Bayesian & AI driven Embedded Perception and Decision-making. Application to Autonomous Navigation in Complex, Dynamic, Uncertain and Human-populated Environments. Synoptic of Research Activity, Period 2004-20 and beyond

Christian Laugier

Bayesian & AI driven Embedded Perception and Decision-making Application to Autonomous Navigation in Complex, Dynamic, Uncertain and Human-populated Environments

Synoptic of Research Activity – Period 2004-20 and beyond

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Part 1: Main personal Research Activities & Achievements

1. Brief synoptic of the past and current Research Activity

The research activity of Dr. Christian Laugier can roughly been subdivided into six main periods, with a major thematic change in 1979 (from Computer Graphics to Robotics) and several thematic and application domains changes:

- ***Period 1*** *(1974-1978):* Computer Graphics & Computer Aided Design (CAD).
- ***Period 2*** *(1979-1985):* Robot Programming & Simulation.
- ***Period 3*** *(1986-1995):* Geometric reasoning for Motion Planning & CAD Robotics.
- ***Period 4*** *(1996-2002):* Motion autonomy & Dynamic simulation for Robotics and Surgical applications.
- ***Period 5*** *(2003-2014):* Geometry and Probability for Motion & Action in Robotics.
- ***Period 6*** *(2015-today):* Bayesian & AI based Perception and Decision-making for Autonomous Navigation in Complex Dynamic, Uncertain and Human populated Environments.

Each research period has conducted to published scientific results, to software developments and to some innovative achievements that have been transferred to the industry, or that have led to the creation of start-ups. A brief overview of this research activity & main achievements for the periods 1 to 4 is available on my home page *http://emotion.inrialpes.fr/laugier* and on the webpage *https://hal.inria.fr/hal-03091861*.

The research work conducted during the periods *5 & 6* relies on a major methodological and thematic change compared to our past research activity[1]:

- In the new research agenda, the emphasis is placed on the development of *new models combining Geometric, Probabilistic and Artificial Intelligence approaches*, with the objective of solving traditional Perception, Decision-making and Control problems in Mobile Robotics, *while taking into account the strong constraints imposed by the real world (in particular: Complexity, Uncertainty, High Dynamicity, Real-time, and Interactions with human beings).*
- From the methodological point of view, we have chosen to simultaneously address three complementary aspects of the problem:
  - ✓ ***Theoretical Foundations*** of the underlying key concepts *(mathematical models & algorithms);*
  - ✓ ***Validation & Certification*** of the developed models & algorithms *(using Simulations tools, Annotated Datasets, Real-world Experimentations, and Formal Methods)*;
  - ✓ ***Innovation & Valorization*** issue *(Technological transfers, Start-ups creation, key Industrial long-term partnerships with companies such as Toyota or Renault, IRT[2] Nanoelec SVA long-term R&D program).*
- Creation in 2004 of the Inria Project-Team *e-Motion*[3], with a significant evolution of the research activity during the period *2009-20*, under the impulse of ***our new findings in terms of Bayesian Perception, Risk Analysis, and Decision-making for robot navigation in human-populated environments.*** These new findings have led us to finalize several R&D actions (in terms of scientific results, software and patents), and to open a new research line and new partnerships (including the French National R&D Institute CEA) for making a decisive step towards the necessary ***software/ hardware integration*** for future Intelligent Mobile Robots and Autonomous Vehicles.

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[1] *I presented a first outline of this new research agenda during the "brainstorming days" organized in March 2002 in Brussels by the EU R&D program "Future Emerging Technologies" (the main objective of this brainstorming seminar was to prepare a new EU call for proposals entitled "Beyond Robotics"). Then, I built a 10-year research agenda to progressively solve the identified key theoretical and technological Robotics problems, by combining Geometric, Probabilistic and AI approaches.*

[2] *IRT: French Technological Research Institute – SVA program: Long-term program on "Safety of Autonomous Vehicles".*

[3] *Inria project-team "e-Motion", created in 2004 after a one year period of incubation of the initial idea. This research team was common to Inria Grenoble Rhône-Alpes and to the LIG Laboratory of the University Grenoble-Alpes (UGA). During the period 2004-14, the e-Motion project-team has received excellent feedbacks from several international evaluation panels: Inria robotics evaluation seminar in March 2009, French AERES evaluation of the LIG Laboratory in February 2010 (score A+ for the e-Motion project-team), and Inria robotics evaluation seminar in March 2013.*

2. Achievements 1: *A new research framework for "Robots in Human Environments"*

As previously mentioned, I have defined and launched in *2004* a new research line for addressing scientific problems related to the future developments of robots operating in Highly Dynamic and Human-populated Environments. This has led to the development of a new framework for addressing *Perception and Decision-making issues, under strong Uncertainty, Dynamics, and Human interaction constraints.*

The main impact of this new research framework can be summarized as follows:

- This new approach has led to original well published and referenced scientific results in the IEEE communities of Robotics & Automation (RAS) and of Intelligent Transportation Systems (ITSS), and to several patents and valorization actions. *See next sections for more details.*
- This new scientific positioning and results have permitted us to obtain National *(ANR, IRT Nanoelec, FUI, etc.)* and European *(IP BACS, IP Prevent, ECSEL Enable-S3, ECSEL CPS4EU, etc.)* projects, but also to sign important bilateral and multi-annual industrial contracts *(Toyota Europe, Denso Japan, Renault, EasyMile, etc.).*
- Thanks to this early positioning and interesting results obtained on this emerging research line, our research team has obtained an international recognition has witnessed by the following events, actions and awards *(see achievements 4 & 5 for more details)*:
  - *IEEE RAS Technical Committee (TC) "AGV-ITS"* [4] created by C. Laugier in *2004* with the objective to develop, to structure and to lead the RAS scientific community in the emergent field of "mobile robots and autonomous vehicles". This *TC* has been renewed several times after having obtained positives evaluations by the IEEE RAS ad hoc committee. *The chairs of this TC have also received two IEEE RAS TC Awards in 2006 and 2013 respectively.*
  - Increasing success of the organization during the period 2007-20 of 12 workshops on "Planning, Perception and Navigation for Intelligent Vehicles" (PPNIV series) in the major conferences of the domain (IEEE/RSJ IROS, IEEE ICRA and IEEE IV). These workshops attracted an increasing number of attendees (50 attendees at ICRA 2007, 130 attendees at IROS 2013 and a record number of 350 attendees at *IROS 2018 and 2019*).
  - Strong involvement in the organization of several IEEE major conferences (ICRA, IROS, IV), and to scientific events (workshops, special sessions, forums) organized in the scope of these conferences.
  - Participation as Invited Associate Editor & Author to the publication of two Springer Handbooks: *Handbook of Intelligent Vehicles (2012) and 2nd edition of the Handbook of Robotics (2014).*
  - Member of the *Editorial Board and/or Steering Committee* of several IEEE journals (e.g. IEEE T-ITS, IEEE T-IV, IEEE Robomech).
  - Several *Scientific Awards* related to the research results obtained in this new framework.
  - Numerous invitations for *Keynote or Plenary Talks* in some major conferences or scientific events of the IEEE RAS and ITS communities (see list of publications).
  - Intensification of the long-term cooperation (R&D contracts, PhD theses, Patents, Software licenses) with some strategic industrial partners: *Toyota (since 2005) and with Renault (since 2010).*

3. Achievements 2: *The "Embedded Bayesian Perception" paradigm*

Robust perception in Open and Dynamic Environments populated by Human beings is an open and challenging scientific problem. Traditional perception techniques can hardly been applied for solving such a problem, mainly because such environments are uncontrolled and generate new strong constraints to be satisfied (in particular high dynamicity and uncertainty). This means that the proposed solutions have to simultaneously take into account various characteristics such as real-time processing, sensors limitations, continuous dynamic world changes, or near future expected evolution of the robot environments (concept of "prediction"); these solutions have also to include explicit models for reasoning about uncertainty (data incompleteness, perception errors, hazards of the physical world).

For that purpose, we have proposed a new paradigm called *"Bayesian Perception".* The foundations of this approach relies in the concept *"Bayesian Occupancy Filter (BOF)"* [1, 2, 4] initially developed in our research team in the PhD thesis of a *Christoph Coué (2004)*, and more recently improved toward an embedded version in the PhD thesis of my former student *Tiana Rakotovao (2017)* [26,28]. The basic idea is to combine à Bayesian filter with a *probabilistic grid representation of the both space and the moving entities*. This model allows the filtering and the fusion of heterogeneous and uncertain sensors information coming from a dynamic space; this Bayesian filtering takes into account the history of the sensors measurements, a probabilistic model of the sensors and of the uncertainty, and a dynamic model of the observed objects motions. *An interesting property of this approach is to continuously generate conservative predictions about the most probably future evolution of the environment (i.e. when velocities are supposed to be stable during a small amount of time), even if the sensing information is temporary not available.*

During the period 2009-14, we have improved the model and developed a parallel implementation of the system on an embedded architecture on a Toyota Lexus and on a Renault Zoé, both equipped with multiple sensors. In 2012, we have

[4] ***TC AGV-ITS:*** *Autonomous Ground Vehicles & Intelligent Transportation Systems.*
Period [2004-12]: Chair (C. Laugier) & co-Chairs (A. Broggi & U. Nunes). Period [2012-18]: Chair (Ph. Martinet) & co-Chairs (C. Laugier & C. Stiller). Period [2018-21]: Chair (Ph. Martinet) & co-Chairs (C. Laugier & M. Ang & D. Wolf).

launched a new partnership with the CEA[5] Grenoble and ST Microelectronic, with the objective to redesign the approach for developing a software / hardware integration based on a multi-core architecture. Such an integration is clearly necessary for a future deployment of the technology (for obtaining a drastic reduction of the size, weight, energy consumption, and cost, while improving the efficiency of the process). This new partnership with the CEA Grenoble has conducted to the launch of a 10-year project in the scope of the *IRT[2] Nanoelec*, for addressing the challenge of the development of embedded solutions for our Bayesian Perception & Decision-making approach. In 2017, my former student *Tiana Rakotovao* proposed a clever solution to this problem in his PhD thesis; this research work has been done under my guidance and the co-guidance of Diego Ruspini (Engineer at CEA), in the scope of our IRT Nanoelec project.

This pioneer research work on the "Embedded Bayesian Perception paradigm" has given rise to *(See achievements 4 & 5 for more details)***:**

- Two PhD theses: Christophe Coué *(initial concept, 2004)* and Tiana Rakotovao *(embedded solutions, 2017).*
- Numerous publications *in major IEEE conferences & journals*, and some publications in International Conferences *in the field of "Embedded Systems and Software" (e.g. Design Automation Conference)*.
- An embedded Bayesian Perception prototype exhibited at *CES 2018*.
- Several patents on the Bayesian Perception basic concepts and on their applications to the next generation of *Advanced Driving Assistance Systems (ADAS) and Autonomous Driving Systems*.
- Creation of our startup *Probayes SA (2003)* & Technological transfer to *Probayes SA (2006).*
- Licenses of our *Bayesian Perception software CMCDOT* recently sold to several industrial companies: *Toyota and two other companies (confidential).*
- Several bilateral industrial contracts (Toyota Europe, Denso Japan, EasyMile).

As this research topic has already reached a good level of maturity, we have recently started to bend our research work for the next 5 years with the aim to represent, extract and process semantic information (in particular by integrating Computer Vision and Deep Learning approaches). See Part 2 of this report.

4. Achievements 3: *Situation Awareness, Prediction & Risk Assessment, Decision under Uncertainty*

Robust perception (using multiple sensors) is the first step towards the analysis and the understanding of a complex dynamic scene, which in turn is a prerequisite for the planning, navigation decision and control steps. Since the environment is dynamic and uncertain, both a *consistent estimation* of the current state and a *prediction* of the most likely evolution of the scene and of its associated *risk of future collisions*, are necessary for being able to take safe and socially acceptable navigation decisions. As far as we know, there was few significant scientific contributions on this subject before the second decade of the 21th century *(see our journal survey paper [10]).*

During the period 2009-20, we have designed and developed two complementary types of approaches for addressing this issue:

- ***Prediction of the most likely future motions of the observed entities (robots, vehicles, pedestrians ...) and collision risk assessment*.** The basic models vas developed during the PhD theses of my former students *Dizan Vasquez (2009), Christopher Tay Meng Keat (2009), Stéphanie Lefevre (2012).* Two complementary approaches have been developed and patented respectively with Toyota and with Renault.

  Recent work on this research line is focusing on the use of new approaches combining Machine Learning and AI-based models. This new research activity has given rise to several international publications, to the filing of several patents, and to the recent defense of the two PhD theses: David Sierra-Gonzalez (2019) and of Mathieu Barbier (2019).
- ***Decision making for a safe and socially acceptable navigation of a robot moving among Human being.*** The basic underlying models have been developed in the scope of the PhD theses of two of my former students: *Chiara Fulgenzi (2009)* and *Jorge Rios-Martinez (2013).* I recently stopped to work on the "social aspect" of the navigation process, which is now addressed in our Inria team-project Chroma by Anne Spalanzani. *My focus is now on the "motion safety" and "human driver's behaviors modelling" issues, with an emphasis on Machine Learning approaches.*

During the period 2009-20, this work has given rise to *(see achievements 4 & 5 for more details)*:

- Numerous publications in high impact conferences and journals (IJRR, IEEE Trans on ITS, IEEE ITSM, IEEE ICRA, IEEE/RSJ IROS, IEEE IV, ISRR), and numerous invited talks.
- 7 PhD theses (Dizan Vasquez, Christopher Tay Meng Keat, Chiara Fulgenzi, Jorge Rios-Martinez, Stéphanie Lefevre, David Sierra-Gonzalez, Mathieu Barbier).
- A book chapter in the Handbook of Intelligent Vehicle (2012).
- Several Scientific Awards related to this recent research line.
- Four patents registered during the period 2010-13: *Inria & Toyota (2010), Inria & Renault (2012), Inria (2013), Inria & Berkeley (2013).*

***This research line is still at the heart of my research program for the next 5 years, with a strengthening of the knowledge & learning based components*. See part 2 for more details.**

[5] *CEA: Commissariat à l'énergie atomique et aux énergies alternatives (French R&D Institute)*

5. Achievements 4: *Publications & Scientific Information Dissemination & Scientific Awards*

Dr. Christian Laugier has authored or co-authored more than **400** scientific publications in *peer-reviewed international journals (~10%) and in peer-reviewed conferences & workshops*. He also co-authored **6** *books chapters* and *about* **20** *patents & registered software packages*. In addition, he gave around **35** *guest keynote, plenary lectures and tutorials*. Most of these publications and guest lectures have been done within the framework of the major IEEE Conferences or Journals in the fields of Robotics & Automation (IEEE RAS) and of Intelligent Transportation Systems (IEEE ITSS).

=> The list of publications & achievements for the period before 2009 is available on my old home-page http://emotion.inrialpes.fr/laugier and on the webpage https://hal.inria.fr/hal-03091861

=> The list of the significant publications & invited talks for the periods 2006-20 is available in the last part of this report.

Brief overview of the Publication & Scientific information dissemination achievements:

- ***Book edition & Journal special issues****:* Contribution to the edition of **2** ***Handbooks***[6] and co-edition of **3** ***Books***[7] in the fields of Robotics and of Intelligent Transportation Systems. Co-edition of several ***Special Issues*** in high impact scientific journals such as IJRR, JFR, Advanced Robotics, IEEE RAM, IEEE T-ITS or IEEE ITSM.
- ***Guest Keynote & Plenary lectures in IEEE conferences:*** Numerous *Guest Keynote & Plenary lectures* in some major IEEE-RAS and IEEE-ITS conferences[8] and in smaller IEEE conferences[9] and in workshops organized in the scope of IEEE/RSJ IROS and IEEE ICRA conferences.
- ***Invited conference papers & talks:*** Numerous invited papers & talks in IEEE International Conferences or Symposiums[10] and in various international workshops or seminars (China, Japan, Singapore, Korea, Thailand, Mexico, Brazil, Syria, Canada, USA, etc.).
- ***Popular publications, speeches and media events:*** Several popular publications on "Robotics problems & solutions" and participation to several media events in the fields of Robotics and Autonomous Vehicles[11].
- ***International tutorials:*** About **20** tutorials on *Robotics* and **5** recent tutorials on *Autonomous Vehicles Technologies*[12] have been done in the scope of summer schools, international conferences, or international cooperation programs. In addition, a *MOOC* entitled *"mobile robots and autonomous vehicles"* and including a chapter on *"Bayesian Perception"* have been broadcasted 3 times in *2015-16* by Inria-uTOP; an online version is available since 2017. *cel-01256021*
- ***International Scientific Events:*** Strong involvement in several *Editorial Boards of IEEE conferences & journals*[13], in numerous *Organizing Committees of IEEE conferences & workshops & forums*[14], and in several *IEEE Awards Committees*. The IEEE RAS Technical committee *AGV-ITS* [3] annually organizes scientific events *focusing on advanced technologies for Intelligent Vehicles*; these events are attracting more and more scientists *(around 300 participants in the last two years).*

Scientific Awards obtained in this recent research line:

- *Best European PhD thesis Award to my former PhD student D. Vasquez (2010).*
- *Best student Paper Award at IEEE IV 2012 to my former PhD student S. Lefevre (co-authors: C. Laugier & J. Ibanez-Guzman).*
- *IEEE RAS TC Awards 2006 (C. Laugier, A. Broggi , U. Nunes) & 2013 (C. Laugier, Ph Martinet, C. Stiller)*
- *IEEE/RSJ IROS Harashima Award for Innovative Technologies (C. Laugier, 2012)*[15].
- *IEEE/RSJ IROS Fellow (C. Laugier, 2016).*
- *IEEE/RSJ IROS Distinguish Service Award (C. Laugier, 2016)*
- *Finalist EU Robotics Technology Transfer Award 2014 (C. Laugier, Inria & K. Mekhnacha, Probayes SA)* [16].

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[6] ***Springer Handbook of Robotics*** *2nd edition (chapter "Intelligent Vehicles", July 2016) &* ***Springer Handbook on Intelligent Vehicle*** *(chapters on "Fully Autonomous Driving", March 2012). Both handbooks are still widely disseminated and referenced.*

[7] ***Books:*** *Springer STAR on "Probabilistic Reasoning and Decision Making in Sensory-Motor Systems'" (P. Bessiere, C. Laugier, R. Siegwart, 2008); Springer STAR on "Autonomous Navigation in Dynamic Environments" (C. Laugier, R. Chatila, 2007); Springer Lecture notes in Computer Science on "Geometric Reasoning for Perception and Action" (C. Laugier, 1993).*

[8] ***IEEE-RAS:*** *IROS 2014 & 2019, ICARCV 2008 & 2014 & 2018 -* ***IEEE-ITS:*** *ITSC 2002*

[9] *FSR 2009, ARSO 2016, Workshop @ ECCV 2018, RWIA 2018, WRC 2019, etc.*

[10] *ISRR, WAFR, ICARCV, ICIT, Workshops at ICRA or IROS, etc.*

[11] ***Recent media events on Autonomous Vehicles:*** *« Assistance à la conduite & Conduite autonome » (Magazine Industrie & Technologies, Sept 2015), « Véhicule autonome et Intelligence artificielle » (Interview & vidéo, TV Chanel Sciences et Vie », Sept 2017), « Le véhicule autonome de demain » (Interview, France Bleu Isère, diffusé le 11 Octobre 2018).*

[12] *EU Emaro Master (ECN Nantes 2015 & 2016), EU Summer School on IV (Compiegne 2017), BIT Beijing (2017), Winter School on AI (2018). These tutorials include a chapter describing the fundamentals of our Bayesian approach.*

[13] *IEEE Conferences: ICRA, IROS, IV, etc. - IEEE Journals: T-IV, T-ITS, Robomech, ISR, etc.*

[14] *IEEE Conferences: ICRA, IROS, IV, FSR, ICARCV, etc. - Workshops & Forums: ICRA, IROS, IV, ICARCV, etc.*

[15] *Harashima Award 2012 for "Outstanding contributions to embedded perception and driving decision for intelligent vehicles".*

[16] *EU Technological Transfer Award 2014 for "Transfer of Bayesian Perception and decision-making technologies in industrial applications".*

6. Achievements 5: *Innovation & Valorization, Startups*

- ***Startups (founding member & scientific advisor):*** 4 startups in the period 1982-92 (ITMI, Getris-Images, Aleph Technologies, Aleph Med) and the startup *(Probayes SA, 2003)* for the commercialization of technologies developed within the framework our recent research line. The startup *Probayes SA* is still very active and was recently acquired by the industrial group "La Poste"; *Scientific Advisor* for *Probayes since 2008.*

- ***Contribution to Technological transfers:***
  - Several technological transfers have been carried out with our former startups in the fields of Robotics, CAD-Robotics, and Dynamic simulation with Human interaction.
  - Our "Bayesian Occupancy Filter" technology has been transferred to Probayes SA in 2006 (for commercialization within the *ProBT* Bayesian Library).
  - Our "Bayesian Perception System software CMCDOT" has been transferred to *Easymile* and to *Toyota* in 2019.

- ***Patents** (more details in section "Publications"):*
  - "Automatic Parallel Parking for cars" (1996)[17] – *Patent application cancelled because of prior partial disclosure.*
  - "Bayesian Occupancy Filter – Initial concept" (2005) – *Patent hold by Inria.*
  - "Bayesian Occupancy Filter - Improved industrial version" (2005)[18] – *Patent hold by Inria & Probayes SA.*
  - "Continuous collision risk assessment for improving vehicle safety" (2010) – *Patent hold by Inria, Toyota, Probayes.*
  - "Collision risk assessment at roads intersections" (2012) – *Patent hold by Inria & Renault.*
  - "Methods and apparatus for improving driving safety" (2013) – *Patent hold by Inria.*
  - "Decision making for collision avoidance systems" (2013) – *Patent hold by Inria & UC Berkeley.*
  - "Dynamic scene analysis method and associated analysis module and computer programme" (2015) – *Patent hold by Inria & CNRS & CEA / IRT Nanoelec.*
  - "Dispositif informatique pour l'aide à la conduite" (2017) – *Patent hold by Inria & CEA / IRT Nanoelec.*
  - "Driving Assistance Method and System" (2017*)* – *Patent hold by Inria & Toyota.*
  - "Semantic Occupancy Grid Estimation" (2018) – *Patent hold by Inria & Toyota.*
  - "Computerized device for driving assistance" (2020) – *Patent under application by Inria & CEA / IRT Nanoelec.*

- ***Bilateral industrial partnerships:***

  The abovementioned technologies have permitted us to establish several long-term bilateral industrial partnerships:
  - *ProbaYes (since 2004):* Commercialization of the Bayesian Library *ProBT* & Collaboration on R&D projects with Toyota.
  - *Toyota (since 2005):* Long-term R&D collaboration, 2 PhD grants, several common patents, common experimental platform (Equipped Lexus).
  - *Denso (2005-08*): Several R&D contracts for the evaluation and the adaptation of the "Bayesian Occupancy Filter" technology to the Denso Automotive Lidar. The license & royalties agreement negotiated during the year 2008 was finally not been signed.
  - *Renault (since 2010):* Long-term R&D collaboration, several contracts, 2 PhD grants, several common patents, transfer of the developed technology on the Renault experimental platform (Renault Technocentre, R&D purpose).
  - *EasyMile (since 2018):* R&D project "Embedded Bayesian Perception for autonomous mobility", in the scope of the IRT Nanolelec SVA project and of several other national R&D projects.
  - *Schneider (2018-19):* R&D project in the scope of IRT Nanoelec, for the development of a "light autonomous electric vehicle for micro-mobility".
  - *Industrial scientific expertise for "future mobility systems"*: Scientific Advisor for Baidu ApolloScape project on autonomous vehicles (2018-19); Scientific expertise for Renault-Nissan of an industrial dossier on the concept of "Robot Taxi" (2017).

[17] *Pioneer work on the innovative concept of "Park Assist" for cars (see https://en.wikipedia.org/wiki/Automatic_parking), but the patent application has been cancelled because of a previous partial disclosure (our ICRA 1996 & IV 1996 publications). Consequently, the transfer of this technology to Toyota has been stopped in 1997, and Toyota developed and commercialized its own "Park Assist" product in 2004. See the following video for illustration (video proceedings IROS 1997): https://hal.inria.fr/hal-03088658*

[18] *This technology is part of the ProBT library commercialized by Probayes SA.*

- Part 2 -
Outline of the Scientific Project & Research Agenda

Research Project: Bayesian & AI driven Embedded Perception and Decision-making. Application to Autonomous Navigation in Complex, Dynamic, Uncertain and Human-populated Environments

1. Outline of the Scientific Project and R&D Context

The scientific project to be tackled over the next 5 years can be seen as a more in-depth exploration of the scientific theme initially launched within the framework of the Inria project-ream *eMotion*, then studied in more depth over the period *2015-20* within the Inria project-team *Chroma*. This thematic focuses on the promising paradigm of *"Bayesian & AI driven Perception and Decision-making for Autonomous Navigation in Complex, Dynamic, Uncertain and Human-populated Environments"*. The scientific foundations of this research line, as well as the main achievements during the period *2004-20* have been briefly described in the first part of this report.

○ *Brief problem statement & approach*

Robust perception & Decision-making for safe navigation in open and dynamic environments populated by human beings is an open and challenging scientific problem. Traditional approaches do not provide adequate solutions for these problems, mainly because such environments are partially unknown, open and subject to strong constraints to be satisfied (in particular high dynamicity and uncertainty). This means that the proposed solutions have to take simultaneously into account characteristics such as real-time processing, temporary occultation or false detections, dynamic changes in the scene, prediction of the future dynamic behaviors of the surrounding moving entities, continuous assessment of the collision risk, or decision-making for safe navigation.

Figure 1 gives a very broad overview of our Embedded Perception & Decision-making approach (more details are available in the past activity reports of the team and in our publications, e.g. *[4, 7, 15, 17, 67]*. Another important topic that we have recently started to address is the challenging problem of *"Validation & Verification"* (see section 3). The following sections briefly present the avenues of research proposed to address the above questions.

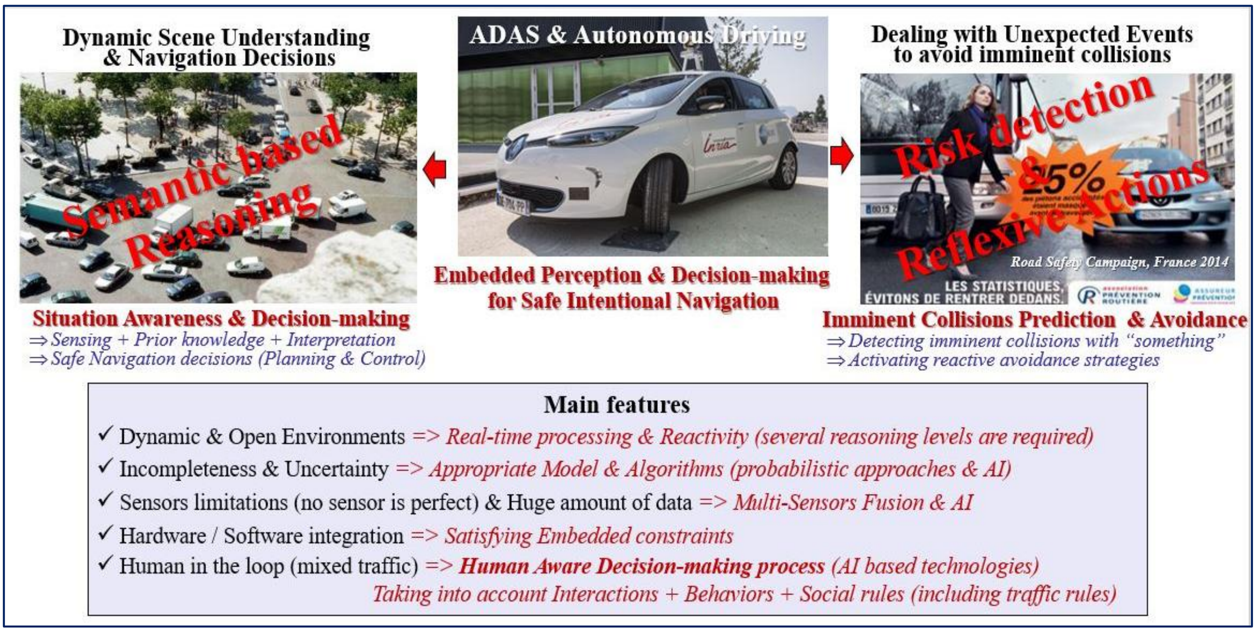

Figure 1: *Illustration of our approach for addressing the problem of Embedded Perception & Decision-making for Autonomous Vehicles (by mixing Bayesian & AI approaches)*

○ *Scientific approach and R&D Context*

As it has been mentioned in section 1, we have chosen to simultaneously address three complementary aspects of the problem: (1) the ***theoretical foundations*** of underlying key concepts *(mathematical models & algorithms)*, (2) the ***validation & certification*** of the developed models & algorithms *(using Simulations tools, Annotated Datasets, Real-world Experimentations using autonomous vehicles and infrastructure connected sensors & devices, Formal Methods)*, and (3) the ***innovation & valorization*** issues in cooperation with our industrial partners and *IRT*[19] *Nanoelec SVA long-term R&D project.*

[19] ***IRT:*** *French Technological Research Institute –* ***SVA project:*** *Long-term R&D program on "Safety of Autonomous Vehicles".*

To conduct this Research and Innovation program, we have established *over the last decade* some targeted long-term partnerships:

- ***A 10 years Strategic partnership and R&D program with CEA[5] & IRT[2] Nanoelec*** *(launched in 2011)***,** for addressing the *Software / Hardware integration* issues for our "Bayesian Embedded Perception" approach. The related SVA (Safety of Autonomous Vehicles) R&D program involves several industrial companies such as *ST-Microelectronics* or *Schneider Electric*, and several SMIs such as *Akeoplus or EasyMile*. Through this strategic partnership, we have carried out several R&D projects having given rise to a PhD thesis, several well-published results, three shared patents and a technological transfer. In order to validate our models & algorithms, we have developed a fairly complete experimental platform including an Automated Renault Zoe equipped with multiple sensors, V2X communication facilities, and our on-board Bayesian Perception / Decision-making / Control systems. As part of a cooperation with Schneider Electric, we recently addressed the concept of "green micro-mobility" in cities, with the objective of incubating a start-up to market the resulting product (a fleet of self-service electric light autonomous vehicles); the main challenge is to adapt our Bayesian perception / decision-making / control approaches to the use of inexpensive (but less efficient) sensors, while being able to operate in real-time with limited computational capacities.
- ***Long-term R&D agreement with Toyota*** *(since 2005)*: The *Inria-Toyota* agreement was renewed respectively in 2014 and in 2018 for additional periods of 4 years. The main research topics covered address the problem of autonomous driving, and more specifically the analysis of road scenes, the prediction and assessment of collision risks, and the use of AI learning techniques for the interpretation of complex road scenes and for the modeling of driver's behaviors. This research work has given rise to numerous publications, 2 PhD theses and to several shared patents.
- ***Long-term research agreement with Renault*** *(since 2009)*: The *Inria-Renault* agreement (mainly for PhD theses) has been renewed several times for periods of 3 to 4 years (the current agreement covers the period *2019-21*). The main research themes covered address the problem of driving assistance (ADAS) and of autonomous driving (AD), with a focus on the safety issue at road intersections (2 PhD theses defended) and on dangerous road situations (PhD thesis to be defended by the end of 2021). This research work has given rise to numerous publications, 2 PhD theses and to several shared patents.
- ***Recent collaboration with EasyMile*** *(since 2018)*: A 2 years collaborative project with EasyMile was launched in 2018 in the scope of IRT Nanoelec. The objective was to adapt our Bayesian Perception approach to the context of autonomous shuttles (the obtained results are confidential). We are still cooperating with EasyMile in the scope of several R&D projects with Renault (FUI Tornado project) and with Iveco (FUI STAR project).
- ***Other related R&D projects*** *(since 2015)*: EU Ecsel *Enable-S3* project *(2015-18, cooperation Renault)*, EU Ecsel *CPS4EU* leaded *(2019-22, cooperation CEA & Valeo)*, SPC *ES3CAP (2018-21, cooperation Kalray)*, PIA *Prissma* (2021-24, under signing, cooperation Vedecom & Institut Eiffel). The main R&D topics addressed in these projects are twofold: *(1) Validation & Certification of new components* of autonomous vehicles (with a focus on Perception and decision-making components), *(2) Improvement of Embedded Perception systems* by combining Bayesian & AI approaches. *See the two next sections.*

○ *Involved Inria team members (eMotion & Chroma)*

Several members (permanent & contractual Researchers, Postdocs, PhD students, Engineers) of the former Inria *eMotion team-project* and of the Inria *Chroma team-project* have actively contributed to the R&D work described in this report *(see first part of this report)*. In addition to my own leadership activity on this research project, several team members continue to contribute (part-time or full-time) to this R&D work:

- Permanent researchers & Engineers: *J. Dibangoye (Ass Prof INSA, part-time), Anne Spalanzani (Ass Prof UGA, part-time), L. Rumelhard (R&D Inria Engineer, full-time).*
- Non-permanent Inria researchers: *A. Renzaglia (SRP[20]), O. Erkent (SRP), D. Sierra-Gonzalez (SRP), A. Gomez-Hernandez (Postdoc).*
- PhD students: *Luiz Serafim-Guardini (PhD thesis Inria-Renault, 3rd year), Manuel Diaz-Zapata (PhD thesis, 1st year)*
- Non-permanent Inria Engineers: *J. Lussereau, T.Genevois, R. Asghar, A. Paigwar, A. Suresh, A. Gonzalez-Moreno.*

2. Bayesian & AI driven Embedded Perception

○ *Brief problem statement & Background*

Perception is known to be one of the main bottlenecks for robot motion autonomy, in particular when navigating in open and dynamic environments is subject to strong real-time and uncertainty constraints. In order to overcome this difficulty, we proposed some years ago a novel paradigm in Robotics called "Bayesian Perception"[21]. The basic idea is to combine a Bayesian filter with a probabilistic grid representation of *both the space and the velocities of the moving entities*. It allows the filtering and the fusion of heterogeneous and uncertain sensors data, by taking into account the history of the sensors measurements, a probabilistic model of both the sensors and the uncertainty, and a dynamic model of the observed objects motions. The core technology is our concept of "*Bayesian Occupancy Filter"* (for constructing "Dynamic Occupancy Grid"), *Figures 2 illustrates [PhD thesis C. Coue, 2004] [1, 2, 4, 7, 35, 42].*

[20] *Scientific Research Position at Inria.*
[21] *The Bayesian programming formalism, initially developed in the eMotion team, pioneered (together with the contemporary work of Thrun, Burgard and Fox) a systematic effort to formalize robotics problems under the Probabilistic Theory. This approach is now pervasive in Robotics.*

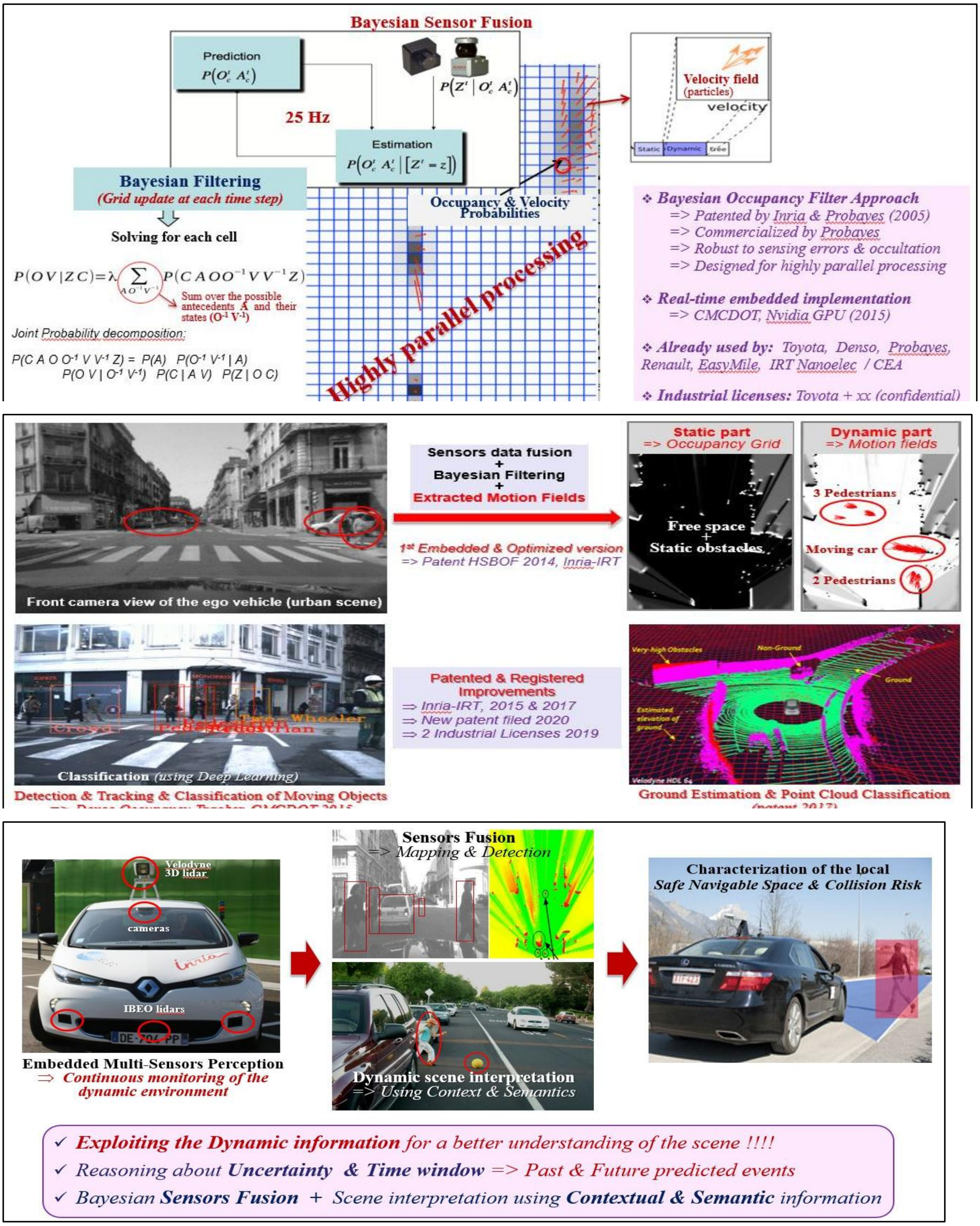

Figure 2: *The Bayesian Perception approach.* ***Top:*** *Bayesian Occupancy Filter paradigm.* ***Middle:*** *Bayesian Filtering Process & Additional features.* ***Bottom:*** *Application to the continuous characterization of the safe navigable space in front of the ego vehicle.*

During the *period 2014-20*, the concept of “Bayesian Perception” has further been developed, expended and valorized. The new version of our Bayesian Perception system is called *CMCDOT* [22]. This research work has given rise to a numerous international publications *[23, 24, 25, 33, 26, 28, 55, 59, 60, 64]*, the PhD defense of Tiana Rakotovao in 2017 *(New models for embedded version on ECU, thesis co-supervised with CEA LETI)*, the filing of several patents, the sale of software licenses to industrial companies, and an ongoing technology transfer with a SME marketing autonomous shuttles, *Figure 3 illustrates (process & results not published because of industrial confidentiality).*

[22] *CMCDOT: Conditional Monte Carlo Dense Occupancy Filter.*

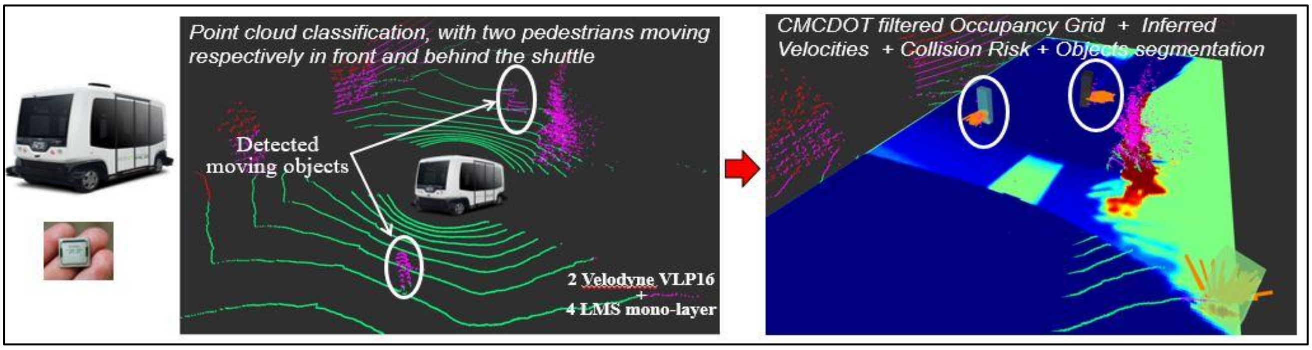

Figure 3: *Integration of the CMCDOT system on a commercial autonomous shuttle (2019). Three main steps: (1) Implemented on Nvidia TX1, (2) Connected to the shuttle control system using ROS, (3) Successfully tested in real-time (at low speed) with the onboard sensors of the shuttle.*

Overview of the R&D agenda and results

As this research line has already reached a good level of maturity, we are going to bend our research work for the next 5 years with the aim to *represent, extract and process semantic information* (in particular by integrating Computer Vision and Deep Learning approaches). Therefore, the main research themes to be emphasized in the coming years are listed below:

- ***New mathematical formulation & implementation of the CMCDOT system.*** The main objective is to improve the efficiency and the robustness of the perception system in *complex and challenging dynamic situations*, while drastically reducing the number of false positives and negatives. New mathematical models & algorithms have recently been developed, implemented and tested. The improvements over to the current version of the *CMCDOT* are significant. Current work focuses on a better integration of *semantic information* in this process, e.g. free space, unknown space, characteristics of static or dynamic obstacle, motion information, clusters of cells having similar properties, motion prediction, collision risk assessment, etc.). A new patent (called *CMCDOT+)* based on some of these improvements has recently been filed.
- ***New concept of "Semantic Occupancy Grid" & Related AI-based approaches.*** The objective is to integrate semantic information in the perception process, in order to have a better understanding of the observed dynamic scenes. To this end, we started 3 years ago to develop models & algorithms to *extract, represent and process semantic information* within the framework of our Bayesian Occupancy Grid formalism. The objective is to build "*Semantic Occupancy Grids"* by fusing *CMCDOT* representations with semantically segmented RGB images (road, sidewalk, buildings, cars, pedestrians, etc.). Our approach relies on the use of *Deep Learning methods* (i.e. using pre-trained high capacity *Deep Neural Networks*), both to perform the semantic segmentation of RGB images and to merge the *CMCDOT* occupancy grids with semantically segmented RGB images, *Figure 4 illustrates [37, 39, 43]*.

  In parallel, we have started to develop additional methods to perform: (1) the *semantic classification of 3D point-clouds* (e.g. ground, obstacles, unknown, etc.) *[34, 54]*, and (2) the *detection & classification of 3D objects in point-clouds* (with or without merging with RGB images) *[51, 50], Figure 5 illustrates*.
- ***AI-based approaches to cope with Varying Weather Conditions and to reason at the Object level.***

  (i) Unsupervised Domain Adaptation: Semantic information provides a valuable source for scene understanding around autonomous vehicles in order to plan their actions and make decisions; however, varying weather conditions reduce the accuracy of the semantic segmentation of RGB images. Deep Neural Networks (DNNs) proved to have a high accuracy and fast implementation in semantic segmentation. However, a tremendous amount of labeled data would be necessary for each weather condition with supervised learning; therefore, we perform *Unsupervised Domain Adaptation (UDA)* so that labeled images are not required for adaptation. The old weather condition is called "source domain" in UDA, while the new weather condition is called "target domain". *Figure 6 illustrates [49]*.

  (ii) Reasoning at the object level: Understanding a complex dynamic scene also requires to reason at the *object level* (i.e. in terms of space occupation, dynamic properties and behavioral models). This is why we have also started to address additional segmentation methods such as *"Instance Segmentation"* or *"Panoptic segmentation"* [23] *[48]*. These methods are still under development as part of Manuel Diaz-Zapata's PhD thesis. The next step is to use this rich semantic information to drastically improve existing *DATMO* [24] approaches, i.e. by inserting a new "classification" step. *This R&D work is carried out as part of our long-term cooperation with Toyota and of the EU project CPS4EU.*

[23] *"Semantic segmentation's" goal is to label an image at the pixel level (grass, sky ...) – "Instance segmentation" focuses on countable objects (people, cars ..) by delimiting them in the image using bounding boxes or segmentation masks – "Panoptic segmentation" combines segmentation and recognition tasks.*

[24] *DATMO: Detection and Tracking of Multiple Objects.*

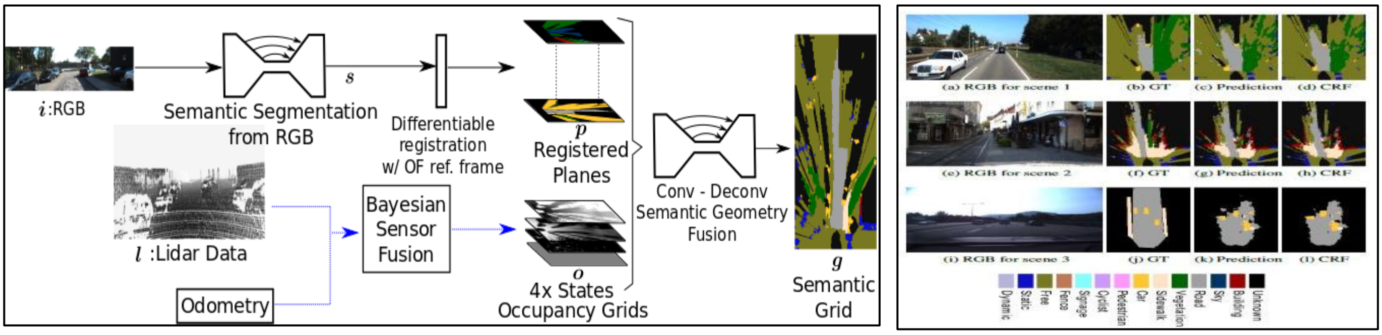

Figure 4: *Constructing "Semantic Occupancy Grid" by fusing CMCDOT Occupancy Grids with semantically segmented RGB images.*
Left: *Overview of the method:* ***i:*** *RGB Image,* ***l:*** *LIDAR data,* ***o:*** *Occupancy grids,* ***s:*** *Output of the segmentation network,* ***p:*** *registered planes as inner representations,* ***g:*** *semantic grid. The continuous black arrows represent the path on which the parameters are learned jointly end-to-end including the registration process, while the blue dotted arrows show the process of the occupancy grid computation.*
Right: *Three scenes with RGB images, Ground Truth (GT), Semantic segmentation predictions (Prediction) and Results of the CRF refinement. Scene 1 and 2 are from Kitti dataset, whereas scene 3 is from our own experimental dataset [43].*

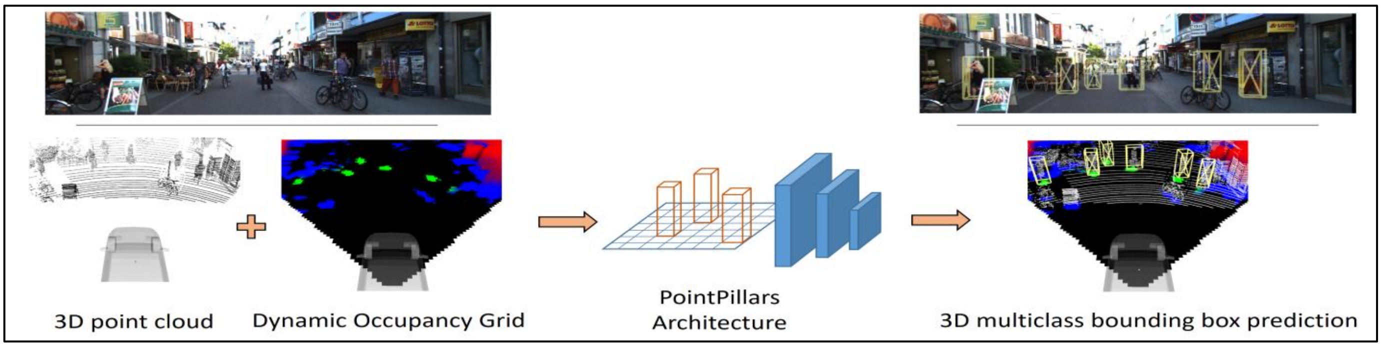

Figure 5: *3D object detection in point clouds leveraging dynamic occupancy grid representations of the environment [51]*

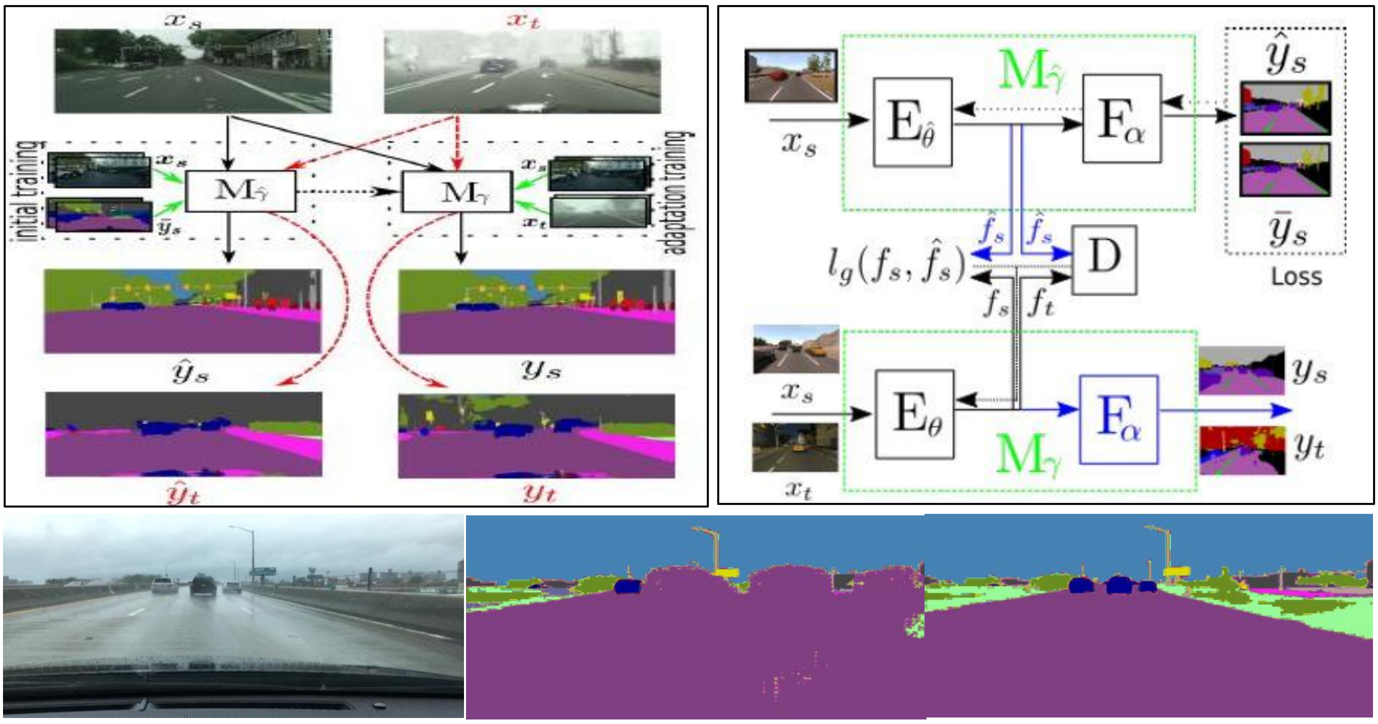

Figure 6: *Illustration of our Deep Neural Network (DNN) approach for Unsupervised Domain Adaptation.*
Top Left: *Adaptation training performed using random RGB images from both "Source domain" (old weather conditions) and "Target domain" (new weather conditions), by using sample images from Foggy Cityscapes Dataset*[25]*. The semantic segmentation model has the architecture of MobileNetV2*[26]*.*
Top Right: *Adaptation with self-supervision of features. Green dotted boxes represent the segmentation model. Dotted black lines represent the back-propagation. Blue lines represent the process without back-propagation.*
Bottom: *Berkley Driving Dataset sample –* ***Left:*** *RGB in rainy;* ***Center:*** *No adaptation (inappropriate segmentation);* ***Right:*** *DLV3 MMD rainy adaptation (road, landscape, 3 cars correctly classified). See [49] for more details.*

[25] *C. Sakaridis, D. Dai, and L. V. Gool, "Semantic Foggy Scene Understanding with Synthetic Data," IJCV 2018.*
[26] *M. Sandler, A. Howard, M. Zhu, A. Zhmoginov, and L. C. Chen, "MobileNetV2: Inverted Residuals and Linear Bottlenecks. CVPR, 2018.*

3. AI-based Situation Awareness & Decision-making for Autonomous Navigation

o *Brief problem statement & Background*

(i) Short-term Motion Prediction & Collision Risk assessment: Predicting the evolution of moving agents perceived in a dynamic and uncertain environment is essential to be able to navigate safely in such an environment (i.e. making the most appropriate navigation decisions in real-time). We recently showed that an interesting property of the Bayesian Perception approach is that it generates *conservative*[27] *short-term predictions* about the likely future evolution of the observed scene, even if the sensing information is temporarily incomplete or not available. See our publications about the *CMCDOT & Collision Risk Assessment approaches [12, 15, 16, 17, 18] [20, 23, 24, 25]*, *Figure 7 illustrates*.

Figure 7: *Illustration of the concept of "Bayesian Short-term Collision Risk" implemented in the CMCDOT system [23, 25]. The approach combines our "Conservative short-term Motion Prediction model" (horizon 3-5 seconds), with a probabilistic estimation of the Collision Risks.*

(ii) Semantic-based Motion Prediction & Situation Awareness: In *environments populated by humans*, the estimation of more abstract properties (e.g. object classes, affordances, agent's intentions and behaviors, etc.) becomes necessary in order to better understand the future[28] evolution of the scene, to be able to predict potential collisions, and therefore to be able to make the most appropriate navigation decisions.

This is why, the main objective of this new line of research is to design an AI-based framework to address the key problem of "Situation Awareness & Decision-making for Autonomous Driving", taking into account the aforementioned features, while overcoming the shortcomings of traditional rules-based reasoning approaches. Indeed, these traditional approaches often work well in low complexity situations, but they also lead to a lack of scalability and mid/long-term forecasting capabilities.

Our approach to solve this problem is to generalize and combine our previously published and patented contributions (obtained through our long-term collaborations with Toyota and Renault respectively), while emphasizing the links between machine learning, motion planning, and decision-making using Dynamic Bayesian Networks (DBN) and / or Partially Observable Markov Decision Processes (POMDP). Our previously developed approach for behavior-based collision risk assessment is illustrated in *Figure 8*. The improvements expected from the introduction of new AI-based methods are discussed in the following sections.

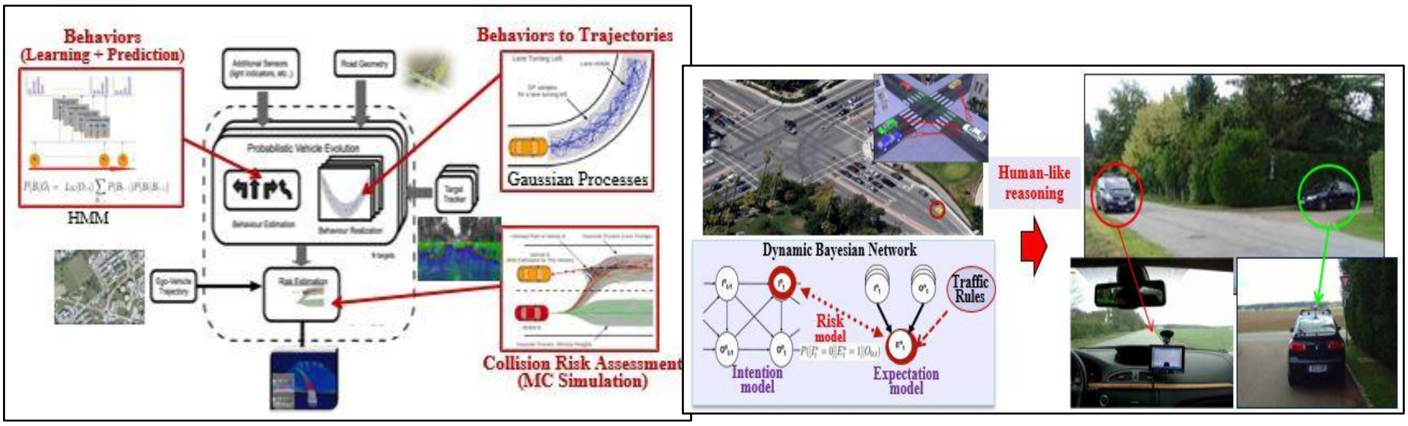

Figure 8: *Mid-term collision risk assessment by reasoning on vehicle's Behaviors & Interactions.*
Left: *Trajectory prediction using objects perception & learned behaviors + Collision risk assessment using Monte-Carlo simulation. Patented by Inria, Toyota and Probayes [12] [Patent n° 4 with Toyota].*
Right*: Collision risk assessment using our "Intention & Expectation" paradigm, implemented using a Dynamic Bayesian Network. This approach is inspired by human reasoning and is has been designed to better take into account the interactions between vehicles in a mixed traffic context (i.e. when some human drivers are in the loop). Best student paper IEEE IV 2012 [17], [Patent n° 5 with Renault], [63].*

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[27] *Conservative short-term prediction: Motion prediction under the assumption that motion parameters are assumed to be stable for a short period of time (typically 3-5 seconds ahead). However, if there is an unexpected dynamic change in the environment during this period of time, the "prediction model" can be updated in less than 40ms.*

[28] *The time horizon considered ranges from a few seconds (e.g. typically 3-5 seconds for the detection of unexpected events), to a longer time interval to generate more elaborate maneuvers taking into account contextual information as well as behavioral and interaction models.*

(iii) Validation & Certification: Autonomous vehicles are in practice *Complex & Critical Cyber Physical Systems (CPS)*, designed to operate under various real-world conditions (high dynamicity, uncertainty, unexpected events, etc.) and to interact with human beings. A few year ago, we started to tackle the open question of the *"Validation & Certification"* of such systems. Indeed, solving this problem is of paramount importance, in order to allow a future deployment of such systems in the daily living space of people. The main idea of our approach is to combine *Realistic Simulation techniques* with *Formal methods*. Some preliminary results have recently been obtained and published by our team within the framework of the *EU Enable-S3* project *[38, 46, 52]*, *Figure 9 & 10 illustrates.*

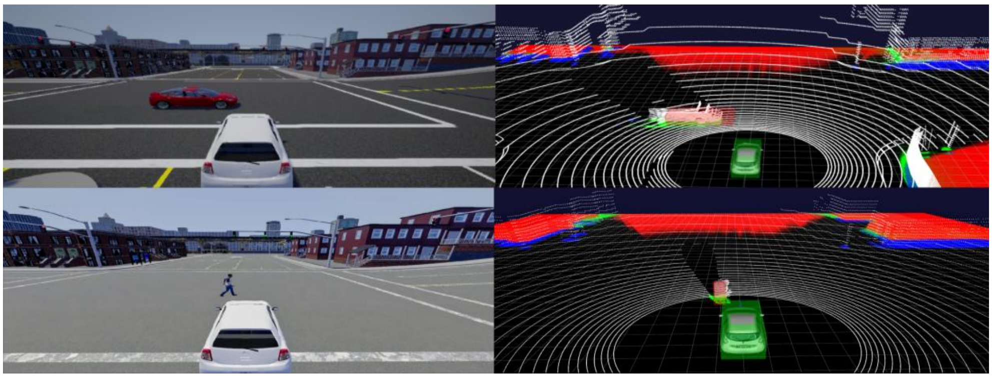


Figure 9: *Validation testing using simulated scenarios.* ***Left:*** *Simulated scenarios in CARLA with the ego-vehicle (white) colliding or not with another vehicle (red) or with a pedestrian crossing the road.* ***Right:*** *Simulated Lidar sensor and corresponding dense occupancy grid generated by the CMCDOT perception system.*

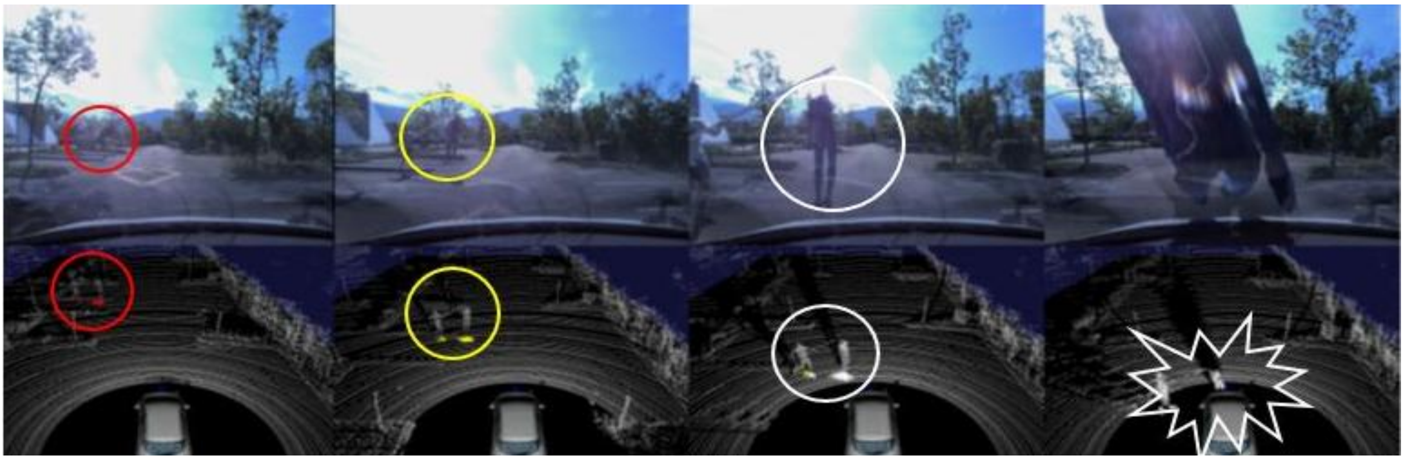


Figure 10: *Illustration of one of the experiments performed with Inria's autonomous car. The scenario reproduces the car colliding with a pedestrian (mannequin) crossing the street [52].*
Top: *Camera view from the car.* ***Bottom:*** *The environment as seen by the Lidar and the CMCDOT "Collision risk grid". The sequence from left to right represents different time stamps. Colors represent the probability of collision in 3s (red), 2s (yellow), 1s (white) and 0s (crash).*

○ *Overview of the R&D agenda and results*

The main objective for the next few years is to extend our current approaches for "dynamic scene understanding & decision making for autonomous driving" *[30, 31, 37, 45, 64] [32, 40, 46]*, in order to be able to cope with *realistic mixed traffic scenarios*. The focus is now on the development of models and algorithms to exploit the mutual benefits of Bayesian and AI approaches, in order to be able to cope with complex mixed traffic scenarios requiring the processing of large data sets and associated semantic information. Emphasis will be placed on the knowledge and learning components of these approaches. In addition, we will continue to develop the validation & certification methods that we have started to address in recent years (by combining realistic simulation and formal methods). Therefore, the main research themes to be highlighted in the coming years are listed below:

- ***Prediction & Semantic Characterization of Collision Risks.*** The main objective of this line of research is to integrate semantic information into the heart of our models for Motion Prediction & Collision Risk assessment. Emphasis is placed on the integration of knowledge learned on the *semantics* of the traffic environment, as well as on *behavioral* & *interaction models* of road users. The main objective is on the one hand to drastically improve the quality of the *predicted motions for all the surrounding traffic participants*, and on the other hand to *semantically characterize* [29] *the risks of collision* between the ego vehicle and the other traffic participants *[63, 64]*. Then, this contextual information can then be leveraged to select the most appropriate and safest navigation or collision avoidance strategy. This research work is closely linked to the concept of "semantic grid" developed within the Bayesian Perception research line presented in the previous section. It also allows us to consider additional criteria such as the "severity of injuries" in collision mitigation scenarios, *Figures 11 & 12 illustrates [53]*. Current work focuses on on-line Planning & Selection of the most appropriate collision avoidance or mitigation trajectories,

[29] ***Semantic Collision Risk:*** *Nature & Severity of the collision risk, Dynamics & Time parameters, Avoidance strategies, etc.*

using an adapted MPPI (Model Predictive Path Integral) approach. *This research work is mainly carried out in the framework of the IRT Nanoelec SVA project, of the PhD thesis of Luiz Serafim-Guardini (in cooperation with Renault) and of the ES3CAP project.*

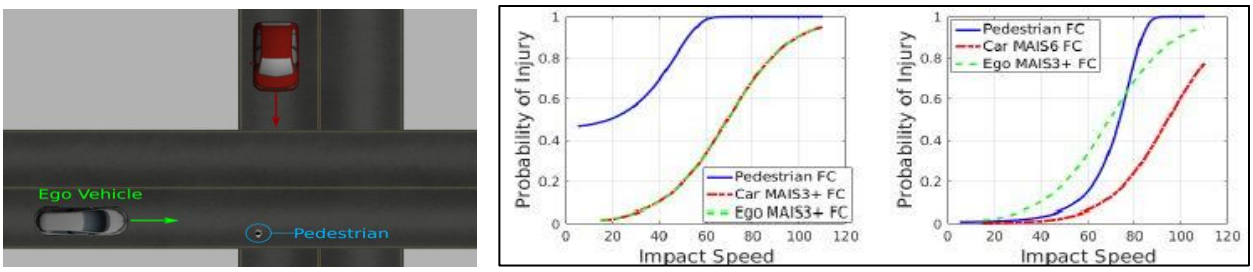


Figure 11: *Illustration of injury curves.* ***Left:*** *Example of scenario.* ***Middle:*** *Vulnerable Road Users (VRU) perspective (safety of vulnerable users takes priority over vehicles).* ***Right:*** *Political/economical point of view (the safety of the occupants of the ego vehicle is a priority).*

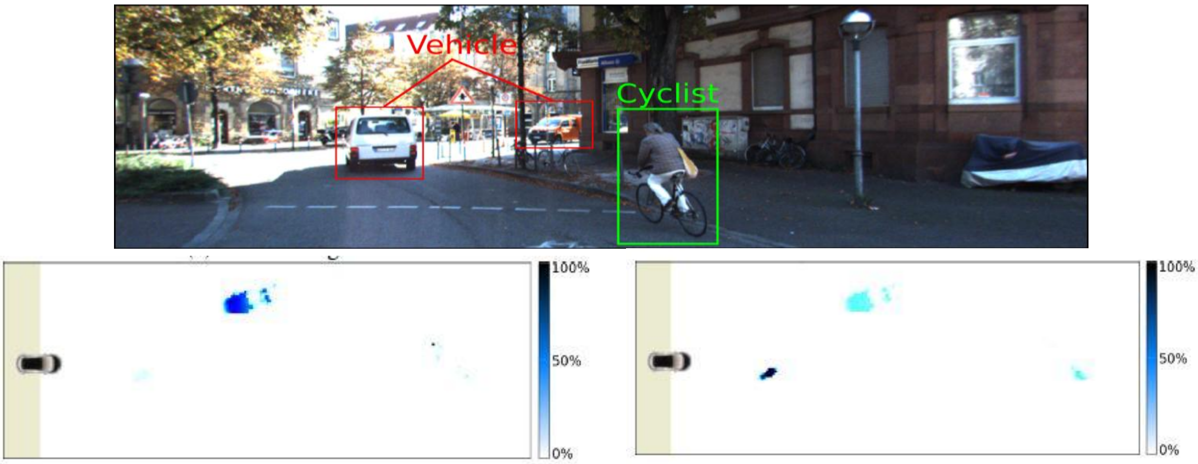
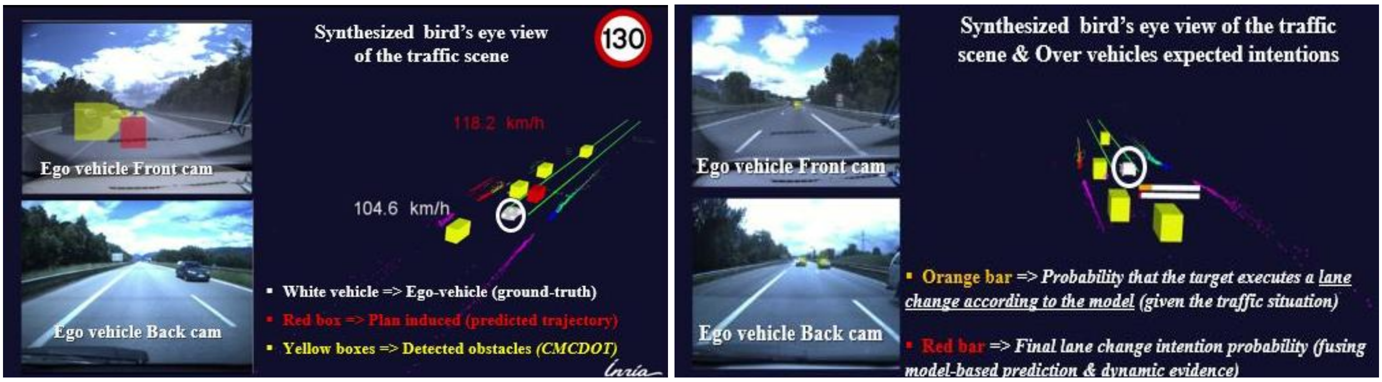


Figure 12: *Probability of Collision with Injury Risk (PCIR) approach, evaluated using KITTI dataset –* ***Top:*** *Scenario analyzed with a classification of moving entities –* ***Bottom left:*** *Results from the VRU perspective –* ***Bottom right:*** *Results for the Economical/political perspective.*

– ***Human-Like Decision-making for Automated Driving.*** Over the past few years, we have started to developed a new IA-based approaches to address the problems of Automated Driving in highways (at high speed) and in Urban road Intersections (at low speed). This research work has given rise to several international publications *[30, 31, 37, 45, 64] [29, 32, 40, 46]*, patents *[Patent n° 7 with UC Berkeley] [Patent n° 10 with Toyota]* and to the PhD theses of David Sierra-Gonzalez and of Mathieu Barbier (respectively in cooperation with Toyota and Renault). *Figure 13 illustrates the approach we are developing for highway environments (in cooperation with Toyota) [30, 31, 37, 45]*.

Our current research work focuses on *Autonomous Driving in mixed traffic mode*[30]**,** while considering various traffic environments and their associated models adaptations (e.g. highways, country roads, urban streets, road intersections, etc.). The main objective is to develop a new framework for *"Human-like decision-making for Automated Driving"*, having the ability to be easily adaptable to a wide class of traffic scenarios (e.g. highways, rural roads or urban environments), as well as different driving modes (full autonomy, driving assistance, mixed traffic mode). By "human-like", we refer to driving actions that respect the traffic rules, show anticipative behavior, avoid collisions (when possible), safely overtake some other vehicles in order to optimize travel time, etc. Another important feature of this approach is to make *autonomous driving decisions more understandable* to other nearby human drivers, and thus reduce the likelihood of collision between an autonomous vehicle and another human driven vehicle.



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[30] *Traffic scenarios in which autonomous vehicles, cars driven by humans and other traffic actors (e.g. pedestrians, cyclists, etc.) share the same space (and therefore interact with each other).*

Figure 13: *Illustration of our approach for Autonomous Driving in highways [PhD thesis David Sierra-Gonzalez, 30, 31, 37, 45, 64].*
Left: *Learn driver behaviors from real driving demonstrations (dataset built using our Lexus vehicle) and Inverse Reinforcement Learning.*
Right: *A realistic human-like driver model is used to Predict the long-term evolution (10s and beyond) of traffic scenes in highways. For short/mid-term, both the "Driver model" and the "Dynamics of the target" provide useful information to determine future driving behaviors. Our probabilistic model fuses Model-based Predictions & Dynamic evidence to produce robust estimate of lane change intentions.*

Indeed, sharing the road with humans constitutes, along with the need for robust perception systems, one of the major challenges slowing the large-scale deployment of automated driving technology. The actions taken by human drivers are determined by a complex set of interdependent factors, which are very hard to model (e.g. intentions, perception, emotions). Therefore, any prediction of human behavior will always be inherently uncertain, and will become even more so as the prediction horizon increases. Then, fully automated vehicles must make navigation decisions based on uncertain states and intentions of surrounding vehicles. *This research work is mainly carried out in the framework of our long-term cooperation with Toyota and of the CPS4EU EU project.*

- ***Validation & Certification using Co-simulation & Formal Methods.*** A few years ago, we started to address the problems of *Validation & Certification* of "on-board Perception & Decision-making components" of future *ADAS* & *AD*[31] systems. This work was initially carried out as part of the *Enable-S3 EU project*, in cooperation with Renault and with the *Tamis* (Inria Rennes) and *Convecs* (Inria Grenoble-Alpes) teams working in the field of Formal Methods. The basic idea is to apply a *"co-simulation approach"* consisting in combining (1) real experiments with an autonomous vehicle, (2) numerous realistic simulations of the same scenario by applying random changes in the values of some parameters, and (3) an analysis of the "execution traces" using a formal method (*e.g. SMC: Statistical Model Checking*) and some selected *"Key Performance Indicators (KPIs)" [52]*. Current and future work will focus on both the realistic co-simulation and formal verification components. *It will mainly be carried out over the next 4 years as part of both the IRT Nanoelec SVA project and the French R&D Prissma project (involving academic research teams and manufacturers from the automotive sector).*

- ***Experimental validation & platforms***
  Real world experiments will continue to be carried out using the Inria & IRT Nanoelec experimental plateforms and several protected test tracks (Figure 14 illustrates). For obvious safety reasons, experiments in real traffic conditions (highways, rural roads, urban areas, etc.) are carried out under the control of an experienced human driver.

Figure 14: *Inria & IRT Nanoelec experimental platforms & Testing facilities (Road intersection, Connected Road Side Unit, Mannequin …).*

4. Publications

A more complete list of publications is available in my extended CV: hal-03147561

Significant publications related to the new research framework *(period 2006-13)*

[1] "Bayesian Occupancy Filtering for Multitarget Tracking: an Automotive Application". C. Coué, C. Pradalier, C. Laugier, T. Fraichard, P. Bessiere. *Int. Journal of Robotics Research*, 2006.

[2] "Efficient GPU-based Construction of Occupancy Grids Using several Laser Range-finders". M. Yguel, O. Aycard, C. Laugier. *International Journal of Autonomous Vehicles*, 2007.

[3] "An Efficient Formulation of the Bayesian Occupation Filter for Target Tracking in Dynamic Environments". C. Tay, K. Mekhnacha, C. Chen, M. Yguel, C. Laugier. *International Journal of Autonomous Vehicles*, 2007.

[4] "Steps Towards Safe Navigation in Open and Dynamic Environments". C. Laugier, D. Vasquez, M. Yguel, T. Fraichard, O. Aycard. *Book "Autonomous navigation in dynamic environments", Edited by C. Laugier and R. Chatila, Springer-Verlag, 2007.*

[31] *ADAS: Advanced Driving Assistance System – AD: Automatic Driving System.*

[5] "The Bayesian Occupation Filter". C. Tay, K. Mekhnacha, M. Yguel, C. Coué, C. Pradalier, C. Laugier, T. Fraichard, P. Bessière. *Book* "*Probabilistic Reasoning and Decision Making in Sensory-Motor Systems", Edited by P. Bessiere, C. Laugier, R. Siegwart, Springer-Verlag,* 2008.

[6] "Intentional Motion On-line Learning and Prediction". D. Vasquez, T. Fraichard, O. Aycard, C. Laugier. *Machine Vision and Applications*, 2008.

[7] "Geometric and Bayesian Models for Safe Navigation in Dynamic Environments". C. Laugier, D. Vasquez, M. Yguel, T. Fraichard, O. Aycard. *Intelligent Service Robotics*, vol.1, 2008.

[8] "Growing Hidden Markov Models: An incremental Tool for Incremental Learning and Predicting Human and Vehicle Motion". D. Vasquez, T. Fraichard, C. Laugier. *International Journal of Robotics Research*, vol.28, nb.11-12, 2009.

[9] "Incremental Learning of Statistical Motion Patterns with Growing Hidden Markov Models". D. Vasquez, T. Fraichard, C. Laugier. *IEEE Transactions on Intelligent Transportation Systems*, 2009.

[10] "Probabilistic motion planning among moving obstacles following typical motion patterns." C. Fulgenzi, A. Spalanzani, C. Laugier. *IEEE/RSJ International Conference on Intelligent Robots and Systems*. St. Louis, Missouri, 2009.

[11] "Error-Driven Refinement of Multi-scale Gaussian Maps Application to 3-D Multi-scale map building, compression and merging". M. Yguel, D. Vasquez, O. Aycard, R. Siegwart, C. Laugier. *International Symposium on Robotics Research*. Lucerne, Switzerland, Oct. 2009.

[12] "Probabilistic Analysis of Dynamic Scenes and Collision Risk Assessment to Improve Driving Safety". C. Laugier, I. Paromtchik, M. Perrollaz, Y. Mao, J.D. Yoder, C. Tay, K. Mechnacha, A. Negre. *Intelligent Transportation Systems Journal* 3.4 , Nov. 2011, pp. 4–19.

[13] "Autonomous Driving: Context and State-of-the-Art". J. Ibanez-Guzman, C. laugier, J.D. Yoder, S. Thrun. *Handbook of Intelligent Vehicles*. Edited by Azim Eskandarian, Vol. 2, Springer, March 2012, pp. 1271–1310.

[14] "A visibility-based Approach for Occupancy Grid Computation in Disparity Space". M. Perrollaz, J.D Yoder, A. Negre, A. Spalanzani, C. Laugier. *IEEE Transactions on Intelligent Transportation Systems* 13.3, March 2012.

[15] "Probabilistic Vehicle Motion Modeling and Risk Estimation". C. Tay, K. Mekhnacha, C. Laugier. *Handbook of Intelligent Vehicles*. Edited by Azim Eskandarian, Vol. 2, Springer, March 2012, pp. 1479–1516.

[16] "Modeling and learning behaviors". D. Vasquez and C. Laugier. *Handbook of Intelligent Vehicles*. Edited by Azim Eskandarian, Springer, March 2012.

[17] "Risk Assessment at Road Intersections: Comparing Intention and Expectation". S. Lefèvre, C. Laugier, J. Ibañez-Guzmán. *IEEE Intelligent Vehicles Symposium*. Alcala de Henares, Spain, 2012, pp. 165–171. ***Best Student Paper.***

[18] "Probabilistic Decision Making for Collision Avoidance Systems: Postponing Decisions". S. Lefevre, C. Laugier, R Bajcsy. IEEE*/RSJ International Conference on Intelligent Robots and Systems, Tokyo, Nov. 2013.*

[19] "Impact of V2X privacy strategies on intersection collision avoidance systems". S. Lefevre, J. Petit, R. Bajcsy, C. Laugier, F. Kargl. *IEEE Vehicular Networking Conference, Boston, United States, 2013.*

Foundational papers: [1], [3], [4], [7], [9], [12], [15], [17], [18]

Significant publications related to the new research framework *(period 2014-20)*

[20] "A survey on motion prediction and risk assessment for intelligent vehicles". S. Lefevre, D. Vasquez, C. Laugier. *Robomech journal, Springer, Issue of July 2014. hal-01053736v1*

[21] "Advances in the Bayesian Occupancy Filter framework using robust motion detection technique for dynamic environment monitoring". Q. Baig, M. Perrollaz, C. Laugier. *IEEE Robotics and Automation Magazine, Institute of Electrical and Electronics Engineers, 2014. hal-00932691v1*

[22] "An open framework for human-like autonomous driving using Inverse Reinforcement Learning". D. Vasquez, Y. Yu, S. Kumar, C. Laugier. *IEEE Vehicle Power and Propulsion Conference, Coimbra, Portugal, 2014. hal-01105271v1*

[23] "Hybrid Sampling Bayesian Occupancy Filter". A. Negre, L. Rummelhard, C. Laugier. *IEEE Intelligent Vehicles Symposium (IV), Jun 2014, Dearborn, United States. 2014. hal-01011703v1*

[24] "Probabilistic Grid-based Collision Risk Prediction for Driving Application". L. Rummelhard, A. Negre, M. Perrollaz, C. Laugier. *International Conference ISER 2014, Marrakech/Essaouira, Morocco. Jun 2014. hal-01011808v1*

[25] "Conditional Monte Carlo Dense Occupancy Filter". L. Rummelhard, A. Negre, C. Laugier. *18th IEEE International Conference on Intelligent Transportation Systems, Las Palmas, Spain, Sept 2015. hal-01205298v1*

[26] "Intelligent Vehicle Perception: Toward the Integration on Embedded Many-core". T. Rakotovao, J. Mottin, D. Puschini, C. Laugier. *IEEE International Workshop on Advanced Robotics and its Social Impacts. ARSO 2015, Lyon, France, July 2015. cea-01176446v1*

[27] "Book Chapter on Intelligent Vehicles". A. Broggi, A. Zelinsky, U. Ozguner, C. Laugier. *Handbook of Robotics 2nd edition, Chapter 62, Edited by B. Siciliano and O. Khatib,, Springer, pp.1627-1656, 2016. hal-01260280v1*

[28] "Integration of Multi-sensor Occupancy Grids into Automotive ECUs". T. Rakotovao, J. Mottin, D. Puschini, C. Laugier. 53rd Annual Design Automation Conference (DAC 2016), Austin, United States, Jun 2016. *cea-01518771v1*

[29] "Functional Discretization of Space Using Gaussian Processes for Road Intersection". M. Barbier, C. Laugier, O. Simonin, J. Ibanez-Guzman. *IEEE 19th International Conference on Intelligent Transportation Systems (ITSC 2016), Rio de Janeiro, Brazil, Nov 2016. hal-01362223v1*

[30] "High-Speed Highway Scene Prediction Based on Driver Models learned from Demonstrations". D. Sierra-Gonzalez, J. Dibangoye, C. Laugier. *IEEE 19th International Conference on Intelligent Transportation Systems (ITSC 2016), Rio de Janeiro, Brazil, Nov 2016. hal-01396047*

[31] "Interaction-Aware Tracking and Lane Change Detection in Highway Scenarios Using Realistic Driver Models". David Sierra-González, Víctor Romero-Cano, Jilles Dibangoye, Christian Laugier. *ICRA 2017 Workshop on Robotics and Vehicular Technologies for Self-driving cars, Singapore, Jun 2017. hal-01534094v1*

[32] "Classification of Drivers Manoeuvre for Road Intersection Crossing with Synthetic and Real Data". Mathieu Barbier, Christian Laugier, Olivier Simonin, Javier Ibanez-Guzman. *2017 IEEE intelligent Vehicles Symposium, Los Angeles, June 2017. hal-01519709v1*

[33] "XDvision: Dense outdoor perception for autonomous vehicles". V. Romero-Cano, C. Laugier, N. Vignard. *IEEE Intelligent Vehicle conference 2017 (IV 2017), Redondo Beach, Los Angeles, June 2017. hal-01672089v1*

[34] "Ground Estimation and Point Cloud Segmentation using SpatioTemporal Conditional Random Field". L. Rummelhard, A. Nègre, A. Paigwar, C. Laugier. *IEEE Intelligent Vehicles Symposium (IV 1017), Redondo Beach, United States, June 2017. hal-01579095v1*

[35] "Embedded Bayesian Perception by Dynamic Occupancy Grid Filtering". L. Rummelhard, C. Laugier. *GTC 2017 - GPU Technology Conference, San Jose, California, United States, May 2017. hal-01672134v1*

[36] "Perception and Automation for Intelligent Mobility in Dynamic Environments". L. Rummerlhard, J. Lussereau, J.A. Alix, C. Laugier, S. Dominguez, Ph. Martinet. *ICRA 2017 Workshop on Robotics and Vehicular Technologies for Self-driving cars, Singapore, June 2017. hal-01592566v1*

[37] "Modeling Driver Behavior from Demonstrations in Dynamic Environments Using Spatiotemporal Lattices". D. Sierra-Gonzalez, O. Erkent, V. Romero-Cano, J. Dibangoye, C. Laugier. *ICRA 2018 - Proceedings of the 2018 IEEE International Conference on Robotics and Automation, Brisbane, Australia, May 2018. hal-01729960v1*

[38] "Statistical Model Checking Applied on Perception and Decision-making Systems for Autonomous Driving". J. Quilbeuf, M. Barbier, L. Rummelhard, C. Laugier, A. Legay. *PPNIV 2018 - 10th Workshop on Planning, Perception and Navigation for Intelligent Vehicles, IROS 2018, Madrid, Spain, Oct 2018. hal-01888556v1*

[39] "Semantic Grid Estimation with a Hybrid Bayesian and Deep Neural Network Approach". O. Erkent, C. Wolf, C. Laugier, D. Sierra-Gonzalez, V. Romero-Cano. *IROS 2018 - IEEE/RSJ International Conference on Intelligent Robots and Systems, Oct 2018, Madrid, Spain, Oct 2018.* hal-01881377v1

[40] "Probabilistic Decision-Making at Road Intersections: Formulation and Quantitative Evaluation". M. Barbier, C. Laugier, O. Simonin, J. Ibanez-Guzman. *ICARCV 2018 – 15th International Conference on Control, Automation, Robotics and Vision, Singapore, Nov 2018. hal-01940392v1*

[41] "Mobile Robots and Autonomous Vehicles". *MOOC edited by C. Laugier & Inria-uTOP* with A. Martinelli & D.Vasquez as co-authors. *Broadcasted 3 times by Inria-uTOP in 2015 & 2016, online version still available since 2017. cel-01256021*

[42] "Tutorial on Autonomous Vehicle Technologies for Perception & Decision-making". C. Laugier. *Tutorial IA2 (Master & Doctoral level), Fall School on AI, Toulouse, Oct. 2018. cel-01969720*

[43] "End-to-End Learning of Semantic Grid Estimation Deep Neural Network with Occupancy Grids". O. Erkent, C. Wolf, and C. Laugier. *Unmanned systems, vol. 7, no. 3, pp. 171-181, Jul. 2019. hal-02302533*

[44] "Driving Behavior Assessment and Anomaly Detection for Intelligent Vehicles". C. Yang, A. Renzaglia, A. Paigwar, C. Laugier, and D. Wang. *IEEE CIS-RAM 2019 - 9th IEEE International Conference on Cybernetics and Intelligent Systems (CIS) Robotics, Automation and Mechatronics (RAM), Bangkok, Thailand, Nov. 2019*. *hal-02355809*

[45] "Human-Like Decision-Making for Automated Driving in Highways". D. Sierra Gonzalez, M. Garzon, J. Dibangoye, and C. Laugier. *IEEE ITSC 2019 - 22nd International Conference on Intelligent Transportation Systems, Auckland, New Zealand, Oct. 2019. hal-02188235*

[46] "Validation Framework Applied to the Decision-Making Process for an Autonomous Vehicle Crossing Road Intersections". M. Barbier, J. Ibanez-Guzman, C. Laugier, O. Simonin. *Book Chapter, Book "Validation and Verification of Autonomous Systems", Springer International Publication, December 2019. hal-02424651v1*

[47] "Vehicle Localization Based on Visual Lane Marking and Topological Map Matching". R. Asghar, M. Garzón, J. Lussereau, C. Laugier. *ICRA 2020 - IEEE International Conference on Robotics and Automation, Paris, France, May 2020. hal-03043594v1*

[48] "Instance Segmentation with Unsupervised Adaptation to Different Domains for Autonomous Vehicles". M. Diaz Zapata, O. Erkent, C. Laugier. *ICARCV 2020 - 16th International Conference on Control, Automation, Robotics and Vision, Singapore, Dec 2020. hal-03041432v1*

[49] "Semantic Segmentation with Unsupervised Domain Adaptation Under Varying Weather Conditions for Autonomous Vehicles". O. Erkent & C. Laugier. *IEEE RAL 2020 - Robotics and Automation Letters, pp. 1-8, May 2020. hal-02502457v1*

[50] "Recognize Moving Objects Around an Autonomous Vehicle Considering a Deep-learning Detector Model and Dynamic Bayesian Occupancy". A.E. Gomez-Hernandez, O. Erkent, C. Laugier. *ICARCV 2020 - 16th International Conference on Control, Automation, Robotics and Vision, Singapore, Dec 2020. hal-03038599v1*

[51] "Leveraging Dynamic Occupancy Grids for 3D Object Detection in Point Clouds". D. Sierra-Gonzalez, A. Paigwar, O. Erkent, J. Dibangoye, C. Laugier. *ICARCV 2020 - 16th International Conference on Control, Automation, Robotics and Vision, Singapore, Dec 2020. hal-03044979v1*

[52] "Probabilistic Collision Risk Estimation for Autonomous Driving: Validation via Statistical Model Checking". A. Paigwar, E. Baranov, A. Renzaglia, C. Laugier, A. Legay. *IV2020 - 31st IEEE Intelligent Vehicles Symposium, Las Vegas, USA, Oct. 2020. hal-02696444v1*

[53] "Employing Severity of Injury to Contextualize Complex Risk Mitigation Scenarios". L.A. Serafim Guardini, A. Spalanzani, C. Laugier, Ph. Martinet, Anh-Lam Do. *IV2020 - 31st IEEE Intelligent Vehicles Symposium, Las Vegas, USA, Oct. 2020. hal-02945325v1*

[54] "GndNet: Fast Ground Plane Estimation and Point Cloud Segmentation for Autonomous Vehicles". A. Paigwar, O. Erkent, D. Sierra-Gonzalez, C. Laugier. *IROS 2020 - IEEE/RSJ International Conference on Intelligent Robots and Systems, Las Vegas, USA, Oct. 2020. hal-02927350v1*

Foundational papers: [20], [23], [24], [25], [28], [30], [31], [37], [38], [39], [40], [46], [48], [52]

Guest Keynote & Plenary lectures *(period 2014-20)*

[55] "Bayesian Perception and Decision: From Theory to Real World Applications". ***Keynote talk*** *at IEEE/RSJ IROS 2014, Chicago, USA, September 2014.*

[56] "Key Technologies for Addressing the Challenge of Autonomous Vehicles". ***Plenary talk*** *at Int. Conf. on Innovations for next generation automobile (INGA'14), Sendai, Japan, October 2014.*

[57] "Technologies for next cars generation". ***Keynote talk*** *at IEEE ICARCV 2014, Plenary session on the "Future of Robotic", Singapore, December 2014.*

[58] "Embedded Bayesian Perception and Risk Assessment for ADAS and Autonomous Cars". ***Keynote Talk*** *at PPNIV-7 workshop, IEEE/RSJ IROS 2015, Hamburg, September 28th 2015.*

[59] "Towards Fully Autonomous Driving ? The Perception & Decision-Making Bottleneck". ***Plenary talk*** *at IEEE ARSO 2016, Shanghai, July 2016.*

[60] "Dynamic Traffic Scene Understanding using Bayesian Sensor Fusion and Motion Prediction". ***Keynote talk*** *at ECCV2018 Workshop "Vision-based Navigation for Autonomous Driving", Munich, Sept 2018.*

[61] "Dynamic Scene Understanding and Upcoming Collision prediction to make Autonomous Driving safer: A Bayesian Approach". ***Plenary Talk***. *International Conference on Robotic Welding, Intelligence and Automation RWIA'2018, Guangzhou (China), Dec 2018.*

[62] "Improving Autonomous Driving Safety through a better Understanding of Traffic Scenes and of Potential Upcoming Collisions". ***Plenary Speech.*** *ICARCV 2018 – Plenary Forum on the "Impact of AI on Robotics and Computer Vision", Singapore, Nov 2018.*

[63] "Impact of AI on Autonomous Driving". ***Keynote talk***. *IEEE World Robotics Conference WRC 2019, Beijing (China), August 2019. hal-02429111*

[64] "A Journey in the history of Automated Driving". ***Pioneer's talk***. *IEEE/RSJ IROS 2019, Macau (China), November 2019. hal-02428196*

[65] "Situation Awareness and Decision-making for Autonomous Driving". ***Keynote talk***. *IEEE/RSJ IROS 2019 Cutting Edge Forum "Robotics, AI and ITS for Autonomous Driving", Macau (China), November 2019.*

Invited Talks & Tutorial *(period 2014-20)*

[66] "Towards Next Car Generation". *Invited talk at Tokyo University (with the support of several Robotics Japanese companies), Tokyo, October 2014.*

[67] "Relever les défis des véhicules autonomies". M. Perrollaz and C. Laugier. *Invited talk at EMM 2014, 12ème rencontres Européennes de Mécatronique, Annecy, France, June 2014.*

[68] "Risk Assessment and Decision-making for Safe Vehicle Navigation under Uncertainty ". *Invited talk at IET Workshop on "Autonomous Vehicles: from the theory to full scale applications", Novotel Paris Les Halles, Paris, June 18th 2015.*

[69] "Bayesian Perception and Decision for Intelligent Mobility". *Invited talk at RII "Smart Cities & Mobility Innovations", San Francisco, May 11th 2015.*

[70] "Bayesian Perception and Decision for next Cars Generation". *Invited talk at Google Self-Driving Cars, Mountain View, May 12th 2015.*

[71] "Bayesian Perception & Decision for Autonomous Vehicles and Mobile Robots". *Invited talk at IEEE ICIT 2016, Session on Cognitive Systems and Automation for Service Robotics and Intelligent Mobility, Taipei, March 2016.*

[72] "Bayesian Perception Technologies and Industrial Applications". C. *Invited talk at Mediatek International Company, Hsinchu, Taiwan, March 15th 2016.*

[73] "Bayesian Perception & Decision for Autonomous vehicles and Mobile Robots". *Invited talk at City-U Seminar, Hong Kong, April 22nd 2016.*

[74] "Embedded Bayesian Perception & Decision-making for Autonomous Mobility in Dynamic Human Environments". *Invited talk at Robotics Symposium, CUHK, T-Stone Robotics Institute, Hong Kong, April 21-22 2016.*

[75] "Perception and Prediction for Autonomous Driving". *Invited talk, 4ème Journée sur la Mobilité Innovante, Clermont-Ferrand, January 2017.*

[76] "Embedded Bayesian Perception for Autonomous Driving". *Invited talk, IS-Auto Europe 2017, Dusseldorf, April 2017.*

[77] "Bayesian Perception & Decision-making for Autonomous Vehicles and Mobile Robots". ***Invited tutorial*** *at Beijing Institute of Technology (BIT), Beijing, May 2017.*

[78] "Embedded Bayesian Perception and Collision Risk Assessment". *Invited talk, ICRA 2017 Workshop on Robotics and Vehicular Technologies for Self-driving cars, Jun 2017, Singapore.*

[79] "Autonomous Vehicles Technologies for Perception and Decision-Making". ***Invited Tutorial***. *Institut d'Automne en IA 2018 (IA2 2018), Campus ISAEE-Supaero, Toulouse, Oct 2018.*

[80] "Dynamic Traffic Scene Understanding: Analysis, Prediction and Collision Risk Assessment". *Invited Talk. Conference SMIV 2018 on "Smart Mobility & Intelligent Vehicle", Versailles, Nov 2018.*

[81] "Embedded Sensor Fusion and Perception for Autonomous Vehicles". *Invited talk. International conference IS Auto Europe 2019, Berlin (Germany), April 2019. hal-02434279*

[82] "Mixing Bayesian and AI approaches for Autonomous Driving". *Invited talk. Technological Conference Minalogic B2B 2019, Grenoble (France), May 2019.*

[83] "Embedded Perception & Decision-making for Safe Navigation in Uncertain, Dynamic and Human Environments". *Invited talk. French Coboteam workshop on "Robots Navigation", on-line event, May 28th 2020.*

[84] "Digital Trust for Autonomous Vehicles". *Invited talk. Annual Scientific Event of the Technological Research Institute (IRT) Nanoelec, In-person event & Web broadcast, Minatec Grenoble, Sept 8th 2020.*

[85] "Increasing Driving Safety: Perception & Assessment of Collision Risks with other Road Users". *Invited talk. Workshop « Safety of Autonomous Vehicles», Final scientific event of the French Tornado R&D Project, Paris, on-line event, Nov 5th 2020.*

Patents

[1] "Automatic Parallel Parking for cars" (1996). *I. Paromtchik & C. Laugier – Patent application cancelled because of prior partial disclosure.*

[2] "Bayesian Occupancy Filter – Initial concept" (2005). *C. Coue, C. Laugier, P. Bessiere, T. Fraichard – Patent hold by Inria.*

[3] "Bayesian Occupancy Filter – Improved industrial version" (2005). *M. Yguel, C. Laugier, K. Mekhnacha – Patent hold by Inria & Probayes SA (Commercialized in the ProBT library of Probayes SA).*

[4] "Continuous collision risk assessment for improving vehicle safety" (2010). *C. Tay, C. Laugier, K. Mekhnacha, E. Mazer, H. Yanaghihara, G. Othmezouri, K. Sakai – Patent hold by Inria, Toyota, Probayes.*

[5] "Collision risk assessment at roads intersections" (2012). *S. Lefevre, C. Laugier, J. Ibanez-Guzman – Patent hold by Inria & Renault.*

[6] "Methods and apparatus for improving driving safety" (2013). *I. Paromtchik & C. Laugier – Patent hold by Inria.*

[7] "Decision making for collision avoidance systems" (2013). *S. Lefevre, C. Laugier, R. Bajcsy – Patent hold by Inria & UC Berkeley.*

[8] "Dynamic scene analysis method and associated analysis module and computer programme" (2015). *C. Laugier, A. Negre, M. Perrollaz, L. Rummelhard – Patent hold by Inria & CNRS & CEA / IRT Nanoelec.*

[9] "Dispositif informatique pour l'aide à la conduite" (2017). *L. Rummelhard, A. Negre, C. Laugier – Patent hold by Inria & CEA / IRT Nanoelec.*

[10] "Driving Assistance Method and System" (2017*). D. Sierra-Gonzalez, V. Romero-Cano, C. Laugier, J. Dibangoye, N. Vignard – Patent hold by Inria & Toyota.*

[11] "Semantic Occupancy Grid Estimation" (2018). *O. Erkent, C. Laugier, C. Wolf, N. Vignard – Patent hold by Inria & Toyota.*

[12] "Computerized device for driving assistance" (2020). *L. Rummelhard, C. Laugier, A. Negre – Patent under application by Inria & CEA / IRT Nanoelec.*

Some recent videos

- https://www.youtube.com/watch?v=RFtfaLm8x9o
  Video Inria entitled "The car of the future, making life easier for drivers" – *C. Laugier, eMotion team, 2014.*

- https://www.youtube.com/watch?v=TDaK3Yku8OA
  Video Inria about "Bayesian Perception Technologies for Intelligent Mobility" – *C. Laugier, Inria-Industry Summit Meeting about "Smart City and Mobility Innovations", San Francisco, May 2015.*

- *https://www.youtube.com/watch?v=uwIrk1TLFiM*
  Video illustrating the "Embedded Bayesian Perception paradigm" – *C. Laugier 2016.*

- medihal-01963296v1
  Video "CMCDOT framework to Autonomous Navigation" – *L. Rummelhard, J.A. David, J. Lussereau, T. Genevois, C. Laugier. Vehicle demonstration event at IEEE/RSJ IROS 2018 (Madrid), Oct 2018.*

- *https://hal.inria.fr/hal-03088658*
  Video & Paper on Pioneer work on automatic parking "Automatic Parallel Parking and Returning to Traffic Maneuvers" – *I. Paromtchik & C. Laugier, Proceedings IROS 1997 (Prior related publications at ICRA 1996 and IV 1996).*