Key Technologies for Addressing the Challenge of Autonomous Vehicles

Christian LAUGIER, First class Research Director at Inria

http://emotion.inrialpes.fr/laugier

Contributions from

Mathias Perrollaz, Christopher Tay Meng Keat, Stephanie Lefevre

Keynote talk, Int. Conf. "Innovations for Next Generation Automobiles"
Sendai (October 2014)

Structure of the talk

- **Context, State of the Art, New Challenges & Approach**

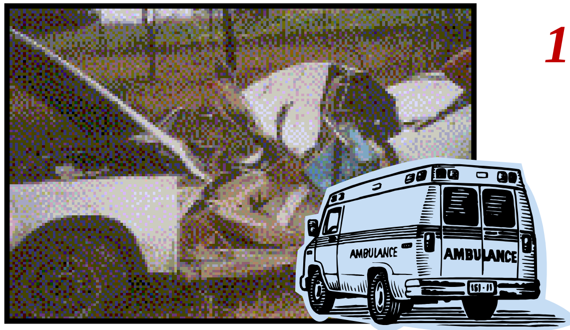
- **Bayesian Perception for Open & Dynamic Environments**
  - ***Bayesian Perception paradigm***
  - ***Embedded Perception & Bayesian Sensor Fusion***

- **Situation Awareness & Risk Assessment**
  - ***Learn & Predict Paradigm***
  - ***Trajectory Prediction & Probabilistic Collision Risk***
  - ***Comparing Intentions & Expectations for Cooperative Safety***

- **Conclusion & Perspectives**

Socio-Economic & Technical context

- Human Society is no more accepting the incredible socio-economic cost of traffic accidents !



1.2 million fatalities / year in the world !!!!

• USA (2007) : Accident every 5s =>41 059 killed & 2.6 million injured
…. Similar numbers in Europe
• France (2008): 37 million vehicles & 4443 fatalities (number reduced by 50% in the past years, thanks to both regulation & improved car technology).
=> Human & financial cost estimated to 23 B€ for 2011 in France !

- **Driving Safety** is now becoming a **major issue** for both governments *(regulations & supporting plans)* and automotive industry *(technology)*

- Thanks to the last decade advances in the fields of ***Robotics & ICT technologies***, ***Smart Cars & ITS*** are gradually becoming a reality
=> Driving assistance & Autonomous driving, Passive & Active Safety systems, V2V & I2V communications, Green technologies … and ***Sensors & Embedded Perception 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*

Governments plans for Robotics & IV Innovation

January 2007

Bill Gates:
"The next hot field will be Robotics"

President Obama announced
Major Robotics Initiatives

Priority Axes (100 M€)

- ❖ **Transportation & Logistics**
- ❖ Defense & Security
- ❖ Environment
- ❖ Intelligent Machines
- ❖ Personal Assistance

34 Industrial Plans (3.5 B€)

- ❖ Robotics
- ❖ **Driverless Car**
- ❖ Embedded Systems
- ❖ Factory of the future
- ❖ ….

State of the Art – *Cybercars technologies*

- **An EU driven concept since the 90's: "Cybercars"**
  - ✓ *Autonomous Self Service* ***Urban & Green*** *Vehicles at low speed*
  - ✓ *Numerous R&D projects in Europe during the* ***past 20 years***
  - ✓ *Several European* ***cities involved***
  - ✓ *Some* ***commercial products*** *already exist for protected areas (e.g. airports, amusement parks …), e.g. Robosoft, 2GetThere , Induct…*

- **Several early large scale public experiments in Europe**

Movie : Floriade 2002, Amsterdam
(2GetThere & Inria)

Movie : Shanghai public demo 2007
(SJTU & Inria, EU FP7 project)

State of the Art – Fully Autonomous Driving

❑ Fully Autonomous Driving

✓ *More than 25 years of research, for both Off-road & Road Vehicles*

✓ *Significant recent steps towards fully autonomous driving …. Partly pushed forward by events such as DARPA Grand & Urban Challenges … and Google Car*

✓ *Fully Autonomous driving is gradually becoming a reality, for both the* ***Technical & Legal*** *point of views (e.g. Recent Nevada law for driverless cars)*

❑ Results & Major events

Pioneer work at INRIA (mid 90's)

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

2010 VIAC Intercontinental Autonomous Challenge
13 000 km covered, 3 months race, leader + followers
=> See Spring 2011 IEEE RAM issue

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

Autonomous Vehicles – Current Limitations

Current Autonomous Vehicles are able to exhibit quite impressive skills …. BUT they are ***not fully adapted to human environments*** *and they are often* ***Unsafe !***

=> DARPA Grand Challenge 2004
✓ *Significant step towards Motion Autonomy*
✓ ***But still some "Uncontrolled Behaviors" !!***

=> URBAN Challenge 2007
✓ *A large step towards road environments*
✓ ***But still some accidents, even at low speed !!***

=> Google Cars 2011 & Other projects in Europe
✓ *Impressive results & fully autonomous driving capabilities*
✓ ***But costly Sensors + Dense 3D mapping required + Human Factor weakly addressed !!***

Some technologies are almost ready for use in some restricted or protected public areas
BUT

✓ *Fully* ***Open & Dynamic environments*** *are still beyond the state of the art !*

✓ ***Safety*** *is still not guaranteed !*

✓ *Many* ***costly onboard sensors*** *&* ***High computing power*** *are still required !*

Intelligent Vehicles – Innovation & Products

❑ Cybercars : Some start-ups & first products

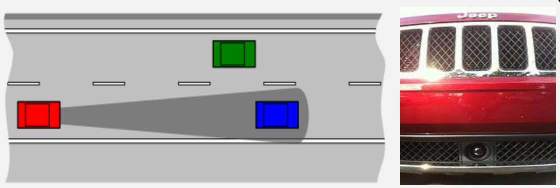
Cycab *(Inria /Robosoft)*

Cybergo *(Induct)*

Amsterdam Schiphol Airport
(2Get'There, 1997-2004)

Cybus, La Rochelle 2012
(CityMobil & Inria)

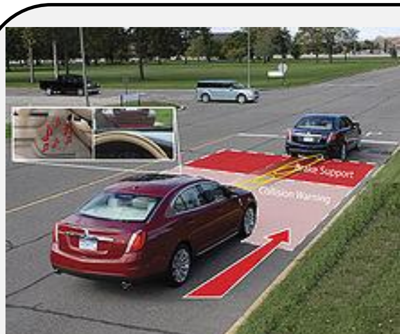
❑ ADAS : Increasing number of products & equipped cars



Adaptive Cruise Control (ACC)

Lane Guidance System *(PCB and Camera sensor from Hundai)*

Night / Bad Weather Vision



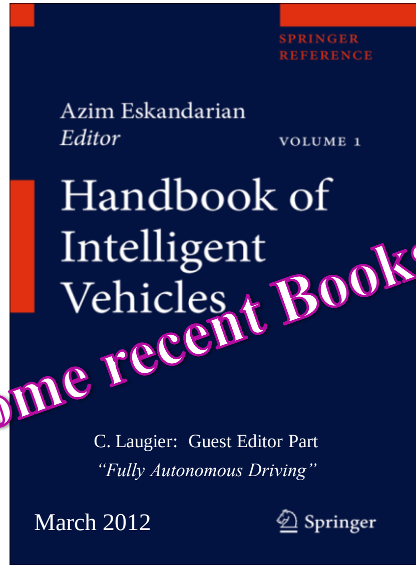
Collision Warning with Brake support
(Lincoln MKS, 2009)

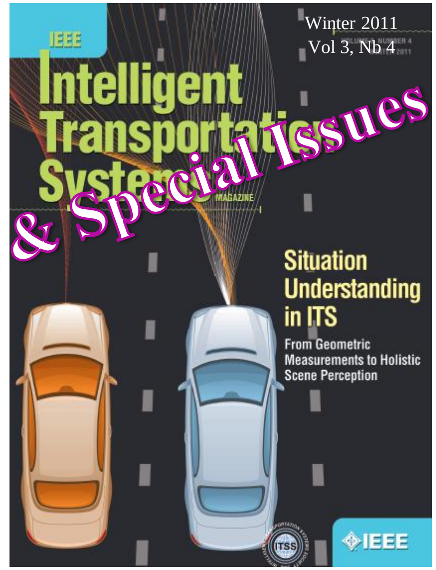
Radar based Pre-Collision System
(Toyota Lexus, 2003)

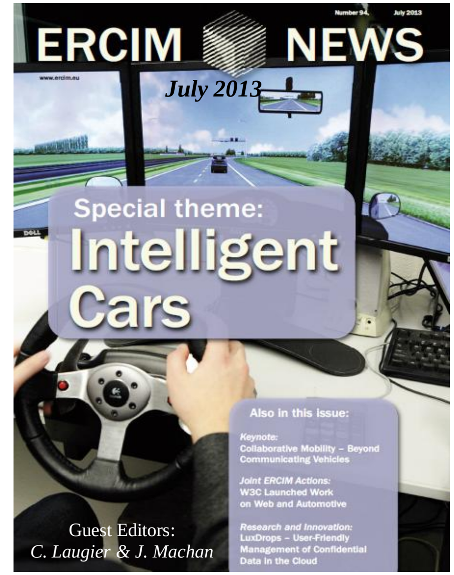
Parallel Parking System
(V1: Toyota Prius 2003 ; V2: Toyota Lexus 2006 & 2010)
=> Inspired by Inria approach 1996

Intelligent Vehicles & ITS – Recent Literature

Some recent Books & Special Issues







IEEE Technical Committee on "AGV & ITS"

Numerous Workshops & Special issues since 2002

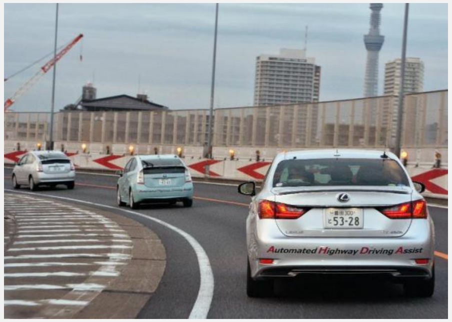
Intelligent Cars & ITS – *Towards Driverless Cars ?*

Horizon 2020-25 ?

Nissan promises a driverless car for 2020

LE FIGARO
Date : 29/08/2013

Google Car 2011
140 000 miles covered



Toyota
"Automated Highway Driving Assist"
(Demo Tokyo 2013, Product 2015)

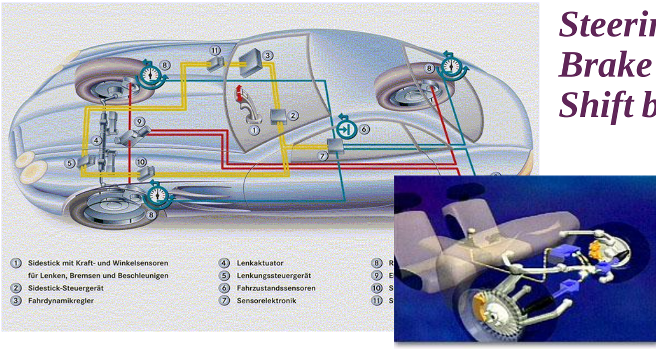
Voitures sans conducteur : Nissan va mettre un robot dans votre moteur !

But also:
Tesla (90% Autonomous, => 2016),
Volvo, Mercedes Class S, BMW …

Autonomous car: An industrial challenge for tomorrow !
The French Minister of Industry promotes driverless car

- ❖ Market Forecast : *8000 cars sold in 2020, about 95 millions in 2035*
- ❖ Still some open questions: *Why driverless cars ? Intelligent co-Pilot v/s Full Autonomy ? Acceptability ? Legal issue ? Driver / Co-Pilot Control transitions ?*

Car technology is almost ready for Driving Assistance & Fully Autonomous Driving



Steering by wire
Brake by wire
Shift by wire

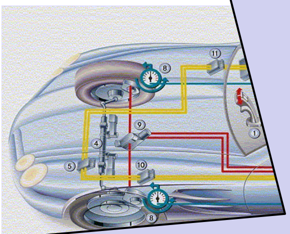
Virtual dash-board
Modern "wheel" ….

Navigation systems
Driving assistance (speed, ABS, ESB …)

Wireless Communication
Speech Recognition & Synthesis
… Towards connected cars

Radar, Cameras, Night Vision, Multiple sensors ….. but also
"Sensor based Active Driving Assistance" (e.g. Automatic Parking)
=> Cost decreasing & Efficiency increasing (future mass production, embedded systems, SoC …) !

Car te… ology is alm…
Drivi… istance & … Drivi…



…ing b…

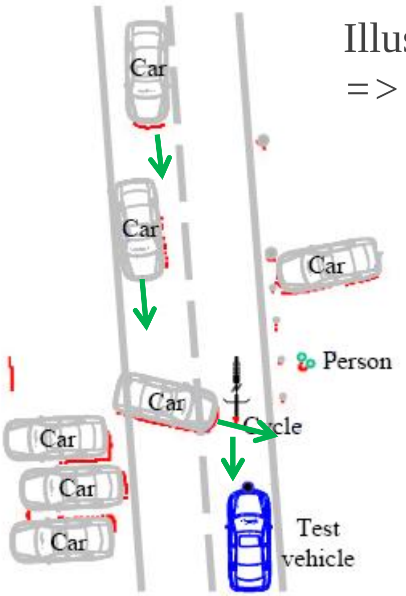
…. But a real deployment of ***Advanced Technologies for ADAS & Autonomous Driving***, requires first to deeply address three main technical issues:

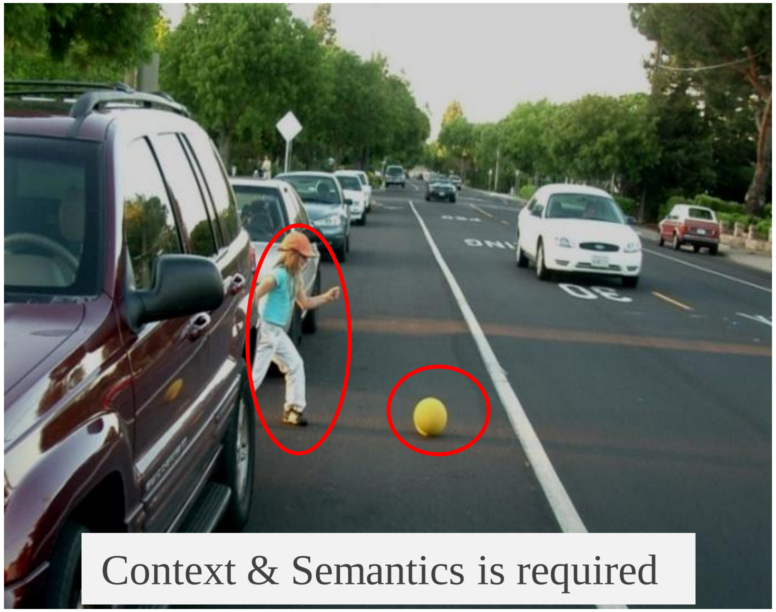
- ✓ ***Robust, Integrated, and Cheap enough "Embedded Perception Systems"***
- ✓ ***Advanced Control & Decision Making technologies … Taking into account Uncertainty***
- ✓ ***Friendly Human – Vehicle Interaction***

Par…
…g (future mass …) !!!!

Challenge 1: **Multimodal Perception & Situation Awareness**

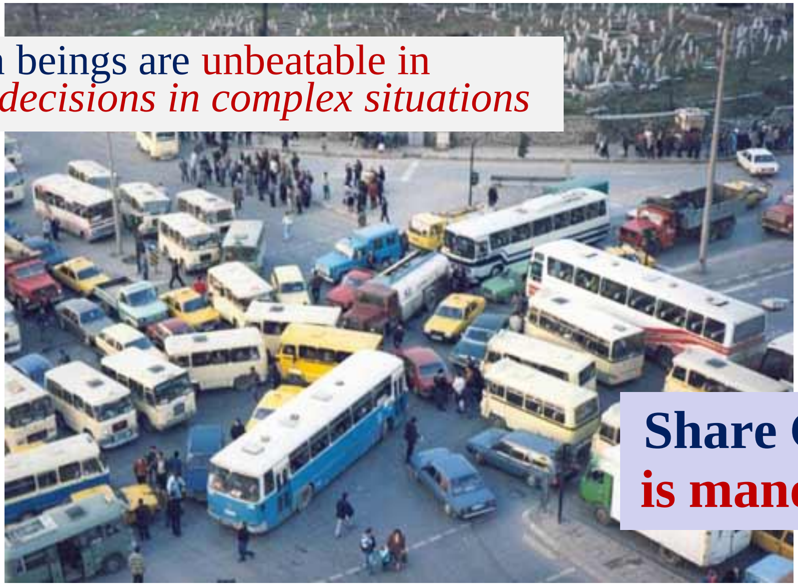
Illustration: Traffic scene understanding
=> *Detect, Track, Classify, Predict*



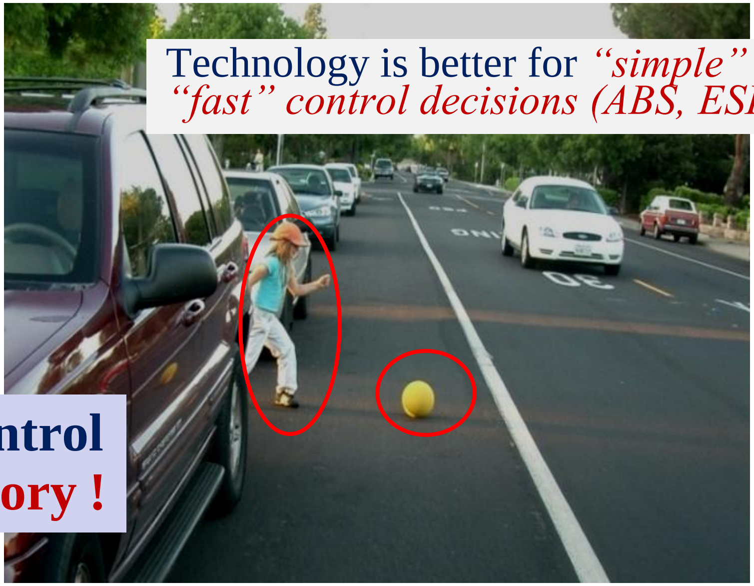


- ❑ Dynamicity & Uncertainty
  => Space & Time + Probabilities
- ❑ Interpretation ambiguities & Semantics
  => History, context, prior knowledge + Sensor fusion
- ❑ Prediction of future states (recently addressed)
  => Behaviors, prediction models
- ❑ Embedded Perception (necessary for deployment)
  => Miniaturization & Software / Hardware integration

Challenge 2: ***Human Aware Navigation & Interaction***



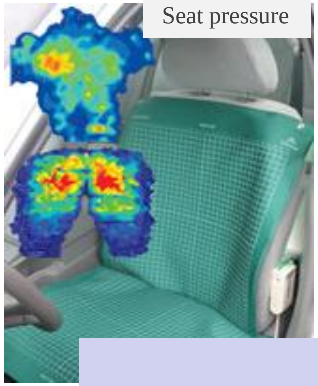
Human beings are unbeatable in *taking decisions in complex situations*



Technology is better for *"simple" but "fast" control decisions (ABS, ESP ...)*

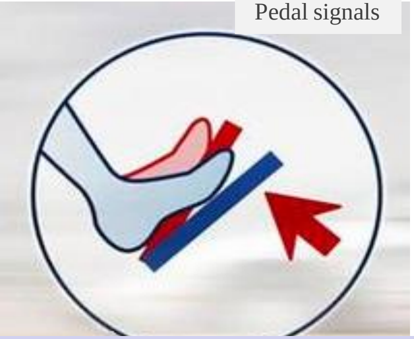
Share Control is mandatory !

.... But ***Driver inattention*** *is still a major cause of accident !*



Seat pressure

Steering actions



Pedal signals

Head /Eye Visual analysis

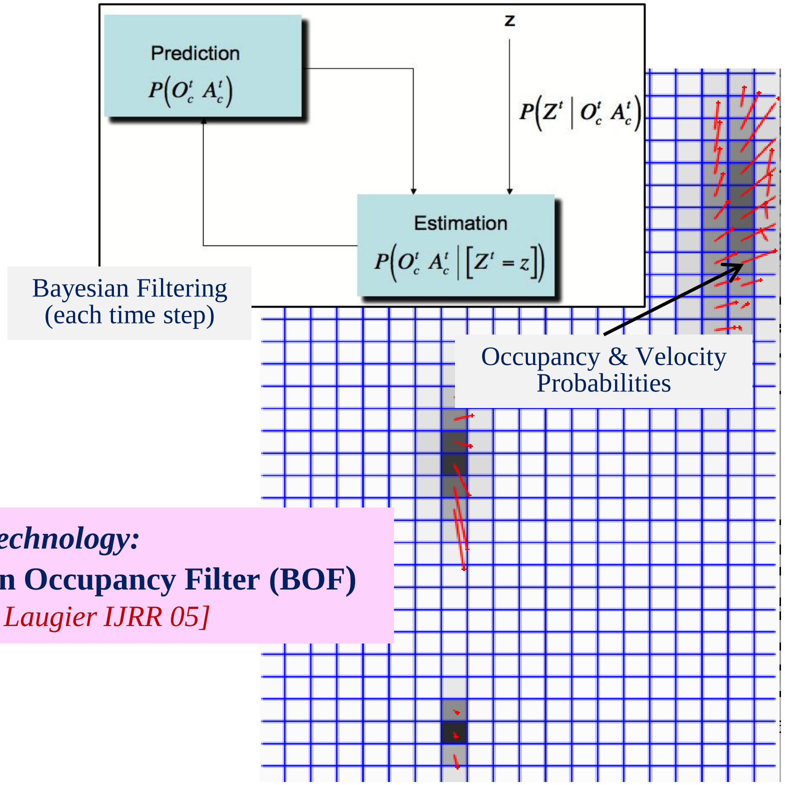
Driver Monitoring *(using on-board Perception)*
+
Safe & Socially Acceptable **Human / Vehicle Interaction is necessary !**
=> "Mutual Driver / Vehicle understanding"

Key Technology 1: *"Bayesian Perception paradigm"*

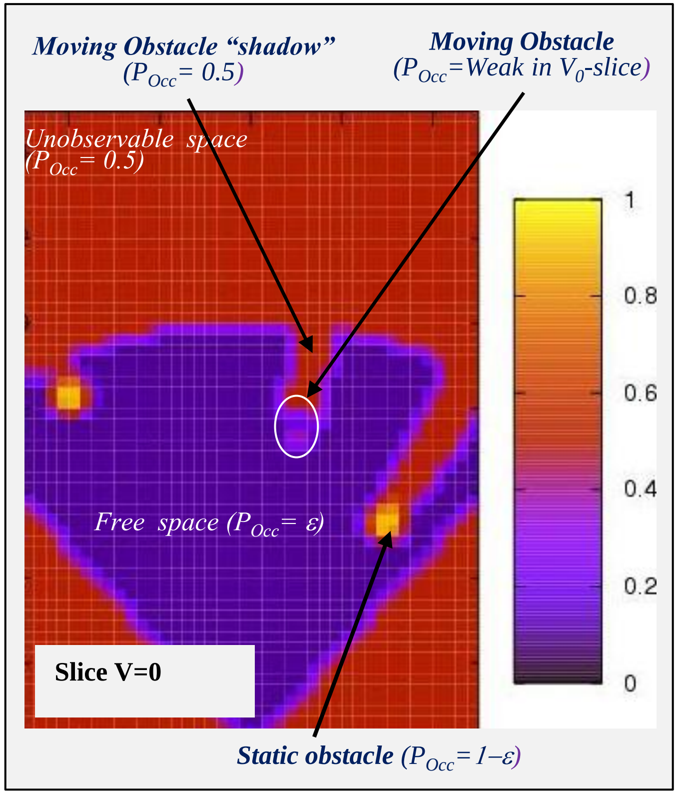
- ***Bayesian Perception for Open & Dynamic Environments***
- ***Embedded Perception & Bayesian Sensor Fusion***

Bayesian Perception for Dynamic Environments

⇒ *Developed by Inria, Patented by Inria & ProbaYes, Commercialized by ProbaYes 2006*
⇒ *Used by: Toyota, Denso, ProbaYes industrial applications + IRT Nanoelec CEA*



A Key Technology:
Bayesian Occupancy Filter (BOF)
[Coué & Laugier IJRR 05]



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

Underlying Conservative Prediction Capability
=> Application to Conservative Collision Anticipation

Autonomous Vehicle (Cycab)

Parked Vehicle (occultation)

[Coue et al IJRR 05]

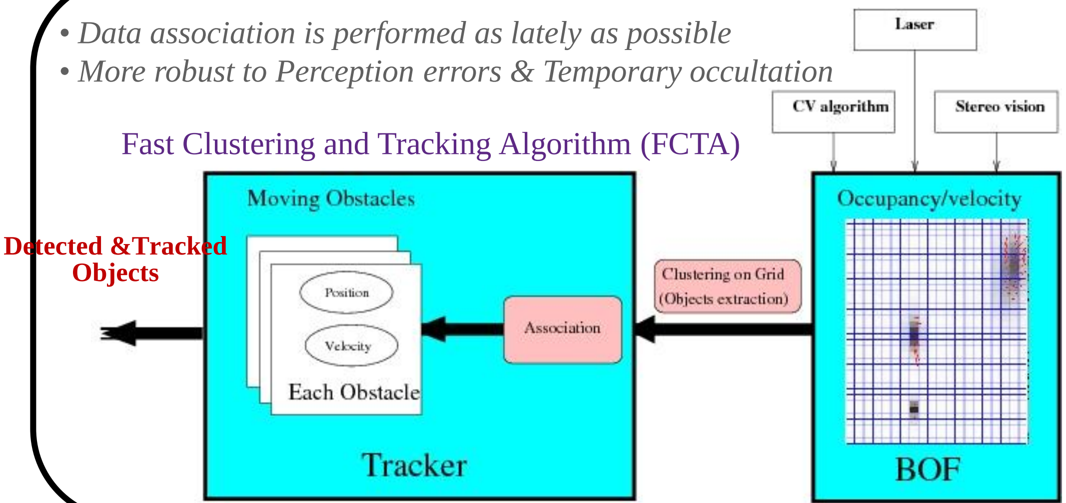
Thanks to the prediction capability of the BOF technology, the Autonomous Vehicle "anticipates" the behavior of the pedestrian and brakes *(even if the pedestrian is temporarily hidden by the parked vehicle)*

Multimodal Bayesian Sensor Fusion

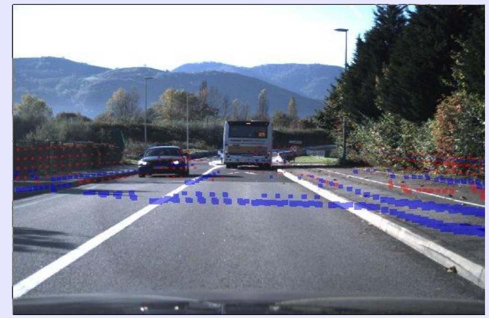
Bayesian Sensor Fusion + Detection & Tracking

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

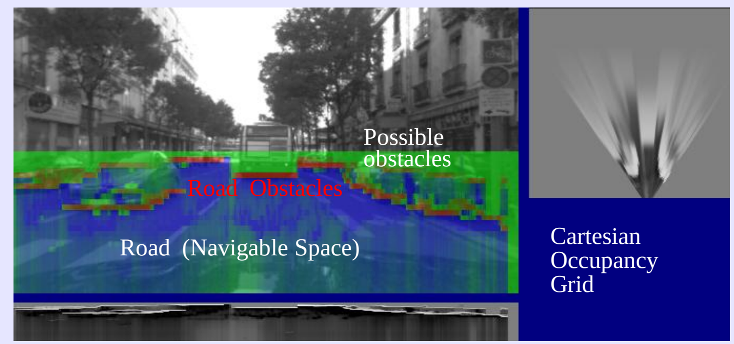
Fast Clustering and Tracking Algorithm (FCTA)



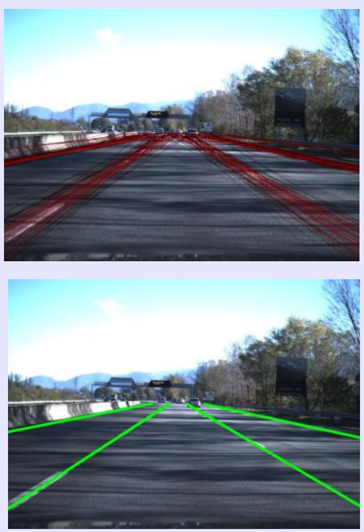
[Mekhnacha 09, Laugier et al ITSM'11]



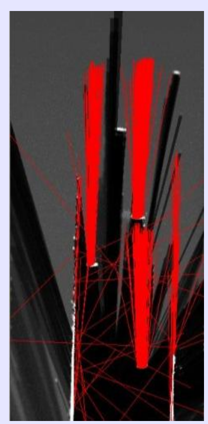
Laser Fusion *(8 layers, 2 lasers)*



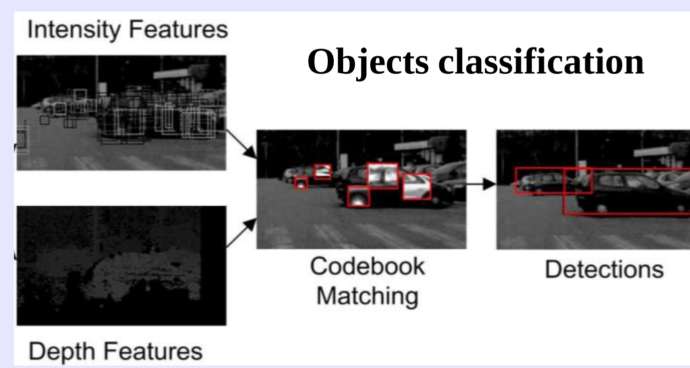
Stereo-vision *(U-disparity OG+ Road/obstacle classif.)*



Multi-Lane tracker



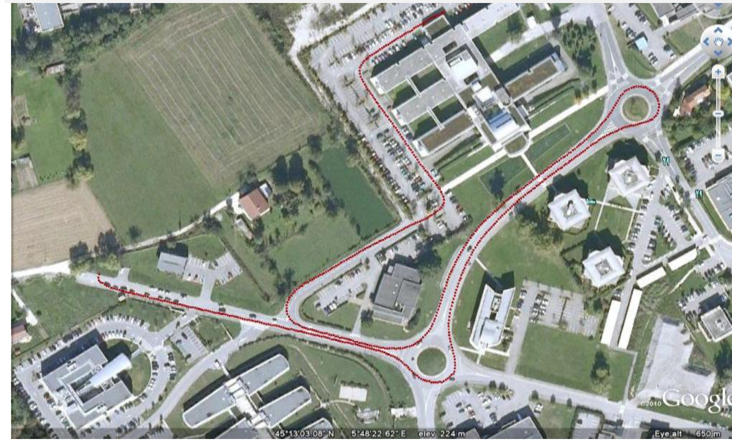
Motion Detection
=> Dynamic grid filtering using Motion data (IMU + Odometry)

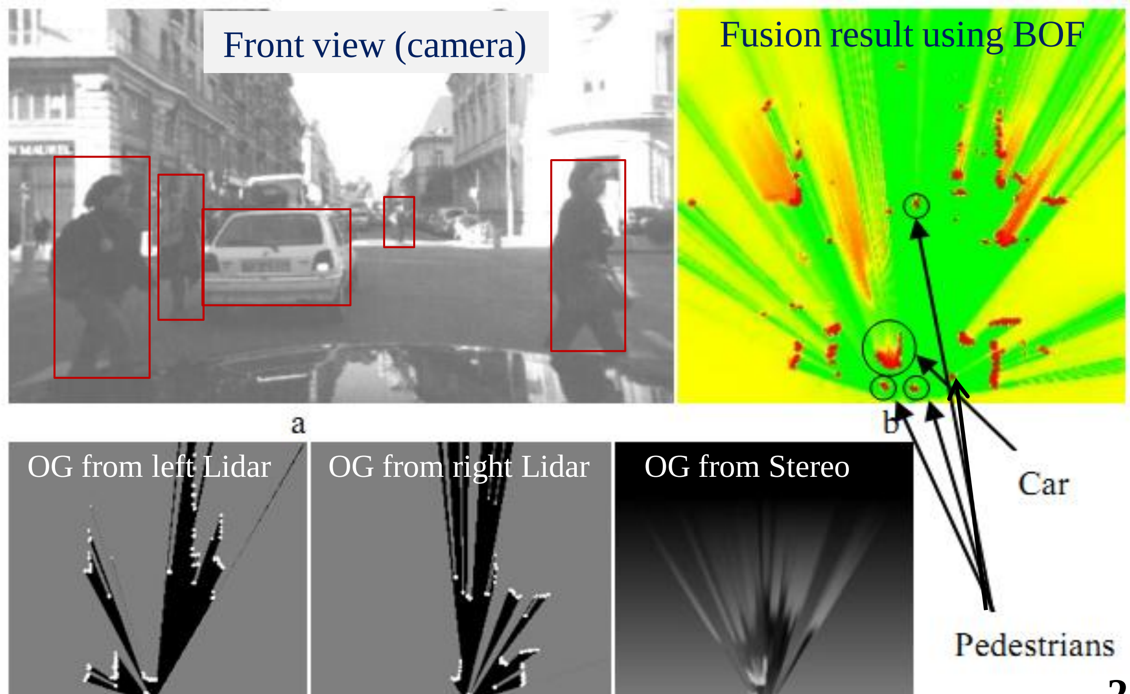


Embedded Perception System (Lexus)

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

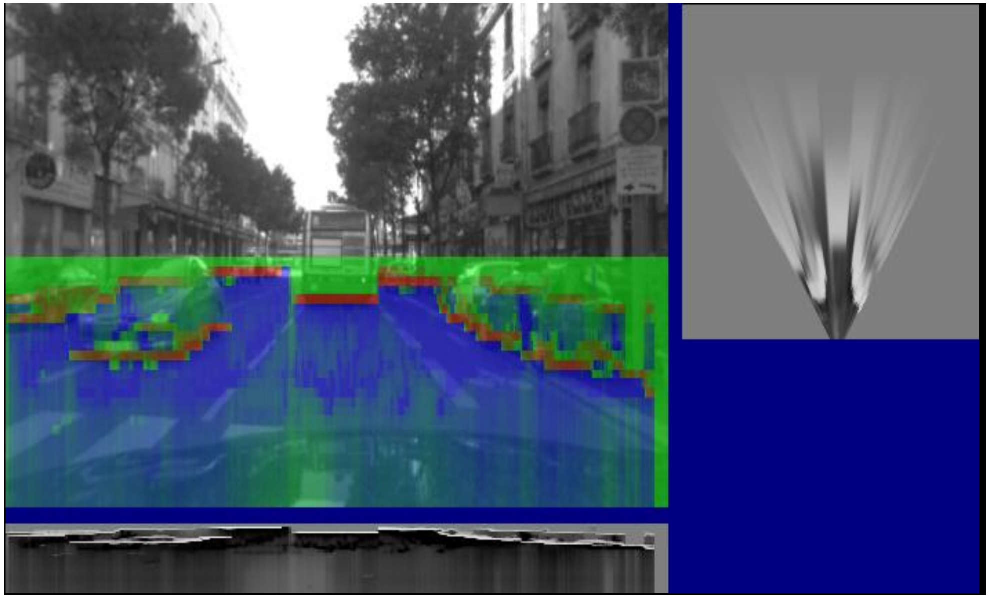
GPS track example
(Using Open Street Map & GPS & IMU & Odometry)

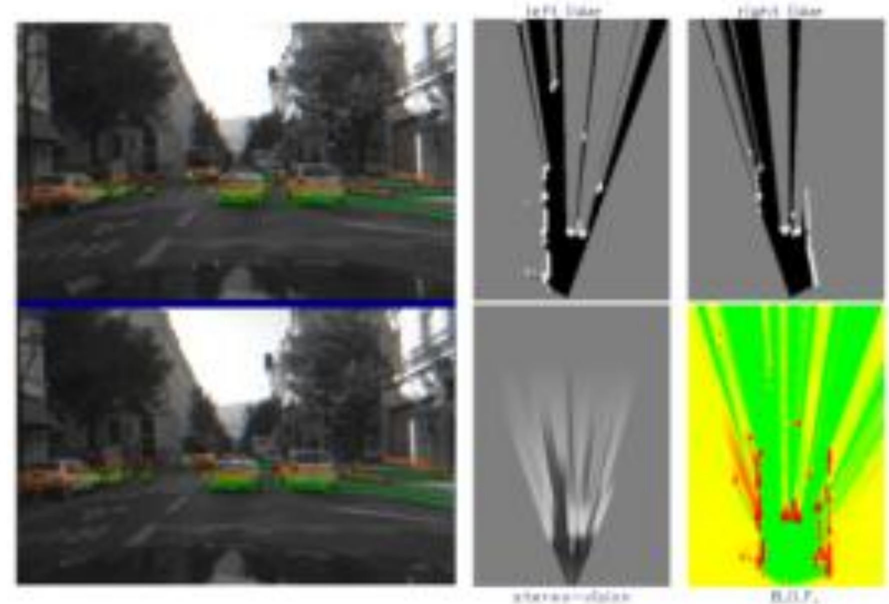




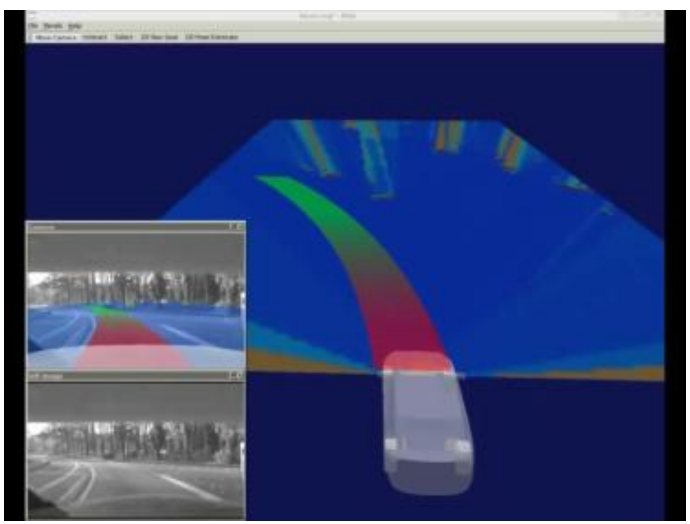
[Perrollaz et al 10] [Laugier et al ITSM 11]
Iros Harashima Award 2012

Bayesian Perception – Some experimental results

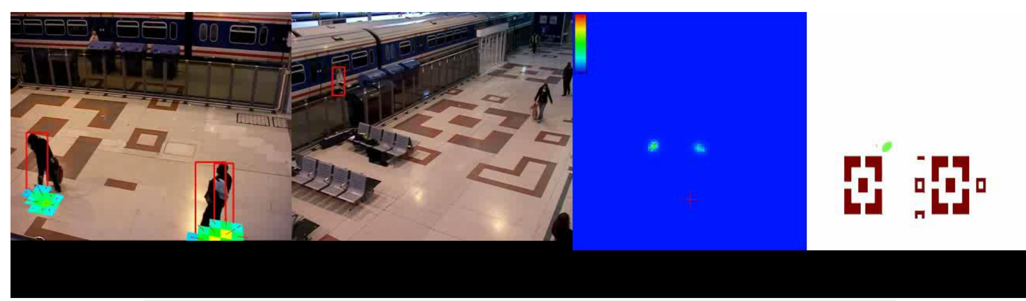




Embedded perception on Lexus (cooperation Toyota)



Navigable Space & Risk



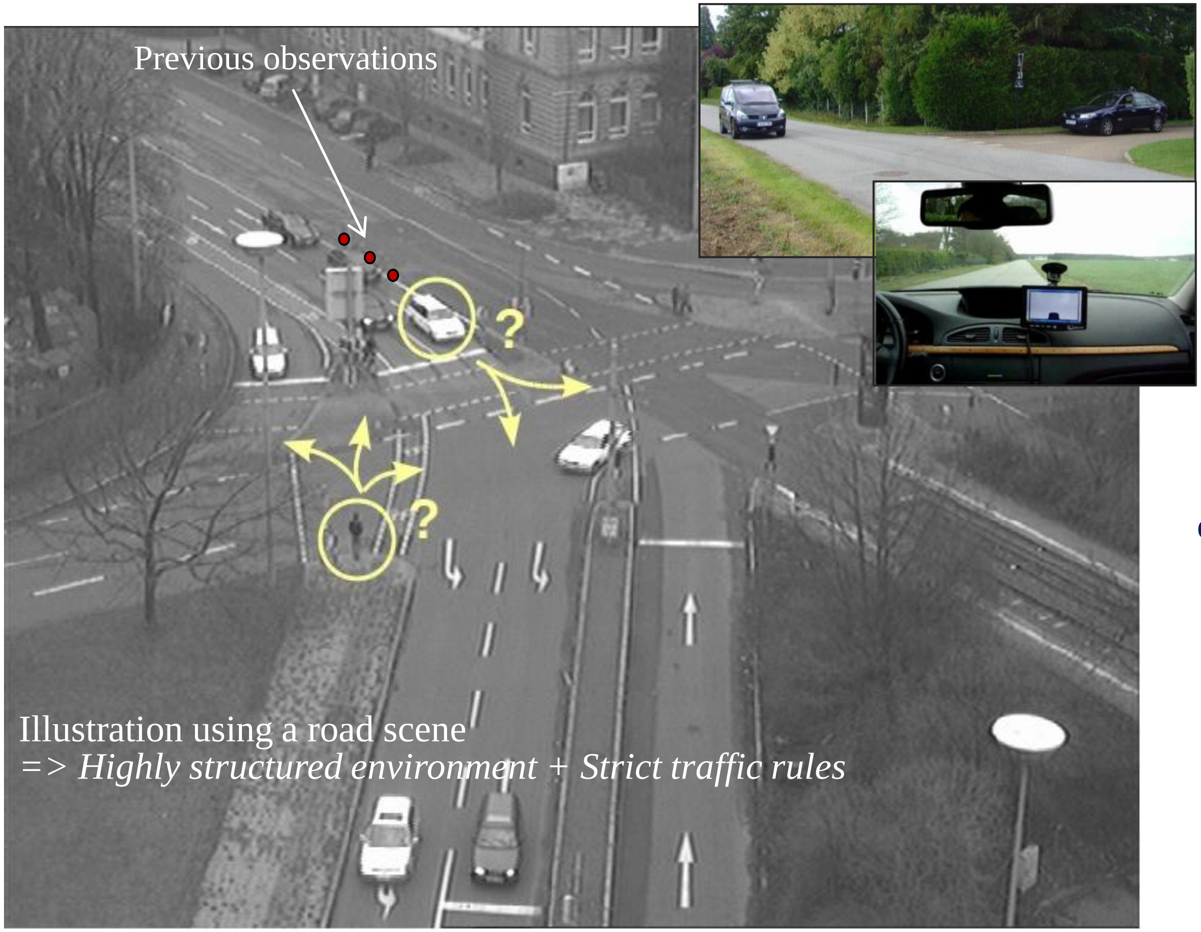
People Detection & Tracking using Fixed Cameras
Inria & Probayes

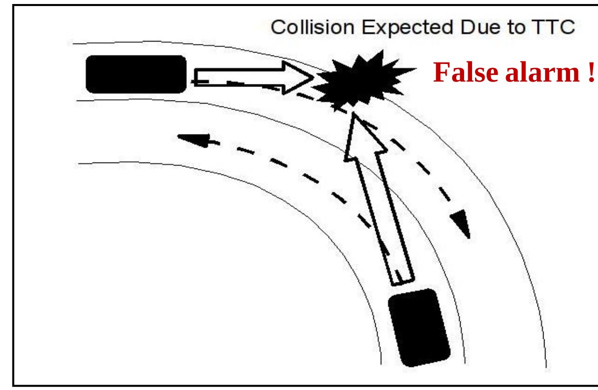
Key Technology 2:
Situation Awareness & Risk Assessment

- ***Learn & Predict paradigm***
- ***Trajectory Prediction & Probabilistic Risk Assessment***
- ***Comparing Intention & Expectation for Cooperative Safety***

Situation Awareness – *Problem statement*

⇒ Understand the **Current Situation** & its **likely Evolution**
⇒ Evaluate the **Risk** of future Collision for **Safe Navigation Decision**





Conservative TTC-based crash warning is **not sufficient** !

Behavior Prediction
+
Probabilistic Risk Assessment

Situation Awareness – Pro lem statemen

Behavior Prediction + Probabilistic ... Assessment

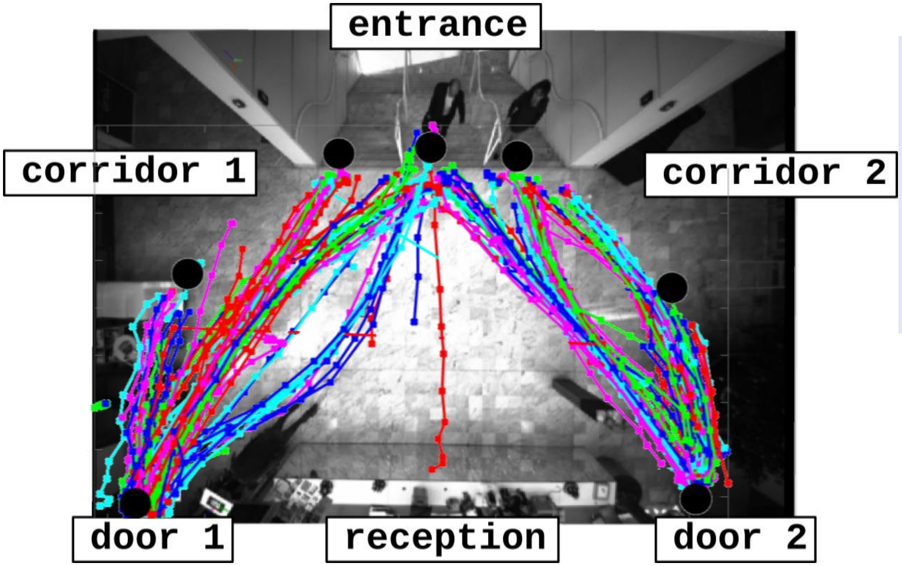
Previous observ...

=> Consistent Prediction & Risk Assessment requires to reason about:

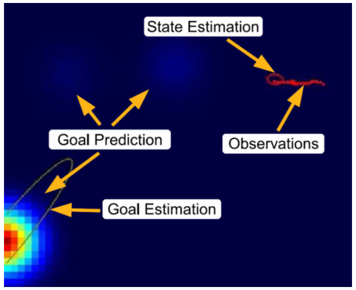
- ✓ **History of obstacles Positions & Velocities**
  => Perception (Datmo) or V2V Communications
- ✓ **Obstacles expected Behaviors**
  => Moving straight, turning, crossing, overtaking, stopping ...
- ✓ **Space geometry / topology**
  => Road lanes, curves, intersections ...
- ✓ **Traffic rules**

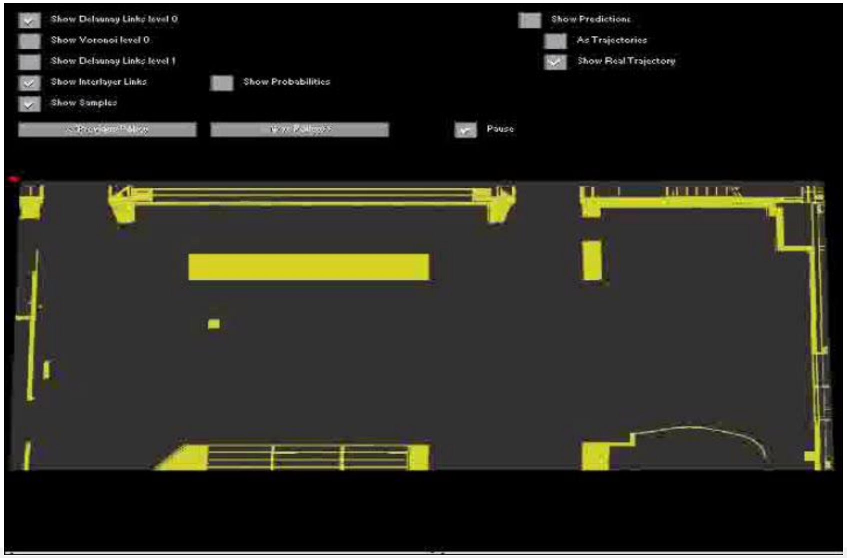
Techno 1: *Behavior Learning & Future Motion Prediction*
The Learn & Predict paradigm

[Vasquez & Laugier 07]



- *Concept of "Intentional Motion" (goal in mind)*
- *Observe & Learn "typical paths"*
- *Continuously "Learn & Predict"*
  - ✓ *Learn => GHMM + Topological maps (SON)*
  - ✓ *Predict => Exact inference, linear complexity*



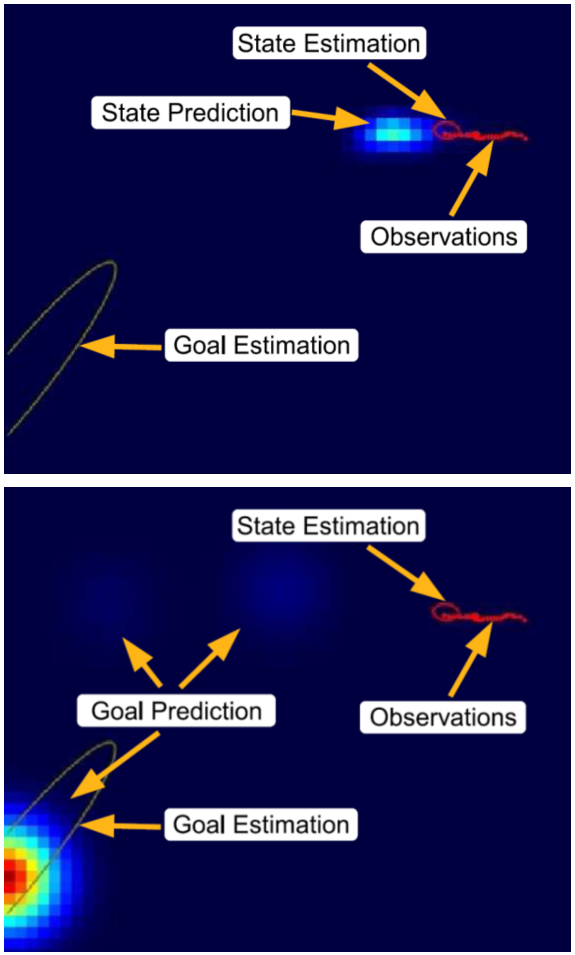


Estimate "Model structure" & "Transition probabilities"

Continuous *Goal & Path* Prediction

Learn & Predict approach – *Automotive application*

[Vasquez et al 07]

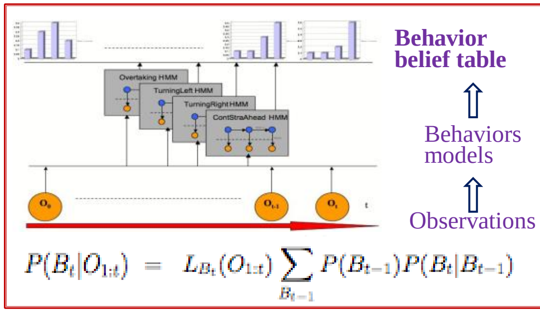


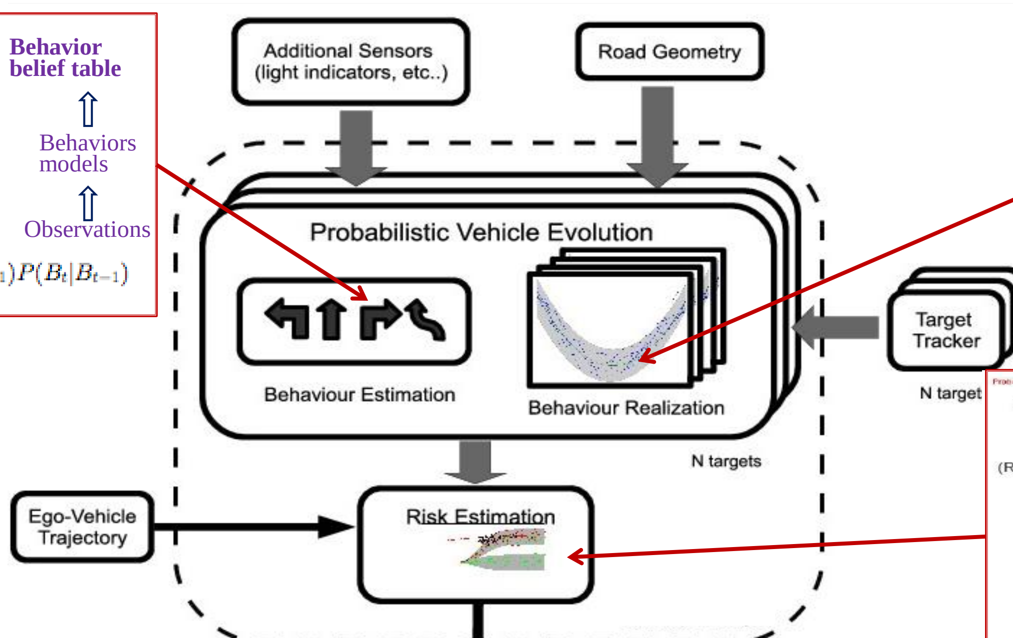
Experiments using Leeds University parking data

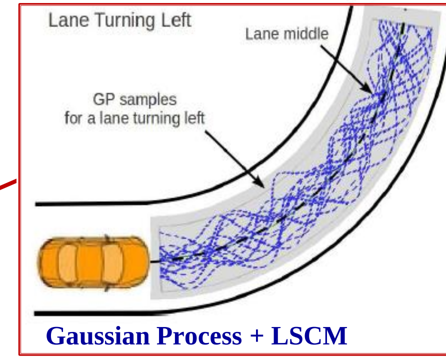
Techno 2: *Trajectory Prediction & Probabilistic Collision Risk*

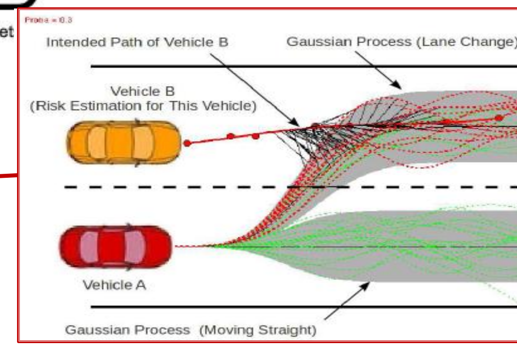
Patent INRIA & Toyota & Probayes 2010

[Tay 09] [Laugier et al 11]



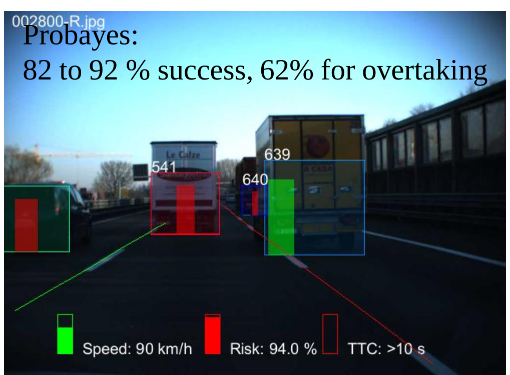




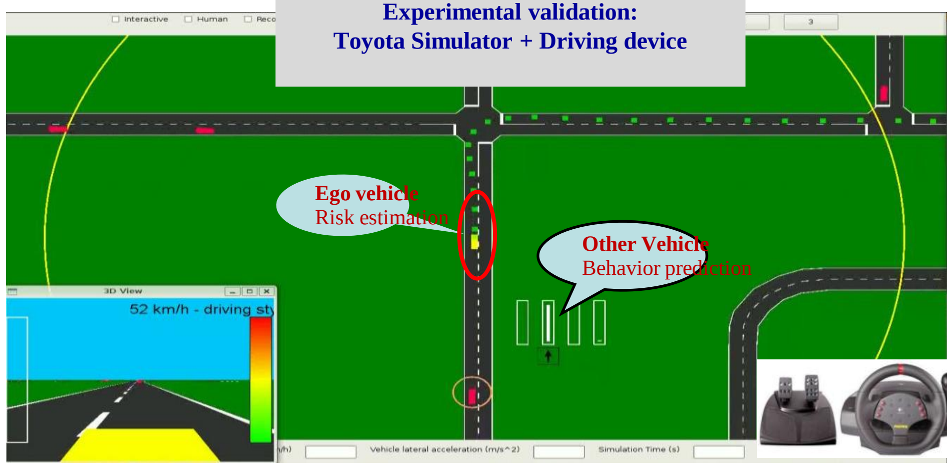


Probabilistic Collision Risk
Calculated for a few seconds ahead

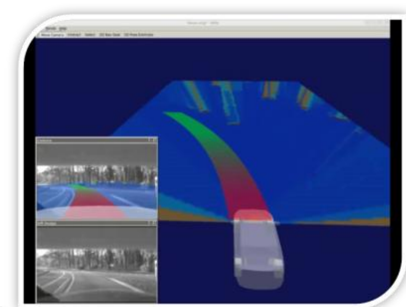
Predicted 3s ahead



Experimental validation:
Toyota Simulator + Driving device

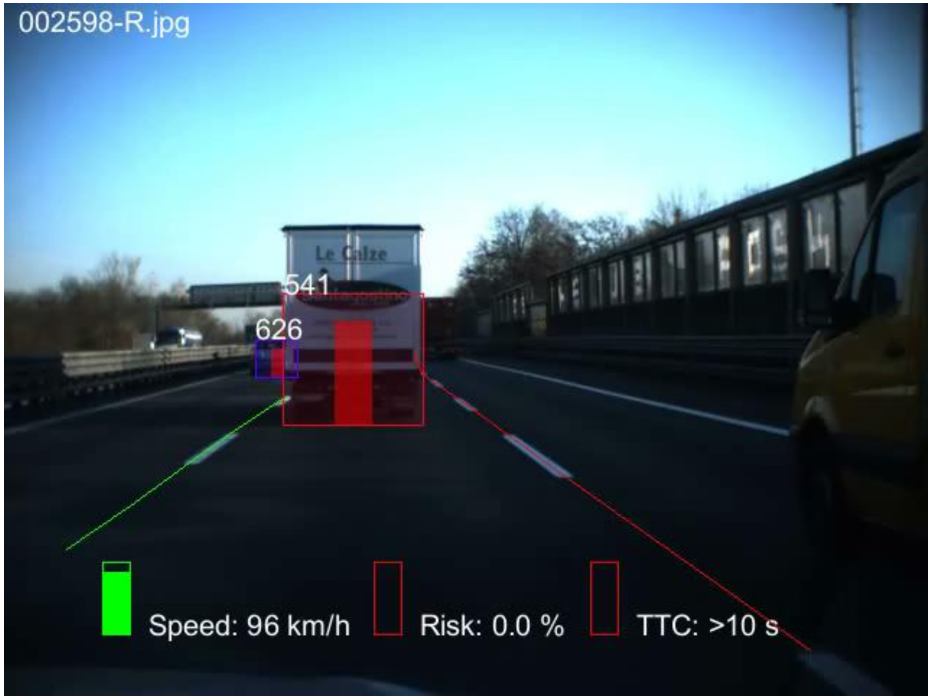


On-line Risk visualization (Lexus)



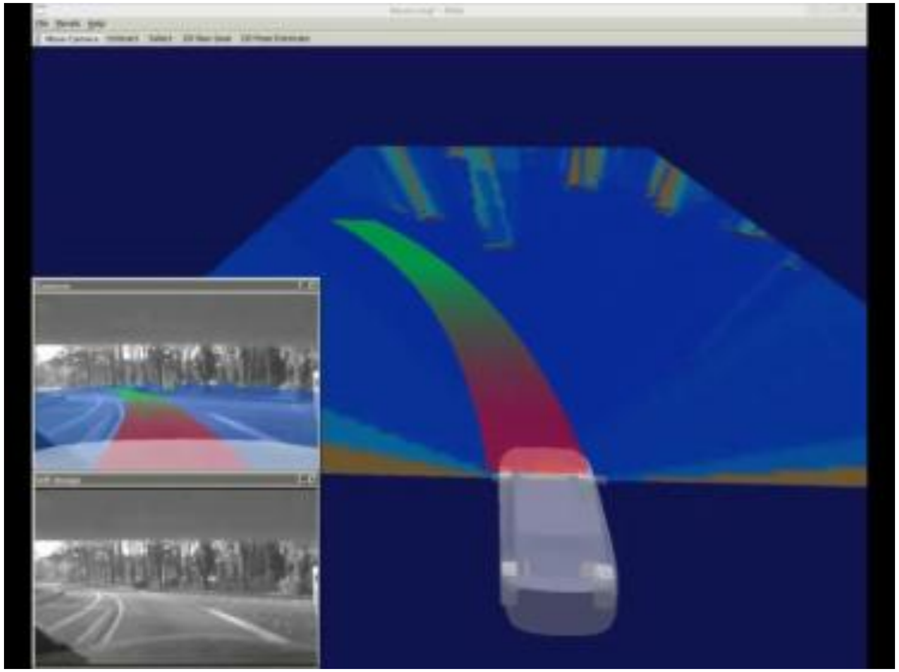
***Trajectory Prediction & Risk** – Experimental results*

[Tay 09] [Laugier et al 11]



Traffic participants behavior prediction & collision risk estimation
Probayes & TME

Navigable Space & Risk (using ROS)



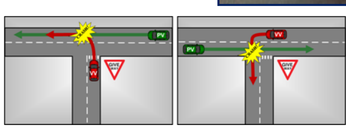
Techno 3: *Drivers Intentions & Expectations paradigm*

[Lefevre & Laugier IV'12, Best student paper] ***Patent Inria & Renault***

Intersection: Risk assessment much more difficult !

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

*90% of accidents are caused by **Drivers Errors***
*=> **Detect Drivers Errors** instead of colliding trajectories*



Our approach: A Human-like reasoning paradigm

- ✓ *Exchanging vehicle states information (V2V communication and/or Perception)*
- ✓ *Estimating **"Drivers Intentions"** from Vehicles States Observations*
- ✓ *Inferring **"Behaviors Expectations"** from Drivers Intentions & Traffic rules*
- ✓*Risk = Comparing Maneuvers **Intention & Expectation** using a **"Dynamic Bayesian Network"***

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

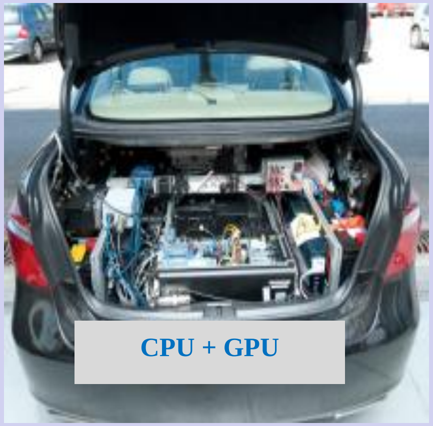
=> Digital map obtained using "Open Street Map"

Current & Future Work
Miniaturized Embedded Perception & Autonomous Driving

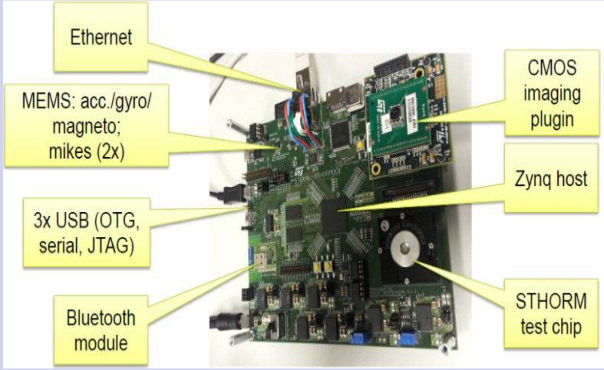
❑ Miniaturization through Software & Hardware integration

✓ *Reduce drastically Size, Weight, Energy consumption, Cost ... while improving Efficiency*
✓ *Cooperation CEA (French Nuclear Energy Institute) & ST Microelectronics*

Today



Objective 2014 & 2016



ST-Horm Multi-core board (STM)
=> First prototype 2013, Optimized version 2014
=> First product 2016, SoC 2018 ?

Validation & Demonstrations (2016)

Renault Zoe
(electric)

❑ Decision & Autonomous Driving *(Perception + Decision + Control)*

✓ *First results on **"Driving Decisional Process"** => Coop. Berkeley & Renault + Patent 2013*
✓ *Two PhD Grants 2013-2016 on **"Autonomous Driving"** => Toyota & Renault*

Two Inria Equipped Experimental Platforms
(sensors & processors fully integrated):
- Toyota/Lexus
- Renault/Zoé

Conclusion

- Thanks to recent advances in the field of ***Robotics & ICT*** technologies, ***Intelligent Cars*** are gradually becoming a reality

Parking Assistant (2004)

Volvo Pedestrian avoidance system (2011)

Fully Autonomous Driving (2020 -25 ?)

- **Embedded Bayesian Perception** & **Situation Awareness & Decision under uncertainty** are *key Technologies for addressing the Challenge of Autonomous Vehicles*. We have proposed, implemented in commercial cars, and tested four main approaches:
  - ***The "Embedded Bayesian Perception paradigm"*** *for dealing with Open & Dynamic Environments populated by Human Beings*
  - ***Three complementary approaches for "Risk Assessment & Decision Making"***
    - ***Learn & Predict paradigm***
    - ***Trajectories prediction + Probabilistic future collision detection***
    - ***Comparing Intention & Expectation for cooperative safety (i.e. with Human Drivers)***

Thank you for your attention
Any questions ?

http://emotion.inrialpes.fr/laugier
christian.laugier@inria.fr