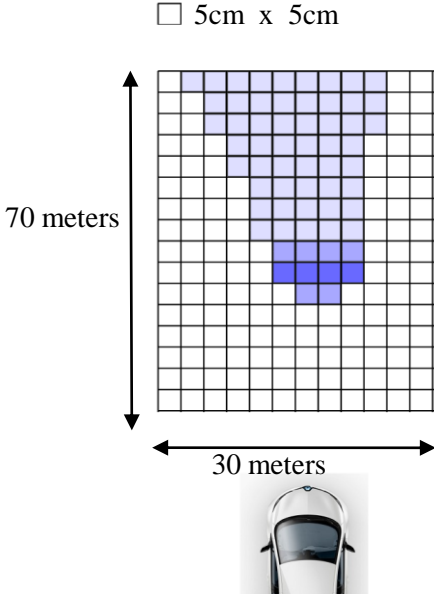
- Configuration with 8 Lidar layers (2x4)
- Grid: 1400 x 600 (840 000 cells) + Velocity samples: 65 536



=> Jetson TK1: *Grid Fusion 17ms, CMCDOT 70ms*



=> Jetson TX1: *Grid Fusion 0.7ms, CMCDOT 17ms*



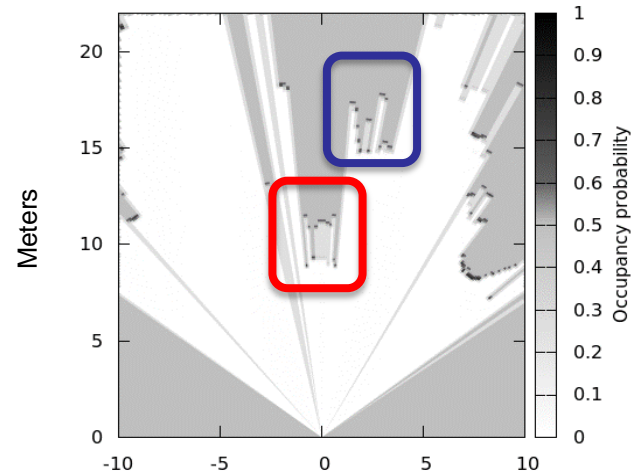
Software / Hardware Integration – μ Controller

PhD Tiana Rakotovao


Implementing MSF (OG without filtering) on μ Controller [1][2]

- ⇒ Low Cost / Energy / Size (widely used in Industrial product)
- ⇒ Implementation based on **Integer Arithmetic** (Quantized Occupancy Probability)
- ⇒ Time performance: **Increased by a factor 5-10**
- ⇒ Energy Consumption: **Decreased by a factor 100**

Inria /Renault Zoé (4 Lidars @ 25Hz)



Multi-Sensor Fusion on μ Controller



ARM Cortex-M3 @48MHz

- No floating-point
- Power consumption < 1Watt
- Low-cost < 2 €



[1] T. Rakotovao, et al. Multi-Sensor Fusion of Occupancy Grids based on Integer Arithmetic. IEEE ICRA 2016
[2] PhD Thesis T. Rakotovao, Feb 2017

Experimental Platforms & V2X



~200 m long
 Parking lots, Road, Intersection
 Traffic Lights
 Cameras, Road sensors, V2X



Autonomous Renault Zoé



2 Renault Twizy



Pedestrian Crash-test platform



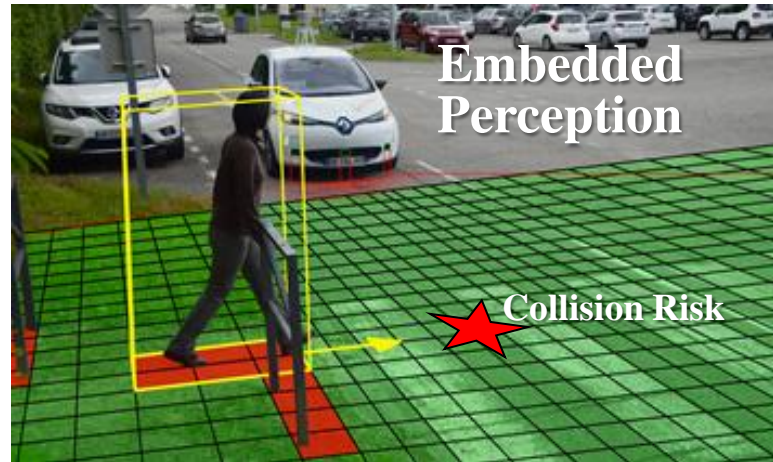
Connected Perception Unit



Connected Traffic Cone

V2X: Extended Collision Risk Assessment

Concept of Distributed Perception



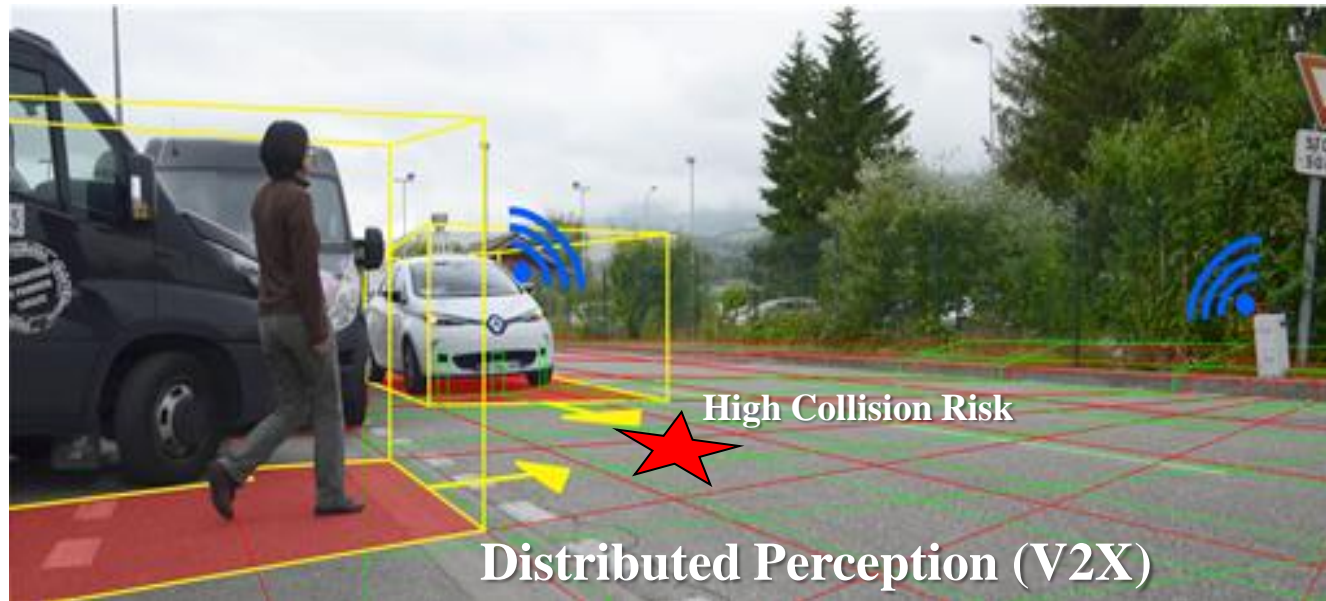
Embedded Perception

Collision Risk

Detection & Collision Risk using embedded Perception



Detection & Collision Risk using Infrastructure Sensors & V2X

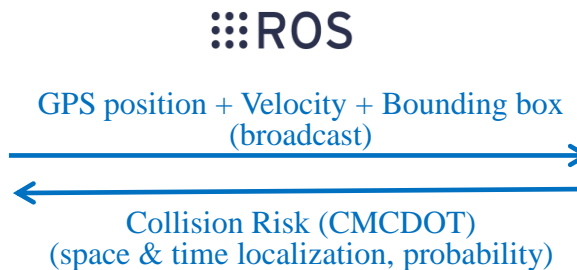


High Collision Risk

Distributed Perception (V2X)

V2X: Data exchange & Synchronization

□ Data exchange



ITS-G5 (Standard ITS Geonetworking devices)
Basic Transport Protocol IEEE 802.11p

Same perception system (DP-Grids + Risk)

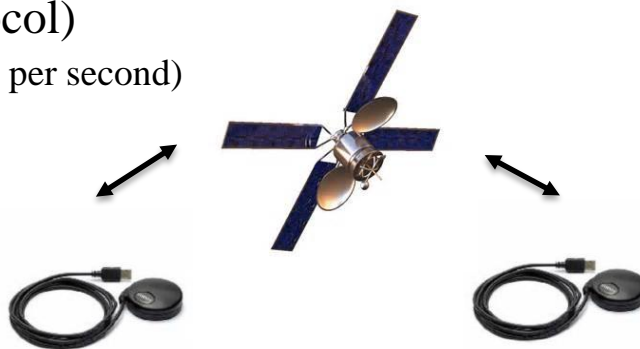
□ Synchronization

Chrony (Network Time Protocol)

GPS Garmin + PPS Signal (1 pulse per second)



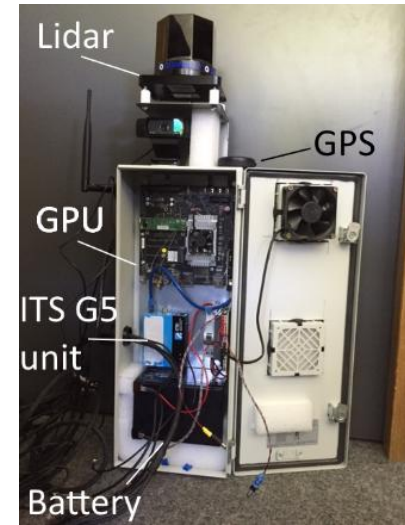
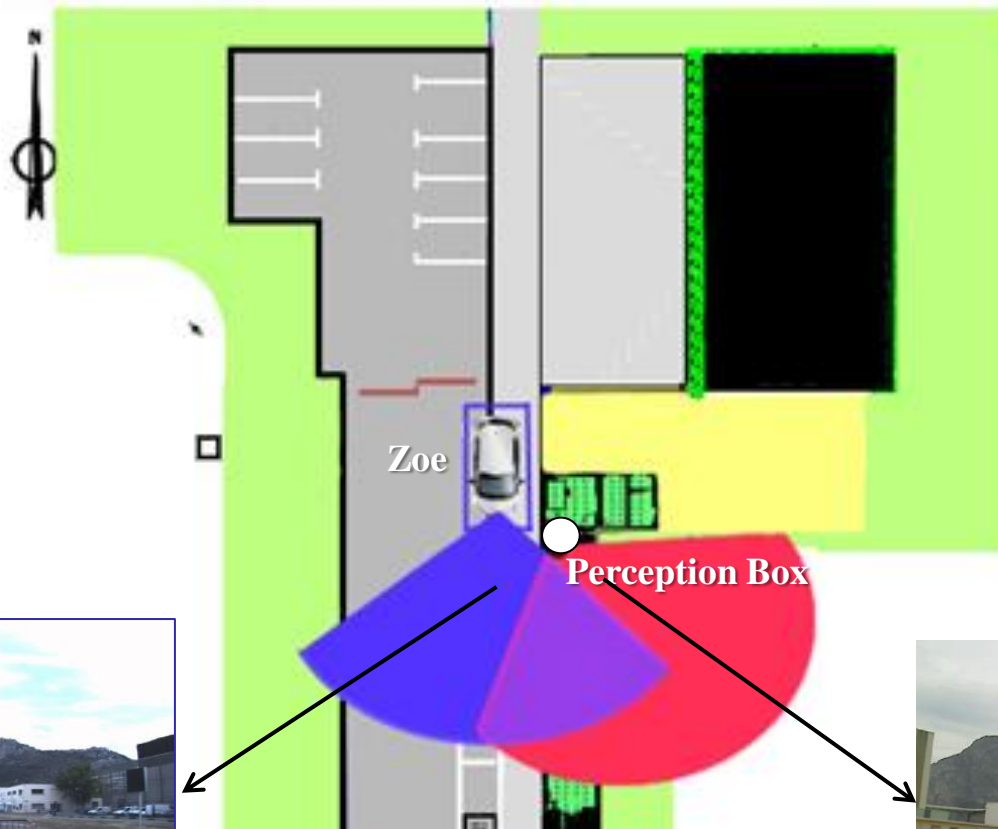
Serial Port



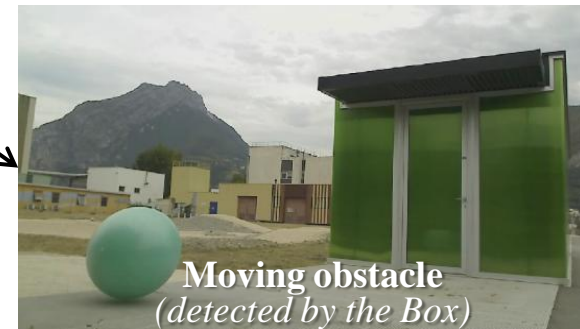
GPIO + UART



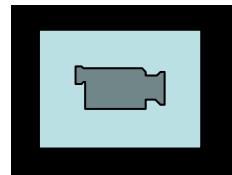
V2X: Distributed Perception Experiment



Camera Image provided by the Zoe vehicle



Camera Image provided by the Perception box

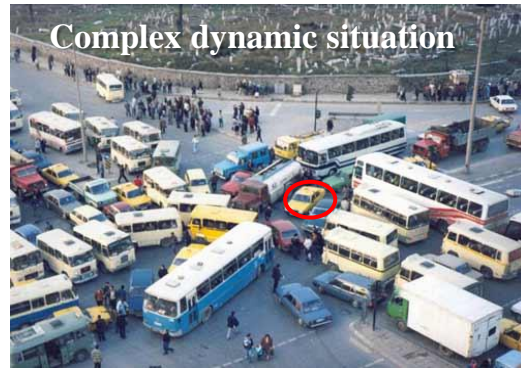


Content of the Lecture

- ❑ Socio-economic & Technological Context
- ❑ Decisional & Control Architecture: Outline
- ❑ Bayesian Perception (*Key Technology 1*)
- ❑ Embedded Perception & Experimental results
- ❑ **Bayesian Risk Assessment & Decision-making**
(*Key Technology 2*)
- ❑ Conclusion & Perspectives

Key Technology 2: Risk Assessment & Decision

=> Decision-making for avoiding Pending & Future Collisions



□ Main challenges

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

□ Approach: Prediction + Risk Assessment + Bayesian Decision-making

- ✓ Reason about *Uncertainty & Contextual Knowledge* (using *History & Prediction*)
- ✓ Estimate probabilistic Collision Risk at a given *time horizon* $t+\delta$
- ✓ Make Driving Decisions by taking into account the *Predicted behavior* of all the observed surrounding traffic participants (cars, cycles, pedestrians ...) & *Social / Traffic rules*

DP-Grids: Underlying Conservative Prediction Capability

=> *Application to Conservative Collision Anticipation*

[Coué & Laugier IJRR 05]

Autonomous
Vehicle (Cycab)



Parked Vehicle
(occultation)

**Pioneer
Results
(2005)**

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*)

Short-term collision risk – Main features

=> *Grid level & Conservative motion hypotheses (proximity perception)*

□ Main Features

- Detect “**Risky Situations**” a few seconds ahead (0.5 to 3s)
- 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 h*)
- Resulting information can be used for choosing **Avoidance Maneuvers**

Proximity perception: $d < 100m$ and $t < 5s$

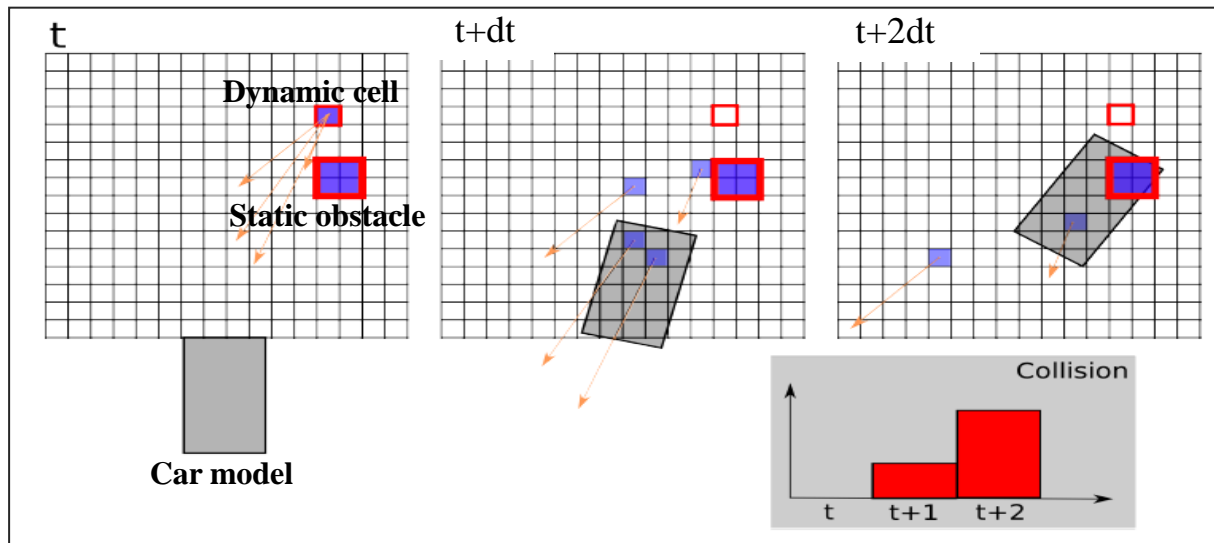
$\delta = 0.5 s$ => *Pre-crash*

$\delta = 1 s$ => *Collision mitigation*

$\delta > 1.5 s$ => *Warning / Emergency Braking*

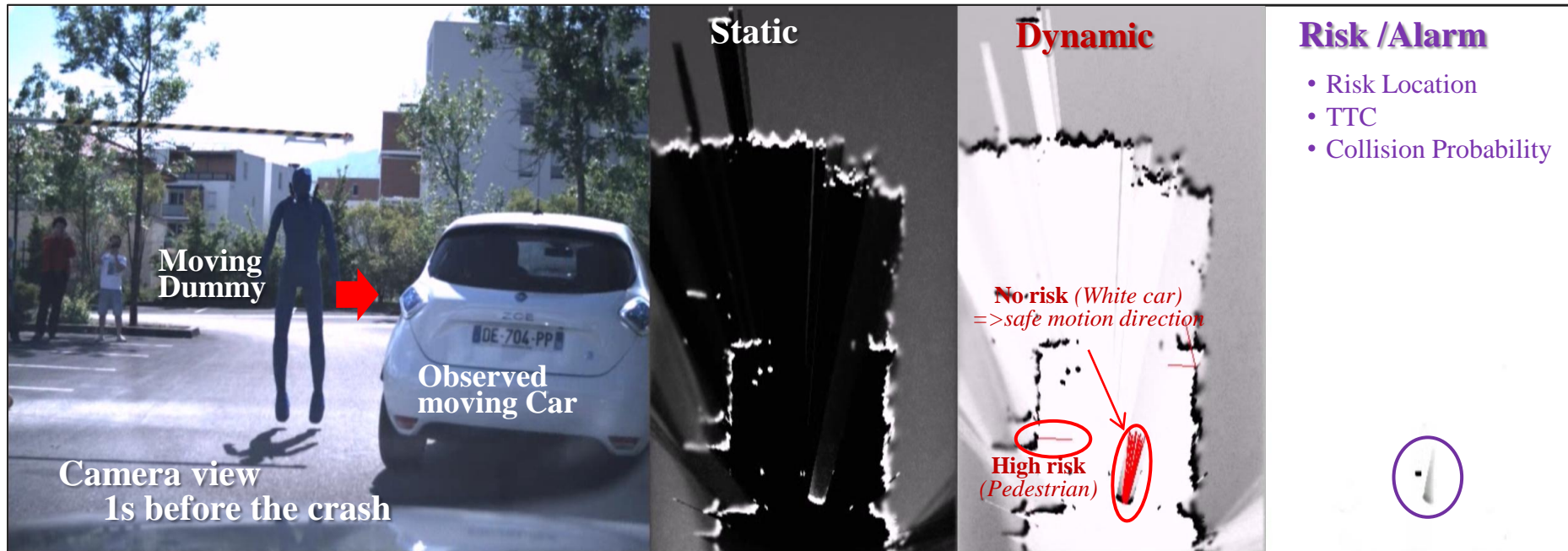
□ Collision Risk Estimation

- ✓ *Projecting over time the estimated Scene changes (DP-Grid) & Car Model (Shape + Motion)*
- ✓ *Evaluate the Collision Risk for every next time step*
- ✓ *Integration of risk over a time range $[t, t + \delta]$*



Short-term collision risk – System outputs

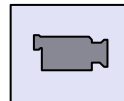
=> *Static & Dynamic grids + Risk assessment*



Short-term collision risk – *Experimental results*

Objectives:

- ✓ *Detect most of potential future collisions*
- ✓ *Reduce drastically false alarms*

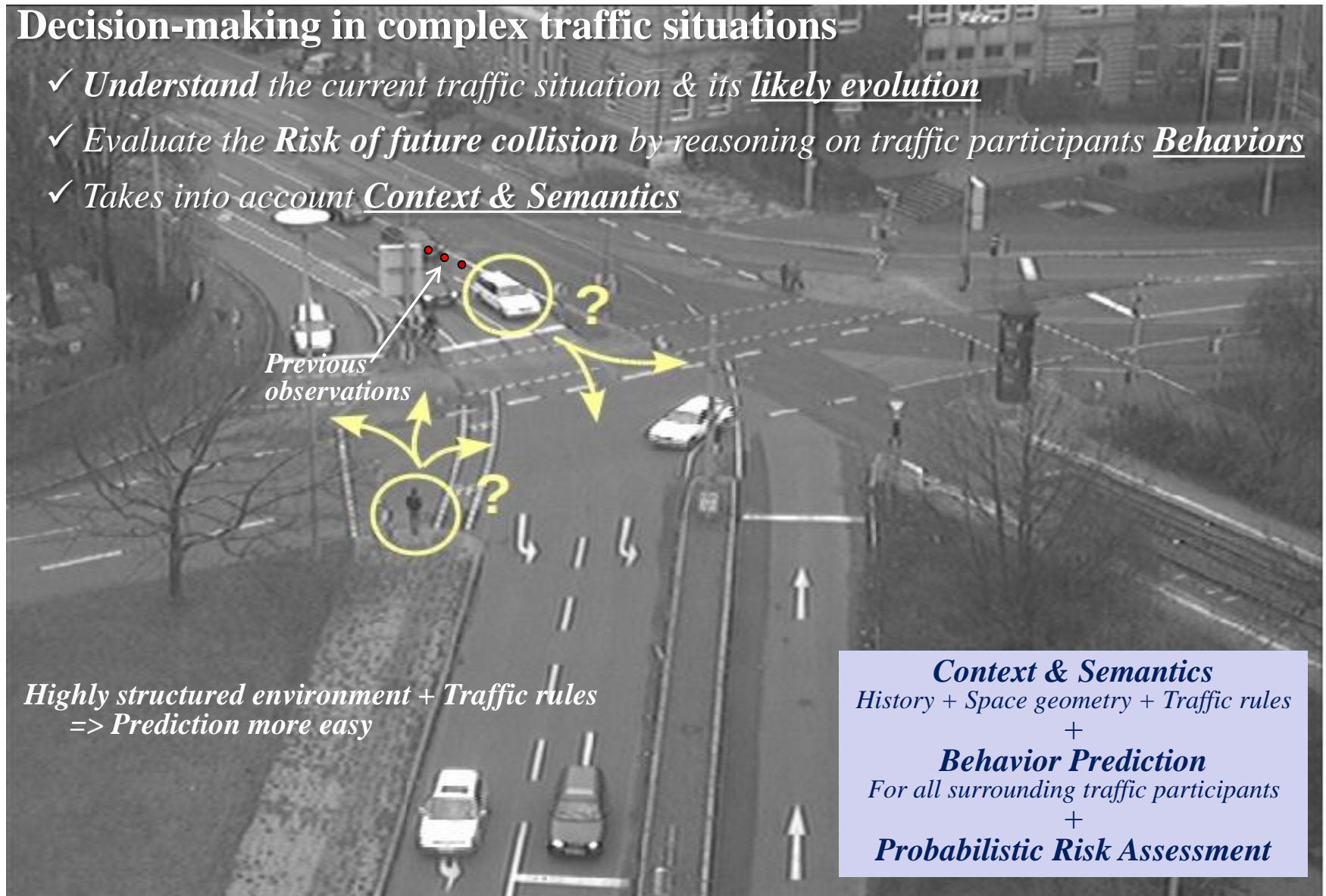


Generalized Risk Assessment (Object level)

- => *Increasing time horizon & complexity using context & semantics*
- => *Key concept: Behaviors Modeling & Prediction*

Decision-making in complex traffic situations

- ✓ *Understand the current traffic situation & its likely evolution*
- ✓ *Evaluate the **Risk of future collision** by reasoning on traffic participants Behaviors*
- ✓ *Takes into account Context & Semantics*



*Highly structured environment + Traffic rules
=> Prediction more easy*

Context & Semantics
History + Space geometry + Traffic rules
+
Behavior Prediction
For all surrounding traffic participants
+
Probabilistic Risk Assessment

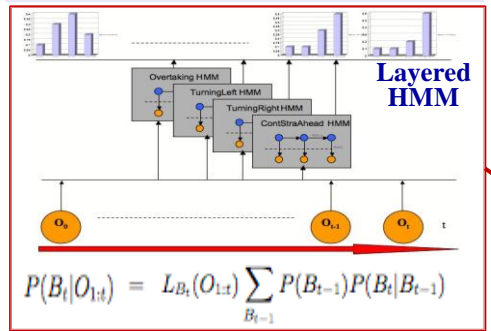
Behavior-based Collision risk (Object level)

Approach 1: Trajectory prediction & Collision Risk Assessment

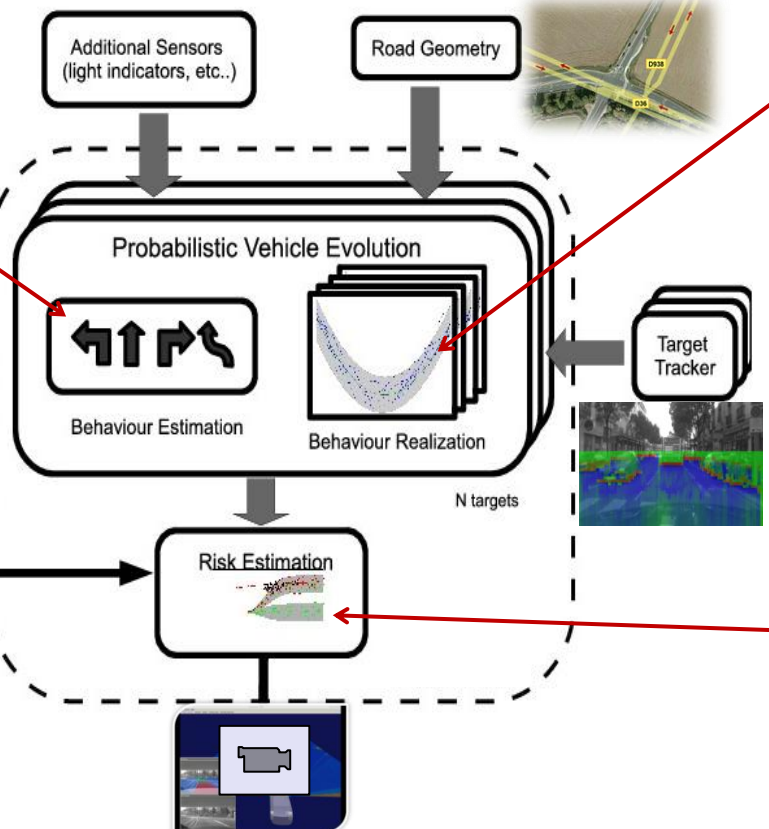
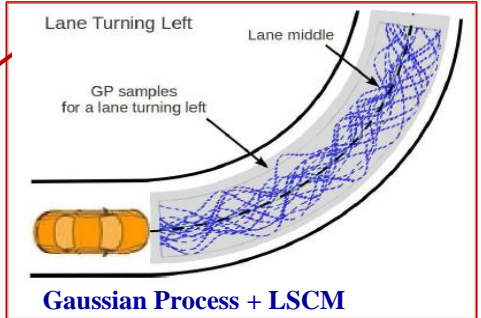
[Tay thesis 09] [Laugier et al 11]

Patent Inria & Toyota & Probayes 2010

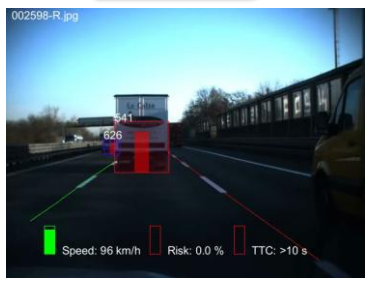
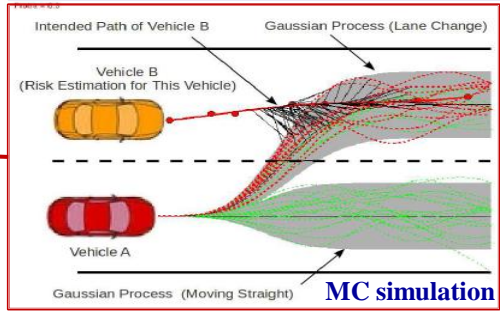
Behavior modeling & learning + Behavior Prediction



From behaviors to trajectories



Collision risk assessment (Probabilistic)



Experimental Results
Behavior prediction & Risk Assessment
on highway
Probayes & Inria & Toyota

Courtesy Probayes

Behavior-based Collision risk (*Object level*)

Approach 2: Intention & Expectation comparison

=> Complex scenarios with interdependent behaviors & human drivers



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

Patent Inria & Renault 2012 (risk assessment at road intersection)

Patent Inria & Berkeley 2013 (postponing decisions for safer results)



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

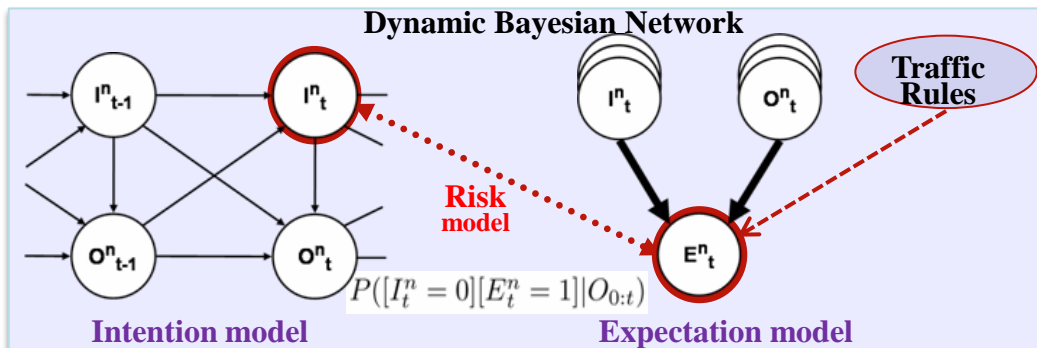
✓ Estimating “Drivers Intentions” from Vehicles States Observations ($X Y \theta S TS$) => Perception or V2V

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

✓ Risk = Comparing Maneuvers Intention & Expectation

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

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

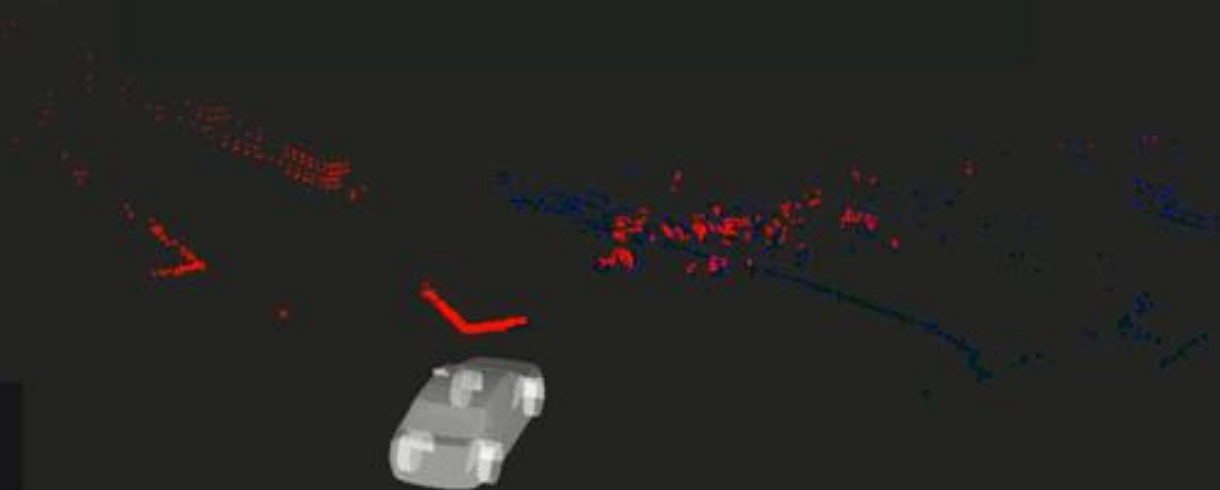


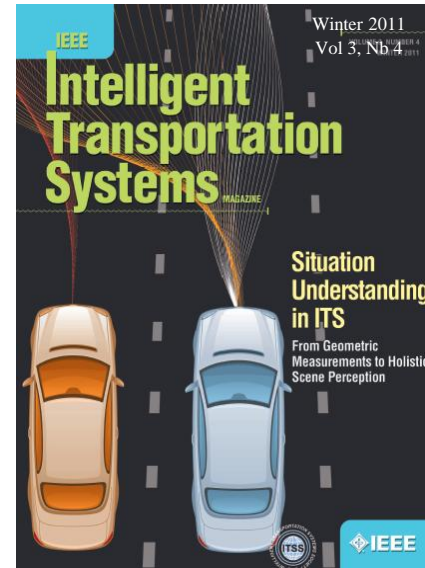
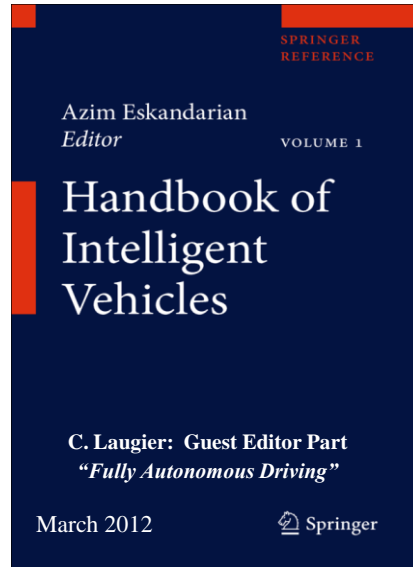
CMCDOT – Experimental results in urban environment

Annotated Video

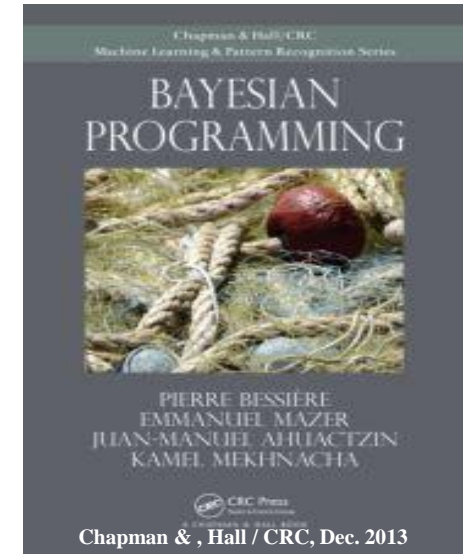
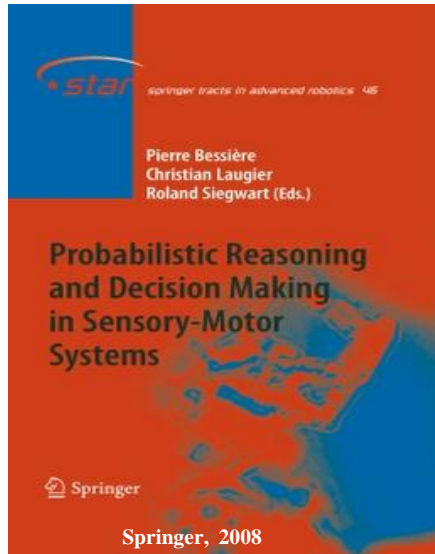


Sensor data





Thank You  Any questions ?



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