Key Technologies for Addressing the Challenge of Autonomous Vehicles

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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

Bill Gates: “The next hot field will be Robotics”

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
- ....

President Obama announced Major Robotics Initiatives
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!
Cybercars: Some start-ups & first products

- Cycab (Inria/Robosoft)
- Cybergo (Induct)
- Amsterdam Schiphol Airport (2GetThere, 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 Hyundai)
- Night / Bad Weather Vision
- Radar based Pre-Collision System (Toyota Lexus, 2003)

Collision Warning with Brake support (Lincoln MKS, 2009)
**Intelligent Cars & ITS – Towards Driverless Cars ?**

**Horizon 2020-25 ?**

Nissan promises a driverless car for 2020

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 !

Carlos Ghosn (Renault /Nissan)

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 ?

**LEFIGARO**
Date : 29/08/2013

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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 system

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 technology is almost ready for Driving Assistance & Fully Autonomous Driving

Steering by wire
Brake by wire
Shift by wire
Virtual dash - on-board
Modern “wheel”
Navigation system
Radar, Cameras, Night Vision, Various sensors, Parking assistance
...
Cost decreasing & Efficiency increasing (future mass production, SOC, embedded systems ... !!!

Wireless Communication
Speech Recognition & Synthesis

Navigation systems
Driving assistance (speed, ABS, ESC...)
...
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
Challenge 1: **Multimodal Perception & Situation Awareness**

- **Dynamcity & Uncertainty**
  \[ \Rightarrow \text{Space & Time + Probabilities} \]

- **Interpretation ambiguities & Semantics**
  \[ \Rightarrow \text{History, context, prior knowledge + Sensor fusion} \]

- **Prediction of future states (recently addressed)**
  \[ \Rightarrow \text{Behaviors, prediction models} \]

- **Embedded Perception (necessary for deployment)**
  \[ \Rightarrow \text{Miniaturization & Software / Hardware integration} \]

Illustration: Traffic scene understanding

\[ \Rightarrow \text{Detect, Track, Classify, Predict} \]

Context & Semantics is required
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!

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*)
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)

- Laser Fusion (8 layers, 2 lasers)
- Stereo-vision (U-disparity OG+ Road/obstacle classif.)

Detected & Tracked Objects

Moving Obstacles
- Position
- Velocity

Each Obstacle

Tracker

Association

Clustering on Grid (Objects extraction)

Occupancy/velocity

Laser

CV algorithm

Stereo vision

[ Mehkhacha 09, Laugier et al ITSM’11 ]

Multi-Lane tracker

Reducing false detections

Motion Detection

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

Objects classification

Intensity Features

Codebook Matching

Detections

Depth Features
Embedded Perception System (Lexus)
CPU+GPU+ROS / Stereo + 2 Lidars + GPS + IMU

PC + GPU + ROS
Inertial sensor & GPS (Xsens Mti-G)

Stereo camera TYZX

2 Lidars IBEO Lux

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

Navigable space & Collision risk

Front view (camera)

Fusion result using BOF

[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**

Previous observations

Illustration using a road scene  
⇒ *Highly structured environment + Strict traffic rules*
Situation Awareness – Problem statement

Behavior Prediction + Probabilistic Risk Assessment

Previous observations

=> 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”
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

\[ P(B_t|O_{1:t}) = L_B(O_{1:t}) \sum_{B_{t-1}} P(B_{t-1})P(B_t|B_{t-1}) \]

- **Behavior belief table**
- **Behaviors models**
- **Observations**

**Probabilistic Vehicle Evolution**

**Risk Estimation**

*Predicted 3s ahead*

- Probayes: 82 to 92% success, 62% for overtaking

**Experimental validation:**

Toyota Simulator + Driving device

On-line Risk visualization (Lexus)
Traffic participants behavior prediction & collision risk estimation

Probayes & TME
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**”
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)

Decision & Autonomous Driving (Perception + Decision + Control)

✓ 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.

- **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)**

Parking Assistant (2004)  
Volvo Pedestrian avoidance system (2011)  
Fully Autonomous Driving (2020 - 25 ?)
Thank you for your attention
Any questions?

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